

**CONCEPTUAL DESIGN AND QUALIFICATION OF HIGHLY EFFECTIVE HEAT EXCHANGERS FOR HEAT
REMOVAL sCO₂ BRAYTON CYCLE TO INCREASE THE SAFETY OF NUCLEAR POWER PLANTS**

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ABSTRACT

The sCO₂-4-NPP European project aims to develop an innovative technology based on supercritical CO₂ (sCO₂) for heat removal to improve the safety of current and future nuclear power plants.

The heat removal from the reactor core will be achieved with multiple highly compact self-propellant, self-launching, and self-sustaining cooling system modules, powered by a sCO₂ Brayton cycle.

Heat exchangers are one of the key components required for advanced Brayton cycles using supercritical CO₂. To this end, two compact and highly effective brazed plates and fins heat exchangers are designed:

- a main heat recovery heat exchanger (CHX), which allows the heat transfer directly from the steam generator to the sCO₂-4-NPP cycle,
- a heat sink exchanger (DUHS), which evacuate the remaining heat to the atmosphere.

An important work has been achieved in the frame of this project to conceive the preliminary design of these components, in close collaboration between Fives Cryo, a French brazed plates and fins heat exchangers manufacturer, the Institut für Kernenergetik und Energiesysteme (IKE) of University of Stuttgart and KSG/GFS Institute, a simulator center, both in Germany.

In fact, several constraints needed to be taken into account. For instance, for the DUHS, the low fans power available for the cycle and the necessary air flow for effective heat exchange

implies considering almost inexistent pressure drops on the air side.

To this end, very specific design ideas have been addressed to meet the desired thermal duty.

Also, this project benefits from the recent results achieved among the European project sCO₂-flex, related to the mechanical resistance of heat exchanger components, the assembly process and their thermal and hydraulic performances, along with Fives Cryo expertise and background.

A second challenge of the sCO₂-4-NPP project is to qualify the designed plates and fins heat exchangers, at cycle operating conditions, in order to meet with pressure vessels codes and regulations according to nuclear requirements.

This paper presents the work achieved on the design of DUHS heat exchanger components and a preliminary part of the qualification of this equipment according to nuclear power plants regulations.

INTRODUCTION

Chernobyl and Fukushima Dai-ichi nuclear accidents are one of the worst catastrophes that the world have seen. In fact, both accidents were classified at the 7th level of the International Nuclear and radiological Event Scale (INES) due to the important amount of radioactive rejections.

Fukushima Dai-ichi accident, for instance, combined both impacts of nuclear accident and high magnitude earthquake. This earthquake caused degradation of the nuclear installation and a loss of confinement. The earthquake also generated an important Tsunami – with higher waves over 15 meters height -

which led to a break-down of the primary cooling systems due to deterioration of seawater intakes, leading to reactor cores melting and spent fuel pool overheating. Important environmental, sanitary and psychological impacts were caused by this disaster ([1],[2]).

Avoiding such dramatic accident is the leitmotiv of the European project sCO₂-4-NPP, which started on autumn 2019 for 3 years, by bringing in nuclear power plants an innovative technology to remove excess heat in case of nuclear accidents, based on supercritical CO₂ (sCO₂).

This new technology will constitute a backup cooling system, linked to the secondary cooling loop which is attached to the steam generator of a Pressurized Water Reactor (PWR) (figure 1) or a Boiling Water Reactor (BWR) [3] (figure 2).

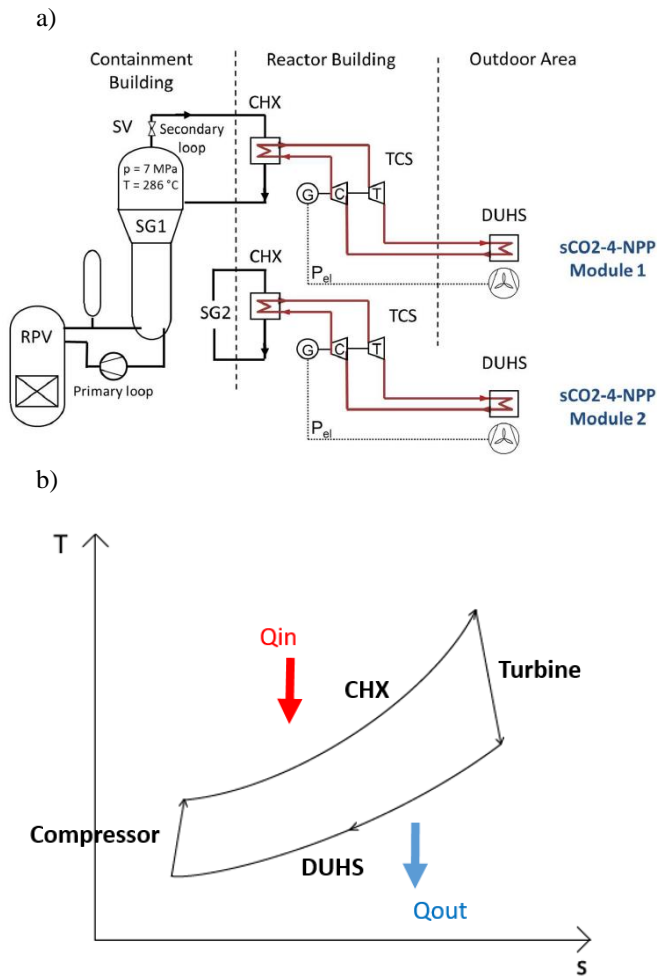


Figure 1: a) Excess heat removal technology constituting a backup cooling system, linked to the secondary cooling loop which is attached to the steam generator of a Pressurized Water Reactor (PWR), and b) the corresponding T-s diagram.

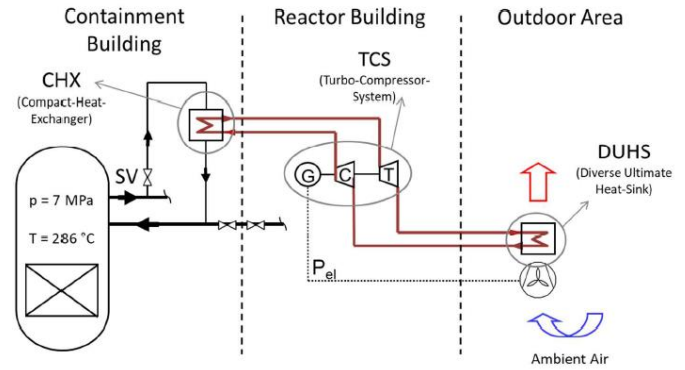


Figure 2: Excess heat removal technology constituting a backup cooling system, linked to the secondary cooling loop which is attached to the steam generator of a Boiling Water Reactor (BWR) [3].

The backup system is based on a closed Brayton thermodynamic cycle ([4],[5]). In case of an accident, a safety valve opens to enable the release of the steam produced by the steam generator into the Compact Heat Exchanger (CHX). The supercritical CO₂ is heated up in the CHX and flows then through the turbine which is linked to the compressor and the generator on the same shaft. The supercritical CO₂ flows through the Diverse Ultimate Heat Sink (DUHS) to be cooled by exchange with ambient air, and then goes through the compressor to restore its initial pressure to flow again in the CHX.

