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Carbon dioxide capture —

Part 2:
Evaluation procedure to assure and maintain stable performance of post-combustion CO$_2$ capture plant integrated with a power plant

Captage du dioxyde de carbone —

Partie 2: Mode opératoire d'évaluation pour assurer et maintenir une performance stable du captage du CO$_2$ post-combustion intégré à une centrale thermique

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 265, *Carbon dioxide capture, transportation, and geological storage*.

A list of all parts in the ISO 27919 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Atmospheric carbon dioxide (CO_2) emissions must be reduced to meet climate change mitigation targets. Including carbon dioxide capture and storage (CCS) in current emission reduction approaches increases the probability of meeting these targets at the lowest cost to the global economy. CO_2 capture from gases produced by combustion of carbonaceous fuels is the only technology capable of dealing directly with emissions from power plants and other industrial sectors, such as cement manufacture and fertilizer production.

This document is the second in a series of standards for post-combustion CO_2 capture (PCC) from a power plant using a liquid-based chemical absorption process. Building on ISO 27919-1 on evaluation of key performance indicators (KPIs), this document provides an evaluation procedure to assure and maintain reliable performance of a PCC plant integrated with a power plant. New or revised standards focusing on other CO_2 capture technologies and approaches will be developed later.

PCC is applicable to all combustion-based thermal power plants. A simplified block diagram illustrating the PCC process is shown in Figure 1.
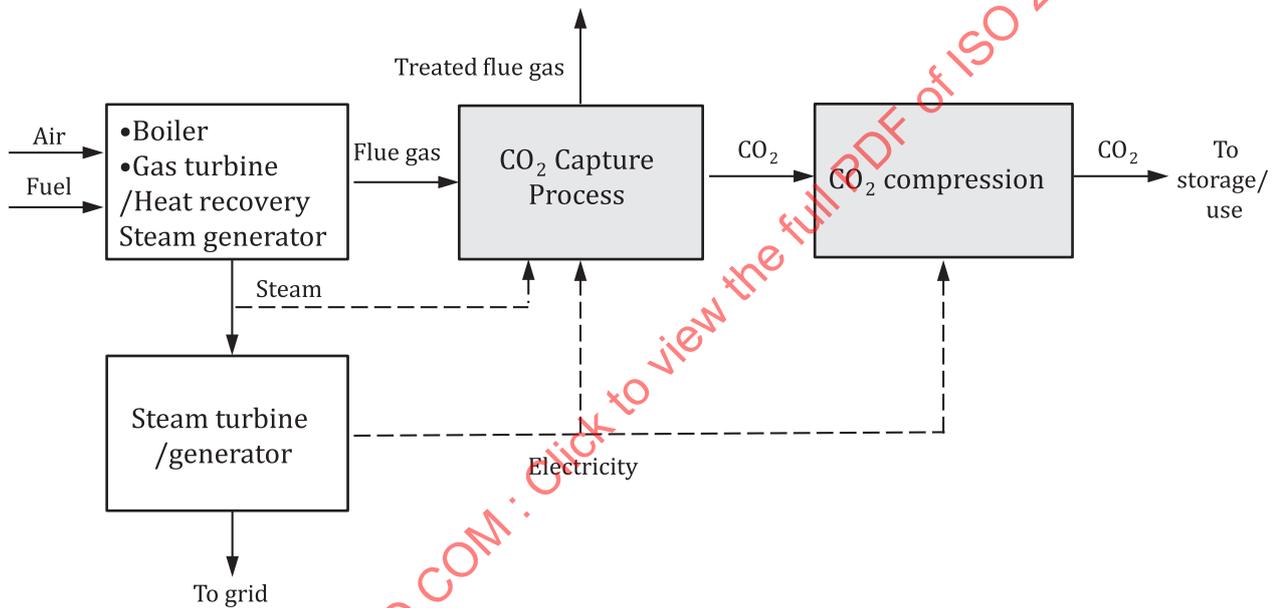
Figure 1 — Simplified block diagram of PCC

In a typical power generation facility, carbonaceous fuel (e.g. coal, oil, gas, biomass) is combusted with air in a boiler to raise steam. The steam drives a turbine or generator to produce power. In a gas-turbine combined-cycle system, the combustion in the gas turbine drives power generation, while steam generated through a heat-recovery steam generator produces additional power. Flue gas from the boiler or gas turbine consists mostly of N_2, CO_2, H_2O and O_2, with smaller amounts of other compounds depending on the fuel used. The PCC process is located downstream of conventional pollutant controls. Chemical-absorption-based PCC usually requires steam to be extracted from the power plant's steam cycle or the use of lower-grade heat sources for absorption liquid regeneration, depending on the absorption liquid and process employed.

The economic and environmental value of a PCC plant is determined by its technical performance, as well as its ability to achieve and maintain stable operation as required by its owners/stakeholders, as follows:

— The owner of the flue gas source has an interest in sustained CO_2-emission reductions.

— The owner of the CO_2-product has an interest being able to supply CO_2 at the desired rate regardless of external conditions.

The CO$_2$ receiver has an interest in CO$_2$-product availability for its own operations.

Thus, this document describes a procedure that combines technology item evaluation procedure with reliability, availability, and in some cases maintainability evaluation methods.

Carbon dioxide capture —

Part 2:
Evaluation procedure to assure and maintain stable performance of post-combustion CO_2 capture plant integrated with a power plant

1　Scope

This document provides definitions, guidelines and supporting information for evaluating and reporting (with respect to the basic design items ongoing, and the operational results of a reference plant or unit as feedback) to ensure the (designed) performance of a PCC plant integrated with a host power plant. The PCC plant separates CO_2 from the power plant flue gas in preparation for subsequent transportation and geological storage. The physical system being addressed is a single power plant, with an optional auxiliary unit to provide thermal energy required for the PCC plant, and a single PCC plant as described in ISO 27919-1.

The formulas and methods to assure and maintain reliable performance, presented in this document, describe issues addressed during the design and construction phases and practices that document reliability and availability during routine operation. These practices would also guide ongoing maintenance programmes.

This document does not provide guidelines for benchmark, comparison or assessment studies for PCC plant operations using different capture technologies (i.e. absorbents), nor does it specify appropriate operating conditions such as temperature etc.

2　Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 27919-1, *Carbon dioxide capture — Part 1: Performance evaluation methods for post-combustion CO_2 capture integrated with a power plant*

3　Terms, definitions, abbreviated terms and symbols

For the purposes of this document, the following terms and definitions apply.

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

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1　Terms and definitions

3.1.1
administrative delay
delay to maintenance incurred for administrative reasons

[SOURCE: IEC 60050-192 (192-7-12), modified — "maintenance action" was changed to "maintenance"]

3.1.2
availability
ability of a *PCC plant* (3.1.20) integrated with the power plant to be in a state to perform as required under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

3.1.3
corrective maintenance
maintenance carried out after fault detection to effect restoration

Note 1 to entry: Corrective maintenance of items disrupts the plant availability.

3.1.4
derated
derating
difference between the maximum and the dependable one, or such a condition

Note 1 to entry: For derated hours, it means operating time with the rated output lowered.

3.1.5
downtime
time interval for which the *item* (3.1.9) is in a state of being unable to perform as required due to internal faults, or *preventive maintenance* (3.1.24)

Note 1 to entry: unavailable time

3.1.6
emergency operation
type of sudden *shut-down* (3.1.36) operation to protect hardware from damage

3.1.7
external influence
critical subjects occurring outside the *PCC plant* (3.1.21) evaluation boundary

3.1.8
failure mechanism
process that leads to failure

Note 1 to entry: The process may be physical, chemical, logical, or a combination thereof.

[SOURCE: IEC 60050-192:2015, 192-03-12]

3.1.9
item
subject being considered

Note 1 to entry: An item may be an individual part, component, device, functional or process unit, equipment, subsystem, or system, related with technology.

Note 2 to entry: An item may consist of hardware, software, people or any combination thereof.

[SOURCE: IEC 60050-192:2015, 192-01-01, modified — "functional unit" was changed to "functional or process unit" and "system" was changed to "related with technology" in Note 1. Note 3 to Note 5 were deleted.]

3.1.10
logistic delay
delay, excluding *administrative delay* (3.1.1), incurred for the provision of resources needed for a *maintenance* (3.1.12) action to proceed or continue

[SOURCE: ISO 20815:2018, 3.1.24]

3.1.11
maintainability
ability to be retained in, or restored to, a state in which the required function can be performed under given conditions

3.1.12
maintenance
combination of all technical and management actions intended to retain an *item* (3.1.9) in, or restore it to, a state in which it can perform as required

Note 1 to entry: Management is assumed to include supervision activities.

[SOURCE: IEC 60050-192:2015, 192-06-01]

3.1.13
mean downtime
MDT
average of the *downtime* (3.1.5)

[SOURCE: IEC 60050-192:2015, 192-08-10]

3.1.14
mean time between failures
MTBF
average time between failures that initiate a forced *outage* (3.1.20), i.e. the quotient of attempted operating hours to the number of forced *outages* (3.1.20)

3.1.15
meantime between maintenance
MTBM
average time between *maintenance* (3.1.12), i.e. the quotient of attempted operating hours to the number of *maintenance* (3.1.12)

3.1.16
mission time
duration of the mission

Note 1 to entry: Mission is the state that the equipment or system is 100 % operational.

[SOURCE: ISO 10438-1:2007, 3.1.19]

3.1.17
nominal product CO_2 capacity
NC
highest continuous flow rate of delivering captured CO_2 under typical representative conditions defined by the plant operator

3.1.18
normal operation
operation where the product CO_2 is exported to the transporting system maintaining the required performance based on ISO 27919-1

3.1.19
on-stream factor
OSF
ratio of the summation of all on-stream time to the *reference period* (3.1.31), with both expressed as hours

3.1.20
outage
time interval for which the *item* (3.1.9) is in a state of being unable to perform as required, for any reason

[SOURCE: IEC 60050-192:2015, 192-02-19, modified — "a disabled state" was changed to "a state of being unable to perform as required, for any reason"]

3.1.21
PCC plant
process and associated equipment that produces a CO_2 stream from combustion gases

[SOURCE: ISO 27919-1:2018, 3.1.26]

3.1.22
PCC plant capacity availability
PCA
availability (3.1.2) of *PCC plant* (3.1.21) from a perspective of *product CO$_2$ amount* (3.1.26) during a *reference period* (3.1.31)

Note 1 to entry: It is mathematically defined by Formula (3).

3.1.23
PCC plant load
ratio of the *product CO$_2$ capacity* (3.1.27) in operation to the *'nominal product CO$_2$ capacity'* (3.1.17)

3.1.24
preventive maintenance
maintenance (3.1.12) carried out in accordance with an established time schedule and performed according to a prescribed criterion

Note 1 to entry: See also condition-based maintenance (IEC 60050-192:2015, 192-06-07), and scheduled maintenance (IEC 60050-192:2015, 192-06-12).

[SOURCE: ISO 23815-1:2007, modified — "criteria" was changed to "criterion". The Note and the following text were deleted "in order to reduce the probability of failure or the degradation of the functioning of a crane"].

3.1.25
project cycle
series of phases of which a project consists, e.g. basic design, engineering, manufacturing, commissioning and operation

3.1.26
product CO$_2$ amount
volume, moles or mass of CO_2 resulting from the PCC process

3.1.27
product CO$_2$ capacity
total flow rate of the captured CO_2 exported

Note 1 to entry: It is generally expressed as product CO_2 amount per hour.

3.1.28
product CO$_2$ producibility
PCPB
ratio of the *product CO$_2$ amount* (3.1.26) produced to the *nominal product CO$_2$ capacity* (3.1.17) accumulated during the *reference period* (3.1.31)

3.1.29
proven technology element
element with low or acceptable uncertainty levels

3.1.30
redundancy
item (3.1.9) where an equivalent unit can be put online to provide the same function if the *item* (3.1.9) fail to provide the service

Note 1 to entry: Redundancy is related to a strategy of design, where a spare system or component is provided so that, even if one item fails, the spare system or component will operate in place of the deficient item such that plant performance is not affected.

3.1.31
reference period
RP
period of time between an initial time and an end time over which all historical or projected performance metrics are measured or projected

Note 1 to entry: Reference period is equivalent to period hours.

3.1.32
reliability
measure of the probability of success for an operation and, the ability of each *item* (3.1.9) to perform its intended function as needed in an assembled *PCC plant* (3.1.20) during a given time interval within the designed conditions without failure

3.1.33
reliable performance
ability of a *PCC plant* (3.1.21) to function reliably as required

3.1.34
schedule compliance
SC
ratio of the *product CO_2 amount* (3.1.26) produced to the scheduled CO_2 product amount requirement met (historical) or to be met (projected) by the *PCC plant* (3.1.21) within a given time period

3.1.35
service hours
accumulated period of time during stand-by and *normal operation* (3.1.18) including *start-up* (3.1.39) and *shut-down* (3.1.36) in between[SOURCE: ISO 3977-9:1999, 3.98, modified — "from main flame ignition through to flame extinction" was replaced by " during stand-by and normal operation including start-up and shut-down in between"].

