# Fabrication technologies for cladded components of molten salt reactors

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## 1. Introduction

Molten salt reactor (MSR) is one of the next-generation nuclear power systems that can fundamentally exclude severe accidents, but this reactor operates in a highly corrosive environment and high radiation irradiation environment, and it is known that most commercial high-temperature materials can be seriously damaged by molten salt corrosion and neutron irradiation [1].

In this way, the safety of reactor vessels and piping exposed to molten salt may be threatened due to molten salt corrosion and irradiation embrittlement, and problems such as periodic replacement of parts, frequent operation interruptions, and generation of radioactive waste may occur.

Therefore, a method of covering the inner surface of parts exposed to molten salt with a corrosion-resistant cladded layer is being considered in the design.

In this paper, we will examine the cladding equipment-related provisions of the high-temperature reactor design code and comment on the cladding equipment development strategy that can be used in marine molten salt reactors.

## 2. ASME code and cladding technologies

### *2.1 ASME Section III Division 5*

Division 5 is defined into six subsections, as presented in Table 1, covering Classes A, B, and SM for metallic coolant boundary components and supports, and Class SN for nonmetallic core components. However, Division 5 is a "Component Code for Design," addressing rules for the safety classification of individual components at the subsystem level. Furthermore, Division 5 does not address materials degradation that may occur during operation due to radiation effects, corrosion, erosion, or material instability. Therefore, such material degradation effects of Division 5 are the responsibility of the plant operator.

The Division 5 code regulations list materials such as 2.25Cr-1Mo steel, 9Cr-1Mo steel, Type 304, Type 316 stainless steel, and Alloy 800H.

Recently, in 2020, ASME approved Alloy 617 through code case N-898, specifying that it can be used for up to 100,000 hours at temperatures up to 1750°F (954°C). Currently, six materials are specified for high-temperature reactor design according to the Division 5 code [2].

Table 1. Organization of ASME Section III Div. 5.

| Code Class | Sub-section | Subpart | Subsection ID | Title | Scope |
|---|---|---|---|---|---|
| General Requirements | | | | | |
| Class A, B, & SM | HA | A | HAA | Metallic Materials | Metallic |
| Class SN | | B | HAB | Graphite and Composite Materials | Nonmetallic |
| Class A Metallic Coolant Boundary Components | | | | | |
| Class A | HB | A | HBA | Low Temperature Service | Metallic |
| Class A | | B | HBB | Elevated Temperature Service | Metallic |
| Class B Metallic Coolant Boundary Components | | | | | |
| Class B | HC | A | HCA | Low Temperature Service | Metallic |
| Class B | | B | HCB | Elevated Temperature Service | Metallic |
| Class A and Class B Metallic Supports | | | | | |
| Class A & B | HF | A | HFA | Low Temperature Service | Metallic |
| Class SM Metallic Core Support Structures | | | | | |
| Class SM | HG | A | HGA | Low Temperature Service | Metallic |
| Class SM | | B | HGB | Elevated Temperature Service | Metallic |
| Class SN Nonmetallic Core Components | | | | | |
| Class SN | HH | A | HHA | Graphite Materials | Graphite |
| Class SN | | B | HHB | Composite Materials | Composite |

### *2.2 Code for cladded components*

Class A structural materials withstand structural loads, while thin cladding materials bonded to the surface protect the base material from corrosion and radiation. Since the cladding material does not bear structural loads, long-term testing of this cladding material is not necessary. Section HBB (HBB-2121 Permitted Material Specifications) under Div. 5 permits the use of non-Code qualified materials for high-temperature nuclear service only when the base material is clad with a cladding material less than 10% thick [3]. However, there are no ASME design rules to evaluate the generation of defects during the interaction of the cladding layer and the base material under high-temperature cyclic loads.

