Application of Thermal Spray Techniques for Combatting High Temperature Corrosion of WTE Superheater Tubes

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EXECUTIVE SUMMARY

Combustion with energy recovery of post-recycling municipal solid waste (MSW), also called waste to energy (WTE), is the only proven alternative to landfilling. Some of the WTE advantages over landfilling are that it avoids landfilling and methane emissions to atmosphere and reduces the volume of MSW by 90%. One of the main operational problems in the WTE industry is the corrosion on the superheater tubes, which is related to the relatively high concentration of chlorine (0.47-0.72 wt%) in the flue gas and the formation of alkaline salts and sulfates. Corrosion affects adversely the operation of WTE plants due to the cost and time needed to repair or replace the superheater tubes. Several coating techniques have been applied for preventing high temperature corrosion (HTC) inside the WTE boilers. The most common techniques are weld overlays, laser claddings, fused coatings and thermal spray coatings.

Thermal spray techniques have proven to be the most effective methods for refurbishing corroded superheater tubes, especially the high velocity oxy-fuel (HVOF) spray technique. Regarding the coating materials, there are numerous studies associated with the effectiveness of different alloys. High chromium, nickel, and nickel-chromium alloys have exhibited a high level of resistance to high-temperature oxidation in chlorine environments.

Based on a comparative analysis of published experimental data from several research studies, coatings with Alloy 625, Alloy C-276, Colmonoy 88, FeCr, IN625, NiCr, NiCrTi, and a kind of tube materials that can be used as coating materials (A625) offer high corrosion resistance and relatively low material cost. All these coating materials have exhibited corrosion rates of less than 1 mm/year in research studies. On the other hand, corrosion rates for some typical superheater tube alloys are extremely high when compared with the above spray coating materials; for example, the corrosion rate for tube material SAN25 has been shown to be over 20 mm/year, and the corrosion rate for tube material SA213 T22 can be as high as 30 mm/year.

Coatings with high chromium, nickel and molybdenum content have high corrosion resistance and can perform outstandingly under high-temperature-high-chlorine conditions. Based on the analysis of several research studies on the subject of SHT corrosion, due to its relatively low price and high corrosion resistance, T92 with a corrosion rate of 0.901 mm/year and a price of $3.09/meter could be a good choice for superheater tubes at 550^{o}C, and P91 with a corrosion rate in 0.601-2.263 mm/year range and a price of $2.11/meter could be another good choice. Besides, the potential coating material, A625, also has good corrosion resistance performance (corrosion rate < 1 mm/year), but its prices, estimated at over $50/meter, are very high in comparison to other coating materials.

The selection of the most suitable coating for superheater tubes will depend on the design and past operating experience of a particular WTE plant. The additional cost for applying the coating, on a per ton MSW basis, may be a relatively small fraction of the gate fee and electricity revenue earned by extending the lifetime of the superheater tubes and thus reducing the plant availability because of the need to repair or replace corroded superheater tubes.

In addition to the research and cost-benefit analysis carried out by the author, the Earth Engineering Center of Columbia University also sought the advice of a European expert on combatting superheater corrosion. His report is shown as Appendix 1 to this thesis.

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Chapter 1: Introduction

In the United States, about 390 million tons of municipal solid waste (MSW) are generated every year [1]. For the post-recycling MSW, the only proven alternative to landfilling is thermal treatment, also called waste to energy (WTE), for the production of energy and recovery of metals and minerals. In addition to the electricity generation (about 0.5 MWh/ton MSW), other advantages of WTE over landfilling are avoidance of landfill methane emissions and reduction of the volume of MSW by 90% [1]. However, MSW contains natural organic compounds and chlorinated plastics (mostly polyvinylchloride, PVC) which on combustion result in a high chlorine concentration in the gas passing through the boiler [2], typically in the 0.47-0.72 wt% range [1]. This, in combination with the high temperature level inside boilers in WTE plants, and the high concentration of alkaline metals (Na, K, etc), heavy metals (Pb, Zn, etc), and sulfates during combustion causes severe high temperature corrosion (HTC) problems; the problem is especially grievous on superheater tubes (SHT) by ash deposits that melt at 300-550^{o}C [3, 4]. Figure 1 is an explanatory drawing of corrosion factors in WTE boilers.

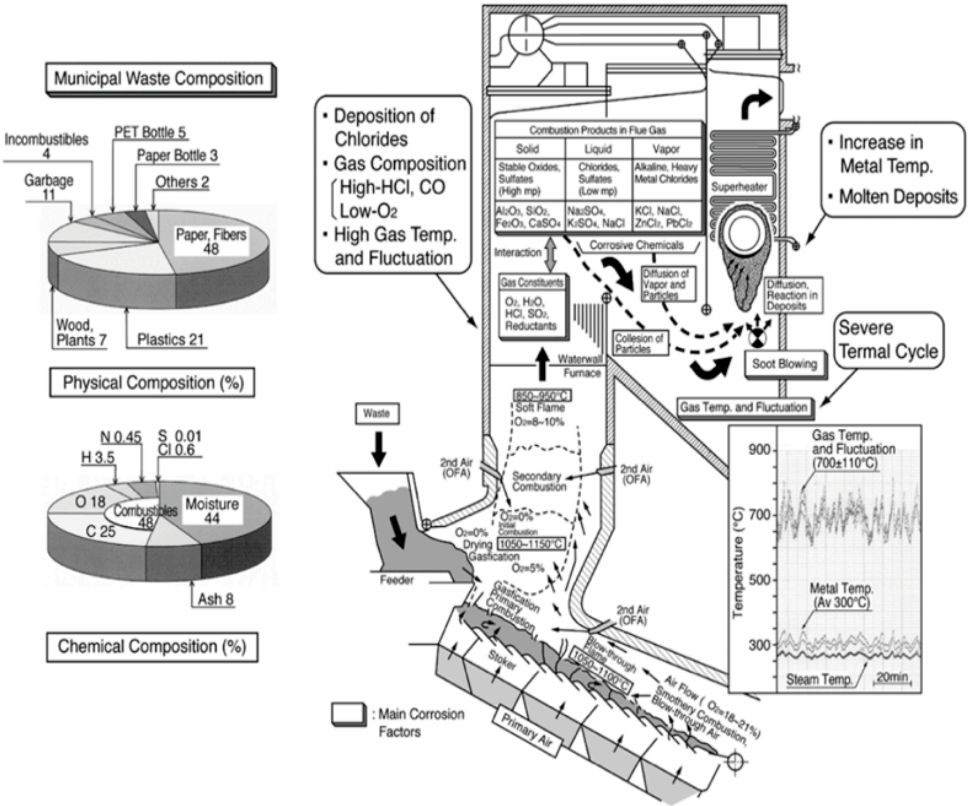


Figure 1. Formation of corrosion environment in WTE Boiler [3]

Boiler tubes, in particular superheater tubes which are subjected to the highest temperature of the metal wall, are corroded by chlorination reactions; also, intergranular and localized corrosion occurs when the protective oxide layer is broken down by molten adhering ash, which can attack even high corrosion-resistance alloys [3]. Ash particles and chloride salts (such as $CaCl_2$, KCl, $ZnCl_2$, $PbCl_2$, or $CuCl_2$), sulfates (such as $ZnSO_4$, $PbSO_4$, $CaSO_4$, Na_2SO_4, or K_2SO_4), oxides, and heavy metal compounds will stick on the surface of superheater tubes that are at a lower temperature than the gas stream. Insufficient conversion from chlorides to sulfates or oxides and the presence of copper on superheater tubes will strongly accelerate the corrosion [2].

The corrosion of superheater tubes is caused by four mechanisms that occur simultaneously [5]. One of them is the corrosion driven by chlorine in gaseous phase, such as HCl and Cl_2. The second mechanism is the condensation of alkali and heavy metals chloride and/or sulfates on the surface of the tubes. The third one is corrosion induced by deposits and the sulfidation of condensed chlorides. The last one is the dissolution of protective oxide and tube metal caused by molten salts eutectics. The corrosion of superheater tubes may lead to material wastage, tube leakages, shortened lifetime of tubes, and unplanned shutdowns of boilers in WTE plants [6]. The corrosion rate of these tubes can be as high as several mm/year [3]. Figure 2 shows a sample corrosion mechanisms on the surface of superheater tubes.

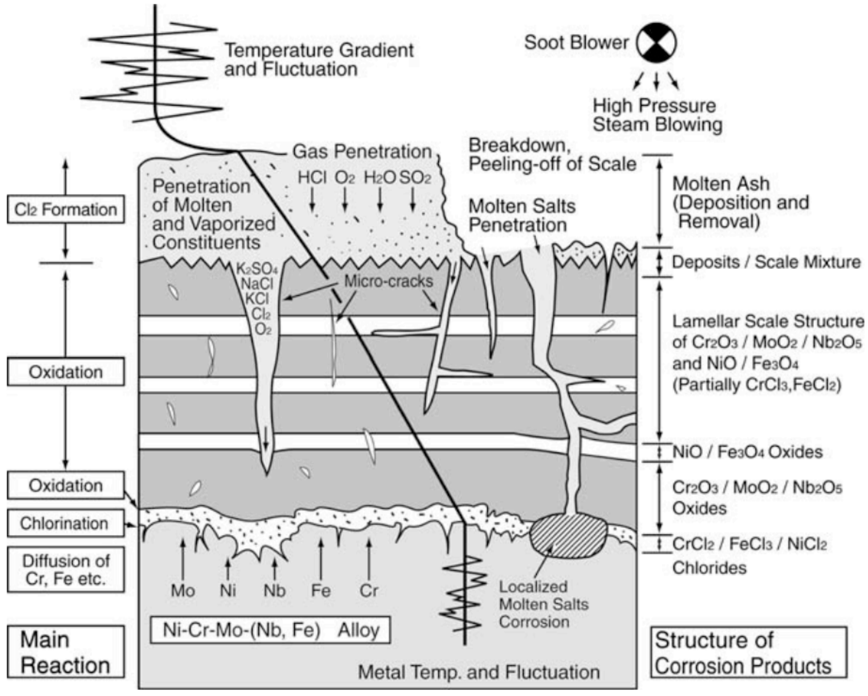


Figure 2. Sample corrosion mechanisms in Ni-Cr-Mo-(Nb, Fe) alloy [3]

In most WTE plants, the steam condition is set up to 400-450°C and 2.9-5.8 MPa to ensure stable operation and reduce corrosion of SHT. Reducing steam temperature can improve the stabilization of protective oxides layer on superheater tubes [4]; however, the demand for higher efficiency of power and heat generation from WTE plants requires an increase in steam temperature [6]. For example, an increase of temperature from 400°C to 500°C can lead to a 20% increase of power generation [5]. However, raising the steam temperature to this level requires that the flue gas around the superheater tubes be at temperatures higher than 650°C, which significantly aggravates the corrosion on the tubes [5].

There have been many superheater tube failures in WTE plants due to HTC [7]. In Europe, until 1996, the following superheater tube failures occurred in plants with steam temperature below 427°C (800 °F). At the Goppingen WTE, superheater tubes failed in less than one year. In 1982, tube failures occurred in the final superheater in less than one year of operation in Bielefeld-Herford plant in Germany. In Wurzburg, Germany, superheater tubes failures occurred after 20,000 hours of service. In European plants with steam temperature from 427 to 482 °C (800 to 899 °F), high SHT wastage rates were experienced at the Hague, Netherlands, Edmonton, U.K. and the Ivry, France plants [7] Table 1 shows the longevity of SHT at several German plants operated at steam temperatures of 438-482°C (900 to 1000 °F).

Table 1. Superheater tube failures in Germany plants operating at 900 to 1000 °F (482 to 438 °C) [7]

Location	**Time to Failure**
Oberhausen	after 10,000 hours
Dusseldorf	after 5 years
Mannherim-North (Plant A)	after 2,000 hours
Mannherim-North (Plant B)	in the first year
Stuttgart	in the first 1,000 hours

The steam conditions were designed to be very conservative in early U.S. plants because of the experience of corrosion problems in the first European WTE plants; however, superheater tube failures still took place. In 1972, tubes began to fail in the superheater after 3,000 hours of service in the Harrisburg plant, Pennsylvania. Later, superheater tubes failed in the first year of operation in the first refuse-fired boiler built in 1974 at Nashville, Tennessee. Chlorine corrosion was the major causes in these two cases. Also, occasional superheater tube failures were reported, due to molten salt attack, at the Akron, Ohio from 1985 in the first U.S. plant burning refuse-derived fuel (RDF). Tables 2-4 list SHT failures at various U.S. plants (1996, [7]).

Table 2. Superheater tube failures in the U.S. plants operating at 700 to 749^{o}F (370 to 398 ^{o}C) until 1996 [7]

Location	**Time to Failure**
RDF-Fired Plants with Suspension and Grate Burning	
Niagara Falls, NY	110 days at full load
Plant A	3,000 hours
Plant B	2 years
Mass-Burn Plants with Rotary Combustors	
Plant C	15,000 hours
Plant D	< 1 year

Table 3. Superheatert tube failures in the U.S. plants operating at 750^{o}F (399 ^{o}C) until 1996 [7]

Location	**Time to Failure**
RDF-Fired Plants with Suspension and Grate Burning	
Lawrence, MA	~2 years
Elk River, MN	2 years(A)
Mass-Burn Plants with Rotary Combustors	
Plant E	3 years
Plant F	< 1 year
Plant G	3 to 3 years

(A)Severe corrosion detected before failure

Table 4. Superheater tube failures in the U.S. plants operating at 800 ^{o}F (427 ^{o}C) or Higher until 1996 [7]

Location	**Time to Failure**
RDF-Fired Plants with Suspension and Grate Burning	
Plant H	~ 1 year(A)
Plant I	2 to 3 years(A)
Mass-Burn Plants with Rotary Combustors	
Saugus, MA	1,600 hours
Plant J	3,000 hours

(A)Severe corrosion detected before failure

Frequent replacement of superhater tubes became the common practice for WTE plants operating at higher steam temperature which increases the thermal efficiency of the plant but also increases the cost of operation [5]. Thus, searching effective methods to prevent HTC problem and extend the lifetime of superheat tubes is an urgent issue.

To reduce the HTC problem in WTE plants, especially on superheater tubes, several methods has been adopted. In the early days, the methods used included adding refractory coatings (e.g. SiC) and metal shields, reducing soot blowing pressure and frequency, installing baffles, moving superheater tubes to lower temperature zone, and upgrades of metal used for superheater tubes [7].

Later, weld overlays, laser claddings, fused coatings, and thermal spray coatings were found to be better methods to deal with the HTC problem in WTE boilers [5]. At the present time, thermal spray coating techniques, which include flame spray, electric arc spray, plasma spray, high velocity oxy-fuel spray, high velocity air-fuel spray, and detonation spray, have been shown at European WTEs to be the best way to protect superheater tubes and prolong their lives. This is due to the fact that a wide variety of materials can be applied by thermal spray techniques to create coatings with outstanding quality, such as low porosity, high hardness, etc. [6] Instead of applying methods which affect the thermal efficiency of the WTE (e.g. lowering steam temperature), coating of the superheater tubes can be more cost-effective.

Therefore, the objective of this thesis was to identify the available thermal spray techniques and coating materials that have been used for prolonging the life of superheater tubes; and provide this information to the U.S. WTE companies so that they may decide on the appropriate thermal spray technique and coating materials to improve superheater tube performance. In addition to the research and cost-benefit analysis carried out by the author, the Earth Engineering Center of Columbia University also engaged the services of a European specialist on combatting superheater corrosion. His report is shown as Appendix 1 to this thesis.

Chapter 2: Coating Techniques for Preventing High Temperature Corrosion inside Waste-to-Energy Boilers

When the steam temperature generated by combustion, for electricity production, is approximately 350°C or lower, carbon steel is generally used for superheater tubes. When the boiler temperature is 400°C or higher, Fe-base and Ni-base austenitic materials are used or are being tested for improving corrosion resistance at higher temperatures in WTE plants [3]. However, metal tubes with better corrosion resistance always cost more, so there should be a balance between cost of superheater tubes and cost of frequent shutting down the plant operation to replace or repair metal tubes. The use of corrosion-resistant coatings on superheater tubes may be preferable if they can extend the lifetime of SHT. In recent years, weld overlays, laser claddings, fused coatings and thermal spray coatings have been commonly applied on superheater tubes for preventing HTC problems inside WTE plants [5].

2.1 Weld Overlays

Weld overlay is also called cladding, weld cladding or weld overlay cladding. It is a welding process to apply one or more metals with specific required characteristics (i.e. corrosion resistance) to a base metal. Instead of joining two pieces of material together, weld overlay applies a layer with corrosion resistant or hard facing onto selected base materials, which is different from general welding. [8] Weld overlay can provide a chemically bonded dense and thick coating layer on base metals. The widely applied Alloy625 weld overlays have been proved that they can provide outstanding corrosion resistance and last 10 years or more with excellent welding workability. As for superheater tubes, the metal inert gas (MIG) welding and plasma powder welding (PPW) are used for preventing HTC problem inside WTE plants. The durability of weld overlays can last 15 years or longer [3]. However, weld overlays also have drawbacks. The major problem is that strong iron (Fe) dilution from base material to the coating will occur, which will reduce the corrosion resistance of the coating. Besides, weld overlays can only provide coating layers with a thickness from 2 to 3 mm [4].

2.2 Laser Cladding

Laser cladding is also called laser deposition, which is a process to add one material onto the surface of another material (base material) [9]. The mechanism of laser cladding is shown in Figure 3. A selected material in wire form or a stream of material powder is fed under the laser beam when the beam is scanned across the surface of target base material. A deposited coating will be left behind after the scanning [9]. The selection of materials for laser cladding is wide, and this technique is precise. It has minimal heat input, and the deposits are completely fused on the base material, so there will be only little or no porosity, which is a significant factor regarding to coating's corrosion resistance. However, until now, laser cladding is only under testing for its application inside WTE boilers [4].