3.1.36
shut-down
event during which all required function of a *PCC plant* (3.1.21), and its equipment, is brought from an operating state to a stoppage state under the control of a programmed sequence

3.1.37
stand-by state
non-operating up state ready to start

3.1.38
starting reliability
SR
probability of successful *start-up* (3.1.39) when the *PCC plant* (3.1.21) is on stream within a specified period

3.1.39
start-up
act of getting a *PCC plant* (3.1.21) and its equipment from a stoppage state ready to activate its *items* (3.1.9) to an operating state

5

3.1.40
technical delay
accumulated time necessary to perform auxiliary technical actions associated with the *maintenance* (3.1.12) action itself

3.1.41
time availability
TA
ratio of the subtraction of the summation of each element of the *PCC plant* (3.1.21) unavailable time from the *reference period* (3.1.31) to the *reference period* (3.1.31)

Note 1 to entry: Available time is calculated by subtraction of the unavailable time from reference period.

3.1.42
time reliability
TR
ratio of the subtraction of *PCC plant* (3.1.21) unavailable time from the time between preventative *maintenance* (3.1.12) to the time between preventative *maintenance* (3.1.12)

3.1.43
unavailability
PCC plant (3.1.21) is not in a state to perform as required due to an internal faults or *preventive maintenance* (3.1.24)

3.1.44
uptime
time interval during which a *PCC plant* (3.1.21) is in a state of being able to perform as required

Note 1 to entry: Absence of necessary external resources may prevent operation but does not affect.

Note 2 to entry: Available time.

3.2   Abbreviated terms

CCS   carbon dioxide capture and storage

DSS   daily start-up and stop

EHS   environment, health and safety

KPIs   key performance indicators

MAD   mean administrative delay

MDT   mean downtime

MLD   mean logistic delay

MR   mission reliability

MTBF   mean time between failure

MTPM   mean time to preventive maintenance

MTTR   mean time to repair

NC   nominal product CO_2 capacity

NPC   nominal product CO_2

OSF on-stream factor

OST summation of each element of on-stream time

PCA PCC plant capacity availability

PCC post-combustion CO_2 capture

PCP product CO_2 produced

PCPB product CO_2 producibility

PCNP product CO_2 not produced

RAM reliability, availability and maintainability

RP reference period

SC schedule compliance

SPC scheduled product CO_2

SR starting reliability

TA time availability

TBPM time between preventative maintenance

TQ technology qualification

TR time reliability

UT unavailable time

3.3 Symbols

n_{FO} number of forced outages

n_{FS} number of failures to start-up

n_{SA} number of starting attempts

n_{SS} number of successful start-ups

$PC_{nominal}$ nominal product CO_2 capacity [t/h]

PR_{BSPC} bonus production in excess of the planned capacity to make up the shortage of product CO_2 production compared with SPC [t]

PR_{NPC} amount [t] of NPC accumulated during the RP [t], calculated using Formula (4)

PR_{PCP} product CO_2 amount produced [t]

PR_{PCU} accumulation of the amount [t] of PCNP due to PCC plant capacity unavailability (excluding external influences) during the RP [t], calculated using Formula (5)

PR_{SPC} scheduled product CO_2 amount [t]

PR_{SSPC} shortage in product CO_2 amount compared to the scheduled during the RP [t]

t mission time in hours [h]

$t_{preventive}$ time period for preventive maintenance (planned) [h]

t_{repair} time period for repair as corrective maintenance (unplanned) [h]

T_{EPDH} equivalent planned derated hours [h], defined as the product of planned derated hours [h] and the size of the reduced capacity[t/h], divided by the NC [t/h] accumulated during the RP [h]; EPDH may be caused by planned outages or capacity reduction resulting from planned maintenance.

T_{ESEDH} equivalent seasonal derated hours [h], defined as the product of the NC [t/h] minus the net dependable capacity [t/h] and the available hours [h], divided by the NC [t/h] accumulated during the RP [h]; ESEDH may be caused by seasonal weather conditions.

T_{EUDH} equivalent unplanned derated hours [h], defined as the product of the unplanned reduced capacity hours [h] and the size of the reduced capacity[t/h], divided by the NC [t/h] accumulated during the RP[h]; EUDH may be caused by forced outages or capacity reduction resulting from unplanned repairs.

T_{FOH} forced outage hours [h]

T_{MDT} MDT comprises of T_{MTTR}, T_{MTPM}, T_{MAD} and T_{MLD} in the case of long-term operation [h].

T_{MTBM} meantime between maintenance [h]

T_{OST} summation of each element of on-stream time [h]

T_{PH} period hours [h]

T_{POH} planned outage hours [h]

T_{RP} reference period [h]

T_{RSH} reserve shut-down or service hours [h]

T_{SH} service hours [h]

T_{TBPM} time [h] between preventative maintenance (TBPM), specifically the period of continuous operation between the shut-down overhaul-based maintenance and the next

T_{UTRP} accumulation of the PCC plant UT (i.e. downtime) during the RP [h] calculated using Formula (2)

T_{UTTBPM} accumulation of PCC plant UT [h] during TBPM (excluding the time period for preventive maintenance)

e base of the natural logarithm

λ failure rate in events per hour

4 Principles

4.1 General

This document describes technology item evaluation procedure with reliability, availability, and in some cases maintainability evaluation methods.

The evaluation procedure in this document assumes the following:

a) A PCC plant shall be designed, manufactured and constructed in line with proven and established engineering practices during the whole project cycle.

b) A PCC plant design may be a combination of proven technology items with some novel items that can contribute to improving the performance and/or economy of construction or operation. The level of novelty is related to the technological readiness of the applied technology items.

c) A shut-down of the PCC plant does not cause immediate stoppage of the upstream power plant.

d) A PCC plant is a maintainable system and availability may be improved if maintainability as well as reliability of each technology item is improved through feedback of operational results, etc.

This document focuses only on critical items and parameters in terms of impact of reliability/availability/maintainability. Noncritical items and noncritical parameters will not be covered.

4.2 Reliable performance

Reliable performance depends on having a PCC plant that performs as required.

Reliable performance has two aspects:

a) that the required performance is satisfied at the initial conditions;

b) that it is maintained during a defined period.

4.3 Ensuring and maintaining reliable performance

For a PCC plant to perform as required over the project cycle the following should be addressed:

a) basic concepts of availability, reliability and maintainability – refer to Clause 5;

b) guidelines for ensuring reliable performance at delivery in terms of design – refer to Clause 6;

c) guidelines for adequate monitoring and for evaluating reliable performance in terms of operation and maintenance – refer to Clause 7 and Clause 8;

d) guidelines for reporting availability – refer to Clause 9 based on Clause 6, Clause 7 and Clause 8.

4.4 Procedure outline

4.4.1 Outline of procedure flow

The evaluation procedure consists of process steps 1 to 6 crossing through actions in the related project cycle phases and the block flow diagram in Figure 2 should be referred to. Process steps 1 to 3 are categorized as normative and outlined with each reference clause. Process step 2 (Details) and 4 to 6 are categorized as informative and also outlined similarly.
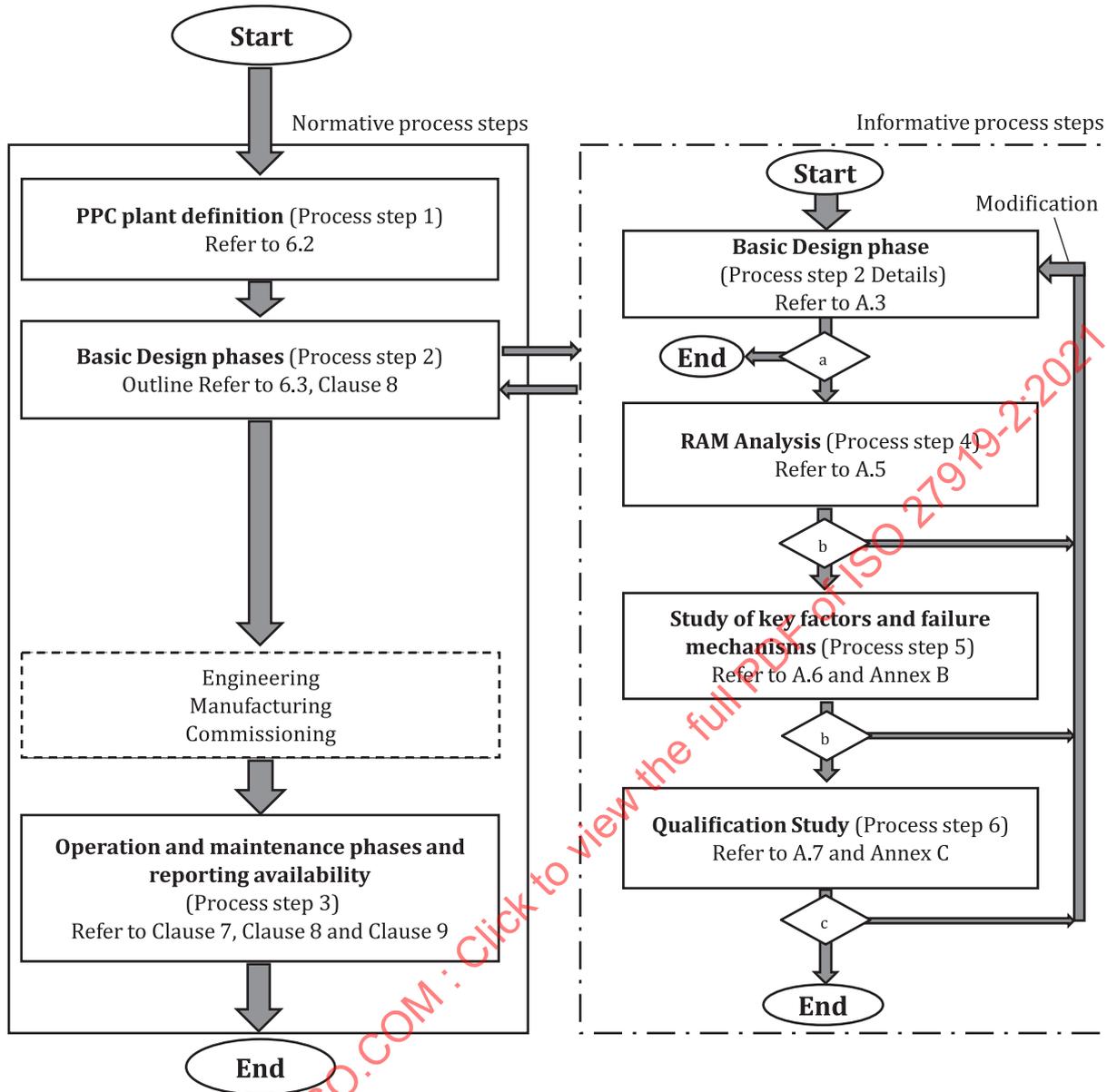
a   If novel items do not exist, go to End and otherwise go down.

b   If novel items become managed or can be treated in the next process step, go down and otherwise return to process step 2 (Details) for modification.

c   If novel items, related to the above process steps become managed, go to End and otherwise return to process step 2 (Details) for modification including abandonment of applied design.

NOTE   Novel item means novel technology items.

Figure 2 — Block flow diagram of evaluation procedure

4.4.2   Process step 1 to 3 outline — Main part

a)   Process step 1 – PCC plant definition

The PCC plant definition sets the basis for the evaluation. The basic design requirement data for a PCC plant should be referred to in 6.2.

NOTE 1   These data are normally provided by the operator side except some performance values, when they are proposed by the supplier.

b) Process step 2 – Basic design phase in the project cycle

The outline should be referred to 6.3 and details should be referred to in A.3. Applied technology shall be completely described as the basis for evaluation.

The following points should be done through previous experience and research and development results:

— review and risk management of key items and parameters; and

NOTE 2   Key items and parameters are normally provided by the supplier.

— review and risk management of operational limits to the PCC design and process.

Refer to A.3.

c) Process step 3 – Operation and maintenance phase in the project cycle

Maintenance and monitoring of the PCC process shall occur to produce the evidence of reliable performance. Refer to Clause 7, Clause 8 and Clause 9.

4.4.3   Process step 4 to 6 outline — Evaluations of items peculiar to a PCC plant with some uncertainty

a) Process step 4 –RAM analysis including definitions of the reliability for each item

The effect of reliability of each item on the overall PCC plant availability should be analysed and quantified. If the availability target is not met, the design should be improved.

b) Process step 5 – Study of key factors and failure mechanisms

The uncertainties in items caused from the gap of the related parameters between experience and the applied design remaining in process step 2 (Details) (e.g. due to items peculiar to a PCC plant) should be qualitatively evaluated from the perspective of possible risk.

In case of significant gaps between PCC experience or research and development and the design requirement for key items and parameters, a study of key factors and failure mechanisms should be conducted.

c) Process step 6 – Qualification study or reporting

Qualification study can be used to manage the risk related to novel items remaining by providing evidence to reduce uncertainties. Refer to A.7 and Annex C.

4.5   Governing principles

The following principles shall govern the evaluation procedure in the above process steps:

a) An overall plan for the evaluation process shall be prepared at the basic design phase. The plan shall include technical considerations and reporting requirements considering all the operating conditions of a PCC plant defined in Clause 7. The plan shall support the management, data collection, control and reporting of the evaluation activities as described in Clause 6 to Clause 9.

b) A basis for the evaluation (i.e. complete design requirements and descriptions of applied design in various documents and drawings depending on importance of technical items and the project situation) shall be developed as described in Clause 6 (6.2: process step 1 and 6.3: process step 2). Additional information on evaluation basis is given in ISO/TR 27912 and ISO 27919-1.

c) Relevant acceptance criteria for reliability, availability and maintainability targets for both the novel technological items, if they exist, and overall PCC plant shall be specified in process step in 6.2. Before quantitative targets are set, the approximate impact of the costs of demonstrating compliance should be considered.

d) Screening of the PCC plant technology items shall be evaluated and screened based on analysing the experience from a reference plant or similar plant and research and development results to classify items (components, interface conditions, etc.) into proven and novel items. Novelty suggests involvement of new technical items which include new component types or changes of critical sizing parameters, or may include the case when known items have not previously been used within required limits of operation (6.3: process step 2).