### *2.3 Evaluation of Cladding Layers*

Barua et al. suggested several cladding techniques for high-temperature service, including weld overlay, coextrusion/corolling, explosion bonding, thermal spray, and cold spray [4]. For example, weld overlay has been widely used in the oil industry for soft cladding materials such as nickel, while explosion bonding has been applied to various materials, including refractory metals. Cold spray has been proven for a range of materials, from pure metals to complex alloys. When applying these methods to high-temperature reactor applications, it is necessary to evaluate the strength and reliability of the generated interface using design-by-analysis methods.

### *2.4 Introduction to Cladding Techniques*

2.4.1 Weld Overlay

As shown in Fig. 1, weld overlay involves layering a corrosion-resistant material onto the base metal using methods such as GTAW (Gas Tungsten Arc Welding). In this case, the phenomenon of dilution zone generation up to a certain depth of the base material must be considered during design.

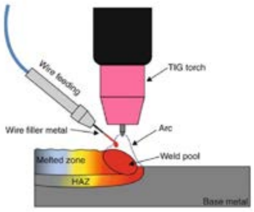


Fig. 1. Concept of weld overlay for cladding.

2.4.2 Thermal Spray

Thermal spray, shown in Fig. 2, is a technique to improve the surface of metallic or non-metallic structures. This process can be used to apply coatings to various materials and components to enhance resistance to wear, erosion, cavitation, corrosion, or heat. The thermal spray method considered in this study is HVOF (High-Velocity Oxygen Fuel) coating, aimed at enhancing erosion and wear resistance and preventing corrosion. When applying this technology to molten salt reactor components, special attention must be paid to the thermal stability of the cladding layer.

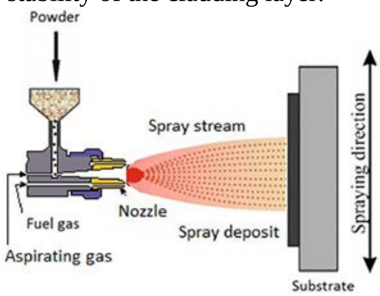


Fig. 2. Concept of thermal spray for cladding.

2.4.3 Explosion Bonding

As shown in Fig. 3, explosion bonding is a cladding layer fabrication technique that uses an explosion as an energy source to form a metallurgical bond primarily on sheet metal components. This technique is advantageous for precisely positioning the cladding layer and allows welding of various metals. However, if the component to be applied is not sheet-shaped, so separate techniques must be developed for MSR.

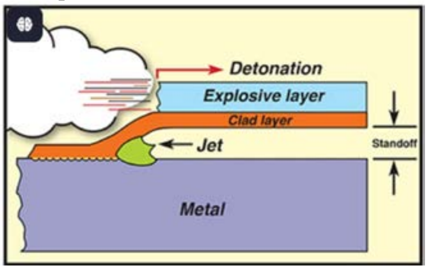


Fig. 3. Concept of explosion bonding.

2.4.4 Plating

Fig. 4 shows an example of Ni plating technology established for repairing damaged lower clad shell of PWR (Pressurized Water Reactor) reactors (ASME CC N-840). It was confirmed that the Ni plating layer could be robustly bonded to Type 309 stainless steel up to a thickness of 1 mm. For molten salt reactor components with a base material of Type 316H SS and a thickness of less than 1 mm, this Ni plating method can be applied to ensure corrosion resistance.

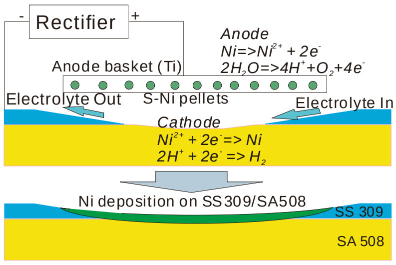


Fig. 4. Concept of Ni plating for PWR clad.

## 3. Summary

- ASME high-temperature reactor design criteria allow the use of non-Code qualified materials only when the base material is clad with a cladding material less than 10% thick.
- Cladding techniques that can be used in marine molten salt reactors include Weld overlay, Thermal spray, Explosion bonding, and Plating.

## ACKNOWLEDGEMENTS

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