Multiple advantages are given by this back-up cooling system modules. They are highly compact so they will not require any major modifications in existing nuclear power plants, self-propellant, self-sustaining and self-launching. They are completely independent of nuclear power plants which makes them easily able to be retrofitted to existing European reactors.

The work presented in this paper focuses mainly on one of the two heat exchangers components, the DUHS. Several constraints need to be taken into account during the design process. In fact, the heat exchangers need to be as compact as possible in size to fit into the available space outside the reactor building. Also, the design should be achieved according to tough operating conditions. Last but not the least, the heat exchangers must be compliant with the rules given by nuclear power plants codes and regulations for materials, manufacturing processes, quality control and testing aspects.

STATE OF THE ART

Systems implemented for heat removal from european PWRs and BWRs are essentially “active” safety systems. “Active” means that these systems rely on pumps which are

activated by motors, themselves powered by electrical source, to allow the transport of water to cool reactors cores. The majority of back-up systems are electricity-powered. The disadvantages of such active systems are that they require external power supply, and to move important quantities of water, so the reservoirs need to be refilled regularly.

Fukushima Dai-ichi disaster proved the disadvantages of the dependence of these safety systems on energy and water supply. Another major disadvantage is the need for operators interventions while an accident occurs.

The recent developments of light water reactors, “passive” safety systems have emerged. These “passive” systems are powered by natural driving forces such as pressure differences, gravity of density differences; no electrical power supply is then required. The disadvantages are that they are not able to be retrofitted to existing nuclear power plants, but only can accompany newly designed reactors. In fact, they require important space or height for installation because the driving forces are low.

For all the reasons mentioned above, sCO₂-4-NPP heat removal system is an interesting and innovative candidate, since it will be:

- easily retrofitted to existing power plants,
- independent of any external source (water or energy...),
- compact system presenting low fingerprint,
- free of operators intervention need.

Supercritical CO₂ based thermodynamic cycles are the subject of several projects on multiple applications, amongst them, sCO₂-flex project, Echogen, STEP-initiative, NetPower ... ([6], [7], [8], [9]).

For the nuclear applications, different applications are enabled by sCO₂ ([10]). For instance, used in Brayton cycle, it was proven that this fluid is highly effective for energy conversion from nuclear heat to electrical power, suitable for generation IV reactors (lead cooled, sodium cooled and molten salt cooled reactors).

Only one project, sCO₂-Hero, addressed specific nuclear power plant boundary conditions with a suggestion of modular heat removal systems to be attached to existing installation without any external power required. This objective was achieved through the construction of a 200 kW sCO₂ loop in a unique PWR glass model at KSG/GfS ([11], [12], [13], [14]).

The project allowed to reach TRL3 (Technology Readiness Level). Some limitations are still to be investigated further, which will be addressed by sCO₂-4-NPP project.

For heat exchangers, the components need to be designed according to severe transient operating conditions, and since they need to be compact, no use of such technology is available yet in nuclear power plants.

BRAZED PLATES AND FINS HEAT EXCHANGERS TECHNOLOGY DEVELOPPED BY FIVES CRYO

Plates and fins heat exchangers (PFHE) technology was selected for this application since it benefits from important compactness and economic cost. A real asset for this technology is the interesting mechanical properties and integrity which could be enhanced to reach Printed Circuit Heat Exchangers (PCHE) level ([15], [16]), well known for withstanding very high pressure levels and temperature constraints, and mostly used for Brayton cycles applications using supercritical CO₂ ([17], [18]). The low material density in PFHE makes it also very attractive solution in comparison to PCHE.

Figure 3 shows an overview of PFHE concept, where the flows are represented by red, green and blue colors, in order to illustrate the adaptability of such technology. However, sCO₂ Brayton cycles only require 2 fluids.

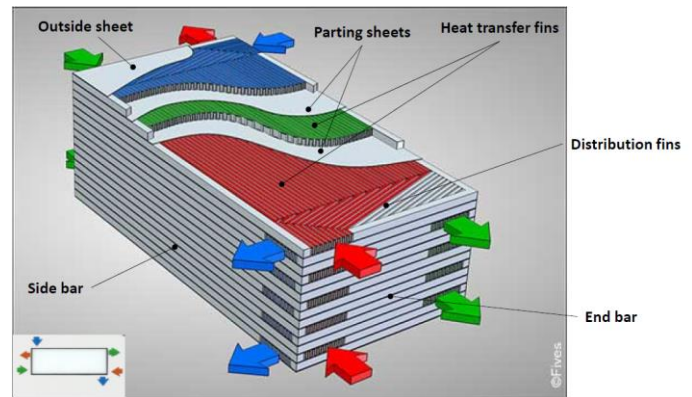


Figure 3: Example of a standard design of a Plates and Fins Heat Exchanger (PFHE) manufactured at Fives Cryo.

A Plates and Fins Heat Exchanger consists of multiple stacked layers, constituted of fins, which are corrugated metal sheets aiming the maximization of heat exchange area. Each fin geometry is characterized by its sheet thickness, fins height, and number of fins per meter. The layers are separated one from the other via partition sheets with a certain thickness, depending on the desired heat exchange; and each layer is closed with lateral bars. The constituted “sandwich” is assembled by diffusion-brazing technique, thanks to filler metal plating on the partition sheets. This filler metal has a liquidus below the solidus of the base metal, which means that the melting point of the filler metal is slightly lower than the base metal. The heat treatment will then allow filler metal melting; after cooling, the filler metal solidifies to ensure all parts cohesion.

After brazing procedure, headers and nozzles are welded on all inlet/outlet sections of the layers (also called “passages”) to allow fluids circulation without mixing, as shown on the **figure 4**.

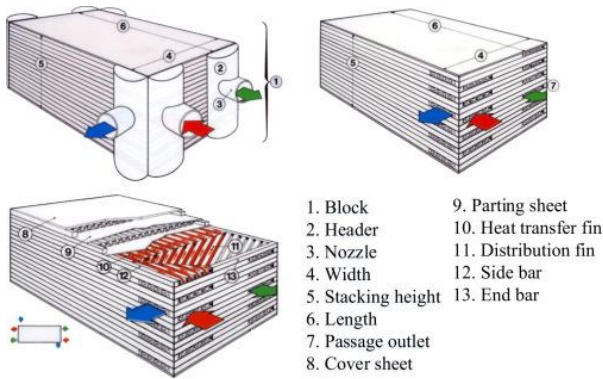


Figure 4: Detailed description of all parts of a brazed Plates and Fins Heat Exchanger (PFHE).

DIVERSE ULTIMATE HEAT SINK (DUHS) DESIGN

Diverse Ultimate Heat Sink (DUHS) design should focus on its size and characteristics, since they are both important elements for nuclear power plants sCO₂ based heat removal system implementation and operation.

In fact, the construction of this system need to be adapted to avoid any breach of nuclear safety and plant security, and resist to heavy weather, earthquake, flooding, pressure waves from detonations and fire, all extreme situations that could lead to reactor malfunction where heat removal system will be needed the most.

Also, penetration of the reactor safety vessel has to be minimized, and the heat removal system has to fit into the existing infrastructure. All piping ways should be as short as possible, in order to be placed as close as possible to the reactor building. To mitigate earthquake relative movement between the components and the reactor building, load from components masses needs to be directed to the basement of the reactor building.

