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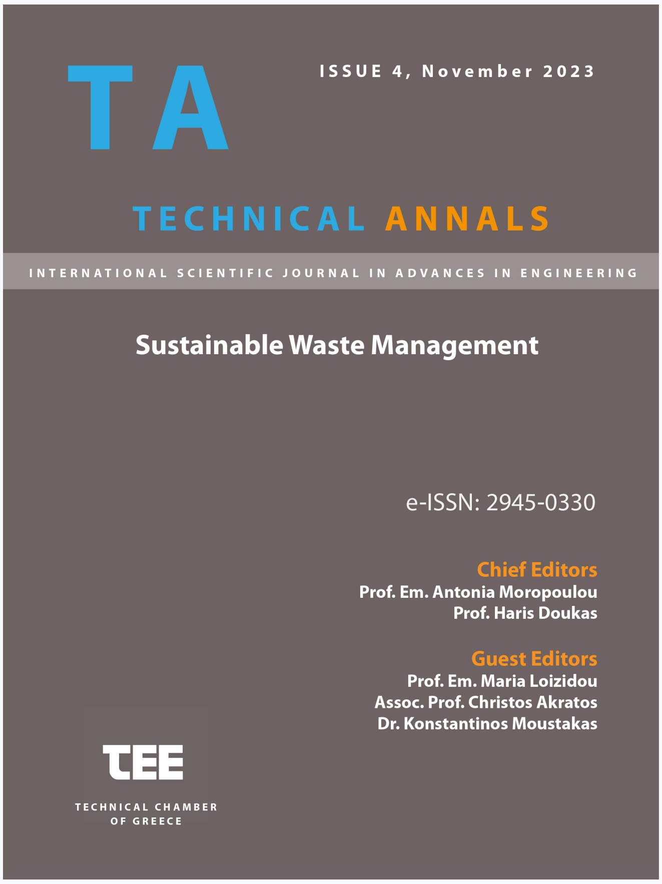

Advances in Corrosion Mitigation for Waste-to-Energy Systems: Evaluating Coatings and Application Techniques

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Advances in Corrosion Mitigation for Waste-to-Energy Systems: Evaluating Coatings and Application Techniques

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Abstract. Waste-to-Energy (WTE) systems, utilizing post-recycled municipal solid waste (MSW) and other biomass materials, have been proven as alternatives to landfilling for sustainable waste management. These processes have offered benefits such as reduced landfill space, decreased methane emissions, and minimized waste volume. However, operational challenges, specifically high-temperature corrosion (HTC) of superheater tubes, have hindered their efficiency due to the presence of chlorine, alkaline salts, and sulfates. To address this issue, a range of coating techniques have been developed, with thermal spray techniques, particularly high velocity oxy-fuel (HVOF) spray, proving to be the most effective for protecting superheater tubes. A comparative analysis of experimental data from multiple studies has indicated that coatings with Alloy 625, Alloy C-276, Colmonoy 88, FeCr, IN625, NiCr, NiCrTi, and A625 offer high corrosion resistance at relatively low material costs, with corrosion rates below 1 mm/year. High chromium, nickel, and molybdenum content coatings have performed exceptionally well under high-temperature and high-chlorine conditions. Notably, T92 and P91, due to their low cost and high corrosion resistance, emerged as strong candidates for superheater tubes operating at 550°C. While A625 has demonstrated excellent corrosion resistance, its high cost has limited its practicality. Ultimately, the selection of suitable coatings has depended on the specific WTE plant design and operating experience. The additional cost of applying these coatings has been a minor fraction of the overall financial gains, as it extends the superheater tubes' lifetime and reduces plant downtime for tube repair or replacement.

Keywords*:* High-temperature corrosion (HTC), Protective coatings, Superheater tubes, Thermal spray techniques, Waste-to-Energy (WTE)

1 Introduction

Globally, approximately 2.01 billion tons of municipal solid waste (MSW) are generated annually, with a growing interest in utilizing waste-to-energy (WTE) technologies for post-recycling MSW management [1]. In addition to MSW, biomass combustion for energy production is gaining traction as a sustainable and renewable energy source. For instance, bioenergy with carbon capture and storage (BECCS) is a technology supported by combustion processes, offering a promising approach to achieve negative carbon emissions [2, 3]. However, the combustion of MSW and biomass presents different challenges due to their distinct compositions. MSW, which contains natural organic compounds and chlorinated plastics (mostly polyvinylchloride, PVC), results in high chlorine concentrations (0.47-0.72 wt%) in the gas passing through the boiler [4,5]. In contrast, biomass materials generally have varying chlorine content depending on their specific composition, with some feedstocks exhibiting lower concentrations than MSW [4]. Regardless of the feedstock, high temperatures inside boilers, along with the presence of alkaline metals (Na, K, etc.), heavy metals (Pb, Zn, etc.), and sulfates during combustion, can lead to severe high-temperature corrosion (HTC) issues. The problem is particularly critical for superheater tubes (SHT), which are affected by ash deposits that melt at 300-550°C [5, 6].

Superheater tube corrosion in combustion systems is a result of four simultaneous mechanisms. The first mechanism involves corrosion driven by gaseous phase chlorine, such as HCl and Cl2. The second mechanism is attributed to the condensation of alkali and heavy metal chlorides and/or sulfates on the tube surfaces. The third mechanism comprises corrosion induced by deposits and the sulfidation of condensed chlorides. Finally, the fourth mechanism entails the dissolution of protective oxide layers and tube metal caused by molten salt eutectics. Superheater tube corrosion can lead to material wastage, tube leakages, reduced tube lifetimes, and unplanned boiler shutdowns in waste-to-energy and biomass combustion plants. The corrosion rate of these tubes can be as high as several millimeters per year [4-7].

In many WTE plants, steam conditions are maintained at 400-450°C and 2.9-5.8 MPa to ensure stable operation and minimize corrosion of superheater tubes [5, 7]. Reducing steam temperature can enhance the stabilization of protective oxide layers on superheater tubes. However, the demand for higher efficiency in power and heat generation necessitates increased steam temperatures. For instance, raising the temperature from 400°C to 500°C can result in a 20% increase in power generation [7,8]. Nevertheless, elevating the steam temperature to such levels requires flue gas surrounding the superheater tubes to reach temperatures above 650°C, which significantly exacerbates corrosion on the tubes [4, 8].

