ETEKINA
Thermal energy recovery

D2.6 – Common commissioning procedure (PU)

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WP 2, T 2.4

Authors: Bakartxo Egilegor, Matteo Venturelli, Fouad Al-Mansour, Marko Peckaj, Sulaiman Almahmoud, Lujean Ahmad and Hussam Jouhara.

Heat pipE TECHnologies for INdustrial Applications.

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Technical References

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
RE = Restricted to a group specified by the consortium (including the Commission Services)
CO = Confidential, only for members of the consortium (including the Commission Services)

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Document history			
V	Date	Beneficiary	Comments
0.0	03/08/2018	IKERLAN	Ikerlan. Preliminary draft version extracted from D2.5
0.0	10/09/2018	IKERLAN	Feedback given from the task participants. Only minor changes from JSI. No additional comments from BUL, nor from UMR
0.1	27/09/2018	IKERLAN	References have been included
0.1	1/10/2018	IKERLAN	Some minor editing changes have been made
1.0	15/07/2019	IKERLAN	The following sentence has been included: ***This document reflects only the ETEKINA authors views and the European Union is not liable for any use that may be made of the information contained therein***
1.1	18/10/2019	IKERLAN	The document has been widely modified to improve the readability of the deliverable. The document has been reorganized into 3 main Chapters: • Definition phase • Pre-commissioning process (component level) • Commissioning (integration level) A more detailed commissioning and testing procedure has been described.
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Summary

This document describes the critical factors for a successful commissioning procedure of a Waste Heat Recovery (WHR) installation that is based on heat pipe heat exchangers (HPHE). The objective of a commissioning procedure is to achieve steady and reliable operating conditions of the WHR installation without altering the productive process operation; in other words, the WHR installation performance must be invisible for the production process.
In order to improve the logical structure of the Commissioning Procedure three main phases have been distinguished:

1. Definition phase
2. Pre-commissioning phase (at component level)
3. Commissioning phase (components integration level)

The definition of a plan considering the Critical Success Factors is fundamental for a successful commissioning process [3]. In this case the common Critical Success factors of a HPHE based WHR system have been considered and a Commissioning process sequence with a checklist has been defined.

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Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 768772.

Introduction

The aim of the commissioning procedure is to verify that the WHR (Waste Heat Recovery) system is ready for its evaluation.
This document describes the procedure to check the installation is ready for being evaluated.
The overall commissioning plan comprises three main phases:

1. Definition phase (chapter 1)
2. Pre-commissioning phase (at component level) (chapter 2)
3. Commissioning phase (components integration level) (chapter 3)

The installation definition, construction and commissioning phases with the used/generated key documents and milestones have been represented in Figure 1. A checklist has been defined to monitor and to follow the overall commissioning plan (Table 3).

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Commissioning procedure

The following diagram (Figure 1) describes the different phases for one new HPHE based WHR installation construction with its commissioning process. The diagram shows the key documents (Acceptance Criteria, P&ID diagram, list of materials, detailed installation drawing, detailed Action Plan, Commissioning report and Validation Report); the activities steps (P&ID definition, installation spatial detailed definition, installation construction, pre-commissioning, commissioning and operation at production conditions) and the milestones ordered temporary for a successful WHR system construction and commissioning.

