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Modification of IPSN's SCANAIR Fuel Rod Transient Code for High Burnup VVER Fuel

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ABSTRACT

The IPSN's transient fuel rod code, SCANAIR, has been modified to analyze pulse tests with high-burnup VVER fuel rods in the Impulse Graphite Reactor (IGR). New and modified models of separate phenomena have been developed, including models for gas plenum temperature, heat transfer from the cladding to the stagnant coolant, the effect of the cladding strain rate on the yield stress, and interruption of the cladding mechanical calculation. Thermal and mechanical properties for the VVER's fuel and Zr-1%Nb cladding were added to the SCANAIR data base on material properties. Changes in the input data file are described, and a sample calculation is presented with the modified code. A FORTRAN listing for the new and modified models is given in an Appendix A.

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1. INTRODUCTION

In the Russian Research Centre "Kurchatov Institute", the behavior of high-burnup VVER-type fuel rods was studied under conditions of reactivity-initiated accidents. Testing of these fuel rods in the Impulse Graphite Reactor (IGR) led to a number of special features. A single fuel rod with an active length of ~150 mm and filled with helium (1.6–2.3 MPa) was put in a capsule that was filled with stagnant coolant (water or air) at room pressure and temperature. This capsule was put in the IGR reactor central channel, and the reactor power was pulsed with a pulse width of 0.7–0.9 sec to simulate a reactivity accident. A large number of tests like this were performed, and they are described in a separate report [1].

A transient fuel rod code was sought to analyze the test data and provide the capability to perform related safety transient calculations. Two codes were obtained for this purpose. One was the IPSN's SCANAIR transient fuel rod code developed at the Cadarache Centre for Studies (France) [2]. The other was the USNRC's FRAP-T6 transient fuel rod code developed at the Idaho National Engineering Laboratory (USA) [3]. Both codes required modification for this application. Modifications to the SCANAIR code are described in this report.

The SCANAIR code simulates the following phenomena under RIA conditions:

- change of thermal-mechanical properties of PWR fuel and clad depending on temperature, burnup, etc.;
- temperature distribution in the fuel rod, taking into account the change in thermal conductivity of the fuel–clad gap caused by the change in the gap width and modification of the gas composition due to fission gas release (FGR) from the fuel;
- stress and strain conditions of the fuel–clad system, including at the stage of the pellet–clad mechanical interaction (PCMI); distribution of axial, hoop and radial stress components in the fuel pellet and cladding is taken into account; thermal expansion, elastic and plastic strains are calculated both for the fuel pellet and cladding;
- behavior of fission gas products in the fuel rod; fuel gas swelling and modification of gas composition and pressure in the fuel rod free volume;
- heat transfer from the fuel cladding to sodium or water coolant.

The current version of the SCANAIR code was developed to simulate fuel rod behavior under PCMI conditions typical for fast RIA processes. However, the code does not contain models to describe fuel rod failure. Besides, the VVER/IGR tests include regimes in which the cladding residual hoop strain reaches 20–40%. The current SCANAIR version does not allow for predicting such strain values. Additional difficulties can be related to difference between material properties of VVER and PWR fuel rods. These are the main reasons why the problem was formulated and solved on estimating the area of the SCANAIR applicability for simulation of RIA processes, in particular, the VVER/IGR tests, and on developing the possible ways to extend this area.

To solve these problems, the VVER/IGR test features were found that require to develop new SCANAIR models and to extend data base on material properties. These features and modifications include:

- the use of VVER fuel rods made it necessary to introduce in the SCANAIR code thermal-physical and mechanical properties of VVER fuel and Zr-1%Nb cladding;
- the use of the air coolant in a number of the tests made it necessary to introduce in the SCANAIR code models for heat transfer under conditions of free convection of gas coolant as well as thermal-physical properties of the air coolant.

At the next stage, several tests with instrumented fuel rods at the IGR reactor were calculated with the SCANAIR code. Comparative analysis of the experimental and calculational data allowed for finding a number of the SCANAIR models to be adopted for the VVER/IGR test features. In particular, to improve the SCANAIR predictions, alternative models were developed for gas plenum temperature calculation and for clad-to-water heat transfer.

A general description of the computer code modifications for SCANAIR and FRAP-T6, along with calculations, materials properties, and the data base for validation, are given in another report [1]. The details of the SCANAIR modifications are given here.

Chapter 2 of the report describes the modifications made in the thermal-physical part of the code to account for features of VVER/IGR fuel rod design and material properties as well as for features of fuel rod cooling under conditions of the ampoule tests. Alternative models are presented for heat transfer to the water and air coolant, gas plenum temperature calculation. Thermal-physical properties of VVER fuel and Zr-1%Nb cladding are described.

Chapter 3 of the report describes the modifications made in the thermal-mechanical part of the code to extend the SCANAIR code possibilities and to account for VVER fuel rod material properties. A model is presented to account for influence of the clad strain rate on the clad yield stress. Thermal-mechanical properties of VVER fuel and Zr-1%Nb cladding are also described in this Chapter.

Programming aspects related to the new version of the SCANAIR code are considered in Chapter 4. New global variables, new and modified subroutines are described in this Chapter.

Chapter 5 is the user's manual for practical use of the version and includes the description of new input data, alternative model for post-processing of output data, and comments for the SCANAIR users on simulation of fuel rod behavior under the VVER/IGR test conditions.

Sample calculational results of VVER fuel rod behavior in the IGR test conditions, given in Chapter 6, demonstrate the application area of the developed version and can be used to check the validity of the run of the VVER/IGR SCANAIR version.

Author's comments on further extension of the SCANAIR code possibilities are given in Chapter 7.

Appendixes present a FORTRAN listing texts of the subroutines, described in Chapter 3, that contain new and adopted models as well as a sample input deck.

2. THERMODYNAMICS

2.1. Introduction

The SCANAIR code calculates the transient temperature field in the fuel rod with account for change in geometrical dimensions of the fuel pellet and cladding in radial direction.

To adopt the SCANAIR thermal-physical part to VVER/IGR features, new models were introduced for gas plenum temperature calculation and clad-to-coolant heat transfer. The SCANAIR data base on material properties was supplemented with thermal-physical properties of VVER fuel and Zr-1%Nb cladding. To simulate the air cooling a model was introduced for heat transfer under conditions of free convection of gas coolant and the air thermal-physical properties were added.

2.2. Physical modeling

2.2.1. Alternative models for gas plenum temperature calculation

This model is based on the assumption that the gas plenum temperature is equal to the weighted average temperature of the inner plenum surface without account for a spring. The inner plenum surface is considered to be formed by surfaces of the cladding, top pellet and fuel rod stopper. The temperature of the cladding and stopper inner surfaces is supposed equal to the temperature of the coolant adjacent to the gas plenum. Thus, the gas plenum temperature is given as follows

$$T_{PL} = (\langle T_{fuel} \rangle A_{fuel} + T_{cool} A_{cool}) / (A_{fuel} + A_{cool}), \quad (1)$$

where $\langle T_{fuel} \rangle$ = average temperature of the fuel pellet, adjacent to the gas plenum;

A_{fuel} = cross section area of the fuel pellet, adjacent to the gas plenum;

T_{cool} = temperature of the coolant, adjacent to the gas plenum;

A_{cool} = total area of the clad and stopper inner surface.

The proposed model can be called a "large" gas plenum model, because it takes into account heat transfer to the coolant, while the SCANAIR original model equals the gas plenum temperature to the temperature of the gas gap between the top fuel pellet and cladding. Thus, the original model does not account for heat transfer to the coolant and can be used only for a "small" gas plenum.

The alternative model of the gas plenum temperature calculation is included in the GFLOW subroutine. The text of this subroutine is presented in Appendix A.1.

2.2.2. Alternative clad-to-water heat transfer model

An alternative law for heat flux vs. wall temperature is proposed for the clad-to-water heat transfer model (Fig. 2.1)

The ***a-b*** section of the curve corresponds to the regime of forced convection. Heat transfer in this regime is described by the Dittus-Boelter correlation [4].

The heat on the ***b-c*** section is transferred from the clad to water under nucleate boiling conditions. The heat flux is calculated by the Thom model [5]. This regime begins when the clad temperature reaches the water saturation temperature T_{sat}.

Critical heat flux q_{CHF} from the cladding is determined by the Kutateladze correlation [6]. When cladding temperature reaches the value correspondent to critical heat flux T_{CHF}, the transition boiling regime starts (section ***c-d***). The heat transfer coefficient in this regime is determined by the linear interpolation.

When the clad temperature reaches the minimum stable film boiling temperature T_{mfb} [7], transition occurs to the film boiling regime simulated by the Labuntzov correlation [8] (section ***d–e***).

If a clad rewetting option is used, in the moment correspondent to the rewetting beginning, heat transfer regime is transmitted to the nucleate boiling regime. The heat transfer coefficient in this regime is determined by the linear interpolation (section ***f–g***).

The heat transfer models different from the SCANAIR original models are described below.

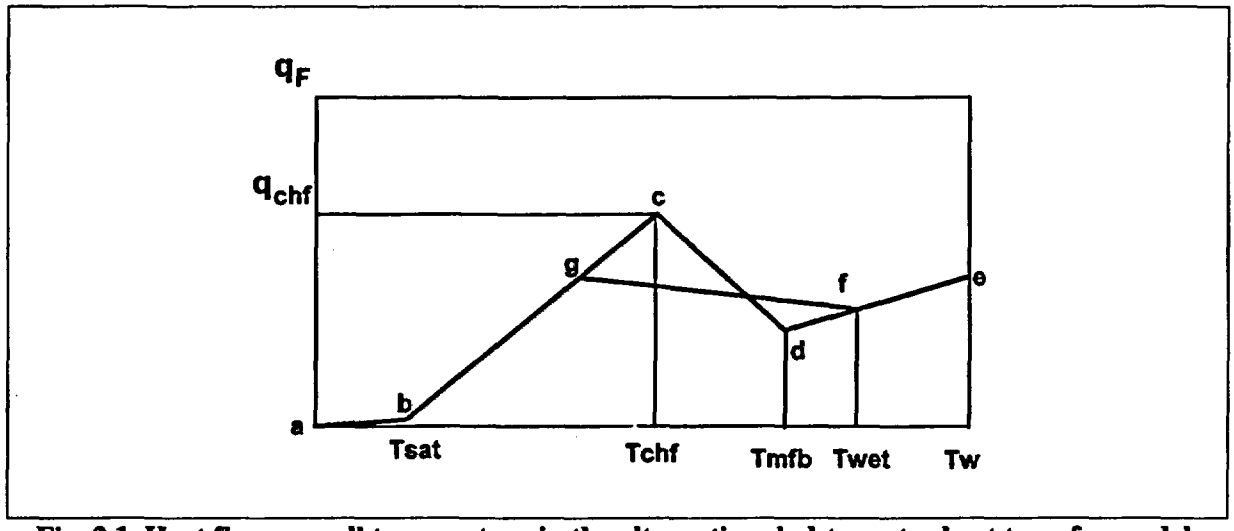

Fig. 2.1. Heat flux vs. wall temperature in the alternative clad-to-water heat transfer model.

The text of the FLXFL subroutine in which the model is chosen for the clad-to-water heat transfer calculation is given in Appendix A.2.

The model to choose the heat transfer regime as well as the critical heat transfer model and the transition boiling model are included in the EXFLT subroutine (Appendix A.3).

2.2.2.1. Nucleate boiling model

The Thom correlation [5] was developed for conditions of subcooled nucleate boiling in pool boiling conditions. This model determines the heat transfer coefficient as follows:

$$\alpha_T = 2000\,(T_c - T_S)^2 \cdot \exp\,(P / 4.34)/(T_c - T_f), \qquad (2)$$

where α_T = clad-to-coolant heat transfer coefficient (W/m^2 K);

T_c = clad temperature (K);

Ts = coolant saturation temperature (K);

P = coolant pressure (MPa);

T_f = coolant bulk temperature (K).

To provide a continuous transition from the forced convection regime to the nucleate boiling regime, the heat transfer coefficient under nucleate boiling conditions is determined by:

$$\alpha_{NB} = \max(\alpha_{DB}, \alpha_T),$$

where α_{NB} = heat transfer coefficient at nucleate boiling (W/m^{2}K);

α_{DB} = Dittus-Boelter forced convection heat transfer coefficient (W/m^{2}K);

α_T = Thom heat transfer coefficient (W/m^{2}K).

The alternative nucleate boiling model is included in the FTHOM function, text of which is given in Appendix A.4.

2.2.2.2. Critical heat flux and transition boiling models

The model proposed for a departure from nucleate boiling criterion is based on a correlation for critical heat flux under subcooled pool boiling conditions [6]:

$$q_{CHF} = 0.23 \cdot h_{fg} \sqrt{\rho_g} \sqrt[4]{\sigma \cdot g \cdot (\rho_f - \rho_g)} + (1 + 0.1(\rho_f / \rho_g)^{0.75} \Delta i / h_{fg}), \quad (3)$$

where q_{CHF} = critical heat flux (W/m^2);

h_{fg} = latent heat (J/kg);

ρ_g = steam density (kg/m^3);

σ = surface tension (J/m^2);

g = gravity constant (m^2/s);

ρ_f = water density (kg/m^3);

Δi = difference between enthalpies of saturated water and subcooled water (J/kg).

According to Eq. (2), the cladding temperature correspondent to critical heat flux T_{CHF} is determined by:

$$T_{CHF}=T_S+(q_{CHF}\exp(-P/4.34)/2000)^{1/2},$$

where T_S = saturation temperature (K);

q_{CHF} = critical heat flux, determined by Eq. (3) (W/m^2);

P coolant pressure (MPa).

A simplified model for transient boiling is based on a linear interpolation of heat transfer coefficient between critical heat flux temperature T_{CHF} and minimum stable film boiling temperature T_{mfb}, defined by Groenveld-Stewart correlation [7] (see item 3.7.1.3. of SCANAIR documentation [2]). Calculational analysis has shown that T_{mfb} is higher than T_{CHF} for a wide range of coolant pressures (0.1 – 16 MPa).

The critical heat flux and transition boiling models are included in the EXFLT subroutine, text of which is given in Appendix A.3.

2.2.2.3. Film boiling model

The Labuntzov model was developed for turbulent flows of film boiling [8]. This model was modified to account for conditions of subcooled water pool boiling and has the following form:

$$\alpha_{FB} = 0.25 \, (\lambda_g^2 \, c_{pg} \, (\rho_f - \rho_g) \, g / \nu_g)^{1/3} (\, 1 + 0.1 \, (\rho_f / \rho_g)^{0.75} \, \Delta i / h_{fg} \,), \quad (4)$$

where α_{FB} = heat transfer coefficient (W/m^2 K);

λ_g = steam thermal conductivity coefficient (W/m K);

c_{pg} = steam specific heat (J/kg K);

ρ_f = water density (kg/m^3);

ρ_g = steam density (kg/m^3);

g = gravity constant (m^2/s);

ν_g = steam kinematic viscosity (m^2/s);

Δi = difference between enthalpies of saturated water and subcooled water (J/kg);

h_{fg} = latent heat (J/kg).

The alternative film boiling model is included in the new FLABUN function, text of which is given in Appendix A.5.

2.2.2.4. Model of transition boiling after rewetting

The rewetting time t_{wet} (point *f* in Fig. 2.1) is determined with the use of independent models and specified in the input deck (TWET in Table 5.1). The value of the heat flux correspondent to the total cladding rewetting (point *g* on Fig. 2.1) is also specified by the user in the input deck (QCHF2 in Table 5.1). The heat transfer coefficient in this regime is determined by the linear interpolation between points *f* and *g* (see Fig. 2.1).

This transition boiling model is included in the EXFLT subroutine, text of which is given in Appendix A.3.

2.2.3. New model of clad-to-air heat transfer

The proposed heat transfer model consists of two parts: natural convection and radiation heat transfer.

Table 2.1 presents the correlations for the Nusselt number under natural circulation conditions for various Gr numbers. For air coolant the Prandtl number is close to 1 and the value GrPr is calculated as follows:

$$\mathrm{Gr\,Pr} = g\ \Delta\rho\ h^3/(\mu\, a), \tag{5}$$

where g = gravity constant (m^2/s);

$\Delta\rho$ = difference between densities of cold bulk coolant and hot near-to-wall coolant (kg/m^3);

h = heated fuel rod height (m);

μ = coolant dynamic viscosity (Pa s);

a = coolant temperature conductivity (m^2/s).

