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\(^1\) Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

\(^2\) The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: [http://europa.eu/abc/symbols/emblem/index_en.htm](http://europa.eu/abc/symbols/emblem/index_en.htm) logo of the 7th FP: [http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos](http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos)). The area of activity of the project should also be mentioned.
EXECUTIVE SUMMARY

FOUNDENERGY, “Waste Heat Recovery Power Generation Based on ORC Technology in Foundry Industry” is a FP7 project within the funding scheme Research for the Benefit of Specific Groups with the participation of the following SME-AG, SME and RTDs: Fundación Tecnalia Research & Innovation (Spain), as project coordinator, Croatian Chamber of Economy (Croatia), Svenska Gjuteriföreningen (Sweden), Foundry Association of the Basque Country and Navarre (AFV), HRS Heat Exchanger S.L.U. (Spain), Presika d.o.o. (Croatia), EPSCO S.R.L. (Italia), Greenbank Terotech Ltd. (UK), Novamina Innovative Technology Center (Croatia), The UK Materials Technology Research Institute (UK), P.P.C. Buzet d.o.o. (Slovenia) and European Investment Casters’ Federation (UK). Foundenergy has been conceived to reduce the energy consumption of the Foundry Industry, an energy intensive sector that accounts for about 4% of total EU energy consumption.

Nowadays, only half of the energy input to gas fired melting furnaces in foundries is absorbed by the material in its melting process, while the rest is lost through different paths. Among these, flue gases constitute the most important path of waste heat with more than 75% of the total energy loss. Due to the growing price of energy and the more restrictive legislation around greenhouse gases emissions, foundries are making big efforts in recovering the waste heat from these flue gases.

Some foundries have already installed recuperators to recover part of the heat carried by the exhaust gases. This heat is currently either used to preheat the raw materials or to preheat the incoming air of the combustion process. Foundenergy project wanted to go one step ahead and introduce a solution that has been already used in other energy intensive industries such as cement manufacturing industry. This solution consists in the use of a low temperature cogeneration system based on the Organic Rankine Cycle (ORC) process to transform the recovered thermal energy into electrical energy.

The heat recovered from the flue gases of the furnace must be transferred to a fluid that can activate the evaporator of the ORC turbogenerator. For this transfer a heat exchanger is needed. The aggressive environment encountered in foundries flue gases, with heavy dust contents, makes the pipes to need a high wear and corrosion resistance. Foundenergy project has worked in the development of a protective coating for steel plain pipes that increases the life of these parts and reduces their maintenance.

The solution developed in this project could be especially useful for the European investment casting industry which is a very energy intensive industry. An average of 55% of the total energy consumed is used in the melting process and more than half of this is lost through the flue gases so it could be recovered and transformed into useful electrical energy by the developed system, contributing to increase the competitiveness of a sector that is facing the threat of USA and China in the last years.
SUMMARY DESCRIPTION OF THE PROJECT CONTEXT AND OBJECTIVES

This project aimed to significantly improve the competitive position of the SME foundry members within the SME-AG partner Svenska Gjuteriföreningen (SG, Swedish foundry association), the Foundry Association of the Basque Country and Navarre (AFV) and the Croatian Chamber of Economy (CCE, with its Association of metalworks in Croatia that is including all foundries), by significantly cutting their operational and energy costs. At the same time they could benefit from the exclusive position to produce, commercialise and control the exploitation of an innovative cutting edge technology into the EU and worldwide markets.

Generally, the EU casting industry is dominated by SMEs, and the FOUNDENERGY project partners SME-AG, AFV and SG SME membership is above 60%, while the CCE passes over 90% of SME membership. In forges and foundries the main energy requirement is the need for large quantities of thermal energy for heating or melting of the product. In gas and coke powered furnaces waste heat is generated in a process of fuel combustion, and once the product has been melted the waste heat is then “dumped” into the environment, even though it could be reused for some useful and economic purpose. The essential quality of the heat is not the amount but rather its value or grade. The strategy of how to recover this heat depends in part on its temperature and on the overall economics involved. Large quantities of hot flue gases are generated from Boilers, Kilns, Ovens and Furnaces. The most significant waste heat source in foundry plants is from kiln furnaces and cupola furnaces. If some of this waste heat could be recovered and reused, a considerable amount of primary fuel could be saved. Precisely, waste heat in this industry comes from the gas fired firing kilns used to pre-heat investment moulds as well as from firing kilns in the supply industry to manufacture ceramic cores.

By deploying innovative and reliable technological solutions energy costs could be decreased and environmental pollution reduced. The most promising solution today would be the use of reliable low temperature cogeneration technologies based on the Organic Rankin Cycle (ORC) process and customization for waste heat recovery and electrical energy production in the Foundry industry. The thermal efficiency improvement of the mentioned process is 20% in comparison with other conventional waste heat power plants that utilize the heat potentials like those available in a Foundry plant. The EC is investing large sums of money in Renewable Energy sources to increase the overall efficiency of technology, improve their cost benefit effects and gradually reduce incentives on renewables. The future landscape of European energy demand and supply will have to make much greater use of new renewable energy sources and focus more upon energy-efficient methods to reach the goals appointed by the European commission - Sustainable Energy Europe. New distributed energy conversion technologies are required to utilize sustainable energy resources suitable for power generation without causing environmental pollution. Therefore, we will work on a product that will remain profitable even with future lower electricity energy tariffs through incentives, resulting with estimated benefit and savings.
for the SME-AG members for each year/foundry of about 170,000€ per year with additional 600 tons of CO₂ savings per foundry each year.

The **strategic overall objective** of the project was to develop a cost effective and low maintenance Waste Heat Recovery system for Power Generation in the Foundry Industry. The designed Waste Heat Recovery system (WHRS) has been based in the ORC process, primarily attached to the waste heat sources within the foundry plants, ultimately to produce electrical energy and sell it directly to the power grids or use it for internal consumption purposes. One of the secondary outputs of this system is also the production of hot water for various purposes and needs, including preheat of smelting components or housing hot water supply.

The most demanding task of the project has lied in the development of the Waste Energy Recovery Boiler (WERB) that was able to efficiently operate in the highly demanding and aggressive conditions of Foundry plant exhaust gas stream. Highly corrosive and oxidizing nature and occasional abrasive dust content of some of its constituents make this a very demanding environment for reliable WERB operation. It was needed to develop and design an overall Waste Heat Recovery System (WHRS) optimized for foundry processes and design customized condenser plant. The integration of the WERB in an existing Foundry plant, process line and interface with ORC plant in overall WHRS unit was another technology challenge. For safe, reliable and optimal working, guidance and control for such a complex system was also an unavoidable task.

Project has been expanded by three conceptual approaches in WERB and WHR systems development:

- Improved Shell & Tube concept (Figure 1a).
- Novel Heat Recovery concept based on Heat Pipe principle (Figure 1b).
- Serpentine bundle concept (Figure 2).

![Figure 1. (a) Conventional shell & tube heat exchanger and (b) heat pipe concept.](image-url)
Based on already gained knowledge by consortium partners and further R&D activities, the following innovative solutions wanted to be developed and implemented:

- Waste Energy Recovery Boiler (WERB) along with wear resistance pipe materials development and WERB design, construction, optimization and validation.
- Design of an integrated Waste Heat Recovery system for power production optimized for Foundry processes.
- Advanced Control and Guidance System.
- Operational Integration and Optimization of WHRS prototype and the ORC system in the Foundry plant.

Within this project a number of SMART-oriented scientific and technical objectives were set. Project objectives are summarised in Table 1.