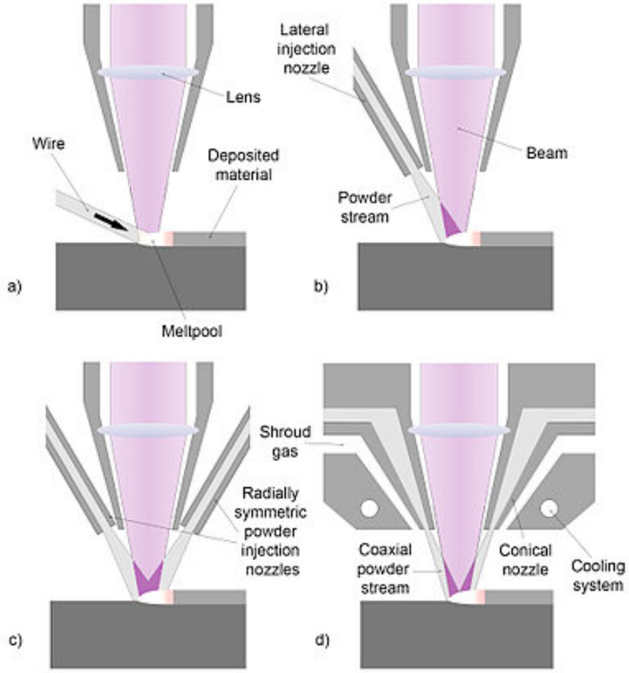


Figure 3. Schematic of four kinds of laser cladding [10]

2.3 Fused Coatings [11]

In the process of forming fused coatings, also called spray and fuse coatings, selected materials are deposited onto the surface of a substrate using a combustion powder spray gun first. After the required thickness of coating has been applied on the substrate, the coating is fused on the substrate at a temperature up to 2,000°F by means of an oxygen-acetylene torch or passing the tube through a furnace to achieve a metallurgical bond will be achieved between the coating and the substrate.

2.4 Thermal Spray

In thermal spray techniques, selected coating materials, either in powder or wire form, are melted first in a heat source generated by a spray gun. The molten particles are then injected onto the surface to be coated by a gas jet of high velocity (Figure 4). Of all the coating techniques that can be used for adding coatings onto superheater tubes, thermal spraying can provide relatively thin layers, ranging from 100μm to 800μm (0.1 to 0.8 mm). The selection of coating materials is not limited, as may be the case with other coating techniques. Also, thermal spray techniques can be operated either on-site or off-site and at relatively low cost [3].

At present, there are seven kinds of thermal spray techniques: Flame spray, electric arc spray, plasma spray, high velocity oxy-fuel spray, high velocity air-fuel spray, detonation spray, and warm spray, which can be used for preventing HTC problem inside WTE plants [6].

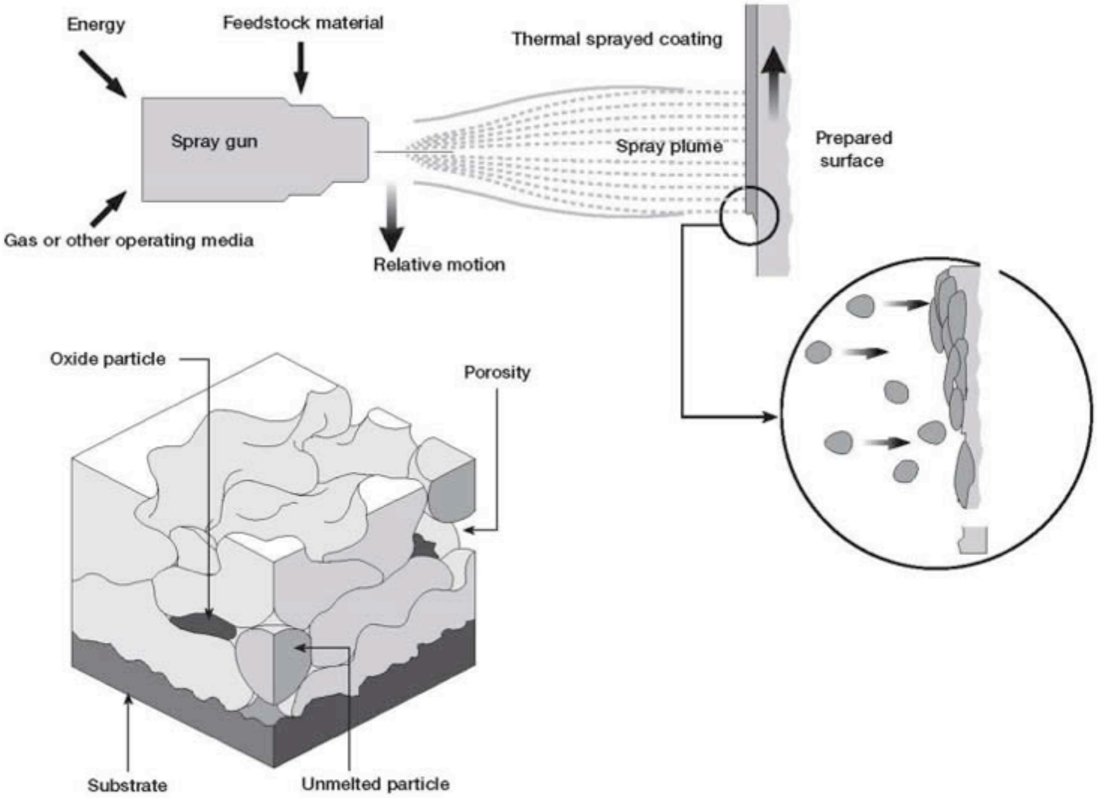


Figure 4. Schematic of thermal spray techniques and the coating formed on the substrate [12]

Chapter 3 Thermal Spray Techniques

Thermal spray techniques were developed by Max Ulrich Schoop in Zurich in the early 1900s. The very first kind of thermal spray technique was wire flame spray, which is also known as metallizing. At that time, the process was to firstly melt metal, either pure or alloyed, in wire form, and then spray the metal onto a substrate by a jet of high-velocity compressed air. The main problem of this technique at the beginning was the high porosity and low bond strength of coatings. Later, electric arc wire spray was developed by Max Ulrich Schoop. In the 1930s, spray materials in power form was introduced in this field. In the 1960s, there was an important breakthrough, which is the introduction of plasma spray that could use both metals and refractory materials [13]. After that, more thermal techniques were developed. As the application of thermal spray techniques become more and more widespread in many industries, the interest in applying to WTE plants also grew.

3.1 Flame Spray

Flame spraying can use feedstock materials in either powder, wire, or rod form [14]. The method of wire- or rod-form feedstock materials is illustrated in Figure 5.

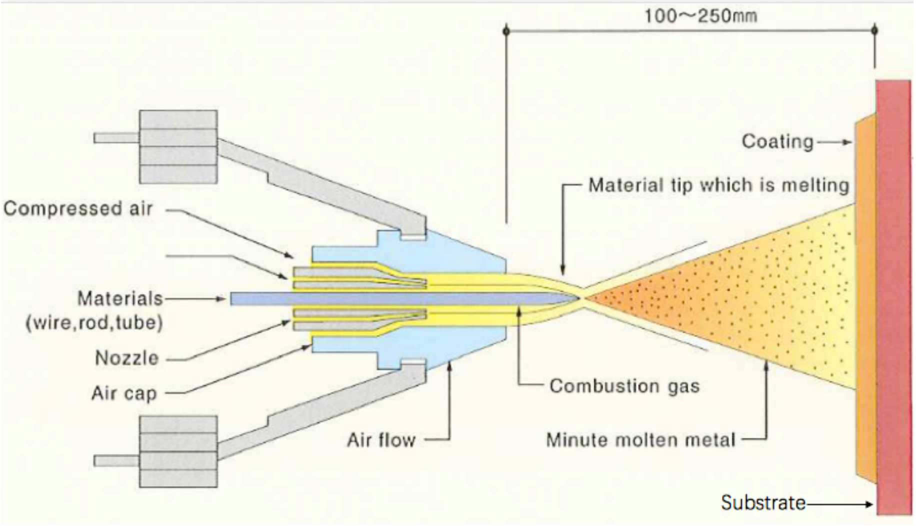


Figure 5. Schematic for flame spray with wire- or rod-form feedstock materials [15]

The feedstock materials are inserted through the center hole of the spraying torch where it is melted by the surrounding combustion gas. The molten particles are then sprayed on to the surface of selected substrates by high-speed compressed air [15]. The mechanism of powdered feedstock materials is shown in Figure 6.

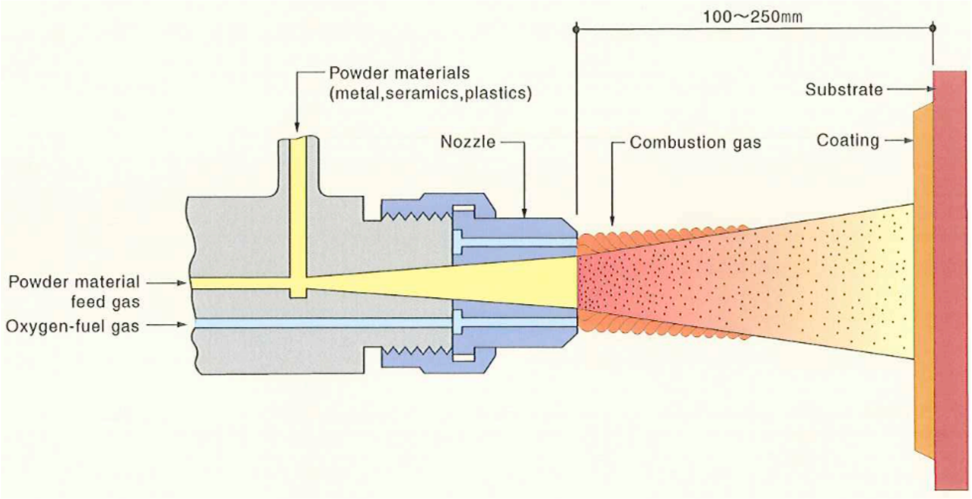


Figure 6. Schematic for flame spray with powder -form feedstock materials [15]

Instead of inserting the feedstock into the spray torch, the powder-form feedstock materials are carried into the torch by the carrier gas stream [15]. The fuel gas can be hydrogen, acetylene, propane, natural gas, etc. [14]. The advantages of this technique are lower equipment cost and flexibility of applying on site [16]. The disadvantages are high porosity (10-20%), low density, and high oxide occlusion (10-20 wt%) of the coating; and lower bond stretch between coatings and substrates, in comparison to other thermal spray techniques [17].

3.2 Electric Arc Spray

The electric arc spray process can be used only with wire-form feedstock materials. Two metallic wires of the same composition are fed at controlled speed into the arc gun and electrically charged with positive and negative polarity. At the point where the two wires come into contact, an electric arc is created and it melts the wires. A compressed gas steam accelerates the molten particles toward the surface of the tube and forms the coating. [18]

Electric arc spraying (Figure 7) is a simple technique that can be used on-site because it only requires electricity and compressed air [13]. Other advantages of electric arc spraying include [16 & 19]:

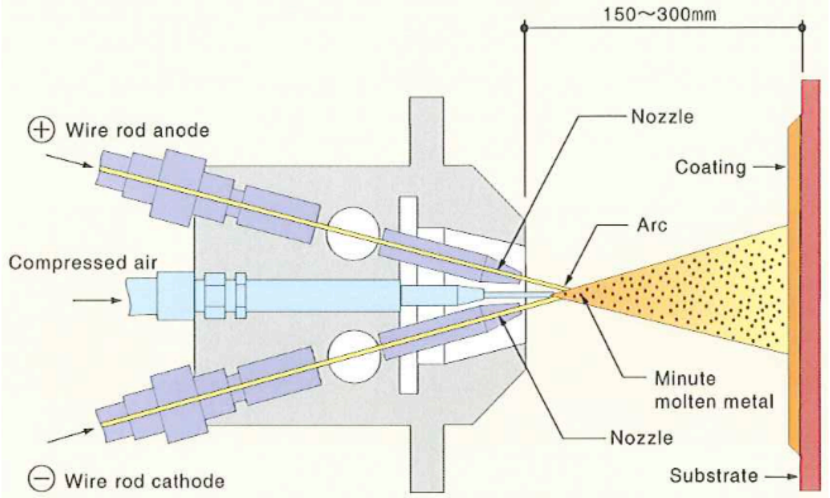


Figure 7. Schematic for electric arc spray [18]

1. Low heat input
2. High bond strength (2 to 3 times greater than flame spray)
3. Denser coating (compared to flame spray)
4. Complete particle meting guaranteed
5. Larger spray area
6. High spray efficiency
7. Lower operating cost (compared to flame spray)

However, this technique also has some drawbacks. The application of feedstock materials is limited to metals in wire form; also during operation, a large amount of fume and dust are emitted. Moreover, the porosity level and the amount of oxide occlusions in the coatings are high and the bond strength is low, as compared with coatings created by plasma spray and high velocity oxy-fuel spray. [20]

3.3 Plasma Spray

During the process of plasma spray, localized ionization and a conductive path for a direct current (DC) arc are formed in between two electrodes, the cathode and the anode, through which flows the plasma forming gas, e.g. argon. The plasma gas is heated by the high voltage arc discharge to extremely temperatures and ionized to form a plasma, which expands and accelerates through the nozzle to form a plasma jet that propels the molten particles onto the coated surface [21 & 22; Figure 8]

Plasma spray is known as atmospheric plasma spray (APS). It also has a variant, which is vacuum plasma spray (VPS). In which molten particles undergo less oxidation in VPS process thus resulting in coatings with better quality. One of the advantages of plasma spray is its low porosity levels in the coating, as low as 1 to 2 percent. Also, the process does not cause degradation of the mechanical properties of substrates [13]. The disadvantages of this technique are its relative high cost and complexity of process [22].

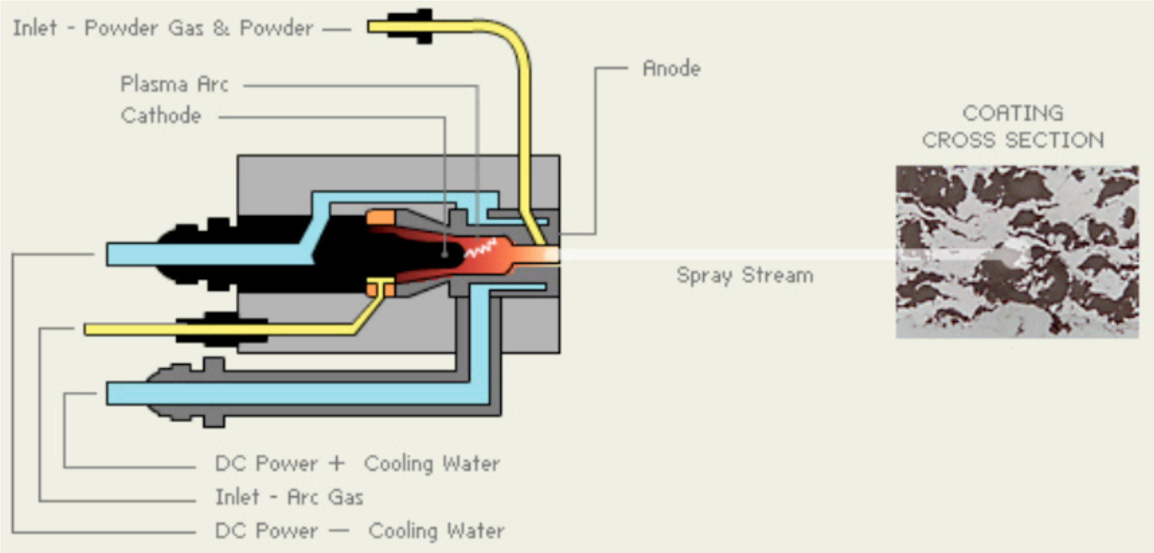


Figure 8. Schematic for plasma spray [21]

3.4 Detonation Spray

Detonation spray is considered to be the first thermal spray process with high velocity. As shown in Figure 9, the composition of detonation gun contains a long gun barrel, which is closed at one end and open at the other end, and it is also water-cooled. Selected coating materials are injected into the gun barrel with a mixture of fuel gas (i.e. acetylene). The fuel gas mixture will be ignited by a spark plug. After that, coating materials will be melted and accelerated to a supersonic velocity, and then injected onto the surface of workpiece. After each work, the gun barrel need to be flushed by nitrogen to remove remaining molten particles inside the gun. [23 & 24]

During the deposition of coating materials, the velocity of molten particles is relatively high, which is about 800-1200 m/s. Thus, the coatings show outstanding morphological features, such as low porosity and high density, and excellent mechanical properties, such as high hardness and bond strength, which provide the coatings with good HTC and oxidation resistance. [25] However, spray materials with low density is not acceptable by detonation gun spray. Besides, the noise level of this techniques is high, and the cost of it is high as well. [26]

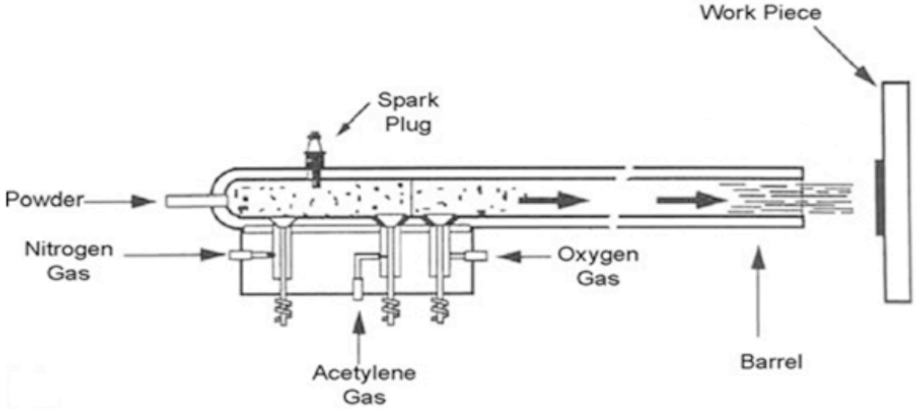


Figure 9. Schematic for detonation gun (D-gun) spray [24]

3.5 Warm Spray

Warm spray is a variant of high velocity oxy-fuel spray, which will be introduced in 3.6. A warm spray system is developed by adding a mixing chamber between the original combustion chamber and nozzle in a conventional HVOF system (JP5000, Praxair Technology Inc., USA) (Figure 10) [27]. During warm spray process, a mixture of fuel (i.e. kerosene [28]) and oxygen is continuously injected into the combustion chamber and ignited by a spark plug. After the combustion chamber, nitrogen gas with adjusted flow rate will be injected into the mixing chamber to ensure that the temperature inside is lower than the melting point of coating materials [27 & 28]. At last, heated particles in solid state with a high velocity beyond the critical velocity for bonding formation between the coating and the substrate will be propelled by gas stream inside the gun onto the surface of workpiece [28]. Warm spray is developed for filling the vacancy between high velocity oxy-fuel spray (with operational temperature between 1500~2500 K) and cold spray (with operational temperature below 800 K) [29]. Due to its controllable temperature and speed, it can help to avoid thermal deterioration of materials' original characteristics [29]. Warm spray is the newly developed thermal spray technique, so there are less applications of warm spray technique for preventing HTC problem inside WTE boilers.