Table 2.1. Correlations for heat transfer under natural circulation conditions.

Gr Pr	Nu	Ref
$10^3 - 10^9$	$0.54\,(\mathrm{Gr\,Pr})^{1/4}$.	[9]
$10^9 - 10^{13}$	$0.15\,(\mathrm{Gr\,Pr})^{1/3}$.	[10]

The heat flux due to radiation from fuel rod cladding to the ampoule wall is given by:

$$q_F = F\,\sigma(T_w^4 - T_g^4), \tag{6}$$

where F = emissivity;

σ = Stefan-Boltzmann constant (W/m^2 K^4);

T_w = clad temperature (K);

T_g = bulk coolant temperature (K).

The clad-to-air heat transfer model is included in the new HWAIR function, text of which is given in Appendix A.6.

2.3. Thermal-physical material properties

Thermal-physical material properties include temperature dependencies for specific heat, enthalpy and thermal conductivity coefficient.

2.3.1. Thermal-physical properties of VVER fuel

2.3.1.1. Specific heat and enthalpy

The VVER fuel specific heat and enthalpy vs. temperature are given in Table 2.2 and Fig. 2.2 [11]. The fuel enthalpy was determined by integration of the specific heat by temperature with condition that the enthalpy is equal to zero at 20 °C.

Table 2.2. VVER fuel specific heat and enthalpy vs. temperature.

Parameter	Temperature (K)														
Temperature (K)	293	500	700	900	1100	1300	1500	1700	1900	2100	2300	2500	2700	2900	3100
Specific heat (J/kg K)	280	287	302	310	314	319	320	328	340	364	390	426	470	520	594
Enthalpy (kJ/kg)	0	57.6	116.5	177.7	240.1	303.4	367.3	432.1	498.9	569.3	644.7	726.3	815.9	914.9	1026

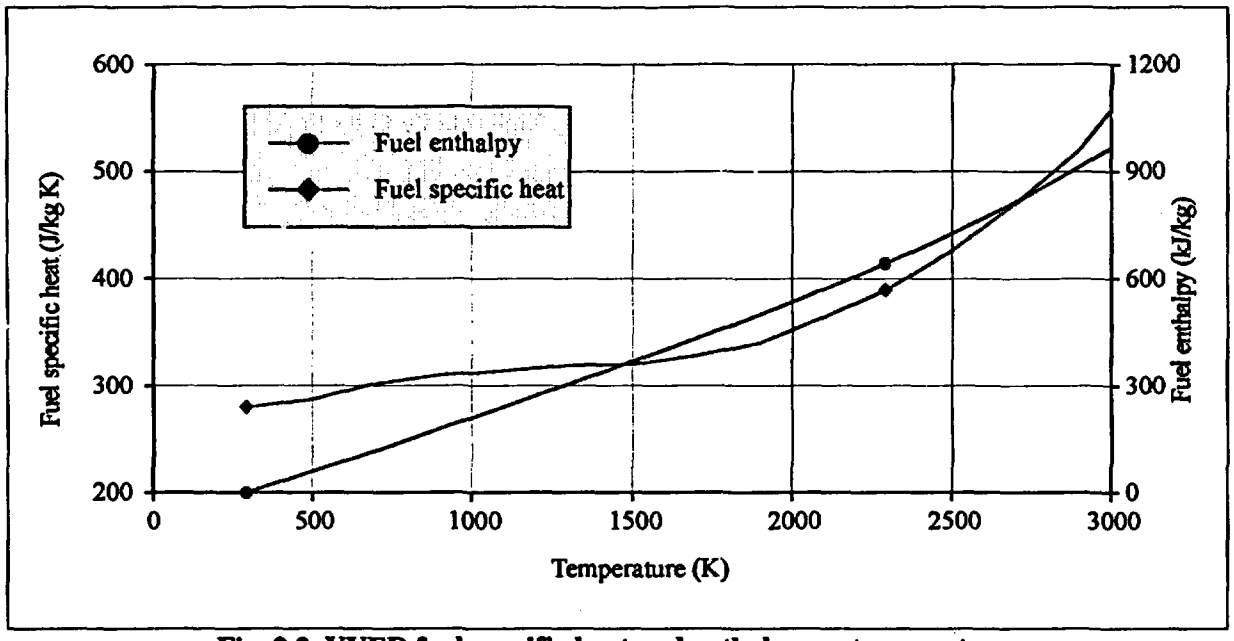

Fig. 2.2. VVER fuel specific heat and enthalpy vs. temperature.

The choice of the option for fuel type between PWR and VVER types is made in the FCP function (Appendix A.7) and the FENTH function (Appendix A.9) for specific heat and enthalpy, respectively. Specific heat and enthalpy for VVER fuel are calculated in the UCPV and UENTHV functions, respectively (Appendixes A.8 and A.10).

2.3.1.2. Thermal conductivity coefficient

Fresh fuel thermal conductivity is determined according to the model [12]:

$$\lambda_0 = 2.158\ \lambda_{0.95}\ \rho\ /\ (32.91 - \rho), \tag{7}$$

where λ_0 = fresh fuel thermal conductivity (W/m K);

$\lambda_{0.95}$ = thermal conductivity of fuel with 95% of theoretical density (W/m K);

ρ = fuel density (g/cm^3).

Thermal conductivity of fuel with 95% of theoretical density is determined by the correlation:

$$\lambda_{0.95} = 100\ /\ (0.0258 \cdot T + 3.77) + 1.1 \cdot 10^{-4} \cdot T + 1.01 \cdot 10^{-11} \cdot T^3 \cdot \exp(7.2\ 10^{-4}\ T), \tag{8}$$

where T = fuel temperature (K).

Burnup fuel thermal conductivity is determined according to the correlation [13, 14]:

$$\lambda_B = \lambda_0\ K_1\ K_2, \tag{9}$$

where λ_B = burnup fuel thermal conductivity (W/m K);

λ_0 = fresh fuel thermal conductivity (W/m K);

K_1 and K_2 = empirical coefficients.

Unitless coefficients K_1 and K_2 are determined as follows [13, 14]:

$$K_1 = (0.053 + 2.2 \cdot 10^{-4} \cdot T) / (0.053 + 0.00171 \cdot b + (2.2 - 0.000533 \cdot b)\, 10^{-4} \cdot T), \quad (10)$$

$$K_2 = 1 - 0.001 \cdot c \cdot b,$$

$$c = 5.31 - 3.42 \cdot 10^{-3} \cdot T + 4 \cdot 10^{-7} \cdot T^2 \text{ for } T < 1773, \quad (11)$$

$$c = 0.5 \text{ for } T > 1773,$$

where b = fuel burnup (MW day/kg U);

T = fuel temperature (K).

The thermal conductivity coefficients for fresh fuel and fuel with burnups of 30 and 60 MW day/kg U are presented on Fig. 2.3. Appendix A.11 contains the texts of the FLAMB function, in which the fuel type option is chosen. Correlations for VVER fuel thermal conductivity coefficient are included in the ULAMBV function, text of which is given in Appendix A.12.

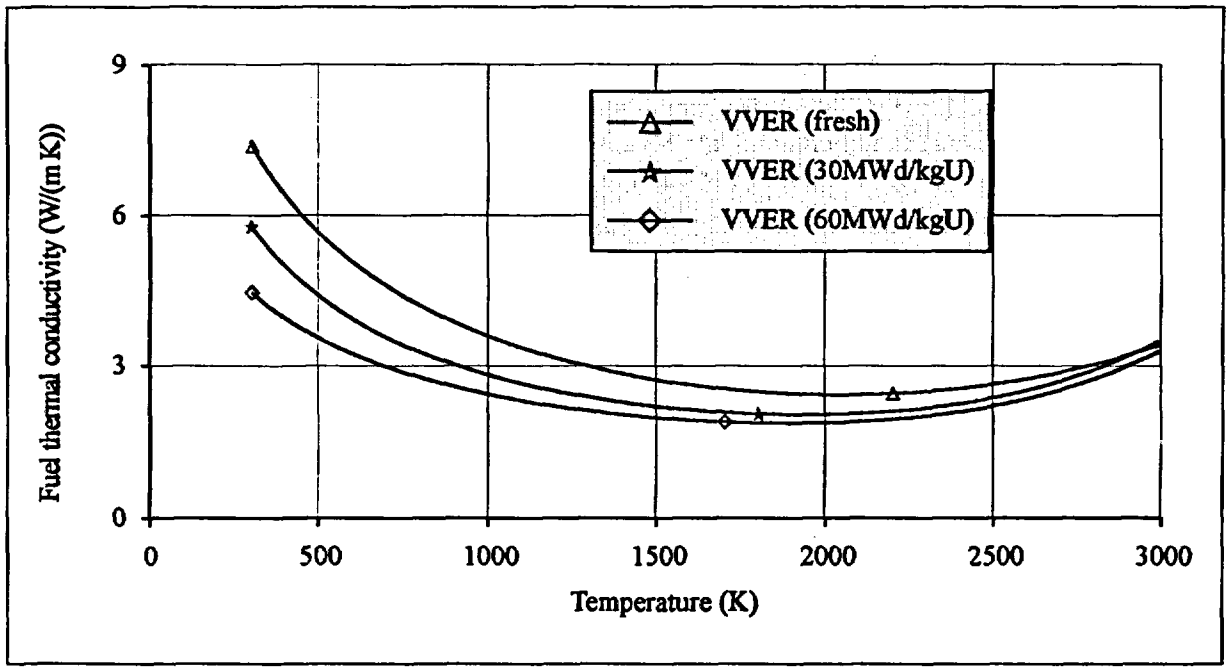

Fig. 2.3. VVER fuel thermal conductivity coefficient for various burnups vs. temperature.

2.3.2. Thermal-physical properties of Zr-1%Nb cladding

2.3.2.1. Specific heat and enthalpy

The Zr-1%Nb specific heat and enthalpy vs. temperature are given in Table 2.3 and Fig. 2.4 [15]. The cladding enthalpy was determined by integration of the specific heat by temperature with condition that the enthalpy is equal to zero at 20 °C.

Table 2.3. Zr-1%Nb specific heat and enthalpy vs. temperature.

Parameter	Temperature (K)														
	393	473	573	673	773	873	883	973	1025	1073	1153	1173	1200	1300	1400
Specific heat (J/kg K)	345	360	370	380	383	385	448	680	816	770	400	392	392	393	393
Enthalpy (kJ/kg)	34.1	61.9	97.5	134	171	209	214	262	301	339	385	393	402	445	485

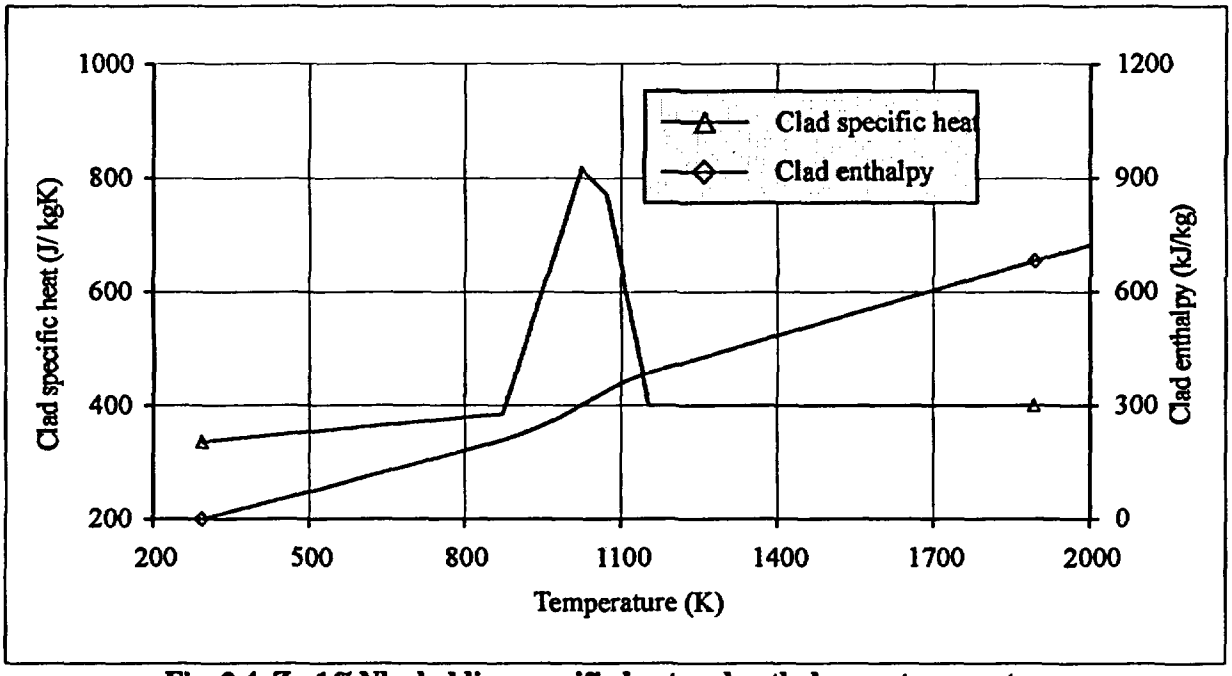

Fig. 2.4. Zr-1%Nb cladding specific heat and enthalpy vs. temperature.

The choice of the option for cladding type is made in the CCP function (Appendix A.13) and the CENTH function (Appendix A.15) for cladding specific heat and enthalpy, respectively.

Specific heat and enthalpy for Zr-1%Nb cladding are calculated in the ZNCP and ZNENTH functions, respectively (Appendixes A.14 and A.16).

2.3.2.2. Thermal conductivity coefficient

The thermal conductivity coefficient of the Zr-1%Nb cladding is determined by the correlation obtained by the experimental results [16]:

$$\lambda = 15.0636 \exp (0.4618\ 10^{-3}\ T), \qquad (12)$$

where λ = thermal conductivity (W/m K);

T = clad temperature (K).

The correlation (12) is presented in Table 2.4 and Fig. 2.5.

Table 2.4. Zr-1%Nb clad thermal conductivity coefficient vs. temperature.

Parameter	Temperature (K)									
	300	500	700	900	1100	1300	1500	1700	1900	2000
Thermal conductivity (W/m K)	17.31	18.99	20.82	22.84	25.05	27.47	30.13	33.05	36.25	37.96

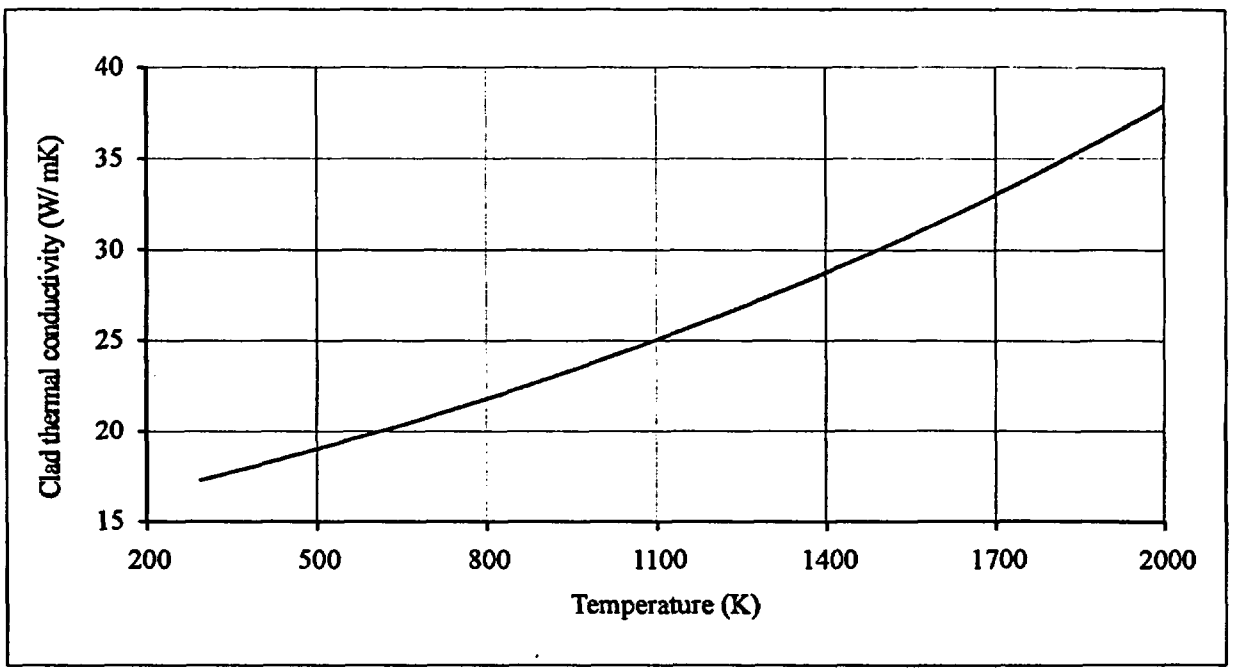

Fig. 2.5. Zr-1%Nb clad thermal conductivity coefficient vs. temperature.