**Table 1. Scientific and technical objectives of the Foundenergy project**

<table>
<thead>
<tr>
<th>Scientific Objectives (SO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall SO - research of novel cost effective solutions for the heat exchanger pipes in temp. range 200-1100 °C and life span of 15 year, to meet Foundry furnaces operating conditions</td>
</tr>
<tr>
<td>SO1 - research and development of the wear resistant material/alloy solutions for the heat exchanger pipes:</td>
</tr>
<tr>
<td>• to ensure strong chemical and thermal resistance</td>
</tr>
<tr>
<td>• that allowed the maximum level of heat transfer</td>
</tr>
<tr>
<td>SO2 - research of cost effective method/process of heat exchanger pipes material/alloy coating coherent to SO1 outcomes.</td>
</tr>
</tbody>
</table>
Technical Objectives (TO)

TO1 Develop, design and manufacturing of Waste energy recovery boiler (WERB), prototype that will operate and resist at the very demanding foundry melting plants with lifetime over 15 years

TO2 Design a Waste heat recovery system (WHRS) for power generation that will be capable to efficiently operate in foundry process conditions with net efficiency higher than 12%

TO3 Develop an advance guidance and control system

TO4 Assembly and integration of WHRS in foundry plant primary process with ORC turbo generator

Expected final results and potential impact and use

The expected final results and their potential impact are summarised in the following table:

Table 2. Expected final results and their potential impact

<table>
<thead>
<tr>
<th>Result</th>
<th>Description</th>
<th>Industrial application</th>
<th>Exploitation strategy</th>
<th>Degree of novelty/innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protective coating</td>
<td>Heat exchanger novel coating alloy</td>
<td>Foundry industry</td>
<td>Ownership</td>
<td>Very High</td>
</tr>
<tr>
<td>WERB</td>
<td>Novel design of shell and tube heat exchanger</td>
<td>Foundry industry</td>
<td>Ownership</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Novel design of heat pipe</td>
<td>Foundry industry</td>
<td>Ownership</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Novel design of serpentine bundle heat exchanger</td>
<td>Foundry industry</td>
<td>Ownership</td>
<td>High</td>
</tr>
<tr>
<td>Control system</td>
<td>Advanced guidance and control system</td>
<td>All</td>
<td>Ownership</td>
<td>Very High</td>
</tr>
<tr>
<td>WHRS</td>
<td>Integrated prototype plant</td>
<td>Foundry industry</td>
<td>Ownership</td>
<td>Very High</td>
</tr>
</tbody>
</table>

The address of the project public web site: [www.foundenergy.eu](http://www.foundenergy.eu)
SCIENTIFIC & TECHNOLOGICAL RESULTS

1) Protective Coatings

Novel coatings for heat exchanger pipes based on metallic alloys, ceramics and composites were investigated for increased life performance and better resistance to corrosion and wear, under harsh foundry exhaust gas conditions. Coating materials were selected based on their heat transfer coefficient and thermal expansion characteristics that will match the characteristics of substrate material. Eighteen different combinations of substrate-coating were selected for performance testing under high temperature, chemical resistance, mechanical properties and thermal cycling characteristics. Saint Gobain Iron foundry facility in Melton Mowbray, kindly provided us permission for investigating the performance of substrates and coated pipes under actual flue gas conditions. Chemical resistance of the substrate-coating combinations were measured under accelerated acidic and alkaline conditions. Nanoindentation was used for measuring the surface hardness and modulus of the samples. Thermal cycling of the samples was also tested to investigate the thermal stress cracking resistance. Finally, surface morphology and change in elemental composition were tested using SEM and EDX measurements.

The first requirement when selecting the candidate substrate and coatings was to understand the operational regime of the proposed foundry site, especially the operating temperature range and the flue gas compositions. Eighteen different combinations of coatings and alloy substrates with different material properties were selected for the initial phase of testing as shown in Table 3. The selected materials were tested in foundry conditions to evaluate the performance of wear and corrosion resistance under high temperature. This method gives the opportunity to assess the compatibility of coatings and substrates. Variations in the thermal expansion of the substrates and alloys cause a build-up of stress during thermal cycling of the foundry plant, which will damage the coating. The effect of corrosion and wear performance will require long term exposure to the foundry conditions that can provide a quantitative estimate of the life cycle performance of the heat exchanger pipes.

<table>
<thead>
<tr>
<th>Coatings</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stainless steel</td>
</tr>
<tr>
<td>Alumina</td>
<td>X</td>
</tr>
<tr>
<td>Cr3C2 - NiCr</td>
<td>X</td>
</tr>
<tr>
<td>Chromium aluminium nitride</td>
<td>X</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>X</td>
</tr>
<tr>
<td>Stellite 6™</td>
<td>X</td>
</tr>
<tr>
<td>Tribaloy™</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 3: Different substrate and coatings combination selected for performance testing
Four different coating techniques were used depending on the selected coating material (Table 4).

**HVOF:** This technique encompasses a variety of processes whereby high pressure, high flow-rate fuel is continuously combusted with a high pressure oxidant within a combustion chamber, at pressures higher than atmospheric. The high temperature combustion gases (2750-2920°C) expand supersonically down a cooled nozzle at speeds approaching 2000 m/s. The coating material in powder form is entrained in a carrier gas and fed into the high temperature, high velocity gas stream. In a similar manner to the D-Gun, confinement of the combustion gases and entrained powder within the nozzle generates rapid particle heating and acceleration, with particle speeds up to 600-800 m/s achieved in some systems. The high particle impact velocity, combined with the low degree of mixing with air and low combustion temperature relative to plasma spraying, results in very dense, low oxide content coatings.

**PECVD:** CVD may be defined as a technique in which a mixture of gases interact with the surface of a substrate at a relatively high temperature, resulting in the decomposition of some of the constituents of the gas mixture and the formation of a solid film of a metal or compound on the substrate. CVD system includes a system of metering a mixture of reactive and carrier gases, a heated reaction chamber, and a system for the treatment and disposal of exhaust gases. The gas mixture (which typically consists of hydrogen, nitrogen, or argon, and reactive gases such as metal halides and hydrocarbons) is carried into a reaction chamber that is heated to the desired temperature by suitable means. The various techniques include resistance heating or graphite heating elements, or induction. In some cases, the substrate is heated directly by passing an electric current through it.

**PVD:** Physical vapour deposition (PVD) processes are deposition processes in which atoms or molecules of a material are vaporized from a solid or liquid source, transported in the form of a vapour through a vacuum or low-pressure gaseous environment, and condense on a substrate. PVD processes can be used to deposit films of elemental, alloys, and compound materials as well as some polymeric materials. Typically, PVD processes are used to deposit films with thickness in the range of few angstroms to thousands of angstroms. Typical PVD deposition rate vary from 10 – 100 A/sec. PVD processes have the advantage that almost any inorganic material and many organic materials can be deposited using pollution-free deposition processes. The deposits can be of single materials, layers with a graded composition, multilayer coatings, or very thick deposits.

**Plasma spray:** Plasma spraying is a thermal spraying technique, in which finely divided metallic and non-metallic materials are deposited in a molten or semi-molten state on a prepared substrate. The thermal plasma heat source (direct current (dc) arc or radio frequency (RF) discharge) with temperatures over 8000K (7700°C) at atmospheric pressure allows the melting of any material. Powdered materials are injected into the plasma jet where particles are accelerated and melted, or partially melted, before they flatten and solidify onto the substrate, the coating being built by the layering
of splats. Due to its versatility and cost-efficiency, plasma spraying is commonly used in numerous industries in the manufacturing environment. The base materials / coating combination can be tailored to provide resistance to heat, wear, erosion and corrosion as well as unique set of surface characteristics.

