Considerations of Material Selection for Control Rod Drive Mechanism of Reaktor Daya Eksperimental

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Abstract. Several materials were considered for the Control Rod Drive Mechanism (CDRM) of Reaktor Daya Eksperimental, which is categorized as High Temperatures Gas-Cooled Reactors (HGTR). Nickel base alloys were found to be more superior compared to other types of materials for the CDRM. This paper reviews the mechanical properties and corrosion behaviour of Ni-base alloys at high temperature. The effect of neutron bombardment on the materials was also reviewed as an important condition. It is likely the that Inconel 625 and Inconel 686 are more suitable for the use of CDRM of HGTR, compared to another alloy, Incoloy 800H. The mechanical properties of Inconel 625 and Inconel 686 exposed at high temperatures are excellent, similar results found on the corrosion resistance. The neutron irradiation caused the embrittlement on Inconel 625 and Incoloy 800H. The yield and ultimate strength decreased insignificantly, ranging from 13-46%. Comparing with other mechanical properties, such as total elongation, it suffered much further reduction, ranging from 60-62%. This result implies that the materials underwent embrittlement.

Keywords: Reaktor Daya Eksperimental, Material Selection, Incoloy 800H, Inconel 625, Inconel 686, Control Rod Drive Mechanism
Introduction
A high-temperature gas-cooled reactor (HTGR) is categorized as one of the Generation IV nuclear reactors and it was first developed in the 1950s. This type of system was designed to simultaneously attain the aims of high energy efficiency and effective hydrogen production. It is also provide high safety even in the occurrence of incidents that took place in Fukushima Reactor. Due to this reason, Reaktor Daya Eksperimental (RDE) selects HTGR type as the reactor to be built in Serpong, Indonesia. This type of reactor has been implemented in Shandong, China, therefore RDE itself will be compared with HTR-10, an HTGR that has been built [1].

One of important component in reactor is the Control Rod Drive Mechanism (CRDM). CRDM system is served as the first reactivity control and shutdown system for HGTR with pebble-bed module. It consists of multiple control rods and drive mechanisms to meet the technical specifications. The control rod, which is pulled up and down by a chain sprocket mechanism of CRDM to realize reactivity control, compensation and shutdown, must be durable under temperature as high as 750°C for a long time, and furthermore at the time of a scram the temperature will attain nearly 980°C. 750°C is the predicted working temperature at the reactor core. Thus, the material persistent strength under high temperature is quite important for the reliability of the CRDM.

Corrosion resistance is also a key performance of CRDM components. High temperature corrosion resistance has become a specific factor that must be fulfilled. Alloys such as Inconel 625 and 688 have offered excellent corrosion resistance for equipment in nuclear reactors, beyond the capability of stainless steels or other materials. These alloys can offer a number of advantages including improved life cycle cost performance, improved reliability, lower maintenance and reduced downtime costs. They are also expected to withstand in helium environment, whereas impurities in the helium coolant, such as oxygen and water vapor, may decrease the corrosion resistance and accordingly shorten the service time of the alloy components in HTGRs. CRDM components will experience irradiation by α and β particles, neutrons and high-energy photons (γ-rays) resulting in damage at the atomic level in the form of ionization and microstructural degradation due to the development of vacancies, interstitials and voids. These microscopic defects induce changes in physical and mechanical properties and are a major factor in determining long-term component reliability. There are hundreds of publications on irradiation hardening of materials including fcc (e.g., austenitic stainless steels, nickel alloys, copper and copper alloys), hexagonal close-packed (hcp) (e.g., Zr and Zr alloys) and body-centred cubic (bcc) (e.g., carbon steels, ferritic steels, etc.) alloys. Starting from very low radiation dose, hardening is one of the earliest indication of irradiation-induced microstructural change in alloys. With the increase in yield strength, elongation decreases and the work-hardening rate decreases. Dose rate seems to play a role in hardening. Klassen and Rajakumar irradiated Alloy 800H and 310 SS using 8.0 MeV Fe4+ ions at doses up to 15 dpa, then subjected the samples to isothermal annealing at 400 and 500 C [2]. Both alloys experienced significant radiation hardening, but the authors found rapid thermal recovery of the radiation damage.

Material Selection of Control Rod Drive Mechanism
The material of control rod of high temperature gas cooled reactors need to endure high temperatures and pressure, high neutron doses and extremely corrosive environment. In former high-temperature gas-cooled reactor plants, materials include various austenitic stainless steels, nickel-base superalloys, was chosen as metallic parts of the control rod drive mechanism. Most of high-temperature gas-cooled reactors built after those, Incoloy 800H is used in common. Accordingly, this paper will review the use of Inconel 625 and 686 and Incoloy 800H as the potential candidate for materials of CRDM from the point of view mechanical properties, corrosion behaviour, and effect irradiation at high temperature. All alloys are nuclear grades [3].
Table 1. Compositions of the Ni-Cr-Mo corrosion resistant alloys

| Alloy          | Fe  | Ni  | Cr  | Mo | W or Nb | Cu   | Other Element |
|---------------|-----|-----|-----|----|---------|------|---------------|
| Incoloy 800H  | 39.5| 33  | 20  | -  | -       | Al 0.15 – 0.60 | Ti 0.15 – 0.60 |
| (HTR China)   |     |     |     |    |         | Ti 0.15 – 0.60 |
| Inconel 625   | 3   | 62  | 22  | 9  | Nb 3.6  |       |               |
| Inconel 686   | 1   | 58  | 20.5| 16.3| W 3.9  |       | Ti 0.02 – 0.25 |