Appendix A.17 contains the texts of the CLAMB function, in which the clad material option is chosen. Dependency of Zr-1%Nb thermal conductivity coefficient on temperature is included in the ZNLAMB function, text of which is given in Appendix A.18.

2.3.3. Thermal-physical properties of air coolant

The following thermal-physical properties of the air coolant are used in the form of temperature polynomials [17]:

$$\lambda = 24.407 + 7.978 \cdot 10^{-2} \cdot t - 3.154 \cdot 10^{-5} \cdot t^2 + 0.802 \cdot 10^{-8} \cdot t^3,$$

$$c_p = 1004.16 - 9.761 \cdot 10^{-3} \cdot t + 55.229 \cdot 10^{-5} \cdot t^2 - 36.275 \cdot 10^{-8} \cdot t^3,$$

$$a = 10^{-6} \cdot (18.788 + 13.484 \cdot 10^{-2} \cdot t + 13.959 \cdot 10^{-5} \cdot t^2 - 4.654 \cdot 10^{-8} \cdot t^3), \qquad (13)$$

$$\mu = 10^{-6} \cdot (17.162 + 49.894 \cdot 10^{-3} \cdot t - 2.935 \cdot 10^{-5} \cdot t^2 + 1.133 \cdot 10^{-8} \cdot t^3,$$

$$\rho = -2.883 \cdot 10^{-3} + 355.06/(t + 273) + 353.527/(t + 273)^2,$$

where λ = thermal conductivity coefficient (W/m K);

c_p = specific heat (J/kg K);

a = temperature conductivity (m^2/s);

μ = dynamic viscosity (Pa s);

ρ = density (kg/m^3);

t = temperature (°C).

The correlations for the air thermal-physical properties are included in the HWAIR function and FLURO subroutine, Correlations for the air thermal-physical properties are included in the HWAIR function and FLURO subroutine, texts of which are given in Appendixes A.6 and A.19, respectively.

3. THERMAL MECHANICS

3.1. Introduction

The mechanical model of the SCANAIR code was developed for modeling of the stress and strain conditions of the fuel rod under pellet-cladding mechanical interaction. The calculational analysis has shown that the code is not able to model large cladding deformations (5 – 10 %) when the cladding is loaded with high inner gas pressure. The calculation fails due to disconvergence of inner mechanical calculations, when the inner gas pressure causes plastic deformation of the cladding. Besides, the clad stress and strain conditions in the SCANAIR mechanical model does not depend on the clad strain rate.

To analyze the VVER/IGR processes a new model was introduced to account for influence of the clad strain rate on the clad yield stress, as well as a model to stop the cladding mechanical calculation, when the clad plastic deformation is caused by the inner pressure, while the thermal calculation is conducted.

The SCANAIR data base on the material properties is supplemented by the material properties of VVER fuel and Zr-1%Nb cladding.

3.2. Physical modeling

3.2.1. New model to account for the influence of the clad strain rate on the clad yield stress

The idea of this model is to correct the clad mechanical behavior to account for the influence of the clad strain rate on the clad yield stress. The experiments on loading of ring irradiated and unirradiated samples of Zr-1%Nb alloy [1] gave the basis for development of the dependence of the yield stress on the strain rate for various temperatures. This correlation was derived in the following form:

$$\sigma_y = \sigma_y^*(\dot{\varepsilon}/\dot{\varepsilon}_o)^m, \tag{14}$$

where

σ_y = yield stress at the given sample strain rate $\dot{\varepsilon}$ (Pa);

σ_y^* = yield stress at the base sample strain rate $\dot{\varepsilon}_o$ (Pa);

$\dot{\varepsilon}$ = clad hoop strain rate (1/s);

$\dot{\varepsilon}_o$ = base sample hoop strain rate (1/s);

m = strain rate sensitivity exponent.

The experimental results were processed and the temperature correlation was derived for the strain rate sensitivity exponent:

$$m = -5.1679\cdot10^{-7}\cdot T^2 + 1.53818\cdot10^{-3}\cdot T - 0.852482 \text{ for } T > 768K, \tag{15}$$

where T = temperature (K).

For temperature less than 768 K strain rate sensitivity exponent is accepted to be constant and equal to: m = 0.025.

The clad hoop strain rate is estimated in the DEPSDT subroutine, text of which is given in Appendix A.20. The model of the clad yield stress correction, according to Eqs. (14) and (15), is included in the CYS function, text of which is given in Appendix A.21.

3.2.2. New model of the clad mechanical behavior calculation

The calculational analysis of the SCANAIR code applicability area has shown that at the moment, when the inner gas pressure causes the clad plastic deformation, the calculation is failed due to disconvergence of the inner mechanical iterations. This failure does not allow to estimate such main calculational parameters as peak fuel enthalpy, peak cladding temperature, etc., because the calculation is failed at the initial stage of the accident modeling. The proposed model makes it possible to continue the calculation of main thermal-physical parameters without the clad mechanical behavior calculation

To find the moment to stop the clad mechanical calculation, at each integration time step, the clad hoop stress caused by the gas inner pressure is estimated.

$$\sigma_\theta = \frac{P_i r_i - P_o r_o}{r_o - r_i}, \tag{16}$$

where σ_θ = estimate for clad hoop strain (Pa);

P_i = inner gas pressure (Pa);

P_o = coolant pressure (Pa);

$r_{i,o}$ = clad inner and outer radii (m).

The clad mechanical calculation is stopped, when the condition is met $\sigma_\theta = \sigma_y$, where σ_y – clad yield stress. In other words, when this requirement is met, clad plastic deformation by the inner gas pressure becomes possible.

The model of defining the moment to stop the clad mechanical calculation is included in the IFAIL subroutine (see Appendix A.22).

The clad mechanical calculation is switched off by equalizing the inner gas pressure to the coolant pressure, it leads to zero clad stresses. This part of the model is included in the GMECH subroutine given in Appendix A.23.

The calculational analysis shows that the criterion is switched on at time step when the fuel-clad gap reopens. The nonconvergence problem could be met in the original SCANAIR after several steps with the reopened gas gap. So, the proposed criterion detects the nonconvergence problem several (about 5) time steps before this problem is actually met in the original SCANAIR calculations.

The calculational experience has shows that the use of this approach allows to calculate the thermal-physical parameters of the fuel rod for all duration of the VVER/IGR processes, if the peak fuel enthalpy does not exceed 150 cal/g for water cooling and 75 cal/g for air cooling. A sample of the calculational results of the VVER fuel rod behavior in the typical IGR test conditions is presented in Chapter 6.

3.3. Mechanical material properties

3.3.1. Fuel mechanical properties

The fuel mechanical properties include Young's modulus, Poisson's coefficient, and thermal expansion.

3.3.1.1. Young's modulus and Poisson's coefficient

Young's modulus for the VVER fuel is given by [11]:

$$E = 2.088 \cdot 10^5 - 1.526 \cdot T^{1.5} + 3.137 \cdot 10^{-2} \cdot T^2 - 4.036 \cdot 10^{-6} \cdot T^3, \quad (17)$$

where E = Young's modulus (MPa);

T = fuel temperature (K).

Correlation (17) is given in Table 3.1 and Fig. 3.1. This correlation is included in the UEMODV function, which text is given in Appendix A.25.

Table 3.1. VVER fuel Young's modulus vs. temperature.

Parameter	Temperature (K)									
	300	600	900	1200	1500	1800	2100	2400	2700	3000
Young's modulus (MPa)	20349	19670	18997	18347	17702	17028	16283	15420	14388	13133

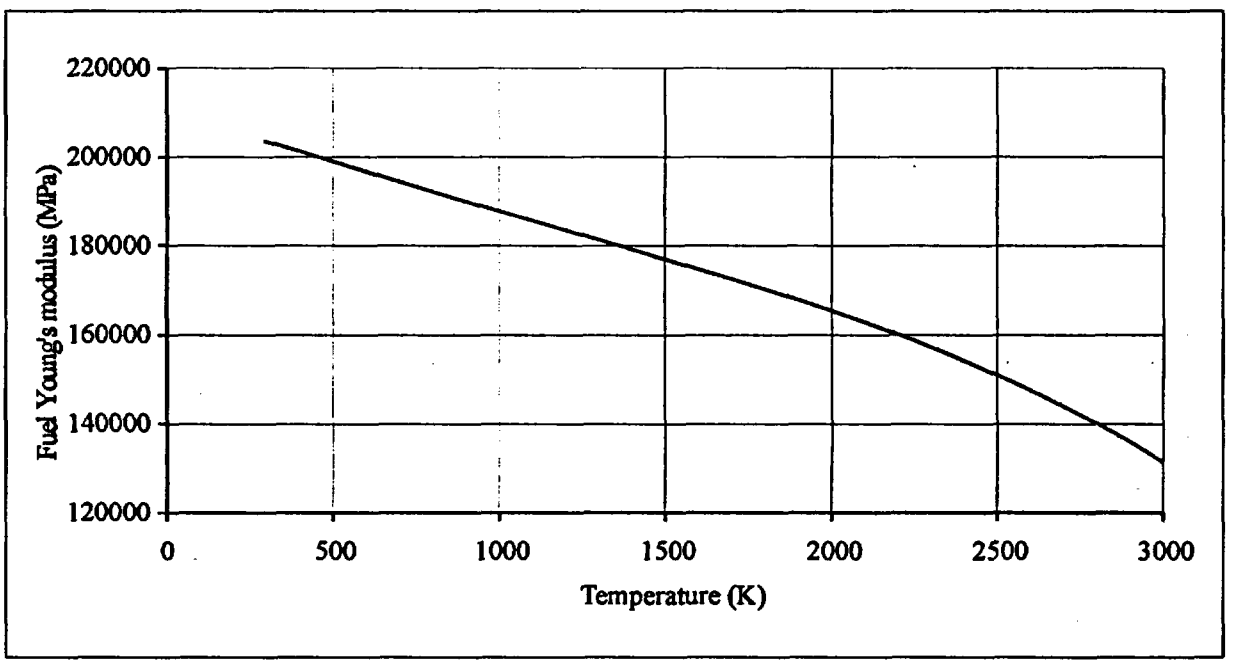

Fig. 3.1. VVER fuel Young's modulus vs. temperature.

The Poisson's coefficient for the VVER fuel is accepted constant: $\nu = 0.315$ [11] (function UNUV, Appendix A.27). The FEMOD and FNU functions are given in Appendixes A.24 and A.26. The fuel type options are chosen in these subroutines for the fuel Young's modulus and Poisson's coefficient.

3.3.1.2. Thermal expansion

The dependence of the VVER fuel thermal expansion on temperature is given in Table 3.2 and Fig. 3.2 [11].

Table 3.2. VVER fuel thermal expansion vs. temperature.

Parameter	Temperature (K)									
	293	600	900	1200	1500	1800	2100	2400	2700	3000
Thermal expansion (%)	0	0.47	0.84	1.23	1.64	2.09	2.59	3.11	3.67	4.27

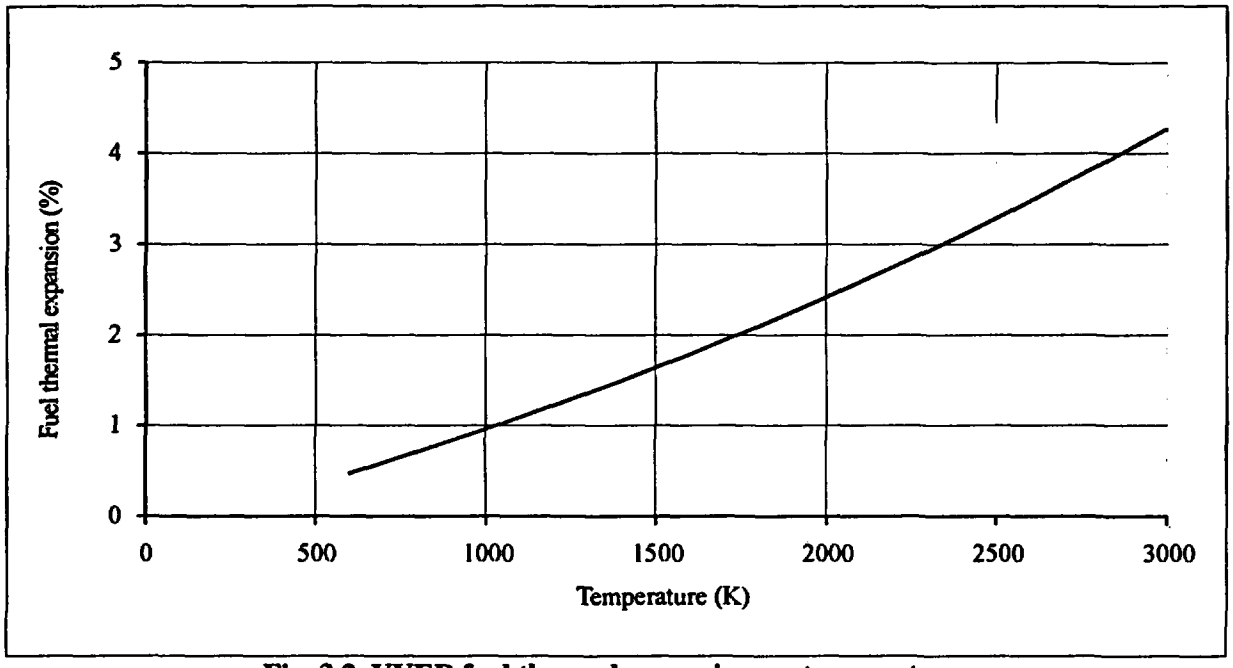

Fig. 3.2. VVER fuel thermal expansion vs. temperature.

The FDILAT function text is given in Appendix A.28, The fuel type options are chosen in this subroutine.

The dependence of the VVER fuel thermal expansion vs. temperature is included in the UDILATV function (Appendix A.29).

3.3.2. Mechanical properties of the Zr-1%Nb cladding

The clad mechanical properties include temperature dependence for the Young's modulus, Poisson's coefficient, thermal expansion and yield stress.

3.3.2.1. Young's modulus

Young's modulus for the Zr-1%Nb cladding is defined by the correlations [16]:

$$E = 1.121 \cdot 10^5 - 64.38 \cdot T, \text{ for } 273 < T < 1073 \text{ K}, \quad (18)$$

$$E = 9.129 \cdot 10^4 - 45.0 \cdot T, \text{ for } T > 1073 \text{ K},$$

where E = Young's modulus (MPa);

T = clad temperature (K).

The Young's modulus of the Zr-1%Nb clad vs. temperature is given in Table 3.3 and Fig. 3.3. This correlation is included in the ZNEMOD function (Appendix A.31). Appendix A.30 contains the CEMOD function text, where the clad option is chosen for calculation of the Young's modulus.

Table 3.3. Young's modulus of the Zr-1%Nb vs. temperature.

