SAFETY STANDARDS

of the

Nuclear Safety Standards Commission (KTA)

KTA 3102.4

Reactor Core Design of High-Temperature Gas-Cooled Reactors
Part 4: Thermohydraulic Analytical Model
for Stationary and Quasi-Stationary Conditions in Pebble Bed Cores

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Comment:

In these English translations of KTA-Safety Standards the words shall, should and may are used with the following meanings:

shall indicates a mandatory requirement,

should indicates a requirement[1] to which exceptions are allowed. However, the exceptions shall be substantiated during the licensing procedure,

may indicates a permission and is, thus, neither a requirement (with or without exceptions) nor a recommendation: recommendations are worded as such, e.g., "it is recommended that ....".

The word combinations basically shall/shall basically are used in the case of mandatory requirements to which specific exceptions (and only those!) are permitted. These exceptions - other than in the case of should - are specified in the text of the safety standard.

1 Please note that in the case of IAEA NUSS standards and ANSI standards, the word “should” indicates a mere recommendation.

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PLEASE NOTE:

Only the original German version of this safety standard represents the joint resolution of the 50-member Nuclear Safety standards Commission (Kerntechnischer Ausschuss, KTA). The German version was made public in Bundesanzeiger No. 44a on March 4,1988. Copies may be ordered through the Carl Heymanns Verlag KG, Gereonstr. 18-32, D-5000 Köln 1.

Nuclear Safety Standards Commission (KTA)

Federal Republic of Germany

Introduction

(1) The Safety Standard KTA 3102 "Reactor Core Design for High-Temperature Gas-Cooled Reactors" comprises the entire field of core design. Within the scope of the thermodynamic and flow-mechanical core design of high-temperature gas-cooled reactors, the following areas are dealt with:

Part 1: Calculation of the Material Properties of Helium
Part 2: Heat Transfer in Spherical Fuel Elements
Part 3: Loss of Pressure through Friction in Pebble Bed Cores
Part 4: Thermohydraulic Analytical Model for Stationary and Quasi-Stationary Conditions in Pebble Bed Cores
Part 5: Systematic and Statistical Errors in the Thermohydraulic Core Design of the Pebble Bed Reactor

(2) This Part 4 specifies the requirements for the thermal and flow mechanical analytical model for pebble bed cores of high-temperature gas-cooled reactors. The pebble bed core consists of a heaped bed of pebbles of identical diameter contained in a cylindrical vessel.

(3) The temperature distribution and mass flow density distribution in the pebble bed are relevant to safety for the design of the fuel elements (release of fission products) and of the core internals as well as for the reactivity behaviour of the reactor core.

1 Scope

(1) This safety standard applies to stationary and quasi-stationary conditions of the reactor core of high-temperature gas-cooled reactors.

(2) The thermohydraulic analytical model shall be used to calculate the cylindrically symmetric distributions of pressure, mass flow density and temperature of the cooling gas in the pebble bed and the temperature profile in the pebbles.

(3) Local distributions of the mass flow density and gas temperature in the area of individual pebbles are not covered by the model. The temperature distributions in the area of individual coated fuel particles in the fuel elements are also not treated.

2 Symbols Used

A_K	surface area of a pebble in the bed
c_p	specific heat of the cooling gas at constant pressure
d_K	diameter of the pebbles forming the bed
G	amount of the mass flow density with respect to the cross section of the volume considered empty
G_r	radial component of the mass flow density vector
G_z	axial component of the mass flow density vector
g	acceleration due to gravity
N	number of types of pebbles (fuel pebbles having different outputs moderator pebbles, absorber pebbles)
p	pressure
$\dot{Q}_j$	thermal output per pebble of type j
$\dot{q}_k$	thermal output density distribution in the pebble
$\dot{q}_s$	thermal output density distribution in the pebble bed
r	radial coordinate in the pebble bed
r_K	radial coordinate in the pebble
T	absolute gas temperature
T_K	absolute temperature in the pebble
T_{Oj}	absolute surface temperature of a pebble of type j
x_j	portion of pebbles of type j
z	axial coordinate of the pebble bed
α	heat transfer coefficient
ε	porosity of the pebble bed, i.e. the relation between the empty volume in the bed and the total volume of the bed
ε_s	degree of emission of the pebble surface
$\lambda_{eff,r}$	effective radial thermal conductivity of the pebble bed subjected to flow
$\lambda_{eff,z}$	effective axial thermal conductivity of the pebble bed subjected to flow
λ_k	thermal conductivity in the pebble
Ψ	coefficient of loss of pressure through friction of the pebble bed
ρ	density of the cooling gas
σ	Stefan-Boltzmann constant

3 Model Equations

3.1 Gas

The pebble bed shall be considered as a continuum in a two-dimensional cylindrical geometry. In this context, mass flow density G, pressure p and temperature T of the gas are determined by the following laws of conservation with respect to mass, momentum and energy and by the boundary conditions specified in Section 4:

Mass:

$$\frac{1}{r}\frac{\partial}{\partial r}(rG_r)+\frac{\partial}{\partial z}(G_z)=0 \qquad (3\text{-}1)$$