Frequent replacement of superheater tubes has become a common practice for WTE plants operating at higher steam temperatures, which improves the thermal efficiency of the plant but also increases operational costs [4, 5,7]. Consequently, finding effective methods to prevent HTC and extend the lifetime of superheater tubes is a pressing issue [10].

To mitigate HTC problems various approaches have been adopted [7-10]. Early methods included adding refractory coatings (e.g., SiC) and metal shields, reducing soot blowing pressure and frequency, installing baffles, relocating superheater tubes to lower temperature zones, and upgrading the metals used for superheater tubes. Subsequently, weld overlays, laser claddings, fused coatings, and thermal spray coatings emerged as more effective solutions for addressing HTC issues in waste-to-energy and biomass combustion boilers.

Thermal spray coating techniques, such as flame spray, electric arc spray, plasma spray, high-velocity oxy-fuel spray, high-velocity air-fuel spray, and detonation spray, have demonstrated success in European WtE plants for protecting superheater tubes and extending their lifetimes [9, 11]. These methods allow the application of various materials, resulting in high-quality coatings characterized by low porosity and high hardness. The process involves using a spray gun to melt the selected coating material, in powder or wire form, and depositing the molten particles onto the target surface with a high-velocity gas jet. Advantages of thermal spray techniques include the ability to create relatively thin layers (100-800µm), a wide range of coating materials, and the flexibility for on-site or off-site application, all at an affordable cost. As a result, thermal spray techniques offer an effective solution for addressing corrosion issues in superheater tubes [9, 11].

Original contributions: The primary contributions of this study lie in its comprehensive technical and economic analysis of various thermal spray techniques and coating materials used for prolonging the life of superheater tubes in waste-to-energy and biomass combustion plants. By employing case studies and drawing on the existing body of research, this study provides a holistic understanding of the factors influencing the effectiveness of different coating materials and their corresponding thermal spray techniques. Furthermore, this research offers valuable insights and guidance to industry professionals and engaged stakeholders in making informed decisions regarding the selection of appropriate thermal spray techniques and coating materials to enhance superheater tube performance. By identifying the most suitable coatings and application methods, this study aims to contribute to the long-term sustainability and economic viability of waste-to-energy and biomass combustion plants.

2 Materials and Methods

2.1 Coating techniques considered

This study considers various thermal spray techniques. These techniques are known for their distinct advantages and limitations in terms of cost, application, porosity, bond strength, and coating quality [7, 11-25]. A summary is provided below:

i. Flame Spray: A low-cost and flexible technique that uses either powder, wire, or rod form feedstock materials. The feedstock is melted by a combustion gas and then sprayed onto the substrate using high-speed compressed air. However, coatings produced by this method have high porosity (10-20%), low density, and low bond strength compared to other techniques [7, 11, 12].
ii. Electric Arc Spray: This technique uses wire-form feedstock materials and creates an electric arc between two metallic wires, melting them. The molten particles are accelerated towards the substrate by a compressed gas stream. Electric arc spray offers low heat input, high bond strength, denser coating, and lower operating costs compared to flame spray. However, it is limited to metal wire feedstock materials and generates significant fumes and dust during operation [12].

iii. Plasma Spray: This method involves ionizing plasma-forming gas between two electrodes, heating it to extremely high temperatures, and using the resulting plasma jet to propel molten particles onto the coated surface. Plasma spray, including atmospheric and vacuum variants, provides low porosity levels and does not degrade the substrate's mechanical properties. However, this technique has a relatively high cost and complexity [7, 11, 21].

iv. Detonation Spray: The first high-velocity thermal spray process, in which fuel gas and coating materials are ignited in a water-cooled gun barrel, creating molten particles that are accelerated towards the substrate at supersonic velocities. This method results in coatings with low porosity, high density, and excellent mechanical properties. However, it is unsuitable for low-density spray materials, has high noise levels, and is expensive [13, 14].

v. Warm Spray: A variant of high-velocity oxy-fuel spray that uses a mixing chamber to control temperature and speed, ensuring coatings maintain their original characteristics without thermal deterioration. This technique is relatively new, and thus has fewer applications in WTE boilers [15-17].

vi. High Velocity Oxy-Fuel (HVOF) and High Velocity Air-Fuel (HVAF) Spray: Both techniques use a mixture of fuel and oxygen (HVOF) or air (HVAF) to create high-pressure flames that melt and propel feedstock particles onto the substrate. These methods produce thicker coatings with strong adhesion and low porosity. However, they have a relatively low deposition rate and higher equipment costs. HVOF spray is the most prevalent technique in WTE applications due to its ability to produce high-quality coatings [18-20, 22-25].

2.2 Coating and tube materials considered

Numerous laboratory tests have been conducted on different coating and tube materials (Tables 1- 3), providing crucial data such as material composition, and corrosion rates and contributing to a better understanding of the interactions and performance under different conditions [5, 9, 20, 22-25]. To comprehensively analyze this data, the following assumptions were made:

i. All test environments exert an equal corrosion effect on the selected coating and tube materials [5, 12].

ii. Technical parameters, aside from the chosen thermal spray technique, do not influence coating quality [5, 12].

iii. The sample superheater tube's unit length is assumed to be one meter [5, 7].

iv. The sample superheater tube's outside diameter is 3.81 cm (1.5 in), and the wall thickness is 0.4572 cm (0.18 in) [5, 7, 12].

v. The WTE plant's operating time is 8,000 hours per year (90% availability) [26].

vi. Coating materials are composed of pure metal elements [11, 12].

vii. The coated superheater tubes' lifetime will be extended by five years, during which only the tube coatings will corrode [9].

viii. Corrosion rates are uniform around the tube [5, 9]. Thus, the volume loss due to corrosion of the superheater tube in each unit period equals the corrosion rate multiplied by the time and the tube's surface area.

ix. Only the costs of tube or coating materials are considered, excluding equipment costs. The cost of metal is a fraction of the total cost for thermally coating one square meter of superheater tubes' surface (Supplementary materials) [12].

x. Experimental coating data obtained at temperatures above 550°C were excluded, as WTE superheater tubes do not operate at higher temperatures [26].

