High Temperature Materials

Training Course on High Temperature Gas-cooled Reactor Technology
October 19-23, Serpong, Indonesia

Japan Atomic Energy Agency
High Temperature Materials in HTGR

Graphite components
- Core structure
- Core support structure

Metallic material
- RPV
- IHX Heat transfer tube
- Coaxial piping
Graphite Components

Graphite Components

PGX
IG-110
PGX
IG-110
PGX
ASR-0RB

# Graphite in HTTR

<table>
<thead>
<tr>
<th>Grade</th>
<th>IG-110 (Moderator)</th>
<th>PGX (reflector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (g/cm³)</td>
<td>1.78</td>
<td>1.73</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>25.3</td>
<td>8.1</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>76.8</td>
<td>30.6</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>8.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Thermal conductivity at 673K (W/m/K)</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Coefficient of thermal expansion at 293 – 673K(10⁻⁶/K)</td>
<td>4.06</td>
<td>2.34</td>
</tr>
</tbody>
</table>

JAEA’s HTTR (IG-110)  

Chinese reactors  
HTR-10 (IG-11)  
HTR-PM(IG-110)
Manufacturing Process of Graphite

Period of manufacturing process: about 6 months

- Coke/Coal tar pitch
- Pulverizing & Mixing
- Kneading
- Pulverizing & Sieving
- Isostatic pressing
- Baking
- Pitch impregnation
- Graphitizing
- Rough machining
- Machining
- Purification
- Chemical processing
- Inspection
Requirements for Graphite

- **Moderator**
  - Isotropic, homogeneous, high density
  - Amount of impurity, dimensional change, thermal conductivity, thermal expansion, young’s modulus, irradiation creep

- **Neutron absorber**
  - Stability for irradiation (dimensional change, thermal expansion, etc.)

- **Insulator**
  - Thermal conductivity and dimensional stability under high stress

- **Fuel coating, sleeve**
  - High strength and irradiation stability due to severe irradiation condition (high fluence and temperature)
  - The same properties are required as moderator

- **Reflector**
  - The same properties are required as moderator.
  - Strength degradation by thermal oxidation
  - Irradiation effect is not important due to low neutron fluence.
A special committee at Atomic Energy Society in Japan established a draft of standard for graphite core components in HTGR (JAEA-Research 2009-042).
Irradiation Effect on Graphite

- It is important for graphite structure of HTGR to have structure stability with the stand points of its lifetime. During the neutron irradiation, gradient of temperature and neutron flux case the local stress and residual stress.

- Irradiation induced stresses are determined by property change of graphite.

- Dimensional change

- Young’s modulus

- Change in thermal expansion

- Change in creep strain

- At the beginning of irradiation, the young’s modulus is increases because the defects produced by irradiation fix the movement of dislocation (pinning effect)
  - Young’s modulus keep increase due to deceasing pores in graphite by dimensional change.

- Thermal conductivity of graphite is dominated by phonon. Irradiation defects make mean free path of graphite and thermal conductivity shows small.
  - A decrease rate of thermal conductivity at high irradiation temperature is small due to annealing effect.
With increasing the neutron fluence, the dimensional change decreases. The dimensional change shrinks maximum at the one fluence point, called turn around, then the dimensional change increase with increasing the fluence.

The dimension and fluence of turn around depend on irradiation temperature, raw material and micro texture.

Isostatic graphite with micro texture shows stable dimensional change.
At the initial stage of the irradiation, the modulus is rapidly increased by the pinning effect of dislocations in graphite crystals.

In latter stage of the irradiation, the modulus is gradually increased by the irradiation-induced dimensional shrinkage, i.e. the decrease of porosity of graphite.

The mean coefficient of thermal expansion is increased at the initial stage of the irradiation and is decreased by the irradiation.
The conductivity rapidly decrease by the initial stage of the irradiation because irradiation-induced defects reduces mean free path of phonon, which dominates the thermal conductivity of graphite.

The lower irradiation temperature gives the greater decrease in the conductivity because that high-temperature irradiation causes annealing recovery of irradiation-induced defects during the irradiation.
Advantage of IG-110 Graphite (1/2)

As you can see the difference of the line slope. The IG-110 graphite shows less scattering performance on the tensile strength test results.