Momentum:

$$\frac{\partial p}{\partial r}+\frac{\psi}{\partial K}\frac{1-\varepsilon}{\varepsilon^3}\frac{G}{2\rho}G_r=0 \qquad (3\text{-}2)$$

$$\frac{\partial p}{\partial z}+\frac{\psi}{\partial K}\frac{1-\varepsilon}{\varepsilon^3}\frac{G}{2\rho}G_z-\rho g=0 \qquad (3\text{-}3)$$

Energy:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{eff,r}\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_{eff,z}\frac{\partial T}{\partial z}\right)- -c_pG_r\frac{\partial T}{\partial r}-c_pG_z\frac{\partial T}{\partial z}+\dot{q}_s=0 \qquad (3\text{-}4)$$

3.2 Pebble

(1) The surface temperature T_{Oj} for N types of pebbles shall be calculated with the following system of equations:

$$\frac{\dot{Q}_j}{A_K}=\alpha\left(T_{0j}-T\right)+\varepsilon_s\sigma\sum_{m=1}^{N}x_m\left(T_{0j}^4-T_{0m}^4\right) \qquad (3\text{-}5)$$

$$j=1\,(1)\,N$$

(2) The temperature distribution in the pebbles shall be calculated with the thermal conductivity equation

$$\dot{q}_K=-\frac{1}{r_K^2}\frac{d}{dr_K}\left(\lambda_K\,r_K^2\frac{dT_K}{dr_K}\right) \qquad (3\text{-}6)$$

and with the following boundary conditions:

$$T_K = T_{0j} \quad \text{for} \quad r_K = \frac{d_K}{2} \qquad (3\text{-}7)$$

$$\frac{dT_K}{dr_K} = 0 \quad \text{for} \quad r_K = 0 \qquad (3\text{-}8)$$

4 Boundary Conditions for the Gas Model Equations

4.1 Total Pebble Bed

(1) The following boundary conditions shall be valid on the cylinder axis of the pebble bed:

$$G_r = 0 \quad \text{for } r = 0 \qquad (4\text{-}1)$$

$$\frac{\partial T}{\partial r} = 0 \quad \text{for} \quad r = 0 \qquad (4\text{-}2)$$

(2) On the outer rim of the pebble bed,

a) mass flow density or pressure distribution,

b) gas inlet temperature profile,

c) energy transport across the rim

shall be defined as boundary conditions.

(3) For the individual rims, the following effects shall be determined:

Side reflector

a) heat transfer,

b) leakage flows,

c) gas inlet temperature.

Bottom reflector

a) mass flow density or pressure profile as a result of radially different flow resistances in the bottom reflector,

b) heat transfer,

c) gas inlet temperature profile in the case of upward flow in the pebble bed.

Cavity above the pebble bed

a) pressure,

b) mass flow density,

c) heat transfer,

d) gas inlet temperature profile in the case of downward flow in the pebble bed.

Core rods

a) inlet or outlet cooling gas flow of the core rod,

b) inlet temperature,

c) heat transfer.

Pebble discharge tubes

Pebble discharge tubes can be described either as part of the pebble bed or by means of boundary conditions.

4.2 Partial Zones of the Pebble Beds

Cell calculations for partial zones of the pebble bed carried out if local effects

a) in the area of inserted core rods,

b) in the vicinity of pebble bed cones,

c) in the area of discharge tubes

are to be described with the two-dimensional analytical model.

The description of the rim results from the coupling of the cell that is being investigate to the remainder of the pebble bed.

5 Thermal and Flow Parameters

5.1 Material Properties of Helium

The material properties of helium shall be calculated in accordance with Safety Standard KTA 3102.1.

5.2 Heat Transfer Coefficient

The heat transfer coefficients in the pebble bed shall be calculated in accordance with Safety Standard KTA 3102.2.

5.3 Effective Thermal Conductivity

(1) The effective thermal conductivity of the pebble bed that is subjected to flow shall be converted into the effective thermal conductivities $\lambda_{eff,\,r}$ and $\lambda_{eff,z}$ in accordance with the cylindrical geometry.

(2) If the influence of the dispersive energy transport in parallel with the direction of flow on the fuel element temperatures is low, the calculations may be simplified by an isotropic approach using the effective thermal conductivity vertical to the direction of flow. The acceptability of this procedure shall be justified.

5.4 Coefficient of Loss of Pressure through Friction

The coefficients of loss of pressure through friction in the pebble bed shall be calculated in accordance with Safety Standard KTA 3102.3.

5.5 Thermal Conductivity of the Pebbles

When determining the thermal conductivity in a pebble the dependence on temperature and neutron fluence shall be taken into account.

5.6 Heat Output Density

The distribution of the heat output density in the pebble bed and in the pebbles shall be determined on the basis of the nuclear core design, taking into account the neutron and gamma radiation into the core internals.

6 Documentation

(1) The numerical methods used for the solution of the model equations in Section 3 and the computer code based on them shall be documented.

(2) The accuracy of the computer code shall be specified and justified with respect to the scope of application. The accuracy shall be demonstrated by a comparison of calculated results with analytical solutions, verifications of suitable experiments or comparative calculations with a computer code, the accuracy of which is known.

Appendix A

Regulations Referred to in this Safety Standard

KTA 3102		Reactor Core Design for High-Temperature Gas-Cooled Reactors
	(6/78)	Part 1: Calculation of the Material Properties of Helium
	(6/83)	Part 2: Heat Transfer in Spherical Fuel Elements
	(3/81)	Part 3: Loss of Pressure through Friction in Pebble Bed Cores