For proven technology items, one may refer to engineering practices.

For novel technology items, a preliminary assessment of the reliability may be performed using available data. If there is insufficient data, the novel technology items may be replaced by proven technology items.

e) All evidence shall be reported and updated with operational experience after plant commission (typically after one year of operation) for the purpose of review or to provide feedback with tangible evidence as instructed (Clause 7, Clause 8 and Clause 9).

The required functions of the PCC plant under given conditions should be evaluated to:

1) confirm that the plant reaches its expected reliable performance (calculated at the basic design phase);

2) make potential adjustments to operation;

3) optimize maintenance activities (Clause 7, 8 and 9: process step 3).

5 Availability, reliability and maintainability - basic concepts for a PCC plant

5.1 General

This clause provides basic concepts of availability, reliability and maintainability for reporting and evaluation of reliable performance applied to a PCC plant. It comprises:

— spatial, temporal and ambient condition evaluation boundary;

— evaluation and quantification of availability;

— evaluation and quantification of reliability;

— evaluation and quantification of maintainability;

— combined aspect of availability, reliability and maintainability;

— unavailability (three categories).

The performance index considered in this clause are:

a) for availability as KPI (refer to 5.3):

— time availability (TA);

— PCC plant capacity availability (PCA);

b) for reliability (refer to 5.4):

— mission reliability (MR);

— mean time between failures (MTBF);

— time reliability (TR);

— starting reliability (SR);

c) for maintainability (refer to 5.5):

— mean time to repair (MTTR);

— mean time to preventive maintenance (MTPM).

See Annex F for a calculation example of performance index.

5.2 Spatial and temporal evaluation boundary

The PCC plant spatial evaluation boundary shall be limited to the area intrinsic or essential to a PCC plant as specified in ISO 27919-1. However, this will depend on the technology used and individual projects.

A typical reference period (RP) for recording operation performance is a period between plant commissioning following a plant-wide maintenance activity and the next shutdown overhaul-based maintenance. This shall be carried out repeatedly between plant commissioning and plant closure, as required.

5.3 Evaluation and quantification of availability

Availability comprises both used and unused abilities of the PCC plant to deliver product CO_2 independent of the PCC plant load. Availability remains the same as long as the reduced ability to perform a required function is not a consequence of internal faults, or preventive maintenance.

Availability can be quantified as:

a) ratio of uptime [h] to the RP [h], called TA, expressed as a percentage;

b) ratio of the amount of actual available product CO_2 [t] to the NPC accumulated during the RP [h], expressed as a percentage. This ratio is PCA.

TA is quantified using Formula (1):

$$TA = \frac{T_{RP} - T_{UTRP}}{T_{RP}} \times 100 \tag{1}$$

where

TA is time availability [%];

T_{RP} is the reference period [h];

T_{UTRP} is accumulation of the PCC plant UT (i.e. downtime) during the RP [h] calculated using Formula (2).

$$T_{UTRP} = \Sigma t_{preventive} + \Sigma t_{repair} \tag{2}$$

where

$t_{preventive}$ is the time period for preventive maintenance (planned) [h];

t_{repair} is the time period for repair as corrective maintenance (unplanned) [h].

Any availability may be evaluated by substituting the time-based elements defined above with various forms of element having the basic relationship with time, which may formulate various definitions of availability. The above can be applied for the production amount-based elements.

PCA is the ratio of the difference between the total amount of NPC accumulated and product CO_2 amount not produced due to PCC plant unavailability to the total amount of NPC accumulated during the RP

and is calculated in [Formula (3)](#). *PCA* is expressed as a percentage in consideration of the temporary capacity reduction due to internal faults, or preventive maintenance.

$$PCA = \frac{PR_{\text{NPC}} - PR_{\text{PCU}}}{PR_{\text{NPC}}} \times 100 \tag{3}$$

where

    PCA   is PCC plant capacity availability [%];

    PR_{NPC} is amount [t] of NPC accumulated during the RP [t], calculated using [Formula (4)](#);

    PR_{PCU} is accumulation of the amount [t] of PCNP due to PCC plant capacity unavailability (excluding external influences) during the RP [t], calculated using [Formula (5)](#).

$$PR_{\text{NPC}} = PC_{\text{nominal}} \times T_{\text{RP}} \tag{4}$$

where

    T_{RP} is the total number of hours during the RP [h];

    PC_{nominal} is nominal product CO_2 capacity [t/h].

$$PR_{\text{PCU}} = PC_{\text{nominal}} \times (T_{\text{EUDH}} + T_{\text{EPDH}} + T_{\text{ESEDH}}) \tag{5}$$

where

    T_{EUDH} is equivalent unplanned derated hours [h], defined as the product of the unplanned reduced capacity hours [h] and the size of the reduced capacity[t/h], divided by the NC [t/h] accumulated during the RP [h]; EUDH may be caused by forced outages or capacity reduction resulting from unplanned repairs;

    T_{EPDH} is equivalent planned derated hours [h], defined as the product of planned reduced hours [h] and the size of the reduced capacity [t/h], divided by the NC [t/h] accumulated during the RP [h]; EPDH may be caused by planned outages or capacity reduction resulting from planned maintenance;

    T_{ESEDH} is equivalent seasonal derated hours [h], defined as the product of the NC [t/h] minus the net dependable capacity [t/h] and the available hours [h], divided by the NC [t/h] accumulated during the RP [h]; ESEDH may be caused by seasonal weather conditions.

5.4 Evaluation and quantification of reliability

MR is the reliability at a time point as a function of the mission time elapsed. MR can, for instance, be expressed by the exponential lifetime distribution if the failure rate is constant during mission time using [Formula (6)](#) (see Reference [1]).

$$MR = e^{-\lambda t} \tag{6}$$

where

MR is mission reliability;

e   is the base of the natural logarithm;

λ is the failure rate in events per hour;

t is the mission time in hours [h].

The reliability of each item during operation of the entire process can be calculated from MTBF [h]. The MTBF of a PCC plant is calculated using Formula (7) (see Reference [1]).

$$MTBF = \frac{T_{PH} - (T_{RSH} + T_{FOH} + T_{POH})}{n_{FO}} = \frac{T_{SH}}{n_{FO}}$$ (7)

where

MTBF is mean time between failures;

T_{PH} is the period hours [h];

T_{RSH} is the reserve shut-down or service hours [h];

T_{FOH} is the forced outage hours [h];

T_{POH} is the planned outage hours [h];

T_{SH} is the service hours [h];

n_{FO} is the number of forced outages.

Figure 3 is to help understanding of time-related terms in Formula (7) to calculate the above terms by operation record.

Key
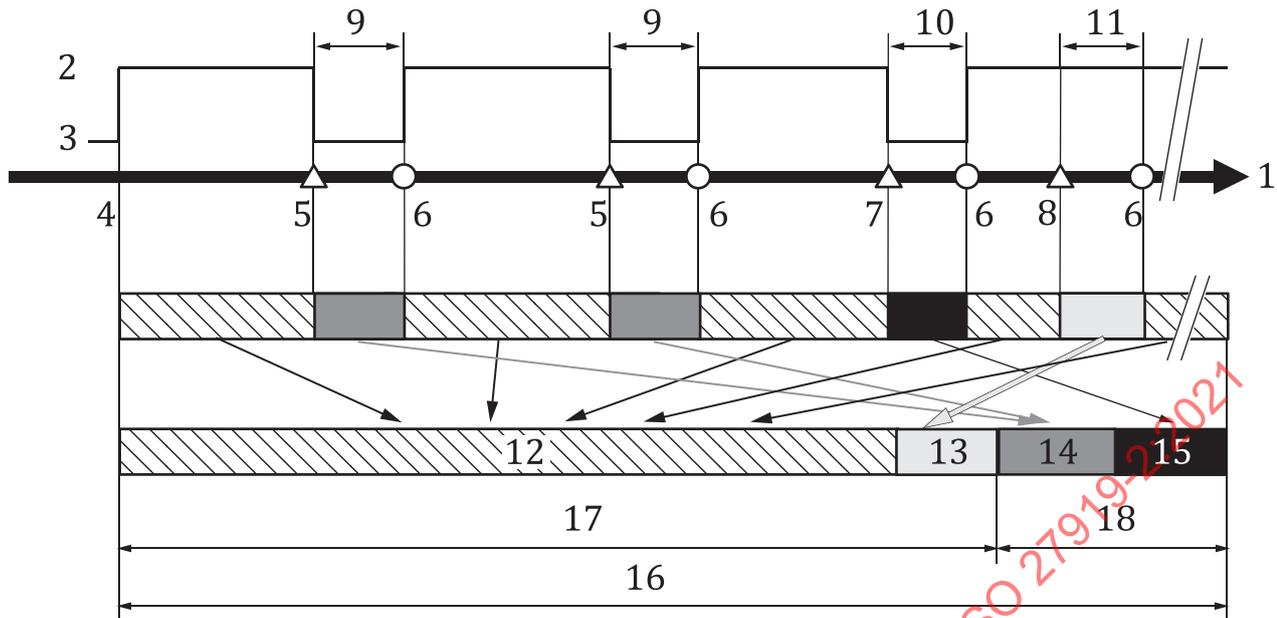
1	time at a PCC plant (hour)	10	preventive maintenance hour
2	uptime	11	reserve shut-down hour
3	downtime	12	T_{SH} (service hours)
4	start-up	13	T_{RSH} (reserve shut-down or service hours)
5	forced outage	14	T_{FOH} (forced outage hours)
6	resume (restart)	15	T_{POH} (planned outage hours)
7	planned outage	16	T_{PH} (period hours)
8	reserve shut-down	17	available hours
9	corrective maintenance hour for repair	18	unavailable hours

Figure 3 — Supplementary explanation for Formula (7)

Reliability defined as the probability that a system will perform a specified function within prescribed limits during a certain period can be expressed by MR. In this case, a larger MTBF results in higher reliability since the failure rate in MR can be 1/MTBF. Then, MTBF figures are often used to project how likely a single unit will fail within a certain period of time.

TR can express the ability of a system to perform its intended function during a given intervals. To calculate TR, Formula (1) for TA can be modified by excluding the preventive maintenance period (see Formula (8)).

Note that MTBF is not always an appropriate index for evaluating the reliability of a PCC plant that is not operating continuously. This is because the chances to perform maintenance during a stoppage can be used to avoid a forced outage of a PCC plant.

$$TR = \frac{T_{TBPM} - T_{UTTBPM}}{T_{TBPM}} \times 100 \tag{8}$$

where

TR is time reliability [%];

T_{TBPM} is the time [h] between preventative maintenance (TBPM), specifically the period of continuous operation between the shut-down overhaul-based maintenance and the next;

T_{UTTBPM} is the accumulation of PCC plant UT [h] during TBPM (excluding the time period for preventive maintenance).

SR is calculated using Formula (9) and is used to evaluate the transient performance of a PCC plant whose operation includes frequent start-up (see Reference [1]).

$$SR = \frac{n_{\text{SS}}}{n_{\text{SS}} + n_{\text{FS}}} = \frac{n_{\text{SS}}}{n_{\text{SA}}} \times 100 \tag{9}$$

where

SR is starting reliability [%];

n_{SS} is the number of successful start-ups;

n_{FS} is the number of failures to start-up;

n_{SA} is the number of starting attempts.

Successful start-ups are when the PCC plant is on-stream within a specified period as evidenced by the export of the product CO_2 or reliable operation of the system through a starting attempt.

A starting attempt is action intended to bring a PCC plant from shut-down to the on-stream state within a specified time limit and both two (starting and ending) conditions should be defined clearly.

5.5 Evaluation and quantification of maintainability

Maintainability is the aspect of maintenance that takes downtime into account and can be measured as the probability that a failed PCC plant can be restored to an operational effective condition within the time interval given by a maintenance action, performed under stated conditions and using specified procedures and resources.

Then, maintainability is quantified by the MTTR [h] through corrective maintenance and the MTPM [h] in the case of long-term operation.

In evaluating maintainability, MTTR and MTPM may be affected by factors other than technical requirement. In such case, logistic and administrative delays should be removed from the evaluation.

5.6 Combined aspect of availability, reliability and maintainability

Availability is generally calculated as a percentage using Formula (10):

$$Availability = \frac{T_{\text{MTBM}}}{T_{\text{MTBM}} + T_{\text{MDT}}} \times 100 \tag{10}$$

where

T_{MTBM} is mean time between maintenance [h];

T_{MDT} is MDT comprised of T_{MTTR}, T_{MTPM}, T_{MAD} and T_{MLD} in the case of long-term operation [h].

NOTE   This availability is called "operational availability".

MTBM and MTBF are indicators for reliability. Because a PCC plant is a maintainable system, availability is affected by MDT.

