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Gas turbine exhaust systems with or without waste heat recovery

Systèmes d'échappement des turbines à gaz avec ou sans récupération de la chaleur résiduelle

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 192, *Gas turbines*.

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

This document has been developed in response to the international market need for a specification relating to the exhaust and heat recovery systems for gas turbines. Purchasers and suppliers will benefit from a standard against which equipment can be purchased, designed and constructed - especially given the challenging nature of the turbulent exhaust gas flow and associated complexity of mechanical design. Equipment is frequently installed in remote and challenging locations both onshore and offshore where maintenance and repair can be prohibitively expensive.

A waste heat recovery unit recovers thermal energy from the waste heat available in gas turbine exhaust gases, exchanged into various heat transfer media such as water, water/glycol mixtures, thermal oils and hydrocarbon gases.

The application of heat recovery devices to gas turbines results in significant thermal efficiency gains and resultant environmental benefit from reduction in CO_2 emissions. Gas turbine exhaust is one of many sources of waste heat energy and can be classed as medium grade within a typical temperature range between 400 °C and 600 °C suitable for Rankine cycle applications.

Gas turbine exhaust systems with or without waste heat recovery

1 Scope

This document specifies requirements and gives recommendations for the design, materials of construction, modelling, controlling, fabrication, inspection, testing, installation, start-up and operation of industrial gas turbine (GT) exhaust systems with or without waste heat recovery unit (WHRU). Gas turbines can be on-shore or off-shore for such sectors as oil and gas, chemical and process industries, utilities, or other intensive energy users.

For this document, the exhaust system means all items in the turbine exhaust gas stream between the GT exhaust gas collector outlet flange and the termination/s to the atmosphere.

The following items are not covered by this document:

— heat recovery steam generator equipment (HRSG);

— supplementary fired systems;

— auxiliary fired systems;

— exhaust gas collector (also known as exhaust plenum);

— fire detection and extinguishing systems;

— emissions controls equipment intended to modify the gaseous composition of the exhaust gas;

— WHRUs that are of the firetube type, where the turbine exhaust gas (TEG) passes through the tubes.

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 3744, *Acoustics — Determination of sound power levels and sound energy levels of noise sources using sound pressure — Engineering methods for an essentially free field over a reflecting plane*

ISO 9614, *Acoustics — Determination of sound power levels of noise sources using sound intensity*

ISO 10494, *Turbines and turbine sets — Measurement of emitted airborne noise — Engineering/survey method*

ISO 10474, *Steel and steel products — Inspection documents*

ISO 12241, *Thermal insulation for building equipment and industrial installations — Calculation rules*

ISO 13704, *Petroleum, petrochemical and natural gas industries — Calculation of heater-tube thickness in petroleum refineries*

ISO 13705:2012, *Petroleum, petrochemical and natural gas industries — Fired heaters for general refinery service*

ISO 13916, *Welding — Measurement of preheating temperature, interpass temperature and preheat maintenance temperature*

ISO 14122, *Safety of machinery — Permanent means of access to machinery*

ISO 14555, *Welding — Arc stud welding of metallic materials*

ISO 15612, *Specification and qualification of welding procedures for metallic materials — Qualification by adoption of a standard welding procedure specification*

ISO 15613, *Specification and qualification of welding procedures for metallic materials — Qualification based on pre-production welding test*

ISO 15614-1, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys*

ISO 19902, *Petroleum and natural gas industries — Fixed steel offshore structures*

ASME B16.9, *Wrought steel butt-welding short radius elbows and returns*

ASME B31.3, *Petroleum Refinery Piping*

ASTM C680-10, *Standard Practice for Estimate of the Heat Gain or Loss and the Surface Temperatures of Insulated Flat, Cylindrical, and Spherical Systems by Use of Computer Programs*

EN 287-1, *Qualification test of welders — Fusion welding — Steels*

EN 1011-2, *Welding — Recommendations for welding of metallic materials — Part 2: Arc Welding of Ferritic Steels*

EN 1991-1-4, *Eurocode 1: Actions on structures — Part 1-4: General actions — Wind actions*

EN 10025-2, *Hot rolled products of structural steels — Technical delivery conditions for non-alloy structural steels*

EN 10025-3, *Hot rolled products of structural steels — Technical delivery conditions for normalized/normalized rolled weldable fine grain structural steels*

EN 10253-2, *Butt-welding pipe fittings. Non alloy and ferritic alloy steels with specific inspection requirements*

EN 13445-3:2014, *Unfired pressure vessels — Part 3: Design*

EN 13480, *Metallic Industrial piping*

EN 15614, *Specification and qualification of welding procedures for metallic materials*

3 Terms and definitions

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

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

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

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

3.1
analogue control signal
control or digital signal that represents a continuous range of values

EXAMPLE A traditional 4-20 mA current loop.

3.2
commissioning
action whereby dynamic checks and tests where the GT is running, the exhaust system is subject to TEG flow and the WHRU is filled with circulating HTMs, progressively loaded with control systems and functioning

3.3
data sheet
formal document containing process and/or mechanical data

3.4
insulation
material applied to either the inside or outside of the exhaust system component casings (e.g. WHRU, ducting, stacks, dampers) in order to reduce the casing material or outer cladding temperature, respectively

3.5
pre-commissioning
static checks and tests where the exhaust system is cold and the WHRU is not filled with HTM and the controls are energized

3.6
purchaser
party that enters into contract with the *supplier* (3.8) for the supply of the exhaust system

Note 1 to entry: The purchaser is the party who specifies the technical requirements. The purchaser can also instruct a *contractor* (3.7), an agent or consultant, authorized to act for, and on his behalf. The purchaser can in some cases also be the GT supplier.

3.7
contractor
party that carries out all or part of the design, engineering, procurement, construction, *commissioning* (3.2) or management of a project or operation of a facility

Note 1 to entry: The *purchaser* (3.6) can choose to undertake all or part of the duties of the contractor

3.8
supplier
party that manufactures or supplies equipment and services to perform the duties specified by the *purchaser* (3.6)

3.9
WHRU tube bundle
hairpin tube bundle arrangement contained within a rectangular casing, or a nested helical coiled tube arrangement contained within a cylindrical casing

4 Abbreviated terms

ALS	Absolute limit state
CFD	Computational fluid dynamics
CHT	Conjugate heat transfer
CSCC	Chloride stress corrosion cracking
COTS	Commercial off the shelf
DES	Detached eddy simulation

DFF	Design fatigue factor
DLE	Dry low emission
DNS	Direct numerical simulation
FAT	Factory acceptance test
FEM	Finite element method
FPSO	Floating production storage and offloading
FLS	Fatigue limit state
FSI	Fluid structure interaction
GT	Gas turbine
HART	Highway addressable remote transducer
HCF	High cycle fatigue
HTM	Heat transfer medium
ITP	Inspection and test plan
LES	Large eddy simulation
LCF	Low cycle fatigue
MLD	Multi louvre damper
NDT	Non-destructive test
P&ID	Piping and instrument diagram
PMI	Positive material identification
PQR	Procedure qualification record
PT	Penetrant test
RANS	Reynolds averaged Navier-Stokes CFD modelling (generally referring to modelling steady flow behaviour)
RFQ	Request for quotation
SDRL	Supplier document requirement list
TEG	Turbine exhaust gas
ULS	Ultimate limit state
URANS	Unsteady Reynolds averaged Navier-Stokes CFD modelling
WHRU	Waste heat recovery unit
WPQ	Welding procedure qualification
WPS	Welding procedure specification

5 Proposals

5.1 Purchaser's responsibilities

The purchaser's enquiry should include data sheets, checklist and other applicable information outlined in this document. This information should include any special requirements or exceptions to this document (see Annex C).

The purchaser is responsible for the correct process specification to enable the supplier to carry out the exhaust system design and manufacture.

The purchaser is responsible to clearly state the supplier's scope of supply.

The purchaser's enquiry should specify the number of copies of drawings, data sheets, specifications, data reports, operating manuals, installation instructions, spare parts lists and other data to be provided by the supplier.

5.2 Supplier's responsibilities

The supplier's proposal should include:

a) data sheets for each exhaust system and the associated equipment;

b) an outline drawing showing as a minimum, layout and clearances, arrangement of tube bundles, platforms, ducting, damper systems and stack;

c) a definition of the extent of shop assembly, including the number, size and weight of prefabricated parts and the number of field welds;

d) a detailed description of any exceptions to the specified requirements including this document;

e) a completed noise data sheet if specified by the purchaser;

f) a time schedule for submission of all required drawings, data and documents;

g) a program for scheduling the work after receipt of an order; this should include a specified period of time for the purchaser to review and return drawings, procurement of materials, manufacture and the required date of supply;

h) a list of utilities and quantities required;

i) if specified by the purchaser, a list of proposed sub-suppliers for major components and items, which can include steel plate, insulation materials, expansion joints, tubes and extended surfaces on tubes, fittings, tube bundle fabrication, dampers, castings, steel fabrication, ladders and platforms and other auxiliary equipment.

The supplier shall identify all parts and components with a shorter estimated lifetime than that specified for the complete system or which will need maintenance and/or removal for service. Expansion joints, damper, actuators and seals are examples of such components.

6 Basic exhaust system design

6.1 General

GT exhaust systems can be with or without a WHRU and damper system which recovers heat from the exhaust of a GT and exchanges this heat into HTM to supplement the thermal requirements of another process. The WHRU enhances the thermal efficiency of the cycle with minimal impact on the operation of the GT itself.

6.2 Exhaust system configuration

Each exhaust system should normally be connected to its own GT. In the event that more than one GT is connected to an exhaust system, then special considerations would apply which are not covered in detail in this document.

6.3 Service life

Unless otherwise stated by the purchaser, the design, selection of equipment and materials and corrosion protection shall be based on a design lifetime of 20 years with 30 starts/stops from cold to full load per year. The supplier should supply the service life and minimum uninterrupted operation interval based on each specific application. The maintenance procedure necessary to achieve these intervals should also be supplied.

NOTE For highly cyclic GT applications, e.g. in single cycle mode, where the start/stop cycles are significantly more frequent, the risk of fatigue on various parts of the WHRU increases.

6.4 Supply responsibility

Supply responsibility for the exhaust system should be either with the GT supplier or contracted directly between the purchaser and the exhaust system supplier.

6.5 GT characteristic data

If the exhaust system is purchased under the GT supplier responsibility then the GT supplier is responsible to provide the required dimensional, acoustic, thermal, flow characteristics (steady state and transient) and mechanical information to the exhaust system supplier as specified in this document.

In the event that the purchaser contracts directly with the exhaust system supplier then it becomes the purchaser's responsibility to obtain this data from the GT supplier and pass it on the exhaust system supplier.

6.6 Required operating envelope

The purchaser is responsible to define the equipment's required operating envelope which should be shown on the data sheets including any dry run requirements as defined in 9.3.2.

The supplier is responsible for ensuring that all items of equipment and components provided are designed for the specified operating conditions.

The supplier shall ensure that the equipment takes account of all potential applied loads (typically seismic, transportation, wind loads, etc.).

6.7 Equipment specification

The exhaust system should be proven in practice, robust, reliable, safe, operable and maintainable.

The exhaust system should be based on the least number of factory-built modules consistent with transport and site erection dimensional and weight restrictions.

The exhaust system shall be designed and constructed to meet all operational cases specified in the RFQ.

6.8 WHRU equipment specification

Materials of construction for the tube bundle pressure parts shall be selected from internationally recognized material codes. The supplier's data sheets shall clearly state the location(s) of each material.

The WHRU shall be designed to provide the required performance with no negative tolerance. The design shall consider the selected fouling factor and required degree of over-surface to ensure that these requirements are met.

NOTE The HTM can typically be the following:

(i) a water/glycol solution;

(ii) hot oil/thermal oil;

(iii) water;

(iv) hydrocarbons, liquid or gaseous.

In the final selection of the HTM, due consideration should be given to operating temperatures and pressures, the degradation limits, surface tension, toxicity, flammability and corrosiveness of the HTM.

6.9 Operating conditions

Each component of the exhaust system (e.g. WHRU tube bundle and supports, casings and linings, ductwork, dampers, etc.) shall be capable of withstanding the most severe temperature specified plus a margin as defined in Clause 8.

6.10 Operating environment

The equipment, including all auxiliaries, shall be designed for operation under the environmental conditions specified by the purchaser. These conditions should include whether the installation is indoors (heated or unheated) or outdoors, maximum and minimum temperatures, unusual humidity, and dusty or corrosive conditions, wind, earthquake and/or sea motions during operation and transport. The unit and its auxiliaries shall be designed for shipment and installation under the specified conditions.

If sub-zero ambient temperatures are specified by the purchaser, then appropriate materials and test procedures should be applied.

6.11 Equipment arrangement

The arrangement of the equipment, including piping and auxiliaries, should be developed jointly by the purchaser and the supplier. It is the purchaser's responsibility to identify dimensional limitations for the location of the exhaust system including space required for tube bundle and/or tube removal as well as any handling weight limitations that apply. The arrangement should be submitted by the supplier to the purchaser for review and agreement during the proposal phase.

The purchaser is responsible for specifying any weight limitations (e.g. maximum total equipment weight, maximum lifted weight). If no such limitations exist, at least the total equipment weight with applicable margin (e.g. ±10 %) should be included in the supplier's proposal.

6.12 Provision for future addition of WHRU

Where specified by the purchaser, the exhaust system shall include provision for future installation of a WHRU. This should include the bolted panel sized for the full exhaust flow to which a future WHRU can be connected. It should also include bolted duct section which can be replaced with a future damper or diverted system.

6.13 Electrical equipment

Motors, electrical components, and electrical installations shall be certified for the area classification specified (class, group, and division or zone).

6.14 Field assembly and disassembly

The supplier shall state in the proposal the proposed method for the disassembly required for repair or replacement of exhaust system parts such as expansion joints, WHRU, dampers or silencers. While tube failures are rare, if specified by the purchaser, the design shall include provision for tube bundle pressure part repair or replacement.

6.15 Special tools and fixtures

If special tools and fixtures are required to disassemble, assemble or maintain the unit, they shall be included in the supplier's proposal and furnished as part of the initial supply of the equipment. For multi-unit installations, the requirements for quantities of special tools and fixtures should be agreed between the purchaser and the supplier.

6.16 Spare parts

Spare parts supplied with the main equipment delivery shall be identical to the fitted parts.

6.17 Deviations

All proposed deviations of the supplier's equipment from this document shall be listed by the supplier with the bid.

7 Documentation

7.1 General

The supplier should provide all drawings, design details, calculations, and analysis, operation and maintenance manuals, and other information necessary for the design assessment, erection, operation and maintenance of the exhaust system installation. All information should be clear and not open to misinterpretation and shall apply specifically to the installation supplied.

The purchaser should specify which documentation is required to be provided in a local language.

The purchaser should specify the format and number of copies of documentation required from the supplier.

Unless otherwise specified and agreed by the purchaser all documentation should be submitted in electronic format.

All calculations and documentation shall be prepared using the agreed unit system for the project.

7.2 Data sheets

Data sheets should be used for the exchange of specification related information between the purchaser and the supplier. The purchaser is responsible for providing the GT data and corresponding WHRU thermal loads for the required duty envelope. The supplier shall provide completed data sheets with confirmation that performance requirements are met.

The recommended data sheet format for WHRUs is available for download using the link given in Annex E.

7.3 Supplier document requirements

The purchaser should provide a SDRL for the exhaust system.

The supplier shall provide the documents listed in Table 1 for review unless otherwise specified by the purchaser.

The purchaser should specify which documents are subject to his approval.

Table 1 — Documentation to be provided by the supplier and reviewed by the purchaser

Document	Remark
Calculations demonstrating compliance with specification requirements, including any pressure part and structural design codes	
Data sheets	Detailing process design and performance data at all specified operating cases. Mechanical, materials and construction data Key dimensions and weight
Suppliers manufacturing data report	
FAT procedure	
Site performance acceptance test procedure	
General arrangement drawings	Showing locations of all interfaces and major dimensions
Hazardous area and ingress protection certification for all electrical components.	
Welding and NDT data, including — WPS and PQR — WPQ — Weld map — ITP — NDT procedures — NDT personnel qualifications — Procedure for storage and handling of filler metals	
Inspection certificates for all metallic materials of construction.	Material certificates in accordance with ISO 10474[a], type 3.1 for all pressure parts and type 2 for materials of exhaust gas ducts/casings. The certificates shall satisfy the applicable code requirements.
Installation, operating and maintenance instructions	
Spare parts list	Commissioning and operational and strategic spare parts lists
Pre-commissioning and commissioning instructions	
Pressure and capacity test certificates for any pressure relief valves	
Pressure test certificates for any fabricated pressure parts	
Quality plan	
Fan and motor curves and data sheets for all fans.	To include: — sound power levels and sound pressure levels — test reports
Sound power levels and sound pressure levels of the equipment.	
P&IDs and controls description including alarm and trip points and cause and effect.	In accordance with appropriate ISO code and shall be complete, comprehensive and consistent

[a] Reference can also be made to EN 10204 with regards to material certificates.

Table 1 *(continued)*

Document	Remark
Tube bundle vibration and resonance analysis	
Fluid, thermal and structural analysis	See Annexes A and B
Structural dynamic analysis	See Annexes A and B
Instrumentation calibration certificates and data sheet	
3D outside dimensional model	
Packing list and handling instructions	
Foundation loading diagrams and support details	
Cross-sectional drawings	
Electrical/instrument layouts	
Insulation/lining details	
Control philosophy and block diagrams	
Electrical termination and hook-up details	
Interface terminal point list	
Hydrostatic/pneumatic test procedure	
Special tool list	
[a] Reference can also be made to EN 10204 with regards to material certificates.	

8 Exhaust system engineering and design

8.1 Overview

Exhaust system components are listed below:

All GT exhaust ducts and transition sections

a) WHRU(s) (Refer also to Clause 9);

b) Damper(s) (Refer also to Clause 10);

c) Stack;

d) Silencing measures;

e) Expansion joints;

f) Structural steel supports.

If WHRU and damper systems are included in the scope of supply refer also to Clauses 9 and 10 for WHRU process-design considerations and tube-bundle design requirements.

8.2 Typical WHRU configurations

There are several possible WHRU configurations. These are mainly characterised by different TEG flow directions, and bypass and silencer arrangements.

8.3 General

As the basis of design for the exhaust system the purchaser is responsible to supply the geometry and boundary conditions at battery limits under all specified design and operating conditions and cases, all as detailed in Annex C.

The purchaser should take account of the fact that the exhaust system downstream of the GT can affect the flow conditions at the battery limit.

The purchaser should specify the maintenance philosophy to be applied in the design of the exhaust system components.

The allowable pressure drop across the exhaust side should be agreed by the supplier and the purchaser, and the supplier shall submit calculated pressure drop figures for each part of the system supplied, with necessary backup information for approval.

The purchaser should ensure that the pressure drop over the entire exhaust system does not result in the maximum allowable GT back pressure being exceeded.

NOTE The WHRU back pressure does reduce the shaft power and increase the fuel consumption/CO_2 emission of the GT, hence the specified limits need to balance the desirability of the low back pressure at the GT with the needs to provide a cost-effective exhaust system.

Flow straightening devices are not recommended.

8.4 TEG flow-induced vibrations

For guidance regarding the assessment of flow induced vibration of the exhaust system casings refer to Annexes A and B.

Supplier shall ensure that TEG vortex shedding frequencies do not coincide with the acoustic frequencies which can cause unacceptable vibration of the WHRU tube bundle and casing or other exhaust system components.

8.5 Exhaust system casing and ducting

8.5.1 General

a) Components should preferably be cold casing (internally lined). Hot casing designs are subject to approval from the purchaser.

b) Hot casing designs have greater thermal expansion and transient thermal stress. There should be no change in insulation design principle along the TEG flow path. If unavoidable (e.g. hot casing exhaust collector and cold casing exhaust system), the transition shall be designed by means of an expansion bellow where each flange of the bellow has the same insulation design and material as the flange it is connected to.

   NOTE The choice of the insulation principle has significant influence on cost/complexity of routine inspections of the system. While a cold casing system can be inspected from the outside while the GT is running (visual, thermographic), a hot casing system requires inspection from the inside to determine condition and mechanical integrity.

c) The purchaser is responsible for defining in the RFQ, the extent of CFD or other flow testing of the ducting.

d) Components should be of circular, square or rectangular construction.

e) For hot casing design, circular shape is preferable.

f) In the event of welded attachments inside the TEG path the supplier shall undertake thermal, flow and mechanical analyses which shall be subject to the purchaser's approval.

g) Transition pieces between duct sections of different cross-sectional areas shall be provided if necessary. Abrupt transitions in cross-section should be avoided.

h) The flow distribution through any change of flow path (shape and direction) should be taken into consideration for the overall system performance and service life (e.g. performance of WHRU, damper, silencer and GT.

