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Evaluation of the Control Rod Super Alloy Material of HTR-PM

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Abstract –*The control rod drive mechanism (CRDM) system is served as the first reactivity control and shutdown system for the high temperature reactor pebble-bed module (HTR-PM) in Shandong, China. And the control rod, which is pulled up and down by a chain sprocket mechanism of CRDM to realize reactivity control, compensation and shutdown, has to be durable under temperature as high as 550 ℃ for a long time. Thus the material persistent strength under high temperature is quite important for the reliability of the CRDM. In this paper, a review on material selection of control rod of high temperature gas cooled reactors, including AVR and THTR-300 in Germany, HTTR in Japan, PBMR in South Africa and Dragon in Britain, was summarized. The major parameters of two kinds of high temperature alloy, incoloy 800H and alloy 625, were compared and discussed. According to the ASME NH volume, a design criterion for the control rod was established and applied in the analysis of the chain by using finite element method. The numerical simulations showed that the chain made of alloy 625 could meet the condition and work for a long time under high temperature.*

I. INTRODUCTION

The control rod drive mechanism (CRDM) system is served as the first reactivity control and shutdown system for the high temperature reactor pebble-bed module (HTR-PM) in Shandong, China. It consists of multiple control rods and drive mechanisms to meet the technical specifications. And the control rod, which is pulled up and down by a chain sprocket mechanism of CRDM to realize reactivity control, compensation and shutdown, has to be durable under temperature as high as 550℃ for a long time, and furthermore at the time of a scram the temperature will attain nearly 980℃. Thus the material persistent strength under high temperature is quite important for the reliability of the CRDM.

II. MATERIAL SELECTION OF CONTROL ROD

The material of control rod of high temperature gas cooled reactors need to endure high temperatures, high neutron doses and extremely corrosive environment. In former high-temperature gas-cooled reactor plants, which include two design categories, the Pebble Bed Reactor and the Prismatic Modular Reactor [DRAGON, Peach Bottom, AVR, THTR, and Fort St.Vrain], materials include various austenitic stainless steels, nickel-base superalloys, was chosen as metallic parts of the control rod drive mechanism as shown in Table 1. Most of high-temperature gas-cooled reactors built after those, 800H is used in common. Then the use of superalloys in HTGR will be introduced in detail.

II.A. Material of Dragon

There are 24 absorber rods each with an effective length of 1.56m and an outer diameter of 63.5mm with a 12.7 mm thick annular packing of boron carbide powder contained by an inner and outer stainless steel sheath. Each rod is suspended on a stainless steel wire and protected from the hot gas by a shield tube. To ensure the support structure from the 750 ℃ outlet coolant gas, a nickel chromium alloy (Nimonic 75) was employed. Compatibility studies carried out on this material in contact with low partial pressures of the gaseous impurities which may be present in the coolant have shown a tendency for strength to fall with an

reactors	Core outlet temperatures(℃)	material	The critical time for the first time
Dragon	750	Nimonic 75	1965
Peach Bottom	750	304 stainless steel	1966
Fort St. Vrain	785	800H	1975
HTTR	950	Inconel 800H	1999
HTR-10	700	800H	2000
PBMR	950	800H	
GT-MHR	950	800H	

Table 1: The material of control rod of high temperature gas cooled reactors.

attendant increase in ductility, no evidence of embrittlement has been found [1].

II.B. Material of Peach Bottom

The Peach Bottom High-Temperature Gas-Cooled Reactor (HTGR) started power operation in January 1967. Full power production was achieved and commercial operation began on May 26, 1967. Thirty-six control rods are provided to serve normal control functions. In addition to the normal control rods, an independent backup shutdown system is provided, which consists of a group of 19 electrically emergency shutdown rods. The 304 stainless steel weldment consisted of the bottom connector, spine, continuity wire, spiders, and spacers [2].