Therefore, availability may be improved if maintainability and reliability are improved. Those relationships are shown in Figure 4.
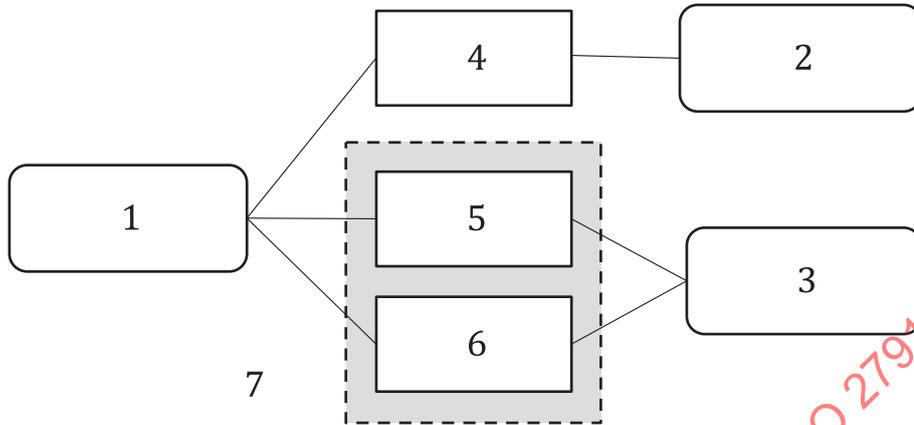
Key

1 availability
2 reliability
3 maintainability
4 MTBM or MTBF
5 MTTR
6 MTPM
7 MDT in addition with MAD and MLD

Figure 4 — Relationships between availability, reliability and maintainability

5.7 Unavailability (three categories)

Unavailability comprises the following hierarchy of events. These can be improved by design knowledge of applied process and monitoring, especially in cases of processes without enough operational experience as explained in a) of 8.2.

a) Unavailability that is foreseen (planned).

b) Unavailability that is unforeseen but with optional postponement (unplanned postponable).

c) Unavailability that is unforeseen but with infeasible postponement (unplanned not postponable).

Unavailability which may have the minimum time limit notice required to complete all necessary preparations should be classified as foreseen (planned). An unplanned postponable event can have an optional minimum hour notice to be ready for the job work order. These values, which may be time available for preparation indicated in 8.1 a) and 8.1 b), should be defined by the user or operator based on its project characteristics.

6 Defining reliability, availability and maintainability in the basic design phase

6.1 General

The evaluation procedure starts at the design phase and consists of PCC plant definition (process step 1) and basic design phase (process step 2) according to 4.4 and 4.5.

6.2 PCC plant description

a) The description of a PCC plant should include basic design requirements and its application conditions, including definition governed by the following information needed for design:

   1) PCC plant configuration, the evaluation boundary and each interface location;

   NOTE 1   Process units and components allocated within each train.

   NOTE 2   Interfaces with other technical systems, physical environment, other operators and persons.

   NOTE 3   Refer to ISO 27919-1:2018, Figure 1.

   2) design conditions at each interface;

   NOTE 4   Flue gas, utilities, chemicals, atmospheric site conditions and other heat transfer media as illustrated in Annex G.

   3) performance requirements of a PCC plant;

   NOTE 5   KPIs, basic performance and utilities consumption defined in ISO 27919-1 are proposed by the supplier and are listed here as performance targets to be confirmed by calculation from interface figures.

   4) interface requirements mandated by a regulatory authority including Health, Safety and Environment.

   NOTE 6   This is outside of requirements other than specified in ISO 27919-1 and is for reference.

b) a reference load pattern;

   NOTE 7   This is a basic operational load pattern considered in the design. The basic load pattern defined in Clause 7 with respect to the product CO2 delivery. Load patterns can influence the PCC plant design and component selection.

c) requirements for performance and stability, if any.

   NOTE 8   As described in ISO 27919-1:2018 (Annex B).

   1) steady state operating ranges from minimum load (%) to maximum load (%) including 100 % (normal) load;

   2) transient conditions due to operational load change or start-up and shut-down.

6.3 Basic design phase

Basic design herein should be understood as preliminary PCC feed. A basic design shall be conducted in accordance with the PCC plant (6.2). Different approaches are needed for equipment/components that are commercially available and for novel equipment/components. The assessment should require evaluation of practical experience and research and development activities. It assumes maintainability targets are achieved. Subsequently the basic design shall be reviewed resulting in an assessment of the PCC plant reliability and availability. The method in informative process step in Figure 2 may be utilised for this purpose. The informative process steps should be followed for the novel equipment/components.

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7 Determining reliability and availability in the operational phase

7.1 General

The performance considered while evaluating availability is limited to those periods when the PCC plant is under controlled operation, without shut-down due to issues with the PCC plant. The availability performance needs to be specified with the requirements for performance monitoring.

The operating results shall be reviewed using KPIs introduced below. The PCC plant treats flue gas, whose acceptable composition depends on the operational characteristics of the absorbents used. The absorbent is subject to degradation, which should be identified as a monitored parameter specified.

Basic load patterns cover the whole process from start-up and off-line conditions and normal operation to shut-down.

Availability is the sum of the values of the representative parameters depending on the KPIs in each load pattern under evaluation. Performance during ramp-up is not defined here. In case frequent shutdowns occur, start-up reliability should be evaluated.

However, for the PCC plant to meet the operability and economical operation requirements of the host power plant, the PCC plant shall meet the requirements of the flue gas source (the host power plant) and shall not impose constraints on this operation during the transient condition of the start-up, shut-down and emergency shut-down with subsequent restart.

7.2 Review of operation result

Availability monitoring on a newly built PCC plant shall be started after successful completion of the performance tests.

KPIs related to operation are introduced below in addition to those introduced in the design phase:

a) PCPB (produced amount basis; refer to 9.2)

b) SC (produced amount basis considering excess capacity with use of the allowance to achieve the production amount target; refer to 9.3)

c) OSF (operating time basis record; refer to 9.5)

The main activities are reporting actual operation results clearly and uniformly through the metric of KPIs introduced in a), b) and c) over the RP.

7.3 Basic load pattern for evaluation and reporting of operation

a) The load pattern for a PCC plant is composed of combinations of the different operational modes, which can be described as follows:

1) normal operation (transient and steady; refer to 7.4);

2) start-up and shut-down (including off-line intervals between these operations; refer to 7.5);

3) emergency operation (refer to 7.6);

4) downtime (for maintenance, modification, repair, etc.; refer to 7.7).

b) Figure 5 gives a typical load pattern and Figure 6 gives the operation diagram where the position of each operational mode is indicated with the different shaded band below its horizontal axis.

Load patterns may vary, depending on commercial conditions such as CO_2 demand from the downstream side and/or reduction of CO_2 emissions. These conditions are governed by external influences, such as host power plant load, feed flue gas volume as feedstock, and limitations of utility supply. These external influences should be made clear.

If a host power plant load or feed flue gas volume is critical, most commonly a PCC plant will follow the host power plant load with the PCC plant load pattern being similar to that of the host plant.

Load patterns are listed in 1) to 5) below and conceptually described in Figure 5:

1) full continuous load;

2) demand of the product CO_2 amount as base load;

3) demand of the product CO_2 amount as intermittent load;

4) daily cycling (or DSS);

5) demand of the peak product CO_2 amount.

There are user specific requirements on the load pattern.

Performance during the steady state comes after transient conditions as described in 7.4.

c) The reference or typical load pattern for a PCC plant shall be defined in the design phase. Measurement of the actual pattern is necessary, since it influences availability and reliability by changing stress levels and environmental conditions, if these differ remarkably from the design conditions. The following parameters shall be determined for the characterisation of the load pattern in addition:

1) MTBF;

2) first start and/or ramp up rate requirement;

3) annual number of the PCC plant forced outage;

4) MDT for the preventive maintenance.

A PCC plant that operates only at low capacity due to low load operation of the power plant is considered fully available in terms of time, while PCPB defined in Formula (11) relates to the amount of PCP.

Key
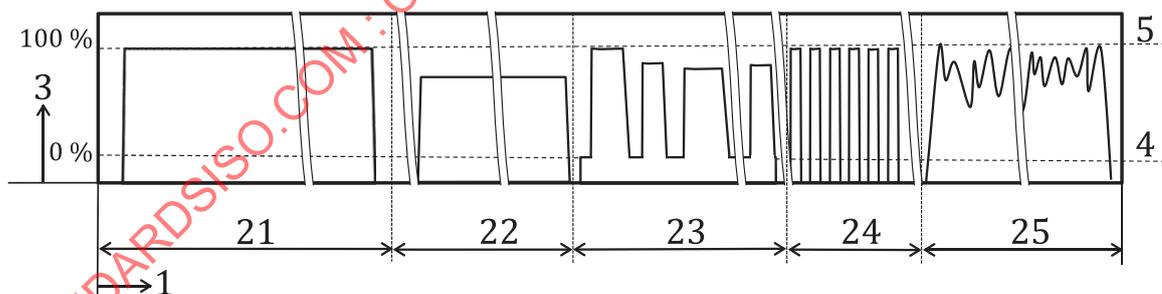
1	time at a PCC plant	21	full continuous load
3	PCC plant load	22	demand of product CO_2 amount as base load
4	minimum load [%]	23	demand of product CO_2 amount as intermittent load
5	nominal load [%]	24	daily cycling (or DSS)
		25	demand of the peak product CO_2 amount

Figure 5 — Typical load pattern for a PCC plant

Key

1	time at a PCC plant	11	shut-down
2	reference period	12	emergency shut-down
3	PCC plant load	13	stoppage due to external influence
4	minimum load [%]	14	product CO_2 export start
5	nominal load [%]	15	product CO_2 export stop
6	actual PCC plant load [%]	16	some technical anomaly or sign relating with trouble which forces reduction of the PCC plant load detected
7	actual capacity of CO_2 provided from the host power plant expressed as percentage after being divided by the nominal capacity of a PCC plant [%]	17	host power plant trip
8	downtime (for maintenance)	18	emergency trip
9	start-up or restart	19	preparation start of host power plant to outage
10	normal operation (transient and steady)		

Figure 6 — Typical load pattern for a PCC plant

7.4 Normal operation (transient and steady)

Normal operation is the PCC plant producing the product CO_2, as indicated by the shaded time period corresponding to key 10 in Figure 6. This includes both steady states and typical transient states.

Normal operation requirements are as follows.

a) The tolerance requirement (the allowable fluctuations range) of performance should be clearly defined and enumerated at the time of evaluation depending on each project and be satisfied during steady state conditions at typical stable full and partial load operation.

   The PCC plant should operate at the minimum load specified that satisfies the stability according to the requirement of the flue gas supply source. At this time, it may be necessary to solve the issues of a lower operating threshold such as a liquid distribution balance within the system.

b) Regarding operation under transient conditions, it shall be confirmed that the PCC plant can be operated without problems when PCC plant load (by 1.3.27) changes from minimum to 100 % and vice versa. The operational load of the PCC plant should be adjusted according to the speed of change in the maximum load (for example, 5 %/min) on the host power plant.

c) KPIs on energy requirement shall be determined as described in ISO 27919-1.

7.5 Start-up and shut-down

Start-up and shut-down are indicated by the shaded time period corresponding to keys 9 and 11 respectively in Figure 6.

Start-up includes the acceptance of the flue gas and preparation of the product CO_2 for transportation. Captured CO_2 produced during start-up but before confirmation of stable production is not considered product CO_2.

PCA during start-up should be interpreted based on the reason for the previous shut-down (internal faults or external influences), since start-ups are inevitably required after shut-down and product CO_2 cannot be exported in this period.

Shut-down of a PCC plant should be performed according to the safe minimum circulation to be ready for re-start depending on the circumstances.

Figure 7 defines the off-line condition according to the readiness (or process temperature) for start-up, considering the operating time required to achieve the goal. It also defines various start-up patterns (activation patterns) of the PCC plant. As an example, the above start-up conditions can be described in terms of in turbine operation regarding start-up and shut-down.

The above definitions of the starting point and the end point are also necessary to clarify the required ramping speed and start-up time according to various start-up patterns of the PCC plant in Figure 7. SR [Formula (9)] is determined by the off-line condition of the PCC plant in Figure 7. When evaluating SR, the starting point may be the hot (stand-by) state, and the goal may be the normal operation state where a PCC plant load should be specified between minimum and nominal. The starting point is quantified with the time period required by the above starting attempt.
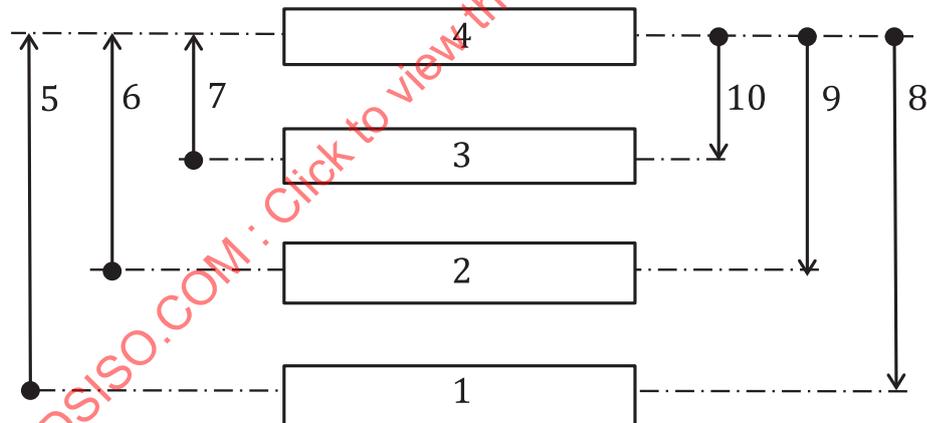
Key

1	cold condition (Long term off-line condition)	6	warm start
2	warm-up state (Short term off-line condition)	7	hot start
3	hot (Stand-by) state (off-line condition)	8	shut-down to cold condition
4	normal operation state	9	shut-down to warm-up state
5	cold start	10	shut-down to stand-by state

Figure 7 — Typical start-up and shut-down diagram for a PCC plant

7.6 Emergency operations

Emergency operations are confined to aspects of safety that are controllable by adequate design of emergency shut-down, such as sudden shut-down of the PCC plant from the load by stopping the power and steam supply and emergency vent of CO_2 to achieve safe status.