NOTE TEG mal-distribution is a particular feature of exhaust systems which can cause:

— preferential heating of the different passes of the coil;

— flow detachment from the duct wall and adverse effect to TEG pressure drop;

— adverse effect to silencer performance and lifetime;

— adverse effect to damper performance and lifetime.

i) Expansion joints should be of fabric or metallic construction and shall be provided in the flue gas ducting as necessary (refer to 8.8).

j) All components (including joints) shall be gas tight to provide zero TEG leakage.

k) Field joints should be seal-welded insulated and lagged in the field during assembly. If this is not practical due to maintenance philosophy or accessibility, extra attention should be given to the design of the field joint.

l) For the component design the gas velocity shall be determined with due consideration of the pressure drop and acoustic requirements.

m) The WHRU casing and ducting walls shall be constructed of steel plate. Plate thickness shall be determined by the overall mechanical design calculations. Plate thickness less than 6 mm for ferritic steel and 5 mm for austenitic steel shall be subject to approval by the purchaser. The material in combination with its corrosion protection should be proposed by the supplier if not stated in the RFQ.

n) Components shall have a design pressure based on the most severe combination of the wind pressure and 1,5 times the maximum operating TEG pressure in the casing, but not less than 50 mbar. If applicable also explosion loads shall be taken into account.

o) Components design shall take into consideration all other imposed loads such as:

(i) lifting and transportation;

(ii) installation;

(iii) motion, e.g. acceleration from transportation, seismic events or offshore floatation;

(iv) snow and ice;

(v) wind.

p) If a combined stack outside the supplier's scope is used, the purchaser is responsible for specifying the maximum positive and negative design pressures taking into account maximum natural draught and maximum back pressure.

q) The design of stiffeners shall take into account thermal expansion and temperature gradients in normal operation and transient cases such as start-up and shut-down (always required for hot casing designs).

r) Components shall be designed to prevent vibration, distortion and warping due to temperature, pressure GT pulsations and internal flow. Effective vibration isolation from the GT is particularly essential. Ducting shall be sufficiently rigid to prevent damage from vibration and avoid drumming when exposed to TEG flow over the complete flow range.

s) Component sections should be suitably stiffened to minimize distortion. Component plate shall be designed to limit the deflections of the span of plate between stiffeners, taking full advantage of multi-span continuity where appropriate, under design conditions.

t) Horizontal (flat) sections should be avoided to provide a drainage slope. All horizontal stiffeners shall be designed to prevent water accumulation e.g. weep holes.

u) The exhaust gas system shall be provided with internal drainage connections at low points.

v) All components shall be designed for the intended lifting or installation procedures.

w) For hot casing design, welded lifting lugs should be removed after initial installation.

x) The purchaser is responsible for specifying any requirement for supporting steelwork in the RFQ.

y) The exhaust system shall be designed to accommodate the calculated thermal expansions, with fixed points local to the WHRU, damper and silencer (where installed) normally providing anchor points.

z) Component supports shall be designed for all live and static loads, including any uplift due to specified wind and/or other loads. The WHRU hydrostatic test condition shall also be considered.

8.5.2 Hot casing design and materials

a) It should be noted that this type of design is susceptible to excessive thermal stresses for the casing, associated stiffeners and structural members even for steady state operation. A FEM analysis shall be carried out to optimize the design to minimize the high thermal stresses during transient conditions and verify that the system will withstand the anticipated number of start/stop cycles during the required lifetime.

b) Hot casing design is inherently unsuitable for units in cyclic operation.

NOTE Design processes can minimise cyclic impacts in steady state conditions but higher thermal stress during transient conditions is unavoidable.

c) In parts of the exhaust duct with highly pulsating flow (usually close to the GT), the duct walls (especially non-circular) can be exposed to risk of high cycle fatigue due to vibration.

d) Square corners are particularly susceptible to high stresses. Therefore, sharp corners shall be avoided and welds not be placed in areas with high stress. If square or rectangular design is used, all corners shall be formed with a radius so that all welding is on the sides of the duct.

e) The casing material selected shall be designed for at least the maximum TEG temperature, as defined in 9.3.2.2 a).

f) Supports shall be provided at each end of horizontal ducting sections and at midpoints as required. One support shall be anchored while the others are free to move on sliding pads or small rollers. Sliding supports shall be designed to allow lateral and axial expansion movements of the ducting. If sliding supports are used they shall be of a high temperature bearing material and heat shielded to protect the bearing material and the structural steel.

The material selection falls into one of the following groups:

(i) Low alloy carbon steel (e.g. 13CrMo4-5, 10CrMo9-10);

(ii) Stainless steel material, ferritic and austenitic (e.g. AISI 316, AISI 321);

(iii) High temperature Ni Cr material (e.g. alloy 800).

g) The following apply to the selected material (type and thickness):

(i) Corrosive aspect of the flue gas and required surface protection should be considered.

(ii) If low alloy steel is selected, strength values at elevated temperature shall be taken from recognized standard and creep shall be evaluated if operation in creep range is expected.

(iii) The temperature limits given in the structural code shall not be exceeded.

(iv) A surface treatment designed for service life at high temperature should be used on all parts to reduce corrosion rate.

(v) A corrosion allowance of 1,5 mm shall be included for low alloy material.

(vi) For ferritic stainless steels a surface coating designed for service life at high temperature shall be used on all parts to reduce corrosion rate.

(vii) Unless otherwise specified by purchaser, austenitic steels can be left uncoated if not insulated or exposed to marine atmosphere. If exposed to marine atmosphere stress corrosion can be a consideration due to chlorides.

NOTE Low alloy steel materials have good thermal conductivity and low thermal expansion properties, it is therefore a good choice regardless of thermal stress. While they tend to have lower creep stresses, alloy materials have higher thermal conductivity and lower thermal expansion making them less susceptible to thermal stress.

Stainless-steel material have good strength values at high temperatures and reduced corrosion rates. Ferritic steels have better thermal conductivity and lower thermal expansion properties than the austenitic steels. Ferritic Steels have lower corrosion resistance than austenitic.

High temperature Ni Cr materials have improved creep strength at very high temperature as well as very good corrosion properties but are more susceptible to high thermal stress due to lower thermal conductivity and high thermal expansion.

h) Refer to 8.5.4 on flange-bolts system design.

8.5.3 Cold casing design material

Selection of material should be guided by the following considerations:

a) Carbon steel

As the operating metal temperature is relatively low compared to hot casing design the main concern in material selection is to minimize corrosion. The low temperature increases the risk of condensation on the casing surface underneath the insulation system. This is especially a concern if there are compounds in the fuels which can form acid, such as sulphur.

b) Stainless-steel material, (e.g. AISI 316, AISI 321)

Where stainless steel is used for marine environment grade SS316 or SS321 shall be used unless otherwise agreed with the purchaser.

For marine environments, stress corrosion is not normally considered to be a problem for material below 60 °C.

(i) Stainless-steel materials may be used in this type of application due to good corrosion resistance or for cases where operation with insulation failure is a specified design condition.

(ii) The purchaser is responsible for specifying if “loss of insulation” should be considered as a design case This mode can be critical for the design and give the maximum level of stress. In cases where the purchaser specifies design for loss of insulation then the provisions for hot casing design shall be considered.

NOTE Damage to insulation can remain undiscovered over a considerable length of time and when discovered operational needs might not allow for immediate repair.

8.5.4 Flange bolts

a) The following factors should be considered in flange bolt design:

(i) flange thickness;

(ii) flange material;

(iii) local temperature increase over time;

(iv) ambient conditions;

(v) gasket type;

(vi) gasket material;

(vii)bolt material;

(viii) bolt manufacturers' procedures.

NOTE For flange-bolt systems, rapid temperature rises in the flanges result in increases in flange thickness due to thermal expansion while the bolt shafts initially remain relatively cold. This can lead, if not addressed properly in the design, to premature (or even immediate) bolt failure, gas leakage and compromised mechanical integrity of the flange connection. If not properly considered, even the first start up cycle can overstretch a wrongly designed bolt resulting in permanent loss of pretension.

b) Where specified by the purchaser, for cold casing design all evaluations mentioned under a) shall be part of the flange-bolt design to make the system robust and able to maintain mechanical integrity in case of loss of insulation (accidental load).

The additional cost associated with this provision can be justified when taking into account the following aspects:

(i) Depending on design and insulation method, the insulation and lining system in flange areas can be more vulnerable than in a straight duct.

(ii) When insulation is lost, the mechanical integrity of bolts in the affected area can be compromised—even during one start/stop cycle.

(iii) Damage to the inside insulation can remain undiscovered over a considerable length of time or when discovered operational needs might not allow for immediate repair.

(iv) When insulation damage inside the duct can have compromised the bolts' mechanical integrity, the exchange of the affected bolts can be costly and time consuming if access is difficult.

c) The supplier shall design flanges, gasket and bolts as one system and ensure that bolts will operate safely within their elastic operational range even when flanges are fully warmed up to expected steady state temperature while the bolt shaft still is at ambient temperature.

d) The gasket material shall not be a part of flange pretension system.

e) The supplier shall ensure that the bolts under all conditions provide sufficient pretension to ensure gas-tightness and mechanical integrity of the flange connection.

f) The flange bolt system shall be designed to the same operating conditions applicable to the exhaust gas system.

g) Exhaust systems without internal insulation usually require the use of tension bolts (extended shaft length). For the installation of pretensioned flange bolts the supplier shall develop detailed procedures including the required anti-seizure compound. This shall take account of the effect of torque on the resulting pretension of the final installation.

h) Material prone to CSCC is considered unsuitable for exhaust system bolts in a marine environment.

i) The method of determining the necessary pretension and ensuring that the specified pretension is provided shall be documented where the flange is designed for greater than 250 °C.

j) Acceptable methods of determining the necessary pretension are:

— FEM analysis (refer to Annex B).

— Stress strain calculations.

k) A torque wrench is considered an acceptable method of providing the necessary pretension.

NOTE Experience has shown that it is very difficult to predict what temperatures flange bolts of exhaust systems are exposed to during operation and over the lifetime of a system. Significant contributors to this uncertainty are:

(i) inconsistent or poor workmanship quality for installation of the internal insulation, especially in flange areas for site-built systems;

(ii) deterioration (local or general) of insulation material;

(iii) potential complete loss of insulation (accidental);

(iv) depending on wind, ambient temperature, precipitation, sunshine and / or orientation the resultant cooling effect can vary hugely.

l) Unless specified by the purchaser, the bolting system selected shall be maintenance free for the service life and the proposed bolt material shall be presented to purchaser for approval.

m) The nut shall be of a design that eliminates the risk of loosening due to vibration or thermal effects during the entire life span of the system.

NOTE Bolt systems are typically not easily accessible for maintenance and inspection.

8.5.5 Surface preparation and treatment

8.5.5.1 Functions

Surface treatment can be required for the following functions:

a) Protection from moisture related corrosion and condensable sulphur contaminants in the TEG. (Note that cold casing designs have potential for condensation of water onto the casing when ambient conditions are such that the casing is below the dew point of the TEG. The dew point is elevated if SO_3 is present in the TEG with resulting condensation of sulphuric acid.)

b) Protection from corrosion from constituents in the insulation.

c) Protection from corrosion from weather.

d) Decorative only.

8.5.5.2 Protection from corrosion

The selection of materials and their associated coating should ensure protection against corrosion from the following:

a) moisture together with condensable sulphur contaminants in the TEG;

b) chlorides in the insulation and possible attack on stainless steel;

c) marine environment (salt) and possible effect on stainless steel;

d) weather.

8.5.5.3 Treatment specifications

If not specified by the purchaser, the supplier should specify in the proposal the type and application details of coatings (internal and external) envisaged to match the specified operating conditions.

The supplier's specification shall include the following information:

a) method statement for surface preparation;

b) method statement for surface treatment;

c) test procedure;

d) touch-up and repair procedure;

e) on-site repair procedure if the surface treatment would be overheated in the event of loss or damage to internal insulation.

8.5.5.4 Requirements for various surface types

8.5.5.4.1 Cold casing, internal surfaces

Where the casing material is susceptible to corrosion due to water or acid dew point it shall be protected by a coating designed for the resulting conditions.

8.5.5.4.2 Cold casing, external surfaces

The treatment shall be suitable for the calculated operating metal temperature plus a margin of at least 100 K to account for solar radiation and hot spots. If the casing is designed to survive loss of internal insulation, the external coating is likely to require repair when the insulation is repaired.

8.5.5.4.3 Hot casing, internal surfaces

It is acceptable that surfaces be left untreated for operational reasons.

A temporary coating should be applied to carbon steel to protect during transportation and storage.

8.5.5.4.4 Hot casing, external surfaces

The treatment shall be designed to withstand the maximum specified TEG temperature and in the case of carbon steel it shall also be designed to protect during transportation and storage.

8.6 Mechanical and thermal analysis

Supplier shall carry out a stress analysis using FEM (Annex B) or other recognised methods in order to verify that all construction elements and details are within predefined acceptance levels.

a) The analysis shall cover both static (e.g. normal operation) and transient cases such as start-up and shut-down.

b) Special attention should be paid to all stress raisers and stress concentration points such as corners, changes in thickness (e.g. flanges), weld undercuts and weld penetrations, equipment mounted to the casing (e.g. lifting lugs, tube hangers, silencer elements), and penetrations.

c) The resonance frequency should also be confirmed by analysis/testing.

d) The possibility for combined creep and thermal fatigue interaction shall be considered in material selection and general design. Refer to Annexes A and B.

8.7 Insulation and refractory

a) All hot equipment and piping should be insulated for energy conservation, frost protection (if sub-zero ambient temperatures are specified), prevention of hot surface ignition sources in hazardous zoned areas, to protect adjacent equipment or personal protection purposes.

b) The insulation should consist of bio-soluble fibre. Ceramic fibre may only be used where local regulations permit and with the agreement of the purchaser.

NOTE Bio-soluble fibre is considered less hazardous to health than ceramic fibre.

c) If energy conservation or prevention of hot surface ignition sources in hazardous zoned areas is not relevant (e.g. stacks) and is not required by the purchaser, alternative means of equipment or personnel protection (e.g. wire screens) can be applied.

d) The required thickness of insulation shall be determined in accordance with ISO 12241, or ASTM C680-10.

e) Unless otherwise specified by the purchaser, for personnel protection and/or the avoidance of low temperature chloride corrosion on stainless steel in marine environments, the external casing temperature shall not exceed 60 °C with the maximum expected air temperature at the operating location and a wind speed of 1 m/s. This calculation excludes the effects of direct solar radiation. Unless otherwise specified by purchaser, surface emissivity shall be taken as 0,7. However, it should be recognized that this might not be achievable for higher ambient temperatures (e.g. in excess of 30 °C).

f) Higher temperatures are permitted at small areas, for example where fasteners, supports or internal attachments are welded to the casing. The hot spot temperature shall not exceed the temperature rating of the hazardous area or the surface coating/paint system.

g) All access doors, hatches and ports for inspection, viewing and maintenance shall be fitted with an insulation system of equal effectiveness to that of the main surfaces. Particular attention should be given to the design, installation and effectiveness of closing joints such that damage is avoided during opening/closing and any resultant hot spots are within acceptable limits.

8.7.1 Exhaust system casing and ducting external insulation (hot casing design)

a) It should be noted that this type of design is more susceptible to excessive thermal stresses for the casing, associated stiffeners and structural members.

b) Care should be taken to apply the external insulation over all the stiffening and structure which is welded to the casing to minimize thermal gradients from occurring in these areas.

c) Care should be taken to apply external insulation over section flanges to avoid hot spots and to prevent thermal gradients from occurring in these regions during steady state operation.

d) External insulation shall be covered with stainless steel liner plates installed with adequate allowance for expansion and ensure that the insulation remains dry and free from ingress of water.

e) Where the risk of hydrocarbon penetration into the insulation cannot be eliminated (e.g. a leakage scenario close to the exhaust system), the insulation shall be fully covered with a hydrocarbon tight membrane under the liner plate. The membrane material shall be able to withstand the TEG temperature.

8.7.2 Exhaust system casing and ducting internal insulation (cold case design)

8.7.2.1 General

a) The insulation shall consist of multiple staggered layers with a protective, floating lining plate.

b) In order to prevent voids compression of the insulation under the lining plates shall be applied during installation, according to insulation manufacturer's instructions.

c) The protective lining plate design shall ensure retention of internal insulation material and should incorporate a separate membrane e.g. pillows, in support of this requirement where required.

d) Lining fasteners shall allow free expansion of the liner plates in all directions without distortion or bulging and shall avoid generating vibration. Materials shall be selected to resist erosion and oxidation.

e) Perforated plates can be used to reduce the noise level. In the case of perforated plates, additional measures to prevent loss of insulating material shall be applied, e.g. stainless-steel cloth.

f) Perforated liner plates shall not be used in areas where the TEG flow pattern represents a significant risk of flow induced damage or premature failure of lining and/or insulation (e.g. for several meters downstream the exhaust collector, bends, transition pieces, duct wall location where the violent flow from turbine compressor bleed impinges).

g) A floating internal lining plate system design should be used for all internal insulation systems. However normal insulation materials are also acceptable for high temperature low flue gas velocity applications without lining plates, but with additional protection measures in accordance with the supplier's instructions.

h) The exhaust system consists of zones with high temperature, high flue gas velocity or a combination of both. The design of the internal lining and insulation system shall be such that long-term reliability without loss of insulation effectiveness is achieved.

NOTE The ducting lining downstream from the GT exhaust system interface flange is subject to highly unsteady TEG flow condition which generates high cyclic stresses on the lining system.

i) The internal insulation system should be designed to withstand the flue gas velocity and temperature.

j) For the casing and ducting sections (tube bundle arrangement excluded), the hot face design temperature for material selection for the liners shall be as follows:

   (i) The maximum TEG temperature plus 30 K, or the highest calculated TEG temperature in the subsequent heat transfer sections plus 30 K.

   (ii) Table 2 provides guidance for the selection of internal lining materials.

Table 2 — Material selection internal lining temperature limitation

Material selection for internal lining	Maximum temperature during continuous operation[a] °C
11 Cr (e.g. SS 409/410)	600
18Cr/8Ni (e.g. 304/316)	700

[a] Above 750 °C metal liners are not recommended.

8.7.2.2 Floating liner plate insulation design

a) The insulating material shall have a minimum density of 128 kg/m^3.

b) The insulation shall be secured in position by a grid of fasteners which retain a stainless-steel cladding plate which covers and protects the insulation material from the erosion due to the contact with high velocity of the hot exhaust gases.

c) Alternative systems if proposed by the supplier shall be subject to the purchaser's approval.

d) The insulation of field-erected connections and module connections require particular design attention. The design of these joints shall ensure that cavities under the steel liner plate are filled with insulation once the joint is completed. All connections between pre-insulated panels and site insulation shall be insulated and designed to avoid discontinuities and insulation loss. Particular attention should be placed on installation for designs where the liner is discontinuous at flanged connections between sections. Poor installation resulting in gaps between adjacent liner panels, can cause elevated external flange temperatures and ingress of TEG behind the liner, which can lead to degradation of the insulation and corrosion damage beneath the liner due to acidic flue gas condensate.

e) The insulation shall be multi-layered in all directions and provide consistent coverage in all relevant areas.

f) Overlapping liner plates shall be appropriate to the flow direction to prevent ingress of TEG behind the liner which can cause distortion and damage to the lining integrity.

g) Where personnel access is required lining plate floors shall be made of minimum 3 mm thick liner plate, whereas walls and roof shall be a minimum of 2 mm thick.

h) At the hot face design temperature, the thermal expansion of any plate shall not exceed 20 mm for the extreme diagonal measured between fastener centres.

i) Where studs type fasteners are used the following minimum requirements shall apply, however the supplier shall remain responsible for the integrity of the design which shall be supported by experience and/or documentation:

(i) Studs shall be welded to the casing.

(ii) Stud guns shall not be used. Alternative systems can be proposed by the supplier for approval by the purchaser.

(iii) Welders shall be individually qualified and test welds shall be subject to destructive testing.

Poor stud to casing welds have been known to result in operation failures and as such particular attention should be paid to this activity.

(iv) Stud to casing weld procedures shall be subject to exhaust system supplier and purchaser approval prior to welding and shall include appropriate surface preparation of the weld area.

(v) Studs shall be M10 minimum for 2 mm plate and M12 minimum for 3 mm plate.

(vi) Unless otherwise agreed with purchaser, studs shall be 316SS material.

(vii) At each stud, the sequence of assembly shall be inner nut, washer, plate(s), washer, final nut. The final nut shall be tightened sufficiently to avoid vibration but not so tight as to restrict plate movement; normally half a turn back from finger tight and secured by a tack weld.

(viii) Plates shall overlap at least 50 mm and holes shall lie at least 30 mm away from the plate edge. Each hole in the plates shall be at least 3 times stud diameter and allow for the maximum thermal expansion of the plates +25 % plus fabrication and installation tolerances. Such expansion tolerance is not always required in case a central pin is used which becomes a fixed point for the sheet. Tack weld shall not only connect nut/stud, but also fix the washer to the nut to prevent the washer from vibrating and grinding through the stud.

(ix) The centre hole (fixed point) should be sized for stud diameter only. Alternatively, the centre location shall be fixed by appropriate tack welds of washer to plate. Studs shall be at least the same grade as the liner plate as a minimum.

(x) In high exhaust gas velocity areas studs should be welded to scallop bars which are in turn welded to the casing. These provide additional dimensional stiffness to the cladding. The design of the scalloping needs to consider thermally induced stresses and ensures that the weld detail is designed accordingly.

(xi) Alternative stud fixing systems can be proposed by supplier for approval by purchaser. Lining system, including stud spacing and stud to casing weld, can be in accordance with methods demonstrated on units which have been in long-term operation if agreed with purchaser.

