Module 3

SELECTION AND SPECIFICATION OF MATERIALS FOR NUCLEAR APPLICATIONS

OBJECTIVES:

After completing this module, you will be able to:

Page 2 ⇔ 3.1 State six important factors for selection of metals/alloys for in–core structural applications.

Page 5 ⇔ 3.2 State the code that has the ultimate authority for materials used for nuclear and pressure vessel applications.

3.3 Identify from a given list of alloys, the alloy used for the following system components in our CANDU generating stations:

Page 5 ⇔ a) calandria tubes,

Page 5 ⇔ b) pressure tubes,

Page 6 ⇔ c) fuel sheathing,

Page 6 ⇔ d) end fittings,

Page 6 ⇔ e) calandria vessel,

Page 7 ⇔ f) primary heat transport system piping,

Page 8 ⇔ g) turbine blading,

Page 8 ⇔ h) turbine shaft/casing,

Page 9 ⇔ i) main condenser tubing (2 alloys),

Page 9 ⇔ j) heat exchangers (3 alloys),

Page 9 ⇔ k) steam generator tubing (2 alloys).

* * *

INSTRUCTIONAL TEXT

GENERAL MATERIAL REQUIREMENTS

Materials for nuclear reactors must simultaneously withstand the effects of high temperature, intense gamma radiation and bombardment by neutrons. At the same time they must be capable of containing the highly radioactive fission products produced in the nuclear reaction. For thermal reactors, efficient use of neutrons is essential and, therefore, core materials must capture very few neutrons or, to maintain a chain reaction, the amount of fissile material must be increased.

Obj. 3.1 ⇔

The major requirements for an in–core structural material are:

(a) good mechanical properties under all conditions of operation,

(b) low absorption of neutrons,

(c) stability under intense gamma and neutron irradiation,

(d) low rate of corrosion with fuel, moderator and coolant,

(e) ease of fabrication,

(f) acceptable cost.

Alloy and stainless steels would be ideal structural materials if it were not for their high level of absorption of neutrons. To use these metals, the fuel would have to be enriched with fissile material to ensure sufficient neutrons for a continuous chain reaction. The selection of materials is basically limited to carbon (graphite), beryllium, magnesium, zirconium and aluminum, if fuel enrichment is not contemplated.

For the CANDU system graphite is porous and not suitable for containing our moderator or coolant. In addition it has poor mechanical properties under complex loading. Beryllium is brittle at room temperature, difficult to fabricate and expensive. Aluminum and magnesium have relatively low melting points (650–660°C) and have insufficient strength for components such as pressure tubes, especially if elevated temperatures are involved.

Zirconium is the most suitable material for in–core components. Pure zirconium has insufficient strength or creep resistance so it must be alloyed to improve mechanical properties. Alloy additions are small, and do not increase neutron absorption such that fuel enrichment is necessary.

Although we are principally interested in the materials used for structural applications, it is also worthwhile noting the major requirements for other essential components of our thermal reactor.

They are as follows:

1. Fuel Material Requirements:

(a) sufficient fissile material to maintain a chain reaction,

(b) dimensional stability,

(c) high melting point,

(d) compatibility with cladding and coolant.

2. Control Material Requirements:

(a) high absorption of neutrons,

(b) dimensional stability under heat, intense gamma and neutron irradiation,

(c) good corrosion resistance.

3. Coolant:

(a) efficient heat transfer,

(b) low neutron absorption,

(c) low rate of chemical reaction with surroundings,

(d) stability under heat, intense gamma and neutron irradiation.

REGULATION OF STANDARDS

Much of the work (design and operational) in our plants is regulated or affected by standards and codes. There are a number of standards and codes with complex inter–relationships but essentially there are two regulatory authorities.

Atomic Energy Control Board (AECB)

This is a Federal authority authorized by "The Atomic Energy Control Act" to develop, control, supervise and license the production, application and use of atomic energy.

Inspection Branch – Ministry of Consumer and Commercial Relations (MCCR)

This is a provincial authority which is authorized by "The Boilers and Pressure Vessels Act" to control the safety of boilers and pressure vessels in Ontario.