Based on the information provided in the research studies listed in Tables 1-3, the density and price/cost of materials can be calculated [27, 28]. A sample calculation is provided in the supplementary materials. In addition, supplementary materials contain complete data for each coating and tube material, the calculated costs of applying coatings to a one-meter-long superheater tube for a presumed five-year-lifetime extension, and the costs of manufacturing one meter of superheater tubes using the selected materials for each research study listed in Table 1.

2.3 Summary of formulas used

In our investigation, we utilized a series of mathematical formulas to analyze and calculate various aspects of our study [12, 18, 23, 25].

1. **Corrosion Rate:** The rate of corrosion was determined by calculating the thickness lost over the test time. The formula used was:
   Corrosion Rate = Thickness Lost / Test Time
2. **Loss of Volume per Year:** This was calculated by multiplying the corrosion rate by the operation time and the surface area of the superheater tube. The formula used was:
   Loss of Volume per Year = Corrosion Rate × Operation Time × Surface Area of Superheater Tube
3. **Loss of Mass per Year:** This was calculated by multiplying the loss of volume per year by the density. The formula used was:
   Loss of Mass per Year = Loss of Volume per Year × Density
4. **Cost for Superheater Tubes' Five-Year-Lifetime Extension:** This was calculated by multiplying the loss of mass per year, the price of the coating material, and the duration of five years. The formula used was:
   Cost for Superheater Tubes' Five-Year-Lifetime Extension = Loss of Mass per Year × Price of Coating Material × 5 Years
5. **Volume of Superheater Tubes:** This was calculated by multiplying the cross-sectional area of the tube by the length of the tube. The formula used was:
   Volume of Superheater Tubes = Cross Section Area of the Tube × Length of the Tube
6. **Cost for Certain Length of Superheater Tube:** This was calculated by multiplying the volume of the tube by the price of the tube material. The formula used was:
   Cost for Certain Length of Superheater Tube = Volume of the Tube × Price of Tube Material

2.4 Effect of thermal conductivity on superheater tube efficiency

Thermal conductivity signifies a material's ability to conduct heat [29]. To gain a general understanding of whether coatings will impact the efficiency of superheater tubes, the following calculations and analysis are performed:

Conductance of a metal material = k / l

Here, k represents the thermal conductivity of materials, usually expressed in units of W/(m·K), and l denotes the thickness of materials, typically measured in millimeters (mm).

2.5 Cost and Benefit Analysis

The cost and benefit analysis (CBA) is based on a specific WTE plant with the following characteristics [26]:

i. Number of Units: Three
ii. Maximum Continuous Rating (MCR) a. Solid Waste Capacity per Unit: 600 tons/day b. Fuel Design HHV: 5,500 Btu/lb
iii. Design Date (MCR) a. Continuous Steam Output: 171,121 lb/hr b. Steam Pressure (at superheater non-return valve outlet): 865 psig c. Steam Temperature (at superheater non-return valve outlet): 830°F d. Feedwater Temperature: 300°F
iv. Heat Loss: 28.65%
v. 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 (2,014 m^2)
vi. The efficiency of 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.

Therefore, the daily electricity production for this three-unit plant can be calculated as follows:

$$3\ Units \times \frac{600\ ton\ MSW}{day-unit} \times \frac{5{,}500\ B\mathrm{tu}}{lb} \times \frac{2204.62\ lb}{ton} \times \frac{0.293071\ Wh}{B\mathrm{tu}} \times \frac{MW\mathrm{h}}{10^6\ Wh} = 6{,}396.5\ \mathrm{MWh/day}$$

Considering the heat loss, the net daily electricity production is:

6,396.5 MWh/day * (1 - 28.65%) * 28% = 1,277.9 MWh/day

With an electricity price of $50/MWh, the plant's daily earnings amount to:

(1,277.9 MWh/day) * ($50/MWh) = $63,894.5/day

3 Results and Discussion

3.1. Selection of Superheater Tube materials

For the future selection of superheater tube materials, it is essential to prioritize those with low corrosion rates and reasonable costs. As illustrated in Figure 1, Alloy 625 demonstrates commendable performance at 525°C and 625°C, while Alloy 263 exhibits relatively low corrosion rates at 575°C, 625°C, and 750°C. Additionally, P91 provides corrosion rates below 5 mm/year at 525°C and 625°C. Furthermore, T92, Sanicro 28, Hastelloy C-2000, and HCM12A display low corrosion rates (<5mm/year) at the tested temperatures [13-25].

Although Alloy 625 presents the best corrosion resistance performance among all examined tube materials, its high price (Figure 1) is a significant drawback. Similarly, Alloy 263 performs well in WTE environments at 525°C and 625°C but is also associated with a high cost. Due to their elevated costs, Alloys 263 and 625 are not ideal choices for superheater tubes. Nevertheless, these substances may be appropriate for use as coating materials, which will be explored further in the subsequent discussion [5, 22, 25].

On the other hand, P91 emerges as a viable choice for tube material, considering its relatively better corrosion resistance at 525°C and 625°C, along with its lower cost compared to other tube materials. Besides P91, T92 also possesses a relatively low price and exhibits good performance in high-temperature-corrosion environments [5, 24].

3.2. Comparison of Corrosion Resistance of Coating Materials

Figure 2 compares the corrosion resistance of the coating materials tested in the cases listed in Table 1. For the sake of clarity, some coating materials are labeled differently to distinguish between various cases. The following coating materials demonstrate relatively low corrosion rates, i.e., less than 1 mm per year:

(a) NiCr sprayed by HVOF,
(b) Alloy C-276 sprayed by HVOF,
(c) IN625 sprayed by HVOF,
(d) NiCrTi sprayed by electric arc,
(e) Tube material A625 (potential coating material),
(f) Colmonoy 88 sprayed HVOF (at 450°C and 500°C),
(g) FeCr sprayed by HVOF,
(h) NiCrBSiFe sprayed by HVOF, and
(i) Alloy 625 sprayed by HVOF.