II.C. Material of Fort St. Vrain

The 330MW Fort St. Vrain Nuclear Generating Station uses a uranium-thorium fuel cycle; graphite for the moderator, fuel cladding, core structure, and reflector; and helium for the primary coolant. The control rods use B_4C absorbers enclosed in Incoloy 800H canisters for structural support [3].

II.D. Material of HTTR

The reactivity control system of HTTR consists of a control rod system and a reserve shutdown system. During normal operation, reactivity is controlled by the control rod system which consists of 32 control rods (16 pairs) and 16 control rod drive mechanisms. The maximum temperature of the control rods reaches about 900℃ at reactor scrams, therefore alloy 800H is chosen for the metallic parts of the control rods of HTTR. The design guideline for the HTTR control rod is based on ASME Code Case N-47-21. Observing the guideline, temperature and stress analysis were conducted, it can be confirmed that the target life of the control rods of 5 years can be achieved [4].

II.E. Material of HTR-10

The control rod system is the controlling and shutdown system of HTR-10, which is designed for reactor criticality, operation and shutdown. There are 10 sets of control rods and driving devices in 10MW High Temperature Gas-cooled Test Reactor (HTR-10), each with an effective length of 2.2m and an outer diameter of 110mm. To insure the control rod from the high temperature helium, a nickel base alloy (Incoloy 800H) was employed. And the control rod is pulled up and down by a chain sprocket mechanism which chose Incoloy 800H as its' metallic parts [5].

II.F. Material of PBMR

The Pebble Bed Modular Reactor (PBMR) being developed in South Africa is a high-temperature helium-cooled graphite-moderated continuous-fuelled pebble bed reactor. The reactor reactivity is controlled by two independent systems, namely the Reactivity Control System (RCS) and the Reserve Shutdown System (RSS). The RCS consists of 12 control rods and 12 shutdown rods in the side reflector and is used to control the reactivity in the core. The control rods consist of a 0.8cm thick B_4C annulus with an outer diameter of 10.0 cm, and with an inner and outer Incoloy 800H structure [6].

II.G. Material of GT-MHR

General Atomics recommended a direct-power-conversion-cycle prismatic reactor design that is essentially the same as the GT-MHR with an additional primary coolant loop to transfer heat to the IHX. The core consists of graphite blocks with an annular-fueled region of 1020 prismatic fuel blocks arranged in three columns. The control rods use B_4C absorbers enclosed in Incoloy 800H canisters for structural support. Carbon/carbon composite (C_f/C) control rod sleeves may be used as an alternative. The control rod is lowered and raised with a flexible high-nickel-alloy cable [7].

III. COMPARISON BETWEEN INCOLOY 800H AND ALLOY 625

Ni-based alloys have traditionally been used for high temperature applications. Therefore, it is only prudent to study their viability in high temperature gas cooled reactors. From the review on material selection of control rod we can know that Incoloy 800H is chosen for the metallic parts of most high temperature gas cooled reactors. Alloy 625 is used in the HTR-PM and modern industry because of its high strength, outstanding fatigue and thermal fatigue resistance, oxidation resistance and excellent weldability and brazeability. Its resistance to stress cracking and excellent pitting resistance in a wide range of temperatures have enabled it to be used extensively for the metallic parts of control rods of HTR-PM. Next, properties of alloy 625 and Incoloy 800H will be compared.

III.A. Mechanical *Properties of Alloy 625 and Incoloy 800H*

Tempe-rature ℃	Modulus of Elasticity, GPa			
	Tension		Shear	
	Anneal	Solution -Treated	Anneal	Solution -Treated
21	207.5	204.8	81.4	78.0
93	204.1	200.6	80.0	76.5
204	197.9	193.7	76.5	74.5
316	191.7	187.5	74.5	71.7
427	185.5	180.6	71.7	68.9
538	178.6	173.1	68.3	66.2
649	170.3	165.5	64.8	63.4
760	160.6	157.2	60.0	60.7
871	147.5	148.2	55.2	57.2