Similar grades of stainless steel can gall so dissimilar grades for the washer and cladding sheets should be considered.

j) If surface treatment is required it shall be applied after welding of the studs.

k) Cut-out areas for penetrations such as access/inspection doors, observation ports and instruments, as well as corners and module seal details should be designed for minimum risk of hot spots.

l) All fastener attachments to casings should be designed for minimum risk of hot spots.

8.8 Noise emission and silencing

a) Where specified by the purchaser, supplier shall include the required silencing measures that are needed as part of the exhaust system in order to meet the overall noise emission requirements specified by the purchaser.

It is recommended that the silencer is supplied as part of the exhaust system scope in order to ensure the overall system is optimised, with respect to silencer location, pressure drop and mechanical design.

The purchaser is responsible for specifying noise emission data at the turbine exhaust.

b) Where specified by the purchaser silencer elements shall be replaceable without hot work. This should involve oversized access doors and/or silencer panels in bolt-together sections. Access doors shall be installed upstream and downstream of each silencer, to permit the removal/replacement of the silencing panels and/or any other component that needs maintenance.

c) Site measurement verification shall be in accordance with ISO 3744 or where needed ISO 9614 for duct wall emissions and ISO 10494 for exhaust stack sound power level.

d) If other noise control measures such as acoustic enclosures are required, they should not in any case obstruct operational or routine maintenance activities.

e) If acoustic enclosures are proposed, prior approval of the purchaser shall be obtained for their construction, materials and access requirements.

f) Acoustic insulation of pipes, valves and flanges as necessary to meet the noise level requirements should be agreed with the purchaser.

g) For cold casing systems, no acoustic insulation shall be fitted on the casing outside to meet the noise requirements.

8.9 Stacks

a) Self-supported stacks greater than 4 outside diameters long shall be designed according to a recognised stack design standard (such as CICIND, ASME STS-01 or other stack design code). The supplier and purchaser should agree which code is to be applied.

b) The purchase is responsible for specifying any minimum stack length or discharge height above an agreed datum.

c) The exhaust gas can reach nearby equipment, working areas or interfere with helicopter traffic. The purchaser is responsible for evaluating the impact of such effects of the exhaust gas plume in determining the required stack height.

NOTE A plume cooling device which induces air to mix with the turbine exhaust gas prior to leaving the stack can be considered to mitigate exhaust gas impingement on adjacent equipment, personnel or helicopter traffic.

d) Measures should be provided to prevent damage by the ingress of rain or snow. This shall include either means to prevent rain/snow ingress or drainage facilities to remove accumulated water in a way that doesn't cause damage. Purchaser has the option to specify particular requirements which can include:

(i) rain hood;

(ii) internal rims;

(iii) drainage facilities;

(iv) damper with built in drain facility.

NOTE Rain hoods have the advantage of protecting against the ingress of rain or snow but the disadvantage of increased pressure drop, disruption of dispersion of exhaust gas and increasing reflected noise to lower elevations.

e) The purchaser is responsible to identify requirement and details of any stack sampling points including temporary TEG composition measurement, e.g. if required by authorities for emission control.

In that case the purchaser is responsible for the definition of the physical dimensions of the connection (e.g. flange details).

The location should be chosen to accommodate the following:

(i) easy access from the outside;

(ii) sufficient space on the outside for handling and inserting the required probe;

(iii) no internals on the inside of the duct (e.g. silencer baffles);

(iv) avoidance of parts of the exhaust system with especially severe flow conditions.

f) Sampling port or ports shall have blind flange bolted covers. Blind flanges shall be fitted with a threaded cap to allow flue gas spot measurements. The blind flange and bolting material shall be the same as the sample port material.

g) The use of uninsulated stacks is subject to the purchaser's approval.

In case of an uninsulated stack, personnel protection shall be provided in areas where access can be required during operation and testing, (i.e. ladders, platforms and base).

8.10 Expansion joints

a) Expansion joint(s) shall be designed for all movements of the exhaust ductwork system and interfacing equipment (axial compression, axial extension, lateral displacements and TEG pulsations).

Supplier shall design each flexible joint to be able to accommodate at least the following within its elastic operational range:

(i) installation tolerances;

(ii) global movements of parts supported on different structures;

(iii) movements due to thermal expansion.

All the above can occur simultaneously in lateral and/or axial direction.

b) Expansions joints should not be required to accommodate excessive installation tolerances, e.g. in excess of 15 mm.

c) Expansion joints should be fabric type, or steel-bellows type with inner sleeves, however fabric type is preferred due to higher flexibility and lower rigidity (both for axial and lateral movements).

d) Fabric expansion joint(s) shall be a flexible multiple layer type and shall be provided with “Bolster Bags” assuring thermal insulation and dampening of flow pulsations. The outer layer shall be fully weather-resistant.

e) Steel-bellows type expansion joints applied to hot casing designs may be insulated and clad externally, such insulation system shall not inhibit the functionality of the expansion joint and shall, if required, be provided with a rain guard. If the expansion bellows design does not require external insulation and cladding, then personnel protection in the form of a guard and a rain shield shall be provided.

f) The fabric shall be bolted between the casings flange and strips. Flange and strips shall be rounded in all directions and smoothly connect in corners without sharp edges.

g) At the outside, where the fabric is pressed and rubbed against the cover strip, an additional protection layer shall be mounted between fabric and strip.

h) Prior to installation of the fabric, the alignment of the flanges should be verified to be within the design tolerance for the expansion joint.

i) Each flange of an expansion joint shall be designed to be compatible with the flange of the neighbouring component it is connected to, for example with respect to material choice, thermal expansion, hot- or cold-casing. If not otherwise stated, the expansion joint shall ensure 35 mm axial movement (extension), 50 mm axial movement (compression) and 20 mm lateral movement (in any direction and in combination with axial movement) as a minimum.

j) Expansion joints shall be designed to accommodate all axial and lateral expansions. These shall consider thermal expansion as well as anticipated deflection of the respective equipment under all specified load conditions (e.g. wind and wave induced motions).

k) Unless otherwise specified, the expansion joint at the GT discharge point should be provided by the GT supplier and the GT supplier should specify the maximum displacements that can be accommodated at this point.

8.11 Steel structures, stairs, ladders and platforms

a) Unless otherwise specified by the purchaser, the support structure and access platforms for on-shore installations should be provided by the exhaust system supplier and for offshore by the purchaser. Supporting steel structures, platforms, stairs, ladders and railings shall be in accordance with purchaser’s requirements.

   Access facilities shall be provided to all inspection/access openings to facilitate the inspection and maintenance requirements specified by the purchaser.

b) Structural design shall take into account the support requirements for all hydrostatic testing (including during manufacture). In addition, all other load cases expected during the life cycle of the equipment, e.g. transport and erection, wind, snow, seismic and explosion loads shall be covered in the design.

c) Platforms, stairs or ladders shall not be mounted to pressure parts or hot casing.

d) The exhaust system including the WHRU package shall be supported independently of the GT package.

e) The layout of the support system should not restrict any work to be carried out on the GT package (inspection, maintenance, partly or complete exchange).

f) The purchaser is responsible to specify if the exhaust system and/or its support structure shall include lifting points or beams with appropriate capacity to be used for work on the turbine package.

g) Such specification should include a material handling strategy describing how components are to be lifted and routed. The steel structure and concept for access ways and platforms shall accommodate such work.

h) Stairs and platforms should provide access to all valves, gauges, instrument process connections, observation points and access doors, and for all other operational purposes.

i) Ladders should only be used for creating extra means of escape or to reach instrumentation which require infrequent access for maintenance.

j) All stairs, platforms and walkways shall comply with the ISO 14122 series.

k) Unless otherwise specified by the purchaser, all main platforms greater than 8 m long shall be provided with an emergency means of escape leading down to ground or deck level (i.e. in addition to normal access).

l) No surfaces above 70 °C should be within reach from stairways, ladders, platforms, etc. If this cannot be avoided for technical reasons, then appropriate shielding shall be provided.

m) Platforms shall have a minimum width of 1m and walkways used only to connect platforms shall have a minimum width of 0,8 m. All locations required for routine operation or access (for example, to dampers, instruments, instrument connections or access doors, etc.) shall be accessible by permanent ladders or platforms. Permanent platform access facilities shall, as a minimum include:

   (i) Exhaust system bottom gas path access platform - one side of exhaust system, full length of exhaust system.

   (ii) Actuator(s) systems (e.g. pneumatic/hydraulic equipment) for exhaust bypass control.

   (iii) Inspection/maintenance platforms for all operational equipment, for example controls, sampling points, control valves, motor operated valves, drain and vent points inaccessible from grade.

   (iv) Stack emission test platform to the flue gas emission (nozzles) and monitoring equipment.

n) Access to instruments and instrument connections shall also be accessible by permanent platforms unless otherwise agreed by the purchaser.

8.12 Preservation, handling, packing and storage

8.12.1 Handling and storage of materials

a) Materials should be handled and stored in accordance with supplier's recommendations.

b) Materials and components shall be new and unused. Products that have been handled or stored in a way or for a length of time that can have led to significant deterioration should be checked before use to ensure that they still comply with the relevant product standard.

c) Structural steel components should be packed suitable for handling and transport, so that permanent deformation does not occur and surface damage is minimized.

8.12.2 Handling and storage of construction material and subcomponents at suppers works

8.12.2.1 General

In the absence of purchaser specifications, the supplier should specify and apply methodologies and measures for preservation and packing to meet the project requirements. The measures should include procedures to protect the equipment during pre-shipment, transportation and storage prior to construction, during construction, before start-up and for prolonged shut-down. Minimum measures pre-dispatch shall include:

a) thorough cleaning and drying;

b) closure of all flange openings for atmospheric protection and to prevent foreign matter from entering during transport or installation;

c) protection of all exposed carbon steel surfaces from atmospheric corrosion;

d) the interior of the carbon steel tube bundles should be purged and maintained with nitrogen at a positive pressure of 0,35 bar g with pressure gauge to monitor that the pressure is sustained or equivalent system.

8.13 Inspection and testing

a) The supplier shall submit an inspection and test plan (ITP) to the purchaser for approval.

b) The ITP shall detail all inspection and testing procedures as described in the supplier's quality plan and as required by the design code.

c) Refer to Annex D for fabrication requirements.

8.13.1 General inspection

a) The ITP shall specify all documentation and equipment inspection requirements and associated testing procedures and all activities that are to be performed to ensure appropriate quality of the equipment and compliance with all applicable standards, codes and specifications.

b) The review, witness and hold points should then be agreed between the purchaser and supplier. A minimum of 2-week notice for inspection points shall be provided by the supplier.

8.13.2 Specific inspection requirements

8.13.2.1 Quality control

a) Welding inspection requirements during fabrication:

   (i) 100 % of the pressure part components, including tubes, fins and welds in the complete exhaust system shall be subject to progressive visual inspection during the manufacturing process.

   (ii) Unless otherwise specified by the purchaser, 100 % of the butt welds in tube bundle(s) and headers shall be subject to progressive radiographic (e.g. X-ray) testing and acceptance during the manufacturing process.

   (iii) Unless otherwise specified by the purchaser, all welds in non-pressure parts shall be subject to 100 % progressive visual inspection and acceptance during the manufacturing process.

   (iv) 100 % of stub-to-header welds [9.2.1 i)] shall be subject to outside surface inspection by penetrant testing (PT) or magnetic particle testing (MPT) to detect weld defects/cracks etc.

   (v) 100 % of the inside surfaces of stub-to-header welds [9.2.1 i)] shall be visually inspected with dental mirror or borescope.

   Any damage or defects to pressure part components arising from the above inspections shall be rectified or replaced, and re-inspected / tested until accepted in accordance with the applicable procedures.

   Stubs of the same material as the header and internal diameter as the tubes shall be welded to the headers and the welds inspected with MP/penetrant from the outside.

   If the welds have passed these inspections, the tubes shall be buttwelded to the stubs and these welds shall be subject to the same inspection regime as the remaining welds of the tube bundle.

b) Where dye penetrant is used, it shall be free of residual chlorides.

8.13.2.2 Insulation

a) The supplier's inspector shall inspect the installation of the entire insulation system during and after the installation process but before liner plates and/or cladding materials are fixed in place and certify the correct installation. This activity shall be part of the ITP and the purchaser shall be invited to attend.

b) The supplier's inspector shall verify that the insulation system complies with the specification, for example:

   (i) the insulating material is of the correct type and specification - K value, density and thickness;

   (ii) the entire area that should be insulated is fully covered, without gaps;

   (iii) the insulation material is installed in accordance with the design, with the correct compression and secure against movement.

c) Photographs shall be used to document the correct installation of the lining system in accordance with the ITP.

8.13.2.3 Liners (for inside insulation)

a) Suppliers ITP shall include verification that fixings (including pins) or other parts which secure liner plates or cladding are installed correctly, are the correct length (to compress the insulation layer), have appropriate mechanical strength and are installed in the correct locations.

b) It is recommended that the supplier engages a specialist lining inspector to verify the lining work.

NOTE Mechanical strength and correct installation of the fixation, and correct overlap are vital to permit free float of the liners during thermal expansion.

8.13.2.4 Verification of effectiveness of insulation

a) Once the system has been subjected to at least 100 operating hours a thermographic survey covering the complete outside of the exhaust system is recommended to be performed while the gas turbine is running at normal load.

b) The purpose of this examination is to:

   (i) verify that the insulation is installed correctly and that the surface temperature and any local hot spots do not exceed the accepted limitations (be aware that measured temperature is effectively influenced by environment condition);

   (ii) establish by visual and thermographic inspection that there are no detectable leaks;

   (iii) confirm that all maximum surface temperatures are not exceeded;

   (iv) provide a record against which future thermographic surveys can be compared in order to evaluate possible changes in insulation performance (degradation, damage, etc.).

9 WHRU engineering and design

9.1 WHRU process design

a) The purchaser is responsible to specify the required process guarantees, for example thermal performances, tube-side pressure loss, draught loss, noise emissions and surface temperature.

b) Unless otherwise specified by the purchaser a 10 % over-surface margin shall be included over and above that calculated for the appropriate design case including in the fouled condition.

c) Table 3 provides suggested exhaust gas side fouling factors

The purchaser is responsible to specify either the value of the internal and external fouling factors or that these should be determined by the supplier based on HTM and TEG data.

Table 3 provides suggested exhaust side fouling factors considering different types of fuel gas and liquid fuel to be fired in the GT and which should be used as guidelines for the purchaser. The table has been grouped into three categories: clean gas, average gas and dirty gas.

Table 3 — Fouling factor for exhaust gas

Type of exhaust gas	Units	Fouling factor
Clean gas (cleaning devices[a] not required)		
GT firing natural gas	m^2°C/W	0,000 176
Average gas (provisions for future installation of cleaning devices)		
Other gas	m^2°C/W	0,000 35
Dirty gas (cleaning device required)		
GT firing liquid fuel (diesel)	m^2°C/W	0,000 528

[a] Cleaning devices include steam and air blowing, water washing, chemical and mechanical processes.

The fouling factors relevant to the HTM side (such as water, water-glycol, hot oil, etc.) can be found in specialist literature or directly available from the fluid suppliers.

The WHRU supplier should indicate in the operating and maintenance manual all the information relevant to the cleaning operation.

d) The supplier should take account of the flue gas velocity profile resultant from the chosen or proposed exhaust system configuration.

e) To prevent degradation of the HTM (e.g. by local boiling or cracking), the maximum HTM temperature in the tube bundle shall be limited such that the operating pressure always exceeds the HTM vapour pressure. To demonstrate compliance, the data sheets shall state:

(i) maximum HTM bulk temperature;

(ii) maximum HTM film temperature;

(iii) HTM vapour pressure at maximum HTM temperature;

(iv) minimum system operating pressure.

f) The supplier shall specify the minimum HTM flow rate that is required to the WHRU when operating in both modulating mode and bypass mode to prevent film boiling or thermal degradation of the HTM. In bypass mode this should include consideration of radiant heat or recirculation from bypass gases.

g) The allowable pressure drop across the HTM side should be agreed by the supplier and the purchaser, and the supplier shall submit calculated pressure drop figures for each part of the system with necessary backup information for approval.

h) Unless otherwise agreed with purchaser, the HTM inlet temperature at the coldest section of any tube shall be at least 10 K higher than the dew point of the TEG for all operating cases. In event that sulphur or other similar contaminants are not present then the dew point becomes the water dew point.

i) When the HTM is flammable then a tube leak has the potential to cause a fire or in extreme cases an explosion. The extent of monitoring and mitigation measures should be agreed between the purchaser and the supplier.

Means of detection can include the following:

(i) temperature;

(ii) combustible materials monitoring;

(iii) opacity monitoring;

(iv) provision for visual observation.

Possible mitigation actions include the following:

(i) water fog;

(ii) carbon dioxide snuffing;

(iii) GT shutdown;

(iv) isolation of the HTM.

9.2 WHRU tube bundle mechanical design

9.2.1 General

a) All joints between pressure parts of the tube bundle shall be of welded construction.

b) The design of the tube bundles and casing should be such that the possibility of TEG bypassing the tube bundle is minimized. The configuration shall also ensure effective clearance of pockets of air or flammable gas during purging, i.e.no stagnant zones.

c) Restriction orifices or reduced header drilling for equalizing flow distribution across tubes with parallel flow shall not be used in any part of the WHRU unless approved by the purchaser.

d) The tube bundle arrangement shall permit free thermal expansion of all tubes, headers, tube supports and casings and linings. The tube bundle arrangement shall take due account of any potential differential heating between individual tube passes.

e) The supports shall be designed and constructed such that within the supplier defined tolerances, the following are achieved:

(i) free thermal expansion of the tubes;

(ii) support for all load cases including operation, transport and hydrotesting;

(iii) provide restraint in all circumferential directions, subject to the tolerances;

(iv) precludes damaging vibration.

f) The tube bundle can either be a rectangular serpentine design or a circular helical coil design.

g) Tube bundles are either arranged in staggered or in line pitch. Supplier may select either configuration unless otherwise specified by the purchaser.

NOTE In line arrangements typically make finding the source of tube leaks easier. Some in line arrangements cannot be fully drainable.

h) Tube-to-header welds shall not be exposed to excessively high heat flux. If such connections occur within the casing, they shall be located outside the main flue gas flow and shielded by baffle plates or tube sheets.

i) Tubes shall not be welded directly to the headers. Instead, stubs of the same material as the header and same internal diameter as the tubes shall be welded to the headers. The welds shall then be inspected with MPT/PT from the outside. In addition, a visual inspection of each weld from the inside shall be performed (e.g. by use of dental mirror or borescope). Only after these verifications have met the requirements of the ITP and quality plan, can the tubes be butt welded to the stubs and be subject to the same inspection regime as for the other butt welds in the tube bundle.

NOTE Poor quality of tube-to-header welds is known to be a cause of WHRU tube bundle failures. Due to bundle geometry, it is usually difficult/impossible to inspect these welds volumetrically (e.g. X-ray) preventing detection of weld defects / failures

The design/manufacturing/inspection regimes described at 8.13.2.1 and 9.2.1 j) allow verification of acceptable weld quality in stub-to-header welds and stub-to-tube butt welds (e.g X-Ray inspection).

j) Tube bundle assemblies including headers carrying the HTM fluid shall be self-draining unless otherwise agreed by the purchaser. The assembly shall be equipped with sufficient drains and vents to permit drainage and filling in the installed position. Unless otherwise specified by the purchaser, drains and vents shall be sized in accordance with 11.2.6.

NOTE It is common practice in piping systems to provide a drainage slope of at least 1:100, but this is impractical in a WHRU tube bundle where tubes are normally horizontal or near-horizontal, consequently complete inherent self-draining is unlikely without assistance. Furthermore, not all tube bundle configurations are inherently self-drainable (e.g. staggered pitch with horizontal flue gas flow).

Tube bundles require draining for one or more the following reasons:

(i) off-load frost protection when HTM is water only;

(ii) for in-situ tube bundle inspection and/or maintenance;

(iii) for tube bundle assembly removal;

(iv) for dry running.

Before being allowed to run dry, a tube bundle that has contained thermal oil or water-glycol, should be drained as far as is practical and then internally force-flushed in accordance with an approved procedure to remove any hydrocarbon residues which can coke or combust under such operating condition. When a tube bundle is intended for thermal oil or water-glycol, but none has been introduced, it can be run dry provided the unit is designed for dry-running. (This allows the turbine and dampers to be commissioned in advance of the HTM system.)

k) For WHRUs configured from multiple bundles, for example where weight and/or installation or maintenance restraints apply, interconnections shall be by intermediate headers and external cross over pipes unless otherwise approved by the purchaser.

9.2.2 Pressure part design

a) The purchaser should specify one of the following paired options shown in Table 4 for tube bundle pressure part design

Table 4 — Applied pressure code for tube bundle design

Tubes	Header
ASME VIII - DIV.1	ASME VIII - DIV.1
ISO 13704	ASME B31.3
EN 13445	EN 13445

b) Unless specified otherwise by the purchaser, external or interconnecting piping shall be designed, fabricated and inspected according to EN 13480 or ASME B31.3. However, the design, construction, inspection, etc., shall be in compliance with the specified code.

c) The supplier’s own stamping in accordance with, for example, ASME VIII is considered adequate.

d) If the WHRU is to be subjected to a high number of start-stop cycles or if there is risk of tube vibration impacting the cycle fatigue of the equipment, then appropriate fatigue analysis should be performed (see Annex B).

e) In the event that tube bundles are subject to cycling flow conditions such as regeneration gas applications, effects of cyclic thermal stresses shall be considered in the design. Calculations shall be provided to demonstrate that the combination of thermal and internal pressure stresses is less than 85 % of that required to produce a crack based on the lifetime number of cycles (see Annex B).