**Incoloy 800H**
Nickel-iron-chromium alloys that have the same basic composition as Incoloy 800H but with significantly higher creep-rupture strength. The higher strength results from close control of the carbon, aluminum and titanium contents in conjunction with a high-temperature anneal. Used in chemical and petrochemical processing, power plants for super-heater and reheater tubing, industrial furnaces and heat-treating equipment.

**Inconel 625**
A nickel-chromium-molybdenum alloy with an addition of niobium that acts with the molybdenum to stiffen the alloy's matrix and thereby provide high strength without a strengthening heat treatment. The alloy resists a wide range of severely corrosive environments and is especially resistant to pitting and crevice corrosion. Used in chemical processing, aerospace and marine engineering, pollution-control equipment and nuclear reactors.

**Inconel 686**
An alloy designed for outstanding corrosion-resistance in a wide range of severe environments. The alloy is used in the most severe environments encountered in chemical processing, pollution control, pulp and paper production, and treatment of industrial and municipal wastes. Chemical processing uses include heat exchangers, reaction vessels, evaporators and transfer piping. Air pollution control applications are stack liners, ducts, dampers, scrubbers, stack-gas reheaters, fans and housings.

**Mechanical Properties of Materials of Control Rod Drive Mechanism**
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 drive, 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 High Temperature Reactor Pebble Module (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 686, 625 and Incoloy 800H will be compared.
Fig. 1 shows the comparison of modulus elasticity in tension and shear mode of Inconel alloy 686, 625, and Incoloy 800H at high temperatures. In general, the integrity of materials in tension and shear decreased with the increasing of temperature, from room temperature to 900°C. The Young’s modulus of Inconel 686 and 625 is almost similar while Incoloy 800H is a bit lower. The shear modulus of elasticity of three alloys shows similar behavior with that of tension modulus of elasticity, the difference is the value of shear modulus is much lower compared tension modulus.

Figure 2 shows yield and ultimate tensile strength of all alloys at various temperatures. The alloys demonstrated similar tendency: yield and tensile strength decrease as the increasing of temperature. This phenomenon is a normal behavior like most of metals do. However, comparing the yield and ultimate tensile strength among those alloys, in room temperature Inconel 625 has the highest value, followed by Inconel 686 and Incoloy 8000H. At working temperature of CRDM which is about 150-750°C, all metals show good integrity, but a great change occurred at 750°C and above. Inconel 625 loses its strength to around 600 MPa, which is also the strength of Inconel 686. Incoloy 800H have a much lower strength, around 200 MPa.

Corrosion Resistance of Materials of Control Rod Drive Mechanism in Impure Hydrogen at High Temperature

Generally speaking, the high temperature resistance of Ni based Cr rich alloys is related to the formation of a dense and adherent chromia surface scale that ‘protects’ from further rapid corrosion. The likely environment in HGTR, helium cooled nuclear systems, is however very specific. The helium coolant should contain traces of impurities typically H$_2$, H$_2$O, CO, and CH$_4$ in the 0.1–10 Pa range [5]. Reactions of water and hydrogen with graphite in a reactor core form mainly carbon mono-oxide and methane[1]. Compositional changes of these impurities change the surface reactions available on the material exposed to an impure helium environment. A very high temperature of above 900°C accelerates the surface reaction rate. Therefore, a material degradation is aggravated by corrosion under a helium environment, which is one of the main obstacles to overcome for the application and successful long-term operation of a HGTR. A stable oxidation prevents material degradation, an internal oxidation lessens mechanical resistance, carburization embrittles the material and decarburization makes the material weak. Moreover, even though surface oxide is protective, a spallation of the oxide can threaten the long-term integrity of the coolant system during the long-term operation of a nuclear power plant. A review of the thermodynamics indicates which reactions are
available on the surface of the materials among oxidation, carburization and decarburization but it does not give us a kinetic preference. This kinetic preference can induce localized corrosion, kinetic irreversibility and long-term material instability leading to a material degradation. Therefore, finding the range of impurity concentration at which the material is stable based on the thermodynamics and kinetics determined through a long term experiment will yield crucial information for a coolant chemistry guideline. In addition to a long-term experiment under a HGTR coolant environment, the development of new alloys superior to commercial nickel-based alloy can also give way to the successful establishment of a HGTR. Commercial nickel-based wrought alloy is strengthened by a solid solution and precipitation hardening mechanism in a wide temperature range of 500-900°C. The $\gamma'$ significantly contributes to the strengthening by forming an anti-phase boundary and preventing a dislocation motion at an intermediate temperature range of 700-800°C but is no longer stable above this temperature range[2]. However, the material needs to fulfill the mechanical property requirements in a narrow, very high temperature range of 850-950°C rather than in a wide temperature range. Therefore, it is valuable to make an effort to find an optimum combination of alloying elements and processing parameters showing the best performance in a narrow temperature range for HGTR.