An example of emergency operation is indicated by the shaded time period corresponding to key 12 in Figure 6. This represents a sudden shut-down operation, not requiring corrective maintenance, and is followed by immediate plant restoration. Corrective maintenance is needed if the PCC plant operation cannot be resumed after an emergency shut-down.

Control systems shall be designed to prevent unsafe conditions and provide alarm signals to warn operators of unsafe operating conditions. They shall have suitable safety trips of its components and, if it is critical, that of a PCC plant as emergency shut-down finally to protect plant personnel and/or equipment.

The impact of the emergency shut-down on the source of steam and flue gas supply should be considered as a part of the safety aspects.

7.7 Downtime

For the constituent elements of downtime relating to corrective and preventive maintenance, refer to Table 1 in Clause 8.

If the transient time periods from a cold condition (see Figure 7) to the nominal load and the shut-down to a cold condition can be shortened, the impact of a maintenance-related PCC plant shut-down for maintenance on product CO_2 transportation can be reduced. This can increase availability of produced amount basis, since during the above transient period no or reduced production of product CO_2 occurs.

7.8 Plant operator organization and training

Other important factors that affect the reliability and the availability of PCC plant are operator skills (including analysis skills). Personnel shall be qualified and competent before working on operation, maintenance and/or analysis of the PCC plant to ensure satisfactory operations and outcomes.

The most critical resource of a performance monitoring programme is the personnel.

To cultivate qualified personnel, staff shall be trained periodically by attending expert or manufacturer's courses as a part of internal training programmes.

NOTE   Successful programmes involve operations, maintenance, and management personnel and promote awareness of the operating context, functional requirement and failure modes of a PCC plant and what affects it, enhancing incentives for improving availability.

8 Implications for maintenance

8.1 General

This clause provides maintenance aspects considered during the design phase and the operation and maintenance phase. Maintainability targets defined in 5.5 shall be achieved on the premise that existing standards and practices not specific to a PCC plant are applied as needed. IEC 60706-2 and IEC 60300-3-10 are in this category. Refer to A.8 for more details.

This clause provides a basis for the exchange of maintenance information between the user, manufacturer, technology supplier and engineering, procurement and construction contractor for transparent evaluation purposes.

8.2 Maintainability and downtime

Table 1 shows a breakdown of downtime and maintenance time from IEC 60050-192[3]. Corrective maintenance time is typically composed of many parameters as described in Table 1 and the typical execution sequence listed below refers to ISO 3977-9.

a) Complete necessary preparations to include being ready for maintenance during shut-down operations including technical delay and fault localization time before or after shut-down depending on the type of unavailability in 5.7.

b) Obtain spare parts, tools and make available qualified maintenance personnel.

c) Repair or replace any failed component (fault correction time).

d) Perform any post maintenance testing including the start-up operation to be ready for flue gas introduction (function checkout time).

The root cause of downtime due to technical failures with associated delays should be made clear through failure analysis.

The evaluation of maintenance time should exclude any associated delay or other downtime due to external influences including influences other than technical requirement.

The logistic delay is determined by external influences and is not counted in the downtime.

The RP should be long enough to cover one or more preventive maintenance cycles.

Table 1 — Detail of downtime and maintenance time

Total maintenance time for restoration										
Up time	Down time									
Operating time	Non-operating time									
Preventive maintenance time				Time to restoration						
				Corrective maintenance time						
Maintenance time									Fault detection time	Administrative delay
Logistic delay	Active preventive maintenance time			Active corrective maintenance time				Logistic delay		
	Technical delay	Preventive maintenance action time	Function checkout time	Technical delay	Fault localization time	Fault correction time	Function checkout time			

8.3 Maintenance strategies

Maintenance strategies may define the rules for the sequence of preventive maintenance work as per IEEE Std. 902. Preventive maintenance has two aspects: condition-based maintenance and shut-down overhaul maintenance, as further explained in a) and b) below respectively. Preventive maintenance increases operational availability and reduces the frequency of corrective maintenance. MTPM is decided in the maintenance strategy and is determined by the planned equipment maintainability. The effectiveness of the preventive maintenance can be measured as the frequency of corrective maintenance events.

Two preventive maintenance approaches may be utilized:

a) Condition-based maintenance

This is based on determining emerging failure, also known as on-condition, or condition-directed. It relies on adequate monitoring of the PCC plant conditions to minimize the impact of or avoid failure. This is achieved through the reduction of the shut-down period needed for preparation or execution of corrective actions within the preventative maintenance programme and through adjustment of shut-down timing thus avoiding unplanned shutdowns.

b) Shut-down overhaul-based maintenance

This is planned in the design phase aims to the avoidance of failures or unscheduled shutdowns of a PCC plant in the future. It is usually based on past maintenance history, coupled with results from performance monitoring programmes and other indicators of equipment condition. This can facilitate satisfactory performance until the next scheduled examination or identify an emerging failure state.

9 KPIs of availability for reporting

9.1 General

This clause provides the following KPIs for "availability reporting" of a PCC plant, as seen from the operator (CO_2 producer) viewpoint.

a) PCA (see 9.2)

b) PCPB (see 9.2)

c) SC (see 9.3)

d) TA (see 9.4)

e) OSF (see 9.5)

A general explanation of KPIs a) to e) and relevant information are given below.

1) Common to all, terms relating to the product CO_2 amount are defined as follows.

— PCC plant load is defined in 3.1.23.

— NC is commonly utilized as the basis of the evaluation and is bound for the whole PCC plant service life. Until this value is determined at the performance test, the ordered or typical design value is used in accordance with the manufacturer's contract agreement.

— NC accumulated during the RP is the basis of the calculation. It is defined by Formula (4).

— Product CO_2 amount produced is defined as the accumulation of product CO_2 amount produced [t] during the RP with CO_2 supplied from the host power plant.

2) The above KPIs a) and d) and b), c) and e) can be calculated by Formulae (3), (11), (12), (1) and (13), respectively. Each term in applied formula can be obtained by collecting and summarizing a value of each shaded sections or time period of the same definition (tagged with the same key in Figure 8) respectively in the actual operation illustrated in the applied figure among Figure 9 to Figure 12 for each KPI (see Table F.1 in Annex F, where a simplified calculation sheet is shown as an example to calculate each KPI).

When calculating the value of all shaded sections, key 3 of the vertical axis is converted from "PCC plant load [%]" to "PCC plant capacity [t/h]".

In calculating each KPI, PCC plant load change can be regarded to occur stepwise (instantaneously) although it has a certain ramp up rate if a PCC plant operates for long-term period, and the transient period by its load change can be considered negligible, compared to the RP.

3) Figure 8 shows the specific breakdown of amount of NPC accumulated [t] into product CO_2 amount of each definition, such as produced or not produced under the different state of a PCC plant with respect to PCA and PCPB.

4) In principle, the KPIs a) to e) apply a total of product CO_2 amount of each definition in its terms in each Formula. PCA applies equivalent hour of each definition in Formula (5) focusing on its

unavailability. The equivalent hour means the hours simply needed to achieve the specified product CO_2 amount with the NC.

5) Annex D can help to classify the various modes of the load pattern according to Figure 8, considering various external influences and the PCC plant state with respect to PCC plant availability and PCPB. This provides the parameters in each formula of 9.2.

6) SC refers to 9.3 for reviewing compliance to the SPC amount [t] in the PCC plant and can be utilized to assess the balance of deviations for the plant's target during the RP. Shortages to its target can be filled out by the excess plant load, if the relevant stake holders, such as the flue gas supply and/ or the CO_2 transport side accept such increase.

7) TA refers to 9.4 to represent the KPIs based on the operating time excluding the impact of external influences (see 3.1.7).

8) OSF refers to 9.5 for evaluation of the period producing the product CO_2 in a PCC plant, focusing on the on-stream period.

9) Each KPI does not include the effect of seasonal derating [ESEDH in Formula (5)].

10) For PCC plant achievability, refer to Annex E to review the integrity of PCC plant by removing both external influences and preventive maintenance from the SC.

9.2 PCC plant capacity availability and product CO_2 producibility

PCA is expressed by the Formula (3) in 5.3 (all parameters are accumulated during the RP).

Figure 8 illustrates the PCA with key 26 and 27 which correspond to PCNP and NPC respectively.

PCPB is the ratio of product CO_2 amount produced to the total amount of NPC accumulated as expressed by the Formula (11).

$$PCPB = \frac{PR_{PCP}}{PR_{NPC}} \times 100 \tag{11}$$
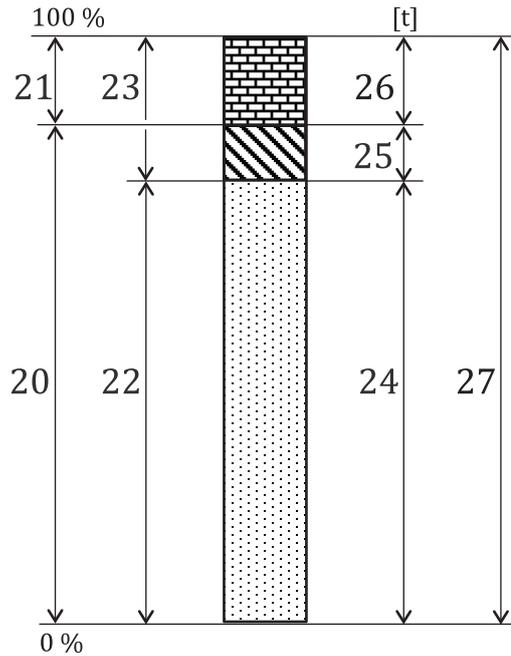
where

$PCPB$ is product CO_2 producibility [%];

PR_{PCP} is product CO_2 amount produced [t] (key 24);

PR_{NPC} is calculated by Formula (4) (key 27).

Figure 8 illustrates the PCPB with key 24 and key 27 corresponding to PCP and NPC respectively. Formula (11) focuses on product CO_2 amount produced by the PCC plant, which can be supplied to the transportation.

Key

20   PCC plant capacity availability [%]
21   PCC plant capacity unavailability [%]
22   product CO_2 producibility [%]
23   product CO_2 non-producibility [%]
24   product CO_2 amount produced [t]
25   product CO_2 amount not produced even though PCC plant is available [t]
26   product CO_2 amount not produced because PCC plant is unavailable [t]
27   amount of NPC accumulated (the product of the NC [t/h] and the RP [h]) [t]

NOTE   All parameters on product CO_2 amount are accumulation during the RP.

Figure 8 — Diagram of PCA and PCPB

The actual state of a PCC plant, considering all kinds of load patterns, can be covered by various combinations of each shaded sections piece defined in Figure 8, as illustrated in Figure 9 where a PCC plant load in operation is recorded along with the time elapsed at a PCC plant.

In case of calculating KPI, refer to 9.1, 2).

In reality the load change will exhibit a steep slope representative of a ramp-up or ramp-down of the PCC plant.
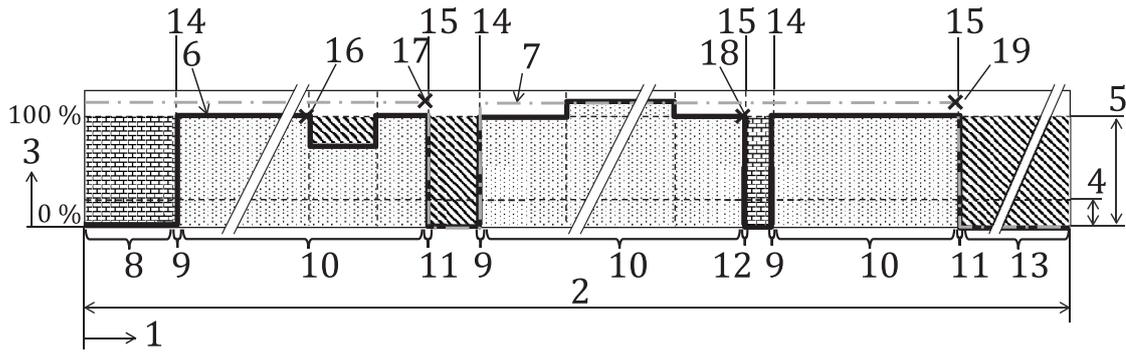
Key

1   time at a PCC plant [h]
2   reference period [h]
3   PCC plant load [%]
4   minimum load [%]
5   nominal load [%]
6   actual PCC plant load [%]
7   actual capacity of CO_2 provided from the host power plant expressed as a percentage after being divided by the NC [%]
8   downtime (for maintenance)
9   start-up or restart
10 normal operation (transient and steady)
11 shut-down
12 emergency shut-down
13 stoppage due to external influences
14 product CO_2 export start
15 product CO_2 export stop
16 some technical anomaly or sign relating with trouble which forces reduction of the PCC plant load detected
17 host power plant trip
18 emergency trip
19 start of preparation for host power plant outage

Figure 9 — Diagram of product CO_2 amount produced and not produced in typical load pattern of a PCC plant (illustrated by various shaded sections defined in Figure 8).