9.2.3 Corrosion allowances

a) When the HTM is not corrosive; an internal corrosion allowance can be unnecessary. However, the purchaser can specify otherwise.

NOTE There can be some risk of external corrosion, for example where tube surfaces operate close to acid dew points, if the bundle is out of operation for longer periods of time, if the bundle is not in operation which includes storage and transport from the point of manufacture up to the point of initial operation, or if there is cold start-up of the turbine.

b) For corrosive conditions, the allowance shall be according to ISO 13705 unless otherwise approved by the purchaser.

NOTE 1 Application of corrosion allowances can force the selection of increased tube wall thickness. Rather than unnecessarily increase the tube bundle weight and cost, the purchaser can consider working with the supplier to identify available margin within the standard wall thickness and consider if that is adequate.

NOTE 2 The thickness of the tube selected for mechanical/manipulation purposes usually exceeds significantly the thickness necessary for pressure containment, where significant allowance can be available within the standard wall thickness.

9.3 WHRU tube bundle design

9.3.1 Tube and bend materials

a) Both "pipes" and "tubes" are permitted and hereafter referred as tubes.

b) The tubes and bends shall be seamless. Header tubes can utilize welded pipe where seamless tubes are not economically available. In this case, weld seams shall not overlap with nozzle welds and appropriate non-destructive examination (NDE) and weld strength reduction factors according to the selected code shall be applied.

c) A straight tube or pipe in a tube bundle shall not be composed of two butt welded parts where the tube length is less than mill production (typically less than 12 m) unless approved by the purchaser.

d) Any return bends shall be butt welded to the tubes and comply with ASME B16.9 or EN 10253-2. Return bends shall match the inside diameter of the connected tubes.

e) Bending of tubes and pipes shall be in accordance with the relevant code. The supplier shall present a bending procedure for the purchaser's approval.

f) In the case of tube bending the supplier shall provide an inspection report demonstrating that wall thinning is within acceptable limits and that surface cracking is absent.

g) Where tubes are bent, the resulting thickness of the tube in corroded condition at the thinnest part shall not be less than the design value calculated in accordance with 9.2.3.

9.3.2 Tube bundle design conditions

9.3.2.1 General

Typical exhaust gas temperatures of gas turbines are in a range where mechanical properties of some commonly used tube bundle materials are highly temperature dependent.

While a too low design temperature for the tube bundle pressure parts can lead to an integrity risk and premature failure, a too conservative design temperature can trigger the use of very costly material which in addition can introduce other technical disadvantages.

9.3.2.2 Determination of tube bundle design temperature

For determination of the correct tube bundle design temperature, the following approach is recommended.

a) Determine the maximum TEG temperature:

The maximum TEG temperature should be determined in close cooperation with the purchaser and its determination is likely to include consideration of the following factors:

(i) type of engine;

(ii) combustion system;

NOTE On some gas turbines with DLE combustion system, the TEG temperature during part load operation can be significantly higher than at full load.

(iii) ambient temperature range;

(iv) fuel(s) used;

(v) range of operational loads:

(vi) exhaust gas conditions applying at the end of the specified operating period, i.e. immediately prior to maintenance;

NOTE An engine due for overhaul has a higher TEG temperature than a new or newly overhauled one.

(vii)turbine trip temperature;

(viii) compressor bleed configuration and use (e.g. bleed to inlet or bleed to exhaust);

(ix) any other factors which can affect the engines operation.

b) Evaluate the operational conditions:

Operational circumstances where the tube bundle is exposed to the TEG temperature while there is no HTM inside the tubes is commonly called “dry run”.

However, for the purpose this evaluation it also means no flow of HTM.

Under such condition no cooling of the tube material is present and the tube material temperature will reach the TEG temperature if the tube bundle is not completely isolated from the TEG.

In many cases, it is impossible to completely rule out occasional dry run. However, a realistic determination of expected operational circumstances and expected extent of dry run is an important input for design and material choice of the tube bundle.

The design temperature of parts and components exposed to TEG shall not be lower than the maximum calculated tube metal temperature in the fouled condition plus a margin of 30 K.

NOTE 1 It is typically the case that the headers, even if not directly exposed to TEG flow, can under dry run condition reach a temperature close to the TEG temperature.

NOTE 2 Even with no dry run anticipated, the margin is required as the following aspects usually cause local tube wall temperatures to be higher than calculated:

(i) HTM flow imbalances;

(ii) TEG flow imbalances;

(iii) peak local heat flux.

Dry run usually is typically taken into consideration for all installations where in case of failure in the HTM system (e.g. circulation) a GT-trip is unacceptable and complete isolation of the bundle cannot be achieved. In such case, one or a combination of the following scenarios can apply:

(i) Short-term no flow pressurized operation

The dry run may occur during start-up or the time it takes between failure in the HTM system until the complete TEG flow is routed through the bypass and depressurizing the HTM system.

(ii) Long-term dry run

Systems that do not have a TEG bypass but where depressurization of the bundle in case of non-operating HTM system is guaranteed.

Systems which do have a TEG bypass but where the damper towards the coil does not guarantee a positive insulation of the coil.

Heat leakage can be, for example TEG leaking through seals or radiation through the damper itself.

Systems which do have a bypass and can even have a damper which guarantees a positive isolation of the tube bundle towards TEG flow from upstream (e.g. by means of double damper and sealing air), but where the layout of WHRU and bypass can lead to a heating of the tube bundle from its downstream side either by radiation or backflow. This scenario is not uncommon in certain compact WHRU designs.

(iii) Long-term pressurized dry run

Systems where heat exposure of the bundle cannot be ruled out and a depressurization of the tube bundle is not possible, for example for operational reasons. This condition should be avoided as it has significant implications to mechanical design.

The possibility of tube service life limitation due to creep should be evaluated as part of the design work.

Creep can be a life-limiting factor even in normal operation (without dry run) depending on a number of factors including TEG temperature, HTM temperature, selected tube material and design code.

With dry run anticipated (especially pressurized) the likelihood of creep limiting the design life increases.

If the spacing between tube supports exceeds 35 bare tube outside diameters (ISO 13705) creep due to sagging should be considered.

If creep limits the service life of the pressure parts below the overall service life of the system specified by the purchaser, the supplier should notify the purchaser and obtain acceptance or propose alternatives if the purchaser requests so.

9.3.3 TEG flow-induced vibrations

For guidance regarding the assessment of flow induced vibration of the casing refer to Annexes A and B.

a) The supplier shall include in the design all measures necessary to ensure that no part of the WHRU tube bundle shall be subject to vibrations that can reduce the life of the systems below the design life or create equipment noise exceeding the specified emissions.

b) Frequencies of gas vortex shedding from the tubes shall not coincide with the natural frequencies of the tubes.

Tables 5 and 6 set out acceptance criteria that shall be verified to ensure that flow induced vibrations are avoided:

Table 5 — Acceptance criteria (frequency) to be verified to check for flow induced vibrations

Frequency	Operating conditions	Tolerance from gas vortex shedding frequency
Natural frequency of the tubes first mode	All conditions	+/−20 %
Natural frequency of the tubes second mode	All conditions	+/−20 %

Table 6 — Acceptance criteria (velocity) to be verified to check for flow induced vibrations

Velocity	Operating conditions	Tolerance from critical velocity: fluid elastic instability
Tube bundle cross-flow velocity	All conditions	−20 %

If dry run is specified by purchaser, the vibration behaviour (natural frequency) of the empty tubes shall be evaluated as well.

c) The supplier shall provide a vibration analysis report showing Strouhal numbers, and the gas vortex shedding frequencies for each tube bundle, as well as the lower natural frequencies of the tubes, and the acoustic frequencies of the WHRU casing taking into account the presence of tubes.

Table 7 shows acceptance criteria that shall be verified to ensure that there are no flow induced vibrations.

Table 7 — Acceptance criteria (vibration) to be verified to check for flow induced vibrations

Vibration	Operating conditions	Limitation
Maximum vibration amplitude	Gas vortex shedding resonance condition	0,02 × OD tube

e) In case the supplier cannot provide a rigorous vibration analysis considering the tube as a multi-span beam and using dedicated proprietary and/or internationally recognized software tools, the simplified calculation procedure reported in Sect. 6 of TEMA can be followed, or similar procedures, which evaluate the potential for vibration in each individual unsupported span of the tube. This simplified calculation procedure considers the tube as a continuous elastic beam on multiple supports with fixed end conditions and simply supported at the intermediate points (tube support locations). The individual spans are each treated as a separate beam with its own end conditions (fixed-pinned, pinned-pinned, etc.) and subjected to local exhaust gas flow velocity distribution. Natural frequencies of the individual spans are calculated and the lowest frequency of the spans is taken as the representative figure of the whole tube. These calculations shall be performed for each type of tube. When the gas flow is non-uniform over the entire tube bundle area, an equivalent uniform modal weighted velocity, such as that defined in ASME Sect. III Div. 1 Appendix N, Article N-1300, shall be considered in the vibration analysis.

9.3.4 Tube supports

a) Unless otherwise specified by the purchaser, tube support spacing shall comply with ISO 13705.

b) Individual tubes shall be supported and guided in a robust and satisfactory manner to prevent distortion (lateral or sagging) and damage due to expansion, fretting or vibration of the tubes.

c) Tube bundles should be bottom supported or suspended.

d) Tube bundles shall not rest on internal insulation or cladding.

e) The tube bundle shall be designed so that detrimental mechanical forces due to thermal expansion of the tubes or their supports are eliminated for all specified conditions including dry running when specified.

f) The tube supports shall be capable of supporting the weight of the tubes filled with HTM as well as withstanding stresses resulting from thermal expansion. Loads occurring due to hydraulic pressure testing shall be considered. Load calculations shall assume a minimum metal-to-metal friction coefficient of 0,3.

g) Unless otherwise specified by the purchaser, loads determined for support of beams shall comply with ISO 19902.

h) Sheer loads shall be resisted by continuous members only. For example, for tube sheets the sheer load shall be taken in the web of the tube sheet and not by stiffeners unless they are continuous in the direction of the sheer load.

i) Tubes shall be supported such that cyclic stresses are kept below the maximum allowable cyclic stress value for the tube material.

j) The tube support shall not be welded directly on the tubes.

k) When tubes are supported by the fins, at least five fins shall rest on the support.

l) Tube supports materials shall be selected for the maximum TEG temperature and be of fully killed pressure vessel quality. The use of dissimilar materials within one component or components connected by welding shall be avoided to eliminate problems associated with differential thermal expansions.

m) Unless otherwise specified by the purchaser, basic allowable stress for tube sheets shall be as follows:

   (i) For constant load, the basic allowable stress at the tube support design temperature level shall comply with ASME IID or ISO 13704.

   (ii) For a combination of constant load and occasional load (e.g. friction or earthquake), the basic allowable stress shall comply with whichever is greater of 2/3 yield stress or the stress level at the tube support design temperature according to ASME IID or ISO 13704.

   (iii) With FEM analysis; based on the design temperature, the specified design life and the specified number of start-stops; the allowable stresses shall be taken from ASME IID and shall follow the rules of ASME VIII Div 2. Consideration of the combination of applicable load stress and thermal stress shall be given. Temperature gradients used in the analysis shall consider local cooling effects such as those derived from CFD analysis (see Annex A).

n) The design and manufacturing tolerances of the tube supports should ensure that each tube at each support point is appropriately supported. If the tubes are supported directly on the tube wall, the opening in the tube support which accommodates the tubes shall have a smooth surface and the edges been carefully deburred/rounded to prevent damage to the tube wall.

9.3.5 Tube fins

a) Fins are normally helically wound strip type of solid or serrated form.

b) Fin materials selection shall be based on the peak calculated tip temperature as listed in ISO 13705:2012, Table 1. This is shown in Table 8.

Table 8 — Maximum fin tip temperatures

Material	Studs Maximum tip temperature °C	Fins Maximum tip temperature °C
Carbon Steel	510	454
2 1/4Cr-1Mo, 5Cr-1/2Mo	593	549
11-13Cr	649	593
18Cr-8Ni stainless steel	815	815
25Cr-20Ni stainless steel	982	982

c) Any other fin material selected for design criteria shall be approved by purchaser.

d) Peak fin tip temperature shall be calculated using established methods and shall take into account the maximum heat flow with fouling as well as any HTM and gas flow imbalances.

e) If dry running is specified by purchaser, the peak fin tip temperatures shall be established accordingly.

f) Unless otherwise agreed by purchaser, fins shall be continuously high-frequency welded to the tubes.

g) Fin tolerances shall comply with those specified in the "International Standard for Dimensions, Tolerances, and Tests of High Frequency Resistance Welded Fins" available from finned tube supplier.

h) When selecting fin density, fin type and tube alignment, the type of fuel to be fired in the GT as shown in Table 9 shall be followed:

Table 9 — Fin selection guidance

Fin data	Risk of light fouling Fuel[a]	Ideal conditions Fuel[b]
Minimum fin thickness, mm	1,5	1,25
Maximum fin density, fins/m	157	236
Maximum fin height, mm	16	25
Fin type	Solid	Solid or serrated
Tube arrangement	In-line or staggered	In-line or staggered

[a] "Light fouling" can occur with sour fuel gas or occasional light oil firing on the GT (back up fuel only, <2 % of operating time) and when the solids concentration (soot) in the flue gas is less than 0,2 mg/m^3 in dry flue gas corrected to 3 % oxygen.

[b] Ideal conditions apply when the fuel gas is sweet (i.e. zero sulphur) and there is no provision for oil firing.

9.3.6 Tube bundle headers

a) If dry running is not specified, the design temperature for inlet and outlet header shall be the HTM maximum operating temperature plus 30 K. However, where dry running is specified in most cases the headers will reach similar temperature to the tubes and hence shall be designed for the same design conditions as the tubes.

b) Headers shall be designed to allow for full expansion of tubes and permit accessibility for maintenance and for welding. Sufficient length shall be allowed on tubes in headers to permit cutting and rewelding of tubes.

c) Tube to header weld detail shall be in accordance with the selected code, or where the code does not define details then the detail should be agreed with the purchaser.

d) Set-in type connections shall not be used when there is risk of fouling or corrosion from the HTM.

e) The headers should be designed to give a uniform flow and to achieve that, be sized so that the dynamic head loss is not more than 5 % of the individual tube pressure drop. Where this results in uneconomic or impractical header size, a higher-pressure loss (up to 10 % of the individual tube pressure drop) can be accepted, but, in this case, the supplier shall determine the effect of resulting maldistribution and demonstrate this does not have a detrimental effect on the design and that resulting film and metal temperatures remain within allowable limits. These calculations shall be made available to the purchaser on request.

10 Dampers

10.1 General

a) The purchaser is responsible for identifying the requirements for TEG flow control into the WHRU, and the degree of WHRU isolation necessary for operational and maintenance purposes.

NOTE Dampers are employed for the following functions:

— connection of the GT exhaust to a bypass stack during GT start-up to allow unrestricted GT start-up time;

— TEG flow regulation for WHRU start-up or control during operation;

— continued GT operation during WHRU shutdown;

— thermal isolation of a shut down WHRU during normal turbine operations.

b) Unless otherwise agreed by the purchaser, dampers shall be subjected to a FAT to demonstrate the required functionality in the cold condition. The content and procedure for the FAT shall be agreed between the purchaser and the supplier.

10.2 WHRU dampers

10.2.1 Damper and isolator types and functions

10.2.1.1 General

Table 10 should be used as guidance in the selection of dampers and isolators.

Table 10 — Guide for selection of dampers and isolators

Type	Function	Remarks
Multi-louvre Damper (MLD)	TEG flow control TEG isolation Stack isolation	ADVANTAGES — Inherently capable of TEG flow control. — The downstream velocities across the duct quickly recover towards a uniform profile. — As each louvre is pivoted about its centre, TEG pressure and flow effects are balanced such that lower torques are required reducing the force requirement for actuation (see comments on actuator selection). — Faster emergency shutdown than a diverter damper.

Table 10 *(continued)*

Type	Function	Remarks
		DISADVANTAGES — TEG leakage rates are inherently greater than the diverter-type as the total length of seals around each louvre exceeds that of the single blade of the diverter type. — The drive linkage shall include a mechanical interlock in order to assure certainty that the GT cannot be dead-headed. NOTE Can be used, in conjunction with other equipment, to achieve 100 % isolation.
Diverter Flap	TEG isolation TEG flow control	ADVANTAGES — Lower TEG leakage than the louvre-type owing to reduced seal length. — Provides certainty that the GT cannot be dead-headed as the blade cannot simultaneously block both exit paths. DISADVANTAGES — TEG flow control is less precise than MLD type owing to gas flow characteristic — Downstream velocity profile across the duct takes longer to recover. — As the drive shaft is along one edge of the blade, a high torque is required to overcome loads exerted on the blade by TEG pressure and flow. — Slower emergency shutdown than louvre dampers. NOTE 1 Can be used, in conjunction with other equipment, to achieve 100 % isolation. NOTE 2 A diverter is inherently larger than a pair of MLDs that would be otherwise needed. However, two MLDs require intervening ducting so total weight is likely to be similar.
Integral circular damper	TEG flow control	FEATURES — Are used in conjunction with circular WHRU configurations where nested helical tube coils are arranged in an annulus around the central TEG bypass. — The arrangement directs TEG into the annulus and/or through the integral bypass duct.

Table 10 *(continued)*

Type	Function	Remarks
		ADVANTAGES — Provides certainty that the GT cannot be dead-headed as the damper cannot simultaneously block the inlet and bypass gas paths. — The downstream velocities across the duct quickly recover towards a uniform profile. — Provides a more uniform TEG distribution to the tube bundle coil. — Faster emergency shutdown than a diverter damper. — Promotes linear gas flow through the unit. DISADVANTAGES — Operates best on vertical units. — Horizontal configurations present design challenges.
Spade plate bolted to duct flange	TEG isolation	ADVANTAGES — Simple, low-cost, device, but should be fitted at a location where duct sections can be parted, (typically adjacent to an expansion joint). — Provides 100 % flow isolation which can potential provide man-safe access in conjunction with dampers. DISADVANTAGES — The turbine must be shut down while the plate is inserted and removed. — Only used for prolonged periods of isolation due to time and labour required to install.
Guillotine slide gate (open top frame)	TEG isolation	ADVANTAGES — An open top frame guillotine provides access to the blade, seal system and actuation system at all times when the guillotine is in the open position. — Potentially provides personnel access isolation in conjunction with seal air, subject to purchaser's enclosed space entry policy. — With the WHRU inlet louvre (or diverter) closed and a seal air fan providing seal air between the louvre (or diverter) and guillotine, the guillotine blade can be lowered into the duct while the turbine is still running.

Table 10 *(continued)*

Type	Function	Remarks
		DISADVANTAGES — Heavier and more complex than a flange bolted spade plate, but can be closed more quickly — Requires limit switches to provide correct signal position for GT start which can reduce availability of the system.
Guillotine slide gate (fully enclosed)	TEG isolation	ADVANTAGES — Can be operated while the turbine is running. DISADVANTAGES — A fully enclosed guillotine requires the turbine to be shut down for access to the blade, seal system and actuation system. NOTE Can provide 100 % isolation in conjunction with seal air.

10.2.1.2 By-pass control

Bypass control can be by diverter, louvre dampers, or integral circular damper.

1) The louvre or integral circular type should be used if required to accurately control the TEG flow to the WHRU during normal operation.

2) Fail safe position is considered to be with the bypass duct open and the WHRU / heating duct closed.

10.2.1.3 Isolators

a) Isolators that assure 100 % TEG seal to the WHRU or bypass should be either:

   (i) diverter damper with seal air system, or

   (ii) louvre dampers with seal air system.

   These isolators are not adequate to allow persons to enter the duct because of the possibility of accidental opening of the damper.

b) Isolators that assure 100 % seal for process and are man safe are subject to the purchaser's enclosed space entry policy. This isolation can be achieved by:

   (i) bolted spade plate;

   (ii) guillotine slide gate with seal air system in combination with dampers.

10.2.1.4 Stack dampers

a) Stack dampers have the following functions:

   (i) to conserve heat within the tube bundle when the GT is off;

   (ii) to protect the tube bundle from rain ingress;

   (iii) to contain any fire within the ducting.

NOTE Only considered when the HTM is flammable.

b) One or more stack damper blades shall be designed such that high duct pressure drives to the open position, reversible when pressure declines in order to ensure that the GT cannot be operated against a closed exhaust system.

10.2.2 Damper and isolator design

10.2.2.1 Design temperature

a) The duct design temperature shall be used for the design of damper.

b) If a design temperature is not specified, the maximum TEG temperature shall be used (see 9.3.2.2).

10.2.2.2 Construction (all types)

a) Damper and isolator casing design, construction and internal insulation shall be to the same standard as the adjacent ducting.

b) Seal elements shall be of heat and corrosion resistant alloy such as Inconel 800 or 625.