Table 2: Mechanical properties of Alloy 625 [8][9]

Temperature ℃	Tensile Modulus GPa	Shear Modulus GPa	Poisson's Ratio
20	196.5	73.4	0.339
100	191.3	71.2	0.343
200	184.8	68.5	0.349
300	178.3	66.1	0.357
400	171.6	63.0	0.362
500	165.0	60.3	0.367
600	157.7	57.4	0.373
700	150.1	54.3	0.381
800	141.3	50.7	0.394

Table 3: Mechanical properties of Incoloy 800H [10]

Table 2 and Table 3 show a comparison of mechanical properties at various temperatures of Alloy 625 and Incoloy 800H.

Alloy state	Tensile strength Rm N/mm²	Yield strength Rp 0.2N/mm²	Elongation A5 %
625	760	345	30

Table 4: Inconel 625 Alloy minimum mechanical properties in the room temperature [9].

Alloy state	Tensile strength Rm N/mm²	Yield strength Rp 0.2N/mm²	Elongation A5 %
800H	450	180	35

Table 5: Incoloy 800H minimum mechanical properties in the room temperature [10]

Table 4 and Table 5 show a comparison of mechanical properties in the room temperature of Alloy 625 and Incoloy 800H. As can be seen from the table, the mechanical properties of Alloy 625 is better than that of the mechanical properties of Incoloy 800H in various temperatures, especially in the room temperature.

III.B. Corrosion resistance of Alloy 625 and Incoloy 800H

Inconel 625 own a very good corrosion resistance in many media, especially with excellent resistance to pitting, crevice corrosion, intercrystalline corrosion, and erode in oxide, also good resistance to inorganic acid corrosion, such as nitric acid, phosphoric acid, sulfuric acid and hydrochloric acid. Inconel 625 can resist the alkali and organic acid corrosion in the oxidation and reduction environment. Effect resists the chloride reduction stress corrosion cracking. Normally no corrosion in the sea-water and industry environments since high corrosion resistance to the sea-water and salting liquid, as well as in high temperature, without sensitivity during welding. Inconel 625 have the resistance to oxidation and carbonizing in the static and cycle environments, also have the resistance the chlorine corrosion [11].

Incoloy 800H has excellent corrosion resistance of different kinds of media in both oxidation and reduction environments, and good resistance to stress corrosion cracking performance in the aqueous corrosion condition as the high content of nickel. Good resistance to pitting corrosion and crevice corrosion cracking performance were owned because of high chromium content. Incoloy 800H has excellent resistance of the organic acid corrosion performance, and inorganic acid such as nitric acid, phosphoric acid. But the corrosion resistance is limited in the sulfuric acid and hydrochloric acid. In addition to the possible corrosion in halide, it has good corrosion resistance in the oxidizing and non-oxidizing salt [12].