Alloy 718 and Colmonoy 88 tested at 550°C also exhibit good corrosion resistance, with rates less than 1.5 mm per year. SW 1641 tested at 450°C demonstrates a corrosion rate of around 6 mm per year. In contrast, the remaining tested coating materials display relatively high corrosion rates, i.e., more than 10 mm per year [13-25].

High-chromium, high-nickel, and nickel-chromium alloys have demonstrated high resistance to high-temperature oxidation and corrosion, making them suitable for thermally sprayed coatings in WTE boilers [34 & 35]. Increasing molybdenum content in nickel-based alloy coatings has been found to improve corrosion resistance in chlorine-rich and chlorine-oxidizing waste incineration environments. Several materials have been tested under WTE conditions for 6000 hours, with corrosion rates decreasing as the [Cr+Ni+Mo] concentration in the alloy increased, regardless of the coating temperature (450 or 550°C). Ceramic coatings have also shown good durability on superheater tubes inside WTE boilers, but their application remains limited [7].

To identify the best choice of coating materials, those with relatively high corrosion rates are excluded from the subsequent analysis.

3.3. Comparison of Cost for Coating Materials and Lifetime Extension

Figure 3 compares the cost of applying each coating material to an assumed one-meter-long superheater tube to achieve a five-year-lifetime extension. To differentiate between various cases, some of the coating materials are labeled with different names, as was done for Figure 3. Among the coating materials with lower corrosion rates in Figure 1, 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 Colmonoy 88 by HVOF (at 450°C, 500°C, and 550°C) exhibit both better corrosion resistance and lower cost. Coating materials SW1641, SW1600, and NiCrBSiFe are excluded due to their high costs, but their data can be found in Supplementary materials [5, 13-25].

Figure 4 features coating materials with corrosion rates of less than 1 mm/year and costs of less than $100 for coating the assumed one-meter-long superheater tube. Some less attractive materials are not included in Figure 4 but can be found in Supplementary materials. NiCr sprayed by HVOF offers both better corrosion resistance and lower cost compared to other potential coating materials. Additionally, Alloy C-276 coating sprayed by HVOF exhibits excellent performance at 525°C and has a relatively low cost [12]. IN625 sprayed by HVOF with DJ demonstrates a very low corrosion rate and cost at its test temperature of 550°C. NiCrTi sprayed by electric arc spray technique shows outstanding performance under high-temperature-corrosion environments, and its cost is low [5].

Although the metal cost for spraying Colmonoy 88 is relatively low (<$50), its corrosion rate is high at the test temperature of 500°C compared to other coating materials; however, it is still less than 1 mm per year. FeCr sprayed by HVOF with CJS has a relatively high corrosion rate but is low-cost compared to other coating materials. As such, it could be considered for superheater tube coating in high steam temperature applications [12, 23, 25].

The tube alloy, A625, provides both an acceptably low corrosion rate and cost at a test temperature of 525°C. All the coating materials presented in Figure 4 offer outstanding corrosion resistance (corrosion rate < 1mm/year). Furthermore, the cost of thermal deposition is at best about $200, for example, for NiCr deposit. When compared to the fabricated NiCr alloy tube price of approximately $30/kilogram, it is evident that thermal coating should only be applied for maintenance purposes. Therefore, WTE companies should evaluate the relative costs of applying these materials in specific WTE applications and choose the one that provides the best overall cost performance.

3.4. Effect of thermal conductivity on superheater tube efficiency

Since the thermal conductivity of metals, in general, is close to 30 W/m K [53], and the thickness of the analyzed superheater tubes is approximately 0.5 cm (0.005 m), the conductance of metals in general is calculated to be 6,000 W/m² K. A typical value for the conductance of gas is around 200 W/m² K [28]. Given that the conductance of metals is generally greater than that of gas, it can be concluded that the overall heat transfer through the tube wall is not controlled by metals. This principle will always hold true since the thickness of the tube wall with coatings cannot be as extensive as several centimeters, ensuring that the conductance of metals will always surpass that of gas. Consequently, applying additional coatings onto superheater tubes will not affect their efficiency.

3.5. Cost-Benefit Analysis of Superheater Tube Coatings

Figure 5 illustrates the cost of selected coating materials for the assumed five-year-lifetime extension. Detailed data on their cost can be found in supplementary materials.

Annually, WTE units undergo approximately 15 days of shutdown for periodic maintenance. Coatings can help reduce maintenance time for superheater tubes, allowing the saved time to be used for continued energy production. It is crucial that the cost of adding coatings does not surpass the revenue generated by the plant during the time saved by extending the lifetime of superheater tubes [4, 26].

As depicted in Figure 5, the metal costs for spraying Colmonoy 88 by HVOF are about 12 times greater than the daily revenue earned by the plant. This means that using Colmonoy 88 as a coating material at 550°C in the assumed five-year period will not result in a loss of profit only if the total superheater tube maintenance time exceeds 13 days. WTE plants generally spend around two weeks on whole-plant maintenance [26]. Consequently, it is unlikely that many days are dedicated solely to superheater tube maintenance; hence, applying very costly coating materials may not be a reasonable choice.

This analysis demonstrated that Alloy 625 sprayed by HVOF can be used as SHT coating materials without affecting the plant's profit if the 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 tubes is more than two days in the assumed five-year period. The remaining selected coating materials could be used when the downtime for superheater tube maintenance is more than one day in total over an assumed five-year period. Some of them would be a good choice even when the maintenance time is only more than half a day.

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

4 Conclusions and Future Research Directions

4.1. Conclusions and Recommendations for Superheater Tube Coatings in WTE Plants

High-temperature combustion and the presence of corrosive components in MSW cause severe high-temperature corrosion (HTC) in superheater tubes. This study found that adding coatings to superheater tubes using thermal spray techniques, especially high-velocity oxy-fuel (HVOF) spray, can effectively extend their lifespan and reduce maintenance issues.