10.2.2.3 Damper insulation

a) The materials and fixing methods of the internal insulation shall be equal or better than that of the adjacent ducting. In order to avoid external hot spots, the design shall minimise heat conduction via parts that penetrate the insulation.

b) No accessible external parts should operate at temperatures hazardous to personnel.

c) No external parts shall exceed the appropriate hazardous area temperatures.

10.2.2.4 Damper actuation

a) The actuator shall be designed for on/off, purge and modulating regulation and normally takes its operating signals from a controller (supplied by the purchaser) with a temperature sensor in the outlet HTM pipe for each unit.

b) The actuator shall be fitted with a positioner and position transmitter wired back to a local accessible junction box.

c) When used for TEG flow control, a system shall be provided such that on power air pressure, hydraulic or signal failure the dampers move to the fail-safe position.

d) The actuator shall have override for manual operation.

e) Where confined space access is required the actuator shall have a manual locking device ensuring its compatibility with enclosed space entry requirements during maintenance and inspection.

f) Actuators shall be selected to provide a margin (typically 50 % to 100 %) over that required by the damper under the most severe operating condition.

g) Drive linkages, including shafts, shall be capable of transmitting at least 110 % of the maximum load that can be imposed on them by the actuator.

h) If a quick change-over is specified, the supplier shall ensure that the operating system is designed accordingly. For example, for pneumatic systems, the supplier should advise the purchaser on the volume of air required to achieve this and agree how this is to be provided without adverse effects on the site compressed air supply.

10.2.2.5 Actuator selection

a) Damper drive should be by pneumatic, electric or hydraulic actuators. The selection depends on the size and type of damper.

b) When a suitable compressed air supply is available, the usual choice is pneumatic actuators because of cost and simplicity.

c) Pneumatically driven dampers should be either double-acting with fail-safe powered from an air reservoir or single-acting with fail-safe by spring-return.

d) Unless otherwise specified by the purchaser, auxiliary pressure parts, for example pneumatic actuation the damper air reservoir, shall be designed and constructed in accordance with EN 13445 or ASME VIII Division 1. Each reservoir shall be provided with a vent, drain, pressure gauge, inspection opening, and be protected by a pressure relief valve. All pressure part calculations shall be submitted to purchaser.

e) To achieve very high thrusts (e.g. for large diverter dampers), the required diameter of a pneumatic actuator cylinder becomes very large. In this case hydraulic systems are typically more practical. Hydraulic actuators operate at higher pressures than pneumatic, and thus achieve the required thrust with a smaller cylinder. The hydraulic fluid is also incompressible and hence there is no risk of "flutter" which can be an issue on large diverter flaps.

NOTE Hydraulic fluids are usually flammable with a typical auto ignition temperature of about 200 °C. Hydraulic actuation enforces a hydraulic system in close vicinity of an exhaust system with a steel surface temperature which can cause auto ignition in case of a hydraulic leak.

f) Hydraulically driven dampers shall use a local or central hydraulic system.

g) The hydraulic cylinder shall be equipped with a lip seal.

h) The actuator shall include all necessary limit switches, positioners, etc., inside a weather proofed casing.

i) The hydraulic system shall be equipped with radiation shield(s).

j) Electric drives are suitable for guillotine dampers. Electric drive can be used for bypass control, but it can be difficult to provide a fail-safe system.

10.2.3 Damper and isolator TEG leakage performance

a) The purchaser is responsible for specifying the isolation requirements, and hence damper seal efficiency for the environment downstream of the damper(s).

b) The specified acceptable leak rate depends on the following:

(i) Heat loss only (energy conservation and pressure build up in the WHRU when operating via the bypass).

(ii) If a good bypass seal is necessary in order to utilise all available TEG in the WHRU.

(iii) Requirements for use of the MLD as part of a safe access system while the GT is operated via the bypass.

(iv) Requirements to run the GT when the HTM and/or the WHRU is out of service.

c) The damper design and construction shall ensure that, within the specified service interval, actual leak rates do not exceed those specified.

d) For bypass dampers, the seal efficiency should be:

(i) Better than 99,8 % on area for both the WHRU and bypass stack (based on process considerations only).

(ii) 100 % (in combination with purge air or other device) for the WHRU if confined space entry into the downstream environment is to be created with the GT running.

(iii) For partial heat recovery applications where all specified operating conditions involve some TEG bypass and isolation is not required, i.e. only flow control function, then simplified damper seals are acceptable.

e) For high sealing efficiency, seals shall be all-metal, non-permeable and flexible, so as to accommodate expansion and movements of the damper and casing.

The supplier shall state in the proposal the degree of TEG flow isolation, as a percentage of TEG flow at maximum load, provided by the damper type proposed.

10.2.4 Seal air isolation system

a) Seal air systems can be used to isolate the TEG flow from downstream equipment. When specified, the following provisions apply.

NOTE Seal air systems can sometimes not be suitable for downstream isolation as the air can be heated and leak into the downstream equipment making the temperature too high for personnel entry.

b) Sealing systems for diverter dampers shall comprise double seal around the perimeter of each blade with a cavity between the seals. Seal air is blown into the cavity at a pressure exceeding that of the duct.

c) Sealing systems for louvre dampers can be achieved either by blowing air into the space between two sets of dampers at a pressure exceeding that of the duct or a tandem louvre blade design where air is blown between the blade skins creating a complete air barrier within the blade.

d) 100 % isolation can also be achieved by blowing seal air between the louvre damper and the guillotine.

e) A valve shall automatically isolate the air supply when seal air is not required to prevent backflow of TEG to the seal air fan(s).

NOTE A nominal purge air flow can be set through a minimum stop/opening on this valve with the seal air fan running continuously.

f) The seal air fan shall be designed for a minimum pressure of 5 mbar at the injection point above the upstream duct pressure at a flow rate that can be expected at maximum worn seals at the damper blades.

NOTE The duct pressure varies with different GT operating conditions and the differential pressure across the closed damper can vary with seal deterioration.

g) The seal air system shall be instrumented to detect any seal leak or loss of air supply which result in lack of adequate differential pressure between the seal air and duct system (in which case a back-up fan should be started).

h) Seal air fans shall be supplied as a set of two 100 % fans, i.e. duty/standby. Means to prevent backflow through the non-operating fan shall be provided, for example a non-return gravity operated flap damper.

i) Each seal air fan volumetric capacity shall be at least twice the calculated seal leak rate to cater for in-service deterioration of the seals.

j) Seal air fan electric motors shall be selected to be "non-overloading".

k) Seal air fans shall comply with specified requirements for rotating equipment and electrical systems.

10.2.5 Damper casing and insulation

a) The damper casing shall be designed and constructed in accordance with the ducting specifications from this document, e.g. for materials, construction details, pressure, temperature, insulation and cladding (hot or cold casing) duty.

b) The lining and insulation requirement of the damper shall also meet the lining requirements stated in this document.

10.2.6 Blades, shaft and operating gear

a) Shafts, blades and seals should be of robust construction and fabricated from materials selected for the operating conditions.

b) Damper components shall be designed to prevent distortion or deterioration due to corrosion, high temperature or TEG flow conditions.

c) Components shall be designed to prevent vibration or fluttering at any blade position under any operating condition.

d) The damper system shall be designed for manual operation and the equipment supplied shall be easily accessible.

e) The damper system shall be equipped with a position indicator.

10.2.6.1 Blades

a) Blades shall not move under the effects of gravity, dynamic pressure or vibration, except when specifically designed to open under the influence of high static pressure in the duct (e.g. stack dampers).

b) The extremes of blade travel in both directions shall be detected by position switches.

c) The mounting brackets of the switches shall be adjustable to allow the closed positions of the damper blade to be set accurately.

10.2.6.2 Operating gear

a) Linkages shall be outside of the ducting, and accessible for inspection and maintenance during normal operations.

b) Linkages shall operate correctly when the duct is displaced, e.g. due to thermal expansion or wind loads.

c) Linkages shall be self-aligning and adjustable and should be designed with little or no maintenance.

d) Position switches shall be wired back to a local accessible junction box.

10.2.6.3 Shaft and bearings

a) The damper shaft shall extend through the duct wall to external bearings and shall be sealed to prevent TEG leakage.

b) The shaft seals can be a labyrinth of metal diaphragms to accommodate expansion, a mechanical seal or a conventional packed gland.

c) The damper shaft bearings shall be of the self-aligning and non-lubrication type. Materials shall be non-jamming (e.g. bronze) and can consist of replaceable pads.

d) The design shall ensure that the shaft at the bearing area is cooled sufficiently to ensure that its rated temperature is not exceeded.

e) Levers shall be attached to shafts by means of sunken keys or rectangular ends.

f) Each shaft shall be marked to indicate the blade position. This mark shall be clearly visible during manual operation, and from grade level.

10.2.7 Requirements specific to damper types

10.2.7.1 Diverter dampers

Diverter dampers shall be provided with brackets for support from local steelwork, details to be agreed with the purchaser.

10.2.7.2 Multi-louvre dampers (MLDs)

a) When a pair of MLDs is used for bypass control, a robust fail-safe (mechanical) interlock shall be included to ensure an open gas-path for TEG at all times.

b) MLDs should be supported from adjacent ducting.

10.2.7.3 Removable spade plate isolators

a) The spade plate shall be provided with sufficient protection against corrosion, both in service and when not in use.

b) The spade plate should be manually inserted from the top of the ducting by means of lifting equipment.

c) The lifting equipment should be assumed to be available as part of normal site maintenance equipment and shall not form part of the isolator supply.

d) The purchaser or the contractor should provide an overhead support and means of access for the lifting equipment. While not in use the spade should be safely and securely stored locally, preferably above the duct.

10.2.7.4 Guillotine slide gate

a) A guillotine slide gate may be similar to a removable spade plate, but with permanently installed operating gear and structural channel frames capable of supporting the assembly and handling the loads associated with opening and closing the assembly.

b) The slot in the duct to insert the spade during use shall be sealed with a flange and designed so that thermal insulation and/or purge system avoid overheating and hot spots.

c) Alternatively, the spade plate should be fully enclosed, enabling the plate to be inserted and removed with the GT operating. This arrangement requires careful design in order to ensure reliability of the position switches and drive mechanism.

d) Guillotine blades should be of robust construction and shall have stiffening designed to prevent distortion at the maximum operating conditions (temperature and pressure).

e) Guillotine blade seals shall be metal leaf type designed to minimize leakage.

f) Guillotine drive mechanisms shall be either chain and sprocket type or worm drive type.

g) To avoid risk of jamming:

   (i) The mechanism shall ensure correct alignment during insertion and removal.

   (ii) The mechanism shall drive the blade in both the open and closed directions.

(iii) The driver and mechanism design shall include a large margin to overcome friction and dead loads (typically 200 % excess capacity).

h) The purchaser is responsible for specifying if manual or automatic operation is required. The drive should be by electric motor. Manual operation is labour-intensive and should only be considered if anticipated use is very infrequent. Where the system is of the fully enclosed type manual operation shall not be used.

i) Position switches shall be provided to prove fully open or fully closed.

11 WHRU system control

11.1 General

a) This clause describes the requirements for control and instrumentation systems and related valves and fittings for operation and protection of the equipment.

b) The purchaser is responsible for the integration of the control of the WHRU with the GT and other associated systems under all defined operating conditions. This should include all project requirements relating to instruments, wiring, junction boxes, impulse tubing, hazardous area rating, IP rating and other such items, and cover WHRU hot and cold standby and start/restart modes.

c) Supplier shall comply with these requirements, taking the following guidance notes into consideration.

11.2 Guidance notes

a) Prior to any start-up a GT/ exhaust system purge sequence should take place, for example according to NFPA 85.

b) The control system should include the TEG flow control inlet/bypass damper arrangement.

c) All necessary instrument process connections should be provided by the supplier.

d) The format of analogue (e.g. 4-20 mA or digital) and logic signals. Damper logic and analogue controls are normally supplied and configured by the purchaser (or the GT supplier) in a control system remote from the WHRU according to a control system description provided by the WHRU supplier.

e) The supplier should include a local damper control panel configured such that in the event of either loss of logic signal or damper power (e.g. instrument air), the damper(s) are driven to the fail-safe position(s).

f) Each pressure instrument should be supplied with a manifold valve, for example 316 SST 5-way valves for DP instruments.

11.2.1 WHRU control philosophy

The purchaser is responsible to specify the required WHRU system control philosophy and the supplier shall comply with such requirements. Typically, a basic control philosophy may be configured as follows:

a) Basic control philosophy:

(i) The analogue control signal to set the damper system position is provided by the remotely located control system.

(ii) The logic control signal to enable the WHRU to function and to operate the damper as required during the GT start-up purge is provided by the remote-control system.

(iii) The HTM flow is maintained constant by the remote-control system.

(iv) The HTM temperature leaving the WHRU is controlled at a constant by varying damper position. Hence variations in WHRU performance at the different operating cases result in a change in the HTM temperature at the WHRU inlet.

NOTE The WHRU/damper purge logic and control logic normally incorporated into the remote-control system generates a permissive logic output for the WHRU to operate (i.e. loss of this signal triggers the dampers to fail-safe). The HTM temperature controller is included in this remote-control system. It generates an analogue output to:

(i) Open and close the dampers as dictated by the logic system to achieve the start-up purge.

(ii) Position the dampers for normal operation.

When WHRU multi-louvre type inlet and bypass dampers (MLD's) are used, they are normally driven by a common actuator via a mechanical link to prevent simultaneous closure of both paths.

b) When the inlet and bypass dampers are driven separately a mechanical interlock is normally provided to prevent simultaneous closure of both paths. If inlet and bypass louvre dampers are driven separately, they can either share a common signal or use separate outputs from the common controller.

11.2.2 WHRU control philosophy — Standby units

a) If the quantity of WHRUs to be supplied includes standby capacity, the purchaser and the supplier should discuss and agree how the load is to be shared/reduced, for example run all units at a lower load, or run fewer units at a higher load.

b) If a WHRU is maintained on standby, purchaser and supplier should discuss and agree how the HTM flow to the standby unit will be varied in the context of the degree of TEG isolation and the use of dump or trim coolers and / or 100 % sealing TEG isolation systems.

11.2.3 Signals

The purchaser is responsible to specify the requirements for control signals and the supplier shall comply with such requirements, taking account of the following notes:

a) All analogue signal transmission to and from the WHRU/damper system shall be of the 2 wire, 4-20 mA DC type.

b) The purchaser should specify the required redundancy philosophy, for example "two out of three" 2oo3 configuration. Binary signals should be provided on a dry contact.

11.2.4 Wiring, junction boxes and protection

The purchaser is responsible to specify the requirements for wiring, junction boxes and protection of same, and the supplier shall comply with such requirements, taking account of the following notes:

a) All instruments and control system devices shall be protected and weatherproofed to maintain an acceptable data transmission and integrity at the stated environmental conditions as noted in equipment data sheets or specifications. The IP minimum rating for external installations should be in accordance with IP56 (EN 60529) and suitably certified for the hazardous zone if applicable.

b) All necessary interconnecting cable trays, conduits and junction boxes with appropriate electrical and weather protection should be designed in accordance with project requirements and supplied prewired to the agreed location and tested in accordance with the ITP.

c) Where a corrosive environment is specified, enclosures should be fibreglass, stainless steel, galvanized, or epoxy resin painted.

d) Junction boxes and other equipment that need to be accessed should be mounted at an accessible location where the maximum height above access platform should be a maximum of 2 m and minimum of 0,5 m.

e) Supplier should clearly indicate all the I/O signals from/to the WHRU, necessary to permit operation, start-up and shutdown of the WHRU and the related accessories.

f) All the instrumentation shall be certified as suitable for the area classification stated by the purchaser.

g) All instrumentation setting, connections and control systems should be fail-safe.

h) All materials for process and pneumatic connections (tubing, compression fittings, manifolds, etc.) may be included in the supplier's scope of supply.

i) Supplier should show on a dedicated layout drawing the position of the junction boxes and the routing of the cable trays.

11.2.5 Control, instrumentation and protection equipment

The purchaser is responsible to specify the requirements for control and instrument equipment, and the supplier shall comply with such requirements, taking account of the following notes:

a) All instrument impulse tubing connections should be arranged to avoid contamination or blockage by dirt or particles.

   All necessary instrument connections within the exhaust system scope of supply should be provided by the supplier to facilitate control monitoring and testing.

b) Typical instrumentation requirements (see Table 12).

Table 12 — Instrumentation definition

Instrument	Function	Supplied by (unless otherwise agreed)	Mandatory or purchaser - Option
Position switch - Bypass damper OPEN	To permit bypass purge	supplier	M
Position switch - WHRU damper OPEN	To permit WHRU purge	supplier	M
Position switch - Bypass damper CLOSED	To permit bypass purge	supplier	O Needed if the inlet and bypass louvres are not driven by a common actuator or protected by a mechanical link.
Position switch - WHRU damper CLOSED	To permit WHRU purge	supplier	O Needed if the inlet and bypass louvres are not driven by a common actuator or protected by a mechanical link.
Position switch - Guillotine damper OPEN	To permit WHRU start or run, i.e. no blockage	supplier	M

Table 12 *(continued)*

Instrument	Function	Supplied by (unless otherwise agreed)	Mandatory or purchaser - Option
Damper local control board with fail-safe system		supplier	M
Tube skin metal temperature thermocouple and transmitter	To indicate maldistribution of HTM flows, blockage of individual flows and associated temperature increase. However, such systems have a tendency to be inaccurate in operation and are potentially unreliable.	supplier	O Quantity agreed between supplier and purchaser.
Duct connection for Pressure transmitter upstream of any damper		supplier	O
Pressure transmitter	To trip GT if duct is blocked. Three pressure transmitters or switches should be installed in the TEG exhaust to indicate high pressure excursions, downstream GT discharge flange and upstream diverter or multi louvres damper to trip GT if duct is blocked. One out of two "1oo2" voting logic for alarm, two out of three "2oo3" voting logic for trip. This shall be mandatory (M) if the exhaust duct/stack can be blocked.	supplier	O
Flanged branch, in WHRU exit duct/stack, with blind cover with chains Blind flanges shall be fitted with a threaded cap	Connection for temporary flue gas spot measurement equipment. Position should take into account proximity of nearby equipment to ensure that a long probe can be inserted to traverse across duct.	supplier	M
Temporary flue gas spot measurement equipment	To fit flanged branch duct connection	purchaser	O
Flanged branch in WHRU exit duct/stack	Connection for permanent continuous emissions monitoring equipment.	Connection by exhaust system supplier	O
Permanent emissions monitoring equipment		Equipment supply to be agreed	O
HTM exit temperature transmitter	To alarm/interlock on high temperature.	purchaser	M
HTM exit temperature transmitter	For HTM temperature controller	purchaser	M
HTM flow transmitter	Low flow alarm/interlock with WHRU running. Low flow alarm/interlock with WHRU bypassed (<100 % damper seal)	purchaser	M
WHRU exit duct smoke detector	To initiate fire extinguishant, flammable HTM systems only	purchaser	O
Tube skin thermocouples or equivalent system	For on-line WHRU lifetime calculation	supplier	O
Tube skin thermocouples or equivalent system measuring instrument/s	For on-line WHRU lifetime calculation	Equipment supply to be agreed	O

c) Temperature measurements should cover approximately 130 % of the expected operating range and shall be installed with thermowells to allow maintenance in operating mode.

d) Pressure measurements should cover approximately 130 % of the expected operating range.

e) End position switches on MLD's should be fitted to the shaft(s) furthest away from where the actuator is connected, to best detect failure on most (if not all) interconnecting linkages.

11.2.6 HTM process side valves and piping

The purchaser is responsible to define the requirements, battery limits and scope of supply for the HTM circuit external to the WHRU and the supplier shall comply with such requirements, taking account of the following notes:

a) The purchaser is responsible for defining the battery limits and scope of supply for the HTM circuit external to the WHRU.

b) Flanged connections of valves should comply with EN 1759-1 or ASME B31.3.

c) Flange connections of valves 1 1/2" (3,8 cm) and lower should be class 300 minimum, except that pressure relief valve outlet flange rating can be class 150.

d) The supplier shall provide valves suitable for venting and draining the coil.

NOTE In addition the following listed valves are typically required See Table 13.

Table 13 — Tube Bundle Valves

Location	Remark
Coil pressure relief valve	The rating and setting of pressure relief valves should be in accordance with the specified code, e.g. API 521. All pressure relief valve outlets should be supported to withstand the reaction forces generated while the pressure relief valves are discharging. Pressure relief valves should discharge to a safe location. The pressure relief valves should be of the direct spring-loaded type with springs exposed to the open air, i.e. with open bonnets. Pressure relief valves should be provided with a lifting gear and clamp for hydro testing. If standby valves have been specified, to enable online testing, maintenance and calibration, an approved interlocking device should be installed to ensure non-restricted relief.
Coil pressure relief valve. Additional requirements if the HTM contains water	The total relief valve capacity should be based on the maximum possible heat input when isolating valves are closed. The maximum heat input should take into account the maximum GT load. Discharge piping arrangement should be designed for steam or liquid discharge.
Coil onlet and outlet isolating valves	These should be located in the nearest accessible positions. To achieve this, the valves should be a short distance from, but not out of sight of the tube bundle connections. These valves may be remotely actuator operated if automatic/remote start-up is specified by the purchaser.
Coil drain valve(s)	These should be hand operated. Connection should be at the lowest point in the bundle or headers. The drain connection and valve should be a minimum of 50 mm NB, but should be sized to drain tube bundle contents within approximately 1 h. The drain should discharge to an HTM storage vessel. The valve shall be accessible from a permanent platform; to achieve this, it should be a short distance from the tube bundle connection. This valve should be remotely actuator operated if automatic/remote start-up is specified by the purchaser.