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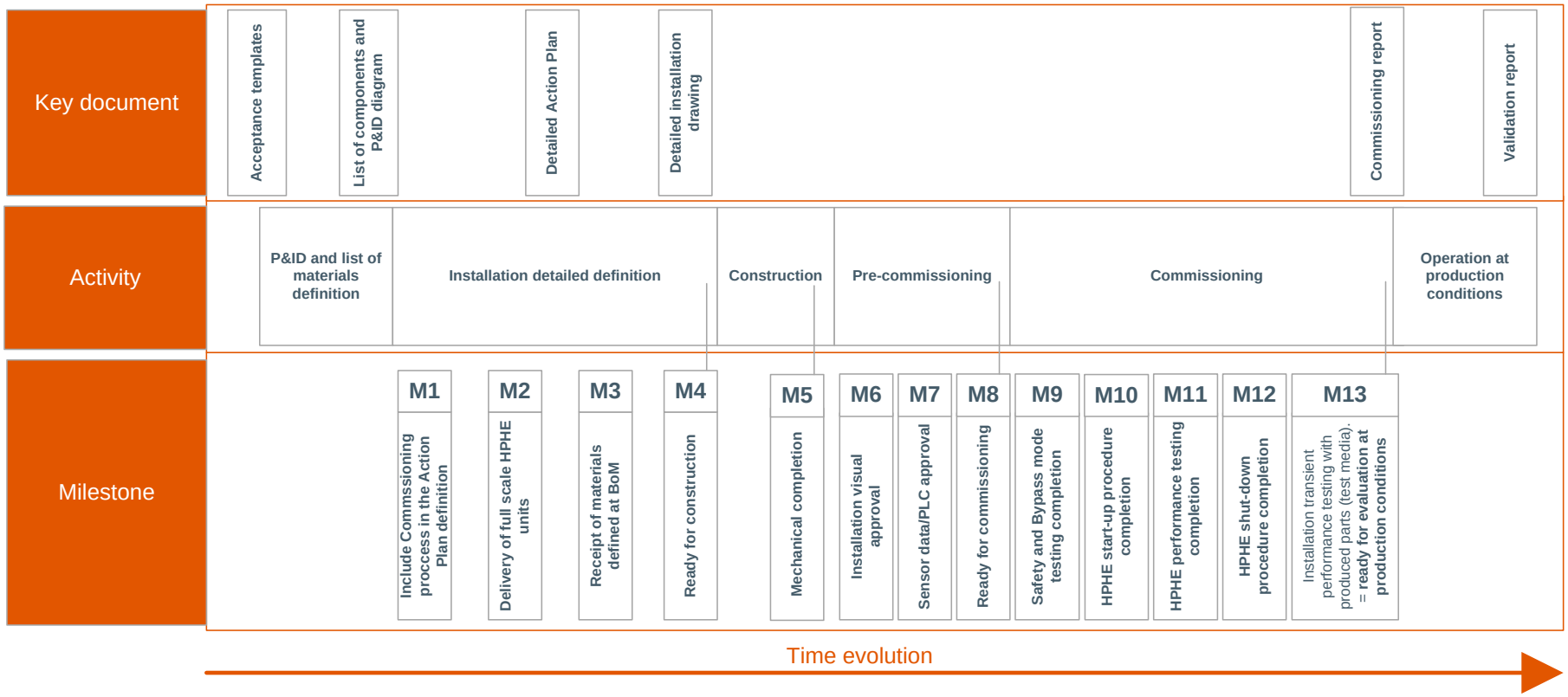

Figure 1. WHR Installation Definition, Construction and Commissioning phases: key documents and milestones [3].

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1 Definition phase

In this part the main critical success factors, the baseline performance indicators and the acceptance criteria for commissioning procedure must be identified. The acceptance criteria based on the baseline performance indicators will be compiled in a document to be used for checking the results of the commissioning procedure. The critical success factors will be used to define the WHR installation itself and to establish what WHR operation modes and how they will be needed to check.

The milestones of the plan and a checklist table to follow and reach a successful commissioning process has been defined.

1.1 Main critical success factors

The main critical factors have to be identified and be considered in advance for a successful installation commissioning definition.

The HPHE based WHR installations will be designed to comply the specific requirements of the processes where they are applied. However, there are critical factors that will be common for any HPHE based WHR installation. Those critical factors are described hereunder.

HPHE secondary stream flowing

The principle to bear in mind is that whenever the primary flow (hot side or evaporator side) is going to flow through the HPHE, the secondary stream (cold side or condenser side) must already be flowing through the HPHE. In that way the HPHE overheating is avoided. The starts-up and shut-down procedures of the installations have to be defined considering that principle.

HPHE emergency procedure

An emergency procedure should be provided to bypass the primary stream away from the HPHE in case of any failure that might occur during operation. This emergency procedure is usually based on primary stream temperature measurement at the inlet of the HPHE and the temperature of the heat pipes within the evaporator side. The heat pipes are protected against overheating to avoid internal high temperature and thereby preventing internal excessive pressure.

In case one of the water heat pipe thermocouples reaches a maximum of 290 °C **or** in case one of the Dowtherm heat pipe thermocouples reaches a maximum of 390 °C, the primary stream is diverted. Once temperature of the primary stream or the heat

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pipes goes below a specific value (380 °C for Dowtherm and 280 °C for water heat pipes) then a bypass valve returns to their common operation mode and the primary stream goes again through the HPHE. In case the bypass is activated unceasingly, then both streams' mass flow rates in addition to the inlet and outlet temperatures should be reported to the technology provider (BUL/ECON) to be analysed.

In case the primary stream driving fans or pumps stop unexpectedly the WHR system valves should be positioned to ensure a safety operation of the productive process (i.e. the exhaust fumes should be diverted through the conventional chimneys).