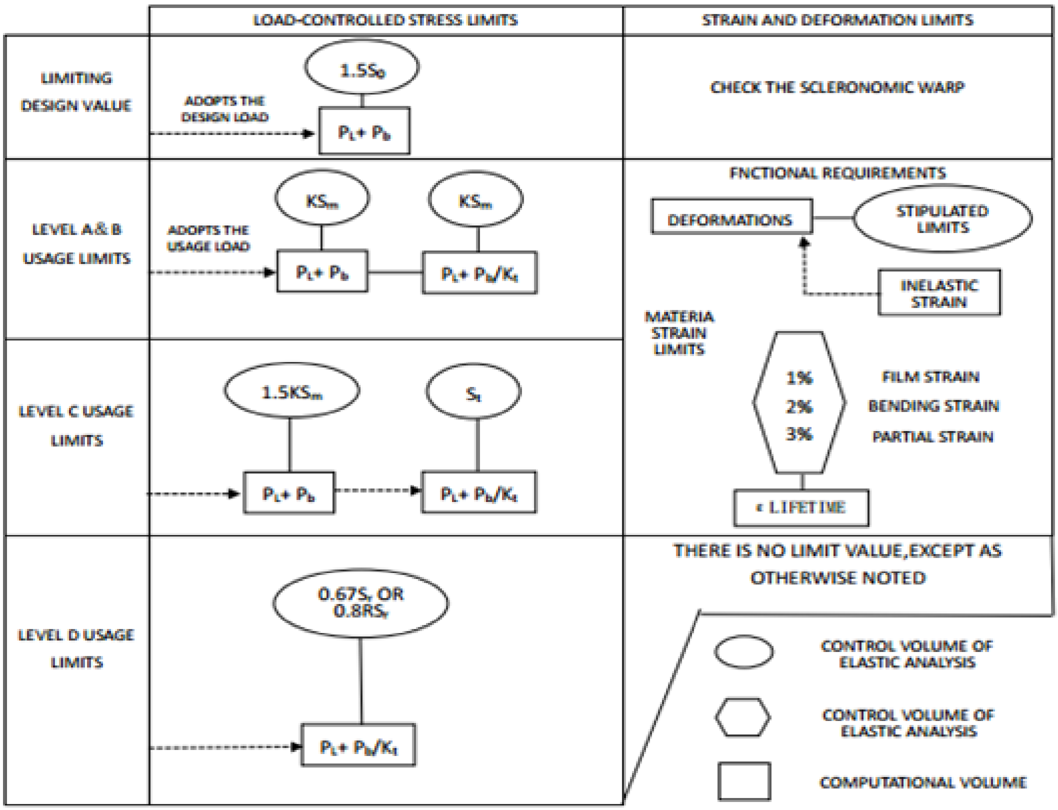

Fig 1: Flow diagram for high temperature design

III.C. Alloy 625 is more suitable for HTR-PM than Incoloy 800H

Excellent corrosion resistance of aqueous medium, good resistance to stress corrosion performance and good fabricability, all of these good properties make Incoloy 800H and Alloy 625 become the good alternative material of HTGR. However, the following factors are considered important in making Alloy 625 more suitable for HTR-PM than Incoloy 800H. First of all, as can be seen from table 2 and table 3, the mechanical properties of Alloy 625 is better than that of the mechanical properties of Incoloy 800H at various temperatures, especially in the temperature of 550℃ (the operating mode A: 550℃,350 thousand hours), which is quite an important advantage for Alloy 625, because of the control rod and the chain must work in the temperature of 550℃ for a long time. Second, the corrosion resistance of Incoloy 800H is limited in the sulfuric acid and hydrochloric acid, along with its poor corrosion resistance in halide, Alloy 625-not Incoloy 800H was chosen for the metallic parts of control rod of HTR-PM.

IV. HIGH TEMPERATURE STRUCTURAL DESIGN GUIDELINE OF CONTROL RODS

Due to the material of control rod drive chain is special, and the temperature of working environment is high (operating mode A, 550℃, 350 thousand hours; operating mode B, 780 ℃ ,600 hours; operating mode C, 980℃, 240 hours), it's obvious that the persistent strength of the chain under high temperature is quite important for the reliability of the CRDM. Fig 1 shows the flow diagram for the elevated temperature design of the HTR-PM control rod. The high temperature design is based on the Subsection NH of 2004 ASME Nuclear Power Codes and Standards NH-3221-1, because the failure modes assumed in the code case are most generic and their integrity evaluation methods are applicable to the design of HTR-PM control rods. The comparison between Alloy 625 and Incoloy 800H have been done in the previous chapter, which proved Alloy 625 is more suitable for HTR-PM than Incoloy 800H. Next, three-dimensional finite element model of the chain will be built, stress analysis of Alloy 625 will be done according to the flow diagram, in order to judge whether Alloy 625 can meet the requirements of the chain.