Table 13 *(continued)*

Location	Remark
Coil vent valve(s)	Connection should be at the highest point in the bundle or headers. Size should be a minimum of 25 mm. The valve should be accessible from a permanent platform; to achieve this, it should be a short distance from the tube bundle connection. The valve should discharge to a safe location away from any work area. This valve should be remotely actuator operated if automatic/remote start-up is specified by the purchaser.
Pressure gauge and valve	The branch connection should be adjacent to the pressure relief valve and fitted with an isolating valve. The isolating valve and gauge should be properly supported and accessible from a permanent platform.

12 Access, inspection and maintenance

12.1 TEG path access

a) The exhaust system shall be equipped with access doors and inspection hatches (openings) to facilitate inspection and maintenance philosophy specified by the purchaser.

b) The number and location of openings, and their function (maintenance and/or inspection) should be agreed between the supplier and the purchaser based on the following guidelines:

(i) Avoid locations where the most unsteady TEG flow patterns are present. Access doors represent a discontinuity in the internal lining and insulation system and should therefore be located in areas where the wall pressure fluctuations (due to unsteady TEG flow) are expected to be lowest.

(ii) Easy access from the outside.

(iii) In particular it should be possible to visually inspect the following:

— all duct and casing internally lined surfaces;

— all WHRU tube bundles from either side;

— all header supports;

— all damper blades, seals, shafts etc., from either side;

— all silencers components - from either side;

— all expansion bellows;

— any flow straightening devices.

c) Unless otherwise specified inspection/access doors should be either rectangular or circular type, 600 mm × 600 mm or 600 mm diameter free opening minimum. Access doors should either be bolted and vertically hinged so that the doors swing open horizontally or bolted with a davit installed to facilitate lifting and removal of the door. Rectangular access doors shall be constructed with rounded corners with minimum radius of 50 mm.

d) Openings such as observation ports for visual inspection from outside, or removable hatches for insertion of temporary instrumentation, should be located and sized to suit the specific requirements.

12.2 WHRU

a) Unless otherwise specified by the purchaser, it shall be possible to access the following areas for the purposes of inspection, repair and maintenance without cutting into casings:

(i) All tube bundle return bends.

(ii) All header connections, i.e. tubes, vents, drains, supports.

(iii) Outside surfaces of end tube bundle supports.

(iv) Inspection/access doors shall be provided upstream and downstream of silencers, diverters, louvres, WHRU tube bundle and any other component installed inside the ducting which needs visual inspection/maintenance, to permit viewing of representative tubes, louvre blades, damper, silencer panels, etc. Access doors shall also be designed for the removal of silencer panels and any other component installed inside the ducting and that needs to be replaced.

(v) Fixed (non-temporary) platforms with ladders, cages, handrails shall be provided for access to each inspection/access doors. Platforms shall also be provided around the WHRU for inspection and removal/insertion of tube bundle for maintenance, and for access to all the components of the diverter and louvre system (i.e. control panel, bearing hoses, leverages, shaft, manual actuation, etc.).

b) The purchaser is responsible to specify requirements for inserting equipment to visually inspect header internal surfaces.

c) Provision for such inspection can be made by including an externally accessible blind flange on each header, or, by means of a removable pipe spool on the inlet and outlet connections.

d) Access to header boxes, WHRU free end, and dampers for maintenance shall be provided.

NOTE Once the WHRU has been shut down and allowed to cool to ambient temperature, personnel can enter the WHRU sections through the access doors provided subject to site confined space entry control procedures.

e) The supplier shall state any special provisions required for prolonged shut down for inspection and maintenance of the WHRU. Facilities for proper draining or blow drying which are required to protect against corrosion during shut-down periods should be considered and agreed with the purchaser.

NOTE Some WHRU tube bundles, if configured with triangular tube pitch and horizontal flue gas flow, might not be naturally and fully self-draining, and require a particular draining procedure.

f) Supplier shall identify in the operation and maintenance (O&M) manual the potential risks of confined space entry. Purchaser is responsible for development of detailed procedures for such entry.

NOTE 1 Measures for exhaust system entry typically include the following:

(i) Gas testing to ensure correct oxygen level and lack of harmful gas.

(ii) Robust interlock to ensure that the GT start is prevented.

(iii) Dampers and/or guillotine interlocks to ensure the correct position with no possibility to be changed.

(iv) Checks that seal air systems as applicable are fully operational.

(v) Entry access watchman and system in place.

(vi) Safe access provision.

(vii) Internal lighting.

NOTE 2 ECFIA Code of Practice and Specific Material Safety Data sheets provides recommendations for confined space entry protection considering the potential exposure to fibres that are part of the lining system.

13 Installation

a) The equipment should be in as few parts as practical considering shipping and handling limitations.

b) The purchaser should advise on the installation method and equipment at site for the supplier to consider the size of each part for easy installation.

c) The supplier shall issue a step-by-step installation sequence with reference to the relevant drawings. This shall include weights, location of the centres of gravity and the identification of temporary supports, lifting lugs or bolt eyes to be used.

d) The design of the site casing, ducting and stack joints and the continuity of the final installed insulation and lining shall be undertaken by the supplier during the engineering phase and all necessary components shall be supplied together with detailed instructions.

NOTE For exhaust systems with internal insulation, which are delivered to site/yard in pre-insulated modules, the correct installation of the insulation and lining system to cover the duct flanges after assembly is critical for the correct function and service life of the whole system.

e) To ensure the faultless installation of insulation and lining system, the supplier shall issue a project-specific procedure with drawings and deliver all required parts and material (e.g. pre-manufactured liner segments, insulation, bolts, nuts, washers, seal weld procedure if applicable).

f) Shop fabricated modules shall be designed to avoid additional welding, forming or other machining operations on the assembly site apart from as noted in g) below. In the case of damage during transport or site fit-up problems a repair procedure should be issued by the supplier and approved by all parties involved.

g) The method of site assembly and sealing of the finished modules should be agreed between the supplier and the purchaser. This shall either be done by seal welding with site installed liner cover or by bolting and gasketing only which is a lower integrity joint but minimizes site installation effort and internal access required.

h) For removable bundles, coils should be transported in the module unless otherwise agreed by the purchaser.

NOTE 1 It is common practice for a representative from the exhaust system supplier be on site to supervise the installation.

NOTE 2 Installation activities include but are not limited to:

(i) Checking the packing on arrival against the packing list.

(ii) Checking the packing for any damage during transportation.

(iii) Verifying that the modules are properly stored on an even ground before installation.

(iv) Visually inspecting the modules after the removal of the packing and before handling or lifting.

(v) Verifying that the installation procedure is well understood by personnel through training and that all necessary tools (e.g. torque wrenches) are available.

(vi) Verifying that the lifting equipment is in good working condition with all certifications up to date and that the operators are qualified to use it.

(vii) Verifying that the slings and shackles are new or in good condition.

(viii) Verifying that the gaskets, bolts and nuts to be used are those specifically purchased for the installation.

(ix) Ensuring, prior to installation, that the position of the support points is such that the installed unit matches the connection to the GT within the tolerances of the expansion joint.

(x) Supervising the installation of each module and checking that the gasket between the module flanges is properly installed.

(xi) Assembling of the different modules of the exhaust system with all its component parts.

(xii) Bolting of the exhaust system to the receiving steel structure or the concrete foundation.

(xiii) Connecting the exhaust system with the GT outlet flange.

(xiv) Connecting the exhaust system bundles with the process piping.

(xv) Installing the instruments according to the hook up drawings and wiring to the junction box.

(xvi) Wiring of the electric motors and of the lighting to the junction box.

(xvii) Verifying that the insulation and lining system covering duct flanges, which are mated at the assembly site, are installed correctly.

(xviii) Verifying that the expansion joints are properly installed without lateral distortion, twisting or excessive axial elongation.

(xix) Verifying that the dampers are properly installed according to the supplier's instructions. It is of particular importance to ensure that the duct flange of the damper is connected and level, as distortions can affect damper sealing.

(xx) Verifying that the flanges of the process piping and the header flanges of the bundles are properly aligned before fitting the gaskets and bolting the flanges.

(xxi) Verifying the fixed point and the sliding points on the steel structure or the receiving foundation.

(xxii) Checking that the stack is vertical.

(xxiii) Applying touch up paint where the paint has been damaged.

(xxiv) Proceeding to the final visual inspection internally and externally.

(xxv) Ensuring that all transport security devices and temporary equipment are removed.

(xxvi) Checking that all the documentation has been supplied.

i) The supplier shall detail any conservation measure to keep the equipment in good condition and avoid corrosion for the period of time between the end of the installation and the commissioning at the site of operation taking into account:

(i) transportation from the site of installation to the site of operation;

(ii) length of time (sometimes several months) between the end of installation and start up;

(iii) weather and environmental conditions at the assembly and operating sites.

j) If the loads during transportation/installation make temporary re-enforcements necessary (e.g. WHRU bundle, damper) which are to be removed before start-up, such measures shall be clearly marked, e.g. painted in red or yellow colour, and removable without hot work or risk of causing damage to the equipment. Documentation specifying these requirements shall be included in the installation procedure together with description of how and when during the installation sequence they are to be removed.

k) All site installed fasteners shall be supplied with a minimum of 3 % spares for site assembly.

14 Pre-commissioning and commissioning

a) The pre-commissioning and commissioning activities correspond to the final checks and tests of the exhaust system to verify that it complies with its design and operational specifications and that it can be operated safely and trouble-free.

b) The pre-commissioning of the exhaust system and WHRU should be undertaken simultaneously with the pre commissioning of the GT and HTM circuit before they are started up.

c) Pre-commissioning and commissioning are very integrated activities which require the involvement of all the parties concerned with the exhaust system supplier, GT supplier, purchaser and any related subcontractors.

d) Although most of these activities take place after the fabrication of the exhaust system, they should be planned and engineered well in advance in order to be executed in a safe and efficient manner.

e) In particular, the planning should define where and when these activities take place.

NOTE For instance, where specified, subparts like the dampers can be partially or fully commissioned through a FAT in the subsupplier workshop before the dampers are shipped to the installation site.

This test requires that the dampers are made fully operational in the workshop including the actuator, the actuator control and the sealing air system (fans with their electric motors, air receiving drum, air piping). This test, for example for MLD's, is intended to demonstrate among other things:

(i) that both dampers are operating smoothly and in parallel (one opening the other closing) over the full range;

(ii) that the bundle damper fully closed, bypass damper fully open is reached within the required period of time, that the sealing air system, if installed, works and that blade seals of the bundle damper rest properly on their seats.

f) The complete exhaust system may be partially or totally commissioned at the site of installation along with the commissioning of the GT, but without the HTM system available.

NOTE In that case, it can prove difficult to commission the HTM circuit which usually involves a considerable flow rate. Moreover, running the GT with the exhaust system and without the HTM implies that the WHRU has been designed to run dry or be fully isolated on the flue gas side, which is not always the case.

g) In most cases, the pre-commissioning and commissioning are completed on the production site, whereas the HTM system is available, and according to a specific program that takes into account the risks presented by live equipment (rotating machines, energized motors or instruments, noise, hot and/or toxic fluids) and the risks of simultaneous works.

h) All site procedures should be strictly adhered to.

Pre-commissioning activities are the following:

(i) Check that the complete exhaust system documentation is on site.

(ii) Check that the spare parts for commissioning and start-up are on site.

(iii) Check that the special tools (for instance, lifting frame for bundle removal) are on site.

(iv) Remove all the temporary protection and supports still in place.

(v) Perform an external and internal visual inspection of the exhaust system. Check that no loose item can fall into the turbine outlet collector. Check that the blades of both dampers (bundle damper and bypass damper) are free to rotate over their full range without touching the insulation cladding of the adjacent modules. Check that there is no water resting on the bundle duct and bypass duct floors. Check with a lamp the good external condition of the bundles.

(vi) Cold stroking of the dampers.

i) Commissioning activities:

(i) Loop testing of any installed instruments and dampers control.

(ii) Testing of alarms, interlocks and trips.

(iii) Trigger the fail-safe position of the dampers and check that it works properly.

15 Performance test

a) Once the plant has reached a stable operational regime corresponding to the specified design case, the operator, purchaser and supplier should undertake a performance test to verify that the performance requirements are met.

b) The purchaser and the supplier should agree on the procedure for the performance test program based on the relevant sections of ASME PTC 4.4.

c) As a minimum the following data should be recorded for comparison with the specified values:

(i) HTM flow rate and inlet/ outlet temperatures to check the WHRU thermal performance;

(ii) HTM inlet and outlet pressure to check that the pressure drop is within acceptable limits;

(iii) TEG inlet and outlet temperatures;

(iv) TEG inlet and outlet pressure to check that the pressure drop on the TEG side is within acceptable limits.

d) If the TEG flow rate is not recorded via a flow metering instrument it should be calculated by the GT supplier.

e) The performance test also gives the opportunity to make final checks normally executed during the commissioning but which can have been postponed for practical reasons.

f) These checks should include but are not limited to:

(i) Infrared (IR) thermographic examination of the entire casing to detect hot spots. This examination includes the stack when it is insulated.

(ii) Noise levels (refer ISO 11204 and ISO 10494).

(iii) Excessive vibrations or drumming of the casing.

(iv) Abnormal displacements of the expansion joints and of the exhaust system sliding point.

(v) TEG leaks to the atmosphere (for instance near modules flanges gaskets or where the bundles headers nozzles pass through the casing).

(vi) TEG sampling taken from the dedicated stack nozzle.

g) The performance test is formalized through a report with a conclusion paragraph that should summarize the corrective actions -if any- agreed on between the parties.

Annex A
(informative)

Application of computational fluid dynamics to exhaust system design

A.1 General

The objective of this annex is to provide the purchasers and suppliers of exhaust duct systems with an overview of the use of CFD assessment in the design and assurance of exhaust duct systems. This is intended to inform the users of this document with respect to:

a) an overview of the key stages and processes within CFD analysis;

b) the types of analysis available;

c) the benefits of each method and how these can aid the design of exhaust duct systems;

d) the limitations, costs and level of expertise required;

e) what each method provides as output and requires as input; and

f) at what stages the various methods can be used within the design and verification process and what benefit they afford.

It is not the intention for this annex to provide detailed best practice for CFD analysis of exhaust systems. CFD best practice is a complex subject and is a function of the problem in hand (i.e. geometry and flow conditions) and availability of input data. As such, an understanding of CFD best practice is accrued through experience and cannot readily be distilled into a simple process to follow.

A.2 Benefits of CFD

Typically this kind of study would be expected to present a significant saving in terms of through-life costs from maintenance and replacement of failures in exhaust systems. Hence, CFD can be an attractive activity for suppliers to help substantiate designs and demonstrate confidence in their long-term performance. This can also aid purchasers by providing a greater level of confidence in the performance of the acquired equipment and helping to differentiate between candidate suppliers.

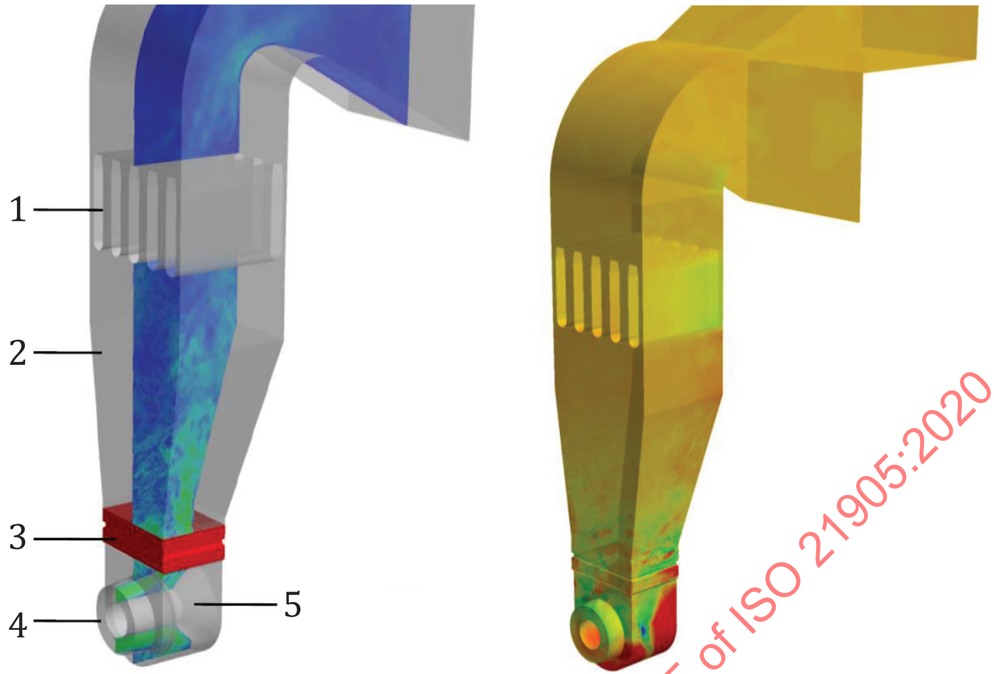
The upfront costs and timescales of CFD analysis need to be considered fully in the project plan, however, the initial outlay and effort can potentially save on future maintenance and downtime costs, which are typically one to two orders of magnitude higher.

A.3 What is CFD?

A.3.1 General

CFD is an important numerical technique in flow analysis (see Figure A.1) whose use in design of exhaust duct systems is become increasingly more common given recent advances in computer power. CFD simulates the fundamental flow equations which describe the conservation of mass, momentum and energy (the Navier-Stokes equations). The flow path is divided into many discrete elements (usually into finite volumes) on which the laws of conservation are applied.

Four key aspects of CFD analysis are: geometry, mesh, boundary conditions and solver. These terms are defined in more detail as shown in Figure A.1.



Key

1 silencer
2 transitions
3 expansion bellow
4 diffuser
5 exhaust collector / plenum

Figure A.1 — Example output from a CFD analysis of an exhaust duct system showing instantaneous flow speed on a plane through the centre of the exhaust (left) and instantaneous pressure distribution on the internals walls (right)

A.3.2 Geometry

The geometry defines both the shape of the exhaust duct passages through which the exhaust gases will pass. Ideally, the geometry should reflect as closely as possible the as-built exhaust system. However, it may be necessary to make some simplifications (e.g. removing small filters and fixing heads) to facilitate the construction of the computational mesh. Care should be taken during the design phase as small changes in geometry can have a significant influence of the resulting flow behaviour.

The extent of the flow domain is an important feature in CFD analysis as the user must specify the flow conditions as inputs at the boundaries (see boundary conditions section below). If the flow domain is too small the boundary conditions can be too close to the region of interest and, therefore, can unduly influence or constrain the flow solution.

A.3.3 Mesh

The term mesh (sometimes termed the grid) defines the array of finite volumes (or cells) which are used to divide the flow domain and across which the laws of mass, momentum and energy conservation are applied. Within each cell the flow properties (i.e. velocity, pressure, density and temperature) are assigned a single value. The computational cost of the analysis scales with the total number of cells. Therefore, there is a desire, where possible, to minimize cell count. However, if too few cells are used the resulting flow solution is likely to be inaccurate.

If an understanding of the likely flow pattern can be obtained *a priori* it is possible to optimize the mesh to improve the overall computational efficiency. For example, in regions of the flow domain where the gradients in flow properties are expected to be low it can be possible to reduce the local spatial resolution of the mesh (i.e. increase the cell size) without adversely affecting the results. Conversely for regions of complex flow (i.e. separated or swirling flow) the mesh resolution should be locally refined to capture these changes in properties faithfully. Used correctly, this technique can provide substantial savings in computational time compared to the use of a uniform cell size throughout the entire domain.

In practice, an understanding of the mesh construction and resolution which are most likely to be appropriate come through the experience of the CFD user in conducting similar analyses. However, on completing a CFD analysis, it is advisable to check how the resolved gradients within the flow domain compare to those expected during the mesh construction phase. If necessary, the mesh can be further refined and the model resolved to provide an improved flow solution.

A.3.4 Boundary conditions

Input to CFD analysis is made by the user in the form of specifying the flow conditions as input at the boundaries. For a model of the internal flow through the exhaust system, these typically comprise definition of the distribution of flow velocities and temperature at the inlet to the exhaust system and specification of the pressure at the outlet.

For a full thermal CFD simulation including the duct walls and insulation, the heat transfer conditions on the external surfaces need to be specified as does the thermal properties of the solid walls (i.e. density, thermal conductivity and specific heat capacity).

Although many types of CFD modelling are possible, each with differing levels of accuracy, often the user defined boundary conditions represent the largest degree of uncertainty in the calculation. This can limit the degree of accuracy obtainable with CFD modelling and should be taken into account when assessing the design against key performance criteria and considering the benefit of adopting a higher fidelity analysis approach.

Ideally, the flow domain should be terminated as far from the region of flow of interest or where the inflow or outflow conditions are benign (i.e. spatial gradients are low) or well characterized by available data. In practice, the application of boundary conditions is often limited by the availability of flow data and geometry and some compromises must be made. However, an understanding of these compromises is key when assessing the level of confidence which can be placed in the results of CFD analysis.