Table 4: Processing method for each substrate-coating combination.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Coating material</th>
<th>Processing method</th>
<th>Bond coat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>Alumina</td>
<td>Plasma spray</td>
<td>MCrAlX</td>
</tr>
<tr>
<td>Mild steel</td>
<td>Cr3C2 NiCr</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Mild steel</td>
<td>Chromium Aluminium nitride</td>
<td>PVD</td>
<td>No coat</td>
</tr>
<tr>
<td>Mild steel</td>
<td>Silicon carbide</td>
<td>PECVD</td>
<td>No coat</td>
</tr>
<tr>
<td>Mild steel</td>
<td>Stellite 6</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Mild steel</td>
<td>Tribaloy T800</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Mild steel</td>
<td>YSZ</td>
<td>Plasma spray</td>
<td>MCrAlX</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Alumina</td>
<td>Plasma spray</td>
<td>MCrAlX</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Cr3C2 NiCr</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Chromium Aluminium nitride</td>
<td>PVD</td>
<td>No Coat</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Silicon carbide</td>
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<td>No coat</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Stellite 6</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>Tribaloy T800</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>YSZ</td>
<td>Plasma spray</td>
<td>MCrAlX</td>
</tr>
<tr>
<td>Copper</td>
<td>Alumina</td>
<td>Plasma spray</td>
<td>MCrAlX</td>
</tr>
<tr>
<td>Copper</td>
<td>Cr3C2 NiCr</td>
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<td>Copper</td>
<td>Tribaloy T800</td>
<td>HVOF</td>
<td>No coat</td>
</tr>
</tbody>
</table>

Chemical Resistance testing methods

Salt spray test was carried using ASTM B 117 for 1000 hours test period. The samples were inspected every 24 hours to monitor the corrosion growth scale. For the three substrates tested using different coatings, stainless steel showed excellent resistance to the alkaline conditions (Figure 3). Mild steel substrates were least resistant and some of the samples had to be removed before completing the 1000 hours test cycle. The corrosion growth in coated mild steel samples initiated through the cracks present at the edges, spreading across the sample and in some cases completely covering the coating surface. Samples that changed in colour with rapid corrosive growth were removed before the 1000 hour cycle.
In the **acid corrosion testing** coated samples were tested in 5% sulphuric acid solution under high temperature (80-90°C) for a period of 4 hours. Fourteen different samples were tested that includes the combination of two substrates (mild steel and stainless steel) and seven different coatings (alumina, chromium carbide, chromium aluminium nitride, silicon carbide, Stellite-6, Tribaloy, YSZ). From the different coatings, cobalt based alloys Stellite-6 and Tribaloy showed complete delamination between the coatings and the substrates. Etching initiated around the sample edges that led to solution penetrating through the interphase causing complete delamination. Five other coatings: alumina, chromium carbide, chromium aluminium nitride, silicon carbide and YSZ were highly resistant and showed no change after the treatment.

![Figure 3: Stainless steel substrate with different coatings after being exposed to 940 hours of salt spray exposure.](image)

**Thermal cycling**

Thermal expansion and contraction of the sample were tested using the thermal cycle experiments. The samples were heated to 600°C and cooled to ambient with the cycle repeated for 5 days. High temperature was maintained between 7-8 hours before the cooling cycle was started. All the samples were tested for thermal cycle under static conditions to investigate the stresses developed during the process causing possible delamination. There was no phase separation between the coatings and substrate during these experiments for all the samples tested indicating good interphase under static conditions. Oxide layer growth formation was observed for most of the samples tested protecting the coating layer from further oxidizing environment.
Mechanical resistance testing methods

Nanoindentation tests were carried using an Agilent G200 system for all the samples. Coatings processed using HVOF and plasma spray techniques had a rough surface finish due to partial melting and splattering of the particles on to the substrate surface. Materials that were processed using HVOF and Plasma spraying techniques were: Alumina, Chromium carbide, Stellite 6, Tribaloy and YSZ. Chromium aluminium nitride and silicon carbide materials were processed using PVD and PECVD techniques respectively. These two samples had a smooth surface finish that aided in the detection of surface when nano indenter made contact with the coated surface. The hardness and modulus values were measured for different coated samples using different loads.

Thermal properties

Heat capacity of a material is the energy required to increase a unit mass of the material by a unit temperature $T$. The materials respond to heat energy by increased vibrational energy and redistribution of the thermal energy to achieve thermal equilibrium. The temperature dependent heat capacities of coating materials are measured using Netzsch STA 449F1 DSC. The heat capacity for each material was measured from room temperature to approximately 1200°C. Chromium aluminium nitride and YSZ shows increase in heat capacity as a function of temperature. Chromium carbide and silicon carbide materials reacted with the platinum crucible above 1000°C and an alternative graphite crucible was suggested. The carbide based materials, chromium carbide and silicon carbide shows decrease in heat capacity due to the reaction between the material and the crucible.

Thermal diffusivities of nitride and zirconia were measured using the laser flash technique. It was seen that it increases with increasing temperature for both materials. Furthermore, the thermal conductivity of the samples follows a similar trend to the heat diffusivity for the two samples. Carbide based samples; silicon carbide and chromium carbide shows reaction with the platinum resulting in no measurement of the thermal diffusivity for the two samples.

Coefficient of thermal expansion (CTE) was measured by dilatometry. The tendency of the material to change in volume in response to change in temperature is defined by the thermal expansion of the material. The degree of expansion due to a unit change in temperature is called the coefficient of thermal expansion and generally varies with temperature. Change in the dimension of the sample was measured in the left $y$-axis and coefficient of expansion measured in the right $y$-axis. For chromium carbide, there is a linear increase in the expansion values with increase in temperature and similar characteristics were observed for aluminium nitride. YSZ shows an increase in expansion up to 1000°C and then decrease in values above that temperature. Due to the nature of the silicon carbide samples with large particle size, enough compaction was not achieved within the crucible to measure the thermal expansion values.

Saint-Gobain trials
Saint Gobain facility in Melton Mowbray, UK, was identified as the test site for carrying out the high temperature, corrosion – erosion testing of the coated pipes. A cupola furnace melts recycled iron in a vertical cylindrical steel shell which is lined internally with refractory material enclosed at the base.

The gases after the recuperator can still be at temperatures around 500°C, a large proportion of the heat is lost due to conduction, convection and radiation as the large diameter duct that carries the gases is reasonably long. The pipes to be tested for high temperature corrosion-erosion under constant flue gas exposure were tested in this region of the duct. The accessibility to the duct area that maintains temperature in the region of ~500°C is shown in the figure below.

To carry out trials in the large diameter flue duct a test rig was required. It would be able to securely hold a number of different substrates and coated samples and it was designed to maximise the number of different samples tested during a trial. The design of the test rig and samples needed to ensure a central position in the flue duct, but not significantly reduce the flow of the flue gases. The material used for this rig was stainless steel and a thermal gasket was considered when sealing the hatch plate to the flue duct.

![Figure 4: Duct area where flue gases are at a temperature of around 500°C and replacement hatch with cylindrical rods welded to the internal surface that mounts the test pipes](image)

The coated samples were put in contact with flue gases during various days and then they were examined in the SEM. The samples that were subjected to flue and as-coated samples were compared. It was concluded that most of the samples show no delamination of the coatings for both the stainless steel and mild steel indicating strong protection of the substrate surface due to the coatings. The difference between the samples was based on the attraction of the flue dust to the surface of the pipes.
Substrates coated using thermal spraying techniques produced a rough surface finish that collected large amount of dust to its surface, whereas CVD and PVD coated samples had smooth surface finish which facilitated the less attraction to the coated substrate surface. EDX of the flue treated pipes were also performed. The qualitative measurements showed the elements of the flue particles coated on to the external surface of the substrates. For the silicon carbide and chromium aluminium nitride there was less attraction to the pipe surface.

