SPIRIT

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Testing Program

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Report of Contributors

	Name	Org	Role/ Title	E-mail
Report leader	Neetu Kumari	TNO	Project Manager	Neetu.kumari@tno.nl
Contributing Author(s)	K. Verplancke	MYK	Project Engineer	koen.verplancke@mayekawa-europe.com
	J. Rauø	SP	Director of Development	jaran@stellapolaris.no
	R. Christiansen	DTI	Project Manager	rech@teknologisk.dk
	E. Hannes	TIS	Business Controller	Evelyn.Hannes@raftir.be
	S. Schultze	GEA	Product Manager	Sebastian.Schultze@gea.com
	M. Kriese	DLR	Project Manager	Maximilian.Kriese@dlr.de
	C. Fleischmann	SPIL	Project Engineer	c.fleischmann@spilling.de
	L. Jurica	SKC	Operational Manager	Ludek.jurica@smurfitkappa.cz
Reviewer(s)	All consortium partners of WP2			
Final review and quality approval	S. Spoelstra	TNO	Project Coordinator	Simon.spoelstra@tno.nl

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DTI: TEKNOLOGISK INSTITUT

DLR: DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV

EHPA: EUROPEAN HEAT PUMP ASSOCIATION

MYK: NV MAYEKAWA EUROPE SA

SINLOC: SINLOC-SISTEMA INIZIATIVE LOCALI SPA

EURAC: ACCADEMIA EUROPEA DI BOLZANO

EHP: EUROHEAT & POWER

DTU: DANMARKS TEKNISKE UNIVERSITET

TVP: TVP Solar

TIS: TIENSE SUIKERRAFFINADERIJ N.V.

TLK: TLK ENERGY GMBH

GEA: GEA Refrigeration Germany GmbH

SPIL: Spilling Technologies GmbH

SKPS: Smurfit Kappa Paper Services B.V.

SKC: SMURFIT KAPPA CZECH SRO

SP: STELLA POLARIS AS

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Executive Summary

Project Information

The SPIRIT project will implement three full-scale (> 0.7 MWth) demonstrations of heat pump technologies integrated at three different process sites in the paper & pulp and food & beverage sectors with sink temperatures between 135°C and 160°C. A successful demonstration of the SPIRIT project will ensure that industrial heat pump technology for high-temperature applications reaches TRL 8. The details of the three demonstration sites are as follows:

Demonstration 1 (SP-MYK-TNO)

- End-User: Stella Polaris – Norway
- Technology supplier: Mayekawa Europe
- Supporting knowledge and innovation center: TNO

Demonstration 2 (TS-GEA-DTI)

- End-User: Tiense Suiker – Belgium
- Technology supplier: GEA Heating and refrigeration technologies
- Supporting knowledge and innovation center: DTI

Demonstration 3 (SK-SPL-DLR)

- End-User: Smurfit Kappa – Czech Republic
- Technology supplier: Spilling Technologies
- Supporting knowledge and innovation center: DLR

Document Purpose

The purpose of this document is to define test program for the demonstrations in close collaboration with the end-users and technology providers for each SPIRIT demonstration. This program will include the conditions under which the heat pumps will operate (experimental program), both static and dynamic. It is provided to all relevant partners for the specification and definition of the minimum requirements for the works.

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Document Scope

This document aims to cover in detail the test program conditions (steady state and dynamic) under which the heat pumps will operate for each SPIRIT demonstration. The specific program will depend per demonstration site. Two measurement campaigns are envisioned. These relate to short term variable operation (within the specific site possibilities) and a long-term stable operation. The first testing campaign will consider multiple conditions and transient operation (including start-up and shut-down). The second measurement campaign focuses on long-term monitoring of the system. These campaign consists of multiple measurement periods.

ABBREVIATIONS AND ACRONYMS

COP: Coefficient Of Performance

HEX: Heat Exchanger

HP: High Temperature Heat Pump

HT: High Temperature

HTHP: High Temperature Heat Pump

IHX: Internal Heat exchanger

MT: Medium Temperature

MTHP: Medium Temperature Heat Pump

PCV: Pressure Control Valve

SPF: Seasonal Performance factor

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1. DEMONSTRATION 1 STELLA POLARIS, MAYEKAWA, TNO

1.1 General Information

1.1.1 Demonstrator

The annual production is around 5000 mt cooked and peeled prawns based on a total volume of 12,500 mtons of raw material (raw shell-on prawns). The current energy supply of steam for the entire production is a Propane boiler with estimated yearly fuel consumption of approximately 9,000 MWh, corresponding to around 2,600 ton of CO_2/year. Stella Polaris aims toward a climate-neutral production; consequently, they have joined the SPIRIT project.