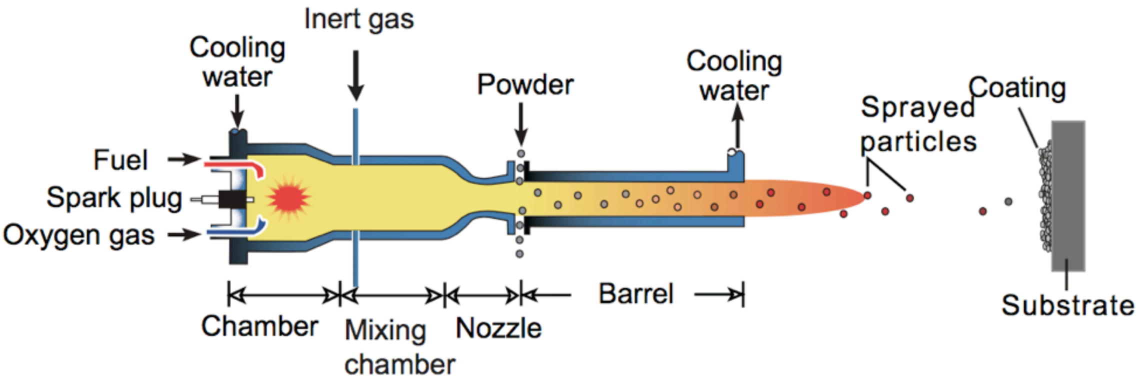


Figure 10. Schematic for warm spray [28]

3.6 High Velocity Oxy-Fuel Spray (HVOF) and High Velocity Air-Fuel Spray (HVAF)

In the high velocity oxy-fuel(HVOF) spray process, a mixture of oxygen and fuel, such as propane, acetylene, or hydrogen are ignited to produce a hot flame with high pressure at supersonic speeds; this high-pressure flame melts the injected powder and propels the molten particles onto the substrate (Figure 11) [13 & 30].

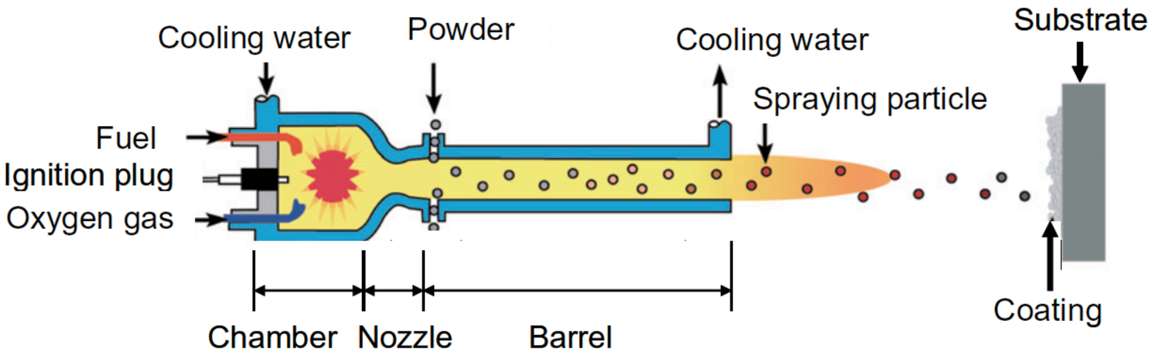


Figure 11. Schematic for warm spray high velocity oxy-fuel spray (HVOF) [28]

High velocity oxy-fuel spraying is widely used for metallic materials because its higher temperature, in combination with the high particle velocity at impingement on the substrate create denser and well-adhering coatings with strong bond to the substrate [31]. Also, HVOF spray can produce coatings with porosity less than 0.5 percent [13].

There are two kinds of HVOF: One of them is high velocity oxy-fuel liquid-fueled (HVOFLF) spray, which uses liquid fuel and a Carbide Jet Spray (CJS) gun; the other one is high velocity oxy-fuel gas-fueled (HVOFGF) spray, which uses gaseous fuel and a Diamond Jet (DJ) gun. DJ guns produce higher temperature and lower velocity than the

CJS process and has been found to be more suitable for feedstock consisting of very small particles [31].

Another thermal spray technique, similar to the high velocity oxy-fuel spray process, is the high velocity air-fuel (HVAF) spray that uses air instead of oxygen, therefore, is less costly to operate. The process of high velocity air-fuel is exactly the same as high velocity oxy-fuel spray. However, the lower temperature of HVAF results in coatings of lower residual tensile and compressive stress [32].

The use of the HVOF spray process is most prevalent in WTE applications because it can produce thicker coatings with higher level of adhesion and lower porosity, in comparison to the other thermal spray techniques. Its drawbacks are relatively low deposition rate (30%-50%), and higher equipment cost. It is always used when high coating density and strength are required [26 & 33].

Chapter 4 Coating and Tube Materials

High-chromium, high-nickel, and nickel-chromium alloys have a high level of resistance for high-temperature oxidation and corrosion [34 & 35]. Thus, these materials have attracted attention and fairly wide application for thermally sprayed coatings in WTE boilers. In particular, it has been shown that an increasing amount of molybdenum increased the corrosion resistance of nickel-based alloy coatings under chlorine-rich and chlorine-oxidizing waste incineration environments [2, 36].

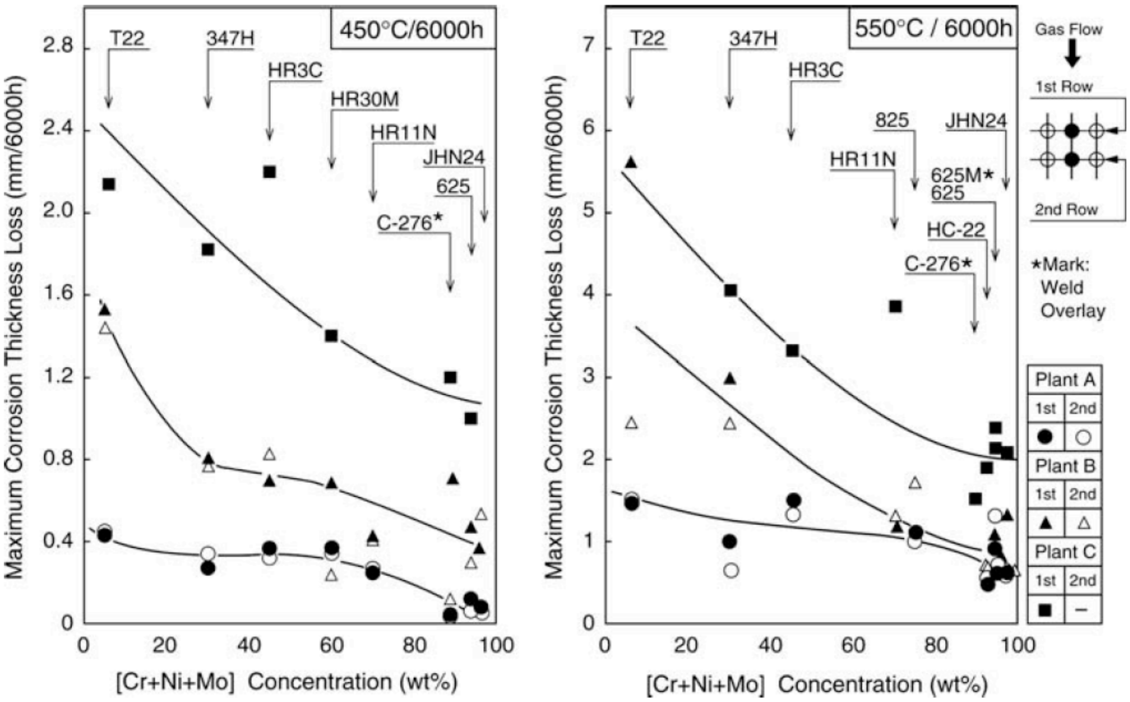


Figure 12. Change in maximum corrosion thickness loss with [Cr+Ni+Mo] concentration of alloys in 6000 h field tests [3]

Figure 12 shows the resistance of several materials tested under a WTE environment for 6000 hours. It can be seen that independently of the coating temperature (450 or 550^{o}C), the rate of corrosion (in mm of thickness/6000 hours) decreased appreciably as the [Cr+Ni+Mo] concentration in the alloy was increased. Ceramic coatings also showed good durability on superheater tubes inside WTE boilers; however, there are fewer application examples of ceramic coatings [4].

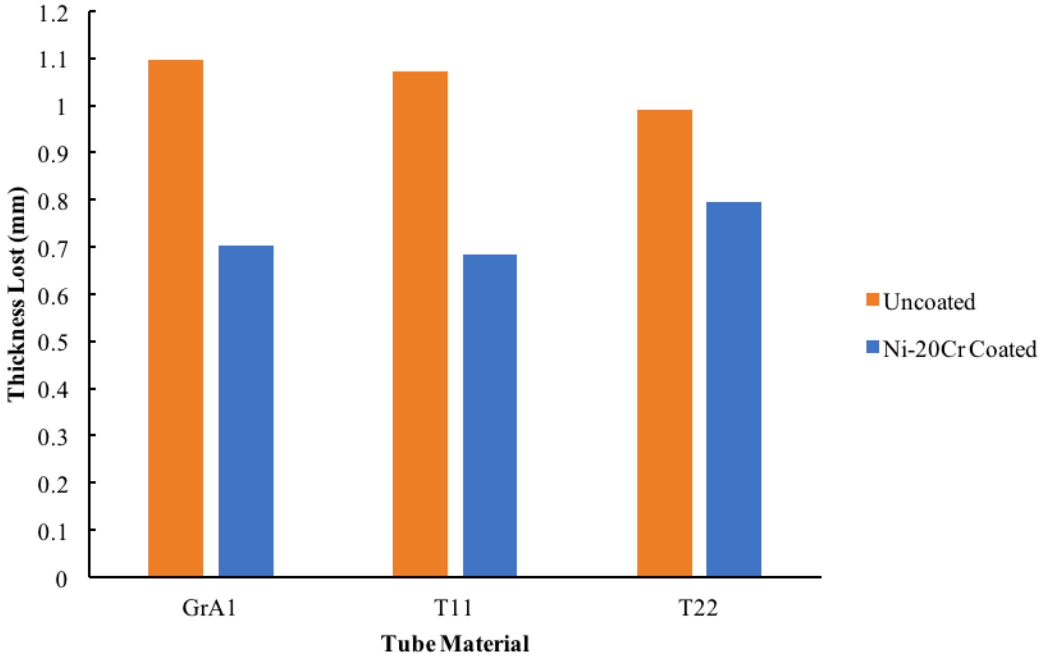


Figure 13. Metal thickness loss for uncoated and Ni-20Cr plasma sprayed steels after 1000 hours of exposure to superheater tube of coal-fired boiler at 755°C [37]

Figure 13 shows an example of the importance of adding coatings onto superheater tubes. This was a test of three kinds of superheater tube materials and one plasma sprayed Ni-20Cr coating, in a coal fired boiler. Although the HCl concentration in such a power plant is much lower than in a WTE boiler, and the temperature is extremely high (755°C), this comparison shows that the plasma sprayed coating decreased the corrosion rate of all three metals.

4.1 Case Studies, Assumptions and Sample Calculations

There have been several laboratory tests of different coating materials and tube materials (Table 5), which provided important information, such as the composition of each materials, the corrosion rate, etc. In order to comprehensively analyze the data of different research studies, the following assumptions were made:

Table 5. Case studies for potential coating materials and tube materials

Case	Technique	Coating Materials	Tube Materials	Test Environment	Temperature	Test Duration	Ref.
1	HVOF (Carbide Jet Spray and Diamond Jet Hybrid guns)	NiCr, IN625, Diamalloy 4006 (Ni-21Cr-10W-9Mo-4Cu), and iron-based partly amorphous alloy SHS9172 (Fe-25Cr-15W-12Nb-6Mo)	X20, Alloy 263, and Sanicro 25	NaCl-KCl-Na2SO4 salt with controlled H2O atmosphere (10% H2O with 6.5 wt.% NaCl, 59 wt.% Na2SO4, and 34.5 wt.% KCl)	525 and 625	168h	6
2	HVOF (Carbide Jet Spray and Diamond Jet Hybrid guns) and Electric Arc Spray	NiCr, IN625, FeCr, and NiCrTi	T92 and A263	In a circulating fluidized bed boiler	550 and 750	5900h	39
3	HVOFGF (gas-fueled) and HVOFLF (liquid-fueled) system. Gas-fueled Diamond Jet (DJ) Hybrid 2600 and liquid-fueled Carbide Jet Spray (CJS). Nozzles 2702 and 2701 were applied with DJ spraying.	NiCr(51Ni-46Cr-2Si-1Fe) and FeCr (Fe-19Cr-9W-7Nb-4Mo-5B-2C-2Si-1Mn) powder		In laboratory exposures simulating biomass boiler conditions (the coated specimens were installed into a superheater area of the boiler with a probe measurement device) and in an actual power plant boiler exposure (with NaCl-Na2SO4-KCl molten salt in water vapor atmosphere).	575 and 625 for lab; 550 and 750 for the actual boiler	168h for lab; 1300/300/5900h for the actual boiler	40
4			13CrMo44, HCM12A, Super 304, Sanicro 28, and Hastelloy C-2000	In the waste-fired power plant, Müllverwertung Borsigstrasse, MVB, in Hanburg, Germany	440	1500h	41
5	Kerosene-fuel-led TAFA-JP5000 HVOF system	NiCrBSiFe, Alloy 718, Alloy 625, and Alloy C-276	P91, A625	45% K2SO4-KCl mixture and gaseous HCl-H2O-O2 containing environments.	525, 625, and 725	168h	42
6	HVOF (Thermal Spray and Induction Heating)	Colmonoy 88, SW 1600, SW1641	SA213 T22	NaCl salt, 8% O2, 12% CO2, 800ppmv HCl, 100 ppmv SO2 with a balance of N2	450, 500, and 550	24h	1

1. All these test environments have the same corrosion effect on these selected coating and tube materials.
2. Except for the selected thermal spray technique, all other technical parameters (e.g. spray distance, fuel ratio, etc.) do not influence the quality of coating.
3. The unit length of sample superheater tube was assumed to be one meter.
4. The outside diameter of the sample superheater tube is 3.81 cm (1.5 in), and the wall thickness of the tube is 0.4572 cm (0.18 in) [43].
5. The operating time of WTE plant is 8000 hour per year (90% availability).
6. Coating materials are made from pure metal element materials.
7. The extension of superheater tube's lifetime is 5 years; in the other words, the lifetime of the coated superheater tubes will add five years to the SHT lifetime because only the coatings on the tubes will be corroded in the assumed five-year period.
8. The corrosion rate will be uniform around the tube, as illustrated in Figure 14.

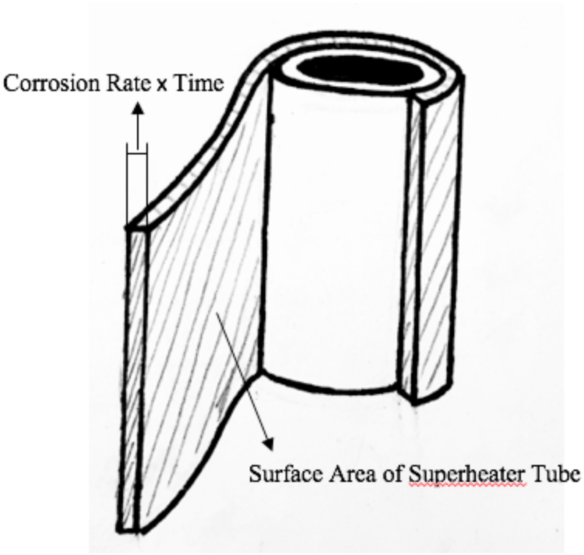


Figure 14 Schematic for assumed uniform corrosion of coating around superheater tube

Therefore, in each unit period of time, the volume loss due to corrosion of superheater tube will be equal to: corrosion rate × time × surface area of superheater tube

9. Only the price/cost of tube or coating materials is considered; other costs, such as equipment cost are excluded in the following cost analysis. Based on a private communication with N.J. Themelis on April 3rd, 2017, the cost of the metal is only a fraction of the total cost of thermally coating one square meter of superheater tubes'

surface. (Appendix 1) [44]

10. Since WTE superheater tubes are not operated at a temperature higher than 550°C, all the experimental coating data obtained at temperatures higher than 550 °C were not included in the following analysis.