Parameter	Temperature (K)									
	300	500	700	900	1100	1300	1500	1700	1900	2000
Young's modulus (MPa)	92710	79836	66960	54084	41738	32738	23738	14738	5738	1000

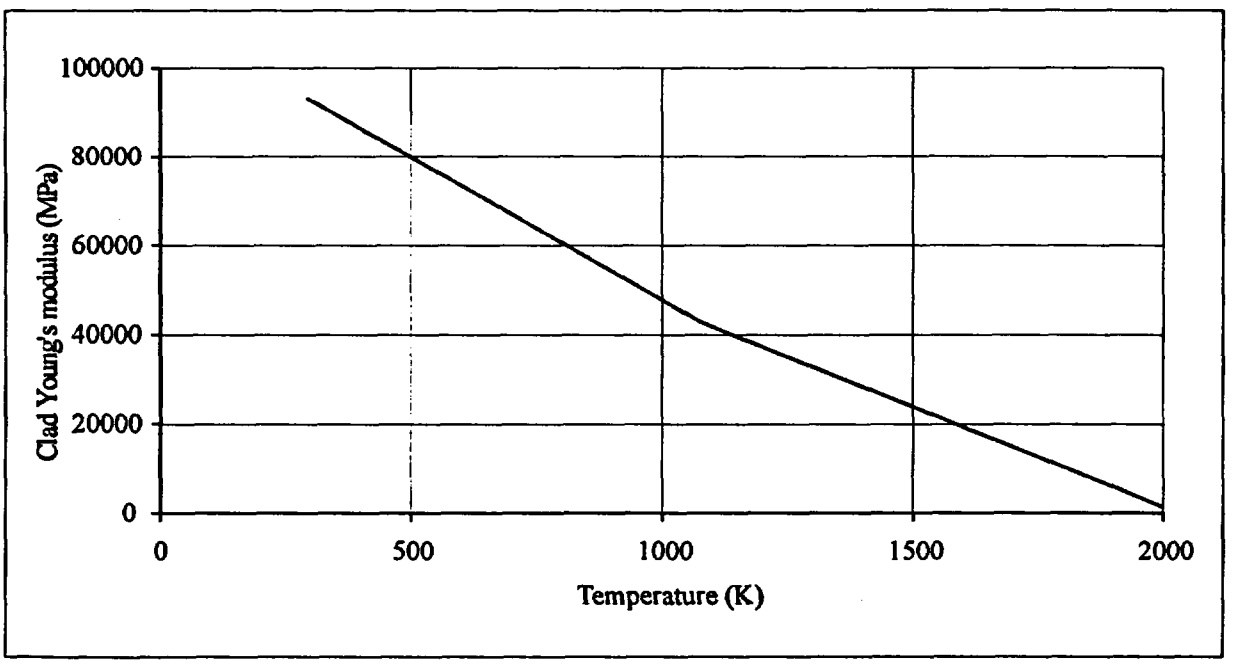

Fig. 3.3. Young's modulus of Zr-1%Nb cladding vs. temperature.

3.3.2.2. Poisson's coefficient

Poisson's coefficient for the cladding of Zr-1%Nb is determined by the correlation [16]:

$$\nu = 0.42628 - 5.556\ 10^{-5} \cdot T, \qquad (19)$$

where ν = Poisson's coefficient;

T = temperature (K).

The Zr-1%Nb Poisson's coefficient vs. temperature is given in Table 3.4 and Fig. 3.4. This dependency is included in the ZNNU function (Appendix A.33). Appendix A.32 presents the CNU function text in which the clad type option is chosen for calculation of the clad Poisson's coefficient.

Table 3.4. The Zr-1%Nb Poisson's coefficient vs. temperature [16].

Parameter	Temperature (K)									
	300	500	700	900	1100	1300	1500	1700	1900	2000
Poisson's coefficient	0.410	0.398	0.387	0.376	0.365	0.354	0.343	0.332	0.321	0.315

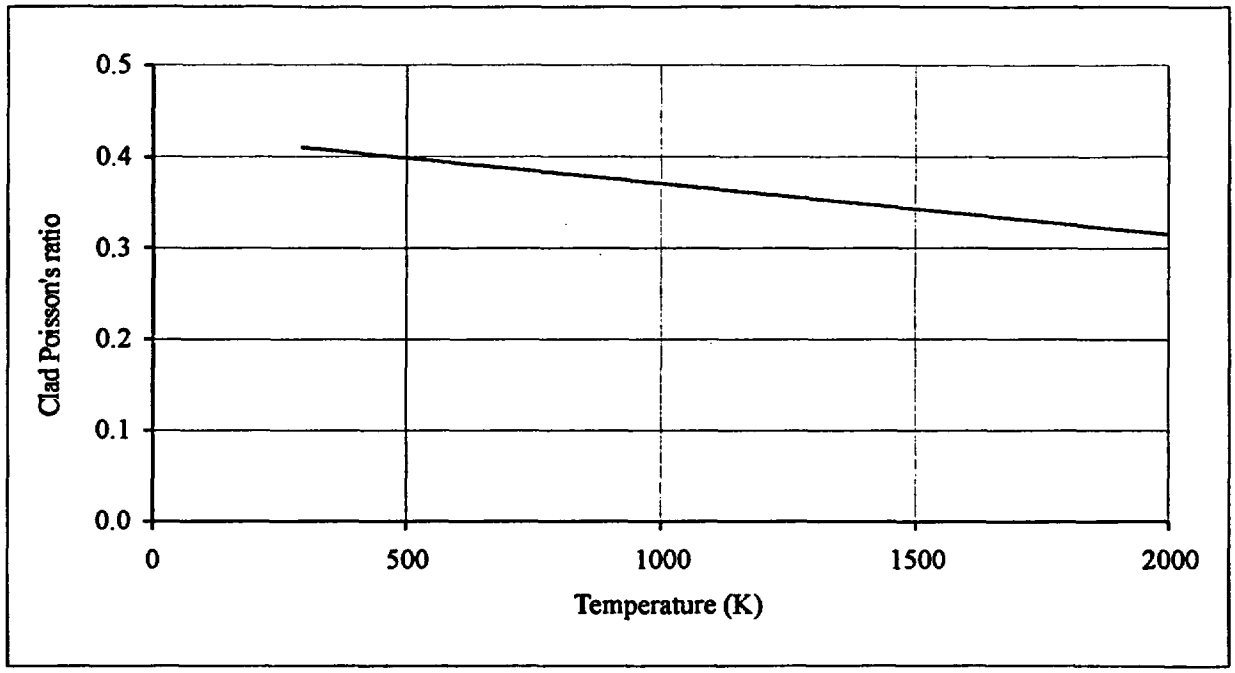

Fig. 3.4. The Zr-1%Nb Poisson's coefficient vs. temperature.

3.3.2.3. Thermal expansion

The thermal expansion coefficients of the Zr-1%Nb cladding for temperatures of 293 K up to 923 K is determined by the function given in Table 3.5. The correlations for calculation of Zr-1%Nb thermal expansion for temperatures above 923 K are given in Table 3.6 [16].

Table 3.5. Temperature dependency of hoop (α_θ) and axial (α_z) thermal expansion coefficients of Zr-1%Nb material for temperatures of 293 K up to 923 K.

Parameter	Temperature (K)							
	293 - 393		393 – 573		573-773		773 - 923	
	α_θ	α_z	α_θ	α_z	α_θ	α_z	α_θ	α_z
Thermal expansion coefficients (1/K)	$5.7\ 10^{-6}$	$5.3\ 10^{-6}$	$5.9\ 10^{-6}$	$5.4\ 10^{-6}$	$6.3\ 10^{-6}$	$5.5\ 10^{-6}$	$6.8\ 10^{-6}$	$5.6\ 10^{-6}$

Table 3.6. Temperature dependency of hoop (ε_θ) and axial (ε_z) thermal expansion of Zr-1%Nb material for temperatures above 923 K.

Temperature (K)	Thermal expansion of Zr-1%Nb material (%)
923 - 1153	$\varepsilon_\theta = -17.95 + 0.0549 \cdot T - 5.4 \cdot 10^{-5} \cdot T^2 + 1.74 \cdot 10^{-8} \cdot T^3$ $\varepsilon_z = -17.28 + 0.0533 \cdot T - 5.3 \cdot 10^{-5} \cdot T^2 + 1.72 \cdot 10^{-8} \cdot T^3$
above 1153	$\varepsilon_\theta = -0.886 + 9.7\ 10^{-4} \cdot T$ $\varepsilon_z = -1.038 + 9.7\ 10^{-4} \cdot T$

The clad isotropic thermal expansion coefficient, used in the SCANAIR code, is determined as: $\alpha=(2\alpha_\theta+\alpha_z)/3$. The plot of the Zr-1%Nb clad isotropic thermal expansion coefficient vs. temperature is given on Fig. 3.5. This dependency is included in the ZNDILA function (Appendix A.35). Appendix A.34 presents the CDILAT function in which the clad type option is chosen for calculation of the clad thermal expansion.

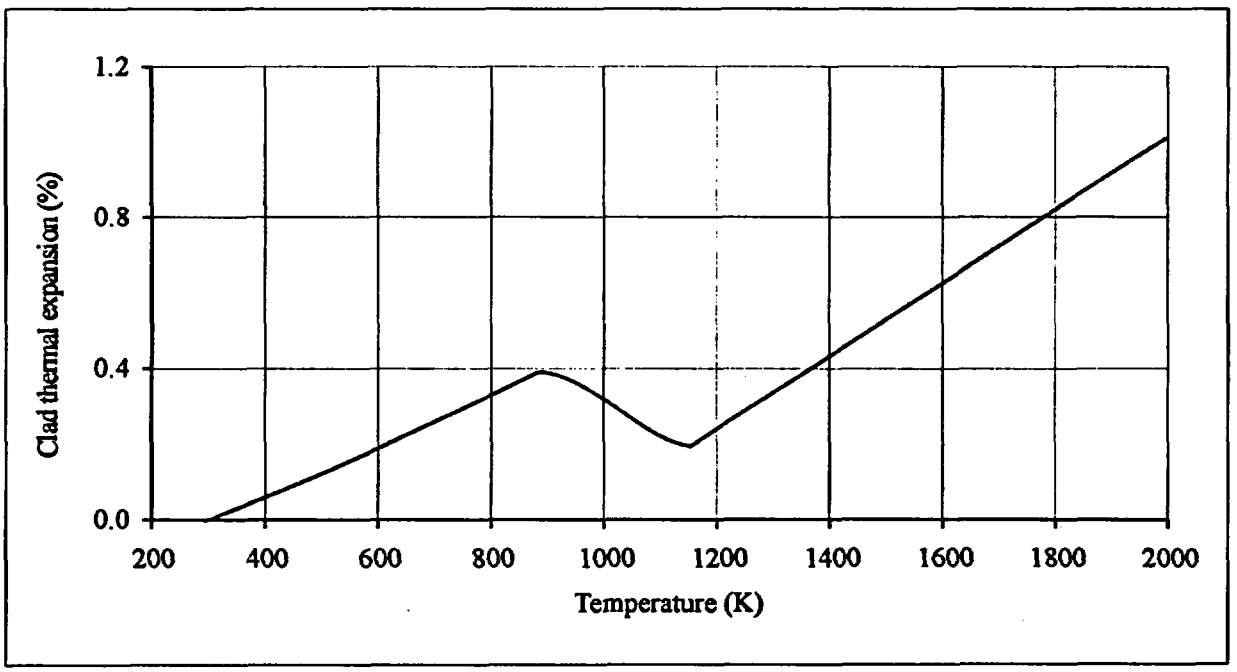

Fig. 3.5. Isotropic thermal expansion coefficient for Zr-1%Nb material vs. temperature.

3.3.2.4. Yield stress

The temperature dependencies for the yield stress of the irradiated and unirradiated Zr-1%Nb clad were obtained in frames of experimental work [1]. These temperature dependencies, that were specified in the SCANAIR input deck, are given in Table 3.7 and Fig. 3.6.

Table 3.7. The temperature dependencies for the yield stress of the irradiated and unirradiated Zr-1%Nb clad [1].

Parameter		Temperature (K)								
		300	500	700	900	1100	1300	1500	1700	2000
Yield stress (MPa)	irradiated	477	389	289	67.9	19.5	9.37	9.37	9.37	9.37
	unirrad.	292	201	143	67.9	19.5	9.37	9.37	9.37	9.37

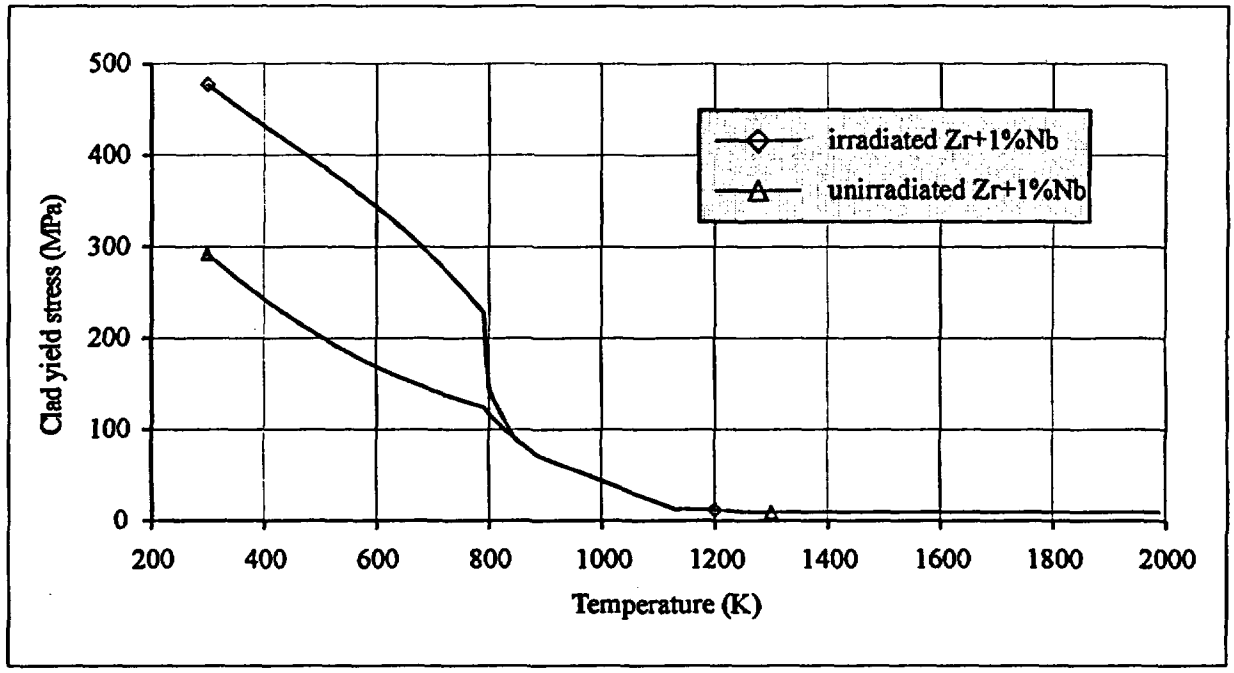

Fig. 3.6. Temperature dependencies for yield stress of the irradiated and unirradiated Zr-1%Nb clad.

4. PROGRAMMING ASPECTS

4.1. New global variables

New global variables were introduced for developed and adopted models. The new global variables are described in Table 4.1.

Table 4.1. New global variables introduced in the SCANAIR/VVER version.

Name	Type	Where stored	Description
CGAS	CHARACTER*8 constant	COMMON /VVERC/	Option to switch off the fission gas behavior calculation
CHT	CHARACTER*8 constant	COMMON /VVERC/	Option to choose the clad-to-water heat transfer model
CPLENUM	CHARACTER*8 constant	COMMON /VVERC/	Option to choose the gas plenum temperature model
FTYPE	CHARACTER*8 constant	COMMON /VVERC/	Option to choose the fuel type
CFAIL	CHARACTER*8 constant	COMMON /VVERC/	Option to switch off the cladding mechanical calculation
EPSDOT	REAL*8 array (20,50)	COMMON /VVERR/	Cladding hoop plastic strain rate
BSTRR	REAL*8 constant	COMMON /VVERR/	Cladding base strain rate
QCHF1	REAL*8 constant	COMMON /VVERR/	Tuning factor for critical heat flux at departure from nucleate boiling
QCHF2	REAL*8 constant	COMMON /VVERR/	Tuning factor for critical heat flux at departure from film boiling
TWET	REAL*8 constant	COMMON /VVERR/	Time moment of the cladding rewetting

All new variables are stored in two common-blocks: VVERC for text constants and VVERR for real arrays and constants.