IV.A. Flow diagram for high temperature design

- Level A and B Service Limits

The stress calculations required for the analysis of Level A and B Service Loadings are based on a linearly elastic material model. The calculated stress-intensity values shall satisfy the conditions as below. The combined primary membrane plus bending stress intensities, derived from PL and Pb for Level A and B Service Loadings, shall satisfy the following limits with:

$$P_L + P_b \leqslant KS_m$$
$$P_L + P_b/K_t \leqslant S_t$$

The factor K_t accounts for the reduction in extreme fiber bending stress due to the effect of creep. The factor is given by

$$K_t = (K + 1)/2$$

The factor, K, is the section factor for the cross section being considered. It is the ratio of the load set producing initial yielding of the extreme fiber of the cross section.

The allowable stress intensity values St is determined for the time, t, corresponding to the total duration of the combined stress intensity derived from PL and P_b/K_t and the maximum wall averaged temperature, T, during the entire service life of the component.

- Level C Service Limits

The stress calculations required for Level C Service Loading analysis are based on a linearly elastic material model. The calculated stress intensity values shall satisfy the conditions as below. The combined primary membrane plus bending stress intensities, derived from P_L and P_b for Level A and B Service Loadings, shall satisfy the following limits, with $1.0 < K \leqslant 1.5$:

$$P_L + P_b \le 1.2KS_m$$
$$P_L + P_b/K_t \le S_t$$

Where K_t is defined as following:

$$K_t = (K + 1)/2$$

- Level D Service Limits

The rules of this paragraph can be used in the evaluation of components subjected to loads specified as Level D Service Loadings.

The combined primary membrane plus bending stress intensities, derived from PL and P_b for Level D Service Loadings, shall satisfy the following limits, with $1.0 \leqslant K \leqslant 1.5$:

$$P_L + P_b/K_t \leqslant \begin{cases} 0.67S_r \\ 0.8RS_r \end{cases}$$

Where K_t is defined as following:

$$K_t = (K + 1)/2$$

IV.B. Finite element analysis

Fig 2 shows three-dimensional finite element model of the chain of HTR-PM, the method of mesh division of the chain is Sweep. Then the path will be set in the place where is most vulnerable and the stress value of the location will be computed. The research about the most vulnerable place has been done by Weikang Li [13] in 2012, and through the study found that the transition of the straight arm and curved arm of a link is the spot of maximum stress, so the path was set up as shown in fig 3.

Fig 3 shows the linearized stress intensity of the path, from which can we see that the maximum stress intensity is 38.131MPa, at the same time, the distribution of stress in the path is easy to be observed.