The primary standards and codes listed below are those which the regulatory authorities, AECB and MCCR, generally accept. They can refer to other codes and standards and often are used as references in many other manuals and standards.

Canadian Standards Association (CSA)

The CSA has a number of codes covering construction and inspection of boilers, pressure vessels, and CANDU nuclear plant components, quality assurance in nuclear plants and manufacturing of components, control and safety systems, and environmental radiation protection.

Canadian General Specifications Board (CGSB)

These standards cover requirements for certification of non–destructive testing personnel.

American National Standards Institute (ANSI)

ANSI publishes a code covering pressure piping except nuclear piping.

Institute of Electrical and Electronics Engineers (IEEE)

IEEE has standards covering protection signal systems.

American Society of Mechanical Engineers (ASME)

ASME is the most extensive code to which many other standards refer. It has been accepted across Canada as a basic document and has several sections covering design and operation of power boilers, heating boilers and pressure vessels; material specifications, specifications for nuclear power plant components and welding and brazing procedures.

ASME – Section II gives material specifications for ferrous and non–ferrous materials and for welding rods, electrodes and filler metals. These specifications are often quite extensive covering chemical composition, impurity limits, basic mechanical properties, method of manufacture and test procedures.

American Society for Testing and Materials (ASTM)

Obj. 3.2 ⇔

ASTM also issues material specifications which in general are the same as ASME specifications. However, **for nuclear and pressure vessel applications ASME specifications are used in preference to ASTM specifications.**

MATERIALS USED IN CANDU UNITS

Pressure and Calandria Tube and Fuel Sheathing Material

These components are all within the core, and require low absorption of neutrons. They will, therefore, be zirconium alloys. Zircaloys were the first zirconium alloys developed for reactor applications and are essentially alloys of zirconium plus tin.

Obj. 3.3 a) ⇔

Zircaloy–2 contains 1.5% Sn, 0.12% Fe, 0.10% Cr and 0.05% Ni. It is not heat treatable and therefore, mechanical properties such as strength and creep resistance are improved by cold working (deformation). It is used for all **calandria tubes**. Initially, pressure tubes were made from Zircaloy–2. However, pressure tube performance in an early (lower power) reactor suggested that pressure tube creep rates would increase for higher power reactors. This led to a change in pressure tube material and design. The new material presented difficulties in welding and, since calandria tubes required seam welding during fabrication, they remained as Zircaloy–2. This was because the operating conditions for calandria tubes were much less severe (lower temperature and pressure) than for pressure tubes.

Obj. 3.3 b) ⇔

The new material, Zirconium–2½% by weight Niobium (**Zr–2½ Nb**), was developed primarily as a stronger zirconium alloy for **pressure tube** applications. Through cold work, higher strength could be developed in thinner sections and pressure tube wall thickness was reduced by almost 1 mm. This reduced parasitic absorption of neutrons by the pressure tubes, and improved fuel burn–up. However, even though Zr–2½ Nb was stronger, the creep rate of the thinner pressure tube has not been less than for Zircaloy–2 pressure tubes.

Zr–2½ Nb is heat treatable. Strength can be increased by a process known as precipitation hardening. This involves rapid cooling from a single phase region (one type of crystal) into the two phase region (two types of crystal) and allowing controlled precipitation and growth of the second type of crystal. This may be a future possibility in the production of pressure tubes.

NOTES & REFERENCES

Obj. 3.3 c) ⇔

Zircaloy–4 contains 1.5% Sn, 0.20% Fe and 0.10% Cr. Leaving out the Ni improved corrosion resistance and ductility and produced a material suitable for **fuel sheathing.** The ductility is important so that the fuel sheathing can accommodate volume changes in the fuel due to thermal expansion and build–up of fission product gases. Oxidation resistance is similar to Zircaloy–2 but hydrogen pick–up* is only about 1/3 – 1/2 of Zircaloy–2.

Calandria, End Fittings and PHT Piping Material

These materials are all outside the core and, therefore, absorption of neutrons is not a concern. Mechanical properties, corrosion resistance and cost are the important factors in selecting alloys for these applications, and therefore, alloy steels and stainless steels are important contenders.