The DUHS heat exchangers components are the most space-consuming, as long with their mass load. A first rough estimation of the area available for DUHS installation is about 540 m² (15 m x 36 m). Since it is not possible to consider an installation as a massive block due to air circulation, a block of 6 cells with a size of 6 m x 15 m each needs to be adopted [19]. 12 Ventilators with about 16' diameter would have been needed, with a shaft power of 46 kW (each), and a pressure of 188 Pa (1.88 mbar) ([3], [19]). The area for heat transfer was given with about 80 000 m², about 76 000 m² for the fins and 4000 m² for the pipe surfaces. From these data, with an effectiveness of 75% for the ventilators, a volume flow of 7.9×10^6 m³/h (some 2200 m³/s) can be estimated.

A way to increase the flexibility to react on decay heat decrease in the long run after shutdown, is to split up the heat removal system into several blocks [3]. Furthermore, equipping each steam generator of a pressurized water reactor with at least one strain would give more flexibility to operate the system not only for heat removal but for steam generator tube leaks (SGTL) too. By definition of a standardized size for such a loop, a modular approach for PWR with different rated power can be taken.

The heat removal capability of one strain should be around 10 MW, where approximately 9.5 MW have to be removed by the DUHS. The maximum air temperature to be considered is 45 °C.

The **table 1** shows the input data used for sCO₂-4-NPP DUHS components design for each unit cell.

FLUID		CO ₂	AIR
TOTAL FLOWRATE	kg/s	30.49	132.49
OPERATING PRESSURE	MPa a	11.92	0.1
ALLOWABLE PRESSURE DROP	kPa	25	0
TEMPERATURE IN	°C	238.66	45
TEMPERATURE OUT	°C	55	115.22
SPECIFIED HEAT TRANSFERRED	MW	9.419	9.419
CORRECTED MTD (GLOBAL)	°C	23.693	

Table 1: Thermodynamic input data used for sCO₂-4-NPP DUHS design.

The calculated output data are shown in **table 2**.

FLUID		CO ₂	AIR
CALCULATED PRESSURE DROP	kPa	8	0
DESIGN TEMPERATURE	°C	-30 °C / 300 °C	
DESIGN PRESSURE	MPa g	23	1
HYDRAULIC TEST PRESSURE	MPa g	29.9	1.3

Table 2: Output design data used for sCO₂-4-NPP DUHS. Calculated pressure drops are considered at nominal flow rate x1

The design leads to 20 heat exchangers cores for each unit, each core has the following dimensions:

- Width : 2000 mm
- Height : 987 mm
- Length : 570 mm

For a total number of 120 cores for all 6 units.

Each core is a counter-flow heat exchanger with a total number of layers of 196 per core.

The layer are distributed as follows:

- 64 layers for CO₂
- 128 layers for air
- 4 “dummy” layers, which are inactive layers, 2 on bottom stacking and 2 on top, to guarantee the mechanical integrity of the heat exchangers cores.

The material for DUHS cores construction is 316 Ti stainless steel (UNS number S31635 / W. number 1.4571). This alloy is suitable for brazing-diffusion bonding and it can withstand high temperature and high temperature differences between fluids. It also benefits from a high mechanical strength and corrosion/erosion resistance.

Each layer with a height of 4 mm. Both CO₂ and air layers contain “plain” fins but with different geometries, as shown on table 3.

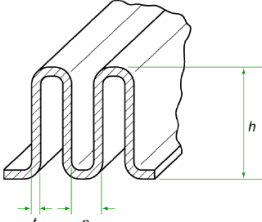
	CO ₂ side fins	Air side fins
Thickness t (mm)	0.3	0.15
Height h (mm)	4	4
FPM p (Fin Per meter)	787.4	393.7
Geometry of “plain fins”		

Table 3: Output design data used for sCO₂-4-NPP DUHS.

The parting sheets between DUHS cores layers are 1 mm thick, external sheets are 4 mm thick.

The thermal performances of our DUHS design are achieved thanks to a smart design: in fact, the stacking pattern used is called “double-banking” [24], leading to an arrangement of 2 air layers against 1 CO₂ layer alternatively. Also, for CO₂ side, each layer is constituted of 6 passes as shown on figure 3, which allows to connect the headers and nipples on only one side of each heat exchanger core (see figure 5), which is quite practical in order to gain space on the unit.

Therefore, there are no headers intended for air side (table 4), since we consider a circulation through the whole width perpendicularly, with subtracting obviously the lateral bars width, as shown on figure 6; which corresponds to an effective passage width of 1928 mm.

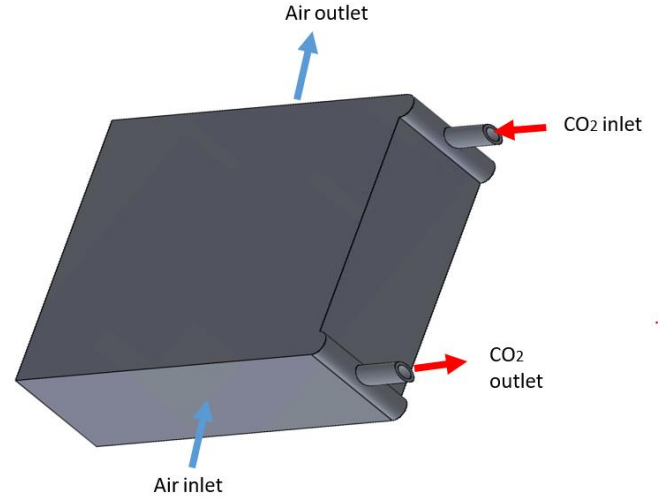


Figure 5: Overall DUHS sketch.

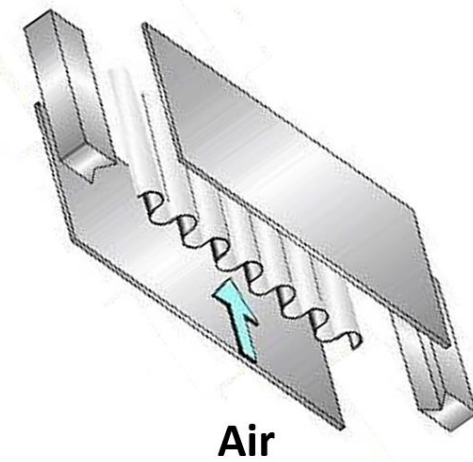
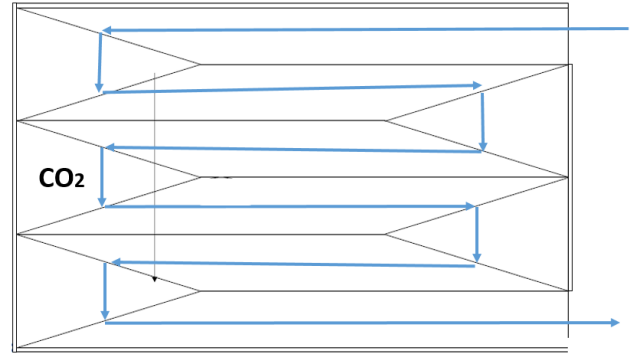


Figure 6: Geometry of CO₂ and Air passages. Fluids circulation is indicated with the blue arrows.