Coatings with high chromium, nickel, and molybdenum content demonstrate outstanding corrosion resistance under high-temperature-high-chlorine conditions. Several coating materials and alloys, including NiCr, NiCrTi, Alloy C-276, IN625, FeCr, Colmonoy 88, and Alloy 625, exhibited corrosion rates of less than 1 mm/year and reasonable application costs. Combining these coatings with better alloy tubes (e.g., P91 and T92) in the initial manufacturing of superheater tube bundles and refurbishing high corrosion areas after a year's operation is recommended for minimum cost and maximum plant availability.

Ultimately, the choice of coating material should consider each plant's specific conditions, as the additional cost for applying coatings should not exceed the revenue generated from extending the superheater tubes' lifetime and reducing maintenance time.

4.2. Future Research Directions

For a more precise evaluation of thermal spray techniques and coating materials, further studies should consider:

i. The impact of pressure on superheater tube thickness and corrosion conditions.
ii. Testing each selected coating material in WTE environments under the same temperatures.
iii. Accounting for parameters influencing the quality of coatings, such as spray distance, powder feed rate, fuel ratio, selection of guns and nozzles, and powdered materials' particle size.
iv. Applying different coatings to different portions of superheater tubes, considering the varying temperature and corrosion effects along their positions.
v. Including additional costs, such as instrument cost, for a more comprehensive analysis.

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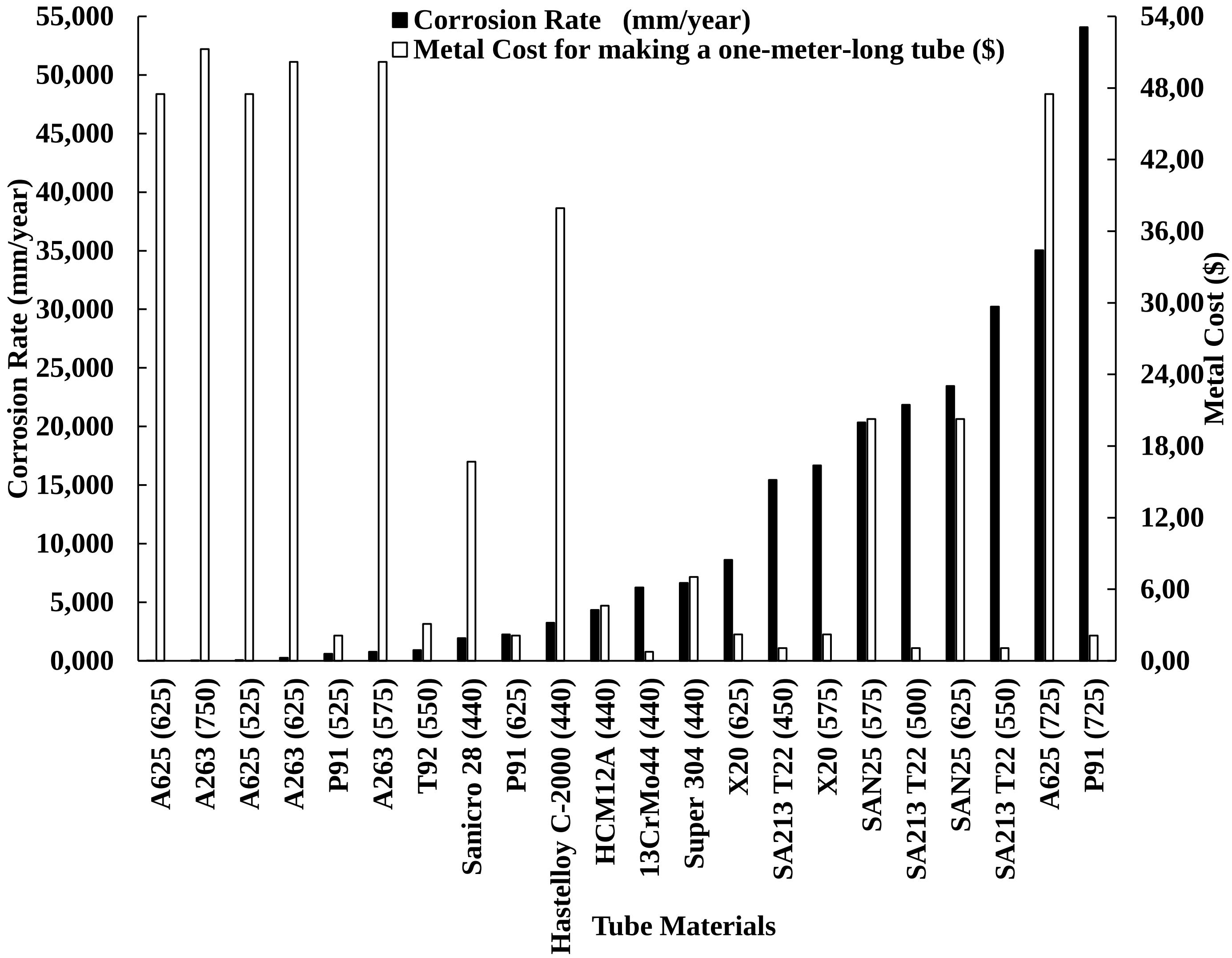

Fig 1. Corrosion Rate and Metal Cost for a One-Meter Superheater Tube (Test Temperatures Indicated in Parentheses).