ETEKINA WHR system transparency for the produced parts

The production processes where the ETEKINA WHR systems is implemented must not be affected by the performance of the ETEKINA WHR system. A reversible installation may be defined to return the original operation mode in case any affection in the produced process occurs. That reversibility function needs to be quick and not halt the production process (i.e. by an emergency-stop).

Coordinated actions. Once the HPHE units are delivered, the technology provider (BUL/ECON) and the end-users put together a plan of logistics and actions considering the production process stops and running calendar; and the length and type of the commissioning tests. The HPHE will be tested during commissioning process under the supervision of the technology provider (BUL/ECON). Commissioning tests will be done by the responsible of the installation. A formal inclusion of the commissioning plan in the detailed action or plan definition of the implementation project (also known as tender document) is crucial for a successful commissioning.

Besides the above-mentioned critical factors each application must consider its own specific critical factors.

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1.2 Baseline performance indicators

The baseline performance indicators are the primary and secondary streams' flow rates and temperature values used for the HPHE design.

Additional baseline performance indicators may exist to check and to ensure that the productive processes are not altered by the WHR installation. Those baseline indicators will be specific variables of the process where WHR system is installed. For example, reference process and produced parts reference pressures and temperatures may also be baseline performance indicators.

1.3 Acceptance criteria

1.3.1 Acceptance criteria for hydraulic performance

Hydraulic acceptance will be based on the comparison of the measured primary and secondary streams' flow rates and the measured pressure drop values across the HPHE with the design values. The design flow rate and pressure drop couple represents a point in the pressure versus flow rate diagram. The obtained flow rate pressure drop pairing point will be in one of the four different relative positions shown in the following graph. For each stream it will be checked at what point the system is expected to work and at which pressure drop it is actually working.

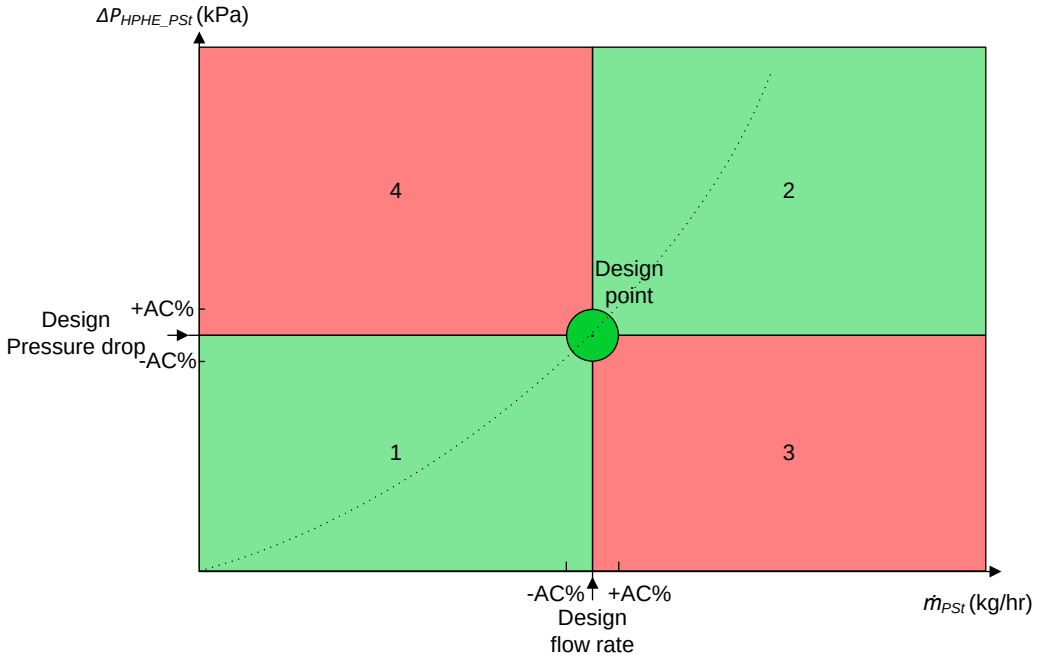

Figure 2- Pressure drop versus flow rate relative 4 positions compared to the design point ±AC, Acceptance Criteria.