FLUID		CO2	AIR
EFFECTIVE PASSAGE WIDTH	mm	83	1928
EFFECTIVE PASSAGE LENGTH	mm	12000	560
TOTAL HEAT TRANSFER AREA	m ²	9376	13581
TOTAL FREE FLOW AREA	cm ²	3002	178802
NOZZLE SIZE (NOMINAL) IN/OUT	mm	2x40	2x40
CONNECTIONS (NOM.) IN/OUT	inch	40 x 1.5	40 x 1.5

Table 4: Output design data used for sCO₂-4-NPP DUHS.

This DUHS design allows to develop a total heat transfer area of 9376 m² for CO₂ and of 13581 m² for air for 1 unit of 10 MW (see **table 4**).

HEAT EXCHANGERS QUALIFICATION ACCORDING TO NUCLEAR POWER PLANTS REGULATION

In addition to sCO₂ cycle heat exchangers design, the project sCO₂-4-NPP aims also to clearly define the qualification strategy for these equipments, including the validation of some key points to assess that the heat exchanger technology is suited for nuclear power plants.

In compliance with the construction code RCC-M [20] and the European Regulation of Nuclear Pressure Vessel [21], Fives Cryo is constituting a note which aim is to present the approach to be followed and the main important and specific documents to be carried out so that the equipment manufactured meets the criteria of the nuclear PED regulation and the selected nuclear construction code. At this stage of the project, not all technical design choices have been yet fixed for the equipments, thus, the qualification methodology needs to be finalized afterwards, and will be presented in full in a future paper.

The documents identified and listed below are considered important for an appropriate design and manufacturing review in accordance with the nuclear PED regulation:

- Risk and hazards analysis (for pressure and radiation aspects) according to the nuclear PED regulation,
- Instruction for use according to the nuclear PED regulation,
- The list of Important Activities for the Protection of Interests (IAPI) according to modified decree BNI 07/02/2012 [22],
- Definition of the Necessary Dimensions to meet the Essential Safety Requirements (NDESR) and control methods,
- The nuclear particular material appraisals according to the nuclear PED regulation,
- The list of material,
- Supply specifications for base metal and filler metal,
- Capacity of inspection in service according to the nuclear PED regulation,

- The program of fabrication,
- The procedures of controls,
- The visual inspection procedure at the end of fabrication,
- The marking procedure,
- The procedure of materials tracing.

For this paper, we will focus on a brief overall description of the content of 4 documents from the previous list:

- Risk and hazards analysis,
- The list of Important Activities for the Protection of Interests (IAPI),
- Definition of the Necessary Dimensions to meet the Essential Safety Requirements (NDESR) and control methods,
- Capacity of inspection in service according to the nuclear PED regulation.

Considering a level 3 defined by the nuclear power plant owner (or nuclear power plant operator) according to ESPN classification, a radiological classification of the system of RP C class and a class 3 according to RCC-M.

1- Risk and hazards analysis

The objectives of the risk and hazards analysis are:

- To identify failure modes (and causes of these failures) which could create operational risks on the pressure aspect and on the radioactivity aspect (hazardous phenomena, such as loss of integrity like fluid leaks or energy release, or noncompliance with the radiological rules),
- To find solutions to remove or reduce (as reasonably possible) the causes of failure. These causes are to be investigated in all phases of life of the equipment (design/manufacture/operation) and for all design situations,
- To identify the applicable essential safety requirements for the equipment.

To this end, it is mandatory to define the physical (as on **figure 7**) and functional description of the heat exchangers required for the heat removal system (as of **figures 1 and 2**).

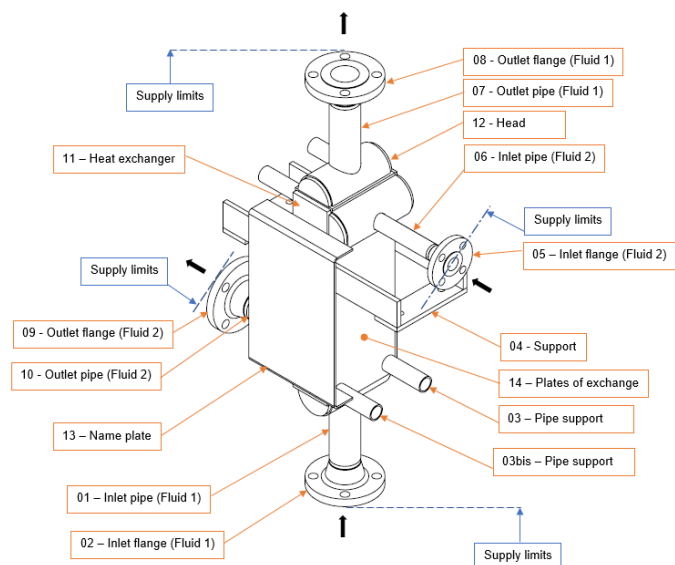


Figure 7: Physical description of a heat exchanger equipment required for risk and hazards analysis.

A functional analysis limited to the circuits defined for the fluids circulating in the heat exchanger is then established (an example is shown on **Annex A**), defining the circuits as blocks, the aim is to specify which parts of the heat exchanger, with its specific designation and function, are in contact with the fluids, and its classification, following :

- PCRP: Parts contributing to pressure resistance
- PP: Part under pressure
- PDA: Directly Attached Party (and are not PCRP)

A list of permanent connections and bolted connections on pressure parts also needs to be established, and a list of selected materials limited to the parts contributing to the resistance to pressure, and to the parts and components acting as parades (directly attached parts, part of the supply) as specified on the examples on **Annex A**.

The risk analysis lists also the codes and standards used for design and manufacture (here the RCC-M and European standards), and the regulatory classification of the equipment and allowable limits (minimum and maximum allowable pressures and temperatures). The calculation of the category and level is achieved in accordance with the European Directive [21] and the ESPN order, taking into account the fluid group, the volume per circuit, and the pressures. The classification about radiation protection is also given.

Supply and equipment limitations are an important elements to specify for risk analysis. In fact, we consider that the equipment (in the regulatory sense) consists exclusively of:

- PCRP (Parts contributing to pressure resistance),
- Parts directly attached to the parts contributing to the pressure resistance.

The supply consists of:

- The regulatory equipment as described above,
- Other elements that are delivered with the equipment, according to a given list.

A specific mention of what the supply does not include is also part of the analysis.

Last but not the least, input data required for risk analysis are to be specified, including:

- Situations and loads; such as charges communicated by the operator in normal operating conditions and Highly Improbable Situations (HIS) and any other charges that could be identified by the manufacturer.
- Aggressions
- Environmental conditions; such as environmental chemistry, ambient conditions and radiological data
- Interface conditions

2- List of Important Activities for the Protection of Interest (IAP) for ESPN level 3 : equipment manufactured according to RCC-M

This part aims to explain the measures taken by the manufacturer of the heat exchangers, to meet the requirements contract reflecting the requirements of the BNI order [22] for supplies important to safety (IPS) in nuclear power plants. It lists the Important Activities for the Protection of Interests (IAP) and associated Technical Controls (TC) for the design, the procurement/subcontracting and for the manufacturing (see tables in **Annex B**).