9.3   Schedule compliance

SC is expressed by the Formula (12).

$$SC = \frac{PR_{SPC} - PR_{SSPC} + PR_{BSPC}}{PR_{SPC}} \times 100 \tag{12}$$

where

> SC is schedule compliance [%];
>
> PR_{SPC} is scheduled product CO_2 amount [t] (key 28);
>
> PR_{SSPC} is shortage in product CO_2 amount compared to the scheduled during the RP [t] (key 30);
>
> PR_{BSPC} is bonus production in excess of the planned capacity to make up the shortage of product CO_2 production compared with SPC [t] (key 31).

In case of calculating KPI, refer to 9.1, 2).
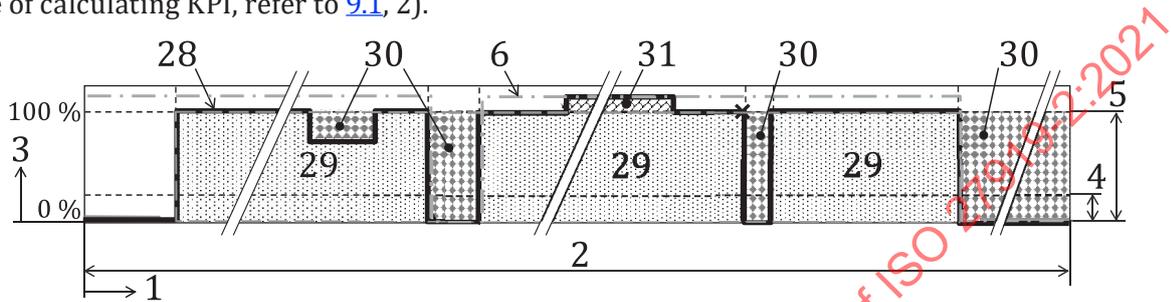
Key

1   time at a PCC plant [h]
2   reference period [h]
3   PCC plant load [%]
4   minimum load [%]
5   nominal load [%]
6   actual PCC plant load [%]
28   scheduled product CO_2 amount [t]
29   product CO_2 amount produced (including the shaded sections tagged with key 31) [t]
30   shortage of product CO_2 amount produced [t]
31   bonus production in excess of the planned capacity to make up the shortage of product CO_2 production compared with SPC [t]

Figure 10 — Diagram of SC

9.4   Time availability

TA is the ratio of the RP length minus the sum of each element of the PCC plant UT to the RP length as expressed by the Formula (1) in 5.3.

RP and element of UT are illustrated as key 2 and key 33 respectively in Figure 11. UT in the actual operation can be obtained by summation of each element (key 33) of UT.

Key

1   time at a PCC plant [h]

2   reference period [h]

3   PCC plant load [%]

4   minimum load [%]

5   nominal load [%]

6   actual PCC plant load [%]

7   actual capacity of CO_2 provided from the host power plant expressed as a percentage after being divided by the NC of a PCC plant [%]

18 emergency trip

33 unavailable time (i.e. downtime) [h]

Figure 11 — Diagram of TA for PCC plant

9.5   On-stream factor

OSF is as expressed by the Formula (13).

$$OSF = \frac{T_{OST}}{T_{RP}} \times 100 \qquad (13)$$

where

OSF is on-stream factor [%];

T_{OST} is the summation of each element of on-stream time [h] (key 34);

T_{RP} is the reference period [h] (key 2).

RP and the element of OST are illustrated as key 2 and key 34 respectively, in Figure 12. The value of OST in the actual operation can be obtained by summation of each element (key 34) of on-stream time defined as the normal operation period (between the start and the stop of the product CO_2 production) in Figure 12.
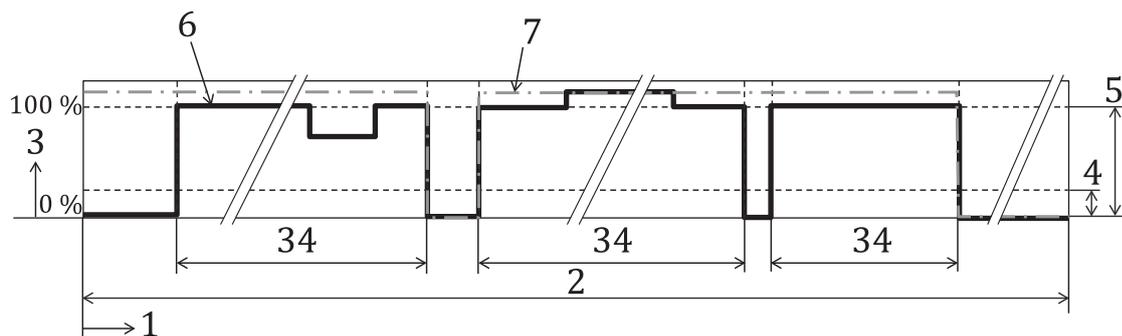
Key
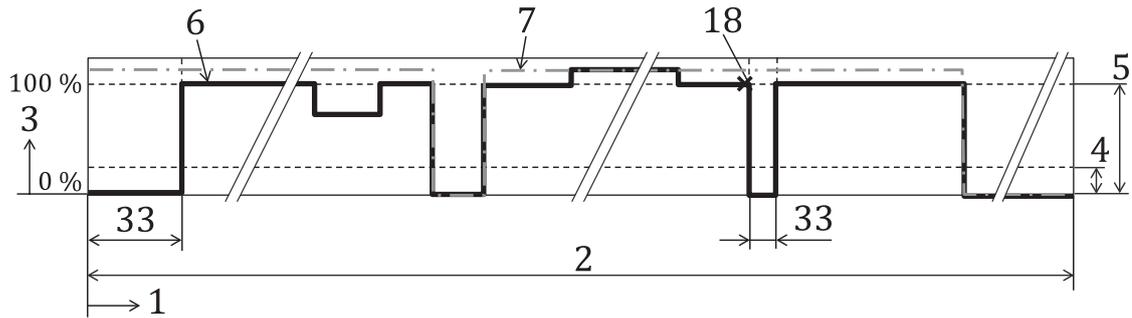
1   time at a PCC plant [h]

2   reference period [h]

3   PCC plant load [%]

4   minimum load [%]

5   nominal load [%]

6   actual PCC plant load [%]

7   actual capacity of CO_2 provided from the host power plant expressed as a percentage after being divided by the NC of a PCC plant [%]

34   on-stream time [h]

Figure 12 — Diagram of OSF for a PCC plant

Annex A
(informative)

Detailed evaluation procedure to assure and maintain stable performance of a post-combustion CO_2 capture plant

A.1 Scope

The evaluation procedure consists of 6 process steps which are required to assure and maintain stable performance of a PCC plant. Please refer to 4.5, especially Figure 2, to support understanding.

A.2 Process step 1 — PCC plant definition

PCC plant definition is determined by the process configuration, the interfaces with the power plant, the external environment, utilities and downstream facilities, and the performance requirements. Refer to 6.2.

A.3 Process step 2 — Basic design phases

A.3.1 Introduction

Review of design or sizing parameters which are the base of process flows, main component specifications and the other subsystem designs if applied specification is within the operational experience range or ensured by research and development results. It comprises the following and is summarized in A.3.2 and A.3.3 respectively.

— Basic design phases for review of design reliability as a function of the selected parameters.

— Specification and prediction of availability in design.

A.3.2 Basic design phases for review of design reliability as a function of the selected parameters

A.3.2.1 Technology description

Technology specified for use should be described and documented as part of the evaluation as appropriate in the contract with the supplier. This depends on the uncertainties of the design applied with the items from A.2 as follows:

a) Required information for description of items;

   1) Detailed technical design information including required data, drawings and other relevant materials sufficient to evaluate maturity;

   2) Description of their functions, intended use, as well as performance expectations;

3) Acceptance criteria including performance requirements, each design condition parameter and assumptions relating to selection or calculations.

b) Design information as expressed in the following documents, etc.

1) Preliminary process flow diagrams and Mass & Heat balances (M&HB). The process flow diagram shows the relationships of items units selected to perform required functions. The M&HB table covers stream flow rates, compositions and operating conditions.

2) Preliminary equipment list with sizing. It includes identification of all equipment with main specifications, providing the total plant footprint based on all major components.

3) Preliminary equipment or machinery data sheets. This summarizes the performance and other technical requirements of an item. This information is also necessary to start the detailed design for fabrication by disciplines of multiple engineering field, or proprietary equipment suppliers.

A.3.2.2 Overall design performance assessment

This is a review to determine if the applied specification of design parameters is within the range of previous experience referring to B.1.3.

All information from 6.2 will be screened to identify and list the parameter referring to B.1.2. The information is checked for completeness of basic design data and any missing items that cover operational needs will be clarified. The parameters to be evaluated are 1) interface conditions and 2) performance requirements including parameters recognized in a) of 6.2.

Each of these items should be compared with successful operations in the references or in a similar plant based on evaluation and analysis of results. Overall system or component items other than simple components inside of the evaluation boundary should be specified through functional partitioning. For this, the whole PCC plant should be separated into process units and their boundary conditions with functional requirements defined for comparison with similar experience.

If a process unit level is not enough detail for comparison with equivalent parts of the reference plant, each item can be further divided into manageable technical blocks. This may include any novel combinations or integration. This analysis should be done at a level where uncertainty can be assessed according to the following indexes:

— functions;

— components and their details, if necessary;

— internal interfaces between components and conditions that component is exposed to;

— internally integrated system.

A.3.2.3 Design performance assessment of component items

The performance assessment of components items through functional partitioning of the process includes the following activities.

a) Evaluation of equipment sizing methods to confirm if previous criteria used in the reference plants are valid. The case of changing sizing parameters from experience should be evaluated.

b) Evaluation of the applied specification of the design parameters to confirm if they are within the range of the previous experience. This includes items supplied by vendors.

c) Evaluation of size and scale up ratio of each component that is key to the PCC performance and other process equipment proven in experience. If the size or scale up ratio is not within the experienced range, multiple units can be considered.

A.3.2.4 Novel technology items

Novel items are identified and analysed by applying functional partitioning.

The performance of the novel items will be assessed using experience obtained from other non-PCC applications or through analysis and extrapolation of research and development results. The performance results obtained will be compared with the performance results from proven technology items currently applied.

A.3.3 Specification and prediction of availability in design

A.3.3.1 General

A PCC plant should be designed to comply with the availability target in consideration of overall economic efficiency. Availability can be determined in the design phase using the previous experience from other plants. Where information on availability is lacking, the application of redundancy and/or increasing the tolerance of items and improvement of maintainability may be used as compensation. supported by designs that anticipate the adverse operating conditions expected to occur. Maintenance strategy developed to minimize MTTR, with the required period to re-start supports operating strategies. The design aspects of availability, reliability identification of items in A.3.3.2 a) and redundancy/tolerance strategy in A.3.3.3 should be prepared. The quantitative availability analysis (Refer to A.5) should be applied with the design procedure in A.3.3.2 c) for calculation.

A.3.3.2 Combined aspects of availability, reliability and maintainability

a) Reliability identification by items

Refer to B.2.

b) Availability features

PCC plant availability should be supported by designs that anticipate the adverse operating conditions expected to occur. In addition, maintenance strategy needs to be developed during the design phase to minimize MTTR, with the required period to re-start and (maintenance strategy needs to) be incorporated in both the design and operating strategies.

Availability at the design phase may be calculated in two ways: TA using Formula (1) and PCA using Formula (3). In general, at the design phase, engineers use the TA formula. Indeed, the load pattern for reference operation, with the PCC plant running at nominal capacity and no curtailment of production should be the load applicable to the design phase. It is noted these two definitions have the following characteristics.

TA is independent of the value of the available capacity and the numerical value of the TA is normally larger than PCA. Since the TA is easy to determine, it is suitable to compare it to the other plants.

In PCA using Formula (3), the following should be considered for evaluation.

— Seasonal influences, such as fluctuations in cooling water temperature, may result in external circumstances that will affect performance of a PCC plant. In these cases, annual average capacity is normally applied as the nominal capacity using no external influences.

— To clarify availability during normal operation, excess production above nominal capacity is not considered in availability calculations. Such production should be evaluated in SC in Formula (12).

c) Application to availability design

Operator will specify availability targets and the technology supplier will provide guidance as to how to best meet them consistent with maintenance strategy. The PCC plant availability design procedure is as follows:

1) Based on the operator's maintenance strategy, the following three items should be defined.

   — an availability target;

   — duration requirements of preventive maintenance;

   — duration requirements of continuous operation.

2) The technology supplier calculates availability requirements during the continuous operation period. This will define requirements of both reliability and maintainability of a PCC plant items.

3) To achieve the availability target set by the operator, the technology supplier should follow the procedure in this document. If it is not technically or economically achievable, the technology supplier together with the operator may find an optimal combination of the 3 requirements listed in 1) above with agreement from the operator.

A.3.3.3   Redundancy/allowance strategy for component capacity and plant performance

a) Application of redundancy

Some components designed with redundancy whereas others should be given operational margins so the components may deliver more than the required rate as extracted (or calculated) from below, considering mitigating effects in failure mode.

— Spare or stand-by component.

— Allowance of component capacity or plant performance margin.

Stand-by redundancy is where an item exists on stand-by, operating only in the event of failure of the duty item. Allowance or performance margin can provide the additional ability flexibly when the same items are operated according to requirements.