**Erosion modelling**

For the purpose of assessing the coating performance for oxidation and erosion, physical modelling techniques were explored and applied. Models were chosen for predicting the growth of the oxidation layer and for predicting the rate of erosion. A computational fluid dynamics model was developed that enabled the application of the chosen erosion model for assessing the coating materials. The growth of the oxidation layer was predicted at 550°C for SiC by using a modified form of the Deal and Grove model. Based on past research, the oxidation on three faces of SiC was considered. The growth of the oxidation layer is highest on the C-face whilst the growth was slowest on the Si-face. The computational model predicted that AlCrN with the maximum hardness would produce the lowest erosion rate whilst alumina with the minimum hardness would produce the highest erosion rate in the selection of materials presented. The erosion rate predicted for Alumina is 90% greater than that for AlCrN. According to these predictions, AlCrN can consider to be the best coating material out of the selection when considering erosion.

**Final selection**

Chromium carbide, silicon carbide and chromium aluminium nitride showed the best overall performance properties for all the testing methods. The three materials were processed using three different techniques: thermal spraying, PVD and PECVD respectively. Depending on the size requirements of the heat exchanger pipes and price per metre for coating the substrate, the final coating material was selected. Thermal spraying has no restriction to the size of the sample to be coated whereas PVD and PECVD techniques are coated within a vacuum chamber and limits the size of the pipe to be coated. From the preliminarily selected three materials chromium carbide has the best performance properties and easy processability for coating varying lengths of heat exchanger pipes.

The three coatings can be used with mild steel and stainless steel substrate materials. Mild steel is the most economical choice but can only be used where temperatures are below 300°C. Above this temperature, stainless steel should be used to assure a longer life of the pipes.
2) Novel Shell & Tube Heat Exchanger

Shell and tube heat exchanger are used extensively through the process industry due to its efficient heat transfer. The main advantages of using this type of heat exchanger are their simplicity and compactness and that they can be used in systems with higher operating temperatures and pressures. In correlation to other heat exchangers, S&T HEX provide comparatively large ratio of heat transfer in correlation to his volume and weight. They are basically used for the transfer of heat in industrial process applications.

A S&T heat exchanger consists of a shell (a large pressure vessel) with a bundle of tubes inside it. Two fluids, of different starting temperatures, flow through the heat exchanger. One flows through the tubes (the tube side) and the other flows outside the tubes but inside the shell (the shell side). Heat is transferred from one fluid to the other through the tube walls, either from tube side to shell side or vice versa. The fluids can be either liquids or gases on either the shell or the tube side.

The S&T HEX designed and built in Foundenergy project (Figure 5) is one of the components of a waste heat recovery system and has the objective of capturing the heat from the waste gases of a foundry furnace and transfer it to a fluid. The waste gases run through the shell side, while the working fluid, in this case pressurized water, flows through the tubes. So the heat is transferred from the shell side to the tube side.

![Figure 5. Final design of the 30kW Shell & Tube Heat Exchanger](image)
The novel aspect of this heat exchanger lies in the tubes as they have been coated with a mixture of Cr$_3$C$_2$ and NiCr, especially developed to be in contact with the foundry flue gases. This coating has a higher corrosion resistance and wear resistance, so the durability of the tubes can be increased.

The final thermal design of the S&T HEX was carried out with the parameters of the gases that can be produced in the test bench in Tecnalia, where this demonstrator was going to be installed and tested. The test bench that Tecnalia has developed in its facilities is comprised of a furnace, where any metal can be melt, a post-combustor, a quenching system, where the gases coming from the furnace are cooled up to a determined temperature, and a bag filter, where the dust of the gases is collected. The heat exchanger was located between the quenching system and the bag filter.

For the heat exchanger design it was necessary to define the conditions in which the gases will exit the quenching tower. In order to obtain a heat potential of 30 kW in the gases, the parameters were established as listed below:

- Temperature of the gases = 350ºC
- Volumetric flow of the gases = 859.4 Nm$^3$/h
- Mass flow of the gases = 499.4 kg/h

The gases would be cooled in the heat exchanger up to 160ºC, so the calculated heat transfer would be:

$$Q \text{ (kW)} = V \text{ (m}^3/\text{s}) \times \rho \text{ (kg/m}^3\text{)} \times C_p \text{ (kJ/kg K)} \times \Delta T \text{ (K)}$$

$$Q \text{ (kW)} = \frac{(859.4/3600) \text{ Nm}^3/\text{s}}{0.675 \text{ kg/m}^3} \times 1.034 \text{ kJ/kg K} \times (350-160)\text{K} = 31.65 \text{ kW}$$

The waste gases enter the heat exchanger at around 350ºC with a flow rate of 500 kg/h and circulate from the shell transferring its heat to the working fluid (water) circulating inside the 36 coated tubes which form the tube bundle. Around 1500 kg/h of pressurized water are heated from 99ºC to 115ºC thanks to the heat delivered by the flue gases, and this water can be used to heat the organic fluid in the evaporator of the ORC system. Some baffles were disposed along the whole tube bundle with the main objective of increasing the heat transfer coefficient.

The heat exchanger was thermally designed with these parameters and it was obtained an equipment made of stainless steel (AISI type 304L) with a total length of 1576mm and a weight of 415 kgs when full of water (Figure 6).

### Table 5: Physical and thermal properties of the AISI304 stainless steel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>7900</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>193</td>
</tr>
</tbody>
</table>
The tube bundle is comprised of 36 pipes disposed in a rectangular pitch (Figure 7). The selected pipes are also made of stainless steel 304L and have the following dimensions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SI</th>
<th>SMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>¾”</td>
<td>19.05mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>0.584”</td>
<td>14.83mm</td>
</tr>
<tr>
<td>Wall</td>
<td>0.083”</td>
<td>2.11mm</td>
</tr>
<tr>
<td>Length</td>
<td>4 ft</td>
<td>1219.2mm</td>
</tr>
</tbody>
</table>

Figure 6. General dimensions of the shell and tube heat exchanger.
Figure 7. Tube bundle
3) Novel Heat Pipe Heat Exchanger

This recuperator is of convective type, comprised of two housings (two air side housings) in form of rectangular prism. Naturally the heat transfer is obtained by heat pipes, by an indirect convection between waste gases and air for ORC unit.

In the lower housing, presented with picture below the waste gases are entering through diffuser and within this housing, heat pipes are extracting the heat from waste gases.

The concept design is modular, meaning that the structure is comprised of two housings with heat pipes, fixed with connection plate. This allows for simple adjustment of size, i.e. thermal power, by adding the heat pipes.

![Heat Pipe Heat Exchanger](image)

The housings are tight separated from each other by a connection plate. The connection plate has six threads M48x2 for the heat pipes. Naturally there are also the Ø12mm holes for M10 bolts to ensure the fixing with barrels. Every housings has two diffusers (inlet & outlet), with favourable geometry regarding air flow distribution. Smaller ends of all four diffusers end with a flange, three of them being standard
Flanges and one being tailored to accommodate the blower. Diffusers are connected to the housings by rectangular flanges, using screws and nuts (M10). The above mentioned flanges serve the purpose of stiffening the structure as well.

Heat pipe is a heat transfer device using working principles of 2 phase flow, latent heat of vaporization and capillary action to circulate a working fluid between heated and cooled regions. The heated region in this case is air housing where the waste gases transfer some of the heat energy to heat pipes. That energy is within heat pipes transferred to another housing by capillary action. The final result is increased air outlet temperature. To enhance heat transfer coefficient fins are added to heat pipe. Due to heat pipe heat exchanger assembly issues the fins are added only to one surface, the evaporator surface.