A.3.5 Solver

The term solver describes the computational algorithms used to compute the flow solution on the mesh. Often the solver is integrated into a software package which also permits some or all of the following:

a) manipulation of the raw computer aided design (CAD) geometry;

b) construction of the computational mesh; and

c) visualization of the results.

There are many COTS CFD solvers available, most of which can accommodate the various types of modelling approaches relevant to exhaust duct systems.

A.4 CFD in exhaust system design

A.4.1 Uses of CFD

The flow within GT exhaust systems is typically highly three-dimensional, unsteady and at a high temperature. The complex nature of exhaust flow leads to CFD being used to characterize flow paths, bulk flow velocities, velocity fluctuations, pressure loss, pressure fluctuations, flow temperatures and dynamic forcing for structural design (static, quasi-static and dynamic loads).

Figure A.2 presents a flow chart showing how numerical analysis methods such as CFD and FE analysis can be combined and integrated into the exhaust duct design process.

The first stage of this process is to define the exhaust duct geometry and flow conditions to be considered. This information feeds into a CFD assessment of the exhaust duct flow, which depending on which CFD method is utilized, results in the calculation of the unsteady or time-averaged internal flow field. This flow data alone is useful in the design and performance assessment of process equipment such as WHRU.

Where unsteady CFD assessments have been conducted, the resulting flow data typically comprises both the internal pressure and temperature fields. These data can be extracted at the internal surfaces of the exhaust duct and mapped across to a finite element (FE) model of the structure in order to calculate the stresses which give rise to high and LCF (see Figure A.2). These results in turn feed into high and LCF assessments of the design and enable improvements to be identified or designs to be substantiated.

In addition to fatigue assessments, a combined CFD and FE approach can also be used to model thermal stresses during start-up and shut-down sequences by the inclusion of time varying boundary conditions to represent the flow from the GT.

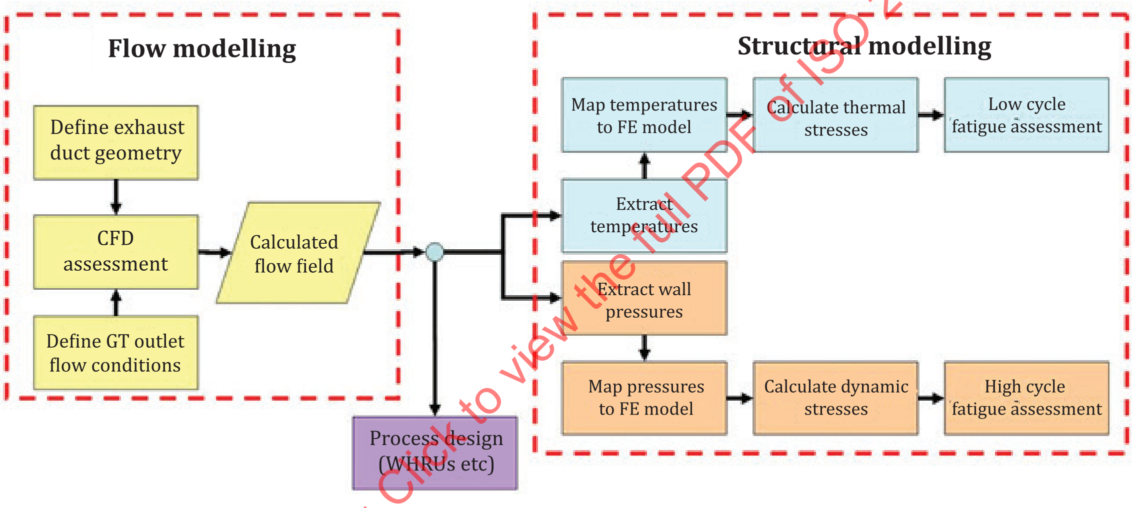


Figure A.2 — Flowchart describing the use of numerical modelling in exhaust duct design

A.4.2 Overview of CFD methods

The greatest challenge to industrial flow simulation is the notion of turbulence. Turbulence is commonly defined as quasi-chaotic fluctuations in flow variables (i.e. velocity, pressure and temperature) which are superimposed on top of steady and coherent flow behaviour. These fluctuations generally act to smear out spatial variations in flow properties and tend to increase pressure loss and heat transfer.

In practice, the turbulent fluctuations are the results of the superposition of many individual vortex-like flow structures termed eddies. The eddies present within turbulent flow span a wide range of sizes and timescales. The largest eddies are of the order of characteristic dimensions of the exhaust duct cross-section and are associated with large amplitude and low frequency (typically less than 10 Hz) pressure fluctuations. The large eddies dissipate very little of their kinetic energy through viscous friction and eventually break up into smaller eddy structures. This process of eddy break up continues such that kinetic energy is transferred from the mean flow to large scale eddies and subsequently to successively smaller eddies. The smaller eddies are associated with lower amplitude and high frequency fluctuations in pressure and it is at these scales where the majority of kinetic energy is dissipated through viscous action into heat.

Theoretically, the governing equations of fluid mechanics (the Navier-Stokes equations) are a complete description of flow behaviour when treated as a continuum, such that the turbulence effects described above can be explicitly simulated, this is termed DNS. However, it may be shown that the overall computational cost of DNS is impractical for most industrial flows, including those within exhaust systems, even with the world's fastest supercomputers. It is widely accepted that given the current rate of growth in computer power, DNS on an industrial scale only becomes practical in 50-100 years from now.

Therefore, in order to conduct CFD for industrial flows, some assumptions must currently be made as to the structure of turbulence and its influence on the bulk flow behaviour. This is conducted through turbulence modelling which uses semi-theoretical and semi-empirical relationships to model some or all of the influence of the turbulence field and reduce the computational cost of the analysis. There are three common approaches which are:

a) RANS:

(i) Uses a statistical model to represent the effect of turbulence on the flow.

(ii) Determines the steady "mean" flow through the exhaust system.

(iii) Provides an indication of undesirable flow features (e.g. flow separation).

(iv) Results can be sensitive to the choice of turbulence model.

b) URANS:

(i) Uses a statistical model to represent the effect of turbulence on the flow and provides a time-resolved calculation of the flow field.

(ii) Provides information on the likelihood of experiencing bulk flow instabilities within the exhaust system. However, detail of the broadband structural excitation is not accessible.

(iii) Can be used to examine changes in the flow and thermal field which result due to global changes in inflow conditions, such as start-up and shutdown transients.

(iv) Simpler to set up and cheaper to run than scale resolving methods (see below) but can be sensitive to the selection of the turbulence model.

c) Scale resolving CFD modelling:

(i) Includes both LES and hybrid RANS-LES approaches.

(ii) Offers full resolution of unsteady flow and surface pressures and the results can be directly mapped across as inputs to structural assessments for fatigue life calculations.

(iii) Impractical for the assessment of start-up and shutdown transients.

(iv) This method is the most complex to develop, is sensitive to the model setup and has the highest computational costs.

Further details of the capabilities, limitations and implementation of these methods are provided in the subsections at the end of this annex.

A.5 Assessment strategy

The type of analysis which is appropriate for a candidate exhaust duct system design depends on a number of factors including:

a) similarity of the design geometry and load conditions to an existing in-service unit;

b) extent of input data available to conduct the assessments;

c) uncertainty in input data and load conditions;

d) degree of confidence the purchaser requires; and

e) timescales and costs.

In the event that the design and load conditions are identical to an existing in-service unit for which many hours of operational experience have been necessary, it is not always necessary to conduct a detailed CFD assessment.

Where the design changes are small, simple steady RANS analysis may be appropriate to confirm that the flow distribution into the WHRU bundle is acceptable and that gross flow separation is not likely to occur. Where this is indicated the same models can be re-run in a transient fashion (URANS) to determine the dominant frequencies of the fluid dynamic excitation and to review these in-light with the resonant frequencies of the structure.

In cases where the design is particularly new or the load conditions are unfamiliar, then it may be appropriate to conduct a wide set of analyses to build confidence in the design in lieu of operational experience.

However, it is noted that most of the most advanced CFD methods require, as input, some upfront modelling with the lower fidelity methods in order to advise on appropriate spatial and temporal resolution and to provide a starting solution for the flow variables. Therefore, even the most advanced CFD assessments are progressive in nature with the opportunity to understand from the various tiers of analysis as the overall assessment proceeds.

A.6 Model extent

Model extent is a key factor in exhaust systems modelling. The unsteady flow structures developed within an exhaust duct system are often strongly influenced by the flow turning within the power turbine diffuser and exhaust collector. The output flow from the collector can be highly non-uniform with areas of flow reversal

Therefore, ideally a model would include the power turbine diffuser and exhaust collector upstream of the divergent exhaust diffuser. Using this approach it is often possible to assign simple uniform flow velocity and thermal boundary conditions at the power turbine diffuser inlet and the development of the flow through the collector, and the non-uniformity at the collector outlet are explicitly resolved.

However, often the geometry of the exhaust collector is proprietary to the GT supplier and/or is not available at the time of the analysis. If this is the case it is necessary to construct a truncated modelling domain which does not include the power turbine diffuser and exhaust collector. This represents the interface between the design remits of the GT supplier and exhaust supplier. However, the resulting challenge lies in the manner in which the inflow is prescribed for which two options are possible:

a) prescription of a uniform flow field normal to the inflow boundary; or

b) prescription of a non-uniform flow field using information provided by the GT supplier.

The flow field distortion at the collector outlet can be considerable. Therefore, the assumption of uniform flow is unlikely to be representative. Flow distortion maps, available from the GT supplier, can be used to provide a first pass estimate of the non-uniformity of the outlet from the collector. However, this is often provided on a coarse resolution grid.

A further complication with scale resolving methods is that they often require the use of an algorithm at the inflow boundaries to synthesize the incoming flow perturbations. In the case that the model extends back to the inlet to the power turbine diffuser, the sensitivity to the choice of algorithm can be low as the majority of the flow unsteadiness which affects the upper sections of the exhaust system are generated through the collector.

Models which include only the upper sections of the exhaust system and are truncated at the collector outlet do not capture the incoming unsteadiness which results from the flow through the collector. These fluctuations influence the flow behaviour in the upper sections of the exhaust system.

In summary, the sensitivity of the results of the modelling to the model extent is not well understood. Therefore, in advance of the planned validation of CFD calculations for exhaust systems flow, it is advised that the model should include the collector geometry.

A.7 Information requirements for CFD analysis

In order to conduct a CFD analysis, the following data is required as a minimum. The data list covers both flow and thermal assessments, for thermal assessments both sets of data are required.

a) **Flow assessment**

(i) geometry of the exhaust duct flow path including the collector;

(ii) GT operating conditions to define mass flow rate, temperature and pressure; and

(iii) inflow velocity profile if the collector is not included in the model.

b) **Thermal assessment**

(i) geometry of the solid structure;

(ii) material properties for all solids; and

(iii) ambient air conditions (temperature and wind speed ranges).

A lack of certainty in any of these data influences the results. Furthermore, different elements of the data listed above are likely to be the property of the purchaser, supplier and GT supplier which can influence the availability of the data. These factors should be borne in mind at early stages of the design such that the purchaser and supplier can review the input dataset and agree an appropriate analysis program.

A.8 Conclusions

This annex gives a brief overview of the use and benefits of CFD in exhaust system design and the methods available. CFD is an advanced modelling technique and the costs associated with the analysis are not insignificant and need to be accounted for in the project plan. However, modelling of this kind can provide benefits to both the supplier and purchaser in terms of increasing the confidence that the delivered design is suitable for the duty. Therefore, the upfront costs of the analysis can be justified with the potential benefits in terms of lifecycle cost saving related to potential for reduced maintenance cost and potential down time.

The costs and timescales involved are small relative to the costs and timescales for exhaust system procurement, installation and maintenance.

The selection of appropriate modelling is unique to each exhaust system in that it is a balance between the degree of confidence required, complexity of the flow behaviour and availability of data. There is a natural cascade of model complexity which can be applied sequentially to develop understanding of the exhaust duct flows and identify requirements for additional layers of modelling fidelity. Often the simpler methods can provide initial screening for potential design issues and inputs to subsequent models.

A.9 Description of CFD model variants

A.9.1 RANS

RANS approach is a popular turbulence modelling approach used in industry and is normally applied to solve engineering flows. Each variable in the set of equations is split into time-averaged and fluctuating parts and the resulting equations are averaged over time. Reynolds averaging introduces a number of additional terms into the Navier-Stokes equations, which are termed the Reynolds stresses.

Turbulence models aim to calculate the Reynolds stresses based on other mean flow variables. A large number of turbulence models exist ranging from zero to multi-parameters models. No single turbulence model has to date been shown to sufficiently represent all flow scenarios and the CFD user must adopt the appropriate model, based on previous experience, experimental validation or by conducting sensitivity studies. Industry standard turbulence models are usually based on the conservation of two variables: turbulence kinetic energy and a dissipation term. The Reynolds stresses are then related to these scalars by a number of generalized coefficients derived from simple experiments on turbulence.

The output from steady RANS models is often interpreted as the calculation of the time-averaged flow behaviour, although strictly speaking the resulting prediction of the bulk flow behaviour assumes that the flow is steady. Steady RANS models can be useful to:

a) identify regions of highly turbulent flow or flow separation which can potentially give rise to unsteady flow behaviour and cyclic pressure loading on the exhaust duct structure;

b) determine the levels of non-uniformity of the inflow into the WHRU bundle for input to the thermal design;

c) calculate the temperature field within the fluid and structure which can be used as input to a FE model to calculate the resulting thermal stresses; and

d) verify the pressure loss through the exhaust system.

Steady RANS models cannot be used to provide information regarding the magnitude of pressure oscillation or frequency content. However, steady RANS calculations are generally computationally inexpensive and can be completed in the order of a day once the model is built. Therefore, the results from steady RANS models can be used as a practical tool early on in the design process to advice on the requirement to conduct more complex analysis.

In the case that the need for more complex analysis is indicated, the results from steady RANS models can be used to advise the solution setup or the starting solution for more complex model variants to expedite the analysis.

A.9.2 URANS

The RANS formulation does not preclude analysis of unsteady flows and the Navier-Stokes equations may be averaged to preserve the time derivative of mean flow terms. This formulation of the equations is termed URANS. In this respect, the equations permit the simulation of the fundamental unsteady behaviour, which is generally spatially coherent, of large magnitude and low frequency and, hence, is of most concern for flow induced vibration. Small scale and high frequency turbulent fluctuations are not captured by this method.

URANS modelling can be useful to:

a) Determine the magnitude and dominant frequency of pressure oscillations within the exhaust duct system, which can be compared against the resonance frequencies of the structure to assess the likelihood for high levels of vibration and fatigue to occur.

b) Calculate the temperature field within the fluid (and structure) during a start-up or shut down transient who can be used as input to an FE model to calculate the resulting thermal expansion and stresses. In this case the resolved fluctuations are more a function of the global variations in inflow throughout the transient as opposed to underlying flow unsteadiness.

Although URANS can in principle resolve the dominant unsteady flow structures, in some cases the natural levels of flow unsteadiness are insufficient to overcome the underlying turbulence model, which is dissipative in nature. In this case a steady solution can result although the model is solved in unsteady configuration. In this case more advanced CFD methods are required to resolve the unsteady flow behaviour.

URANS modelling generally uses the same CFD models initially constructed for steady RANS. In the case that the fundamental pressure oscillations are of interest, the steady RANS solution can also provide a useful starting solution for URANS, which helps to accelerate the analysis.

URANS analysis is typically an order of magnitude more computationally expensive than steady RANS. Using modern parallel-computing URANS analyses typically take from a few days to one week to complete.

A.9.3 Large eddy simulation

LES methods aim to explicitly capture the behaviour of the largest flow eddies while limiting the use of modelling to the smallest flow eddies. The largest eddies are generally of a similar length scale to that of the exhaust duct cross-section and constitute the largest, most spatially coherent lowest frequency loading and, therefore, the improved resolution of these features provides benefit for flow induced vibration studies. Fortunately, these eddies are the most computationally efficient to resolve. By contrast the smaller eddies are much more intensive to compute but are associated with lower magnitude and higher frequency loading and, therefore, can be represented with models without significant degradation of the solution.

LES requires very fine bespoke computational meshes and small-time steps compared to those used for URANS. A simplified turbulence model is used to represent the transfer of energy to small scale eddies which are below the resolution of the mesh. The addition of the simplified turbulence model allows LES to use slightly coarser meshes than DNS (in which all important scales of turbulence are resolved).

Within LES methods the solution time increments defined by the user should be compatible with the characteristic time periods of the unsteady flow features of interest. As a result, LES is the only method of those discussed here capable of calculating the pressure loading across a wide range of frequencies (broad band). By comparison URANS is generally only capable of resolving single frequency tonal components and their harmonics (narrow band). In general, LES solutions take considerable time to settle into a state where the pressure oscillations are statistically robust; therefore, these methods are restricted to the consideration of steady operating conditions and are not appropriate for modelling start-up or shut down sequences.

A further complication is that turbulence is explicitly resolved as velocity fluctuations opposed to being calculated as a statistical quantity within the flow solution. Therefore, it is necessary to use an algorithm at the inflow boundaries to synthesize the incoming flow perturbations. Again, there is benefit to placing the model boundaries as far upstream from the region of interest as possible such that the synthetic perturbations have time to develop in a physical manner (i.e. grow or decay) which reduces the sensitivity of the results to the choice of algorithm.

While LES can be run using the models built for URANS, the mesh requirements are substantially different; results can be at best poor and at worst invalid. Therefore, these analyses are computationally expensive, complex to set up, take in excess of a week to complete on a modern parallel- computer cluster and should only be undertaken by a CFD practitioner with considerable experience in these methods. As a result, at present, these methods are most appropriate for the final verification of a design or for diagnosis of a flow induced vibration problem observed on an in-service system as opposed to parametric design studies.

A.9.4 Hybrid methods

There are a variety of hybrid methods, the most common being DES, and all in some degree couple LES and RANS approaches to turbulence modelling. This coupling is achieved such that where the mesh resolution is sufficiently fine the turbulent detail is captured explicitly with minimal modelling, as in the LES approach. Conversely, where the resolution is insufficient to capture the detail, such as near walls, the model returns to the full turbulence modelling approach of RANS. The aim of the hybrid approaches is to provide methods which are intermediate to URANS and LES with respect to the level of computational effort required while maintaining the ability to capture the full broadband pressure spectrum.

In practice, although some saving on effort can be made, the cost of the solution is closer to that of LES than URANS. Hybrid methods often use algorithm at inflow boundaries in a similar manner to LES to describe the incoming turbulence. In some hybrid-method variants these algorithms are also required at the interface between the LES and RANS regions. Therefore, considerable experience is required with the specific implementation of hybrid methods to ensure that the interface between methods does not unduly influence the flow behaviour.

Annex B
(informative)

Application of thermal and structural analytical techniques to exhaust system design

B.1 General

The intention of this annex is to provide guidelines to the purchasers and suppliers of exhaust duct systems regarding the use of thermal and structural analysis in the design and assurance of such systems.

Operating experience indicates that there is significant evidence of premature equipment failure from temperature and stress related mechanisms (thermal fatigue) causing cracking, deformation and insulation breakdown with resultant hot exhaust gas leakage. Hence, there is increasing industry interest in the application of analytical techniques to underpin designs and provide robust documentary evidence for specified lifetime.

B.2 Exhaust system equipment covered

This annex covers the following exhaust system equipment:

a) exhaust gas collector;

b) exhaust system inlet ducting;

c) exhaust system casing;

d) exhaust system outlet ducting;

e) exhaust system bypass ducting;

f) stacks.

This equipment can be of either ‘cold’ or ‘hot’ casing designs, where, clearly, the former can be preferred as being significantly less vulnerable to thermal fatigue.

B.3 General

B.3.1 System of units

The following system of units should be used:

Length:	mm
Force:	kN
Mass:	kg
Acceleration:	m/s^2
Density:	kg/m^3

Pressure:	MPa (N/mm^2)
Stress:	MPa (N/mm^2)
Temperature:	°C
Temperature interval:	K
Sound pressure	dB (re 2x10-5 Pa)

B.3.2 Material

All ducting attachments and supports welded to the ducting shall be of the same material.

Materials of construction selection shall be as defined in this document.

All bolts selection shall be as defined in this document.

B.3.3 Material factors

Material factors in different load combinations are given in Table B.1.

Table B.1 — Material factors

Load combination	Material factor
SLS	1,0
ULS	1,15[a]
FLS	1,0
ALS	1,0

[a] Material factor for bolts is given as 1,3.

Basic Operational Loading

B.3.4 Self weight

The self-weight of the system should be calculated from the detailed design of the equipment. To ensure a conservative approach, a contingency factor of 10 % should be added to the calculated self weight. If the equipment is weighed prior to the analysis, this factor may be omitted. To increase the loading from self weight in cases of mismatch between model weight and expected weight (e.g. due to removed details) in a FEM analysis, it is recommended to add point masses or scale the gravity acceleration applied. Altering of the density of the material in the FEM analysis should be done with care as this changes the thermal capacity of the structure.

B.3.5 Thermal

In the structural calculations, the loading due to thermal expansion shall be included. This may be applied through FEM analysis by performing a thermal analysis and importing the temperature profile to a structural analysis.