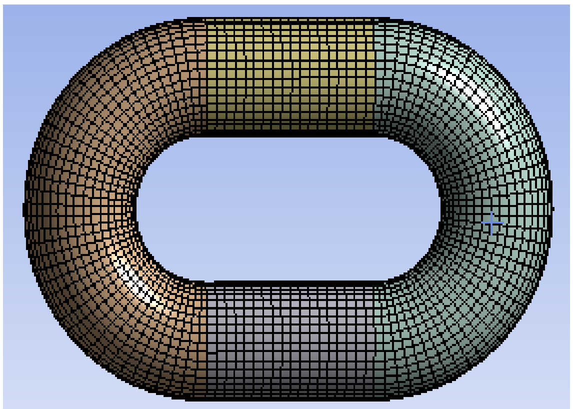

Fig 2: Meshing

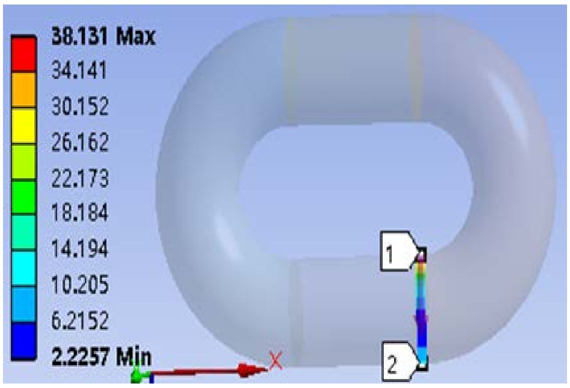

Fig 3: Linearized stress intensity

IV.C. Design curves

Figs. 4-5 show design curves of tensile strength S_u, yield strength S_y, allowable stress intensity value S_m, respectively. Definitions of the values are the same as those in the Code Case NH-3221. However, design material data on Alloy 625 available in the Code Case is below 750℃. Allowable stresses and design curves on Alloy 625, which are needed for the design of the chain, were determined up to temperature of 980℃ in this study based on existing data. Material data tested from experiments is used for the determination.

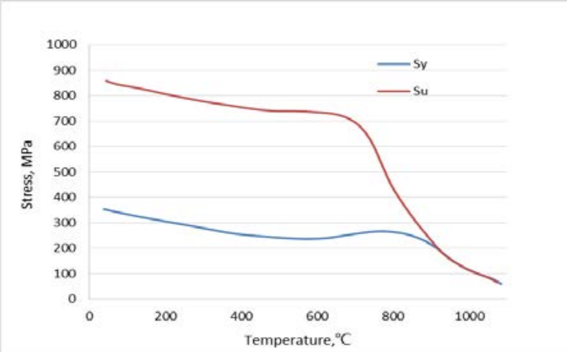

Fig 4: S_y and S_u, Alloy 625

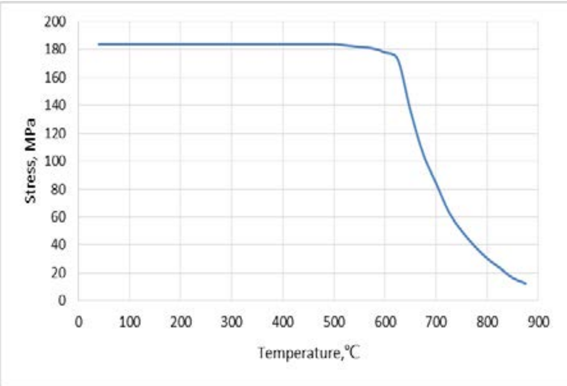

Fig 5: S_m, Alloy 625[8]

IV.D. Results of research and design

During normal operation of the high temperature test operation mode, in other words, in the operating mode A, when the control rods are withdrawn from the core, the maximum temperature of the chain is approximately 560℃ by preliminary temperature analysis. According to the analysis of the ansys software, the maximum P_L+P_b=30.117MPa, which much less than $1.5S_m$, at the same time, the maximum P_L+P_b/K_t <<KS_m. So the chain can satisfy in the operating mode A.

In the operating mode B in which the maximum temperature of the chain is 780℃, the maximum P_L+P_b=30.125MPa, which much less than $1.5S_m$=60MPa, at the same time, the maximum P_L+P_b/K_t=22.792MPa<40MPa, which is allowable stress intensity value under the temperature of 780℃. It's obvious that the chain is safe in the operating mode B.

V. CONCLUSION

In this paper, a review on material selection of control rod of high temperature gas cooled reactors, including Fort St. Vrain and Peach Bottom in America, HTTR in Japan, PBMR in South Africa and Dragon in Britain, was summarized. The major parameters of two kinds of high temperature alloy, incoloy 800H and alloy 625, were compared and discussed. The corrosion resistance of Incoloy 800H is limited in the sulfuric acid and hydrochloric acid, along with its poor corrosion resistance in halide, the material is not suitable for HTR-PM. And the mechanical properties of Alloy 625 is better than that of the mechanical properties of Incoloy 800H at various temperatures, especially in the room temperature, which is quite an important advantage for Alloy 625.

At last, according to the ASME NH volume, a design criterion for the control rod was established and applied in the analysis of the chain by using finite element method. The numerical simulations showed that the rod and the chain made of alloy 625 could meet the condition and work for a long time under high temperature.

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