※ T.S. Byun, Statistical Characteristics of Facture Strength and Toughness of Nuclear Graphite, INGSM-10
The first loaded IG-110 graphite in HTTR had excellent strength properties and small variation. Then graphite blocks had enough safety margins to the stress limits. Therefore, it was verified that the IG-110 is the high quality graphite regulated by graphite design.
## Metallic Materials in HTTR

<table>
<thead>
<tr>
<th>Material</th>
<th>Product form</th>
<th>Components</th>
<th>Service conditions</th>
<th>Maximum allowable temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 1/4Cr-1Mo steel</td>
<td>Plate, forging,</td>
<td>Reactor pressure vessel</td>
<td>440°C</td>
<td>550°C</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>Shells of intermediate heat exchanger, primary pressurized</td>
<td>430°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>water cooler, etc.</td>
<td>4.8 MPa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outside pipe of concentric double pipe</td>
<td>430°C</td>
<td>4.8 MPa</td>
</tr>
<tr>
<td>Hastelloy XR</td>
<td>Tube, plate,</td>
<td>Intermediate heat exchanger heat transfer tubes</td>
<td>955°C</td>
<td>1000°C</td>
</tr>
<tr>
<td></td>
<td>forging</td>
<td></td>
<td>0.29MPa</td>
<td></td>
</tr>
<tr>
<td>SUS321</td>
<td>Tube</td>
<td>Primary pressurized water cooler heat transfer tubes</td>
<td>380°C</td>
<td>650°C</td>
</tr>
<tr>
<td>SUS316</td>
<td>Bar</td>
<td>Core restraint mechanism</td>
<td>450°C</td>
<td></td>
</tr>
<tr>
<td>1Cr-0.5Mo-V steel</td>
<td>Forging</td>
<td>Core restraint mechanism</td>
<td>450°C</td>
<td>450°C</td>
</tr>
</tbody>
</table>

*: absolute pressure,
Note: Control rod sleeves are made of Alloy 800H, whose maximum allowable temperature at a scram is 900°C.
Temperature limitation for metallic material is approx. 800°C. Cooling is required to use in high temperature condition above 800°C.

Hastelloy XR is used with limiting pressure load or temperature by keeping the difference between internal and external pressure or utilizing insulation.
• Conventional RPV steel can be deployable with the intrinsic cooling scheme

RPV temperature < 350°C

Intermediate heat exchanger

<table>
<thead>
<tr>
<th>Type</th>
<th>Vertical helically-coiled counter-flow heat exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer rate</td>
<td>10 MW</td>
</tr>
<tr>
<td>Design pressure (shell)</td>
<td>4.8 MPa</td>
</tr>
<tr>
<td>Design pressure (tube)</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>Design temperature (shell)</td>
<td>430 °C</td>
</tr>
<tr>
<td>Design temperature (tube)</td>
<td>955 °C</td>
</tr>
</tbody>
</table>

Shell
- Outer diameter: 2 m
- Overall height: 11.0 m

Tube
- Number: 96
- Outer diameter: 31.8 mm
- Thickness: 3.5 mm
- Material: 2.25Cr-1Mo steel (shell), Hastelloy XR (tube)

Hastelloy XR was developed based on Hastelloy X in conjunction with Mitsubishi Material Co.

- Manganese and Silicon contents are optimized to form stable and adherent oxidation films.
- Cobalt content is optimized to reduce radioactive contamination in primary cooling system.
- Aluminum and Titan content is optimized to suppress internal oxidation and intergranular attack.
- Boron content is limited up to 100 ppm in weight in the standard specification.
- Within the range, increasing Boron content introduces significant improvement of creep resistance.

Cross-sectional Views after Corrosion Test (1000°C, 10,000 hrs, in impure helium gas)
<table>
<thead>
<tr>
<th>Structure</th>
<th>HTTR</th>
<th>GTHTR300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor pressure vessel</td>
<td>2 1/4Cr-1Mo</td>
<td>SA533, SA508 (Mn-Mo)</td>
</tr>
<tr>
<td>Core structural material</td>
<td>IG-110 and PGX</td>
<td>IG110 and IG11</td>
</tr>
<tr>
<td>Core barrel</td>
<td>-</td>
<td>Alloy 800H</td>
</tr>
<tr>
<td>Core restraint mechanism</td>
<td>1Cr-0.5Mo-V and SUS316</td>
<td>C/C composite</td>
</tr>
<tr>
<td>Control rod</td>
<td>Alloy 800H</td>
<td>C/C composite</td>
</tr>
<tr>
<td>IHX heat transfer tubes</td>
<td>Hastelloy XR</td>
<td>Hastelloy XR</td>
</tr>
<tr>
<td>Turbine rotor blade</td>
<td>-</td>
<td>Ni superalloy</td>
</tr>
</tbody>
</table>
Concept of control rod element

Control rod sheath: C/C composite (fabrication)

Connecting rod: C/C, SiC/SiC composite (oxidation resistance, strength)

For the design of the ceramic components of VHTR it is important to investigate,

- Irradiation behavior
- Oxidation behavior

of the mechanical/thermal properties

Mock up with C/C composite (CX-270G, Toyo Tanso)

Conditions

Temperature: <1500°C
Neutron fluence: - 2dpa
Coolant: Helium gas with small amount of impurities
Max. weight: 250 kg