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If the obtained flow rate and pressure drop values are within the hydraulic acceptance criteria of the design flow rate and pressure drop values, the HPHE is responding hydraulically as expected and the hydraulic acceptance will be completed. Otherwise, the flow rate-pressure drop pairing will be in one of the four different relative positions shown in the following graph. Each HPHE has its own design specifications designed according to each demo case requirements. The hydraulic commissioning will consist in testing and checking the real flow rate and pressure drop coupling values and comparing them with the design values. Depending of the results and according the acceptance criteria defined when the installation was ready for the commissioning, the hydraulic performance will be accepted or not. The following acceptance tables are provided to be filled by the party responsible for the installation.

Table 1- DC3 Hydraulic acceptance table

Commissioning Aspect	Design values		Measured values		Relative Position	Acceptance	Date	Signature
	ΔP (kPa)	$\dot{m}$ (kg/hr)	ΔP (kPa)	$\dot{m}$ (kg/hr)				
Primary Stream					1,2,3 or 4	YES/NO		
Secondary Stream					1,2,3 or 4	YES/NO		

Apart from the mentioned hydraulic specification, depending of the application, additional specifications may be required for the HPHE design. For example, absolute pressure maximum limits, minimum limits, etc. In the case that there are any additional specified hydraulic variables, they should be verified and included in the corresponding demo case specific hydraulic commissioning procedure.

1.3.2 Acceptance criteria for thermal performance

The HPHEs are designed based on the primary stream flow rate, its inlet temperature and the secondary stream(s) flow rate(s) and its (their) inlet temperature(s). Based on the design specifications, there is a design performance thermal power value for each demo case that will be used as a reference for thermal commissioning. However, not only the thermal power will be checked, the temperature inlet and outlets and flow rates will be evaluated and compared to the design specified values. For thermal commissioning steady performance conditions will have to be established. Once the temperature and flow rates reach a steady condition, the values measured will be compared with the design values. Once the WHR system reaches a steady performance, the values will be compared with the design points. If they are within the acceptance criteria values the thermal commissioning will be finished.

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Table 2- Common thermal acceptance table

Commissioning Aspect	units	Design values	Measured Calculated values	criteria	Acceptance	Date	Signature
T_{PSt_In}	°C				NO		
T_{PSt_Out}	°C				NO		
T_{SSt_In}	°C				NO		
T_{SSt_Out}	°C				NO		
$\dot{m}_{PSt}$	kg/h				NO		
$\dot{m}_{SSt}$	kg/h				NO		
CP_{PSt}	KJ/kgºC				NO		
CP_{SSt}	KJ/kg-ºC				NO		
$\dot{Q}_{PSt}$	kW				NO		
$\dot{Q}S_{St}$	kW				NO		

In case the inlet temperatures and the flow rates do not comply with the acceptance criteria the installation should be reviewed and adjusted. In case the outlet temperatures and transferred thermal power do not comply with the acceptance criteria the HPHE component will require a supervision of the technology supplier.

1.3.3 Acceptance results

The acceptance testing results will be collected by the party responsible for the installation of the industrial partner. The WHR system installation will be revised as many times as required until all the commissioning aspects will be within the acceptance criteria. From that moment the commissioning procedure will be completed, and the commissioning acceptance is finalised and signed by the party responsible for the installation. The evaluation period can then start.

1.4 Plan milestones and checklist table

To monitor the WHR construction and commissioning process, several milestones have been defined. These milestones are shown in Figure 1 in a chronological sequence (top to bottom). The temporary associated activities and the used/generated key documents are showed in the same level (at same temporal point or height). The first milestone is the formal inclusion of the commissioning plan in the detailed implementation project (i.e. tender or action plan). Once the installation has been implemented (Milestone M5), the pre-commissioning procedure will start focusing on the validation at component level. Once the pre-commissioning phase is achieved (milestone M8), the commissioning procedure will start focusing on the validation of the installation as a multi-components' integration. The above defined milestones will be achieved by checking several aspects of the installation. A checklist table (Table 3) has been defined to facilitate the commissioning progress.

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Table 3- Overall Commissioning Progress Checklist