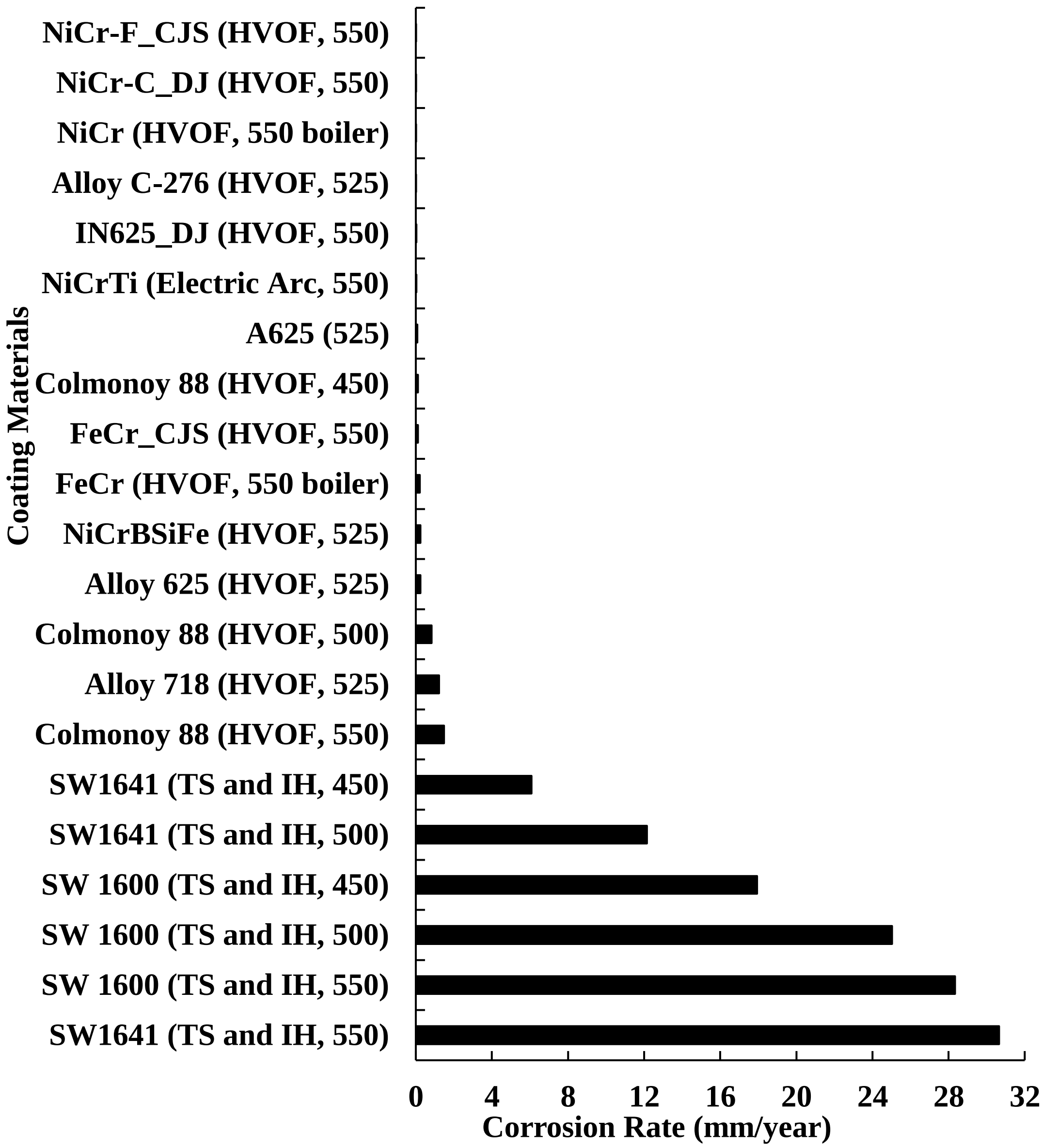

Fig 2. Estimated Corrosion Rate for Coating Materials (Test Temperatures and Techniques Shown in Parentheses; "F" in "NiCr-F" Represents "Fine" Powder, "C" in "NiCr-C" Represents "Coarse" Powder; "TS and IH" Denotes "Thermal Spray and Induction Heating").

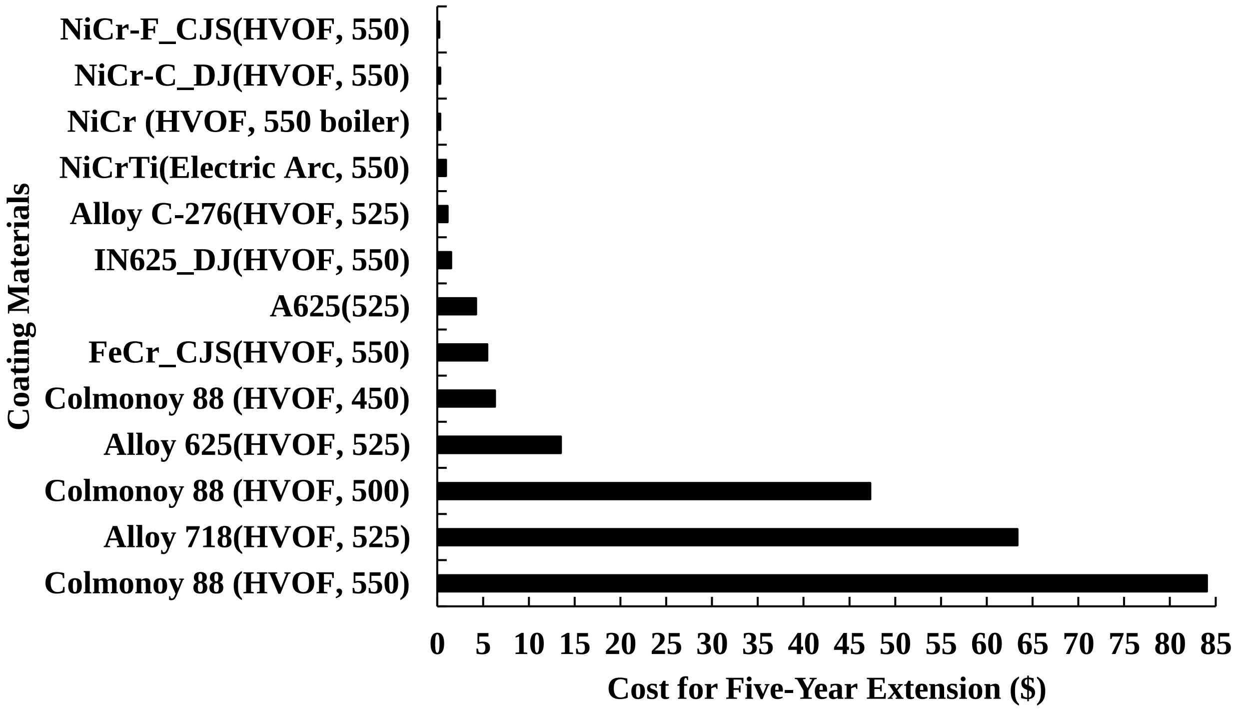

Fig 3. Metal cost for spraying coating materials onto a one-meter-long superheater tube for five-year-lifetime extension. The test temperature and technique used for each coating material are shown in parentheses. "F" in "NiCr-F" indicates the use of fine powder, while "C" in "NiCr-C" indicates the use of coarse powder. The estimated cost includes the material cost and the labor cost of applying the coating.