3- Definition of the Necessary Dimensions to meet the Essential Safety Requirements (NDES) and control methods

The purpose of this document is to define the NDES, such as shapes, uncertainty measurements, resolution, maximum allowable error, specification limits and tolerances; the control of these NDES and the traceability of the controls in compliance with the regulation [21] and [23] for the heat exchangers components.

The NDES are the regulatory dimensions in connection with:

- The pressure risks: these NDES are the dimensions for which non-compliance with the specifications call into question the results of design related to applicable Essential Safety Requirements (ESR). These are the dimensions (input data and/or output data), considered important by the manufacturer for the pressure risks at the design stage, in the implementation of equations for design by formula or in calculation models for a design by analysis.

- The radiological risks: these are the dimensions that make it possible to satisfy radiation protection requirements. For example, this can be the slope of a flow, the roughness of a part...
- The overpressure protection: these are the dimensions related to compliance with the protection against overpressure. For example, the flow diameter (for an injection nozzle) or the stroke of a safety accessory...
- An identified dimension during the risks / hazards analysis.

The equipment technical drawing is the mean to identify these NDESR. This identification is based on a dialogue between design teams and manufacturing teams to ensure that the identified NDESR are measurable during manufacturing stage, either directly or indirectly.

The identified NDESR are given in Annex C of this document.

This table gives:

- The reference and the designation of the NDESR,
- The reference of the drawing,
- The design value of the NDESR,
- The specification limit for this value,
- The stage of control/measurement,
- The measuring devices,
- The resolution of the measuring device.

The NDESR are generally:

- Thicknesses of parts for the pressure resistance (thickness of flanges, of heads, of cones, of pipes...),
- Inside or outside diameters of parts for the pressure resistance,
- Geometry of threads,
- Radii of connections ...

For these NDESR control and measurement, a control procedure is established: a document defining the procedures allowing to assess the conformity of an equipment with the technical drawings.

This procedure must contain the following parts:

- Scope (equipment...),
- Applicable documents,
- Reference documents,
- Required qualifications for the operators in charge of the control / measurement,
- Preparation of surfaces and ambient conditions (degreasing, cleaning, temperature ...),
- Measurement method:

- o Geometry of the part, type and range of dimension,
- o Measuring device with its measuring range and its resolution,
- o Units,
- o Accessibility, configuration of the part,
- Extent of control,
- Stage of control,
- Verification of measurement tools,
- Rules for the sampling,
- Measurement uncertainty of measuring devices,
- Compliance criteria,
- Recording methods of control / measurement,
- Report content.

4- Capacity of inspection in service according to the nuclear PED regulation

The purpose of this last document is to report and justify of the inspectability of the heat exchangers in compliance with the PED and the nuclear regulation [21], to ensure a permanent safety of the equipment (after the first commissioning by the owner) and to ensure the radiation protection of the stakeholders performing the inspection of the equipment.

The manufacturer must ensure the feasibility of inspections (visual, dimensional, NDT, etc.) to meet the needs identified in the risks analysis and reported in the instruction for use manual. This feasibility includes an analysis of the adequacy between the suggested means of examination and:

- The geometry,
- The accessibility,
- The grade,
- The type of degradations,
- The conditions of radiation protection.

The assumptions considered for this analysis are as follows:

- o Insulation is removable,
- o Equipment is decontaminated before inspection,
- o Surfaces are clean,

The necessary inspection for the in-service safety (internal / external) shall be realized equipment without fluid, without pressure and at room temperature.

If the fluid is radioactive, surfaces that may be touched during the inspection should be cleaned beforehand to limit contamination.

The in-service safety inspection are carried out under the responsibility of the power plant operator by qualified and

competent personnel who shall be able to identify the potential defects and degradations and to assess their severity.

These actions are carried out under the responsibility of the power plant operator who is in charge of shutting down the installations.

The accessibility to the equipment and environment where it is installed shall be clearly defined and indicated by the power plant operator. A specific attention is given to the definition of the area classification in terms of radiation, and the dose rate is calculated. It is recommended to make a dosimetric survey of the area in order to establish the most accurate dose rate.

However, the classification of the area may change, it is imperative to check the nuclear power plant operator's radiation protection map at the time of inspection.

Also, it is the responsibility of the operator to make available the necessary means (scaffolding...) for the inspection of the equipment in accordance with the regulations.

Equipment inspection occurs in 2 major steps: internally and externally.

Internal inspection applies to all internal surfaces accessible without compromising the pressure vessel integrity, as follows:

- Internal surfaces of the elements subjecting to pressure,
- Internal surfaces of the inlet and outlet nozzles and flanges,
- Internal surfaces of welds,
- Surfaces of accessible internal elements in the equipment (some parts of distribution fins...)

Internal inspection can be carried out with an endoscope, which could be accessorized with a pole to limit the exposure of hands.

External inspection of the equipment is applied on its external surface, which includes:

- External surfaces of the elements subject to pressure and attached parts on equipment,
- External surfaces of the inlet and outlet nozzles and flanges,
- External surfaces of welds.

Insulation of the equipment shall be removed. External surfaces of the equipment (external sheets, headers, pipes, welds...) shall be inspected by installing specific means of access. The welds are all marked on technical drawings of the equipment.

Generally, only a direct visual control is required. In case of doubt, a dye penetrant test can be carried out.

An example of an inspection table specifying areas to be controlled, defects to be detected, means of inspection and estimated duration for inspection is presented in **Annex D**.

CONCLUSION

The sCO₂-4-NPP project aims to develop an innovative technology based on a Brayton cycle using supercritical CO₂ for heat removal to improve the safety of current and future nuclear power plants.

The cycle's components are subject to severe operating conditions due to the nature of this working fluid. In particular, heat exchangers are equipments confronted to high levels of pressure and temperature.

The prior usual choice for this application is PCHE technology, thanks to its thermal and hydraulic performances but especially for its mechanical integrity. PFHE developed at Fives Cryo, thanks to its higher compactness at a moderate cost, could be a better choice for sCO₂ Brayton cycle applications if its mechanical and corrosion resistance are improved.

To that end, a new development is performed: in the frame of sCO₂-4-NPP project and its precursor sCO₂ flex project [9], Fives Cryo develops the design and manufacturing of stainless steel heat exchangers.

An additional important step is also to qualify the designed heat exchangers according to regulatory and licensing requirements dedicated to nuclear power plants environment. Some overall regulatory aspects are addressed in this paper.

Interesting progress was achieved on these topics. This gives a fair confidence to succeed in PFHE technology qualification to be part of future sCO₂ Brayton cycles for heat removal in nuclear power plants, by the end of the sCO₂-4-NPP project.