The dimension of heat pipes are the following: length of 1050mm (evaporator length 700mm, adiabatic length 25.8mm and condenser length approximately 342.2mm). The heat pipe has an outer diameter of 28mm and an inner diameter of 26mm e.g. wall thickness is 1mm.

In order to avoid air leakage from two housing into air special gaskets have been implemented into heat pipe HEX design. The gasket design is derived from the heat pipe design, specifically from the heat pipe connection design. Other factors affecting the selection of appropriate gaskets are:

- Working temperature: the waste gases have a temperature around 500°C-550°C which significantly influence on the gasket material selection.
- Pressure: the pressure is another key factor, however there is no significant pressure that should be taken into account.
- Sealing material combination: air vs. air

Taking into mindset all the above specified factors, Novaform SK was taken for gasket material. That is High-quality aramid fibres and functional fillers are the basic materials used to manufacture novaform® SK, reinforced by a galvanised zigzag twill fabric (1.0314), homogeneously embedded in an NBR matrix.

Gasket main features:

- extremely high tensile strength
- outstanding pressure resistance
- maximum temperature stability
- unique mechanical resistance and reliability
- stable long-term sealing properties, even under extreme conditions
4) Novel Serpentine Bundle Heat Exchanger

The third heat exchanger that has been designed is the serpentine bundle heat exchanger. This type of heat exchanger has several advantages such as its modularity, simpler design and lower price.

This serpentine was designed to work with Therminol 66, which is a high performance highly stable synthetic heat transfer fluid offering extended life and very low top-up rates resulting in reduced running costs and minimal downtime for operations at temperatures up to 345°C.

It was decided that the serpentine bundle should contain 6 meters tubes bent two times in order to form a “S” shape (Figure 9).

![Figure 9. S-tube](image)

After calculated the heat exchange surface (130 m²) and corresponding tube length the following recuperator geometry was chosen:

- 50 Serpentine coils, each serpentine coil consisting of 5 S-tube.
- So the overall we have 250 S-tubes in corresponding length of 1500m.

However, this was smaller than calculated (1636m), but in thermodynamics calculation the value of heat transfer coefficient is given in accuracy range of 15%. The stated geometry was chosen due to geometric and thermodynamic optimum.

![Figure 10. Serpentine coil](image)
5) Advanced Guidance and Control System

The Advanced Control System for Waste Heat Recovery System (ACS-WHRS) has been designed to control and monitor facility for waste heat recovery in Foundry industry. Heat energy is taken from the flue gases and it is transferred to the working fluid (oil or water) through the heat exchanger and afterwards directed back to the exhaust. The working fluid is circulated to Organic Rankine Cycle (ORC) turbogenerator where heat energy is transferred to electrical energy.

Designed control and monitoring system is fully capable of autonomous control of all heat exchangers plant procedures and operations. Moreover, it has Fault Detection and Diagnosis implemented.

ACS-WHRS was divided in two main parts, on-site and of-site part of system. Both of them will be described in text below.

Control software design

For the purpose of controlling Foundry power plant control software has been developed to satisfy all of the project requirements. Software was developed on National instruments cRio real time platform and in NI Labview 8.5 IDE with NI RT v2.4 module for real time modules. There are two main modes of operation, automatic and remote via TCP/IP connection.

High level control software was developed mainly for the purpose of testing and debugging of Foundry facility. It is designed to overtake control from NI cRio so that operator could control facility over Internet or LAN. Main difference between this and other parts of software is that this part runs on PC or an ofsite computer and not on cRio. That is because we wanted to optimize use of cRio platform. As mentioned before for communication with cRio we used NI Shared Variables which internally use TCP/IP connections.

On site control & monitoring system

On-Site system is directly connected to actuators and sensors installed on facility with analog and digital IOs. System is installed on PLC described previously. Main function of this system is to control and monitor all of the system actuators and sensors and to regulate temperature and flow of oil, air and water.

Main valve is used to direct the air flow to the heat exchanger when shut heat exchanger and ORC are not functional and this is used in case of major fault of component of waste heat recovery system or its maintenance.

Heat exchanger pump is used to regulate flow and temperature of thermo oil that goes to ORC and to regulate it according to ORC optimum intake temperature. ORC Turbogenerator has the requirement to work in high efficiency regime. The aim of the control is holding those input parameters in optimum
range. Pump is controlled via frequency inverter. The frequency inverter has a task of working as a power amplifier. Pump and frequency inverter are described in other sections of this document. To regulate flow and temperature, in addition to the regulator, we used lookup tables that contain information about oil properties depending on the oil temperature. Thermal oil density depends on temperature. In that manner a better accuracy of regulator is assured.

Air cooler unit is used to regulate temperature of water used by ORC. The cool water is needed for cooling and condensing evaporated medium that is used for movement of steam turbine. The hot water flows through air cooler and water temperature decreases depending on fans power. It is also being controlled through frequency inverters and feedback is given from thermometers. The algorithm includes advanced control of fans to decrease fans energy consumption. Fan motors should work in high efficiency regime.

Figure 11 presents the principal schematic of advanced control system for heat exchanger. Physical processes and flows of air, oil and water are presented. Also, regulation loops may occur. As stated earlier, the main part is Compact central processor unit. Its function is to collect all relevant parameters by analogous and digital inputs/outputs, control some of them and show them on the User Interface.

On-Site part of system can work in two modes, automatic (normal) operation mode and service mode. In automatic mode user can only monitor and emergency shut down the system if fault detection and
safety procedures fail due to force majeure. Service mode is manual mode used for testing parts of the system.

**Of site control & monitoring system**

Of-Site system is mainly used for monitoring and logging data for purpose of of-site inspection of system. This system gather data from Of-Site system through TCP/IP connection represented as web page. Of-Site system cannot control the system. This is done for protection of system and employees near facility. To access Of-Site system, user needs to login on Of-Site web application trough web browser.
6) Waste Heat Recovery System prototype

Waste Heat Recovery is a process in which heat is recovered from hot streams with potential high energy content, such as hot flue gases from a generator or steam from cooling towers or even waste water from different cooling processes such as in steel cooling. The recovered heat can be used for different applications depending on the quantity of heat recovered. The system developed in Foundenergy project has been designed to be used in medium waste heat temperatures (230-650°C) and with the objective of transforming the recovered heat into electricity.

WHRS based in the S&T HEX concept

A Waste Heat Recovery System (WHRS) prototype based in the shell&tube heat exchanger concept has been designed, built, tested and validated at pilot plant scale. This WHRS is able to recover up to 28 kW of thermal energy from the flue gases coming from a gas-fired foundry furnace and convert it into 3 kW of electrical power to be used internally.

In order to achieve this objective, the system is formed of a S&T HEX, which has also been developed and built in the project, and a turbogenerator. The turbogenerator is based on the Organic Rankine Cycle (ORC) technology, which is a technology which uses an organic fluid to recover heat from low or medium temperature sources to convert it into useful work, which can itself be converted into electricity.

This turbogenerator is composed of the following components:

- Evaporator
- Expander
- Generator
- Condenser

Five different fluids are needed in this recovery system.

- Hot flue gases from foundry plant process, which is the source of energy for the heat recovery system.
- Pressurized water, which is a heat transfer medium used to transfer the energy received from the hot gases to the ORC working medium.
- ORC working medium. A different organic fluid is selected depending on the operation of the ORC process. A commercial pentafluoropropane (R245fa) is used in this case.
- Water, which is ORC condenser cooling medium. It is used to cool the organic fluid in the condenser.
- Air flow through air cooler dedicated for cooling condenser water.
Flue gas from the foundry furnace comes out from the chimney with temperatures above 200°C. This hot gas then enters the heat exchanger where it suffers an enthalpy decrease. That heat is absorbed by water and carried to the ORC evaporator.