Commissioning Progress Checklist			
1	Is the commissioning process included in the Detailed Action Plan?	If not	Specify tentative dates of commissioning process and include them in the Detailed Action Plan (D4.1).
		If yes	Milestone M1 achieved. Monitor the installation construction process.
2	Is the mechanical construction completed?	If not	Monitor the installation construction process.
		If yes	Milestone M5 achieved. Start with the pre-commissioning process (visual approval, reaction of each device to the control signals and sensor/transducers readings registration in the DAS).
3	Are the components installed according to the P&ID diagram?	If not	Modify the installation according to the P&ID.
		If yes	Milestone M6 achieved. Follow with the next steps of the pre-commissioning process.
4	Do the control and Data Acquisition System (DAS) read correctly the signals provided by the sensors/transducers?	If not	Review the wiring, the range, the zero adjustment, the power supply, the scale, units, etc.
		If yes	Follow with the next steps of the pre-commissioning process.
5	Do the devices (at component level) react as expected to the control signal and when they are power-on and off?	If not	Review the wiring, the power supply, the non-power position, the spinning direction, etc.
		If yes	Milestone M7 achieved. Follow with the next steps of the pre-commissioning process.
6	Is the pre-commissioning process successfully finished?	If not	Monitor the pre-commissioning process.
		If yes	Milestone M8 achieved. Start with the commissioning process.
7	Test at cold temperatures in both streams. Do the installation elements react correctly to the control/emergency-stop according to the different operation modes: primary stream by-pass, heat recovery mode (start-up and shut down), emergency stop mode, other specific modes?	If not	Review the control outputs signals (software and hardware), the wiring and the non-power position.
		If yes	Milestone M9 achieved. Start with the real HPHE start-up performance at steady temperature and flow rate conditions.
8	Are the inlet conditions (temperature and flow rate) of both streams within specified acceptance values?	If not	Review the Fans/pumps running point, the circuits pressure drops and all the possibilities to bring the installation to the specified running conditions.
		If yes	Milestone M10 achieved. Check the outlet temperatures, the transferred heat and the thermal balance.
9	Does the HPHE performance comply with the acceptance criteria?	If not	The HPHE component requires supervision of the technology supplier (BUL/ECON).
		If yes	Milestone M11 achieved. Check HPHE shutdown procedure.
10	Does the HPHE shutdown procedure successfully finished?	If not	Check how long the secondary stream should flow through the secondary circuit.
		If yes	Milestone M12 achieved. Start the commissioning procedure at primary and secondary stream transient (real) conditions.
11	Test at primary and secondary stream transient (real) conditions. Do the heat source and heat sink processes keep their original operational specifications?	If not	Evaluate how the primary and secondary flow rate and temperature variations affect the source and sink processes pressures and temperatures. Determine acceptable performance specifications.
		If yes	Milestone M13 achieved. The installation is ready for evaluation at production operating conditions.

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2 Pre-commissioning process

The pre-commissioning process is based on the verification at component level (devices and sensing elements) of the installation individually; while the commissioning process is focused on the verification at system level considering the integrated components in the installation. The pre-commissioning process focuses on checking the location and positioning of the elements, their electrical connection and control answer testing. The pre-commissioning process will start when the mechanical construction of the installation is completed (when the Milestone M5 is achieved). Within the pre-commissioning process the following verifications will be done:

1. **Inspection of piping & components layout (Milestone M6)**

Based on the list of components and linked with the P&ID diagram, all the elements, their location, the piping sizes and piping layout will be checked by a visual inspection comparing them with the P&ID diagram description. Any observed conditions not addressed by the P&ID drawing will be noted, notified and the installation will be modified. The visual inspection of the piping layout should be repeated afterwards.

2. **Air purging**

In the demo cases where there are liquid streams loops, air purging procedure will be executed by recirculation of the fluid repeatedly until there are no air presence evidences in the circuits (unexpected noises, pressure fluctuations in manometers, flow anomaly fluctuations, etc.). A visual inspection will be done to check the absence of leakages.

3. **Sensor and Data Acquisition System (DAS) commissioning**

The measured values provided by the sensors will be checked and the sensors with out of range values will be identified. The electrical signal outputs (for instance, V, mA, etc.) of those failure sensors and their conversion to the measured physical units will be verified. The temperature values of the inlet and outlet of the primary stream and of the secondary stream, ambient temperature and waste heat stream temperature will be verified and noted down. Primary and secondary streams flow rates will be verified and noted down. In case flow rates are measured indirectly by equivalent sensor signals (such as by dynamic pressure or velocity measures), their values will also be verified and noted down. Natural gas and electricity consumptions of the heat sink processes and the BOP (Balance of Plant) auxiliary components will be verified and noted down. The coherence of the values and the time step of registered values will be checked. Sensors labels and their correct position in the registered data file will be verified. If there is more than one acquisition system, their time synchronization will be

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checked. If there are clock time differences they should be adjusted for a coherent and right data cross evaluation.

4. **Electric commissioning and Programmed Logic Control (PLC) commissioning at component level (Milestone 7)**

The wiring will be checked. The power-on and power-off answer of the drivers (fans, pumps, valves, etc.) providing the feeding signal from the PLC will be individually checked. The spinning direction of pumps and fans and the variable speed actuators, in case they are, will be checked.