NOTATIONS TABLE

sCO₂: Supercritical CO₂

CHX: Compact Heat eXchanger

DUHS: Diverse Ultimate Heat Sink

PWR: Pressurized Water Reactor

BWR: Boiling Water Reactor

PFHE: Plates and Fins Heat Exchanger

PCHE: Print Circuit Heat Exchanger

HIS: Highly Improbable Situation

TC: Technical Controls

NDES: Necessary Dimensions to meet the Essential Safety Requirements

ESR: Essential Safety Requirements

DESIGN CALCULATIONS TABLE

Effective passage width:

For CO₂, width of the passes

For AIR, heat exchanger width – lateral bars (2000-2x36)

Effective passage length:

For CO₂, number of passes x heat exchanger width (6 x 2)

For AIR, heat exchanger length – 5mm indent at each side

Total heat transfer area:

Number of cores x number of layers / core x effective width x effective length x fins area / m²

Total free flow area:

Number of cores x number of layers / core x effective width x fin free flow area / m

Air flow rate:

It has been calculated to balance the exchanger in terms of heat. The Brazed plate fin heat exchanger are usually insulated, and consequently, we do not consider any heat leak to the outside.

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DISCLAIMER

“This text reflects only the author’s view and the Commission is not liable for any use that may be made of the information contained therein.”

REFERENCES

- [1] Yotaro Hatamura (2015). The 2011 Fukushima Nuclear Power Plant Accident, How and Why it Happened. Elsevier Ltd.
- [2] Tomoyuki Kobayashi (2019). Social Identity Threats Following the Fukushima Nuclear Accident and its Influence on Psychological Distress. Japan

- [3] Jeanne Venker (2015). Development and Validation of Models for Simulation of Supercritical Carbon Dioxide Brayton Cycle and Application to Self-Propelling Heat Removal Systems in Boiling Water Reactors. Germany
- [4] M. E. Siddiqui (2018). Energy Analysis of the S-CO₂ Brayton Cycle with Improved Heat Regeneration. Saudi Arabia.
- [5] K. R. Zada (2018). Analysis of Supercritical CO₂ Brayton Cycle Recuperative Heat Exchanger Size and Capital Cost with Variation of Layout Design. USA.
- [6] <https://www.sco2-flex.eu/>
- [7] <https://www.echogen.com/>
- [8] <https://www.step-initiative.org/>
- [9] <https://netpower.com/>
- [10] Houbo Qi (2018). The Application of Supercritical CO₂ in Nuclear Engineering : A Review. USA.
- [11] <http://www.sco2-hero.eu/>
- [12] Marcel Straët (2017). Cycle Calculations of a Small-Scale Heat Removal System with Supercritical CO₂ as Working Fluid. Germany.
- [13] Alexander Hacks (2018). Turbomachine Design for Supercritical Carbon Dioxide within the sCO₂-Hero.eu Project. Germany.
- [14] Ales Vojacek (2018). Performance Test of the Air-Cooled Finned-Tube sCO₂ Sink Heat Exchanger. Czech Republic.
- [15] Sarah Tioual-Demange (2019). Highly Efficient Plate-Fin Heat Exchanger (PFHE) Technical Development for s-CO₂ Power Cycles. France.
- [16] Sarah Tioual-Demange (2020). Industrial Technical Development and Qualification of Highly Efficient Stainless Steel Plates and Fins Heat Exchanger For Heat Removal Supercritical CO₂ Brayton Cycle Applied to Nuclear Power Plants. France.
- [17] D. Shiferaw (2016). Economic Analysis of sCO₂ Cycles with PCHE Recuperator Design Optimisation. USA.
- [18] I. Jentz (2015). Modeling the Mechanical Integrity of Airfoil Printed Circuit Heat Exchangers. USA.
- [19] GEA (2013). Luftkühler – Datenblatt. Luftgekühlter Wärmetauscher für CO₂. Germany.
- [20] AFCEN RCC-M (Rules of Conception and Construction of Mechanical Equipments for Nuclear Sites 2018 edition).
- [21] PED Directive 2014/68/EU on the harmonization of the laws of EU member states concerning pressure vessels construction.
- [22] Order of 07/02/2012 on General Rules on Basic Nuclear Installations (BNI).
- [23] Order of 30/12/15 on nuclear pressure vessels and safety accessories for pressure vessels protection.
- [24] K. Nikitin (2006). Printed Circuit Heat Exchanger Thermal-Hydraulic Performance in Supercritical CO₂ Experimental Loop. Japan.

ANNEX A

EXAMPLES FOR PHYSICAL AND FUNCTIONAL ANALYSIS

1- Functional analysis table (limited to the blocks “circuit 1” and “circuit 2”)

Block	Part number	Designation	Function	Component classification (Part)	Part in contact with the fluid
Circuit 1	01	Inlet pipe	Inlet nozzle for fluid 1	PP	Yes
Circuit 1	02	Inlet flange	Inlet nozzle for fluid 1	PP	Yes
	03 / 03bis	Pipe support	To maintain exchanger in service	PDA	No
	04	Support	To maintain exchanger in service	PCRP	No
Circuit 2	05	Inlet flange	Inlet nozzle for fluid 2	PP	Yes
Circuit 2	06	Inlet pipe	Inlet nozzle for fluid 2	PP	Yes
Circuit 1	07	Outlet pipe	Outlet nozzle for fluid 1	PP	Yes
Circuit 1	08	Outlet flange	Outlet nozzle for fluid 1	PP	Yes
Circuit 2	09	Outlet flange	Outlet nozzle for fluid 2	PP	Yes
Circuit 2	10	Outlet pipe	Outlet nozzle for fluid 2	PP	Yes
Circuit 1 and 2	11	Heat exchanger	To ensure heat transfer between two fluids	PP	Yes
Circuit 1 and 2	12	Head		PP	Yes
	13	Name plate	To identify the unit	PDA	No
Circuit 1 and 2	14	Plates of exchange	participates in heat transfer between two fluids	PP	Yes

- PCRP: Parts contributing to pressure resistance
- PP: Part under pressure
- PDA: Directly Attached Party (and are not PCRP) |

2- List of permanent connections and bolted connections on pressure parts

*The numbers corresponds to **figure 7** above*

Designation	Type	Classification		
		Assembly on the parts contributing to the resistance to pressure (and which are not parts under pressure)		
		Resuming the pressure forces	Tightness	Other
Assembly between pipe nozzle (01,06,07,10) and head (12)	<u>Welded</u>	X		
Assembly between Support (04) and heat exchanger (11)	<u>Welded</u>	X		
Assembly between plate of exchange (14)	<u>Brazing</u>	X	X	
Assembly between pipe nozzle (01,06,07,10) and flange nozzle (02,05,08,09)	<u>Welded</u>	X		
Assembly between heat exchanger (11) and head (12)	<u>Welded</u>	X		

3- Selected materials (table limited to parts contributing to the resistance to pressure, to the parts and components acting as parades (directly attached parts, part of the supply), to the parts and components acting as parades, for the blocks "circuit 1" and "circuit 2")

Component	Part number	Materials	Reference
Inlet pipe	01	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3304
Inlet flange	02	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3301
Pipe	03	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3304
Support	04	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3307
Inlet flange	05	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3301
Inlet pipe	06	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3304
Outlet pipe	07	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3304
Outlet flange	08	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3301
Outlet flange	09	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3301
Outlet pipe	10	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3304
Heat exchanger	11	Austenitic Stainless steel	
Head	12	Austenitic Stainless steel	
Name plate	13	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3307
Plates of exchange	14	Austenitic Stainless steel	Z2 CND 17-12 according to STR M3307