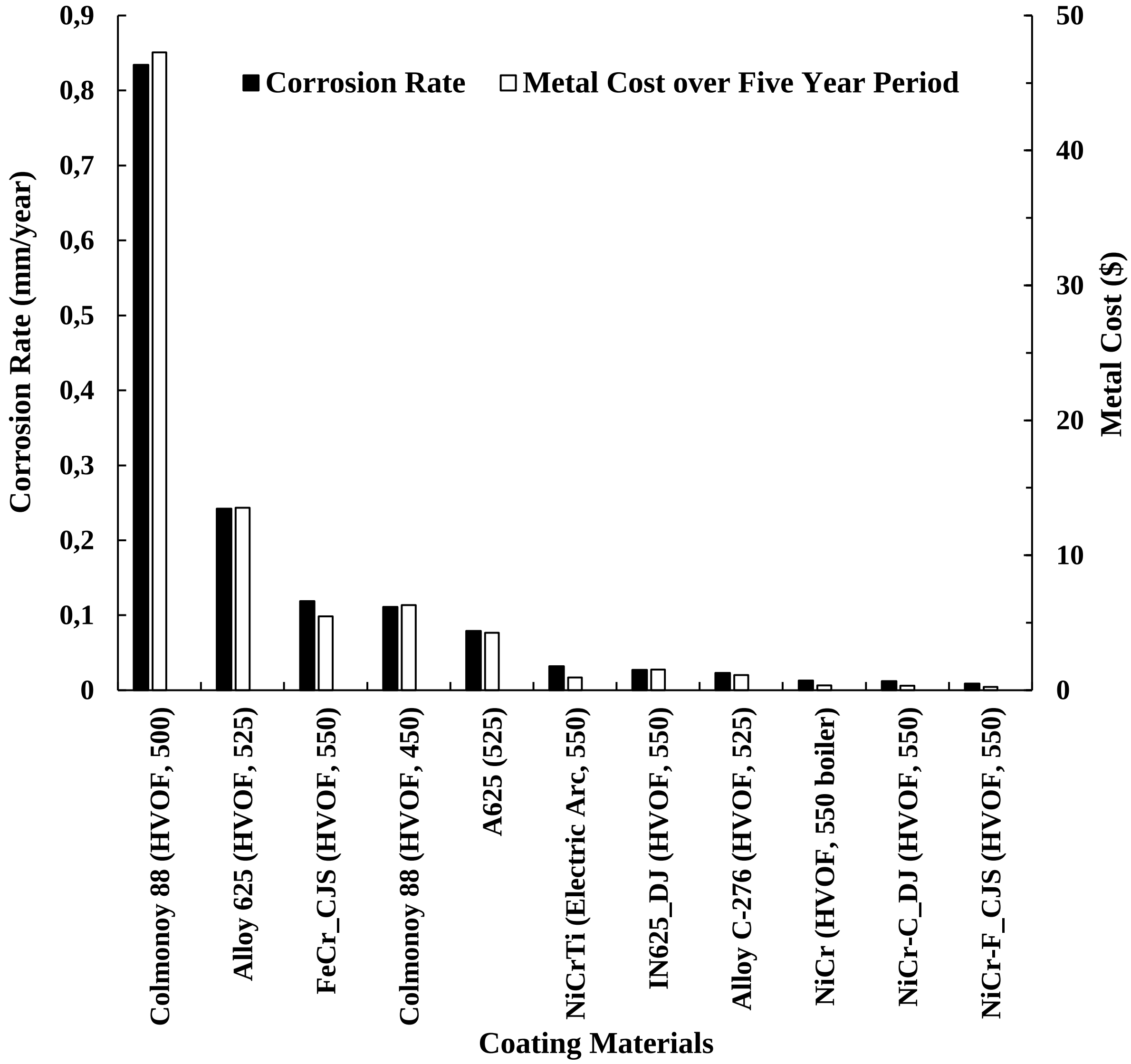

Fig 4. Estimated corrosion rates (<1 mm/year) and metal costs (<$100) for coating materials sprayed using various techniques and temperatures for a five-year-lifetime extension of super-heater tubes. The techniques and temperatures used for testing are shown in parentheses. "F" in "NiCr-F" denotes fine powder, while "C" in "NiCr-C" denotes coarse powder.