3 Commissioning process

The commissioning process is focused on the verification of the performance of the installation at system level as it is comprised by multiple components that interact with each other. The commissioning process will start when the pre-commissioning process is completed (when the Milestone M8 is reached). Within the commissioning process the following verifications will be done:

3.1.1 Safety and Bypass operating modes testing

The aim of this test is to verify the switch between different operation modes that are commanded by the PLC signals. The main operation modes will: the primary stream bypass and the heat recovery mode (including start-up and shutdown procedures). However additional operating modes may exist (i.e. emergency stop mode or other specific modes required by the specific application). The switch from one mode to the others will be tested. These tests will be done at cold conditions to avoid any damage due to any failure.
Once the correct switch from different modes will be verified (milestone 9 reached) the next step will be to test the different operation modes at current high temperature conditions.

Two general operating modes have been defined:

- HPHE bypass mode
- HPHE operation mode (= Heat Recovery mode= HR mode)

The bypass mode operation is designed to protect the HPHE in case of failure (or for maintenance operations). In this mode, the primary stream bypasses the HPHE and does not go through it. The heat recovery mode refers to the operating mode of the WHR system designed under ETEKINA project to recover waste heat and to use it in the heat sink processes.

Within the HPHE operation mode (Heat Recovery mode), start-up and shutdown steps must also be checked. At cold conditions, at start-up conditions, the sequence of secondary stream flow through the HPHE prior to the primary stream flow though the HPHE will be verified. In the same way, at shutdown conditions, the sequence of primary stream flow bypassing the HPHE prior to the secondary stream flow bypass will be verified.

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There will be a control switch or equivalent signal to change the operation mode from bypass mode to heat recovering mode and vice versa.

The operation modes are distinguished by the specific paths that involved streams must follow. Therefore, each operation mode will be identified by specific valves positions and specific drivers running (fans or pumps) to conduct the streams for their respective correct paths through the pipes of the installation. In this commissioning step, the valves' position and the drivers (fan, pumps, etc.) will be checked in all operating modes (in bypass mode, in HR mode, in other existed specific operation mode) commanding from the PLC the required signal to test and revise all operation modes.

Once the switch of different operating modes is verified at cold temperature conditions the milestone M9 will be reached. Afterwards, the real HPHE start-up, heat recovery and shutdown performance testing at steady temperature and flow rate conditions will be start.

3.2 HPHE performance at steady conditions

3.2.1 HPHE start up and Heat Recovery performance testing

Start-up operating mode will be activated, and the following sequence will be checked:

1. Initially only the secondary stream (at steady flow rate and at steady design temperature) will circulate through the HPHE.

2. The steady inlet conditions (temperature and flow rates) of secondary stream will be verified (Table 1 and Table 2).

   In case the flow rates are not the expected values, review the secondary stream driving fans/pumps running point, the circuits pressure drops and all the possibilities to bring the installation to the specified running conditions.

3. Afterwards the primary stream (at steady flow rate and at steady design temperature) will circulate through the HPHE.

4. The steady inlet conditions (temperature and flow rates) of the primary stream will be verified (Table 1 and Table 2).

   In case the flow rates are not the expected values, review the primary stream driving fans/pumps running point, the circuits pressure drops and all the possibilities to bring the installation to the specified running conditions.

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5. The outlet temperatures, the transferred heat and the thermal balance are checked.
6. The time it takes for the system to reach steady temperature conditions. This value shows the dynamic answer of the WHR system, that is, when the available waste energy is ready for its re-use. This information is useful to determine if a preheating operation mode may be required.

   The available waste heat and the recovery energy will be evaluated to verify the recovery of 40% sensible heat target value is reached.

7. In case the values are within the expected values the party responsible for the installation will sign the templates. The milestone M11 will be achieved and the next HPHE shutdown procedure will be tested.

   In case the performance result does not comply with the acceptance criteria the HPHE component requires supervision of the technology supplier (BUL/ ECON).

3.2.2 HPHE shutdown testing

Shutdown operating mode will be activated, and the following sequence will be checked:

8. The secondary stream (at steady flow rate and at steady design temperature) will keep circulating through the HPHE meanwhile the primary stream (at steady flow rate and at steady design temperature) will bypass the HPHE.

9. The time is measured to verify how long it takes for the secondary stream to cool down the HPHE until the Dowtherm heat pipes temperature is below 200°C, and the water heat pipe temperature is below 150°C.