Stainless steel is strong and very corrosion resistant but has a wide range of mechanical properties depending on the composition. The most influential alloying element present in all stainless steels is chromium. Some also have significant amounts of nickel. The amount of chromium and the presence or absence of nickel determine the type of crystal structure (and therefore, material properties). In our nuclear stations we use two types of stainless steel: **martensitic** and **austenitic.**

Obj. 3.3 d) ⇔

Martensitic stainless steels may also be called heat treatable or 400 Series**. Generally they contain less than 14% Cr with variable carbon content. These steels can be rapidly cooled from a high temperature to form martensite, a non–equilibrium crystal structure in steels which is very hard, strong and brittle. To relieve brittleness, the steels are tempered, allowing a controlled decomposition of some of the martensite to equilibrium crystal structures. Martensitic steels are weldable and easily fabricated and machined (these operations are generally performed before heat treatment). End fittings on pressure tubes must be very corrosion resistant to prevent deterioration of the seal between fueling machine and pressure tube. They also must be strong and hard as the joint between end fitting and pressure tube is formed by rolling or plastically deforming the pressure tube into grooves in the end fitting to provide leak tightness. **Martensitic stainless steel** is used for pressure tube **end fittings.**

Obj. 3.3 e) ⇔

Austenitic stainless steels are also known as 300 Series** or 18–8 stainless. These steels contain nickel as well as chromium, are non–heat treatable and have low carbon (less than 0.15%). Chromium provides the corrosion resistance whereas nickel acts to stabilize the austenite crystal structure, which normally exists only above 700–800°C.

* *Hydrogen in zirconium alloys causes delayed hydride cracking and will be discussed in Module 5 of this course.*

** *American Iron and Steel Institute (AISI) designation.*

Austenite has certain properties not found in the normal room temperature crystal structures of steels. It is non–magnetic and does not show a ductile brittle transition temperature. If we recall that intense neutron radiation *raises* the ductile brittle transition temperature, it will become obvious that in radiation environments it is desirable to use materials without this property, especially if operating at ambient temperatures. The **calandria** is subjected to intense radiation fields and operates generally around 60°C, so **austenitic stainless steel** was selected as the best choice of material. The excellent corrosion resistance of this stainless steel was also a factor in its selection.

Obj. 3.3 f) ⇔

Plain carbon steels are among the most versatile and least expensive construction materials. However, they have very poor corrosion resistance, especially in an aqueous environment with ready access to oxygen. This poor corrosion resistance is a result of the brittle porous oxide film, which does little to protect the metal from further corrosive attack. In stainless steels, the presence of chromium helps to form a strong adherent oxide film, which is relatively impervious. In plain carbon steels, it is possible to improve the performance of the oxide film by providing optimum conditions for growth and limiting the amount of oxygen available. In the heat transport system this treatment is possible and **plain carbon steels** were selected for the **primary heat transport piping**. Corrosion control is effected by maintaining the heat transport fluid at a pH of 10 (by addition of LiOD) and addition of H_2 to recombine with O_2 formed by radiolysis*.

Turbine Shaft, Casing and Blading Materials

The many parts of a steam turbine work under varying conditions of service, and effective design involves selection of appropriate materials for each part. The CANDU reactor (as do other water cooled reactors) produces a low pressure, low temperature saturated steam. The turbine should be capable of handling large volumes of wet steam for efficient power generation. Maximum steam pressure and temperature will be about 4 MPa and 250°C and the highest moisture content expected about 12%. Important characteristics for selection of materials for turbine components will include:

a) high strength and toughness to withstand the pressure of steam and other imposed loads,

b) good wear resistance to withstand the erosive effects of entrained moisture in the steam,

c) good corrosion resistance,

d) good creep properties to withstand stresses developed by rotational motion.

* *This is discussed in the 224 Chemistry course.*

Low alloy and stainless steels generally exhibit the properties required, and are important materials for turbine components.