To determine the maximum thermal gradient, the minimum external temperature shall be combined with the maximum wind speed and the maximum design exhaust temperature.

To determine the maximum temperature of a cold casing, the maximum external temperature shall be combined with the minimum wind speed and the maximum design exhaust temperature.

The maximum design exhaust temperature should be 25 K above the maximum operating temperature of the gas turbine.

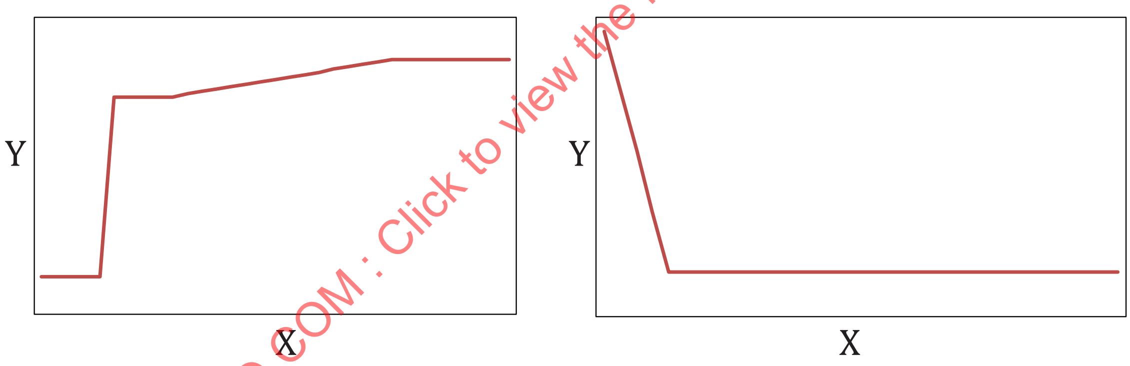
B.3.6 Steady state

To apply the loading in a steady state thermal FEM analysis, it is recommended to apply a convection loading to both internal and external surfaces. Alternatively, the internal surface temperature may be assumed equal to the exhaust gas temperature. The steady state heat transfer coefficient figures should be calculated from the flow pattern or preferably to be determined through a CFD and CHT analysis of the applicable system. The steady state external heat transfer coefficient should be calculated considering minimum or zero wind speed.

B.3.7 Transient

Due to the thermal heat capacity and thermal conductance, transient effects during start up and shutdown may temporarily increase the stress levels in certain parts of the structure. As the effect is mainly during start up and shutdown, it is mostly affecting the thermal fatigue (LCF) life. Hence, the transient thermal effects should be considered in areas where the thermal conductance and heat capacity may temporarily increase the thermal mismatch, e.g. at large brackets and at flanges.

As for the steady-state analysis, the thermal loading in the transient analysis can be applied by convection. An alternative is to perform a CFD analysis with time-dependent mass flow and temperature and couple the CFD analysis to an FSI analysis to determine the stress distribution throughout time. The transient curves describing the convection film figures and temperatures during start up and shutdown should be determined through CFD analysis or through measurements performed during operation of similar systems. Typical curves are shown in Figure B.1, as shown the temperature and convection rise from zero to idle very quickly and with a gentler rise from idle to full power as the entire system heats up.



Key

X time

Y exhaust gas temperature

Figure B.1 — Exhaust gas temperature during start up and shutdown

B.3.8 Pressure

The internal static pressure should be the calculated static pressure (e.g. through CFD analysis) applied with an added factor of 1,5 but shall be 50 mbar minimum.

B.3.9 Flow linear momentum

In cases where the flow direction is changed through the path of the ducting, the directional change of flow linear momentum causes resultant force acting on the ducting. This thrust must be reacted by the external brackets. The flow linear momentum is given by the mass flow and the fluid speed. As the speed is a vector, the change of flow direction causes a resultant force [see Formula (1)]:

$$F = \dot{m} \times v \qquad (1)$$

B.3.10 Wind

The environmental loading due to wind loading shall be calculated at the given elevation and the effect due to loading in any wind direction shall be evaluated. Shielding from other large equipment may be included. The wind loading shall be combined and coincide in direction and act simultaneously as the wave loading. Note that the maximum wind speed is the worst case for loading, but the minimum wind speed is the worst case for external surface temperature.

B.3.11 Wave

At all installations on a floating structure, the effect due to wave motion shall be included in the analyses. The horizontal motion in any direction should be combined with minimum and maximum vertical loading. The motion characteristics shall be determined for the applicable position of the installation in each case. The stress due to wave loading should be calculated in any direction. The wave and wind loading shall be combined and coincide in direction and act simultaneously.

B.3.12 Snow and ice

The additional loading effect due to snow and ice shall be evaluated for both on-line and offline conditions.

B.3.13 Vortex shedding

Vortex shedding calculation according to EN 1991-1-4 shall be performed.

B.3.14 Natural frequency

In cases where the pulsation of the exhaust gas pressure can excite the natural frequencies of the exhaust ducting, a modal analysis shall be performed. The lowest applicable calculated natural frequency shall be at least 1,5 times the frequency of the exhaust gas from the turbine (typically 15-18 Hz, however, a lower value can be generally expected). The analysis shall have the correct boundary conditions and pre-stress from the self-weight of the ducting shall be included. In cases of calculated natural frequencies within the critical range, additional stiffeners increasing the natural frequencies should be evaluated carefully as the introduction of additional stiffeners can decrease fatigue life due to thermal loading (LCF). To evaluate the effect of frequencies within the critical range, an FSI analysis can be performed as input to a HCF analysis.

B.3.15 Creep

The maximum calculated steel temperature shall be evaluated and compared with the material creep data. If any calculated steel temperatures are within the creep range of the material, creep analysis shall be performed according to EN 13445-3.

B.4 Load combinations

B.4.1 General

The relevant load combinations according to the applicable design code shall be calculated in the absence of these typical values are given below.

B.4.2 SLS

The design criteria for an SLS combination are given as a maximum deflection of $L/200$, where L is the length between the supports. For a cantilever, L is twice the protruding length. Since the criteria is a limitation in deflection, the combination is highly applicable for a cantilever exhaust stack, but in cases where the ducting is supported by a support structure tower, the load case is not applicable to the ducting itself. However, it should be separately evaluated as a part of the support structure calculation.

B.4.3 ULS

ULS load combination with the relevant loading shall be calculated in combination ULS-A and ULS-B with load factors as shown in Table B.2. The analysis should be performed in all applicable load directions. The wind loading shall be applied as a 100 year, 3 sec gust calculated according to B.3.10 (wind). Wave loading shall be applied as 100-year wave motion. All loading with variable direction should coincide and be applied simultaneously.

Table B.2 — ULS Load Combinations

Action combination	Self weight (permanent)	Thermal loading (deformation)	100 year wind and wave (environmental)	Internal pressure (variable)	Flow linear momentum (variable)
ULS-A	1,3	1,0	0,7	1,0[a]	1,3
ULS-B	1,0	1,0	1,3	1,0	1,0

[a] Refer to B.3.9.

Hence, no additional load factor in ULS-A should be applied.

The design criteria in ULS combination is given below:

$$\sigma < \frac{\sigma_{0,2}}{\gamma_m}$$

where

σ is the actual value of reference stress;

$\sigma_{0,2}$ is the yield strength;

γ_m actual material factor.

For hot casing systems, the deformation driven stresses due to thermal loading often result in calculated stress levels well above the criteria given above. To show that the critical stresses above the allowable originate from the thermal loading, linear analysis with the thermal loading excluded should be performed. As the thermal stresses originate from the prescribed thermal deformation of the ducting it can be less critical for structural integrity as any stresses from prescribed force loading. In such cases, plastic analysis of the system shall be performed to safely document that the structural strength is sufficient. LCF analysis shall be calculated in such cases to document fatigue life.

B.4.4 FLS

The exhaust system shall be documented for a service life. In the FLS load combination, all load factors shall be considered as 1,0 hence the maximum operating temperature may be applied in lieu of the maximum design temperature. The effect of LCF and HCF shall be calculated and if applicable be combined using Palmgren-Miner rule. It is recommended to use FEM analyses as basis for the fatigue calculations. Guidelines for analysis setup (mesh density, stress readout etc.) may be taken from DNV-RP-C203.

B.4.5 LCF

The exhaust systems most prominent to LCF issues are hot casing systems. The extreme thermal loading of such systems results in large thermal gradients and hence stresses. Even though such stresses from prescribed loading do not necessarily impose any structural strength issues (see B.4.3) the repeated plasticity can impose LCF issues.

To evaluate the fatigue effect due to the thermal loading, LCF analysis according to EN 13445-3:2014, chapter 18 of critical areas (e.g. flanges and large brackets) shall be performed for all hot casing systems. To include any transient effects, a transient thermal analysis describing the temperature profile throughout the loading cycle shall be performed and serve as input to the structural analysis. Calculated linear-elastic stress range or total strain range shall be used as input to fatigue analysis according to EN 13445-3.

B.4.6 HCF

Analysis of possible HCF from all applicable loading shall be performed. Loading that can impose HCF issues are mainly (but not limited) to fluctuating internal pressure and wave loading. When calculating HCF DNV-RP-C203 may be applied. Generally, for systems and details not single critical for structural integrity, a DFF of 1,0 is acceptable. Single critical details not available for inspection (e.g. covered by insulation) should incorporate a DFF of 3,0.

B.4.7 ALS

The following accidental loading can be applicable for gas turbine exhaust systems:

— loss of insulation;

— fire;

— explosion;

— earthquake;

— extreme environmental loads;

(10 000-year wind and wave loading)

— platform accidental heel.

All load factors and material factors shall be considered as 1,0 in the ALS condition. The functionality of the system can be impaired, but the ALS calculation shall ensure that the loading does not lead to total loss of structural integrity. The applicable nominal loading from permanent, environmental and variable loads shall be included in combination with the current ALS loading. The ALS check may be omitted if an overall evaluation shows that a collapse does not entail danger of loss of human life, significant pollution or major financial consequences.

Annex C
(informative)

Information to be provided by purchaser

C.1 General

This annex specifies the purchaser-supplied information which should ideally be provided as part of a request for quotation (RFQ) for a complete exhaust system. In the absence of relevant information, the supplier shall be entitled to adopt standard solutions in keeping with good practice as set out elsewhere in this document and applicable statutory requirement.

C.2 General

1) Quantity of exhaust system (total);

2) Quantity of exhaust system working/standby;

3) Tag numbers for main items of equipment;

4) Thermal duty at design point for each exhaust system unit;

5) Location, e.g. onshore inland, onshore coastal, offshore platform or offshore floating;

6) List of nominated or preferred suppliers;

7) Any purchaser requirements additional to those of this document.

(Commercial information such as contact details, document submittal procedures, inspection requirements etc., shall be addressed elsewhere.)

C.3 Scope of supply

8) A list of all items in the required scope of supply, including bolting and gaskets;

9) Battery limits;

10) Define supplier services required for site erection, for example site installation, supervision only, erection instructions only;

11) Define supplier services required for commissioning e.g. commissioning, supervision only, commissioning instructions only;

12) State if any of the following items are to be included:

   a) WHRU comprising tube bundle with inlet and outlet headers;

   b) inlet and outlet transition ducts;

   c) TEG ducting;

   d) exhaust stack;

   e) flue gas bypass facility;

   f) bypass stack;

g) flue gas flow control damper with actuator;

h) flue gas isolating system;

i) plume cooling device;

j) flexible gas tight expansion joints;

k) internal or external insulation;

l) associated instrumentation control and electrical equipment;

m) associated cabling;

n) handling and lifting facilities;

o) special tools;

p) lifting frame for the coil;

q) HTM local piping external to the WHRU; if required specify the design code;

r) HTM local vent and drain piping;

s) HTM isolation valves;

t) HTM pressure relief valves.

C.4 Climatic and imposed loadings

C.4.1 Climate and ambient data

13) Maximum, normal and minimum ambient temperatures;

14) Humidity;

15) Rainfall details;

16) Snowfall/ice details;

17) Especially stringent conditions, e.g. maritime environment, desert, dust, etc.;

18) Altitude.

C.4.2 Imposed loadings due to climatic and environmental effects

19) Wind maximum gust speed and directions and relevant code;

20) Earthquake zone rating and soil factor occupancy factor and other relevant parameters;

21) Snow load (including impact e.g. from ice if applicable);

22) For offshore applications, the pitch and roll data during tow-out and operation;

23) For FPSO or other floating sites, the pitch and roll data during operation and emergency conditions.

C.4.3 Imposed loadings due to mechanical effects

24) Live load;

25) Interface loads (from turbine outlet flange);

26) Vibration levels;

27) Imposed loading from structure;

28) Blast loading (if any) with duration damage criteria, loading basis and other relevant parameters;

29) Wind load requirements, e.g. importance factor.

C.5 GT Data

C.5.1 GT Details

30) Make and model of GTs;

31) Quantity of GTs;

32) Configuration of GTs and exhaust systems, e.g. unitised (one exhaust system per GT), two GTs into one exhaust system;

33) Gas turbine fuel type(s) and analysis. For every fuel type, analysis shall state any sulphur content, since it is not always included in the exhaust gas composition and can have an effect on various aspects of the design (e.g. materials, finning, HTM temperature, stack).

C.5.2 GT operating data

C.5.2.1 Data to be provided for each operating case

34) TEG flow (design and maximum);

35) GT exit temperature (design and maximum);

36) Pressure (design and maximum);

37) TEG specific heat at relevant temperatures, or sufficient information for the WHRU vendor to derive same;

38) TEG analysis including any emissions;

39) If GT fogging is applied, resulting changes in TEG properties, for example analysis, specific heat capacity at constant pressure and temperature shall be included in the TEG data;

40) Variability of the GT exit temperature over lifetime;

41) Start-up curve identifying peak gas temperature.

C.5.2.2 Operating details

42) The magnitude and frequency of load changes;

43) Variations in TEG flow with GT load;

44) Operation profile (frequency of hot, warm, cold starts; expected frequency of trips);

45) Expected lifetime (e.g. 20 or 25 years);

46) Number of hours running per year;

47) Number of GT starts per year;

48) If different fuels are to be used (e.g. dual fuel gas turbines) the expected distribution of numbers of start events and running hours per year per fuel.

C.5.2.3 TEG flow characteristics

49) Velocity profile of the TEG at the terminal point between GT and exhaust system at start up, shut down, part and full flow conditions;

50) Table (or CFD output) that specifies radial component pulse of the GT at different loads;

51) Bleed valve influence on exhaust gas. Some provision needs to be made for design of flow corrective device during design stage (is usually more of an issue for industrial installations with radial exhaust, less problematic if the exhaust is axial, although there have been some issues with some new GT types).

C.5.2.4 GT interface: dimensions, orientation and elevation

52) Terminal details of the GT exhaust flange, to include dimensions, location, bolting;

53) Maximum allowable forces on the GT flange;

54) Noise level of the turbine exhaust;

55) Movements of the GT exhaust flange to permit proper specification of expansion joint;

56) In case of internal insulated exhaust collector, details about the insulation/lining shall be exchanged/coordinated between the involved parties to ensure that the insulation/lining covering the flange connection at the interface of the two scopes of supply meet the requirements lined out in this document;

57) In case of internal insulated exhaust collector, the material which the collector exit flange is made of shall be stated in order to ensure equal thermal expansion of the mating flange.

C.6 Exhaust system thermodynamic design

C.6.1 Design operating case, design requirements

58) If the thermal duty at more than one operating condition is specified, the supplier shall determine which is the most onerous, and that shall be considered as the “design case”;

59) Required performance guarantees the “design case” and any other cases;

60) Identify sufficient operating cases to define minimum and maximum heat recovery requirements, maximum gas temperatures and maximum exhaust flow and applicable intermediate conditions;

61) Heating surface margin: state in percentage terms how much additional surface is to be provided over and above that necessary for the design case (if other than 10 %, e.g. to reduce weight);

62) Outside tube fouling factor: purchaser may specify or may require the supplier to determine it based on TEG specification including any contaminants;

63) Inside tube fouling factor: purchaser may specify or may require the supplier to determine it based on HTM specification including any contaminants;

64) Maximum allowable static pressure at the inlet battery limit of the exhaust system supply for operating and bypass modes;

65) HTM controlled temperature and allowable controlled tolerance at WHRU exit;

66) HTM temperature at WHRU inlet at design case;

67) HTM pressure at WHRU inlet at design case;

68) Provide HTM product data sheet giving properties and specification, including specific heat, capacity, viscosity, thermal conductivity and density over applicable temperature range.

C.7 Utilities available

C.7.1 Instrument air (if applicable)

69) Instrument air pressures at local terminal point for piping design and max./normal/minimum operating;

70) Instrument air quality and dew point temperature.

C.7.2 Hydraulic power unit (if applicable)

71) Hydraulic fluid data sheet;

72) Pressures at local terminal point for piping design and max./normal/minimum operating.

C.7.3 Electrical

73) Electrical supply for controls, solenoids etc.;

74) Electrical supply for motors;

75) Define hazardous area zones;

76) Enclosure protection IP rating;

77) Electric motor specifications (if any).

C.8 Laws, regulations, codes and standards

C.8.1 Legal requirements applicable in the territory of the site

78) Applicable territorial laws, regulations, codes and standards, environmental standards;

79) Any special statutory or other regulations with which the equipment is required to comply.

C.8.2 Project standards, for example

80) The name of the third party inspecting authority to be commissioned by the purchaser;

81) The name of the regulating authority, e.g. PED, ASME.

C.8.3 International Standards

82) Pressure parts' codes for tube bundle, external piping and damper air reservoir;

83) Other codes: e.g. for purge “NFPA 85: Boiler and Combustion Systems Hazards Code”;

84) Electrical specifications for hazardous area;

85) Noise and vibration;

86) Any preference for design codes for fatigue analysis if that is not addressed by the specified code.

NOTE ASME provides little guidance on designing for cyclic operation. EN has some requirement for fatigue analysis.

C.9 Emission control equipment

87) Define requirements for emission control equipment, e.g. NOx, CO, sulphur and particulates;

88) If emission control equipment is not to be fitted during construction, state if space shall be allowed for later addition.

C.10 Mechanical design

C.10.1 WHRU tube bundle mechanical design

89) Tube bundle design pressure;

90) Tube bundle design temperature;

91) Select option for design code for tubes and header:

   a) Tubes and headers to ASME VIII, division;

   b) Tubes to ISO 13704 and headers to ASME;

   c) Tubes and headers to EN 13445 (not usual but also permitted).

92) If ASME code is specified, select stamping option:

   a) Designed and constructed generally in accordance with ASME VIII, division 1, but **without** the ASME “U” stamp;

   b) Fully compliant with ASME VIII, division 1, including the ASME “U” stamp.

93) Select option for tube bundle arrangement:

   a) Staggered tubes (also known as triangular pitch). This is usually most economical with lowest tube surface, weight and cost, but some arrangements with triangular pitched hairpin coil are not fully gravity drainable;

   b) In-line tubes (also known as rectangular pitch). It is easier to find leaks in an in-line arrangement;

   c) Supplier selection.

94) Select option for system mechanical design temperature and pressure:

   a) Tube bundle, casing and outlet ducting designed for maximum gas temperature in run dry, vented and drained condition;

   b) Tube bundle, casing and outlet ducting designed for maximum gas temperature in run dry, full design pressure condition;

   c) Tube bundle, casing and outlet ducting designed for local maximum metal temperature at under worst-case normal operation. There may also be a need for limited dry running for GT string testing.

95) Tube bundle material, i.e. tubes, bends and headers, fins and supports (if not to be selected by supplier);

96) Corrosion allowances; inside tubes (HTM side), outside tubes (gas side) (if not to be selected by supplier);

97) Additional NDT on tube return bends, e.g. to detect surface cracking;

98) Specify drain connection size or use supplier standard;

99) Specify if hot casing design is acceptable;

100) Material handling strategy describing how components are to be lifted and routed.

C.10.2 Welding and NDT

101) Welding code for tube bundle, if not specified by the design code;

102) Welding code for ducting if not supplier standard;

103) Any supplementary requirements (e.g. concerning welding qualifications);

104) NDT for tube bundle (if not 100 %) together with any requirements for PMI;

105) NDT for ducting.

C.10.3 Casing and ducting

106) Shape for ducts, rectangular or circular (if not to be selected by supplier);

107) Exhaust system design pressure (if not selected by supplier);

108) Exhaust system material, e.g. stainless steel (if not to be selected by supplier);

109) External surface temperature limitations. (see also "Insulation");

110) Exhaust system supporting requirements, e.g. number, type and location of available supporting system (steelwork or concrete foundations);

111) Design code(s) to be used for mechanical design of exhaust system casing, ductwork and supports, e.g. internationally recognised AISC or EN code, if not selected by supplier;

112) Inspection hatches: preferred locations and dimensions.

C.10.4 Bolting and gaskets

113) Specify bolting and gaskets (if not to be selected by supplier).

C.10.5 Expansion bellows

114) Specify type of expansion bellows, fabric or metal (if not to be selected by supplier).

C.11 Insulation

C.11.1 Insulation location options

115) Specify insulation philosophy, if not supplier selection:

a) Internal insulation, hence cold casing steel;

b) External insulation, hence hot casing steel.

C.11.2 Insulation materials

116) Specify insulation materials, if not supplier selection:

a) Internal insulation;

b) Internal insulation liner grade and thickness;

c) External insulation material;