![Figure 12. Schematic diagram of ORC system](image)

After experiencing the enthalpy increase in the evaporator, working medium is directed to the expander where it adiabatically expands and thereafter enters the condenser. In order for expanded vapour to condense, it passes its enthalpy to the cooling water. After condensing, it is being pumped to the pressure of evaporation and directed back to the evaporator, where the cycle is completed. Condenser water is taken from the general network so it enters the condenser at room temperature. After absorbing the heat of condensation its temperature rises around 10-15ºC at the exit of the condenser. This hot water can be used for different applications.

The WHRS has been integrated in the demonstration plant prepared at Tecnalia's facilities in San Sebastian and has been tested during 3 weeks. The integration has consisted in the adaptation of the pilot plant in Tecnalia to locate the WHRS and perform the final testing. The duct between the quenching tower and the bag filter has been bypassed and the heat exchanger has been located in the middle. Close to the heat exchanger has been located the ORC unit. The connection between the evaporator of the ORC unit and the heat exchanger has been made through flexible tube where pressurized water will circulate (Figure 13 and Figure 14). The flue gases are cooled from 350°C to around 160°C in the shell & tube heat exchanger and the heated fluid (water) goes to the evaporator of the ORC system in order to evaporate the organic fluid and generate mechanical energy in the expander to activate the generator and produce some electricity.

The testing process has been carried out during 3 weeks. First of all, the setup of the system was done and later the conditions of a real foundry were simulated, achieving the calculated thermal power in the flue gases and introducing both chlorides and abrasive particles in the gas stream.

Finally, all the data collected during the testing trials was analyzed and the behavior and durability of the heat exchanger was studied, mainly focused in the pipes.
Figure 13. Location of the WHRS prototype in the test bench in Tecnalia
Figure 14. WHRS prototype in the test bench in Tecnalia just before starting the trials.

The S&T heat exchanger has been tested during the validation trials of the WHRS. The objectives of this testing were mainly two:

1. Measurement of the efficiency of the heat exchanger before and after the trials and comparison with the theoretical maximum efficiency.

2. Study of the behaviour of the pipes during the trials and check if the coated pipes had better performance than the uncoated pipes when being subjected to a waste gas stream with abrasive and corrosive particles in it.

As it was not possible to have the system working 6 months to have a more approximate vision of the system in real working conditions, accelerated testing was carried out. This testing lasted around 60 hours. So the heat exchanger was working during 60 hours transferring heat from the gases in the shell to the pressurized water inside the pipes. The materials of the heat exchanger have been subjected to various effects:

- A hot flue gas stream. The average flow of the gas stream was 310 kg/h and the maximum temperature that was reached during the trials was 450°C.

- Thermal stress cycles: as the post-combustor generating the flue gases was switched on and switched off every day, the gases increased their temperature from a minimum temperature of around 80°C to the peak temperature of around 450°C. Flue gas condensation temperature was 120°C so condensation effect was promoted.

- The effect of chlorides in the gases. To simulate the effect of the chlorides that are usually encountered in the flue gases of aluminium melting furnaces, salt spray was introduced in the gas stream during 15 hours.

- The effect of abrasive particles in the gases. To simulate the effect of abrasive particles that are usually encountered in the flue gases of aluminium melting furnaces, aluminium silicate was introduced in the gas stream during 10 hours.

- The effect of the water inside the pipes. Pressurized water (6-7bar) coming from the tower was circulated during 60 hours at a flow rate of 1500l/h.

From the trials, it has been validated the WHRS prototype based in the S&T HEX concept. It has been demonstrated that the efficiency (82%) of heat exchanger is close to the theoretical efficiency (85%) even in accelerated aging conditions. Not only the heat exchanger materials and coating have been validated but also the design of the HEX (Tube & Shell), in a temperature range (450-420°C) higher than service temperature (350°C). On the other hand, it has been shown that ORC concept as a power take-off machine, what should be automatically self-controlled.
It should be explained that in TECNALIA test facilities (plasma furnace and filters) is rigid test bench and there was no by-pass designed for flue-gas and so the ORC unit is the only way to maintain the stability of the plasma furnace and filter safe integrity. It was designed an emergency way where the flue gas and BES-HEX were refrigerated directly by refrigeration water system from TECNALIA.

Next, efficiencies of the system (ORC and global) are summarized in Figure 15.

![Figure 15 Efficiency summarize](image)

**Validation of the Heat Pipe HEX**

As a result of a strong collaboration between MaTRI and a fully operating foundry (Saint-Gobain, UK), a well iterated and engineered solution was specified and designed for the novel Heat-pipe WHRS, to determine the efficiency of heat pipe technology within a heat exchanger. Due to the extremely high temperatures that the system will be working with, there were many health and safety implications to consider. Subsequently, these implications limited the design due to the decisions that were made regarding the change from oil to air as the heat transfer medium, along with the conclusion that it would not be safe to have the heat pipes situated directly in the flue duct. The area in the foundry where MaTRI had permission to situate the system was at the flue just after the recuperator where the temperatures are at their highest (550°C). MaTRI carried out the procurement and fabrication of the novel Heat-pipe WERB and WHRS and the heat pipes to be used by a heat pipe specialist. After alterations were made to allow the heat pipes to fit into the WERB, they were then protective coated with ‘Chromium Carbide - Cr$_3$C$_2$-NiCr’ using a ‘Thermal Spraying – High Velocity Oxy Fuel’ process which was the initial project result at the beginning of the project.
For industrial validation a hot air blower was installed at the input of the primary circuit to simulate the flue gases which would be passing through the system when installed in the foundry. The hot air blower is variable in terms of flow and temperature. For the tests both of these parameters were set to maximum. The blower for the secondary circuit and blower control box was installed along with all necessary sensors and instruments. A thermocouple was attached to a fin of one of the heat pipes so a live temperature reading could be taken in order to gauge when the heat pipes had stabilized and stopped rising in temperature. This was only used as a temporary ‘check’ to verify the other temperature sensors in the system. It will be removed and not used when installed at the foundry. Thermocouples were inserted into bosses on the inlets and outlets and a seal was created with compression glands. These were then used to take temperature readings and determine the temperature difference between the inlets and outlets.

When the air speed reading from the hot air blower was taken (air speed 1) it was 2.8m/s at its maximum speed. This air speed was then matched with the blower on the heat recovery side of the system (air speed 2). By doing this it made it easier to interpret the results as temperature was the only variable and so removed the need to consider mass flow rate as a power variable - hence allowing direct comparison between temperatures as a reflection of power.
Table 7: Air speed and temperature measurements in the first trial.

<table>
<thead>
<tr>
<th>Air Speed 1 (m/s)</th>
<th>Air Speed 2 (m/s)</th>
<th>T2 (°C)</th>
<th>T1 (°C)</th>
<th>T3 (°C)</th>
<th>T4 (°C)</th>
<th>Overall System Efficiency (%)</th>
<th>Circuit 1 Effectiveness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>2.8</td>
<td>128</td>
<td>223</td>
<td>27.5</td>
<td>55.5</td>
<td>29.5</td>
<td>42.6</td>
</tr>
</tbody>
</table>

Table 8: Air speed and temperature measurements in the second trial.