Based on the detailed information provided in each research study listed in Table 5, the density and price/cost of materials can be calculated. A sample calculation is shown below:

Table 6. Composition of alloy (wt.%)

Ref	**Material**	**Ni**	**Fe**	**Cr**	**Mo**	**Al**	**Nb**	**Ti**
39	Alloy 625	63.79	5	21.2	8.3	0.5	1.2	0.01

Table 7. Price of metals ($/kg)

Ni [45]	**Fe** [46]	**Cr** [47]	**Mo** [48]	**Al** [49]	**Nb** [50]	**Ti** [51]
10.44	0.0596	1.85	15.25	1.726	92.54	3.87

Table 8. Density of metals (g/cm^3) [52]

Ni	**Fe**	**Cr**	**Mo**	**Al**	**Nb**	**Ti**
8.908	7.874	7.14	10.28	2.7	8.57	4.507

$Density\ of\ Alloy\ 625$:

$$\begin{aligned}&= 63.79\%\times\frac{8.908\mathrm{g}}{cm^3} + 5\%\times\frac{7.874g}{cm^3} + 21.2\%\times\frac{7.19g}{cm^3} + 8.3\%\times\frac{10.28g}{cm^3}\\&+ 0.5\%\times\frac{2.7g}{cm^3} + 1.2\%\times\frac{8.4g}{cm^3} + 0.01\%\times\frac{4.43g}{cm^3}\\&= 8.56\mathrm{g/cm^3}\end{aligned} \tag{1}$$

$Unit\ Price\ of\ Alloy\ 625$:

$$\begin{aligned}&= 63.79\%\times\frac{\$\ 10.44}{\mathrm{kg}} + 5\%\times\frac{\$\ 0.05958}{kg} + 21.2\%\times\frac{\$\ 1.85}{kg}\\&+ 8.3\%\times\frac{\$\ 15.25}{kg} + 0.5\%\times\frac{\$\ 1.726}{kg} + 1.2\%\times\frac{\$\ 92.54}{kg} + 0.01\%\times\frac{\$\ 3.87}{kg}\\&= \$\ 9.44/\mathrm{kg}\end{aligned} \tag{2}$$

The complete data of each coating and tube material, the calculated results of the cost of applying a coating onto the one-meter-long SHT for an assumed five-year-lifetime extension, and the cost of making one meter of superheater tubes using the selected materials for each research study listed in Table 5 are shown in Appendix 2 of this report.

4.2 Results

4.2.1 Tube Materials

For future consideration of superheater tube materials, obviously, the ones with low corrosion rate and reasonable cost will be the appropriate choices. For example, as shown in Figure 15, A625 has good performance at 525°C and 625°C. Also, A263 has relatively low corrosion rates at 575 °C, 625°C, and 750°C. Furthermore, P91 can provide corrosion rates of less than 5 mm/year at 525°C and 625°C. In addition, T92, Sanicro 28, Hastelloy C-2000, and HCM12A have relatively low corrosion rate (<5mm/year) at temperatures they were tested.

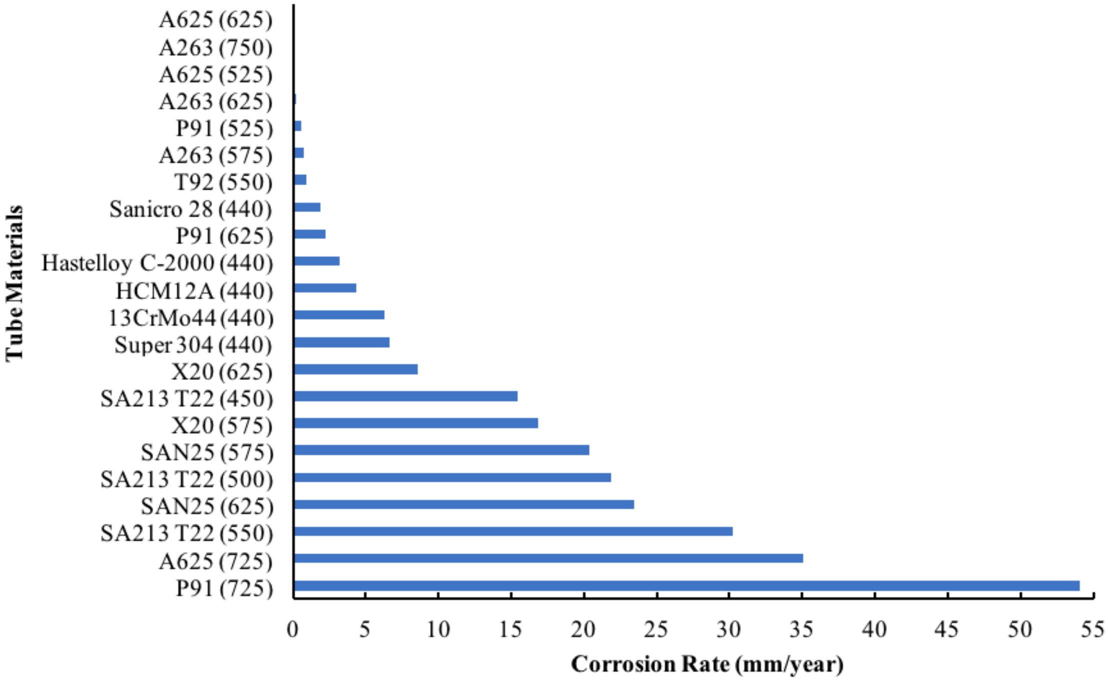


Figure 15. Corrosion rate for tube materials (test temperatures are shown in parentheses)

Although A625 exhibits the best corrosion resistance performance among all the examined tube materials, its price is very high (Figure 16). Similarly, A263 performs well in a WTE environment at 525°C and 625°C, but its price is also high. Due to their high cost, A263 and A625 cannot be a good choice for superheater tubes; however, they may be very good to be used as coating materials, as will be discussed in Section 4.2.2.

On the other hand, P91 can be a good choice as tube material since it has a relatively better corrosion resistance, at 525°C and 625°C, and lower cost in comparison to other tube materials. In addition to P91, T92 also has a relatively low price and good performance in high-temperature-corrosion environment.

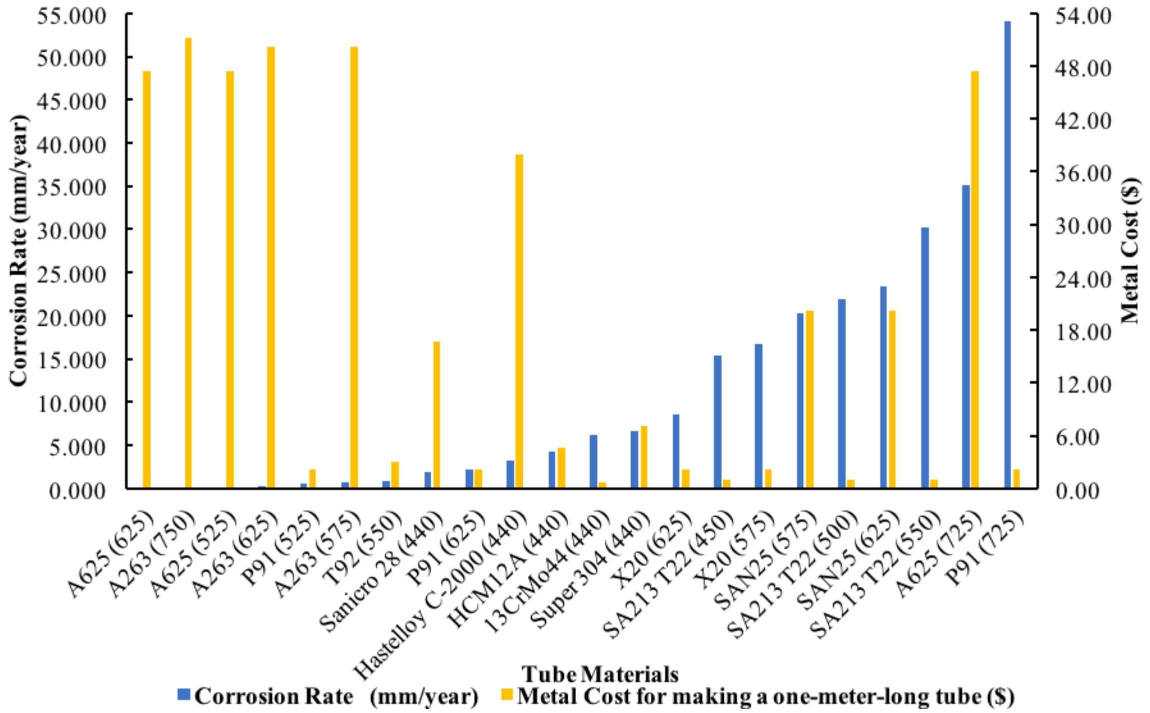


Figure 16. Corrosion rate and metal cost for making a one-meter superheater tube (test temperatures are shown in parentheses)

4.2.2 Coating Materials

Figure 17 compares the corrosion resistance of the coating materials tested in the cases listed in Table 5. In this Figure, some of the coating materials are named differently in order to be easy to differentiate between different cases. The following coating materials:

- NiCr sprayed by HVOF,
- Alloy C-276 sprayed by HVOF,
- IN625 sprayed by HVOF,
- NiCrTi sprayed by electric arc,
- the tube material A625 (potential coating material),
- Colmonoy 88 sprayed HVOF (at 450°C and 500 °C),
- FeCr sprayed by HVOF,
- NiCrBSiFe sprayed by HVOF, and

- Alloy 625 srpayed by HVOF

exhibited relatively low corrosion rates, i.e., less than 1 mm per year.

Alloy 718 and Colmonoy 88 tested at 550°C also provide good corrosion resistance, of less than 1.5 mm per year. SW 1641 tested at 450°C had a corrosion rate around 6 mm per year. As for the rest of the tested coating materials, their corrosion rates are relatively high, i.e.., more than 10 mm per year. In order to find out the best choice of coating materials, the ones with relatively high corrosion rate are excluded in the following analysis.

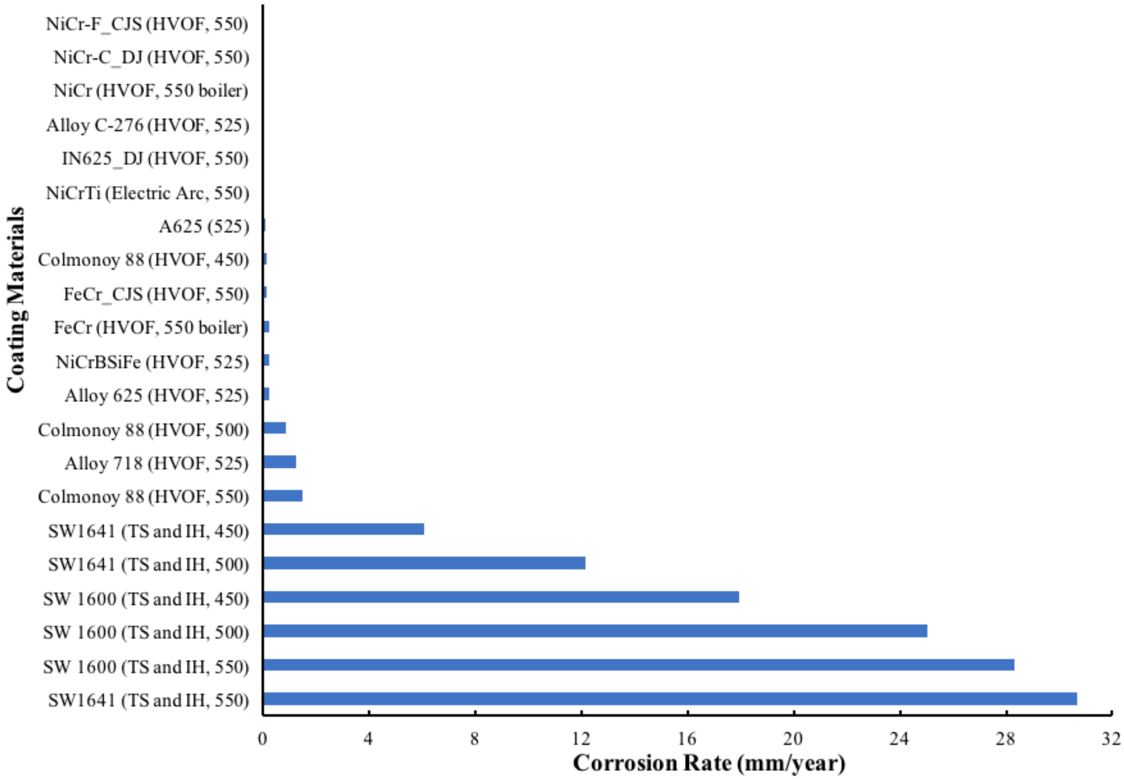


Figure 17. Estimated corrosion rate for coating materials (test temperatures and techniques used are shown in parentheses; "F"in "NiCr-F" stands for "fine", which mean that fine powder was used for the test, "C" in "NiCr-C" stands for "coarse", which mean that coarse powder was used for the test; "TS and IH" means "thermal spray and induction heating")

4.2.3 Relative cost of application of coating

Figure 18 is a comparison of the cost for adding each coating material onto the assumed one-meter-long superheater tube, in order to achieve a five-year-lifetime extension. As was done for Figure 17, some of the coating materials are described by different names, in order to differentiate. Among the coating materials with lower corrosion rate in Figure 16, NiCr sprayed by HVOF, NiCrTi sprayed by electric arc spray technique, Alloy C-276 sprayed by HVOF, IN625 sprayed by HVOF with DJ, the tube material A625 (potential coating material), FeCr sprayed by HVOF with CJS, and Colmonoy88 by HVOF (at 450°C, 500°C, and 550 °C) have both better corrosion resistance and lower cost. Coating materials SW1641, SW1600, and NiCrBSiFe are not included because of their very high cost but can be found in Table 14 Appendix 2..

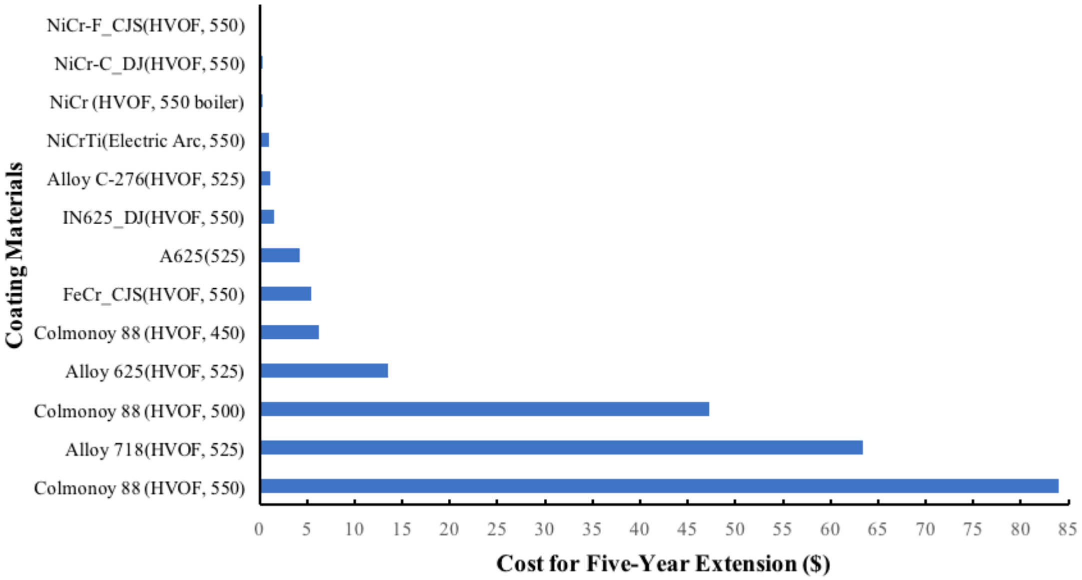


Figure 18. Metal cost for spraying coating materials onto the assumed one-meter-long superheater tube for five-year-lifetime extension (test temperature and techniques used are shown in parentheses; "F"in "NiCr-F" stands for "fine", which mean that fine powder was used for the test, "C" in "NiCr-C" stands for "coarse", which mean that coarse powder was used for the test.)

Figure 19 includes coating materials with corrosion rate of less than 1 mm/year and cost of less than $100 for coating the assumed one-meter-long superheater tube; some of the less attractive materials have not been included in Figure 19 but can be found in Appendix 2. NiCr sprayed by HVOF can provide both better corrosion resistance and lower cost when compared with the rest of potential coating materials. Also, Alloy C-276 coating sprayed by HVOF has excellent performance at 525 °C, and it is relatively low-cost. IN625 sprayed by HVOF with DJ has very low corrosion rate and cost at its test temperature 550°C. NiCrTi sprayed by electric are spray technique performed outstandingly under HTC environment and its cost is low.

Although the metal cost for spraying Colmonoy 88 is relatively low (<\$50), its corrosion rate is high at the test temperature of 500 °C, in comparison to the other coating materials; however, it is still less than 1 mm per year. FeCr sprayed by HVOF with CJS has relatively high corrosion rate but it is low-cost in relation to other coating materials. Thus, it could be considered for SHT coating for high steam temperature applications.