Inconel alloy 625 has good resistance to oxidation and scaling at high temperature. Its performance in an extremely severe test is shown in comparison with that of other materials in Figure 3. In this test, periodic weight-loss determinations indicate the ability of the alloy to retain a protective oxide coating under drastic cyclic conditions. 982°C is a temperature at which scaling resistance becomes a significant factor in service.

![Figure 3. Corrosion behaviour at high temperature of Inconel 625 and other type of nickel base alloys](image)

Inconel 625 shows parabolic curve until 1000 h exposure at high temperature. In the early stage of oxidation test, the weight per unit area of Inconel 625 increased as the time of cyclic exposure increases. It is related with the growth activation of Ni and Cr oxide [6,7]. This process occurred until all alloying elements on the surface reacts with the oxygen in the atmosphere.

Regarding the oxidation characteristic of Inconel 686, it is suggested has similar behavior with Inconel 625, as they have a closely chemical composition.

In case of Incoloy 800H, it has similar chemical composition with Hastelloy X, therefore, it is predicted that both alloys have similar tendencies when they are exposed at high temperature. The chemical composition of both alloys is shown below;
Effect of Neutrons on Mechanical Properties.
The word fluence is used in this report instead of descriptions such as neutron accumulation, neutron dos% and neutron exposure which were previously used in the literature. Fluence means time integrated neutron flux and its units are n/cm². It can be applied to thermal, epithermal, or fast neutrons. The neutron energy should be specified. The units nvt may be used for thermal neutrons. The use of the word fluence is specifically recommended by ASTM Subcommittee E-10 on Radioisotopes and Radiation Effects. In this report, the fluences are generally for fast neutrons. Almost all investigators report their fluence in terms of fast neutrons with energies greater than 1 MeV, although some investigators use 0.1 MeV, 0.5 MeV, or fission neutrons (~3 MeV). In this report, a fast neutron is taken as a neutron having an energy larger than 1 MeV unless otherwise stated.

Mixed Thermal and Fast Fluence
Tensile Properties. A large number of tensile tests have been performed on irradiated Incoloy 800H and Inconel 625 specimens between 600-650°C. These specimens were irradiated between 700-740°C. From Fig. 4, it becomes apparent that the yield strength increases with increasing fast fluence if the irradiation takes place at high temperature. However, the irradiation temperature plays a major role in causing irradiation-induced effects, since significant increases in yield strength take place at lower irradiation temperatures while no changes occur at an irradiation temperature of about 400°C. At an irradiation temperature of 740°C a considerable decrease in yield strength occurs and the reduction in ductility is somewhat less than that when the material is irradiated at lower temperatures. This dependence of strength on the irradiation temperature is probably due to over-aging of the complex alloy at the higher irradiation temperatures [8].

Figure 4. Yield strength of Inconel 625 and Incoloy 800H after irradiated at various rate [8].

Figure 5. Ultimate strength of Inconel 625 and Incoloy 800H after irradiated at various rate [8].
Figure 6. Total Elongation of Inconel 625 and Incoloy 800H after irradiated at various rate [8].

Figure 7. The change of mechanical strength of Inconel 625 and Incoloy 800H after irradiated at various rate.

In Fig. 5 shows the ultimate strength of Inconel 625 and Incoloy 800H after irradiated at various rate. A similar behavior is demonstrated by ultimate tensile strength of both alloys with that of yield tensile strength above. The alloys suffer embrittlem

ent due to irradiation [9].

Fig. 6 is the total elongation of Inconel 625 and Incoloy 800H after irradiated at various rate. The data shows consistent behavior as shown in yield and ultimate strength. The alloys have loss their ductility, therefore the total elongation dropped to a lower value [9].

From the data shown above in Fig. 4 - 6, we can calculate the change of mechanical properties of Inconel 625 and Incoloy 800H after irradiated at various rate (Fig. 7). Incoloy 800H suffered more embrittlement rather than Inconel 625. The average value of yield strength change of Incoloy 800H is around 44%, much lower than Inconel 625, 13% only. In terms of ultimate tensile strength, Incoloy 800H was stronger by 46% but loss the ductility by 62%, in average, while Inconel 625, was stronger by 16% but loss in ductility by only 59%. These results indicate the Inconel 625 is better material after exposed in irradiated environment at fast rate.

Conclusions
The results of this study have provides several recommendation, as follows;
1. Mechanical strength of Inconel 686, 625, and Incoloy 800H at high temperature was compared and it was observed that Inconel 686 and 625 shows similar results, while Incoloy has a much lower strength.
2. Corrosion behavior of Inconel 625 at high temperature is excellent by the result of parabolic curve until 1000 h exposure.
3. The effect of neutron exposure at fast rate has cause embrittlement on Inconel 625 and Incoloy 800H. Both alloys showed similar behaviour.
4. Inconel 625 and Inconel 686 are suitable for CRDM application.

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