<table>
<thead>
<tr>
<th>Air speed 1 (m/s)</th>
<th>Air Speed 2 (m/s)</th>
<th>T2 (°C)</th>
<th>T1 (°C)</th>
<th>T3 (°C)</th>
<th>T4 (°C)</th>
<th>Overall System Efficiency (%)</th>
<th>Circuit 1 Effectiveness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>5.6</td>
<td>121.5</td>
<td>223</td>
<td>26</td>
<td>45</td>
<td>18.7</td>
<td>45.5</td>
</tr>
</tbody>
</table>

The results obtained from heat pipe heat exchanger testing indicate following issues and modification of the WHRS:

1. The heat pipe heat exchanger has to be insulated. The whole heat exchanger surface has greater temperature than surrounding temperature (the ambient temperature). By insulation, the heat loss will be reduced. Lost amount of heat energy will be transferred to heat pipes and air temperature is going to be increased.

2. Used heat pipes are being designed for operating temperature of app. 550°C which fully correspond to exhaust temperature from Saint-Gobain foundry (500°C-550°C). The temperature obtained from hot air blower was 223°C. That is significantly lower temperature than needed operating temperature of 500°C-550°C. Since heat pipe is thermal transfer device whose operation is based on liberation of latent heat, operating temperature should match the temperature of phase change corresponding to the pressure inside the heat pipe. The final result is departure from optimum working regime; resulting in lower air output temperature.

3. Additionally heat transfer can be increased by increasing the length of the diffusers.

Initial pre-commissioning trials at the foundry at Saint Gobain were carried out but at the time were still experiencing problems with their furnace operations and this impacted on the temperatures that were available through the exhaust flue. Also there were other factors that need to be further investigated regarding the sample in-take of the hot exhaust air from the exhaust flue pipe to pass through the WERB’s primary circuit 1 for these trials. Further investigation and trials to be carried out to determine the reason for the initial poor results, but due to the issues at the foundry already encountered which has resulted in approximately five months delay the project has now come to the end of the projects duration. Foundenergy are committed to continue with these trials until this matter has been concluded.
Further Recommendations to consider for the improvement to capture the high temperature exhaust flue gases are:

- Investigate whether an issue in the restriction in the in-take pipe supplying sample gases from the exhaust flue such as:
  - In-take pipe diameter
  - Pipe bend restrictions
  - Gas dust / debris causing blockage
  - Valve operation, both input and output
  - Possible temperature and air flow measurement ports before the inlet valve

- Investigate the pressure drops throughout the system

- Improve / added insulation to the WERB and all WHRS piping

**Validation of the serpentine bundle HEX**

The exhaust stream of waste gases leaving the foundry furnaces is collected and directed to the WERB. The whole WHRS is presented in Figure 17.

Flue air with certain abrasive particles is leaving the chimney with average temperature of 300 °C. Hot air then enters the heat exchanger where it suffers an enthalpy decrease. That heat is absorbed by thermal oil and carried to the ORC evaporator. Thermal oil enters the heat exchanger with temperature of 140 °C, absorbs the heat energy from hot air and leaves the exchanger with 270 °C. Having its enthalpy increased, it enters the ORC evaporator where its heat is delivered to ORC working medium which therefore evaporates. After experiencing the enthalpy increase in the evaporator, working medium is directed to the turbine where it adiabatically expands and thereafter enters the condenser. In order for expanded vapor to condense, it passes its enthalpy to the cooling water. After condensed, it is being pumped at the evaporation pressure and directed back to the evaporator, where the cycle is completed. Condenser water enters the condenser with 60 °C. After absorbing the heat of condensation its temperature reaches 80 °C at the exit of the condenser. In order to be cooled down, the water is circulated through air cooler where it releases heat to the air in the cross flow, reaching the exit of the cooler with initial 60 °C.
Designed waste heat recovery system based on serpentine bundle heat exchanger was integrated into foundry Bujan in Novi Marof (Croatia). The purpose of this heat exchanger is to use the waste energy from foundry an aluminium melting furnace and convert it into heat for plant heating purpose. The heat exchanger was coupled with five fan coiler unit (FCU) with pipe work as presented in figure below.
Measured parameters:

- Inlet water temperature
- Outlet water temperature
- Inlet waste gases temperature
- Outlet waste gases temperature
- Water flow
- Water pressure
- Thermal power (indirectly)

For the plant heating purpose, water was used as heating medium. The highest water temperature allowed in heating systems usually does not exceed 120°C. Therefore, accepting such practice, we put the system under gauge pressure of 3 bars before putting the WHRS system in operational mode. Thereby safety against water evaporation is provided.
POTENTIAL IMPACT AND MAIN DISSEMINATION ACTIVITIES

The materials and technologies developed in Foundenergy have been specially tailored to reduce the overall energy consumption of the foundry industry, a very energy intensive sector, responsible of around 4% of the total energy consumption in the EU.

The European foundry industry is facing increasingly tough competition from low cost and emerging countries particularly China and India, and also from more technologically advanced countries such as Japan and USA. There is general agreement that the best way for European foundry industry to successfully compete is through the creation and development of value added products with high knowledge contents that fit the perspective of the foundry industry. The materials and know-how developed within the project will contribute in introducing new solutions to recover part of the thermal energy lost through the waste gases of melting furnaces and transform it into electricity that can be used internally.

The technologies developed within Foundenergy project will have an important impact in the environmental sustainability through an important reduction of the energy consumption in foundries and another important impact in the competitiveness of the European Foundry Industry, contributing to the main reasons why this project was conceived (Figure 19).

Figure 19. Summary of the main impacts of the Foundenergy project results.
ENVIRONMENTAL SUSTAINABILITY

The EU established in 2007 an ambitious plan to contribute to the environmental sustainability. This plan is based in three targets, known as “20-20-20” targets:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU’s energy efficiency.

The technology developed in Foundenergy will contribute in a direct way to the improvement of the energy efficiency of foundry processes thanks to the reuse of part of the energy used in the melting processes. Nowadays, around half of the energy input in the melting processes is absorbed by the material in order to be melted, but the other 50% of this energy is lost through different paths. Foundries are making some efforts in reducing this energy losses, but the higher amount of thermal energy (around 70% of the total losses) is lost through waste gases. As these gases are difficult to recover and need from high investments from the foundries, most of them throw these gases to the atmosphere, so energy efficiencies of these processes are usually quite low. The technology developed is able to recover part of the heat of these gases through one of the WERBs that has been developed and transform it later into electrical energy, with an overall efficiency of the recovery system of around 10%.

On the other hand, if the electricity produced through the recovery system is consumed internally, the total energy consumption of the industry could be reduced, thus contributing somehow to the reduction of the greenhouse emissions, which is another target.

COMPETITIVENESS

The principal economic benefit that the SME-AGs and their numerous national and EU wide members will have is the huge energy costs savings in operations of their plants, through the CO2 savings, as well as savings on the existing costs for waste heat/air quality treatment. Besides, at the association that are of multidisciplinary nature (CCE), the benefit of the SME members will be obtained through the production and installations of plant components that the integrated product will be consisted of. On the other side the core group SMEs will obtain significant benefits from the technology sales on the EU and global markets, from the direct components and system sales or through the technology licensing incomes.

The average target selling price of a recovery system of 300kWe installed into the foundry plant is estimated to be 590,000€ although it is expected that the costs will be reduced as the supply chain becomes established and we obtain better purchasing power through higher volumes from our European approach. This cost is based on projected production costs and profitability requirements, as determined by our consortium using our collective experience. This cannot be compared to a purchase price of similar product because there are no such products available on the market yet matching the
FoundEnergy product. To validate this target selling price we have surveyed key stakeholders through their associations and by direct contacts. These interviews have helped validate our objectives and targets, ensuring that our product is capable of meeting market needs. Our initial costing reveals that materials, manufacturing, integration and component costs for this WHRS will vary between 550,000€ and 650,000€, including labour, but excluding initial plug and tooling costs which will be amortized over 5-8 years.