The goal is to demonstrate a cascaded high-temperature heat pump with two stages consisting of an ammonia cycle (low stage) and pentane cycle (high stage). The low stage is based on piston compressor technology, whilst the high stage is based on screw compressor technology. The heat pump takes up waste heat from the existing refrigeration plant and produces heat in the form of steam to be used in the process. The high stage heat pump will supply steam at a temperature around 145°C with a capacity of ~700 kW at design conditions. The heat produced is able to cover the full demands of the process under normal operating conditions and therefore offsets the need for steam produced from the fossil fuel-based boiler, electrifying the prawn cooking production processes of Stella Polaris. The technology provider for this demonstration case is Mayekawa, an experienced manufacturer of customized heat pumps for optimized efficiency and a wide range of temperature and capacities.

1.2 Preliminary Testing Program

The preliminary test program for the demonstrations is defined in collaboration with the end users and technology providers. This program includes the short-term and long-term operations under which the heat pumps will be subjected, and their performance monitored.

The measurement campaigns consist of two types covering **short-term** variable operation and **long-term** stable operation. The first is intended to evaluate the performance of the system under dynamic operation and/or to evaluate the optimum operation settings of the heat pump. With the second type of test the long-term

performance of the heat pump will be defined. In addition, faults of components due to degradation, etc., can also be identified.
This testing program is planned in a manner that Stella Polaris process plant is not affected in any way that could have an impact on the product and/or in its standards.

The program includes different source heat conditions but one single sink temperature condition. Any variations of the conditions on the sink side can directly impact the steam network, which is part of the Stella Polaris process.

- Short term tests
  - Ramp-up/down – during start and stop of the HP (msec intervals)
  - IHX optimization – variations in intermediate heat exchanger saturation temperatures.
  - Compressors rpm – variation of both compressors rpm
  - Steam pressure – variation of steam pressure (preferably for higher values than SP process requires)
  - Oil temperature – temperature will be set by Mayekawa during commissioning.
- Long term tests
  - Operation for 2000 – 3500 hours
  - Oil sampling
  - Other.

Short term tests

The short-term testing will cover a variety of investigations of the heat pump and process integration: (1) transient operation, (2) intermediate heat pump loop optimization, and (3) part load operation.

The transient operation will be achieved during start-ups/shutdowns. The main parameter that can variate is the speed of the compressors. With this method, the cooling and heating capacity can vary depending on the circumstances to provide the optimum operating performance.
Variation of the speed of the compressors:

- Ammonia compressor speed ranges from 750-1450 rpm with an operating speed of 1070 rpm and a (cold) start-up speed of 750 rpm.
- Pentane compressor speed 1500-3600 rpm with an operating speed of 2500 rpm and a (cold) start-up speed of 750 rpm.

Another short-term test that will be investigated is optimizing *the intermediate cycle*. Within the intermediate cycle with ammonia (medium temperature heat pump), certain degrees of freedom do not depend on the heat source and heat sink, allowing

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optimization. For instance, the condensing temperature of the ammonia heat pump could be varied (the nominal design was set to 82ºC). As a consequence, the evaporating temperature of the high-temperature heat pump will also be varied. The range of condensing temperature of the intermediate cycle will be set between 75ºC and 90ºC (only possible with elevated heat source temperature). The optimization aims to find the performance optimum of the cascade heat pump.

The *part load operation* will be limited, given that the heat pump is highly dependent on the ammonia refrigeration plant and the steam network. Still, some available opportunities for operation outside the nominal point are available:

Testing condition range - Heat source side:

The heat source is defined by the NH_3 refrigeration cycle from the existing cooling system. Therefore, the temperature is also defined by this loop. On the heat source side, very limited controlled variations of the operating conditions can be performed.

Testing condition range - Heat sink side:

If the steam boiler (gas) is operated in parallel with the Heat Pump, then the heating capacity in the sink side of the HTHP can be variated. This could be done by changing the speed of the compressors. When this happens, the flow rate of both loops (MT, HT) changes. This could affect the approach temperatures in the source and sink heat exchangers.