ANNEX B

LIST OF IAPI AND ASSOCIATED TECHNICAL CONTROLS

1- For design

	AIP	Defined requirements			Associated Technical Controls	
		Main characteristics and/or parameters of the RCC-M	Information necessary for carrying out operations	Recording	Type	Recording
Design	1	Studies / design	Allowable stresses Grades Thicknesses (dimensions) Corrosion allowance Drawings Input Data : => Design temperatures (mini/maxi) / design pressures (mini/maxi) => Fluids => Seismic studies => Regulatory and radiation data from the Operator => Specification of equipment => Load cases to be taken into account for each situation	- Calculation note of pressure vessel - Calculation note of Supports - Drawings - Risks and Hazards Pressure and Radiation analysis	Carrying out the technical control of the studies : - Calculation notes - Drawings - Procurement specifications - Manufacturing and test procedures. Verification of study documents by individuals different from those that made them	Visa of the first page of each document Visa of checking sheets
	2	Studies / preparation	Provisional chronological list of procurement operations, of manufacturing operations, of control operations and of testing operations Input data : => Procurement specification from Operator => Regulatory and radiation data from the Operator => Drawings BPE => Manufacturing and test procedures	- List of applicable documents - Follow up document - Welding book - Welding tracking forms - Brazing book	Verification by Quality Department Verification by Welding Department Verification of documents (welding book, brazing book, welding tracking forms...) by individuals different from those that made them	Visa of the first page of each document

		AIP	Defined requirements			Associated Technical Controls	
			Main characteristics and/or parameters of the RCC-M	Information necessary for carrying out operations	Recording	Type	Recording
Procurement / Subcontracting	10	Procurement of material / Process of material fabrication	<ul style="list-style-type: none">- Dimensions- Marking- Chemical analysis- Mechanical properties- Corrosion test- Defects in the material after transformation (forging, casting...)	<ul style="list-style-type: none">- Draw ings- Procurement material specifications- Subcontracting order	<ul style="list-style-type: none">- Report / certificate of material from provider- Follow up document	<ul style="list-style-type: none">- Verification at reception of material by warehouse site of the material / parts- Verification at reception by quality personnel of the report / certificate of material- Quantitative and qualitative verification	Visa of follow up document
	20	Heat treatment (partial, simulated, final)	<ul style="list-style-type: none">- Mechanical properties- Metallurgical structure	<ul style="list-style-type: none">- Used furnace- Thermocouple (nb, mark, location)- Identification of the part- Position of the part in the furnace- Description of the thermal cycle- Sample of mechanical test	<ul style="list-style-type: none">- Records of heat treatment- Records of mechanical tests- Temperatures diagrammes for furnace and material / parts (during heat treatment)	<ul style="list-style-type: none">- Validation of the different steps of heat treatment- Verification of the recorded curves- Verification of the mechanical characteristics	<ul style="list-style-type: none">Visa of follow up documents of providerEventual visa of other documents associated to verification
	30	Non destructive volumetric testing (RT, UT)	<ul style="list-style-type: none">- Defects in the fabrication of the part- Weld / brazing defects	<ul style="list-style-type: none">- Interpretation- Devices used- Mark of blocks control- Personnel- Adjustments- Parameters of radio examination- Radio element used- X ray cassette composition- Exposure time- Elements / chemicals for radiogram developing- Recording of control results	<ul style="list-style-type: none">- Procedures- Reports of examinations- Radiogramms- Data acquisition	<ul style="list-style-type: none">- Verification of information necessary for carrying out operations- Film sample replay (at least 3% of radiograms)- Verification of application of procedures (UT/RT)- Verification of used parameters (RT/UT)- Verification of examinations reports- Verification of the qualification of testing personnel- Verification of testing procedures RT/UT by certified Expert level 3 and by EDF- Validation NDT procedure by the manufacturer- Verification of the calibration of used devices	<ul style="list-style-type: none">Visa of follow up documents of providerEventual visa of other documents associated to verification
	40	Surface Treatment / Painting	<ul style="list-style-type: none">- Application of RCC-M Part F- Qualification of procedure if necessary- Thickness, coat of paint- Paint system used	Specification of Client / Operator	<ul style="list-style-type: none">- Report of thickness- Report of adhesion	<ul style="list-style-type: none">- Verification of personnel qualifications for painting- Calibration of used devices- Verification of temperature and humidity- Verification of conditioning / packaging with products for use in nuclear power plant- Verification of painting according to procedures- Verification of reports (thickness and adhesion)	<ul style="list-style-type: none">Visa of follow up documents of providerEventual visa of other documents associated to verification
	50	Implementation of permanent assemblies (marking, welding, brazing, buttering, weld adding...)	<ul style="list-style-type: none">- Surfaces, denseness- Technological defects- Dimensional visual- Chemical analysis- Mechanical properties- Appropriate metallurgical structure	<ul style="list-style-type: none">- Welding / brazing procedure forms (welding energy...)- Chemical analysis for filler metal and base metal- Skills of welders / brazers / personnel- Non destructive tests to be realized	<ul style="list-style-type: none">- Qualification of procedure welding / brazing reports (QMOS)- Records of welders / personnel qualification- Acceptance form of filler metal- Tracking forms for welding and brazing- Reports of examinations	<ul style="list-style-type: none">- Verification of approval of welding book and brazing- Verification of welders qualifications- Verification of results for dimensionnal and visual inspection- Verification of filler metal lots- Verification of appropriate welding / brazing procedures forms- Verification of results for non destructive tests (surfacic and volumetric)- Realization of specimens coupons- Verification of eventual repairs	<ul style="list-style-type: none">Visa of follow up documents of providerEventual visa of other documents associated to verification