Obj. 3.3 g) ⇔

Martensitic stainless steel, as noted earlier, has excellent corrosion resistance, and can be treated to improve mechanical properties. Turbine blading basically converts the heat energy of the steam to kinetic energy. The blading will be subjected to substantial centrifugal forces developed during rotation, as well as the impact of high pressure, high velocity steam. Moisture entrained in the steam and moisture from condensing steam will tend to erode the blades. **Martensitic stainless steel** is hard and wear resistant and has good creep properties as well as high strength. It is used as both **high pressure and low pressure turbine blading**. Design and selection of material for blading is so sophisticated that different blading stages use different grades of martensitic stainless steel.

Obj. 3.3 h) ⇔

Low alloy steels are steels with alloying elements such as Ni, V, Cr, Mo, Si, Mn, Nb, added to a total of less than 5% to improve mechanical properties. Casings are essentially pressure vessels, but also transmit imposed loading (thermal and static) to the foundations, while maintaining alignment of the turbo–generator unit. They support fixed elements and, in the case of blade or rotor failure, act as containment for pieces of rotating equipment. The shaft (rotor) is the primary rotating element and carries the moving blades. It is subjected to centrifugal loading through rotation, torque due to work done on moving blading by the steam, and high temperatures and pressures. In addition, because of its weight and support problems, it should have a high degree of stiffness. The properties required in **casings and shafts** are found in a group of **chrome–moly steels**. They contain essentially 1.5 – 2.5% Cr and 0.5 – 1.0% Mo with smaller additions of V, Ni, etc. Chromium increases corrosion resistance adds to high temperature strength and increases the steels ability to harden. Molybdenum deepens hardening, raises high temperature and creep strength and improves abrasion resistance.

Steam Generator, Condenser and Heat Exchanger Tubing

The primary purpose of heat exchangers is to transfer heat energy from one fluid to another without intimate contact or mixing between the fluids. The materials used for heat exchangers must therefore have:

a) good thermal conductivity,

b) adequate mechanical properties at the operating temperature,

c) good corrosion resistance,

d) reasonable wear/erosion resistance.

NOTES & REFERENCES

Traditionally these properties have been best met by copper alloys, but the more severe operating conditions encountered are forcing a move to other materials such as Inconel, stainless steel and even titanium. In CANDU stations, the major heat exchanger materials are Admiralty Brass, Cupro–Nickels, Monel and Inconel.

Obj. 3.3 i) ⇔

Admiralty Brass is basically a cartridge or 70/30 brass with 1 – 2% tin added for improved corrosion resistance. It is very ductile with excellent cold forming characteristics. It has good thermal conductivity (1/3 that of copper) and excellent corrosion resistance in fresh, salt and brackish water. However, like all copper alloys it is susceptible to attack by dissolved oxygen and carbon dioxide and it also suffers impingement or pitting at high fluid velocities. Because of its advantages, **Admiralty Brass** was selected for tubing in the **main condensers**. However, in practice we are finding that there is excessive erosion of the tubing (primarily resulting from condenser design) and, for Bruce B and Darlington, **stainless steel tubing** has been selected.

Obj. 3.3 j) ⇔

Cupro–Nickels are alloys of copper and nickel. These alloys have lower thermal conductivity than brasses (1/10 that of copper) but much improved resistance to impingement attack. They generally have the best resistance of all copper alloys to aqueous corrosion and are more immune to stress corrosion cracking. The 90/10 and 70/30 **Cupro–nickels** are used for **heat exchanger tubing** in high pressure feedheaters and the moderator heat exchanger. However, the trend in newer stations such as BNGS–B is to **stainless steel** and nickel chromium alloys such as **Incoloy**.

Obj. 3.3 k) ⇔

Monel, like Cupro–nickels, is an alloy of nickel and copper but is predominantly nickel; average composition being 70% Ni and 30% Cu. Thermal conductivity in monels is somewhat lower than Cupro–Nickels but they have improved corrosion resistance under high flow conditions. Monels are particularly resistant to cavitation and impingement but are sensitive to the presence of oxidizing agents such as Fe^{+++} or Cu^{++} ions or dissolved oxygen. **Steam generators** and bleed coolers are heat exchangers with rather severe service conditions and **Monel** was selected as tube material at Pickering A&B.