The tube alloys, A625, can provide both acceptable low corrosion rate and cost at a test temperature of 525 °C. All of the coating materials shown in Figure 19 offer outstanding corrosion resistance (corrosion rate < 1mm/year). Besides, according to N.J. Themelis, the cost of thermal deposition is at best about \$200, for example, NiCr deposite. When compared with the fabricated NiCr alloy tube price of about \$30/kilogram, it is obvious that thermal coating should be applied only for maintenance purposes. Therefore, WTE companies should examine the relative costs of application of these materials in specific WTE applications and choose the one offering the best overall cost performance.

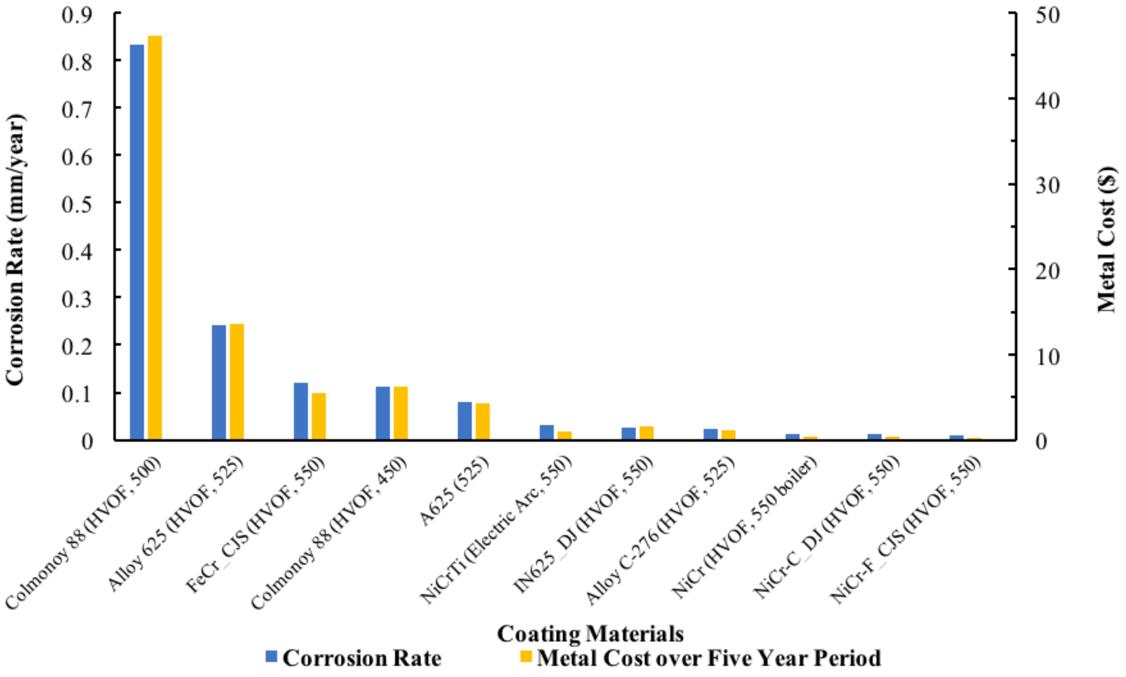


Figure 19. Estimated corrosion rate (<1 mm/year) and metal cost (<\$100) for coating materials sprayed for five-year-lifetime extension (test temperature and techniques used are shown in parentheses; "F"in "NiCr-F" stands for "fine", which mean that fine powder was used for the test, "C" in "NiCr-C" stands for "coarse", which mean that coarse powder was used for the test.)

4.3 Thermal Conductivity

Thermal conductivity represents the ability for a material to conduct heat [52]. To have a general view to identify if coatings will affect the efficiency of superheater tubes, the following calculation and analysis are done:

$$\text{Conductance of a metal material} = \frac{k}{l} \qquad (3)$$

where k is the thermal conductivity of materials, and ℓ is the thickness of materials. Since the thermal conductivity of metal in general is close to 30 W/m·K [53] and the thickness of analyzed superheater tubes is approximately 0.5cm (0.005 m). Thus, the conductance of metals in general is equal to $\frac{30\ \mathrm{W/m\cdot K}}{0.005\ \mathrm{m}}$ = 6,000 W/m^2·K. A general value for the conductance of gas is approximately 200 W/m^2·K [53]. Since the conductance of metals in general is greater than the conductance of gas in general, it shows that the overall heat transfer through the tube wall is not controlling by metals. This statement will always work since the thickness of tube wall with coatings cannot be thick as several centimeters, so the conductance of metals will always be greater than the conductance of gas. As a result, applying additional coatings onto superheater tubes will not affect the tubes' efficiency.

Chapter 5: Cost and Benefit Analysis

This analysis is based on a specific U.S. WTE plant [43] with the following characteristics:

1. Number of Units: Three
2. Maximum Continuous Rating (MCR)
   (a) Solid Waste Capacity per Unit: 600 tons/day
   (b) Fuel Design HHV: 5,500 Btu/lb
3. Design Date (MCR)
   (a) Continuous Steam Output: 171,121 lb/hr
   (b) Steam Pressure (at superheater non-return value outlet): 865 psig
   (c) Steam Temperature (at superheater non-return value outlet): 830 ^{o}F
   (d) Feedwater Temepratrure: 300 ^{o}F
4. Heat Loss: 28.65%
5. Heating Surface Summary (Circumferential)
   Superheater III: 5,278 ft^2
   Superheater II: 5,372 ft^2
   Superheater I: 11,027 ft^2
   Total Heating Surface of Superheater: 21,677 ft^2 (2014 m^2)

According to Professor N.J. Themelis, the efficiency for the turbine inside the plant is assumed to be 28%, and the price for electricity produced by the plant is assumed to be \$50/MWh.

Thus, in one day, the amount of electricity that can be produced by this three-unit plant can be calculated as following:

$$3\ Units \times \frac{600\ ton\ MSW}{day\text{-}unit} \times \frac{5{,}500\ Btu}{lb} \times \frac{2204.62\ lb}{ton} \times \frac{0.293071\ Wh}{Btu} \times \frac{MWh}{10^6\ Wh} = 6{,}396.5\ \text{MWh/day} \quad (4)$$

$$6396.5\ \text{MWh/day} \times (1\text{-}28.65\%) \times 28\% = 1{,}277.9\ \text{MWh/day} \quad (5)$$

Since the price for electricity is \$50/MWh, this plant can earn

$$(1{,}277.9\ \text{MWh/day}) \times (\$50/\ \text{MWh}) = \$63{,}894.5/\text{day} \quad (6)$$

Figure 20 shows the cost of selected coating materials from Chapter 4 for the assumed five-year-lifetime extension. Detailed data for their cost are shown in Table 16 in Appendix 2. Every year, WTE units are shut down for about 15 days for periodic maintenance. Coatings can help to reduce the maintenance time for superheater tubes, and the time saved will be used to continue producing energy. It is essential that the cost for adding coatings should not exceed the revenue earned by the plant in the time period saved by extend the lifetime of superheater tubes. As shown in Figure 20, the metal costs for spraying Colmonoy 88 by HVOF are about 12 times greater than the revenue earned by the plant in a day, which means that the plant will not lose profit only when the superheater tube maintenance time in total is more than 13 days when using Colmonoy 88 as coating material at 550 °C in the assumed five-year period. According to Professor N.J. Themelis, in general, WTE plants use approximately two weeks for the maintenance of entire plants. Thus, there should not be too many days that are spent especially for superheater tube maintenance; therefore, coating materials that are very costly to apply cannot be reasonable selections.

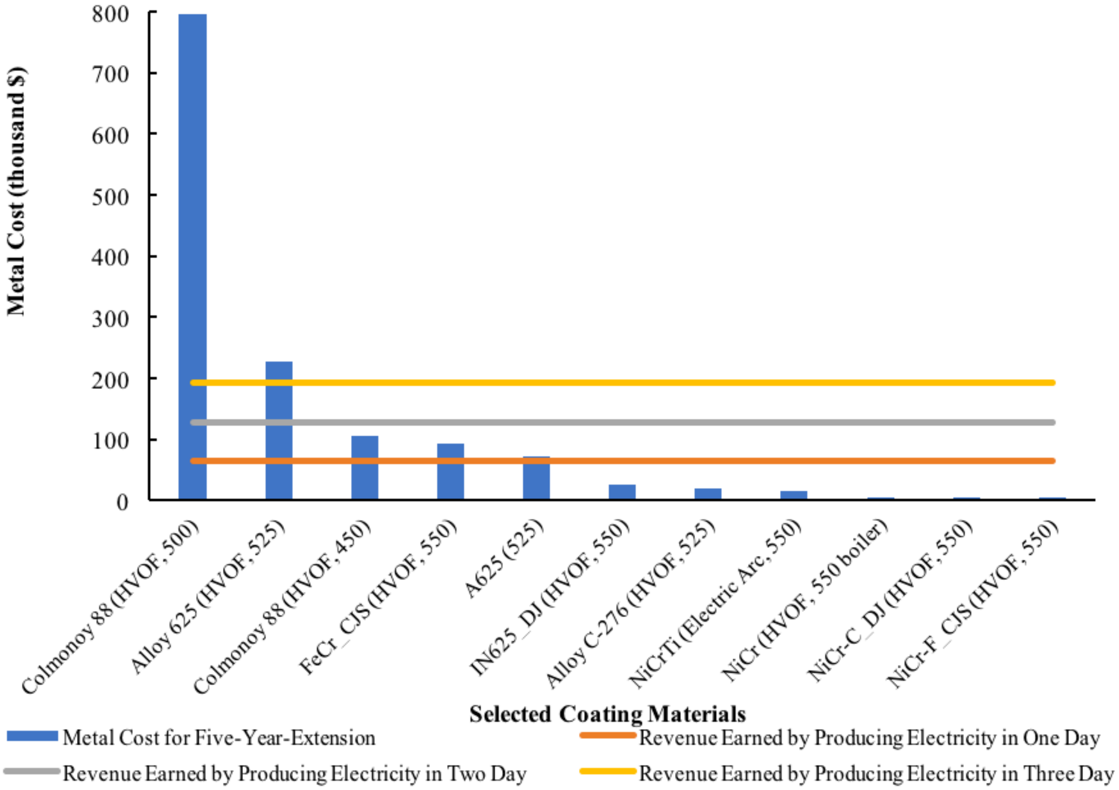


Figure 20. Metal cost for adding selected coating materials for five-year-lifetime extension (test temperature and techniques used are shown in parentheses; "F"in "NiCr-F" stands for "fine", which mean that fine powder was used for the test, "C" in "NiCr-C" stands for "coarse", which mean that coarse powder was used for the test.)

This analysis showed that Alloy 625 sprayed by HVOF can be used as SHT coating materials without affecting the plant's profit, when current downtime for superheater tube maintenance is more than four days in the assumed five-year period. Colmonoy 88 sprayed by HVOF, FeCr sprayed by HVOF with CJS, and A625 will be suitable coatings when the maintenance time for superheater tube is more than two days in the assumed five-year period. The rest of selected coating materials could be used as coating materials when the downtime for supereheater tube maintenance is more than one day in total in an assumed five-year period. Some of them would be a good choice even when the maintenance time is only more than a half day.

In summary, when selecting coating materials and methods of application, in addition to considering the SHT unit corrosion rate and cost, it is essential to compare the estimated cost with the revenue can be earned during the number of days that are saved by using SHT coatings that prolong the lifetime of superheater tubes.

Chapter 6: Conclusions and Further Study

6.1 Conclusions

Thermal treatment or waste-to-energy (WTE) is the only proven alternative to landfilling for managing post-recycling municipal solid waste (MSW). WTE prevents the leakage of methane and reduces the volume of MSW by 90%. However, due to the high content of chlorine, alkaline metals, heavy metals, and sulfates contained in MSW and under high temperature combustion, severe HTC corrosion, especially on superheater tubes, occurs and leads to material wastage, tube leakages, shortened lifetime of tubes, and unplanned shutdowns of boilers in WTE plants. Adding coatings onto superheater tubes can be a cost-effective method for reducing the superheater tube maintenance problem. Thermal spray techniques, especially the high velocity oxy-fuel (HVOF) spray technique, have proven to be a good way to prolong the life of WE superheater tubes.

Coatings with high chromium, nickel and molybdenum content have high corrosion resistance and can perform outstandingly under high-temperature-high-chlorine conditions. Based on the analysis of several research studies on the subject of SHT corrosion, due to its relatively low price and high corrosion resistance, T92 with a corrosion rate of 0.901 mm/year and a price of \$3.09/meter is a good choice for refurbishing superheater tubes operated up to 550^{o}C, while P91 with a corrosion rate of 0.601-2.263 mm/year and a price of \$2.11/meter is another good choice. Besides, A625 has better corrosion resistance performance (corrosion rate < 1 mm/year) as well, but its price, estimated at over \$50/meter, is very high in comparison to other coating materials.

In view of the relatively high cost of applying thermally sprayed coatings, either at the shop or at the plant, the overall conclusion reached is that the best practice is to use better alloy tubes (e.g. P91 and T92) in the initial manufacturing of the superheater tube bundles –even though they are costlier than the SA213-T22 tubes. Then, after a year's operation, use the HVOF spray coating of corrosion-resistant coatings (e.g. Colmony 88, Alloy 625, FeCr, in625, Alloy C-276, NiCr) or the electric arc spray coating (NiCrTi) to refurbish the high corrosion/erosion areas. This combination will result in the minimum cost and highest plant availability.

In summary, NiCr sprayed by HVOF is a good material to use for coating SHT in a WTE environment. NiCrTi sprayed by electric arc spray technique also has good performance as coating material. Alloy C-276 sprayed by HVOF also provides good corrosion resistance. IN625 sprayed by HVOF with DJ works good at 550 ^{o}C. FeCr sprayed by HVOF can perform good in a WTE environment with a temperature of 550 °C as well. As for Colmonoy 88 sprayed by HVOF, it could work at either 450 °C or 500 °C. Besides, Alloy 625 sprayed by HVOF can provide outstanding corrosion resistance, too. With regard to the alloys that are used to form SHT tubes, A625, will be good for operation as high as 525°C. All of these coating materials have exhibited corrosion rates of less than 1 mm/year and reasonable cost of application.

Each WTE plant will use several days in a year to shut down the plants for maintenance. Since no WTE plants have operated at a temperature over 500°C, based on the steam generators performance guarantees data provided by one specific U.S. WTE plant, Colmonoy 88 sprayed by HVOF cannot ensure the plant not to lose profit by applying it as a coating at a WTE environment with a temperature of 500 °C. Alloy 625 sprayed by HVOF (525 °C) can be chosen as coating materials only when the maintenance time for superheater tubes is more than four days, which ensures that the revenue earned by producing energy is higher than the cost for adding coatings to extend the lifetime of superheater tubes for the assumed five-year period. FeCr sprayed by HVOF with CJS (550°C), Colmonoy 88 sprayed by HVOF (450 °C), and A625 (525 °C) will also work when the maintenance time for superheater tube is more than two days for the assumed five-year period. As for the rest of materials mentioned in Chapter 4, they all are appropriate choices for coating materials because of their good corrosion resistance and ability to ensure the profit for the plant when the maintenance time for superheater tubes is more than one day.

The final decision of coating materials has to consider the actual condition of each plant because the additional cost for applying the coating should not exceed the gate fee and electricity revenue earned by extending the lifetime of the superheater tubes and reducing the time used for repairing or replacing the superheater tubes.

6.2 Further Study

There are many factors that could affect the results of selected thermal spray techniques and coating materials. For a more precise decision, the following factors should be considered for further study:

1. As for the test environment, pressure should be considered as well because it is a determine factor for the thickness of superheater tubes, and it also affects the corrosion condition on the tubes.

2. Each selected coating materials should be test in WTE environment under the same selected temperatures for a more comprehensive analysis.
3. As for thermal spray techniques, several parameters should be considered due to their influence on the quality of coatings. These parameters include spray distance, powder feed rate (if applicable), fuel ratio, selection of guns and nozzles, powdered materials' particle size (if applicable), etc. [6].
4. Since the temperature and corrosion effect varies along the position of superheater tubes, applying different coatings in different portion of superheater tubes could be considered due to different corrosion environment in the same WTE plant.
5. Besides metal cost, the other costs, such as instrument cost, should also be considered.