The heat sink is the steam generation driven to the Prawn cooker. The Prawn cooker requires to maintain its internal temperature at approx. 100 ºC. This is achieved by the pressure and temperature maintained within the Prawn cooker. A PCV controls the pressure of the steam at the steam outlet of the Prawn cooker. For the heat pump side, the steam pressure is controlled by another PCV, which is set at the required pressure of the steam network (3.2barg).

Other testing parameters:

- Variation of the rpm of the compressors. This will result in changes in thermal capacity, intermediate cond/ev temperature, mass flow rate, and ΔT in the heat exchangers. This can also give a curve of the compressors' performance. (I.e., volumetric and isentropic efficiency of the compressor)
- Variation of the oil cooling temperature, which is recovered in the steam loop. This modification will affect the steam loop.
- Variation of steam pressure via the steam pressure control valve (PCV). By changing the set point of the pressure control valve.

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Long term testing

The nominal conditions will be used for the long term. The operating conditions are set by the heat supply in the refrigeration plant and requirements of the Stella Polaris process (refrigeration plant of NH3 and steam loop).

The nominal conditions are set as follows:

- Steam network:
  - Supply at 145°C
  - Heating capacity 600 kWth (950 kg/hr steam production)
- Ammonia refrigeration plant
  - Source at 18°C
  - Heating capacity 290 kWth

For long-term testing operation, the heat pump will run for between 2000 to 3500 hours per year. The maximum operating hours of the Stella Polaris process is of around 3600 hours. The aim is to investigate the system performance over a longer period of time, checking in detail the performance, compressor lubrication, etc.

Methodology of testing

A statistical method will be used to establish if a stable operation was achieved. Several statistical quantities that can provide insights into the stability of the process are:

- The average value of the measurements over time, which we call the arithmetic mean.
- The variance, which tells us how much the measurements differ from the average.
- The coefficient of variation is the ratio of the variance to the average value.

A lower value of the coefficient of variation means that the data is more stable. In simple terms, it tells us if the measurements are close to each other or spread out.

Results and data analysis

Heat pump

- Heating capacity (nom, max)
- Cooling capacity
- COP
- SPF
- Annual power consumption
- Annual stand-by power consumption

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Compressor

- Isentropic efficiency
- Volumetric efficiency
- Overall efficiency

2. DEMONSTRATION 2 TIENSE SUIKER, GEA, DTI

2.1 General Information

2.1.1 Demonstrator

Tiense Suikerraffinaderij is a sugar producer with a history dating back 180 years. They have production plants located in both Belgium and the Netherlands, and they are in turn owned by the German sugar producer Südzucker AG, which has plants located all throughout Europe. The production of sugar is a quite energy intensive process, as it requires the sugar from the sugar beets to be dissolved in water, and later for that water to be evaporated to crystallize the dissolved sugar. The process implemented by Tiense is made more efficient by running the same steam through 8 evaporators in series that operate at decreasing pressures, with the final three evaporators operating under a vacuum. The Spirit project is focused on the plant located in Tienen, where the steam is generated by a boiler that consumes fossil fuels, primarily natural gas.

The Tienen plant operates two different production campaigns, the beet campaign and the thick juice campaign. The beet campaign is the main production campaign, where the sugar is extracted directly from the beets and crystallized during the evaporation process. However, some of the sugar does not crystallize during the beet campaign but remains in a thick intermediate product called the 'thick juice'. The thick juice campaign is thus the production campaign where this intermediate product is evaporated to crystallize the remaining sugar. This usually only requires two of the evaporators. The average steam consumption for the beet campaign is 110 T/h and lasts from September to January (130 days). For the thick juice campaign, the average steam consumption is 80 T/h and it lasts from end March to start May (around 45 days).

The goal of this demonstration case is to divert 4 MW of capacity from the boiler and instead deliver this energy via a high temperature heat pump. The heat pump will draw heat by condensing the low-pressure steam that exits the last evaporator and deliver it back to the system by evaporating pressurized water and piping the resulting steam into the first evaporator. The heat pump is based on a GEA screw compressor, and the chosen refrigerant is R-601 (n-Pentane).