Spare or stand-by components should be kept to a minimum, depending on the owner's policy.

b) Application of spare or stand-by redundancy

Spare or stand-by components and subsystems improve reliability and availability, depending on its native values under the applied conditions, but cause installation and maintenance costs to increase. In this case assumption in 4.1 c) should be considered, even if trouble in the PCC plant causes it to shut-down.

Critical equipment may not be redundant but not limited to the following cases, if it is uneconomical to provide a spare; if the manufacturer has no capacity to provide a spare and cannot be substituted; the manufacturing period is long, and spares are difficult to obtain.

c) Allowance of component capacity and plant performance

The capacity margin should be set by applicable standards, by industry practice, or by a supplier to mitigate operational uncertainty. The additional margin should be set by the following agreement by all parties. These should be controlled in total to avoid duplication throughout the project cycle.

A margin on fouling of a component or degradation of process part along with elapsed time should be made to maintain its performance during the required period based on the general standards and/or component or process part specific experience (obtained by a supplier).

The margin allocated for uncertainty, of a technology item with limited operating experience, should be reduced with increasing operating time.

If the assessed reliability of an item is not acceptable, then re-design or replacement needs to be started as early as possible to ensure reliability improvements.

By reliability programme planning and monitoring, the actual margin of a component should be determined after commissioning. It should be re-evaluated from an optimization viewpoint by the quantitative availability analysis shown in A.3.3.2 applying measured figures of reliability, referring to B.2.

In some cases, margins hide component deficiencies or may defer required maintenance to a convenient time.

A.4 Process step 3 — Operation phase

Maintenance and monitoring (of the PCC process) to produce the evidence of reliable performance (refer to Clause 7, Clause 8 and Clause 9).

Unavailability analysis used in Clause 9 to identify root causes for deviations from the design and may help improve the reliability of a PCC plant through its feedback of experience to design, operation or maintenance. A data base of lessons learned obtained from results of unavailability analysis may demonstrate the maturity of a technology.

A.5 Process step 4 — RAM analysis

A.5.1 Outline

This step is to determine the optimum availability attainable through a quantitative evaluation against the target. Subsystem and component design requirements the primary objective define best effort reliability and maintainability of each component.

RAM analysis is a well-established methodology which can effectively assess a PCC plant, whether it is in design, or in operation. The details are referred to in Reference [5] in the case that the PCC plant in study satisfies the initial performance.

RAM analysis can provide the following contribution in the basic design.

— The conclusions can be demonstrated and verified through the commercial operation, evaluating if it reaches expected availability target., and covering the project cycle of the operational phase to be utilized during operation.

— For design of novel items, suggestions for the definition of reliability and maintainability requirements for installed components, to achieve specified availability over the specified period.

— Advice on identification of the items, best possible design changes for overcoming such criticality and a qualitative evaluation of the effects of applied design change for items with insufficient reliability.

To carry out RAM analysis, the following should be considered.

The above evaluation action assumes that the PCC system is a collection of equipment with a proven track record to obtain the value and no influence of novel design is possible and that the PCC plant in study satisfies the initial performance, as the base case and that the PCC plant in study satisfies the initial performance, as the base case.

— If PCA target is specified, related conditions indicated in PCC plant (6.2), basic design information (A.3), load pattern (Clause 7) and maintenance strategy (Clause 8) be consistent with the redundancy/allowance strategy for component capacity and plant performance (A.3.3.3) for possible modification in these strategies of items to overcome the novel items in iterative ways.

— If a change of the configuration occurs from a previous experience a check of the parameters in design is necessary to ensure the reliable performance.

— A quantitative analysis of PCC plant to confirm fulfilment of the availability target should be carried out after having solved the technical uncertainties as soon as practicable.

A.5.2   Input data of reliability

RAM analysis models require experience data, such as failure frequencies, fault scenarios and consequences of the item failures to be fed into.

Enough measured data particular to a PCC plant is generally not available to conduct a RAM analysis, in the public domain.

Collection of reliability and degradation data of items should be taken from operational experience with items in a PCC plant. Especially for items, it is necessary to evaluate qualitatively based on best industrial practice, referring to B.2 and information provided by 6.2 and A.3.2 and the following should be considered.

a)   For proven items

Proven technology elements are handled, ensuring compliance with an applicable standard or industry practice.

The historical data of known components and the knowledge from the reference plants with similar or the same process should be the base.

The data for known components is available from a public database where mechanical and electrical malfunctions are collected from service record related information in components of industrial plants as explained in B.2.2.

b)   For novel items

Data for this category is not readily available.

If the data of a PCC plant design in study deviates remarkably from experience in reference plant or similar experience, the gap should be analysed to prepare the input data (including reliability) to conduct a RAM analysis in process step 6. A valuable source of information for assessing the reliability of novel item is the TQ procedure in Annex C.

The analyst would have to access different sources of information in order to find the relevant data required for the novel item referring to Annex B.

c)   Fault scenarios

To establish fault scenarios attributed to the PCC plant requires a high level of knowledge regarding the applied processes and equipment. System designs should be examined from the perspective of reliability considering many cases of operation. The analyst would also have access to different sources of information in order to understand the parameters and failure mechanisms required to assess the applied technology referring to B.3.2.2

A.5.3   Analysis

The conclusions of a RAM analysis identify those parts of the installation that are critical in meeting performance targets. Its actual utility may also depend primarily upon the plant composition of the proven and the novel technology items, if the collected data from both B.2 and B.3 are applied.

Then the reliability of the novel items should be improved through redundancy and allowance strategy as well as directly possible many countermeasures referring to B.2.

A.5.4 Contribution of RAM analysis in maintenance

A RAM analysis will provide insight on the optimum maintenance, upon inspection or overhauls that are required periodically to achieve objectives and maintenance practices required to mitigate plant performance risks also caused by the novel items.

A.6 Process step 5 — Study of key factors and failure mechanisms

A.6.1 Outline

Unproven items can be evaluated by related key factors which are typical and may be investigated frequently and the failure mechanisms of each failure mode.

When evidence for management of risks about novel technology cannot be acquired only from actual service experience or similar proven industrial plant experience directly, it can be obtained by analysing the differences of the values of related parameters between experience/knowledge and design under study. Unproven items should be analysed from the perspective of avoiding risks due to the deviation of parameter values from experience. The analysis should be conducted by understanding the possible failure mechanisms and the countermeasures linked to overcome using other information sources. To prepare the evidence in Annex B in addition to the conventional ones, it is necessary to access the reliable and secure information sources.

NOTE   Novel items are not necessarily considered unproven in the context of this step.

A.6.2 Procedure

a)   The data particular to a PCC plant, which may be insufficient in process steps 2 to 4, should be studied to find out if such function is intended for the novel items, in case that the evaluation side has not enough experience in a PCC plant and the following are items to be studied to support the above.

b)   Key factors that could impact the reliable performance of a PCC plant and their countermeasures are taken into consideration to implement in the actual PCC plant, from the planning stage if possible, to prevent the occurrence of the corresponding failures.

c)   The consideration of monitoring locations or checkpoints may be included in the design to obtain dependable data during the PCC plant operation and maintenance should be added after operation to assess and respond to events that could lead to degradation or shut-down of the PCC plant equipment.

d)   Identify problems typically encountered that would decrease availability and reliability of the PCC plant and its countermeasures and solutions if possible.

e)   In this stage, it is necessary to access the reliable and secure information sources to confirm if it is not possible to find out the evidence that provide confidence to failure mode concerned, such should be obtained in process step 6.

A.7 Process step 6 — Qualification study

A.7.1 Outline

This step is a summary of study on novel items not managed through the above process steps to define and aids in preparing evidence to define its reliability for novel items after analysis of the risk and failure mechanism relating with countermeasures.

A.7.2 Procedure

The provision procedure of reliability data, in respect of evidence that functions as required within specified conditions is shown in Figure C.1 as guidelines, focusing on novel items. This may try to quantify, and improve, if needed, its reliability from generated evidences, as follows:

a) Basis for evaluation (qualification basis in Figure C.1) should be refined mainly based on the information developed in process step 1.

b) Technology item classification (technology assessment in Figure C.1): a novel item identified in process step 2 should be refined as indicated in Annex C.

c) Threat assessment succeeded from process step 6

d) Selection of evaluation methods base d on an overall plan for the evaluation process (qualification plan in Figure C.1)

e) Data collection: The activities (analyses and tests) to collect evidence (refer to execution of the plan in Figure C.1 and see process step 2 and process step 5).

Evaluate whether the evidence produced meets the requirements of the design basis in Basis for evaluation, referring to B.3.2.1 and performance assessment in Figure C.1. By using the gathered data, conduct an item/process unit and total of PCC plant availability analysis, feeding them back to process step 4 and compare that with decision criteria. Repeat steps a) to e) until compliance with decision criteria is achieved, if the performance requirement can be compromised with reliability of a PCC plant.

Novel items (for which relevant requirements on specification for success normally do not exist) or items with high or unacceptable uncertainty levels on failure to the requirement can be applied to the commercial plant, if it meets technical requirements developed by the qualification study.

If the final acceptance of the item's qualification study has not been achieved, make recommendations to replace with proven technology items if the required functions can be achieved or alternatively, reduce the operating range for the technology to ensure adequate performance margin.

A.8   Supporting information on implications for maintenance

Accessibility may be a key factor to be considered during the design phase, as will the ability to lift and install components and to align and test them.

Maintenance support systems or provisions, which includes, technical publications such as overhaul procedures and maintenance manuals, spare parts, maintenance personnel with their training, testability, maintenance data acquisition systems and tools supporting maintenance. These should be tailored by the operator mainly based on information from the supplier.

Refer to ISO 3977-9 regarding respective responsibilities of suppliers and operators, includes the technical requirements to maintain component expected operational lifetime, coating lifetime and the intervals between inspections to maintain the unit in the safe and reliable condition. These issues are to be examined to see how they are influenced by the load pattern and type of fuels in the host power plant.

The inherent maintainability should be confirmed during manufacturing and operation phases.

Based on collection, analysis and feedback of maintenance data, effectiveness evaluation of maintenance and design improvement of the PCC plant with supplier advice should be confirmed.

Annex B
(informative)

The reference plant and its component experience

B.1 General

B.1.1 Outline

This clause provides the following a) to d) utilizing the experience from the reference plant with its components, similar/same proven technologies in the industry and research and development activities from pilot to full commercial scale of the applied technology:

a) information for process step 2 (A.3) to identify novel items (see B.1.3);

b) data utilized for process step 4 (A.5) for RAM analysis (see B.2);

c) advice to process step 3 (Clause 7, 8 and 9) in performance monitoring (see B.2.3);

d) information for process step 5 (A.6) and 6 (A.7) (see B.3.1).

B.1.2 Critical parameter list

Iterative with classification of technological items A.3.2.2, the following analysis for each item should be conducted.

a) Vital parameters governing design affecting key issues in operational and performance requirements are defined as critical parameters or applied specification of the critical design parameters, if it is information needed for design. The critical parameter list summarizes and should cover all items of this kind.

b) The acceptable range of the given parameters should be determined from the procedure in A.3.2.2. to find out novel items where the selected specification of the critical parameters affecting the current design are out of this range.

c) Some of critical parameters may not be understood depending on technology readiness level and should be linked with possible failures and failure mechanisms. If a requirement for a technical item is not correct or missing due to lack of data/knowledge about such influences, difficulties may arise affecting several performance items.

d) Critical parameters related with novel items identified in process step 2 (A.3) should be established. The specific critical parameter of an individual item may propagate to another related items and should be reviewed against the entire PCC plant in the iterative ways.

Examples are in, Table G.1 and Table G.2, as matrixes for classification of novel items with their locations (systems) in a PCC plant.

B.1.3 Access to data

a) The information, which is collected from report of a PCC plant experience or literature relating similar equipment and operating conditions of concern, may include challenges and uncertainties and should be investigated referring to process steps 1, 2 and 3 to reduce risks.

b) In case that new items are included, numerical checks of the performance before operation should be done per process step 2 based on generally recognized simulators, handbooks or literature. The

result is limited to checking critical parameters related to the capacity, and main design parameters such as gas or liquid velocity and coefficients of heat and mass transfer.

c) It is preferable to access precise, dependable data that documents the factors that increase reliable performance in large-scale commercial plants. Such data which should be provided by operators or technology suppliers of an actual PCC plant for review are defined or listed, if potentially applicable to the applied technology.

d) When operational experience of technology is used as evidence of fulfilment of requirements, then operating conditions, design parameters, environmental conditions or applications (system characteristics) in which the technology has been used should be referenced. Such experience should preferably be traceable and accessible to the analyst to avoid incorrect interpretations.

e) Generally, the relevant experience data, such as obtained through process step 3, can be a valuable source of evidence, if the designs that functioned acceptably in service are considered.

B.2 Guidelines for use of proven industrial plant component data

B.2.1 Input of critical parameters from proven industrial plant component data

The knowledge and experience in industry with proven technology can be referred. The operational experience should be analysed based on the procedures in A.3.2.2 and A.3.2.3 to confirm that applied specification of the parameters is within this range. The following is a sample of input in consideration. Only some elements of the novel items may remain due to additional requirement or different application area.

a) The pre-treatment section of a PCC plant is generally similar to those of the Air Quality Control (AQC) plants, except that there may be a severe restriction on the concentration of impurities and mist in the treated flue gas. This can be evaluated within the experience of the AQC, which has many references up to a large-scale capacity of a plant (also its component accordingly). The critical parameters of these areas should be verified involving experts in this industry.

b) CO_2 compression has many uses in chemical or gas treatment plants up to a large-scale capacity of a plant (also its component accordingly). In locations downstream of a regenerator of a PCC plant, the product CO_2 may entrain a mist as well as trace flue gas components and impacts of these may not be clear.

c) Tower internal specifications may be common to those in chemical plants where the vendor has considerable experience and interest in the uniformity of local velocities of both liquid and gas and the method considering the change of liquid properties.

d) The design of heat exchangers is covered by chemical industry standards depending on type. The specific concerns are scaled-up in case of larger plants and those common to all capacities. Countermeasures against those of degradation, fouling and corrosion of related components changing with time are technologies such as filter system to mitigate the above concern during operation.