4.2. New and modified subroutines

New and modified subroutines of the SCANAIR code are described in Table 4.2, including name, status and initial function of the subroutines, as well as the aim of the modification. Each subroutine is in file with the same name and extension F. For instance, function CCP is in file CCP.F. The "modified" status means that this subroutine was in the original SCANAIR subroutines. The first column of Table 4.2 contains the numbers of Appendix in which the text of this subroutine is given.

Table 4.2. New and modified subroutines and functions of the SCANAIR/VVER version

№	Name	Status	Function	Modification
Adopted and new thermal-physical models				
1	GFLOW	modified	Calculation of flow of fission gas products through the fuel porosity to the free volume	Introduction of the new model for calculation of gas plenum temperature and option to switch off fission gas behavior modeling (see 2.2.1)
2	FLXFL	modified	Calculation of clad-to-coolant heat flux	Option to choose the clad-to-coolant heat transfer model (see 2.2.2)
3	EXFLT	new	Driver of clad-to-water heat transfer coefficient calculation (see. 2.2.2)	
4	FTHOM	new	Calculation of clad-to-water heat transfer coefficient in nucleate boiling conditions (see 2.2.2.1)	
5	FLABUN	new	Calculation of clad-to-water heat transfer coefficient in film boiling conditions (see 2.2.2.3)	
6	HWAIR	new	Calculation of clad-to-air heat transfer coefficient in natural circulation conditions (see 2.2.3) and air thermal-physical properties (see 2.3.3)	
Thermal-physical material properties				
7	FCP	modified	Driver of fuel specific heat calculation	Introduction of the option to calculate VVER fuel specific heat
8	UCPV	new	VVER fuel specific heat calculation (see 2.3.1.1)	
9	FENTH	modified	Driver of fuel specific enthalpy calculation	Introduction of the option to calculate VVER fuel specific enthalpy
10	UENTHV	new	VVER fuel specific enthalpy calculation (see 2.3.1.1)	
11	FLAMB	modified	Driver of fuel thermal conductivity calculation	Introduction of the option to calculate VVER fuel thermal conductivity
12	ULAMBV	new	VVER fuel thermal conductivity calculation (see 2.3.1.2)	
13	CCP	modified	Driver of cladding specific heat calculation	Introduction of the option to calculate Zr-1%Nb cladding specific heat
14	ZNCP	new	Zr-1%Nb cladding specific heat calculation (see 2.3.2.1)	
15	CENTH	modified	Driver of cladding specific enthalpy calculation	Introduction of the option to calculate Zr-1%Nb cladding specific enthalpy
16	ZNENTH	new	Zr-1%Nb cladding specific enthalpy calculation (see 2.3.2.1)	
17	CLAMB	modified	Driver of cladding thermal conductivity calculation	Introduction of the option to calculate Zr-1%Nb cladding thermal conductivity
18	ZNLAMB	new	Zr-1%Nb cladding thermal conductivity calculation (see 2.3.2.2)	
19	FLURO	modified	Driver of cladding density	Calculation of the air density

№	Name	Status	Function	Modification
			calculation	(see 2.3.3)
			Adopted and new mechanical models	
20	DEPSDT	new	Determination of cladding hoop plastic strain rate (see 3.2.1)	
21	CYS	modified	Driver of cladding yield stress calculation	Introduction of the model for calculation of the yield stress with account for cladding hoop plastic strain rate (see 3.2.1)
22	IFAIL	new	Determination of the moment to stop modeling of cladding mechanical behavior (see 3.2.2)	
23	GMECH	modified	Driver of mechanical calculations	Introduction of the new model to stop modeling of cladding mechanical behavior (see 3.2.2)
			Mechanical material properties	
24	FEMOD	modified	Driver of fuel Young's modulus calculation	Introduction of the option to calculate VVER fuel Young's modulus
25	UEMODV	new	VVER fuel Young's modulus calculation (see 3.3.1.1)	
26	FNU	modified	Driver of fuel Poisson's coefficient calculation	Introduction of the option to calculate VVER fuel Poisson's coefficient
27	UNUV	new	VVER fuel Poisson's coefficient calculation (see 3.3.1.1)	
28	FDILAT	modified	Driver of fuel thermal expansion calculation	Introduction of the option to calculate VVER fuel thermal expansion
29	UDILATV	new	VVER fuel thermal expansion calculation (see 3.3.1.2)	
30	CEMOD	modified	Driver of cladding Young's modulus calculation	Introduction of the option to calculate Zr-1%Nb Young's modulus
31	ZNEMOD	new	Zr-1%Nb cladding Young's modulus calculation (see 3.3.2.1)	
32	CNU	modified	Driver of cladding Poisson's coefficient calculation	Introduction of the option to calculate Zr-1%Nb cladding Poisson's coefficient
33	ZNNU	new	Zr-1%Nb cladding Poisson's coefficient calculation (see 3.3.2.2)	
34	CDILAT	modified	Driver of cladding thermal expansion calculation	Introduction of the option to calculate Zr-1%Nb cladding thermal expansion
35	ZNDILA	new	Zr-1%Nb cladding thermal expansion calculation (see 3.3.2.3)	
			Input data initialization	
36	FGEOM	modified	Geometric data initialization	Initialization of the list of new input data (see Table 4.1)

5. USER'S GUIDE

5.1. New input data

New input data were introduced for the developed and modified models. Table 5.1 contains the new global variables that are input data. These variables are initialized in the FGEOM subroutine, text of which is given in Appendix A.36. A sample input deck with the use of new input data is given in APPENDIX B.

Table 5.1. New input data introduced in the SCANAIR/VVER version.

Name	Input data block	Description	Possible values and comments
CGAS	PILOT	Option to switch off fission gas behavior modeling	**'yes'**- fission gas behavior is simulated (default) 'no'- fission gas behavior is not simulated *see Appendix A.1 with text of the GFLOW subroutine*
CPLENUM	GAP	Option to choose the gas plenum temperature model	**'s'**- "small" gas plenum model (default) 'l'- "large" gas plenum model *see Eq. (1) and Appendix A.1 with text of the GFLOW subroutine*
FTYPE	FUEL	Option to choose the fuel type	**'pwr'**- PWR fuel properties are used (default) 'vver'- VVER fuel properties are used *see Appendixes A.7, A.9, A.11, A.24, A.26, A.28 with texts of the subroutines in which the fuel type is chosen*
CFAIL	CLAD	Option to switch off cladding mechanical behavior calculation	**'no'**- cladding mechanical calculation is not stopped (default) 'yes'- cladding mechanical calculation is stopped *see 3.2.2 and Appendix A.23 with text of the GMECH subroutine*
BSTRR	CLAD	Base clad strain rate (1/s)	2.D-3- deformation rate of the samples in the tests on determination of yield stress vs. temperature (1.D-3 – by default) *see Appendix A.21 with text of the CYS subroutine*

Name	Input data block	Description	Possible values and comments
CHT	FLUID	Option to choose the clad-to-water heat transfer model	**'cht0'**- original heat transfer model is used (default) 'cht1'- alternative heat transfer model is used *see 2.2.2 and Appendix A.3 with text of the EXFLT subroutine*
QCHF1	FLUID	Tuning factor for critical heat flux at departure from nucleate boiling	0.8.D0- tuning factor by which critical heat flux calculated by Eq. (3) is multiplied to detect departure from nucleate boiling (1.D0 – by default) *see Appendix A.3 with text of the EXFLT subroutine*
QCHF2	FLUID	Tuning factor for critical heat flux at departure from film boiling	0.5.D0- tuning factor by which critical heat flux calculated by Eq. (3) is multiplied to detect departure from film boiling (1.D0 – by default) *see Appendix A.3 with text of the EXFL subroutine*
TWET	FLUID	Rewetting time (s)	4.D0- time at which cladding surface is rewetted (1.D30 – by default)

The CGAS option allows for calculation of fresh fuel (option 'no'), however, the input deck should formally contain the data as for the burnup fuel, i.e., data on gas distribution in fuel, burnup, etc.

The calculational analysis shows that it is expedient to use the "large" gas plenum option (option CPLENUM 'l') when the analyzed gas plenum height is 5 times or more as much as its diameter.

Base deformation rate of the samples in the tests on determination of yield stress vs. temperature for clad material corresponds to the value $\dot{\varepsilon}_0$ in Eq. (14).

The critical heat flux at departure from nucleate boiling corresponds to point ***c*** on Fig. 2.1. The critical heat flux at departure from film boiling corresponds to point ***g*** on Fig. 2.1.

At the rewetting time transition from the film boiling to transition boiling occurs in all axial slices of the cladding.

Introduction of the new models and properties in the SCANAIR code provides new possible options for input data already existent in the original SCANAIR. These options are listed in Table 5.2.

Table 5.2. New options for input data already existent in the original SCANAIR

Name	Input data block	Description	New possible value and comments
MATERIAL	CLAD	Option to choose clad material type	'zr-nb'- material properties for Zr-1%Nb cladding are used *see Appendixes A.13, 15, 17, 30, 32, 34 with texts of the subroutines in which the cladding material type is chosen*
FLUID-TYPE	FLUID	Option to choose coolant type	'air'- heat transfer model in natural circulation conditions and air thermal-physical properties are used *see Appendixes A.3, 19 with texts of the subroutines in which the coolant type is chosen*

5.2. Alternative post-processing utility

The standard post-processing procedure used in the SCANAIR code is based on the use of the possibilities of the SIGAL environment [18]. The SCANAIR input deck contains a block in which a user can specify which information should be output in process of calculation. The output data files are in binary format and after calculation can be post-processed with the use of standard procedures of the SIGAL environment for plotting and printing. However, features of the SCANAIR use for analysis of the IGR/VVER processes did not allow for the use of all post-processing opportunities of the SIGAL environment. In particular, personal computers were used for calculations, while the SIGAL standard procedures were developed for working stations. As a result of this discrepancy, when working with personal computers it proved to be impossible to print plots with the use of the SIGAL standard procedures.

In relation to these restrictions, the problem was formulated and solved on development of an alternative post-processing utility for the SCANAIR/VVER version. The input data for this utility should be the SCANAIR output data in binary format with time histories of main calculational parameters. This utility should convert the information from these files to the text format that makes it possible to work with standard graphic packages (GRAPHER for Windows or EXCEL).

Names and brief description of the SCANAIR output files required for the work of the alternative post-processing utility are given in Table 5.3. As a result of the work of the alternative post-processing utility, the OUT_T.DAT text file is generated with time histories of main calculational parameters.

A list of main calculational parameters from the OUT_T.DAT file is given in Table 5.4. The file header contains identifiers for each variable, given in the 2nd column of Table 5.4. A sample output file is attached to the report in the electronic form.

All spatially-distributed parameters are output for the axial section with the peak power. Inner gas pressure and fission gas release relate to the whole fuel rod.

One of the main problems for analysis of the RIA processes is fuel rod failure analysis. For this reason and to simplify output data, the stress-state parameters for cladding are presented radially averaged, while parameters of fuel mechanical behavior are presented for outer surface of the fuel pellet.

Table 5.3. The SCANAIR output files required for the work of the alternative post-processing utility.

File name	Brief description of information, containing in the output file
'T&DT'	Time and time step
'ABSTRACT'	Main global radially-averaged parameters
'FMASSES'	Mass of each fuel calculational node
'FTEMP'	Temperature field in fuel
'CTEMP'	Temperature field in clad
'S-TEMP'	Temperature at fuel pellet and cladding surfaces
'FSTRESS'	Radial, hoop and axial components of the stresses in fuel
'FTHSTR'	Fuel thermal expansion
'FPLSTR'	Radial, hoop and axial components of the fuel plastic strains
'F-VM-EPS'	Radial, hoop and axial components of the fuel effective strains
'FSWSTR'	Fuel gas swelling
'CSTRESS'	Radial, hoop and axial components of the stresses in the cladding
'CTHSTR'	Cladding thermal expansion
'CPLSTR'	Radial, hoop and axial components of the clad plastic strains
'C-VM-EPS'	Radial, hoop and axial components of the clad effective strains

Table 5.4. Output parameters of the alternative post-processing utility for the SCANAIR/VVER version.

№	Identifier of parameter	Unit	Parameter	Geometric position
1.	TIME(S)	s	Calculational time	
2.	TF_CEN(K)	K	Temperature	Fuel centerline
3.	TF_OUT(K)	K	Temperature	Fuel outer surface
4.	TFAVE(K)	K	Temperature	Average over fuel radius
5.	TC_IN(K)	K	Temperature	Clad inner surface
6.	TC_OUT(K)	K	Temperature	Clad outer surface
7.	EDEP(CAL/G)	cal/g	Energy generated in fuel	Average over fuel radius
8.	HF(CAL/G)	cal/g	Fuel enthalpy	Average over fuel radius
9.	EREM(CAL/G)	cal/g	Energy leakage	Clad outer surface
10.	F2CF(kW/M2)	kW/m^2	Heat flux	From fuel to cladding
11.	C2WF(kW/M2)	kW/m^2	Heat flux	From cladding to coolant
12.	ALG(W/M2/K)	$W/(m^2K)$	Gas gap conductance	From fuel to cladding
13.	AL(kW/M2/K)	$kW/(m^2K)$	Heat transfer coefficient	From cladding to coolant
14.	PIN(MPa)	MPa	Inner gas pressure	Average over inner free volume
15.	DGAP(MM)	mm	Gap width	Between fuel and clad
16.	CSIGR(MPa)	MPa	Radial component of the stress	Average over cladding radius
17.	CSIGT(MPa)	MPa	Hoop component of the stress	
18.	CSIGZ(MPa)	MPa	Axial component of the stress	
19.	CEPSPR(%)	%	Radial component of the plastic strain	
20.	CEPSPT(%)	%	Hoop component of the plastic strain	
21.	CEPSPZ(%)	%	Axial component of the plastic strain	
22.	CEPSTH(%)	%	Thermal expansion	
23.	CEPSVM(%)	%	Effective strain	
24.	FSIGR(MPa)	MPa	Radial component of the stress	Outer fuel surface
25.	FSIGT(MPa)	MPa	Hoop component of the stress	
26.	FSIGZ(MPa)	MPa	Axial component of the stress	
27.	FEPSPR(%)	%	Radial component of the plastic strain	
28.	FEPSPT(%)	%	Hoop component of the plastic strain	
29.	FEPSPZ(%)	%	Axial component of the plastic strain	
30.	FEPSTH(%)	%	Thermal expansion	
31.	FEPSVM(%)	%	Effective strain	
32.	FSWSTR(%)	%	Gas swelling	
33.	FGR(%)	%	Fission gas release from fuel	Average over fuel volume

6. SAMPLE OF CALCULATIONAL RESULTS OF VVER FUEL ROD BEHAVIOR UNDER IGR TEST CONDITIONS

6.1. Input data

The main parameters of the input data for the proposed sample of the calculational results of VVER fuel rod behavior under IGR test conditions are given in Table 6.1. To decrease the output information one axial slice is considered.

The input deck text is given in Appendix B, the floppy disk with electron version of this file is attached to the report. The power history and yield stress vs. temperature for irradiated Zr-1%Nb cladding are not presented in Appendix B to reduce the volume of the information. The new input data are given in **bold** font.

Table 6.1. Main parameters of the input data for the sample calculational results of VVER fuel rod behavior under IGR test conditions.

Parameter	Value
Number of axial calculational nodes	1
Number of radial calculational nodes in fuel	20
Number of radial calculational nodes in cladding	7
Height of the fuel rod	150 mm
Total energy deposition	256 cal/g
Calculational time	10 s
Integration step	0.005 – 0.01 s
Option of burnup fuel	yes
Fuel type	VVER
Fuel grain radius	3 μm
Gas plenum model	"large" gas plenum
Initial inner gas pressure	1.7 MPa
Clad material	Zr-1%Nb
Base cladding strain rate	0.002 1/s
Clad mechanical calculation stop	yes
Coolant	water under normal conditions
Clad-to-water heat transfer model	alternative
Rewetting time	4.5 s

The information on radial distribution of porosity, Pu concentration, burnup, density, fission gas concentration, temperature at the end of base irradiation, and radial power profile in fuel were determined with the use of the TOSUREP code [19]. The TOSUREP code was developed for simulation of fuel rod behavior under base-irradiation conditions. The details of the procedure to find burnup fuel parameters is described in [1].