	AIP	Defined requirements			Associated Technical Controls	
		Main characteristics and/or parameters of the RCC-M	Information necessary for carrying out operations	Recording	Type	Recording
Fabrication	100	Receipt/Identification of supplier and/or prefabricated material	Compliance with contractual requirements	- Procurement specification - Drawings - Inspection certificate / Fabrication report	Visa on the follow up document	Quantitative and qualitative verification Visa on the follow up document
	200	Non destructive volumetric testing of welds	Weld defects	- Interpretation - Devices used - Mark of blocks control - Personnel - Adjustments - Parameters of radio examination - Radio element used - X ray cassette composition - Exposure time - Elements / chemicals for radiogram developing - Recording of control results	- Procedures - Reports of examinations - Radiograms - Data acquisition	- Verification of information necessary for carrying out operations - Films sample replay (at least 3% of radiograms) - Verification of application of procedures (UT/RT) - Verification of used parameters (RT/UT) - Verification of examinations reports - Verification of the qualification of testing personnel - Verification of testing procedures RT/UT by certified Expert level 3 and by EDF Visa of follow up documents Eventual visa of other documents associated to verification
	300	Machining (bevel, drilling...)	Dimensions	Procedure of welding / brazing	- Report of dimensionnal / visual inspection - Report of dye penetrant test	- Verification of necessary informations - Verification of application of applicable procedures - Verification of records of dye penetrant test - Verification of the qualification of personnel in charge of examination Visa of follow up documents Eventual visa of other documents associated to verification
	400	Forming (hot bending, cold bending, rolling...)	- Affected materials (dimensions, denseness, physical properties...) - Technological defects - Mechanical properties - Residual stresses	- Qualification of forming - Heat treatment - Skills of the personnel	- Report of the parameters - Trackings sheets	- Reports of forming procedures qualifications - Verification of forming parameters in workshop - Realization of specimens coupons Visa of follow up documents Eventual visa of other documents associated to verification
	500	Implementation of permanent assemblies (marking, welding, brazing, buttering, weld adding...)	- Surfaces, denseness - Technological defects - Dimensional visual - Chemical analysis - Mechanical properties - Appropriate metallurgical structure	- Welding / brazing procedure forms (welding energy...) - Chemical analysis for filler metal and base metal - Skills of welders / brazers personnel - Non destructive tests to be realized	- Qualification of procedure welding / brazing reports (QMOS) - Records of welders / brazer / personnel qualification - Acceptance form of filler metal - Tracking forms for welding and brazing - Reports of examinations	- Verification of approval of welding book and brazing book - Verification of welders / brazers qualifications - Verification of results for dimensionnal and visual inspection - Verification of filler metal lots - Verification of appropriate welding / brazing procedures forms - Verification of results for non destructive tests (surface and volumetric) - Realization of specimens coupons - Verification of eventual repairs - Verification of welding / brazing parameters (first application by procedure and by personnel and by site) Visa of follow up documents Eventual visa of other documents associated to verification
	600	Heat treatment (partial simulated, final)	- Mechanical properties - Metallurgical structure	- Used furnace - Thermocouple (nb, mark, location) - Identification of the part - Position of the part in the furnace - Description of the thermal cycle - Sample of mechanical test	- Records of the heat treatment - Records of mechanical tests - Temperatures diagrams furnace and parts (during heat treatment)	- Presence during the different steps of heat treatments - Verification of the recorded curves - Verification of the mechanical characteristics Visa of follow up documents Eventual visa of other documents associated to verification
	700	Cleaning	- Management of temporary elements - Risk management for Foreign Material Exclusion FME - Elimination of foreign material	- Installation - Removal	Follow up document	- Verification of the installation and removal procedures - Verification of the removal of temporary elements and FME (by internal and external visual inspection) Visa of follow up documents Eventual visa of other documents associated to verification
	800	Assembly of static equipment (flanges, piping, nozzles...)	- Completion of pressure equipment - Presence of all compliant assemblies - Documents for hydraulic test / burst test - Tightening of flanges - Identification / marking of equipment	- Follow up fabrication - Follow up assemblies - Form for hydraulic test and burst test - Drawings	- Follow up document - Procedure for hydraulic test and burst test - Records / reports	- Verification of tightening flanges - Verification of approval of hydraulic test procedures and burst test procedure - Realization of hydraulic test and burst test of equipment - Verification of non conformity forms - Visa of follow up documents - Report for hydraulic test - Report of burst test - Eventual visa of other documents associated to verification

ANNEX C

LIST OF NDESR (OR DNRE)

References DNRE	Designation of part	DNRE of the part	Value to be measured	Specification limits from design	Specification limits reduced by EMT	Procurement standard	Drawing reference	Control stage	Measuring device	Measuring range (Resolution) of measuring device
A1	Head outlet fluid 1	External diameter of pipe nozzle	60.3 mm	± 1 mm	± 1 mm	NFEN10216-5	xxx	Procurement	Calliper	0-300 (0,01)
A2		Thickness of pipe nozzle	2.6 mm	± 0,1 mm	± 0,07 mm	NFEN10216-5	xxx	Procurement	Measuring arm	0-60 (0,03)
A3		Position of nozzle on head	200.0 mm	± 2,0 mm	± 1 mm	-	xxx	After permanent assembly	Tape measure	0-300 (1)
A4		Closure end diameter	88.9 mm	± 1 mm	± 1 mm	NFEN10216-5	xxx	Procurement	Calliper	0-300 (0,01)
A5		Closure end thickness	3.2 mm	± 0,1 mm	± 0,07 mm	NFEN10216-5	xxx	Procurement	Measuring arm	0-60 (0,03)
A6		Outside diameter flange	19.0 mm	± 0,1 mm	± 0,07 mm	NFEN1092-1	xxx	Procurement	Measuring arm	0-60 (0,03)
A7		Diameter drilling flange	100.0 mm	± 2,0 mm	± 2,0 mm	NFEN1092-1	xxx	Procurement	Calliper	0-150 à 0-300 (0,01)
B1	Support	Weld throat pipe support / plate	4.0 mm	min	4.1 mm mini	-	xxx	After assembly	Throat measuring	0-20 (0,1)
B2		Position of support	200.0 mm	± 2,0 mm	± 1 mm	-	xxx	After permanent assembly	Tape measure	0-300 (1)
R1	All	Internal roughness	3,2 ou 6,3 microm	mini	mini	-	xxx	After permanent assembly	Visual touch pad	-
U1	All	Out of roundness	2,0 mm	maxi	2,0 mm maxi	-	xxx	Procurement	Calliper	0-300 (0,01)
T11	Sampling	Thickness of fin	1,0 mm	± 0,1 mm	± 0,07 mm	NFEN10028-7	xxx	After forming and brazing	Measuring arm	0-60 (0,03)
H11		Heigh of fin	50,0 mm	± 1 mm	± 1 mm	NFEN10028-7	xxx	After forming and brazing	Calliper	0-300 (0,01)
F11		Fins Per Inch (FPI)	20,0 mm	± 1 mm	± 1 mm	NFEN10028-7	xxx	After forming and brazing	Calliper	0-300 (0,01)
yyy	yyy	yyy	yyy	yyy	yyy	yyy	yyy	yyy	yyy	yyy

ANNEX D

EXAMPLE OF EXTERNAL INSPECTION TABLE

<i>Area to be inspected / controlled</i>	<i>Defects to be detected (residual risks of hazards analysis)</i>	<i>Means of inspection</i>	<i>Estimated duration</i>
Entire equipment except welds	Control as complete as possible to identify: <ul style="list-style-type: none"> - Possible traces of corrosion (pitting, presence of corrosion products cracking, heat-insulating corrosion...) - Mechanical failure (deformations, shocks, cracks, fatigue...) 	Direct visual control Eye + lighting	25 min
Circular weld C1	Identical	Direct visual control Eye + lighting	10 min
Circular weld C2	Identical	Direct visual control Eye + lighting	10 min
Weld L1	Identical	This weld is accessible and can be seen directly on half of its perimeter. Since the weld is subjected to the same operating conditions throughout its circumference, it is considered that the visible half is representative of the non-visible half.	5 min
Flange nozzle outlet fluid 1	Check absence of sagging and the condition of the flange facing when removing the flanges	Direct visual control Eye + lighting	5 min
Flange nozzle inlet fluid 1	Check absence of sagging and the condition of the flange facing when removing the flanges	Direct visual control Eye + lighting	5 min
Flange nozzle outlet fluid 2	Check absence of sagging and the condition of the flange facing when removing the flanges	Direct visual control Eye + lighting	5 min
Flange nozzle inlet fluid 2	Check absence of sagging and the condition of the flange facing when removing the flanges	Direct visual control Eye + lighting	5 min
Critical part detected	Loss of thickness if necessary	Measurement of residual thickness by US (by external side)	

Total estimated duration for the external inspection of equipment: xx min.

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