References

1. Sharobem, T.T. (2016). Mitigation of High Temperature Corrosion in Waste-to-Energy Power Plants.
2. Galetz, M. C., Bauer, J. T., Schutze, M., Noguchi, M., & Cho, H. (2013). Resistance of Coatings for Boiler Components of Waste-to-Energy Plants to Salt Melts Containing Copper Compounds. Journal of Thermal Spray Technology, Volume 22(5), Page 828-837.
3. Kawahara, Y. (2006). Application of High Temperature Corrosion-Resistant Materials and Coatings Under Severe Corrosive Environment in Waste-to-Energy Boilers. Journal of Thermal Spray Technology. Volume 16(2). Page 202-213.
4. Kawahara Y. (2016). An Overview on Corrosion-Resistant Coating Technologies in Biomass/Waste-to-Energy Plants in Recent Decades.
5. Epelbaum, G., Hanson, E., & Seitz, M. (2010). New Generation of Tube Surface Treatments Help Improve EfW Boiler Reliability. NAWTEC18.
6. Oksa, M., Tuuna, S. and Varis, T. (2012). Increased Lifetime for Biomass and Waste to Energy Power Plant Boilers with HVOF Coatings- High Temperature Corrosion Testing Under Chlorine-Containing Molten Salt. Journal of Thermal Spray Technology, Volume 22(5), Page 783-796.
7. Krause, H.H., and Wright, I.G. (1996). Boiler Tube Failures in Municipal Waste-to-Energy Plants. Materials Performance, Volume 35, Number 1, Page 46-54.
8. What is weld overlay? Renown Oil & Gas LTD provides an answer to commonly asked weld overlay questions. Retrieved from http://www.renown-oil-and-gas.co.uk/wp-content/uploads/2012/01/Information-Sheet-What-Is-Weld-Overlay.pdf
9. Laser cladding process. Retrieved from

http://www.lasercladding.co.uk/Laser-Cladding-Process.aspx
10. Cladding (metalworking). Retrieved from https://en.wikipedia.org/wiki/Cladding_(metalworking)
11. Spray & fuse hardfacing. Retrieved from http://www.thermalspray.com/thermal-spray-coatings/thermal-spray-coating-processes/spray-fuse-hardfacing/
12. What is thermal spray coating & how is the coating formed and how does it work? Retrieved from http://metal-spray-coating.com/what-is-metal-spray/
13. Ort, S., & Wagner C. (2012). Better Bonding: A Thermal Spray Primer. The Fabricator. Retrieved from http://www.thefabricator.com/article/metalsmaterials/better-bonding-a-thermal-spray-primer
14. Flame Spray. Retrieved from http://www.tstcoatings.com/flame_spray.html
15. Flame Spray. Retrieved from https://www.ofic.co.jp/en/r_and_d/thermalspraying/pdf/flame_spraying.pdf
16. Wire Arc Spray vs. Wire Flame Spray. Retrieved from http://www.polymet.us/wp-content/uploads/2012/05/Wire-Arc-Spray-vs-Wire-Flame-Spray.pdf
17. What are the Disadvantages of Flame Spraying? Retrieved from http://www.twi-global.com/technical-knowledge/faqs/process-faqs/faq-what-are-the-disadvantages-of-flame-spraying/
18. Electric Arc Wire Spray. Retrieved from https://www.oerlikon.com/metco/en/products-services/coating-equipment/thermal-spray/processes/electric-arc-wire/
19. Arc Spraying. Retrieved from https://www.ofic.co.jp/en/r_and_d/thermalspraying/pdf/arc_spraying.pdf
20. What are the Disadvantages of Arc Spraying? Retrieved from http://www.twi-global.com/technical-knowledge/faqs/process-faqs/faq-what-are-the-disadvantages-of-arc-spraying/
21. Plasma Spray. Retrieved from http://www.tstcoatings.com/plasma_spray.html
22. Plasma Spray Process. Retrieved from http://www.gordonengland.co.uk/ps.htm
23. Detonation Thermal Spraying Process. Retrieved from http://www.gordonengland.co.uk/ds.htm
24. Singh, L., Chawla, V., & Grewal, J. S. (2012). A Review on Detonation Gun Sprayed Coatings. Journal of Minerals & Materials Characterization & Engineering, Volume

11, No.3, Page 243-265

25. Saladi, S., Menghani, J. V., & Prakash S. (2014). Characterization and Evaluation of Cyclic Hot Corrosion Resistance of Detonation-Gun Sprayed Ni-5Al Coatings on Inconel-718. Journal of Thermal Spray Technology, Volume 24(5), Page 778-788.
26. Guide to Thermal Spray Welding (Metalizing). Retrieved from http://www.weldguru.com/spray-welding.html
27. Watanabe, M., Komatsu M., & Kuroda S. (2012). WC-Co/Al Multilayer Coatings by Warm Spray Dedosition. Journal of Thermal Spray Technology, Volume 21(3-4), Page 597-608
28. Kuroda, S., Kawakita, J., Watanabe, M., & Katanoda, H. (2008). Warm Spraying – A Novel Coating Process Based on High-Velocity Impact of Solid Particles. Science and Technology of Advanced Materials.
29. Kawakita, J., Katanoda, H., Wwtanabe, M., Yokoyama, K., & Kuroda S. (2008). Warm Spray: An Improved Spray Process to Deposit Novel Coatings. Surface & Coatings Technology 202 (2008) 4269-4373.
30. What is the difference between the thermal spray processes? Retrieved from http://www.twi-global.com/technical-knowledge/faqs/process-faqs/faq-what-is-the-difference-between-the-thermal-spray-processes/
31. Oksa, M., Tuuna, S. and Varis, T. (2012). Increased Lifetime for Biomass and Waste to Energy Power Plant Boilers with HVOF Coatings- High Temperature Corrosion Testing Under Chlorine-Containing Molten Salt. Journal of Thermal Spray Technology, Volume 22(5), Page 783-796.
32. HVAF. Retrieved from http://www.gordonengland.co.uk/hvaf.htm
33. HVOF or Detonation Gun. Retrieved from http://plasma-tec.com/hvof-detonation-gun
34. Tuominen, J., Vuoristo, P., Ma¨ntyla¨, T., Ahmaniemi, S., Vihinen, J., & Andersson P.H. (2001). Corrosion behavior of HVOF-sprayed and Nd-YAG laser-remelted high-chromium, nickel-chromium coatings. Journal of Thermal Spray Technology, Volume 11(2), Page 233-243.
35. Chatha, S. S., Sidhu, H. S., & Sidhu, B. (2012). High-Temperature Behavior of a NiCr-Coated T91 Boiler Steel in the Platen Superheater of Coal-Fired Boiler. Journal of Thermal Spray Technology, Volume 22(5), Page 838-847.
36. Guilemany, J.M., Torrell, M., & Miguel, J.R. (2007). Study of the HVOF Ni-Bases Coatings' Corrosion Resistance Applied on Municipal Solid-Waste Incinerators. Journal of Thermal Spray Technology. Volume 17(2). Page 254-262
37. Sidhu, B.S., & Prakash, S. (2005). Nickel-Chromium Plasma Spray Coatings: A Way to Enhance Degradation Resistance of Boiler Tube Steels in Boiler Environment. Journal of Thermal Spray Technology, Volume 15(1), Page 131-140.

38. Guilemany, J.M., Torrell, M., & Miguel, J.R.. (2007). Study of The HVOF Ni-Bases Coatings' Corrosion Resistance Applied on Municipal Solid-Waste Incinerators. Journal of Thermal Spray Technology. Volume 17(2). Page 254-262
39. Oksa, M., Metsäjoki, J., & Kärki J. (2014). Thermal Spray Coatings for High-Temperature Corrosion Protection in Biomass Co-Fired Boilers. Journal of Thermal Spray Technology, Volume 24(1-2), Page 194-205.
40. Oksa, M., & Metsajoki, J. (2014). Optimizing NiCr and FeCr HVOF Coating Structures for High Temperature Corrosion Protection Applications. Journal of Thermal Spray Technology, Volume 24(3), Page 436-453.
41. Viklund, P., Hjornhede, A., Henderson, P., Stalenheim, A., & Pettersson R. (2011). Corrosion of Superheater Materials in a Waste-to-Energy Plant. Fuel Processing Technology 105 (2013) 106-112.
42. Pual, S., & Harvey M.D.F. (2012). Corrosion Testing of Ni Alloy HVOF Coatings in High Temperature Environments for Biomass Applications. Journal of Thermal Spray Technology, Volume 22(2-3), Page 316-327.
43. Steam Generators Performance Guarantees Data from Covanta
44. Fauchais, P. & Vardelle, A. Industrial Applications of Thermal Spraying Technology, Chapter 18.
45. Nickel Prices and Nickel Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/nickel/
46. Iron Ore Monthly Price - US Dollars per Dry Metric Ton. Retrieved from http://www.indexmundi.com/commodities/?commodity=iron-ore
47. Chromium Prices and Chromium Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/ferro-chrome/
48. Molybdenum Prices and Molybdenum Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/molybdenum-oxide/
49. Aluminum Prices and Aluminum Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/aluminum/
50. Niobium (≥99%). Retrieved from http://www.metal.com/metals/productinfo/201102250606
51. Titanium Prices and Titanium Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/ferro-titanium/
52. Thermal Conductivity. ://www.nde-ed.org/EducationResources/CommunityCollege/Materials/Physical_Chemical/ThermalConductivity.htm
53. Themelis, N.J. Transport and Chemical Rate Phenomena, WTERT web
54. Density of the Elements. Retrieved from http://www.periodictable.com/Properties/A/Density.al.html
55. Tungsten Prices and Tungsten Price Charts. Retrieved from

http://www.infomine.com/investment/metal-prices/ferro-tungsten/

56. Carbon Element Facts. Retrieved from http://www.chemicool.com/elements/carbon.html
57. Boron. Retrieved from https://www.hobart.k12.in.us/ksms/PeriodicTable/boron.htm
58. Manganese Prices and Manganese Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/manganese/
59. Silicon. Retrieved from https://www.metalprices.com/metal/silicon/silicon-metal-98-5-china
60. Copper Prices and Copper Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/copper/
61. Cobalt Prices and Cobalt Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/cobalt/
62. Vanadium Prices and Vanadium Price Charts. Retrieved from http://www.infomine.com/investment/metal-prices/ferro-vanadium/
63. Historical Phosphate Rock Prices and Price Chart. Retrieved from http://www.infomine.com/investment/metal-prices/phosphate-rock/all/
64. Sulfur Price. Retrieved from https://www.tasweeq.com.qa/En/RegulatedProducts/Pages/QatarSulphurPrices.aspx?AspxAutoDetectCookieSupport

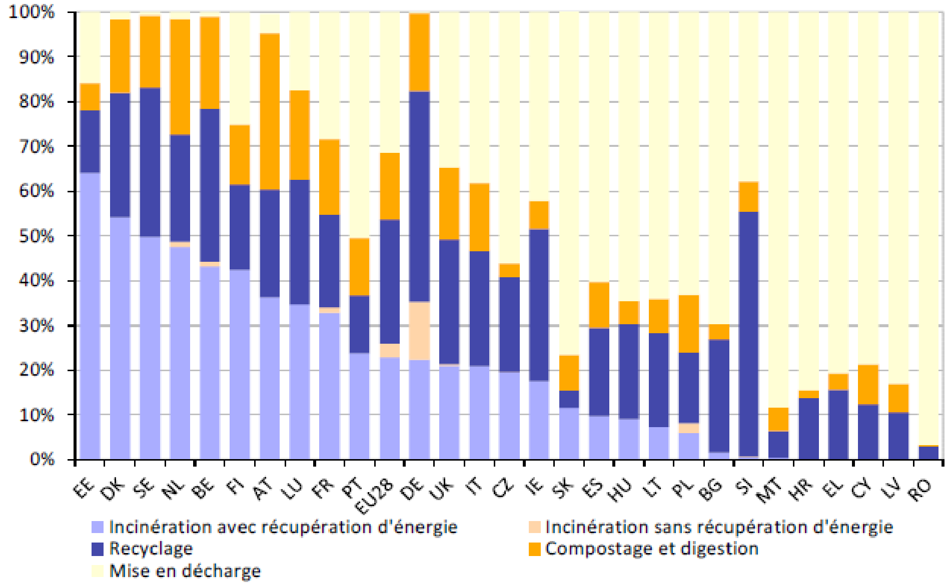
Appendix 1. Report by E.U specialist on combatting corrosion of WTE superheater tubes by means of thermal spray coatings in E.U.

Introduction

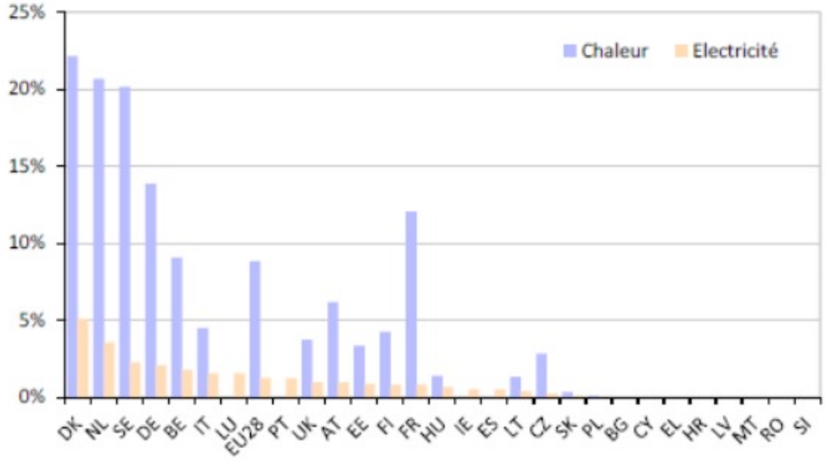
Combustion of MSW with energy recovery (WTE) in Europe is used in 409 plants to produce electricity and heat. The energy recovery from WTE plants amounts to 1.3% of the electricity and 8.9% of the district heating in northern E.U. According to data compiled by the European Confederation of Waste Energy Recovery Units (CEWEP), the EU's 409 waste-to-energy facilities in 2012 treated 74 million tonnes of waste, producing 30 TWh of electricity and 74 TWh of heat. Ecoprog, a consulting firm specializing in the sector, estimates that between 2014 and 2017 capacity growth will come mainly from the United Kingdom and Poland, where 25 new incineration plants are planned.

Good maintenance of WTE plants is important in minimizing the downtime of WTE plants. This includes ensuring that superheater tubes assemblies have the longest possible lifetime. The usual practice in the E.U. is for heat exchanger tubes and banks of tubes to be made of low carbon steel which is then covered by a layer of Inconel 625. In France, almost 100% of the superheater tubes are restored by a welding means (CMT, Laser, etc.). However, this solution does not obviate the need for more efficient solutions to increase steam temperature and thus the electricity generation per ton of MSW combusted. In order to achieve this, thermal spraying of tubes is practiced in several countries of the E.U. and other parts of the world.

Method of managing MSW in EU2 (%, 2013)

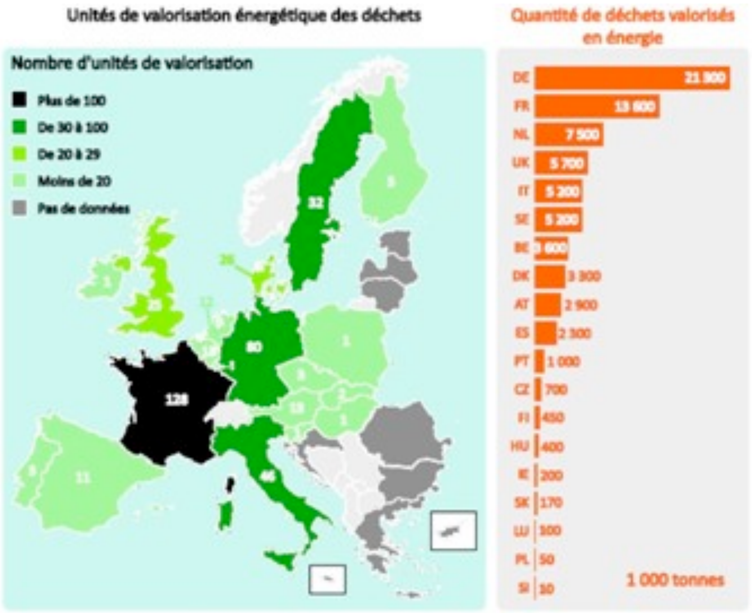


Fraction of energy produced by WTE in the E.U. 28 (as % of total, 2013)



Source des données: Eurostat (nrg_105a et nrg_106a), 2013.

Valorisation des déchets en énergie dans l'UE (2012)



Source des données: CEWEP, 2012.

Confédération européenne des unités de valorisation énergétique des Déchets (CEWEP)

Processes and materials

The thermal spraying processes used to form protective layers on superheater tubes (SHT) depend on whether they are formed in the workshop or on site. In the workshop, Atmospheric Plasma Spraying (APS) and high velocity oxyfuel spraying (HVOF) allows the spraying of metallic oxides or carbides. Metal oxide coatings such as alumina, zirconia or titanium oxide are sprayed by APS plasma with nickel-based basecoats. The carbide coatings (generally tungsten or chromium) are sprayed using HVOF or HVAF (air). These processes are still under development and for the most part the subject of theses supervised by laboratories, Universities and Grandes Ecoles.

On site spray coating of superheater tubes is done by Arc Spraying or HVOF to form metallic coatings (NiCr 80-20, Inconel 625).

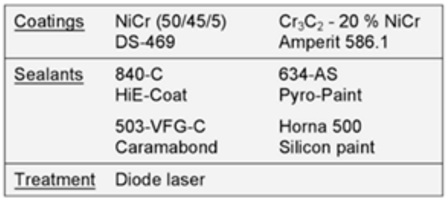
In Europe, there are subcontracting workshops for coating WTE superheater tubes using Arc-Spray and HVOF. Currently, these specialized workshops offer Inconel 625 deposits and NiCrBSi refolded alloys with or without metal carbide additions (depending on the wear problem of each incineration plant).
Les dépôts Arc Spray et HVOF

The Arc Spray deposits formed on new SHT panels in the workshop are priced about 1500 €/m2 (US$1,650/m2). The repair of SHT on site costs between 1900 and 2200 €/m2 depending on the ease of access to the panels in the WTE plant and the geographic location of the plant in relation to that of the repairman. HVOF deposits are 10 to 20% higher. The operation of thermal spraying on site is divided into several stages:

- Cleaning of the damaged part of the panel to be repaired,
- Sandblasting of the part to be coated,
- Deposition of Inconel 625, Ni20Cr, Ni50Cr, Ni21Cr9Mo,

Inconel 625 Arc Spray on site

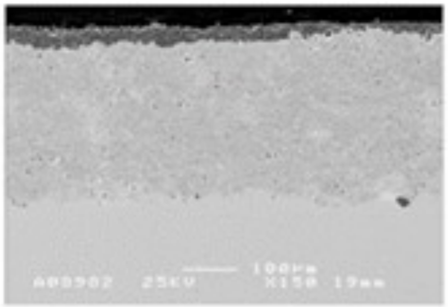
- Impregnation of the coating (Ceramabond most efficient: 503-VFG-C Single part, alumina-filled, phosphate-bonded, abrasion and corrosion resistant sealer for thermal spray applications to 3000 ºF (1650 ºC).).