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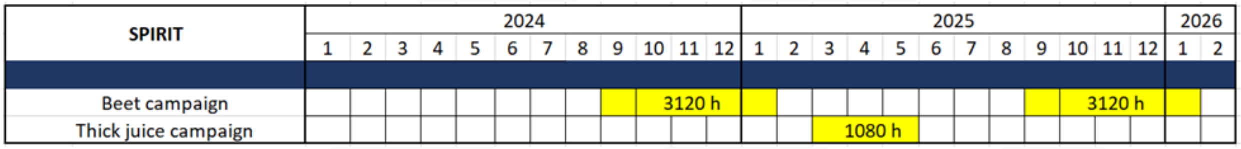
2.2 Preliminary Testing Program

This document describes the overall idea and plan for the test program of the High Temperature Heat Pump (HTHP) that is to be installed at the Tiense sugar plant, as part of demo case 2. The test program will be executed after the commissioning phase of the HTHP. This chapter describes the overall intended test program, and will be planned in more details before the commissioning of the heat pump.

Testing of the HTHP installed at the Tiense sugar plant requires that a production campaign is ongoing. This is because there are no plans for integrating separate piping for the HTHP such that it can perform tests independently of the plant. Testing is thus limited to the two annual production campaigns: the thick juice campaign and the beet campaign. The duration of each campaign is shown in Figure 1.



SPIRIT	2024												2025												2026	
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2
Beet campaign									🟨	🟨 3120 h	🟨	🟨	🟨								🟨	🟨 3120 h	🟨	🟨	🟨	
Thick juice campaign															🟨	🟨 1080 h	🟨									

Figure 1: The duration of each campaign

The two production campaigns have separate operating conditions, as shown in Figure 2.

Operating conditions for campaigns	
Thick juice campaign	**Sink side, steam evaporation temp.: 114 °C** **Sink side, steam pressure: 1.7 bar (a)** **Source side, steam condensation temperature: 76 °C** **Source side, steam pressure: 0.4 bar (a)**
Beet campaign	**Sink side, steam evaporation temp.: 138 °C** **Sink side, steam pressure: 3.6 bar (a)** **Source side, steam condensation temperature: 76 °C** **Source side, steam pressure: 0.4 bar (a)**

Figure 2: The two production campaigns have separate operating conditions

The planned tests are divided into the categories described below.

- Continuous operation at operating conditions in order to determine the heating and cooling load, heat losses and COP. This includes:

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  - Operation during the production campaigns – max. heat pump capacity for as long as possible (when other parts of the test program is not being made).
  - Operation at part load – variation of heat pump capacity (50-100 %).

- Startup and shutdown tests:
  - Startup test – determine startup-HEX flow/temp requirements & potential issues with the startup process.
  - Shutdown test – determine time needed to shut down and potential issues with the shutdown process.

- Off design tests: Determine the heating and cooling load and COP.
  - Beet campaign sink pressure – variations of sink pressures higher than operating pressure
  - Thick juice campaign sink pressure – variations of sink pressures higher than operating pressure.

- Dynamic behavior tests:
  - Compressor speed – vary compressor speed and measure response
  - Receiver level – vary level setpoints and measure response.
  - Sink condensate level – vary level setpoints and measure response.
  - Source condensate level – vary level setpoints and measure response.
  - Compressor oil temperature – vary temperature setpoints and measure response (for rotor injection oil, not oil for bearings).

- Oil sampling:
  - Oil samples are taken throughout all operations of the HTHP to monitor its quality and to discover potential issues. Reference sample to be made just after start-up of the compressor.

- Noise level:
  - Sound measurements to be done in order to validate requirements is met.

- Refrigerant flow
  - Clamp-on flow meter will measure refrigerant flow rates to give more datapoints to model the system with (as a digital twin).

- Optimization:
  - Oil temperature – reduce cooling of oil if possible (to reduce heat losses).
  - VI slider – determine optimal VI slider position.

  - Working fluid condensation temperature – determine optimal temperature/pressure.

Limits on test conditions

Testing of the HTHP is limited to some extent by the conditions that are possible to achieve in the Tiense process.

On the source side the temperature and pressure are fixed, as the source is vacuum steam returned from the end of the process, and there is no possibility of regulating this.

The sink side conditions are also partly dictated by the process, but a pressure control valve is intended to be installed after the HTHP, such that a sink pressure higher than the process can be achieved. A lower sink pressure than the operating conditions described in Figure 2 is not foreseen. The maximum steam pressure to be tested is unknown but is dictated mainly by factors related to the HTHP, such as safety valve release pressure, performance of the HTHP at elevated condensation pressures, etc. Since the condenser/sink generates steam, increasing the sink pressure also increases the outlet temperature of the sink steam, because the evaporation temperature increases.