10. If the HPHE is shut down successfully the milestone M12 will be reached and the next commissioning test can be started: Start the commissioning procedure at primary and secondary stream transient (real) conditions.

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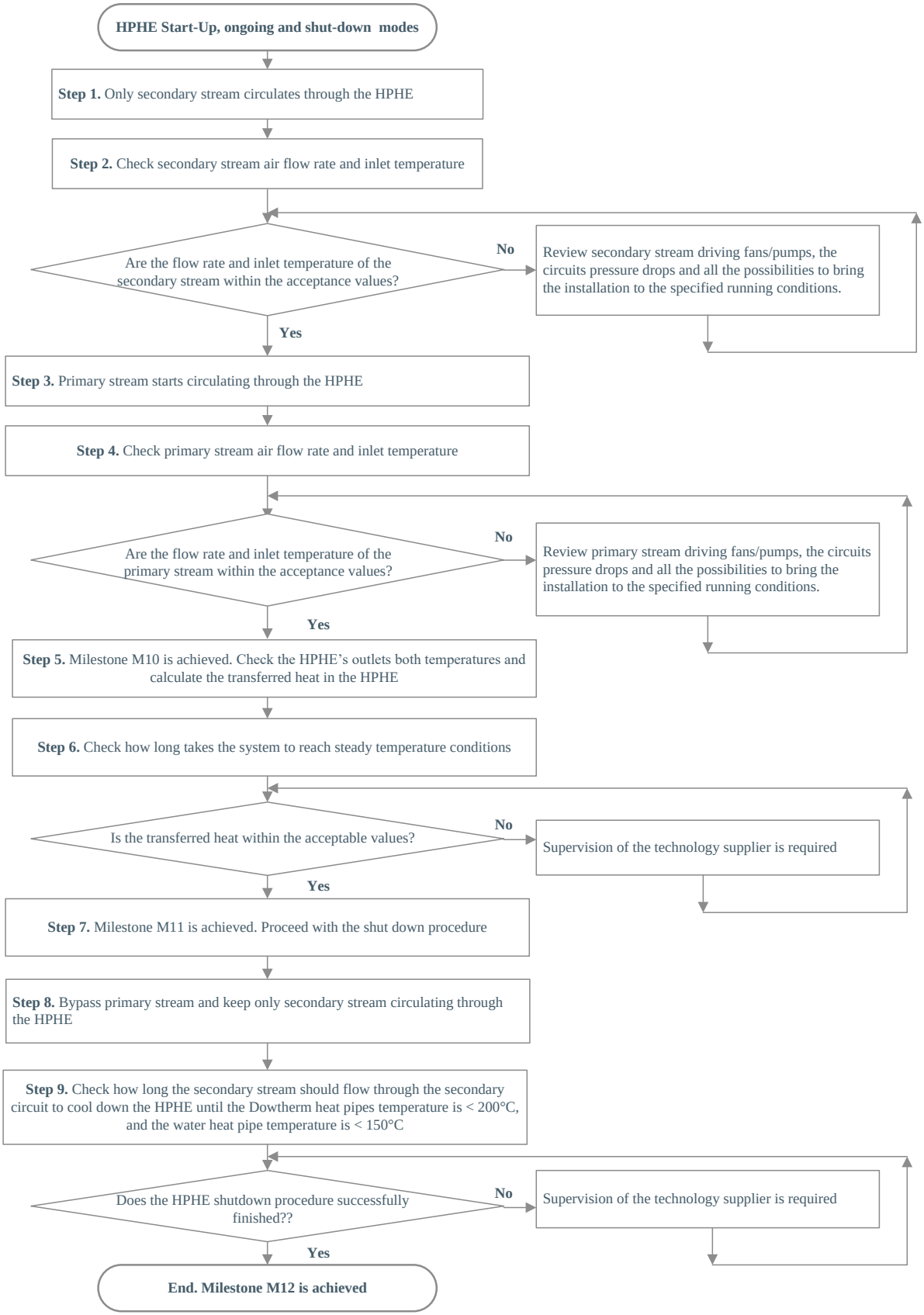

Figure 3.Flow diagram of HPHE start-up, ongoing and shut-down operation commissioning at steady conditions

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3.3 Installation transient performance testing

The heat source and sink processes involved on the WHR systems are part of dynamic productive processes with their own start-up and shutdown procedures that may not be happening simultaneously. For example, the source process where the waste heat is delivered can start at Sunday evening and the sink process where the waste heat is going to be reused can start at Sunday midnight, a bit later than the previous process. In that case there will be moments where the waste heat cannot be re-used in the sink process. However, that waste heat can be used for preheating the WHR system to overcome its inertia.