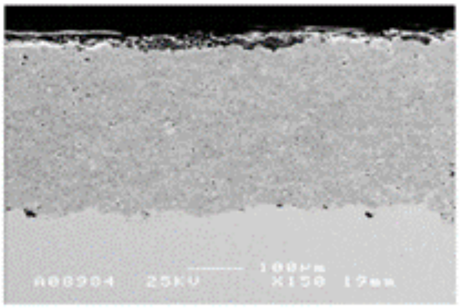
Coatings	NiCr (50/45/5) DS-469	Cr_3C_2 - 20 % NiCr Amperit 586.1
Sealants	840-C HiE-Coat	634-AS Pyro-Paint
	503-VFG-C Caramabond	Horna 500 Silicon paint
Treatment	Diode laser	

Onsite densification

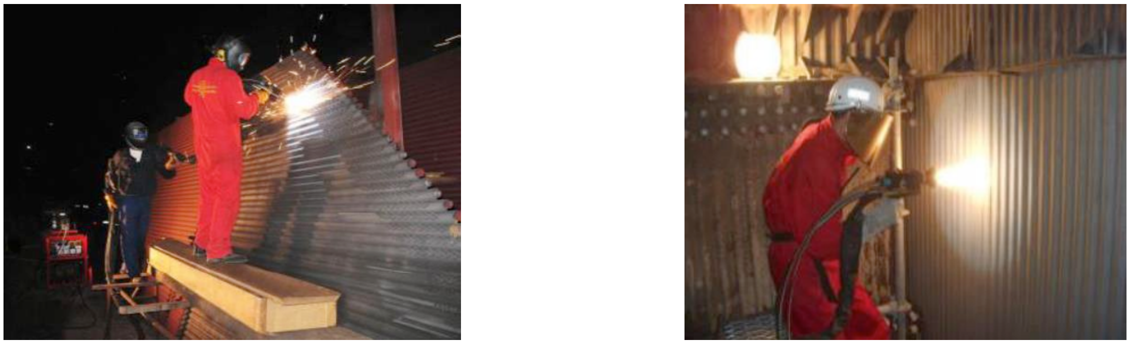
Densified coatings of tubes, Armour



SEM micrograp of the cross section of NiCr - Cr3C2 coating sealed with sealand sealand 503 before the corrosion test



SEM micrograp of the cross section of NiCr - Cr3C2 coaing sealed with 503 after the corrision test



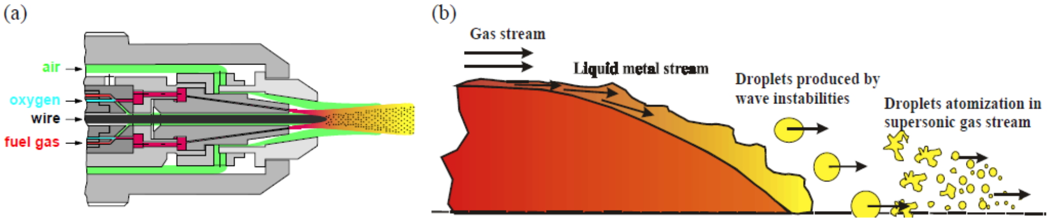
Refurbishing of SHT with Inconel 625 Arc Spray on site

The HVOF and Arc Spray processes are also used in Europe by the Oerlikon-Metco Company, both in the workshop and on site. The coatings are generally nickel based: Ni 50Cr (cored wire), Ni 21Cr 14Mo 3W 2.5Fe (solid wire) and Ni 21Cr 9Mo 4 (Nb + Ta) (solid wire). Some proprietary materials, called METCO Boil, are more efficient than Inconel 625. Most of the deposits are formed by robots.

Oerlikon Metco Smart Arc system robotically spraying a boiler waterwall section in shop.

For the Arc Spray and HVOF deposits, impregnation is essential to obtain a sufficient lifetime to make these deposits cost-effective.

A "HVOF" High Velocity Combustion Wire - HVCW-flame-fil system made similar deposits with encouraging results very similar to those achieved with the conventional HVOF system (JP 5000, WOKA 400, etc.). A schematic diagram is shown below:



(a) HVw 2000 system for High Velocity Combustion Wire (HVCW) spraying process. (b) Schematic illustration showing the formation of droplets during the atomization process at the wire tip

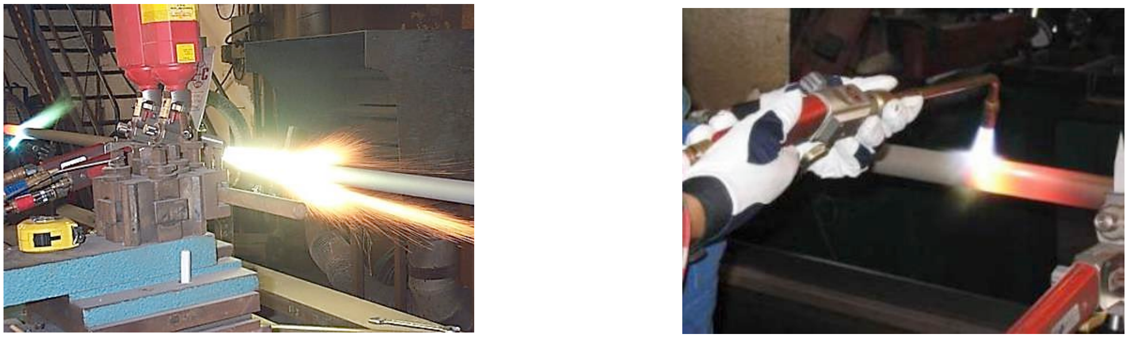
Real image of the plume showing shock diamonds formed by a HVCW gun nozzle. Spraying of Hastelloy C-276 with propane as fuel gas and wire feed rate of 1.6 m/min (HVw 2000 system). This process Is still under development.

High velocity wire flame spraying gun

Coatings of remelted NiCrBSi alloys are only made in Europe on steel tubes such as:

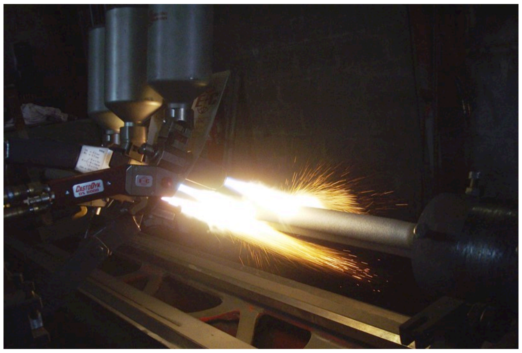
- 10 CrMo
- 9 10
- 13 CrMo 4 4
- 15 MB 3
- P91, P92
- X20

Generally, the NiCrBSi alloy (self fluxing alloy) is used to make the refreshed coatings (hardness 62 HR C). This alloy, for high erosion areas may contain about 40% of tungsten carbide. Deposition and remelting are carried out by robots. Only the ends of the tubes are manually coated and remelted.



R evêtement en atelier de NiCrBSi

Projection flamme poudre (dépôt) *Refusion du dépôt*

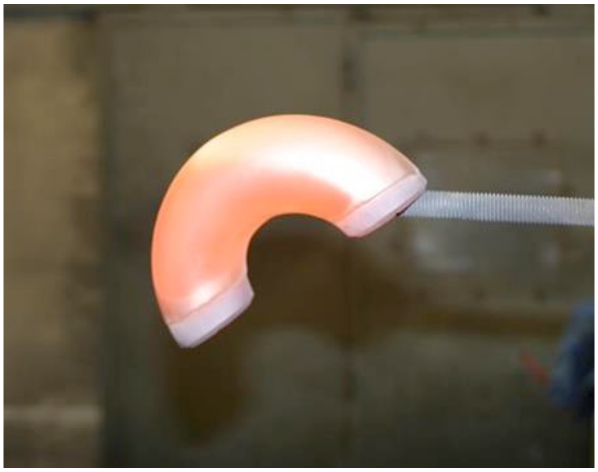


NiCrBSi sprayed with 3 powder flame spray gun

Group of coated tube ready to use

The price of coating depends on SHT diameter and, per linear meter of tube, ranges from 150 euro for 38 mm diameter tube to 340 euro 88.9 mm diameter SHT.

The elbows connecting the tubes are coated manually. In this case, the dexterity of the operator is very important to obtain a constant thickness and homogeneous remelting, of equal quality to that obtained by the robot coating of the tubes (photo below).



Coude en fin de refusion

Service life of coated parts

It is very difficult to predict the life of coated tubes and parts because operating conditions differ among WTE plants. Also, occasionally MSW may be mixed with other wastes causing additional corrosion that may shorten the lifetime of the coated parts. In the case of parts resurfaced with Inconel 625 by welding (Mig, laser, PTA) the service life is approximately 8 to 10 years for the walls of the combustion chamber (first course).

In the case of thermally sprayed parts of self-fusing alloys (type NiCrBSi), the service life is comparable to those coated by welding of Inconel 625 and much better on the superheater and economizer tubes in the 2nd and 3rd runs .

For parts coated with Inconel 625 by Arc-Spray, Wire Flame or Powder methods, the lifetimes are very variable. It can be estimated that in the worst cases the lifetime is one year whereas in the most favorable cases the lifespan varies from 2 to 3 years. We have not yet had enough experience with ARC SPRAY + IMPREGNATION (Sealants) on the combustion chamber panels. This solution is not yet applicable on the superheater and economizer tubes.

In the case of deterioration of certain part of panels, it is possible to repair on site during the regular yearly maintenance of the plant, thuis extending the life of the tubes by one year.

Ongoing projects to improve the corrosion resistance of thermally sprayed deposits

To increase the performance of WTE plants in the US by increasing steam temperature to> 450 ° C.

1 ° - Replace *the Inconel 625 with an Inconel of higher resistance to corrosion and temperature. Industrial tests are currently underway with Inconel 686 and Inconel 718, both of which are well suited for high temperatures (> 600 ° C). Also, in the case of using self-fusing alloys («soldering »), changes in composition have been made to Inconel 686 by adding the elements B and Si to the sprayed powder, resulting into the formation of a NiCrBSI coating. This type of modification can also be carried out with Inconel 718.*

2 ° - Use of Cold Spray thermal spray equipment.

The advantage of Cold Spray is that it does not change the characteristics of the powder used: There is no oxidation, nor structural change, and very low porosity (porosity <1%), plus good adhesion to the substrate. With this type of spray there is no limitation in coating thickness and a superior corrosion resistant coating can be formed. Materials that have been used in cold spray coating of SHT with good include Inconels, NiCr alloys, and McrAlY type super alloys are likely to give good results. An advantage of the Cold Spray process is that the coating is formed without heating the substrate (maximum 120 ° C for small parts and ven less less for parts such as tubes or panels.

Tests on cold spray are under way in Europe at the R&D stage.esearch and Development level. There have been no plant tests as yet. For references, please see: Hot Corrosion Behavior of Cold-Sprayed Ni-50Cr Coating in an Incinerator Environment at 900°C Harminder Singh, T.S. Sidhu, S.B.S. The HP Cold Spray process is beginning to be applied in aeronautics to alleviate corrosion problems (magnesium alloy part repair (e.g., helicopter gear box - ARL work in the US).

Conclusions

There are good prospects in the field of WTE power plants to increase the WTE efficiency by increasing the steam temperature (> 450 ° C). A superheater tube treatment that will allow this advance is the development of self-fusible alloy deposits or by means of the developing Cold Spray process. However, in France and Europe, it will not be easy to convince WTE plant operators to carry out factory testing of new developments, even when laboratory results are very encouraging. Plant operators tend to see the cost of treatment without considering the lifetime aspect and beneficial effect of long SHT life on plant availability.

Translation from French by N.J. Themelis, March 31, 2017

Subsequent Questions to Consultant and his Answers

Q: You stated cost of 1500 euro per square meter of HVOF coating of NiCr at the shop:

a) When this is done, what would be the typical, or usual, or preferable thickness of coating applied?
   A: The thickness must be ≤ 350 microns

Q: Is the cost proportional to thickness of HVOF coating applied?
A: No because in the evaluation of the cost it is included the cost of the installation of the work (time before to start and after to finish the coating). The cost 1500 euro can be down to 1300 euro; it's depending on the company in charge of the work.

Q: Is most of the cost, per square meter and thickness, due to the particular metal composition of the powder used? Or due to the application process?
A: Most of the cost is due 80% to the application process

d) If a US WTE company is interested in a large scale industrial test of HVOF coating - of tubes or panels HVOF coated at a shop - what would be the most promising (longer lifetime) metal powder and coating thickness you would recommend (e,g, NiCr, or other)
A: It depends on the characteristic values of the pressure and temperature (443°C is too high for the HVOF coating of your US WTE) The HVOF coating it is not use in Europe. Regarding the temperature of the US WTE it is recommended to weld (cladding) 3 mm thick Inconel 686 or Colmonoy 22. Longer time 2 years without fluxage, 1 year with flux age (fluxing)

Q: In the course of Dinayi's thesis we compiled data on the surface area of superheater banks (see below this note). The superheater bank of an 1800 ton/day WTE had a total surface area of 2,014 m2. Assuming that one wanted to HVOF NiCr on these superheaters at a shop and using your 1,500 euro/m2 would come to a cost of 3 million euro. In your experience, does this number make sense for a plant of that size?
A: The cost of the HVOF NiCr is correct. In function of the characteristics of the superheater mentioned in the note 3 million euro make non sense. The cost of Colmonoy 22 (Inco 686) and maybe Inco 718 cladded is the same but with better life time. In France and in India we are testing the Cold Spray process (the coating is more dense than the HVOF coating). This CS application is very interesting because we don't have deformation when we spray on the walls.

It is difficult to know what is the best solution because each incinerator is different in function of the wastes and the managing. In Europe, the majority of the corrosion protection of the superheater is ensured by welded (cladding) coating with the thick layers. Is difficult to found the better process and the better material. If I collect new solution I will be happy to inform you in the future.

Appendix 2 Tables of Data Analyzed and calculations made in this study

Appendix 2-1 Tables of Data Analyzed in this study

Table 9. Composition for each coating material

Ref	Material	Ni	Fe	Cr	Mo	Al	Nb	Ti	W	C	B	Mn	Si	Cu	Co	V	P	S
38	Alloy 625	63.79	5	21.2	8.3	0.5	1.2	0.01										
6	NiCr	51.8	1.1	45	…		…		…	…	…	…	2.1	…				
6	IN625	63	2.5	21.5	9		3.7		…	…	…	0.1	0.2	…				
6	Diamalloy4006	54	1	20.5	9		…		10	0.75	0.75	…	…	4				
6	SHS9172	…	28	25	6		12		15	4	5	3	2	…				
39	NiCr	51.3	…	46.5	…		…	…	…				2.2		…			
39	IN625	66.5	…	21	8.8		3.5	…	…				0.2		…			
39	FeCr	…	60.1	19	3.6		7.1	…	8.6				1.6		…			
39	NiCrTi	55.25	…	44	…		…	0.75	…				…		…			
40	NiCr	50.2	1.1	46.5	…		…		…	0.1	…	…	2.1					
40	FeCr	…	52.3	18.6	3.6		7.1		8.6	2.1	5	1.1	1.6					
42	NiCrBSiFe	70.6	4.6	17.2	…	…	…	…	…	0.8	3.1	…	3.7			…	…	…
42	Alloy 718	53.24	17.9	18.78	3.04	0.48	5.26	…	…	0.03	0.004	0.01	0.1			…	0.004	0.002
42	Alloy 625	67.209	0.081	21	8	…	3.48	…	…	0.03	…	0.1	0.1			…	…	…
42	Alloy C-276	58.976	5.09	15.55	16.48	…	…	…	3.81	0.004	…	0.06	0.03			…	…	…
1	Colmonoy 88	56	10.9	15					17.3	0.8								
1	SW 1600	75.1		15	2.5						3.1		4.3					
1	SW1641	52.9		37.1	3						3.6		3.4					

Table 10. Composition for each tube material

Ref	Material	Ni	Fe	Cr	Mo	Al	Nb	Ti	W	C	B	Mn	Si	Cu	Co	V	P	S
6	X20	0.55	85.2	11.25	1	…	…	…	…	0.2		1	0.5	…	…	0.3		
6	A263	49.44	0.7	20	5.85	0.6	…	2.15	…	0.06		0.6	0.4	0.2	20	…		
6	SAN25	25	43.1	22.5	…	…	0.5	…	3.6	0.1		0.5	0.2	3	1.5	…		
39	T92	…	87.9	9	0.6			…	2				0.5		…			
39	A263	51.5	0.5	20	5.8		…	2.2	…						20			
41	13CrMo44	0.1	97.73	0.85	0.5					0.12		0.5	0.2					
41	HCM12A	0.5	84.335	11.3	0.5				2	0.11	0.005	0.5	0.5			0.25		
41	Super 304	9	68.57	18	…		0.4			0.03		0.8	0.2	3				
41	Sanicro 28	30.6	36.41	26.6	3.3					0.09		1.6	0.5	0.9				
41	Hastelloy C-2000	58.893	1.2	22.5	15.7					0.007		0.2	…	1.5				
42	P91	0.33	88.615	8.9	0.96	0.01	0.08	0.005	0.05	0.12	…	0.48	0.23			0.2	0.015	0.005
42	A625	61.537	3.76	21.5	9.12	0.1	3.52	0.24	…	0.024	…	0.14	0.05			…	0.008	0.001
1	SA213 T22		96.65	2.25	1					0.1								