Taking the average electricity price of 0.0685 €/kWh and the 20 €/ton of CO\textsubscript{2} throw to the atmosphere, and then considering additional savings that the insertion of the plant could produce, the total earnings of power sales (agglomerated with other benefits) in 4 years from this plant installed on foundry site could reach 668,000€. Considering the cost of the capital of 6% (with paid interests of 85,000EUR) and the plant value of the 590,000€, we could assume that this plant will be paid back even in approx 4 years. Therefore, as a renewable energy source, the payback period of 4 years is very acceptable for any foundry plant, when the normal IRR on renewable plants is still around 10 years or above. The additional benefit for the SME-AG members will be the discounted price on the product that will speed up the return on investment time, thus enabling the SME quicker savings on future operations.

Estimated benefit and savings for a foundry of the SME-AG is about 170,000€/year with additional 600 tons of CO\textsubscript{2} savings/year. Estimating that approximately 200 users of the SME-AG community foundries are equipped with the developed technology the amount of energy savings would be around 34,000,000€ and 120,000 tons of CO\textsubscript{2} savings per year. Considering that the first five years the SMEs will pay back the investment, the real savings effects will be in the next period, bringing the total savings in the first 10 years up to total 222M€, when costs of the introduction of the technology are subtracted.

Besides the direct savings that the SME-AG members will benefit from direct savings, there’s a huge opportunity for the WHRS to be placed on the worldwide market thus giving the SME-AG members and the core group SMEs another boost in economic benefits. We have assessed the potential market for the technology developed in Foundenergy locally, nationally and internationally and our key market opportunities for the product will be initially the foundry industry. With the newly implemented technological solutions that this project will provide by creating higher levels of differentiation, the partners will be able to overcome market obstacles in order to be able selling the product on the global markets. The differentiation for the worldwide market will be gained through adequate IPR protection activities.

As a primary market, we estimate that our technology will be conquered between 5-10% of overall foundry market, first in our own SME-AG community members, then EU wide and finally worldwide, giving a total potential market size for this technology of just over 100 plants per annum after fifth year of technology exploitation.

Besides the direct financial benefits, there are several societal objective that will be reached by the results obtained in the project, however beside all others benefits the major economic output is that the
developed technology project will **generate new jobs at the technology enablers and safeguard jobs at the technology beneficiaries (both user SME-AG community)**. The estimation in jobs safeguarding for incoming ten years is rather complex to be made, however linking it to the estimated sales volume of the Foundenergy WHRS, it could be varying from 500-1000 jobs.

**DISSEMINATION ACTIVITIES**

Different dissemination activities have been carried out during the 3 years of duration of the project. Information related to the activities of the project has been published in different relevant publications close to the foundry industry such as Foundry Trade Journal International and Fundipress. The AFV and SG have also published periodically information of Foundenergy in their respective technical bulletins distributed to their members, all of them from the foundry industry. The REEMAIN platform has also published an interview with the project coordinator once the project finish was close, explaining the main results achieve in the project. This platform deals with resource and energy efficiency.

Apart from the publications, Foundenergy has been present in numerous fairs during these last three years and also in a couple of very important conferences with a poster an even a talk in the European Investment Casting Conference. A leaflet has been prepared and distributed in both conferences among the participants.

Newsletters have also been an important way of dissemination, preparing one after each Consortium Meeting, relating the latest advances of the project. These newsletters have all been published in the webpage of the project ([www.foundenergy.eu](http://www.foundenergy.eu)), which has been periodically updated with new information of the project and related news.

**EXPLOITATION OF RESULTS**

In order to tackle the market with the challenging Foundenergy solutions, partners have produced the initial Exploitation Plan for the use of the foreground results which is defined in the following table:

<table>
<thead>
<tr>
<th>Years</th>
<th>Phase</th>
<th>Description</th>
<th>Participants</th>
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</thead>
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Table 9. Exploitation plan for use of foreground results
| 1  | Product development phase | During this period (1 year), research and innovation activities for developing 3 concepts have been performed. With these innovations, partners have built a complete prototype and have carried out an extensive testing programme during this phase to ensure that new designs can operate efficiently at extreme conditions. During this period COORDINATOR has sought to establish a trademark and ensure that organizational innovations are fully protected, and new contacts with foundries are made. | all participants |
| 2-4 | Focused exploitation | Initial Exploitation phase will concentrate on establishing a market presence in Croatia, Sweden, Spain and UK. Also consortium partner SG-AG already acts as COORDINATOR's partner for this activities and distributor in Scandinavia which can benefit for effective installation. Hence, Croatia, UK and Spain are the right starting sales routes for the Foundenergy due to the intense presence of foundry plants in those countries. | COORDINATOR CCE (CROATIA) AG (SWEDEN) AFV (SPAIN) GBANK (UK) |
| 4-8 | EU market expansion | The main activity during this period will be to consolidate the market mainly in Europe, and use the revenues from sales over the previous 3 years to penetrate key new markets, such as Turkey, Russia, etc. During this period, COORDINATOR expects the demand to ramp up significantly as the organization builds a portfolio of successful installations. As a result, COORDINATOR expects to license some aspects of production as well as approving new business partners and customers. | COORDINATOR Beneficiaries (SME-AG) New EU business partners and customers |
| > 8 | Global market expansion | Once the Foundenergy technology has sufficient European penetration, it will be in a position to exploit the market abroad, on a global scale. There are several potential countries US, China, India and Brazil identified where partners can use the technology. As such, the consortia members will monitor the market situation throughout the project and will collate consortia findings in the project’s Exploitation Plan. | COORDINATOR Beneficiaries (SME-AG) New worldwide partners |

The consortium has so far discussed an exploitation strategy that incorporates management of knowledge, intellectual property and of its inter-relation with the various innovation-related activities planned. This also includes various management activities to ensure that the results
are adequately protected and that the dissemination is carried out without threatening the partners’ ability to protect the knowledge.

Consortium has agreed that only the beneficiaries (SMEs and SME_AG) will own the IPR from the project and RTD performers: Tecnalia, Novamina and Matri are expressly prevented from owning any of the resulting IPR from the project. Any other results that may arise from the Project will also be owned by the SMEs or SME-AG. This is clearly stated in both Grant agreement and the Consortium agreement.

Different types of outputs will be developed within the Project. These include patent conceptual design of the WERB (Waste Energy Recovery Boiler), WERB tubes material, software expert models and databases for the integrated optimization and other secret know-how. The most valuable project results are:

- Patenable protective wear resistant WERB coating material and coating technology.
- Waste Heat recovery power generation guidance and control system for foundries.
- WERB design as fully functional prototype integrated in foundry.

Although the first idea was to develop two different WERBs, based in the shell and tube concept and based in the heat pipe concept, finally it was decided to develop a third one: a serpentine bundle as well.

Distribution and value of the IPR results among SMEs is displayed in the DoW and the Consortium agreement.

All the SMEs agreed on percentage of the IPR assigned to them, as well as with the foreground and background IPR and exploitation rights distribution, what is also supported by the Consortia agreement. The ‘fair and reasonable conditions’ definition in DoW is defining the relationship between SME partners where the SME’s will share with the rest of the consortia their background information which is needed for the exploitation of foundenergy outcomes by current market conditions discounted depending on situation.

Background owned by the RTD performers or the SME partners which is or will be found necessary for the implementation of the project will be granted royalty free to all partners. For use purposes after the end of the project access to background will be granted royalty free. The Exploitation Manager will take the responsibility for IPR protection.