6.2. Calculational results

The OUT_T.DAT text file contains the output calculational information of the considered case and is attached to the report in the electronic form. Based on this file the plots for time histories of some parameters were plotted. These plots are given on Fig. 6.1 - Fig. 6.5.

Time histories of energy parameters, including fuel rod power, energy deposition, fuel enthalpy, energy leakage from cladding surface, are given on Fig. 6.1. Fig. 6.2 shows change in temperature parameters and clad-to-coolant heat transfer coefficient. Information on time change of inner pressure and hoop clad stress is presented on Fig. 6.3. Fig. 6.4 presents time history of total clad and fuel hoop strains and fuel-clad gap width. Time histories for fission gas release from fuel and fuel gas swelling are given on Fig. 6.5.

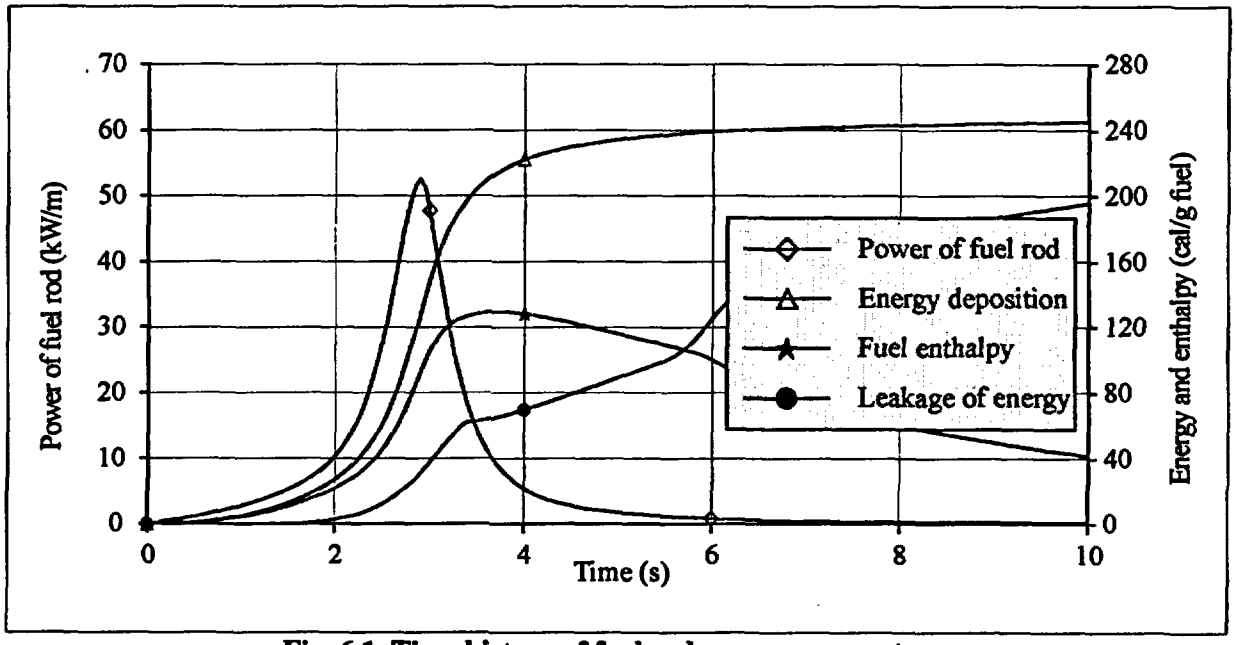

Fig. 6.1. Time history of fuel rod energy parameters.

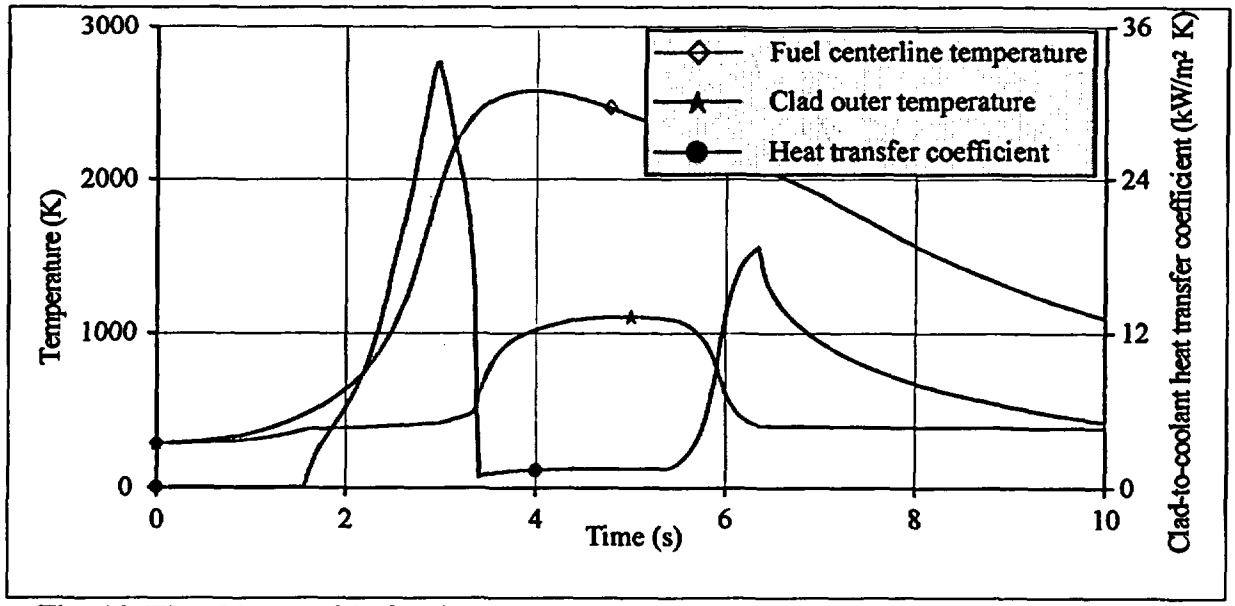

Fig. 6.2. Time history of fuel rod temperature parameters and clad-to-coolant heat transfer coefficient.

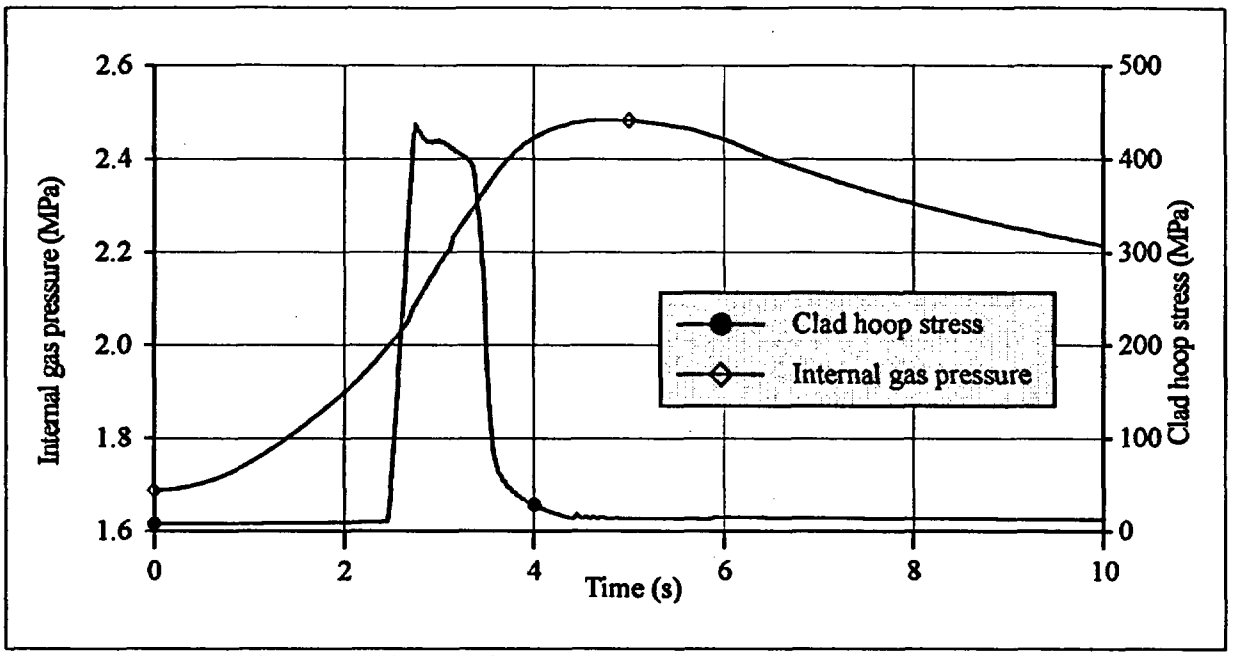

Fig. 6.3. Time history of internal gas pressure and clad hoop stress.

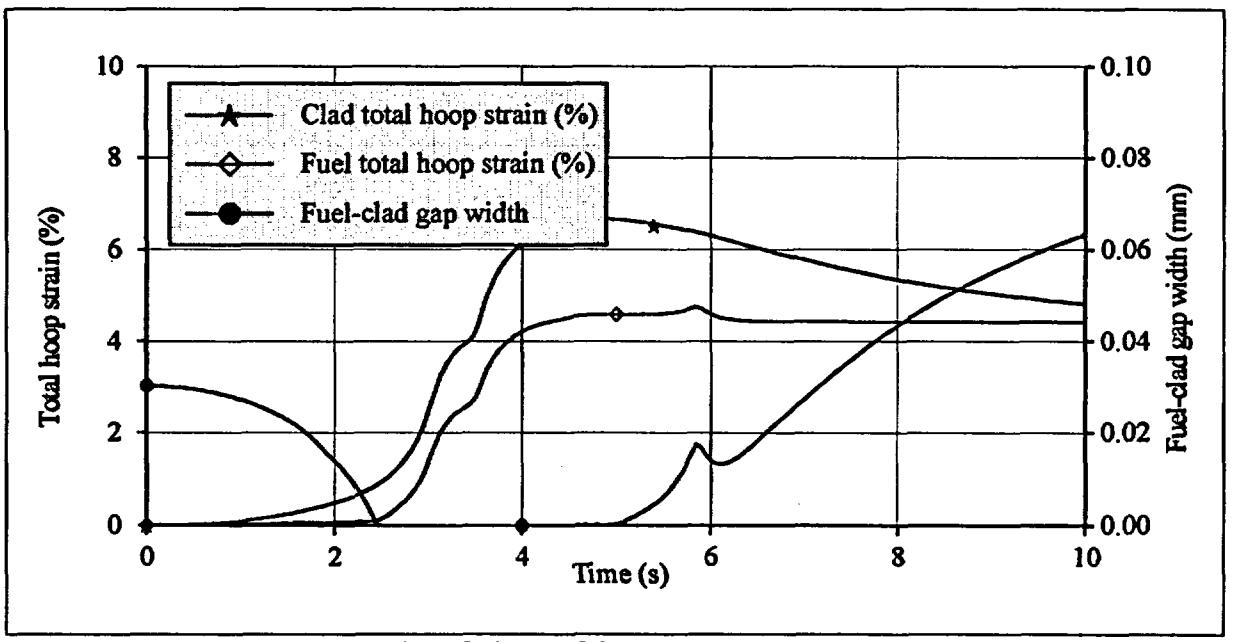

Fig. 6.4. Time history of total clad and fuel hoop strains and fuel–clad gap width.

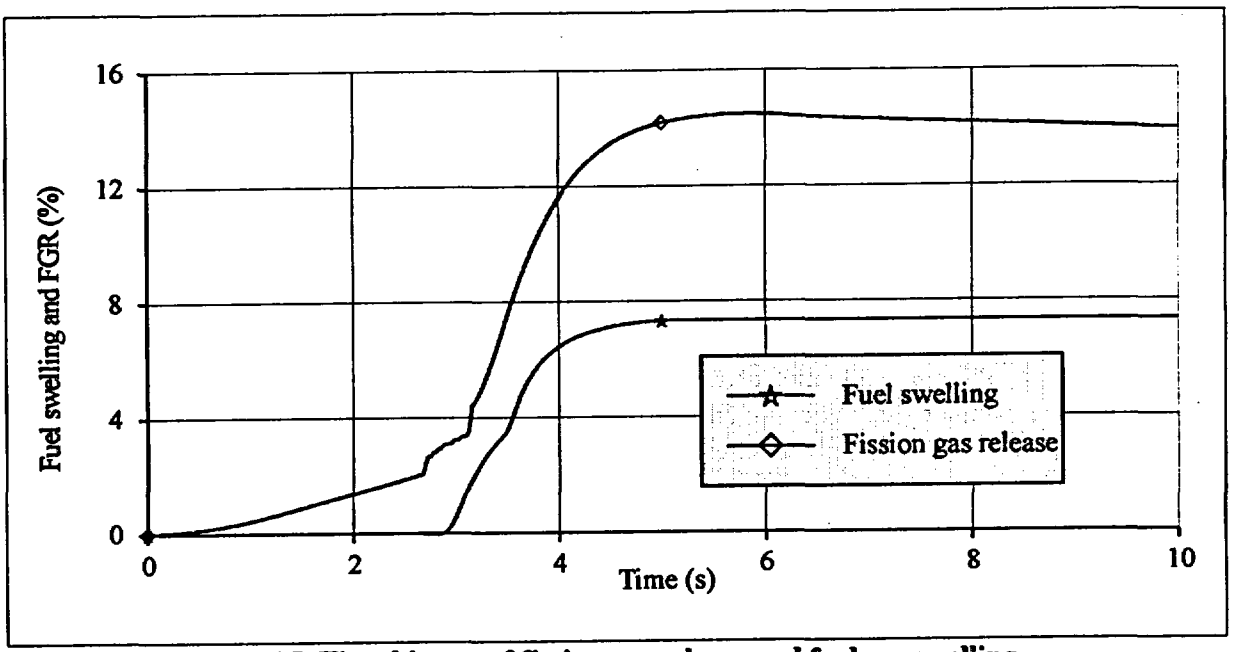

Fig. 6.5. Time history of fission gas release and fuel gas swelling.

7. COMMENTS ON THE SCANAIR/VVER CODE

The calculational experience in simulation of the IGR/VVER processes has allowed the authors of this report to develop the viewpoint concerning the first steps that should be done for extending the SCANAIR code possibilities to simulate thermal-mechanical processes in fuel rod in a fast reactivity-initiated accident.

7.1. Cladding mechanical behavior models

In the process of the calculations a problem was met of calculation failure caused by disconvergence of inner mechanical iterations when the inner gas pressure causes cladding plastic deformation (see 3.2.2). To solve this problem a detailed analysis is necessary from viewpoint of both physical and numerical modeling. The possible ways of solving this problem could be correction of the cladding deformation curve used in the SCANAIR code, including the use of the model similar to proposed in 3.2.1 to account for influence of the clad strain rate on the clad yield stress.

One of the important problems, when thermal-mechanical processes in fuel rod in RIA are analyzed, is fuel rod failure estimation. Therefore, the urgent problem is development of cladding failure models and criteria. The important part of this work is review of available approaches to fuel rod cladding failure estimate in emergency conditions and selection of the criteria and models accepted for RIA analysis. The approaches proposed in this report to stop the cladding mechanical calculation (see 3.2.2) can be used in development of the cladding failure models under gas pressure.

7.2. Fuel rod cooling models

The application of the proposed alternative clad-to-water heat transfer model (see 2.2.2) is limited by the pool subcooled boiling conditions. Besides, in this approach conservation equations are not solved for the coolant. This approximation can be valid for ampoule test conditions, but cannot be used for accident analysis in reactor conditions.

The current version of the SCANAIR code contains the coolant behavior model based on mass and energy conservation equations for single-phase coolant in 1-D (axial) homogeneous and equilibrium approximation. This model was developed and used for sodium cooling conditions. Modeling of heat transfer to water under conditions of reactivity accident will require account for effects related to appearance of vapor phase (occurrence of high density and velocity gradients, change in flow regimes, cooling conditions, etc).

The first step in development of the clad-to-water heat transfer in a reactivity-initiated accident under reactor conditions could be addition of the momentum conservation equation for the coolant to the mass and energy conservation equations. Corresponding closure relations (friction factors, local hydraulic resistance, etc.) should be included in the model. It is necessary to correct and supplement the heat transfer coefficient package to account for flow and heat transfer regimes that can occur in a reactivity accident in reactor conditions.