B.2.2 Evaluation of the quality of the databases of proven industrial plant components

This clause provides guidelines on industrial plant component data utilization, cited from public open databases in addition to specific vendor's experiences relating with a PCC plant in a technology evaluation study.

The databases listed in References [6], [11] and [12] in relevant specific industries can be used as a source for historical data. When using the date bases, all available data should be checked to confirm that data have not been intentionally excluded without evaluation. More, relevant data can be found in the plant suppliers having operational experiences or the vendors supplying them the related equipment.

When evaluating the quality of reliability data, the following should be considered:

a) Quality of the data available in the database

Data quality depends on many factors related to the data collection process; The analyst can prioritize data based on completeness of available information.

b) Quality of the database structure

The quality of the database is related to its consistency. More details on best practices and recommendations for quality databases can be found in ISO 14224. Some vital information that normally should be available for the database to get a high score according to ISO 14224 includes system boundaries, failure modes, the number of failures and the operating and the operating calendar time in addition to description of system characteristics, like design parameters, operational conditions preventive maintenance and environmental conditions.

c) The relevance of the data in the database

Both the relevance and the final evaluation of the reliability of data sources of the database should depend on the intended use of the data. The information that is relevant and sufficient for one analysis may not fit for a more detailed analysis.

Reliability data can differ significantly depending on the specific dataset selected with little information to support the selection of dataset among a significant number of failures in all groups.

B.2.3 Performance monitoring

Performance monitoring can be an overall, long-term effort to measure, sustain, and improve PCC plant reliability, capacity and maintenance planning.

ISO/TR 27912:2016 may be used as reference to the classification assessment, see 7.6, for example.

ASME PTC-PM-2010[4] can be referred to after the fundamental concept in of the reference Section 1. The guidelines are arranged by subsection given below. The description of the components common to a PCC plant can be seen in the sample provided in Reference [4], mainly in the balance-of-plant portion, is valid. Heat rate can be interpreted as the specific heat requirement of CO_2.

a) Programme Planning in section 2.1 in Reference [4].

b) Instrumentation in section 2.2 in Reference [4].

c) Performance Monitoring Implementation in section 2.3 in Reference [4].

Each technical characteristic should be imported from a PCC plant.

B.3 Items particular to a PCC plant and its components

B.3.1 General

This clause provides guidelines on the selection of plant component data particular to a PCC plant.

B.3.2 Items in each subject for evaluation of reliability and availability

B.3.2.1 Performance evaluation

The objective of this evaluation is to confirm its performance as one part of reliable operations (excluding target reliability) are as stated in the design basis. The performance evaluation is carried out to quantify overall performance of the technology, checking the margin against e ach acceptance criteria in the design basis before and after operation. The performance test procedure should be defined referring to ISO 27919-1.

B.3.2.2   Supportive information

This clause provides information on key issues at the current knowledge level. Then in the concerned area has been generally presented in the public domain as the literature and operator's report. Table B.1 illustrates topics and check items particular to the PCC plant for process step 5 and 6.

This analysis is designated to discover the failure mechanisms to determine appropriate countermeasures that recommend access or communication with proprietary information sources.

Table B.1 — Key issues and items to be checked

Key issues	Items to be checked	Countermeasures (if any)
Corrosion	Material, location, size, operating condition, operating time with better management of corrosion issues. PCC technologies to reduce solvent degradation and to optimize absorber feed gas composition, which reduces concentration of nitrogen oxide and sulphur dioxide in flue gas as much as possible, is required. Note corrosion in the flue gas pre-treatment area and the CO_2 compression area can belong to the existing plant experience area and should be referred to the information in the corresponding area. Measure change in wall thickness of heat transfer tubes of reboiler and reboiler vessel.	Add anti-corrosion additives to solvent. Change solvent. Check materials of construction.
Emission	Emission mechanism, measurement method, explanation of influencing factors and countermeasures for prevention with reference. Measure change in wall thickness of heat transfer tubes of reboiler and reboiler vessel.	Add anti-foaming agent to solvent. Install washing stage at the outlet part of absorber/desorber.
Leaks	Leak points, reason for leak and countermeasures. Leakage from mechanical seal or gasket.	Use proper mechanical seal or gasket.
Absorbent loss	Explanation of influencing factors and countermeasures with reference. Measure composition of outlet gas of absorber and SO_4 ion concentration in solvent.	Add anti-oxidation and anti-foaming additives to solvent. Install high efficiency DeSOx system upstream of the absorber.
Efficiency decreases due to fouling of heat exchangers	Filters and other countermeasures may be required to address particulates in absorbents.	Clean heat exchanger tube surfaces.
Scale-up	Reference large size equipment, plant and components, philosophy of scale-up and its influence on performance. To achieve large-scale applications of CCS, securing reliability is essential and appropriate. Criteria must be established for its evaluation. Key component technologies of a complete PCC plant have been deployed at scales large enough to meaningfully inform discussions about CCS on large commercial fossil fired host power plants. This can be used if there is no large-scale experience.	

Table B.1 *(continued)*

Key issues	Items to be checked	Countermeasures (if any)
Foaming	Management system of solvent properties Foaming in solvent systems may cause system malfunctions by flooding that leads to an off-spec product, lost production and solvent losses Measure pressure loss across absorber and desorber.	If pressure loss increases, add anti-foaming agent to solvent. Bleed of used solvent and feed of fresh solvent.
Exposure to amines in work areas	EHS aspects and follows Safety Data (SD) instruction of the applied chemical including absorbent EHS aspects	Masks, safety goggles and protective gloves Add engineering barriers to avoid exposure.
CO_2 stream variations during operation	Possible adverse effects by changes in one or more operating parameters. Measure amine concentration in solvent and Liquid to Gas Flow (L/G) ratio in absorber.	Keep them at set values when flue gas condition is constant.
Start-up and shut-down of process	Adverse effects resulting from start-up and shut-down. Before start-up and shut-down, measure the solvent temperature in absorber and desorber.	Before start-up, pre-heat the solvent and check its temperature. Before shut-down, stop the reboiler steam and check the solvent temperature.
Relationship with other areas	Adverse effects by failure of other plants or restrictions to the other plant(s).	
Flow and CO_2 quality verification	Acceptable or actual variations.	
Impurities in the flue gas	A wide variety of impurities contained in the flue gas, especially emitted by coal-fired plants, may affect reliability and the cost of the PCC process depending on their concentrations and types. Some impurities require a long-term assessment for their impact. For this reason, a long-term operability and reliability confirmation is useful to demonstrate the efficiency of the process and to determine the effectiveness of commercially viable countermeasures	

Table B.1 *(continued)*

Key issues		Items to be checked	Countermeasures (if any)
Hardware design	a)	Choose solvent vendor with good test results / references	Proper design based on operation experience
	b)	Duplication of critical equipment (e.g. pumps)	
	c)	Good/proper knowledge of flue gas composition prior to design	
	d)	Selection of equipment design, e.g. plate heat exchanger is compact and efficient but more challenging to operate/maintain compared to shell/tube heat exchanger	
	e)	Location of and choose of emission monitoring instruments and sample system	
	f)	Proper design of Reboiler dedicated to stripper	
	g)	Don't underestimate the utility system/complexity in design (Electrical system, cooling water system, control system, etc.)	
	h)	Avoid location in potentially explosive atmospheres / explosion hazardous area	
	i)	Choice of material	
	j)	Valve design (leakage in gaskets and drain plugs)	
Performance monitoring location	a)	Monitor solvent hot side of plant regards to corrosion	
	b)	Emission monitoring in absorber stack	
Problems typically encountered	a)	Too many instruments/alarms/trip	
	b)	Quality/complexity on electrical and instrument system	
	c)	Leakage due to material/gaskets/design not compatible with solvent	

Annex C
(informative)

Technology Qualification

TQ is the process of providing the evidence that technology (items) will function within specified operational limits with an acceptable level of confidence. The result of the qualification evaluation is reported as evidence that the technology meets the specified requirements for the intended operation.

A basic TQ process is visualised in Figure C.1. Each step of the process shall be documented making the conclusions traceable. The required level of detail for documentation tends to increase as the TQ process progresses. Feedback loops between the steps imply that the process is iterative in nature. Consideration should be given to design modification to improve performance, safety, longevity and ease of manufacture or operation, amongst others. Modification of specifications may also take place. Such modification will trigger full or partial iterations of the basic TQ process in order for the TQ basis to be satisfied. More details about TQ is given in DNVGL-RP-A203 for reference.

An example of application of TQ as described by DNVGL-RP-A203 to a PCC technology may be found in DNVGL-RP-J201.
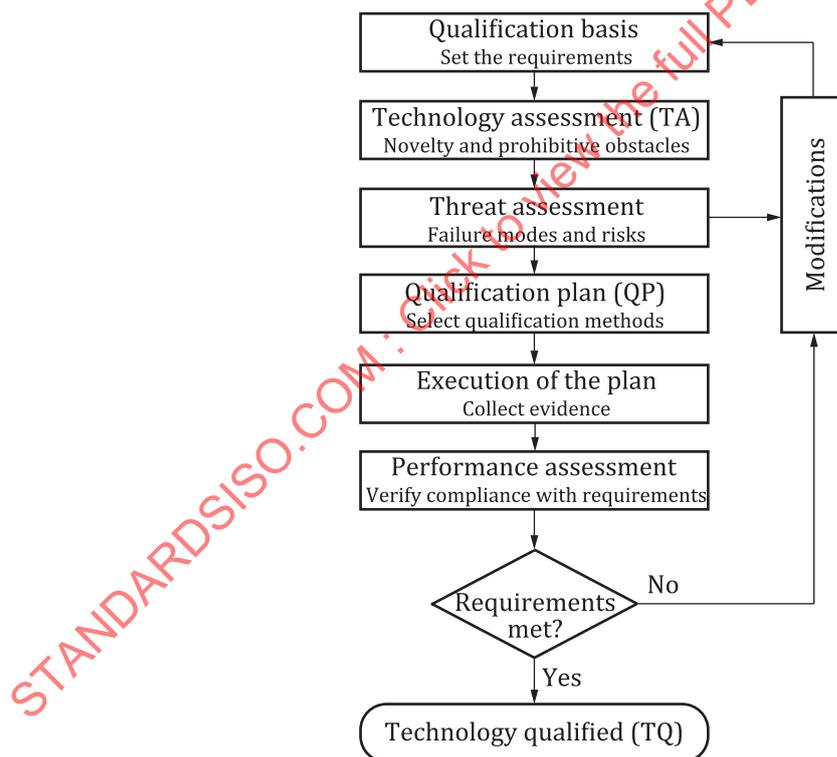

Figure C.1 — Steps in the basic TQ procedure applied for novel technology items [9].

Annex D
(informative)

Classification of influences for PCC plant capacity availability and Product CO$_2$ producibility in Clause 9

Regarding PCA and PCPB, terms in calculation formula key number, i.e. the product CO$_2$ amount produced, the product CO$_2$ amount not produced) shown in Figure 8 and Figure 9 are illustrated in Table D.1, classifying respective influences within PCC plant load pattern and events (example of causes) that cause the above using influences in top column of Table D.1.

Table D.1 — Classification of influences for PCA and PCPB in Clause 9

Influences			PCC plant capacity Availability		PCPB		Shade designated for each product CO$_2$ amount in Figure 8 and Figure 9	Example of PCC plant load pattern and events
State of PCC plant	internal faults/ external influence	Planned/ Unplanned						
Available	N/A	N/A	20		22		24	Product CO$_2$ is produced at PCC plant nominal load
	External	Planned/ Unplanned	20		22	23	24 / 25	·A certain CO$_2$ supply of upstream to PCC plant ·A certain product CO$_2$ demand by downstream of PCC plant.
	Internal	Planned	20	21			26	Load-up, load-down, etc.
		Unplanned						Troubles with some components which force reduction of capacity.
	External	Planned	20				25	No CO$_2$ supply of upstream to PCC plant or no product CO$_2$ demand of downstream of PCC plant, which is noticed before enough to complete preparations.
		Unplanned						Any event to cause shut-down of PCC plant that occurs upstream or downstream of PCC plant, such as equipment for transport or store CO$_2$
Un available	Internal	Planned			23		26	The required performance cannot be met, such as no-load, operation case such as no-load operation case, resulting to discharge recovered CO$_2$ to atmosphere as it is off-spec, with less than minimum PCC plant load.
		Unplanned	21					The required performance cannot be met, such as any unstable or transient conditions like emergency trip, etc, due to off-spec CO$_2$
		Planned						Modification, preventive maintenance, etc.
		Unplanned						Unforeseen troubles, repair (corrective maintenance), etc.

NOTE   For key number 20 to 26, refer to Figure 8 and Figure 9. Multiple key numbers can coexist in the same load pattern and events case.