The answer of the WHR system will be affected by the waste heat availability, the inertia of the system and by the sink process's demand schedule.

In this commissioning process step, the HPHE performance in those transient conditions will be checked using test media (equivalent to the produced parts, or waste parts) and the WHR system will be validated in real operative conditions. The target of this test is to validate that involved components (HPHEs, furnaces, dryers, water loops, etc.) will be running within its safety operation temperatures and pressures ranges.

Every time the sink process demands heat, the waste heat should be available and in case not, an auxiliary heating system should provide the required heat energy to the sink process. Different situations are described in the following diagram:

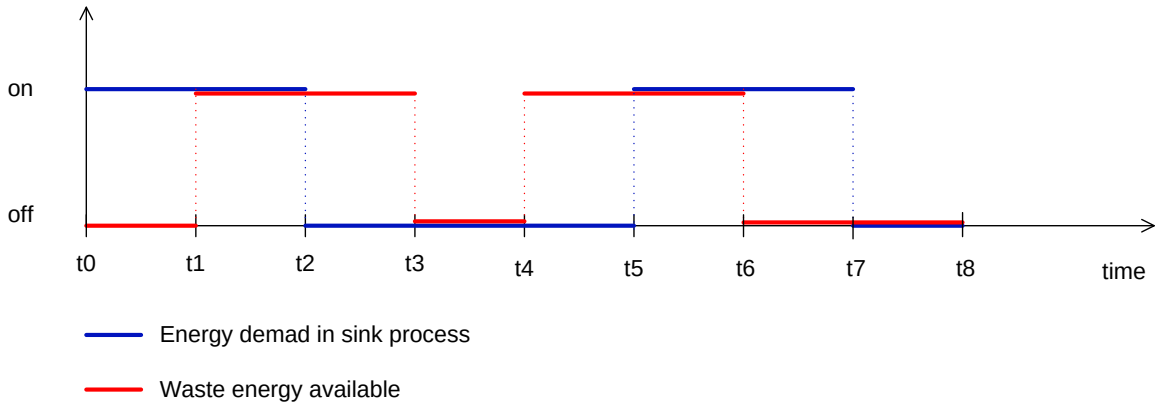

Figure 4. Different temporary situations of waste energy availability and energy requesting by the sink process

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Table 4. Required operation mode depending on the waste energy availability and requested heat in heat sink process

Time step From tx to ty (tx-ty)	Waste energy availability	Heat demand in sink process	Required operation mode
t0 - t1	No	Yes	Total bypass of HPHE
t1-t2	Yes	Yes	Start-up, preheating mode if exists, and WHR mode. If waste > demand, then evaporator partially bypassed If waste < demand, then auxiliary systems must be running
t2-t3	Yes	No	Shutdown operation mode (secondary stream circulating through the HPHE but not through the sink process -> equivalent to preheating mode if exists) and afterwards total bypass of the HPHE
t3-t4	No	No	Total bypass of the HPHE
t4-t5	Yes	No	Total bypass of the HPHE
t5-t6	Yes	Yes	Start-up, preheating mode if exists, and WHR mode. If waste > demand, then evaporator partially bypassed If waste < demand, then auxiliary systems must be running
t6-t7	No	Yes	Shutdown operation mode (secondary stream circulating through the HPHE and through the sink process). Auxiliary heating system running and afterwards total bypass of the HPHE
t7-t8	No	No	Total bypass of the HPHE

This test will last a reasonable time that includes at least one start-up and shutdown sequences of both heat source and heat sink productive processes to ensure all the transients situations described in the above Figure 4 and Table 4 are considered.
The following variables will be registered:

- the temporal evolution of the operation modes: when the heat recovery mode starts and how long it takes; when the preheating mode (if exists) starts and how long it takes; when the total by-pass mode or partial bypass is operating and how long it takes; when the emergency operation is operating (if needed).
- the temporal evolution of the temperatures and pressures of the involved components (HPHEs, furnaces, dryers, water loops, etc.) will be registered

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The analysis of that information will be used to verify that primary and secondary flow rate and temperature variations will not affect the specifications of the source and the sink processes.

In case the result complies with the acceptance values the milestone 13 will be achieved and the installation will be ready for evaluation at production operating conditions.
The commissioning process will be finished.

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