After such a model is verified and its applicability area is estimated, the next step could be made in development of the proposed model: revealing and detailed description of the two-phase effects that significantly influence fuel rod cooling conditions in reactivity accidents.

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APPENDIX A. Texts of new and modified subroutines and functions of the adopted SCANAIR/VVER version

A.1. Subroutine GFLOW

```
C&N     subroutine GFLOW
C&F     function : calculation of the flow of gaseous FP through the
C&F                porosities to the gap-plenum
...
      SUBROUTINE GFLOW (NSLICE,NM,NFM,DT,RAD,ZFUEL,TSOL,POROSI,VLOWPL,
     I                  VUPPL,PERM,XNGAS0,XNGAP0,TEMP,TSURF,QEP,
     O                  XNGAS,XNGAP,PINNER,TFLUID,PFLUID)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
...
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
...
C    computation of the sum over the slices of the quantity V/RT :
C>vver> new model for gas plenum temperature calculation
      IF(CPLENUM.EQ.'S'.OR.CPLENUM.EQ.'s') THEN
         TLOWPL=(TSURF(1,1)+TSURF(2,1))/2.D0+273.15D0
         TUPPL=(TSURF(1,NSLICE)+TSURF(2,NSLICE))/2.D0+273.15D0
      ELSEIF(CPLENUM.EQ.'L'.OR.CPLENUM.EQ.'l') THEN
C       areas of low plenum inner surfaces and fuel bottom surface
         SLOWPL=2.0D0*VLOWPL/RAD(NFM+2,1)+PI*RAD(NFM+2,1)**2
         SLOWF=PI*(RAD(NFM+1,1)**2-RAD(1,1)**2)
C       computation of average temperature of bottom fuel slice
         TL=0.0D0
         DO 1 I=1,NFM
            TL=TL+TEMP(I,1)*PI*(RAD(I+1,1)**2-RAD(I,1)**2)
1        CONTINUE
         TL=TL/SLOWF
C       areas of upper plenum inner surfaces and fuel top surface
         SUPPL=2.0D0*VUPPL/RAD(NFM+2,NSLICE)+PI*RAD(NFM+2,NSLICE)**2
         SUPF=PI*(RAD(NFM+1,NSLICE)**2-RAD(1,NSLICE)**2)
C       computation of average temperature of top fuel slice
         TU=0.0D0
         DO 2 I=1,NFM
           TU=TU+TEMP(I,NSLICE)*PI*(RAD(I+1,NSLICE)**2-RAD(I,NSLICE)**2)
2        CONTINUE
         TU=TU/SUPF
C       temperatures of low and upper plenum
         TLOWPL=(TL*SLOWF+TFLUID(1)*SLOWPL)/(SLOWF+SLOWPL)+273.15D0
         TUPPL=(TU*SUPF+TFLUID(NSLICE)*SUPPL)/(SUPF+SUPPL)+273.15D0
      ELSE
         WRITE(*,*)'WRONG PLENUM OPTION:',CPLENUM
         STOP
      ENDIF
C<vver<
...
C>vver>
C    inner pressure :
      IF(PINNER.NE.PFLUID)PINNER=(XNGAP(1)+XNGAP(2)+XNGAP(3))/SVSRT
C    option to switch off fission product calculations
      IF(CGAS.EQ.'not')RETURN
C<vver<
C fission product calculations follow
...
      RETURN
      END
```

A.2. Subroutine FLXFL

```
*-----------------------------------------------------------------
C&N     subroutine FLXFL
C&N
C&F     function : calculation of the flux from a material to a fluid
C&F                and its derivatives.
...

C&C     calls :
C&C     EXFL : driver of the heat exchange coefficient with the fluid
C&C     EXFLT : alternative driver of the heat exchange coefficient with the fluid
C&C
      SUBROUTINE FLXFL (H,R1,R2,XLAM,TEMP,TFLUID,PFLUID,QFLUID,XFLUID,
     I                  DH,ZCLAD,SECT,TSURF,
     O                  FLUX,DFLUX1,DFLUX2,DFLUX3,RES,RESFL,HEXC,T)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION DHEXC(3)

C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
C
CINC:               - mathematical or physical constants -
      DATA PI /3.141592654D0/
CINC-----------------------------------------------------------------------
      SURF=2.D0*PI*R2*H
C
C     resistance of the material :
      RES=ABS(R2-R1)/2.D0/SURF/XLAM
C
C>vver>
C     resistance of the fluid :
      IF(CHT.EQ.'CHT1'.OR.CHT.EQ.'cht1') THEN
C       VVER heat transfer model
         CALL EXFLT (TFLUID,PFLUID,QFLUID,XFLUID,DH,ZCLAD,SECT,TSURF,
     O   HEXC,DHEXC,T)
      ELSEIF(CHT.EQ.'CHT0'.OR.CHT.EQ.'cht0') THEN
         CALL EXFL  (TFLUID,PFLUID,QFLUID,XFLUID,DH,SECT,TSURF,
     O   HEXC,DHEXC)
      ELSE
         WRITE(6,*)'WRONG OPTION FOR HEAT TRANSFER PACKET',CHT
         STOP
      ENDIF
C<vver<
...
      RETURN
      END
```

A.3. Subroutine EXFLT

```
*-----------------------------------------------------------------------
C&N     subroutine EXFLT
C&N
C&F     function : calculation of the heat exchange coefficient between
C&F                the fluid and the clad by IGR/VVER option
...
C>vver>
      COMMON/VVERR/EPSDOT(20,50),BSTRR,QCHFC1,QCHFC2,TWET
C<vver<
SAVE TSMA
...
IF (CFLUID(1:5).EQ.'water') THEN
C
C       saturation and minimum stable film temperature :
         TSAT=H2OTS(PFLU)
         TMF=FTGRST(PFLU)
```

```
C>vver>
          ROLIQ=WATRO(PFLU,TSAT)
          ROVAP=VAPRO(PFLU,TSAT)
          SIGMA=WATSIG(TSAT)
          HVALI=VAPH(PFLU,TSAT)-WATH(PFLU,TSAT)
          DRO=ROLIQ-ROVAP
C         computation of the critical heat flux :
          QCHF=0.13D0*HVALI*ROVAP**0.5*(SIGMA*9.81D0*DRO)**0.25
C         correction due to water subcooling
          DH=WATH(PFLU,TSAT)-WATH(PFLU,TFLU)
          QCHF=QCHF*(1.+0.1*(ROLIQ/ROVAP)**0.75*DH/HVALI)
C
C         user's tuning
          QCHF =QCHFC1*QCHF
          QCHF2=QCHFC2*QCHF
C
          TCHF=TSAT+DSQRT(QCHF*DEXP(-PFLU/4.34D6)/2.D3)
          TCHF2=TSAT+DSQRT(QCHF2*DEXP(-PFLU/4.34D6)/2.D3)
C
C         user's rewetting time
          IF(DABS(T-TWET).LE.1.D-3)TSMA=TCLAD
C
C        forced-convection (Dittus-Boelter) :
          IF (TCLAD.LT.TSAT) THEN
              HEXCH =FDBOEL(PFLU,TFLU,VFLU,DHYD)
              DHSDTC=0.D0
              HEXCH2=FDBOEL(PFLU,TFLU+EPS,VFLU,DHYD)
              DHSDTF=(HEXCH2-HEXCH)/EPS
              HEXCH2=FDBOEL(PFLU,TFLU,VFLU+EPS,DHYD)
              DHSDV =(HEXCH2-HEXCH)/EPS
C
C        nucleate boiling (Thom) I
           ELSE IF (TCLAD.GE.TSAT.AND.TCLAD.LT.TCHF.AND.T.LT.TWET) THEN
              HEXCH =FTHOM(PFLU,TFLU,VFLU,DHYD,TCLAD)
              HEXCH2=FTHOM(PFLU,TFLU,VFLU,DHYD,TCLAD+EPS)
              DHSDTC=(HEXCH2-HEXCH)/EPS
              HEXCH2=FTHOM(PFLU,TFLU+EPS,VFLU,DHYD,TCLAD)
              DHSDTF=(HEXCH2-HEXCH)/EPS
              DHSDV =0.0D0
C
C        nucleate boiling (Thom) II
           ELSE IF (TCLAD.GE.TSAT.AND.TCLAD.LT.TCHF2.AND.T.GE.TWET) THEN
              HEXCH =FTHOM(PFLU,TFLU,VFLU,DHYD,TCLAD)
              HEXCH2=FTHOM(PFLU,TFLU,VFLU,DHYD,TCLAD+EPS)
              DHSDTC=(HEXCH2-HEXCH)/EPS
              HEXCH2=FTHOM(PFLU,TFLU+EPS,VFLU,DHYD,TCLAD)
              DHSDTF=(HEXCH2-HEXCH)/EPS
              DHSDV =0.0D0
C
C        transition boiling I
           ELSE IF (TCLAD.GE.TCHF.AND.TCLAD.LT.TMF.AND.T.LT.TWET) THEN
              HCHF  =FTHOM (PFLU,TFLU,VFLU,DHYD,TCHF)
              HMFB  =FLABUN(PFLU,TFLU,TMF)
              HEXCH =HCHF-(HCHF-HMFB)*(TCLAD-TCHF)/(TMF-TCHF)
              HEXCH2=HCHF-(HCHF-HMFB)*(TCLAD+EPS-TCHF)/(TMF-TCHF)
              DHSDTC=(HEXCH2-HEXCH)/EPS
              HCHF  =FTHOM (PFLU,TFLU+EPS,VFLU,DHYD,TCHF)
              HMFB  =FLABUN(PFLU,TFLU+EPS,TMF)
              HEXCH2=HCHF-(HCHF-HMFB)*(TCLAD-TCHF)/(TMF-TCHF)
              DHSDTF=(HEXCH2-HEXCH)/EPS
              DHSDV =0.0
C
C        transition boiling II
           ELSE IF (TCLAD.GE.TCHF2.AND.TCLAD.LE.TSMA.AND.T.GE.TWET) THEN
              HCHF  =FTHOM (PFLU,TFLU,VFLU,DHYD,TCHF2)
              HSMA  =FLABUN(PFLU,TFLU,TSMA)
              HEXCH =HCHF-(HCHF-HSMA)*(TCLAD-TCHF2)/(TSMA-TCHF2)
              HEXCH2=HCHF-(HCHF-HSMA)*(TCLAD+EPS-TCHF2)/(TSMA-TCHF2)
              DHSDTC=(HEXCH2-HEXCH)/EPS
              HCHF  =FTHOM (PFLU,TFLU+EPS,VFLU,DHYD,TCHF2)
```

```
            HMFB  =FLABUN(PFLU,TFLU+EPS,TSMA)
            HEXCH2=HCHF-(HCHF-HSMA)*(TCLAD-TCHF2)/(TSMA-TCHF2)
            DHSDTF=(HEXCH2-HEXCH)/EPS
            DHSDV =0.0
C
C       film boiling in inverted annular flow (modified Labuntzov) :
         ELSE IF(TCLAD.GE.TMF) THEN
            HEXCH =FLABUN(PFLU,TFLU,TCLAD)
            HEXCH2=FLABUN(PFLU,TFLU,TCLAD+EPS)
            DHSDTC=(HEXCH2-HEXCH)/EPS
            HEXCH2=FLABUN(PFLU,TFLU+EPS,TCLAD)
            DHSDTF=(HEXCH2-HEXCH)/EPS
            DHSDV =0.D0
         ELSE
            STOP 'EXFL: REGIME MAP ERROR'
         ENDIF
C
C    air coolant
      ELSE IF (CFLUID(1:3).EQ.'air') THEN
C
         HEXCH =HWAIR(TFLU,TCLAD,HM,DHYD)
         HEXCH2=HWAIR(TFLU,TCLAD+EPS,HM,DHYD)
         DHSDTC=(HEXCH2-HEXCH)/EPS
         HEXCH2=HWAIR(TFLU+EPS,TCLAD,HM,DHYD)
         DHSDTF=(HEXCH2-HEXCH)/EPS
         DHSDV =0.D0
C<vver<
C
      ELSE IF (CFLUID(1:6).EQ.'sodium') THEN
C
         HEXCH =HWNA(TFLUID,VFLU,DHYD)
         DHSDTC=0.D0
         HEXCH2=HWNA(TFLUID+EPS,VFLU,DHYD)
         DHSDTF=(HEXCH2-HEXCH)/EPS
         HEXCH2=HWNA(TFLUID,VFLU+EPS,DHYD)
         DHSDV =(HEXCH2-HEXCH)/EPS
C
C    other...?
      ELSE
         WRITE(6,1000) CFLUID
         STOP
      ENDIF
...
      END
```

A.4. Function FTHOM

```
C>vver>
*-----------------------------------------------------------------------
*     SCANAIR.....:   fthom.F   2.2
*     version creation..:   94/10/12 15:54:52
*     mask creation.....:   95/12/04 17:55:01
*-----------------------------------------------------------------------
C&N     function FTHOM
C&N
C&F     function : calculation of heat exchange coefficient given by the
C&F                Thom correlation (nucleate boiling regime)
C&F                This coefficient is computed in USI (W/m2/K)
C&V
C&V     input arguments :
C&V        PFLU .... fluid pressure (Pa)
C&V        TFLU .... fluid temperature (Kelvin)
C&V        VFLU .... fluid velocity (m/s)
C&V        DHYD .... hydraulic diameter (m)
C&V        TCLAD ... clad temperature (Kelvin)
C&V
```

```
C&C     called by :
C&C        EXFLT : calculation of the clad <-> fluid heat exchange
C&C                coefficient
C&C
C&C     calls :
C&C        H2OTS
C&C
      FUNCTION FTHOM (PFLU,TFLU,VFLU,DHYD,TCLAD)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C     computation of the specific properties of the fluid : water
C     specific heat (CPLIQ), water density (ROLIQ), water viscosity
C     (VILIQ), water conductivity (CDLIQ), saturation temperature(TSAT)
      CPLIQ=WATCP(PFLU,TFLU)
      ROLIQ=WATRO(PFLU,TFLU)
      VILIQ=WATVI(TFLU)
      CDLIQ=WATCD(PFLU,TFLU)
      TSAT =H2OTS(PFLU)
C
C     computation of convection heat exchange coefficient :
      REYN=ROLIQ*VFLU*DHYD/VILIQ
      HCONV=0.023*CDLIQ/DHYD*REYN**0.8*(VILIQ*CPLIQ/CDLIQ)**0.4
      HCONV=MAX(HCONV,100.D0)
C
C     wall superheat :
      DTSAT=TCLAD-TSAT
C
C     computation of the heat exchange coefficient :
      FBOIL=2.D3*DTSAT**2*DEXP(PFLU/4.34D6)/(TCLAD-TFLU)
      FTHOM=MAX(HCONV,FBOIL)
      RETURN
      END
C<vver<
```

A.5. Function FLABUN

```
C>vver>
*-------------------------------------------------------------------
C&N     function FLABUN
C&N
C&F     function : calculation of the heat exchange coefficient
C&F                clad <-> fluid  according to the modified Labuntzov
C&F                correlation. This correlation corresponds to a stable
C&F                film boiling regime.
C&F                The coefficient is computed in USI (W/m2/K)
C&V
C&V     input arguments :
C&V        PFLU .... fluid pressure (Pa)
C&V        TFLU .... fluid temperature (Kelvin)
C&V        TCLAD ... extern clad temperature (Kelvin)
C&V
      FUNCTION FLABUN (PFLU,TFLU,TCLAD)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
CINC:               - mathematical or physical constantes -
      DATA PI /3.141592654D0/
CINC-------------------------------------------------------------------
C
C     computation of the specific properties of the fluid : satutation
C     temperature (TSAT), liquid density (ROLIQ), steam density (ROVAP),
C     steam viscosity (VIVAP), steam conductivity (CDVAP), superficial
C     tension (SIGMA) and latent heat (HVALI).
C     The steam film properties are computed at the mean temperature
C     (clad temperature + water temperature)/2
      TSAT=H2OTS(PFLU)
      TFILM=(TCLAD+TSAT)/2.D0
```

```
      ROLIQ=WATRO(PFLU,TFLU)
      ROVAP=VAPRO(PFLU,TFILM)
      VIVAP=VAPVI(TFILM)
      CDVAP=VAPCD(PFLU,TFILM)
      SIGMA=WATSIG(TSAT)
      HVALI=VAPH(PFLU,TSAT)-WATH(PFLU,TSAT)
C
C     computation of the heat exchange coefficient :
      DRO=ROLIQ-ROVAP
      DTSAT=TCLAD-TSAT
      XL=2*PI*(SIGMA/9.81/DRO)**0.5
      CPVAP=VAPCP(PFLU,TFILM)
      HCLFL=0.25D0*((CDVAP**2)*CPVAP*ROVAP*DRO*9.81/VIVAP)**0.33
      DH=WATH(PFLU,TSAT)-WATH(PFLU,TFLU)
C     correction due to water subcooling
      COEFF=(1.D0+0.1D0*(ROLIQ/ROVAP)**0.75*DH/HVALI)
      HCLFL=HCLFL*COEFF
      FLABUN=HCLFL*DTSAT/(TCLAD-TFLU)
      RETURN
      END
C<vver<
```