Table 11. Price and density for each material element

Element	Ni	Fe	Cr	Mo	Al	Nb	Ti	W	C	B	Mn	Si	Cu	Co	V	P	S
Price ($/kg) [44-50&54-63]	10.44	0.06	1.85	15.25	1.726	92.54	3.87	24.04	24	5000	1.68	1.65	4.918	28.8	16.01	0.111	0.082
Density (g/cm^3)[53]	8.908	7.874	7.14	10.28	2.7	8.57	4.507	19.25	2.26	2.46	7.47	2.329	8.92	8.9	6.1	1.823	1.96

Table 12. Calculated price and density for coating materials

Ref	Material	Price ($/kg)	Density (g/cm^3)
38	Alloy 625	9.44	8.56
6	NiCr	6.28	7.96
6	IN625	11.78	8.60
6	Diamalloy4006	47.67	9.60
6	SHS9172	267.15	9.01
39	NiCr	6.25	7.94
39	IN625	11.92	8.63
39	FeCr	9.6	8.76
39	NiCrTi	6.61	8.10
40	NiCr	6.16	7.93
40	FeCr	260.11	8.32
42	NiCrBSiFe	162.94	8.06
42	Alloy 718	11.46	8.27
42	Alloy 625	11.86	8.62
42	Alloy C-276	9.88	9.20
1	Colmonoy 88	10.48	9.89 [1]
1	SW 1600	163.57	7.73 [1]
1	SW 1641	186.72	6.31 [1]

Table 13. Calculated price and density for tube materials

Ref	Material	Price ($/kg)	Density (g/cm3)
6	X20	0.59	7.77
6	A263	12.32	8.46
6	SAN25	5	8.41
39	T92	0.8	8.02
39	A263	12.48	8.53
41	13CrMo44	0.2	7.86
41	HCM12A	1.2	8
41	Super 304	1.86	7.85
41	Sanicro 28	4.31	8.04
41	Hastelloy C-2000	9.04	8.71
42	P91	0.56	7.81
42	A625	11.49	8.58
1	SA213 T22	0.28	7.85 [1]

Table 14. Data and calculated results for applying different coating materials on a one-meter-long sample superehater tube for an assumed five-year-lifetime extension

Category	**Ref**	**Materials**	**Thickness Lost under Relative Tests (μm)**	**Test Time (hour)**	**Corrosion Rate (mm/year)**	**Loss of Volume after 8000-hour Operation per Year (cm^3)**	**Density (g/cm^3)**	**Loss of Mass after 8000-hour Operation per Year (kg)**	**Price ($/kg)**	**Metal cost for Five-Year-Lifetime Extension ($)**
Coating Materials	38	Alloy 625(powder, DJH 2600, 760 °C)	35.8	12	26.134	2856.71	8.56	24.45	9.44	1154.20
	38	Alloy 625(wire, HVT, 760 °C)	5.9	12	4.307	470.80	8.56	4.03	9.44	190.22
	6	Diamalloy4006_CJS(HVOF, 575 °C)	102	168	5.319	581.37	9.60	5.58	47.67	1330.28
	6	Diamalloy4006_CJS(HVOF, 625 °C)	25	168	1.304	142.49	9.60	1.37	47.67	326.05
	6	Diamalloy4006_DJ(HVOF, 575 °C)	15	168	0.782	85.50	9.60	0.82	47.67	195.63
	6	Diamalloy4006_DJ(HVOF, 625 °C)	25	168	1.304	142.49	9.60	1.37	47.67	326.05
	40	FeCr (HVOF, 550 °C in boiler)	-	-	0.217	23.72	8.32	0.20	260.11	256.67
	40	FeCr (HVOF, 575 °C in lab)	-	-	1.380	150.85	8.32	1.26	260.11	1632.26
	40	FeCr (HVOF, 625 °C in lab)	-	-	1.485	162.33	8.32	1.35	260.11	1756.46
	40	FeCr (HVOF, 750 °C in boiler)	-	-	0.363	39.68	8.32	0.33	260.11	429.36
	39	FeCr_CJS(HVOF, 550 °C)	13.6	1000	0.119	13.02	8.76	0.11	9.6	5.48
	39	FeCr_CJS(HVOF, 750 °C)	18.8	1000	0.165	18.00	8.76	0.16	9.6	7.57
	6	IN625_CJS(HVOF, 575 °C)	150	168	7.821	854.96	8.60	7.35	11.78	433.07
	6	IN625_CJS(HVOF, 625 °C)	45	168	2.346	256.49	8.60	2.21	11.78	129.92
	39	IN625_DJ(HVOF, 550 °C)	3.1	1000	0.027	2.97	8.63	0.03	11.92	1.53
	6	IN625_DJ(HVOF, 575 °C)	75	168	3.911	427.48	8.60	3.68	11.78	216.54
	6	IN625_DJ(HVOF, 625 °C)	20	168	1.043	113.99	8.60	0.98	11.78	57.74
	39	IN625_DJ(HVOF, 750 °C)	73.6	1000	0.645	70.48	8.63	0.61	11.92	36.25
	40	NiCr (HVOF, 550 °C in boiler)	-	-	0.013	1.42	7.93	0.01	6.16	0.35
	40	NiCr (HVOF, 575 °C in lab)	-	-	4.095	447.63	7.93	3.55	6.16	109.33
	40	NiCr (HVOF, 625 °C in lab)	-	-	2.215	242.12	7.93	1.92	6.16	59.14
	40	NiCr (HVOF, 750 °C in boiler)	-	-	0.063	6.89	7.93	0.05	6.16	1.68

Table 14. Data and calculated results for applying different coating materials on a one-meter-long sample superehater tube for an assumed five-year-lifetime extension (continued)

Category	Ref	Materials	Thickness Lost under Relative Tests (μm)	Test Time (hour)	Corrosion Rate (mm/year)	Loss of Volume after 8000-hour Operation per Year (cm^3)	Density (g/cm^3)	Loss of Mass after 8000-hour Operation per Year (kg)	Price ($/kg)	Metal cost for Five-Year-Lifetime Extension ($)
Coating Materials	6	NiCr_CJS(HVOF, 575 °C)	110	168	5.736	626.97	7.96	4.99	6.28	156.71
	6	NiCr_CJS(HVOF, 625 °C)	55	168	2.868	313.49	7.96	2.50	6.28	78.35
	6	NiCr_DJ(HVOF, 575 °C)	52	168	2.711	296.39	7.96	2.36	6.28	74.08
	6	NiCr_DJ(HVOF, 625 °C)	30	168	1.564	170.99	7.96	1.36	6.28	42.74
	39	NiCr-F_CJS [A] (HVOF, 550 °C)	1	1000	0.009	0.96	7.94	0.01	6.25	0.24
	39	NiCr-F_CJS [A] (HVOF, 750 °C)	5.3	1000	0.046	5.08	7.94	0.04	6.25	1.26
	39	NiCr-C_DJ [B] (HVOF, 550 °C)	1.4	1000	0.012	1.34	7.94	0.01	6.25	0.33
	39	NiCr-C_DJ [B] (HVOF, 750 °C)	11	1000	0.096	10.53	7.94	0.08	6.25	2.61
	39	NiCrTi(Electric Arc, 550 °C)	3.7	1000	0.032	3.54	8.10	0.03	6.61	0.95
	39	NiCrTi(Electric Arc, 750 °C)	11	1000	0.096	10.53	8.10	0.09	6.61	2.82
	6	SHS9172_CJS(HVOF, 575 °C)	30	168	1.564	170.99	9.01	1.54	267.15	2057.91
	6	SHS9172_CJS(HVOF, 625 °C)	35	168	1.825	199.49	9.01	1.80	267.15	2400.90
	6	SHS9172_DJ(HVOF, 575 °C)	25	168	1.304	142.49	9.01	1.28	267.15	1714.93
	6	SHS9172_DJ(HVOF, 625 °C)	25	168	1.304	142.49	9.01	1.28	267.15	1714.93
	42	NiCrBSiFe(HVOF, 725 °C)	99.1	168	5.169	565.02	8.06	4.55	162.94	3710.22
	42	NiCrBSiFe(HVOF, 625 °C)	17.1	168	0.893	97.59	8.06	0.79	162.94	640.81
	42	NiCrBSiFe(HVOF, 525 °C)	4.6	168	0.239	26.17	8.06	0.21	162.94	171.81
	42	Alloy 718(HVOF, 725 °C)	150.9	168	7.869	860.13	8.27	7.11	11.46	407.59
	42	Alloy 718(HVOF, 625 °C)	9.3	168	0.485	53.07	8.27	0.44	11.46	25.15
	42	Alloy 718(HVOF, 525 °C)	23.5	168	1.223	133.71	8.27	1.11	11.46	63.36
	42	Alloy 625(HVOF, 725 °C)	4.6	168	0.242	26.45	8.62	0.23	11.86	13.52
	42	Alloy 625(HVOF, 625 °C)	1.2	168	0.060	6.61	8.62	0.06	11.86	3.38

[A] "F"in "NiCr-F" stands for "fine", which mean that fine powder was used for the test.

[B] "C" in "NiCr-C" stands for "coarse", which mean that coarse powder was used for the test.

Table 14. Data and calculated results for applying different coating materials on a one-meter-long sample superehater tube for an assumed five-year-lifetime extension (continued)

Category	Ref	Materials	Thickness Lost under Relative Tests (μm)	Test Time (hour)	Corrosion Rate (mm/year)	Loss of Volume after 8000-hour Operation per Year (cm^3)	Density (g/cm3)	Loss of Mass after 8000-hour Operation per Year (kg)	Price ($/kg)	Metal cost for Five-Year-Lifetime Extension ($)
Coating Materials	42	Alloy 625(HVOF, 525 °C)	4.6	168	0.242	26.45	8.62	0.23	11.86	13.52
	42	Alloy C-276(HVOF, 725 °C)	1056.5	168	55.090	6021.91	9.2	55.40	9.88	2736.84
	42	Alloy C-276(HVOF, 625 °C)	4.2	168	0.221	24.16	9.2	0.22	9.88	10.98
	42	Alloy C-276(HVOF, 525 °C)	0.4	168	0.023	2.48	9.2	0.02	9.88	1.13
	1	Colmonoy 88 (HVOF, 450 °C)	0.3	24	0.111	12.16	9.89	0.12	10.48	6.30
	1	Colmonoy 88 (HVOF, 500 °C)	2.3	24	0.834	91.21	9.89	0.90	10.48	47.27
	1	Colmonoy 88 (HVOF, 550 °C)	4.1	24	1.483	162.15	9.89	1.60	10.48	84.03
	1	SW 1600 (TS and IH[C], 450 °C)	49.1	24	17.939	1960.96	7.73	15.16	163.57	12397.14
	1	SW 1600 (TS and IH, 500 °C)	68.6	24	25.022	2735.21	7.73	21.14	163.57	17291.92
	1	SW 1600 (TS and IH, 550 °C)	77.6	24	28.332	3097.00	7.73	23.94	163.57	19579.15
	1	SW 1641 (TS and IH, 450 °C)	16.6	24	6.073	663.79	6.31	4.19	186.72	3910.38
	1	SW 1641 (TS and IH, 500 °C)	33.3	24	12.145	1327.57	6.31	8.38	186.72	7820.76
	1	SW 1641 (TS and IH, 550 °C)	84.0	24	30.659	3351.36	6.31	21.15	186.72	19742.93
Tube Material That Can be Used as Coatings	6	A263(575 °C)	15	168	0.782	85.50	8.46	0.72	12.32	44.43
	6	A263(625 °C)	5	168	0.261	28.50	8.46	0.24	12.32	14.85
	39	A263(750 °C)	4.9	1000	0.043	4.69	8.53	0.04	12.48	2.50
	42	A625(525 °C)	1.7	168	0.079	8.64	8.58	0.07	11.49	4.26
	42	A625(625 °C)	0.5	168	0.024	2.66	8.58	0.02	11.49	1.31

[C] “TS and IH” means “thermal spray and induction heating”

Table 15. Data and calculated results for making a one-meter-long sample superehater tube

Category	Ref	Materials	Thickness Lost under Relative Tests (μm)	Test Time (hour)	Corrosion Rate (mm/year)	Volume of One-Meter Superheater Tube (cm^3)	Density (g/cm^3)	Weight (kg)	Price ($/kg)	Price for making a one-meter-long tube ($)
Tube Materials	6	A263 (575 °C)	15	168	0.782	481.57	8.46	4.07	12.32	50.19
	6	A263 (625 °C)	5	168	0.261	481.57	8.46	4.07	12.32	50.19
	39	A263 (750 °C)	4.9	1000	0.043	481.57	8.53	4.11	12.48	51.27
	6	SAN25 (575 °C)	390	168	20.336	481.57	8.41	4.05	5.00	20.25
	6	SAN25 (625 °C)	450	168	23.464	481.57	8.41	4.05	5.00	20.25
	6	T92 (550 °C)	103.9	1000	0.910	481.57	8.02	3.86	0.80	3.09
	6	X20 (575 °C)	320	168	16.686	481.57	7.77	3.74	0.59	2.21
	6	X20 (625 °C)	165	168	8.604	481.57	7.77	3.74	0.59	2.21
	41	13CrMo44 (440 °C)	715	1000	6.263	481.57	7.86	3.79	0.20	0.76
	41	HCM12A (440 °C)	495	1000	4.336	481.57	8.00	3.85	1.20	4.62
	41	Super 304 (440 °C)	760	1000	6.658	481.57	7.85	3.78	1.86	7.03
	41	Sanicro 28 (440 °C)	220	1000	1.927	481.57	8.04	3.87	4.31	16.69
	41	Hastelloy C-2000 (440 °C)	370	1000	3.241	481.57	8.71	4.19	9.04	37.92
	42	P91 (725 °C)	-	168	54.086	481.57	7.81	3.76	0.56	2.11
	42	P91 (625 °C)	-	168	2.263	481.57	7.81	3.76	0.56	2.11
	42	P91 (525 °C)	-	168	0.601	481.57	7.81	3.76	0.56	2.11
	42	A625 (725 °C)	-	168	35.035	481.57	8.58	4.13	11.49	47.48
	42	A625 (625 °C)	-	168	0.024	481.57	8.58	4.13	11.49	47.48
	42	A625 (525 °C)	-	168	0.079	481.57	8.58	4.13	11.49	47.48
	1	SA213 T22 (450 °C)	42	24	15.442	481.57	7.85	3.78	0.28	1.06
	1	SA213 T22 (500 °C)	60	24	21.852	481.57	7.85	3.78	0.28	1.06
	1	SA213 T22 (550 °C)	83	24	30.223	481.57	7.85	3.78	0.28	1.06

Table 16. Detailed cost data for selected coating materials from Chapter 4 based on the information provided by Covanta

	Ref	Materials	Metal Cost for Five-Year-Lifetime Extension (Thousand $)
Coating Materials	42	Alloy 625(HVOF, 525 °C)	227.49
	42	Alloy 625(HVOF, 625 °C)	56.87
	42	Alloy 625(HVOF, 725 °C)	227.49
	42	Alloy 718(HVOF, 625 °C)	423.14
	42	Alloy C-276(HVOF, 525 °C)	18.95
	42	Alloy C-276(HVOF, 625 °C)	184.77
	1	Colmonoy 88 (HVOF, 450 °C)	106.04
	1	Colmonoy 88 (HVOF, 500 °C)	795.32
	39	FeCr_CJS(HVOF, 550 °C)	92.14
	39	FeCr_CJS(HVOF, 750 °C)	127.37
	39	IN625_DJ(HVOF, 550 °C)	25.69
	39	IN625_DJ(HVOF, 750 °C)	609.94
	40	NiCr (HVOF, 550 °C in boiler)	5.84
	40	NiCr (HVOF, 750 °C in boiler)	28.3
	39	NiCr-C_DJ(HVOF, 550 °C)	5.6
	39	NiCr-C_DJ(HVOF, 750 °C)	43.98
	39	NiCr-F_CJS(HVOF, 550 °C)	4
	39	NiCr-F_CJS(HVOF, 750 °C)	21.19
	39	NiCrTi(Electric Arc, 550 °C)	15.96
	39	NiCrTi(Electric Arc, 750 °C)	47.45
Tube Material That Can be Used as Coatings	42	A263(575 °C)	749.69
	42	A263(625 °C)	249.69
	39	A263(750 °C)	42.02
	6	A625(525 °C)	71.63
	6	A625(625 °C)	22.04
Revenue Earned by Producing Electricity in One Day (Thousand $)			64

Appendix 2-2 Sample Calculations (Formula Used)

$$Corrosion\ Rate = (Thickness\ Lost)/(\mathrm{Test}\ Time) \tag{7}$$

$$Loss\ of\ Volume\ per\ Year = (Corrosion\ Rate)\times(Operation\ Time)\times(Surface\ Area\ of\ Superheater\ Tube) \tag{8}$$

$$Loss\ of\ Mass\ per\ Year = (Loss\ of\ Volume\ per\ Year)\times(Density) \tag{9}$$

$$Cost\ for\ Superheater\ Tubes'\ Five\text{-}Year\text{-}\mathrm{Lifetime}\ Extension = (Loss\ of\ Mass\ per\ Year)(Price\ of\ Coating\ Material)(5\ Year) \tag{10}$$

$$Volume\ of\ Superheater\ Tubes = (Cross\ Section\ Area\ of\ the\ Tube)\times(Length\ of\ the\ Tube) \tag{11}$$

$$Cost\ for\ Certain\ Length\ of\ Superheater\ Tube = (Volume\ of\ the\ Tube)\times(Price\ of\ Tube\ Material) \tag{12}$$