Development of a VHTR Fuel Performance Analysis Code COPA

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1. Introduction

The fuel performance analysis code for a very high temperature gas-cooled reactor (VHTR) predicts the structural, thermal, and chemical behaviors of the VHTR fuel during the reactor operation or under accident conditions. Through these predictions the code supports a fuel fabrication process development, establishes the core design and operation limits of the VHTR, and produces the licensing data. Many countries are trying to develop and license their own computer code. However, no fuel performance analysis codes have obtained a license worldwide.

HTR Fuel Technology Development Division at KAERI (Korea Atomic Energy Research Institute) is developing a VHTR fuel performance analysis code named COPA (Coated Particle). This study describes the development status and functions of the COPA code.

2. Modules of the COPA code

The COPA code consists of nine modules: COPA-MECH [1,2], COPA-FAIL [3], COPA-TEMTR [4], COPA-TEMPEB, COPA-TEMBL, COPA-FPREL, COPA-MPRO, COPA-BURN, and COPA-ABAQ [5]. Every module has its own functions and models.

The COPA-MECH performs thermo-mechanical calculations on three coating layers of a fuel particle by using an analytical solution. The models are one-dimensional for intact particles or failed particles. The COPA-TEMTR performs thermal deterministic calculations on a particle by using a finite difference method. This model is one-dimensional for a particle. The geometric elements are a kernel, a gap between a kernel and a buffer, a buffer, and an IPyC (Inner Pyrocarbon) layer, a SiC (Silicon Carbide) layer, and an OPyC (Outer Pyrocarbon) layer. The COPA-FAIL performs probabilistic calculations to estimate the failure probabilities of coating layers during an experiment or a reactor operation. The COPA-FAIL uses a Monte Carlo method and the COPA-MECH. The COPA-TEMPEB performs thermal deterministic calculations on a pebble by using a finite difference method. This model is one-dimensional for a pebble.

The COPA-TEMBL performs thermal deterministic calculations on a block by using a finite difference method. This model is 1/2-dimensional for a block. The COPA-FPREL performs diffusion calculations of gaseous and metallic fission products through particle layers and a fuel element. The COPA-MPRO calculates the material properties of the kernel, coating layers, fuel element, and structural materials. The COPA-BURN calculates the neutron flux, burnup, fluence, and fission product inventory throughout a fuel particle, a fuel element, and a core. The COPA-ABAQ performs thermal and mechanical deterministic calculations on a free fuel particle by using ABAQUS [6]. These models are two-dimensional for intact particles or particles with fully de-bonded layers and partially de-bonded or cracked particles.

The COPA code is currently able to perform thermal and mechanical calculations on a free fuel particle and has been used to calculate the IAEA CRP-6 normal operation benchmark cases [7]. The COPA-TEMPEB, COPA-TEMBL, COPA-FPREL modules will be completed by the end of 2006. The COPA-BURN, COPA-ABAQ will be developed in 2007.

3. Physicochemical Models and Material Properties

The VHTR fuel is a TRISO-coated fuel particle and a fuel element (pebble or compact). The TRISO particle consists of a kernel (UO_2 or UCO), a buffer layer, and three coating layers (an IPyC, a SiC, and an OPyC). There is a gap between the kernel and the buffer. The fuel element contains and fixes a lot of the TRISO particles.

The models for the kernel are a densification, swelling, fission gas release, radioactive inventory, kernel migration, heat generation and transfer, and a burnup and fluence with time. The related properties are the specific heat, density, porosity, thermal conductivity, thermal expansion coefficient, Young's modulus, and Poisson's ratio, and the solid and gaseous swelling rate.

The models for the gap and buffer are a CO and CO_2 production, gas pressure, densification, and KCMI (Kernel and Coating layers Mechanical Interaction). The material properties needed in the performance analysis of the buffer are the density, porosity, specific heat, thermal conductivity, and heat conductance in the gap.

The models for the PyC and SiC layers are the pressure vessel failure, chemical attack, thermal degradation, irradiation-induced dimensional change and creep, as well as a de-bonding, and a crack. The material properties needed in the performance analysis of the PyC and SiC layers are their density, specific heat, thermal conductivity, thermal expansion coefficient, Young's modulus, Poisson's ratio, irradiation-induced creep coefficient, irradiation-induced dimensional change, Weibull modulus and Weibull strength.

The diffusion of the fission products throughout the fuel particle and element should be specified. The diffusivities and source terms are needed in the diffusion analysis. The material properties related to the VHTR fuel depend on the fluence or burnup, irradiation temperature and other material properties. In the area of the VHTR fuel, no databases of the material properties describe exactly their dependency. A lot of tests and experiments are being performed and planned in many countries to obtain the correct data of the material properties and fuel performance. The HTR Fuel Technology Development Division will perform the irradiation tests from 2007 on and participate in the GEN-IV irradiation tests. In the COPA code, the material properties are filed and programmed in the COPA-MPRO module.

4. Conclusion

The COPA code consists of nine modules which predict the structural, thermal, and chemical behaviors of a VHTR fuel during a reactor operation or under accident conditions. The COPA code is one of the computer codes taking part in the IAEA-CRP-6 benchmarking. The stresses and failure fractions calculated by the COPA-MECH and COPA-FAIL showed a good agreement with the other countries' codes. All the modules of the COPA code will be completed by the end of 2007. For a superiority of the code, it is very important to create a database of the material properties expressed in the functions of the fluence or burnup, temperature, and other material properties.

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