Inconel, like some types of stainless steels, is an alloy of iron, chromium and nickel but it is nickel based. It suffers almost no corrosion in flowing water (salt, natural or brackish). In stagnant conditions, where chlorides, phosphates and hydroxides can concentrate, Inconel is susceptible to pitting and stress corrosion cracking. In pure water it is not as sensitive as Monel to the presence of dissolved oxygen. This latter property led to the selection of **Inconel** as **steam generator tubing** at BNGS–A&B where boiling is allowed in certain fuel channels. With boiling occurring, it becomes more difficult to suppress dissolved oxygen which is produced by radiolytic breakdown of water.

SUMMARY OF THE KEY CONCEPTS

- For metal/alloy in–core structural applications, six important factors for selection exist:
  - a) good mechanical properties under all conditions of operation,
  - b) low absorption of neutrons,
  - c) stability under intense gamma and neutron irradiation,
  - d) low rate of corrosion with fuel, moderator and coolant,
  - e) ease of fabrication,
  - f) acceptable cost.
- For nuclear and pressure vessel applications, ASME specifications are the ultimate authority.
- Calandria tubes, which must be seam welded during fabrication, are made from Zr–2. The less severe operating conditions experienced by the calandria tubes allow them to be made from this lower strength Zr alloy.
- A strong, heat treatable alloy of Zirconium known as Zr–2½Nb is used for pressure tubes in CANDU reactors. It offers lower parasitic absorption of neutrons than earlier pressure tube materials because its higher strength allows a thinner tube wall.
- Zircaloy–4, a more corrosion resistant and ductile Zr alloy, is ideal for use as fuel sheathing.
- CANDU end fittings must have high corrosion resistance, strength and hardness. Martensitic stainless steel is suitable, since it is easily machined and is heat treatable to give excellent strength and hardness.
- Since austenitic stainless steel does not show a ductile/brittle transition temperature under neutron irradiation, it is used for the calandria vessel.
- Primary heat transport piping is made from plain carbon steel. This is a relatively inexpensive material and its corrosion can be readily controlled by chemical conditioning of the coolant.
- The excellent hardness and creep resistance of martensitic stainless steel allows it to perform well as both high and low pressure turbine blading.
- The strength and operating temperature demands of turbine shafts and casings require them to be made from special chrome–moly low alloy steels.
- Main condenser tubing in newer stations is made from stainless steel because of its improved erosion resistance. Older stations used Admiralty Brass, chosen for its good thermal conductivity and corrosion resistance.

NOTES & REFERENCES

- Heat exchanger tubing material selection has undergone a similar evolution from cupro–nickels in early stations to stainless steel in newer stations.
- Pickering stations have steam generator tubing made from a nickel–copper alloy known as Monel. With boiling present in fuel channels at the Bruce stations, steam generator tubing is made from Inconel. Inconel has improved resistance to effects caused by dissolved oxygen.

Page 12 ⇔ You can now do **assignment questions 1 – 13.**

ASSIGNMENT

1. State six factors considered important in the selection of material for core structural components.
2. State the code that has the ultimate authority for materials used for nuclear and pressure vessel applications.
3. State the alloy used for calandria tubes in CANDU generating stations.
4. State the alloy used for pressure tubes in CANDU generating stations.
5. State the alloy used for fuel sheathing in CANDU generating stations.
6. State the alloy used for end fittings in CANDU generating stations.
7. State the alloy used for calandria vessels in CANDU generating stations.
8. State the alloy used for primary heat transport system piping in CANDU generating stations.
9. State the alloy used for turbine blading in CANDU generating stations.
10. State the alloy used for turbine shafts/casings in CANDU generating stations.
11. State two alloys used for main condenser tubing in CANDU generating stations.
12. State three alloys used for heat exchangers in CANDU generating stations.
13. State two alloys used for steam generator tubing in CANDU generating stations.

Before you move on to the next module, **review the objectives** and make sure that you can meet their requirements.

Original by: A. Wadham, ENTD

Revised by: P. Bird, WNTD

Revision: R-2, June 1993