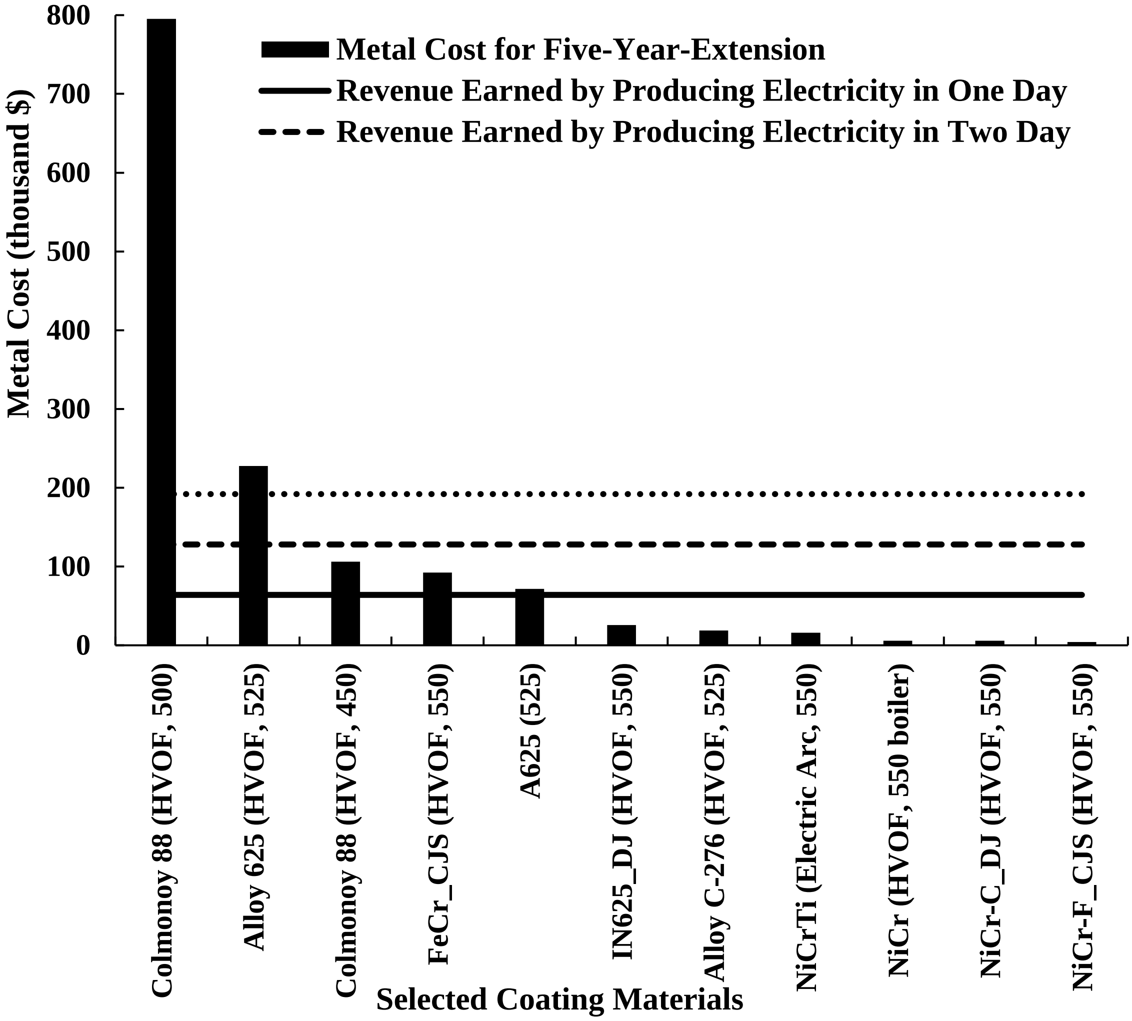

Fig 5. Metal cost for adding selected coating materials for five-year-lifetime extension (test temperature and techniques used are shown in parentheses; “F”in “NiCr-F” stands for “fine”, which means that fine powder was used for the test, “C” in “NiCr-C” stands for “coarse”, which means that coarse powder was used for the test.) The cost is estimated for a one-meter-long superheater tube.

Table 1. 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	9
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	22
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	23
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	24
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	25
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	5

Table 2. Composition for each coating material

Ref	Material	Ni	Fe	Cr	Mo	Al	Nb	Ti	W	C	B	Mn	Si	Cu	Co	V	P	S
20	Alloy 625	63.79	5	21.2	8.3	0.5	1.2	0.01										
9	NiCr	51.8	1.1	45	…		…		…	…	…	…	2.1	…				
9	IN625	63	2.5	21.5	9		3.7		…	…	…	0.1	0.2	…				
9	Diamal-loy4006	54	1	20.5	9		…		10	0.75	0.75	…	…	4				
9	SHS9172	…	28	25	6		12		15	4	5	3	2	…				
22	NiCr	51.3	…	46.5	…		…	…	…				2.2		…			
22	IN625	66.5	…	21	8.8		3.5	…	…				0.2		…			
22	FeCr	…	60.1	19	3.6		7.1	…	8.6				1.6		…			
22	NiCrTi	55.25	…	44	…		…	0.75	…				…		…			
23	NiCr	50.2	1.1	46.5	…		…		…	0.1	…	…	2.1					
23	FeCr	…	52.3	18.6	3.6		7.1		8.6	2.1	5	1.1	1.6					
25	NiCrBSiFe	70.6	4.6	17.2	…	…	…	…	…	0.8	3.1	…	3.7			…	…	…
25	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
25	Alloy 625	67.209	0.081	21	8	…	3.48	…	…	0.03	…	0.1	0.1			…	…	…
25	Alloy C-276	58.976	5.09	15.55	16.48	…	…	…	3.81	0.004	…	0.06	0.03			…	…	…
5	Colmonoy 88	56	10.9	15					17.3	0.8								
5	SW 1600	75.1		15	2.5						3.1		4.3					
5	SW1641	52.9		37.1	3						3.6		3.4					

Table 3. Composition for each tube material

Ref	Material	Ni	Fe	Cr	Mo	Al	Nb	Ti	W	C	B	Mn	Si	Cu	Co	V	P	S
9	X20	0.55	85.2	11.25	1	…	…	…	…	0.2		1	0.5	…	…	0.3		
9	A263	49.44	0.7	20	5.85	0.6	…	2.15	…	0.06		0.6	0.4	0.2	20	…		
9	SAN25	25	43.1	22.5	…	…	0.5	…	3.6	0.1		0.5	0.2	3	1.5	…		
22	T92	…	87.9	9	0.6			…	2				0.5		…			
22	A263	51.5	0.5	20	5.8		…	2.2	…						20			
24	13CrMo44	0.1	97.73	0.85	0.5					0.12		0.5	0.2					
24	HCM12A	0.5	84.335	11.3	0.5				2	0.11	0.005	0.5	0.5			0.25		
24	Super 304	9	68.57	18	…		0.4			0.03		0.8	0.2	3				
24	Sanicro 28	30.6	36.41	26.6	3.3					0.09		1.6	0.5	0.9				
24	Hastelloy C-2000	58.893	1.2	22.5	15.7					0.007		0.2	…	1.5				
25	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
25	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
5	SA213 T22		96.65	2.25	1					0.1								