The compressor is limited in speed from 1500 to 3600 rpm.

Part load tests are possible within a wide range because the HTHP will only supply a fraction of the total heat demand of the process. This means that the sink and source flows are separate (running in parallel) from the main process flows, and as such the flows can be adjusted to the output of the HTHP.

Methodology of testing

A definition of 'steady state' must be made with respect to the allowable variance of the measurement parameters. This will likely depend on how steady the boundary conditions are, i.e.. the sink and source flow rates, the temperatures, and the pressures. All tests will require that the measurement parameter has reached steady state before the measurements can be considered valid for the given test conditions.

Results and data analysis

Heat pump:

- Heating capacity (max, part load)
- Cooling capacity

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- COP
- SPF
- Annual power consumption
- Annual stand-by power consumption
- Optimal settings of HP parameters (oil temp., slider pos., condensing temp., etc.)
- Noise levels

Compressor:

- Isentropic efficiency
- Volumetric efficiency
- Overall efficiency

3. Demonstration 3 Smurfit Kappa, Spilling, DLR

3.1 General Information

3.1.1 Demonstrator

Smurfit Kappa is a producer of corrugated packaging. The site of the demonstrator partner is located in the Czech Republic where 74.5 kton of product is being produced every year. One step in paper production is the drying process, which is accomplished by utilizing steam in order to heat the drying cylinders. Currently, the steam is generated by using a boiler fired by natural gas (95%) and biogas (5%). The amount of CO_2 released by this process refers to 19 kton per year. Smurfit Kappa aims to decrease the amount CO_2 emission, and therefore, their dependency on carbon-based fuels. As a consequence, the implementation of an industrial heat pump serves their ambition.

Given the needs of the demonstrator plant, Spilling has been selected to be the technology supplier. Spilling technologies is a well-known producer of steam piston compressors for large, tailor-made machines which are suitable for temperatures exceeding 160°C. In the scope of the SPIRIT project, Spilling has the ambition to develop standardized steam compressor units aiming for a smaller and containerized unit which can be produced in series. The compressor which will be integrated into the production process is a four-cylinder piston compressor which delivers high-pressure steam at 6 bara and 159°C. The low-pressure steam leaving the drying cylinders is guided through the compressor and refed to the process.

3.2 Preliminary Testing Program

This document describes the overall idea and plan for the test program of the High Temperature Heat Pump (HTHP) that is to be installed at the Smurfit kappa's paper production plant, as part of demo case 3. The test program will be executed after the commissioning phase of the HTHP. The preliminary test program for the demonstrations is defined in collaboration with the end users and technology providers, which defines the measurement series for the demonstrator 3.

- In general, 2000 operating hours should be achieved in a year

  - operating 24h – 7 days a week that correspond to 83,5 days
- Based on the 3-week maintenance interruption

<u>Measurement series</u>

- Nominal load operation
  - Mass flow rate of around 600 kg/h
  - In total 1000 operating hours → will be our main case
    - let's assume three campaigns of three weeks each
  - Will be our main case → just to see how everything works together
- Part-load operation
  - Mass flow rate varies from 250 – 1000 kg/h
  - In total 600 operating hours
    - let's assume two campaigns of three weeks each
  - $P_{el} = f(\dot{m})$
    - electrical power demand / COP as function of steam flow rate from around 250 to 1.000 kg/h (suction side)
- Variation of compressor inlet pressure
  - Variation of inlet pressure possible between 0,8...1.5 barg
  - Variation of outlet pressure possible between 5 barg...5,5 barg
    - The required amount of condensate will be an interesting parameter
  - @ nominal mass flow rate & @ mass flow rate from of 250 and 1.000 kg/h
    - In total 600 operating hours
      - let's assume three campaigns of three weeks each
      - 200 hours each case
  - $P_{el} = f\left(\frac{p_{out}}{p_{in}}\right)$
    - Electrical power demand / COP as function of compression ratio
- Verification of the regulation behavior (accuracy and speed) of the compressor for p(in)-controlled operation and fluctuating p (in)
  - In total 600 operating hours
    - let's assume two campaigns of three weeks
- Which amount of condensate needs to be injected dependent on the load condition with respect to the desired degree of overheating
  - In total 300 operating hours
    - let's assume one campaign of three weeks