A.6. Function HWAIR

```
C>vver>
C&N      function HWAIR
C&N
C&F      function : computation of the heat exchange coefficient wall <-> air
C&F                 (unit : W/m2/C)
C&F
C&V        input arguments :
C&V           TFLUID .. fluid temperature (K)
C&V           TCLAD ... wall temperature (K)
C&V           H ....... height of the rod (m)
C&V           DHYD .... hydraulic diameter (m)
C&V
      FUNCTION HWAIR(TFLUID,TCLAD,H,DHYD)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*8 CFLUC,CWALLC,CHEXC,CPOROC,CCLAD,CFLUID,CSTICK
      COMMON /COPTIO/ CFLUC,CWALLC,CHEXC,CPOROC,CCLAD,CFLUID,CSTICK
C     Boltzmann constant (W/m2/K4) :
      DATA SIGMA /5.672D-8/
C
C     hot air temperature (K) and density (kg/m3)
      T1=(TCLAD+TFLUID)/2.0
      RHO1=-2.883D-3+355.06/T1+353.527/T1**2
C     cold air temperature (K) and density (kg/m3)
      T2=TFLUID
      RHO2=-2.883D-3+355.06/T2+353.527/T2**2
C     density head (kg/m3)
      DRHO=RHO2-RHO1
C     hot air temperature (C)
      T1=T1-273.15
C     dynamic viscosity of air (Pa*s)
      AMU=17.162+49.894D-3*T1-2.935D-5*T1**2+1.133D-8*T1**3
      AMU=AMU*1.D-6
C     temperature conductivity of air (m2/s)
      ATEMP= 18.788+13.484D-2*T1+13.959D-5*T1**2-4.654D-8*T1**3
      ATEMP=ATEMP*1.D-6
C     Raley number
      RA=DRHO*9.81*H**3/(AMU*ATEMP)
C     thermal conductivity of air (W/m K)
      ALAM=24.407+7.978D-2*T1-3.154D-5*T1**2+0.802D-8*T1**3
      ALAM=ALAM*1.D-3
      RA=MAX(RA,1.D-12)
      IF(RA.LT.1.D9) THEN
```

```
         HWAIR=0.59*ALAM*RA**0.25/H
       ELSE IF(RA.LT.1.D13) THEN
         HWAIR=0.021*ALAM*RA**0.4/H
       ELSE
         HWAIR=0.1*ALAM*RA**0.33/H
       END IF
C
C    computation of the emissivities :
       IF (CCLAD(1:4).EQ.'zirc'.OR.CCLAD(1:5).EQ.'zr-nb') THEN
         EMISSC=CEMISS('ZrO2',TSURC)
       ELSE
         EMISSC=CEMISS(CCLAD,TSURC)
       ENDIF
C    radiative heat exchange coefficient :
       HWRAD=SIGMA*(TCLAD**2+TFLUID**2)*(TCLAD+TFLUID)*EMISSC
C
       HWAIR=HWAIR+HWRAD
       RETURN
       END
C<vver<
```

A.7. Function FCP

```
C&N     function FCP
C&F     function : calculation of the specific heat of the fuel of VVER type
C&F                unit : J/(g*deg)
C&V     input arguments :
C&V       TSOL .... solidus temperature (Celsius)
C&V       TLIQ .... liquidus temperature (Celsius)
C&V       TEMP .... temperature (Celsius)
C
      FUNCTION FCP (TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
      IF (FTYPE(1:3).EQ.'pwr') THEN
          FCP=UCP(TSOL,TLIQ,TEMP)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
          FCP=UCPV(TSOL,TLIQ,TEMP)
      END IF
C<vver<
      RETURN
      END
```

A.8. Function UCPV

```
C>vver>
C&N     function UCPV
C&F     function : calculation of the specific heat in a VVER fuel mesh
C&F                unit : J/(g*deg)
C&V     input arguments :
C&V       TSOL .... solidus temperature (Celsius)
C&V       TLIQ .... liquidus temperature (Celsius)
C&V       TEMP .... temperature (Celsius)
C
      FUNCTION UCPV (TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION FCPV(30)
      DATA FCPV  /293.0D0, 280.0D0,            500.0D0, 287.0D0,
     +            700.0D0, 302.0D0,            900.0D0, 310.0D0,
```

```
     +            1100.D0, 314.0D0,            1300.D0, 319.0D0,
     +            1500.D0, 320.0D0,            1700.D0, 328.0D0,
     +            1900.D0, 340.0D0,            2100.D0, 364.0D0,
     +            2300.D0, 390.0D0,            2500.D0, 426.0D0,
     +            2700.D0, 470.0D0,            2900.D0, 520.0D0,
     +            3100.D0, 594.0D0/
C    latent heat of UO2 (J/G) :
      DATA XLH /280.08D0/
      TK=TEMP+273.15D0
C    solid phase :
      IF (TEMP.LE.TSOL) THEN
         UCPV = XITAB (15,TK,FCPV)/1.D3
C    transition phase :
      ELSE IF (TEMP.LE.TLIQ) THEN
         UCPV=XLH/(TLIQ-TSOL)
C    liquid phase :
      ELSE
         UCPV=0.485
      ENDIF
      RETURN
      END
C<vver<
```

A.9. Function FENTH

```
C&N     function FENTH
C&F     function : calculation of the enthalpy of the fuel of VVER type
C&F                unit : J/g
C&V     input arguments :
C&V        TSOL .... solidus temperature (Celsius)
C&V        TLIQ .... liquidus temperature (Celsius)
C&V        TEMP .... temperature (Celsius)
C&C
      FUNCTION FENTH (TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
      IF (FTYPE(1:3).EQ.'pwr') THEN
          FENTH=UENTH (TSOL,TLIQ,TEMP)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
          FENTH=UENTHV (TSOL,TLIQ,TEMP)
      END IF
C<vver<
      RETURN
      END
```

A.10. Function UENTHV

```
c>vver>
C&N     function UENTHV
C&F     function : calculation of the VVER fuel enthalpy by integrating
C&F     specific heat law (J/g)

      FUNCTION UENTHV (TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION FENTV(30)
      DATA FENT /293.0D0, 0.000D0,             500.0D0, 57.60D0,
     +           700.0D0, 116.5D0,             900.0D0, 177.5D0,
     +           1100.D0, 240.1D0,             1300.D0, 303.4D0,
```

```
     +            1500.D0, 367.3D0,            1700.D0, 432.1D0,
     +            1900.D0, 498.9D0,            2100.D0, 569.3D0,
     +            2300.D0, 644.7D0,            2500.D0, 726.3D0,
     +            2700.D0, 815.9D0,            2900.D0, 914.9D0,
     +            3100.D0, 1026.D0/
C    latent heat of UO2 (J/G) :
      DATA XLH /280.08D0/
      TK=TEMP+273.15D0
C    solid phase :
      IF (TEMP.LE.TSOL) THEN
         UENTHV = XITAB (15,TK,FENT)
C    transition phase :
      ELSE IF (TEMP.LE.TLIQ) THEN
         UENTHV = 1027.3845D0 + XLH*(TEMP-TSOL)/(TLIQ-TSOL)
C    liquid phase :
      ELSE
         UENTHV = 1027.3845D0 + XLH + 0.485*(TEMP-TLIQ)
      ENDIF
      RETURN
      END
```

A.11. Function FLAMB

```
C&N     function FLAMB
C&F     function : calculation of the thermal conductivity of VVER fuel
C&F                unit : W/(mm*deg)
C&V     input arguments :
C&V        TSOL .... solidus temperature (Celsius)
C&V        TLIQ .... liquidus temperature (Celsius)
C&V        POROSI .. porosity
C&V        BRNUP ... burn-up (atom per cent)
C&V        OSU ..... stoechiometry
C&V        TEMP .... temperature (Celsius)
      FUNCTION FLAMB (TSOL,TLIQ,POROSI,BRNUP,OSU,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
      IF (FTYPE(1:3).EQ.'pwr') THEN
         FLAMB=ULAMBM (TSOL,TLIQ,POROSI,BRNUP,OSU,TEMP)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
         DENS=FRO (0.D0,0.D0,0.D0,POROSI)
         FLAMB=ULAMBV (DENS,BRNUP,TEMP)
      END IF
C<vver<
      RETURN
      END
```

A.12. Function ULAMBV

```
C>vver>
C&N     function ULAMBV
C&N
C&F     function : calculation of the VVER fuel local thermal conductivity
C&F                unit : W/(mm*deg)
C&V     input arguments :
C&V        DENS .... density (g/mm3)
C&V        BRNUP ... burn-up (atom per cent)
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION ULAMBV (DENS,BRNUP,TEMP)
```

```
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      TK=TEMP+273.15D0
c     density in g/cm3
      RHO=DENS*1.D3
C     burnup in MWd/kgU
      BUP=BRNUP*9.375D0
C     thermal conductivity for fresh fuel with 95% density
      ULM095=100.D0/(0.0258D0*TK+3.77D0)+1.1D-4*TK + 1.01D-11*TK**3*EXP(7.2D-4*TK)
C     thermal conductivity for fresh fuel with the given density
      ULMB=2.158D0*ULM095*RHO/(32.91D0-RHO)
C     coefficient to account for fuel composition
       AK1=(0.053D0+2.2D-4*TK)/(0.053D0+0.016D0*BRNUP+(2.2D-4-0.005D-4*BRNUP)*TK)
C     coefficient to account for fuel porosity
      IF(TK.LE.1773.D0)THEN
         B=4.4D0-3.2D-3*TEMP+4.D-7*TEMP**2
      ELSE
         B=0.5
      END IF
      AK2=1.D0-0.001D0*B*BUP
      ULAMBV=ULMB*AK1*AK2/1.D3
      RETURN
      END
C<vver<
```

A.13. Function CCP

```
C&N     function CCP
C&F     function : calculation of the specific heat of a clad material
C&F                unit : J/(g*deg)
C&V     input arguments :
C&V        CMAT .... name of the material
C&V        TSOL .... solidus temperature (Celsius)
C&V        TLIQ .... liquidus temperature (Celsius)
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION CCP (CMAT,TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*(*) CMAT
      IF (CMAT(1:4).EQ.'zirc') THEN
         CCP=ZCP(TSOL,TLIQ,TEMP)
C>vver>
      ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
         CCP=ZNCP(TSOL,TLIQ,TEMP)
C<vver<
      ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
         CCP=Z2CP(TEMP)
      ELSE IF (CMAT(1:5).EQ.'steel') THEN
         CCP=STCP(TEMP)
      ELSE
         WRITE(6,1000) CMAT
         STOP
      ENDIF
      RETURN
      END
```

A.14. Function ZNCP

```
C>vver>
C&N     function ZNCP
C&N
C&F     function : calculation of the specific heat in a Zr-1%Nb mesh
C&F                unit : J/(g*deg)
C&V
      FUNCTION ZNCP (TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C     latent heat of zircalloy (J/G) :
      DATA XLH /252.D0/
```

```
      DIMENSION ZCP(30)
      DATA ZCP   /393.0D0, 345.0D0,            473.0D0, 360.0D0,
     +            573.0D0, 370.0D0,            673.0D0, 380.0D0,
     +            773.0D0, 383.0D0,            873.0D0, 385.0D0,
     +            883.0D0, 448.0D0,            973.0D0, 680.0D0,
     +            1025.D0, 816.0D0,            1073.D0, 770.0D0,
     +            1153.D0, 400.0D0,            1173.D0, 392.0D0,
     +            1200.D0, 392.0D0,            1300.D0, 393.0D0,
     +            1400.D0, 393.0D0/
C    latent heat of zircalloy (J/G) :
      DATA XLH /252.D0/
      TK=TEMP+273.15D0
      IF (TEMP.LE.TSOL) THEN
         ZNCP = XITAB (15,TK,ZCP)/1.D3
      ELSE IF (TEMP.LE.TLIQ) THEN
         ZNCP=XLH/(TLIQ-TSOL)
      ELSE
         ZNCP=0.4D0
      ENDIF
      RETURN
      END
C<vver<
```

A.15. Function CENTH

```
C&N     function CENTH
C&F     function : calculation of the enthalpy of a clad material
C&F                unit : J/g
C&V     input arguments :
C&V        CMAT .... name of the material
C&V        TSOL .... solidus temperature (Celsius)
C&V        TLIQ .... liquidus temperature (Celsius)
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION CENTH (CMAT,TSOL,TLIQ,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*(*) CMAT
      IF (CMAT(1:4).EQ.'zirc') THEN
         CENTH=ZENTH (TSOL,TLIQ,TEMP)
C>vver>
      ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
         CENTH=ZNENTH(TSOL,TLIQ,TEMP)
C<vver<
      ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
         CENTH=Z2ENTH (TEMP)
      ELSE IF (CMAT(1:5).EQ.'steel') THEN
         CENTH=STENTH (TEMP)
      ELSE
         WRITE(6,1000) CMAT
         STOP
      ENDIF
      RETURN
1000  FORMAT (//,10X,' no enthalpy data for the clad material ',A8,//)
      END
```

A.16. Function ZNENTH

```
C>vver>
C&N     function ZNENTH
C&F     function : calculation of the enthalpy of the Zr+1% Nb by
C&F                integration of the specific heat law
C&F                unit : J/g
C&F
      FUNCTION ZNENTH (TSOL,TLIQ,TEMP)
```

```
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION ZENT(32)
      DATA ZENT  /293.0D0, 0.000D0,            393.0D0, 34.10D0,
     +            473.0D0, 61.90D0,            573.0D0, 97.50D0,
     +            673.0D0, 134.0D0,            773.0D0, 171.0D0,
     +            873.0D0, 209.0D0,            883.0D0, 214.0D0,
     +            973.0D0, 262.0D0,            1025.D0, 301.0D0,
     +            1073.D0, 339.0D0,            1153.D0, 385.0D0,
     +            1173.D0, 393.0D0,            1200.D0, 402.0D0,
     +            1300.D0, 445.0D0,            1400.D0, 485.0D0/
C     latent heat of zircalloy (J/G) :
      DATA XLH /252.D0/
      TK=TEMP+273.15D0
      IF (TEMP.LE.TSOL) THEN
         ZNENTH = XITAB (16,TK,ZENT)
       ELSE IF (TEMP.LE.TLIQ) THEN
          ENTHS = 0.4D0*TSOL + 33.467D0
          ZNENTH = ENTHS + XLH*(TEMP-TSOL)/(TLIQ-TSOL)
       ELSE
          ENTHL = 0.4D0*TSOL + 33.467D0 + XLH
          ZNENTH = ENTHL + 0.4D0*(TEMP-TLIQ)
      END IF
      END
C<vver<
```

A.17. Function CLAMB

```
*---------------------------------------------------------------------
C&N     function CLAMB
C&N
C&F     function : calculation of the thermal conductivity of a clad material
C&F                unit : W/(mm*deg)
C&F
C&V     input arguments :
C&V        CMAT .... name of the material
C&V        TEMP .... temperature (Celsius)
C&V
C&C     called by :
C&C        TROD   : assembling and "pre-solution" of the rod thermal
C&C                 system
C&C        TSOLVR : solution of the rod thermal system
C&C
      FUNCTION CLAMB (CMAT,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*(*) CMAT
C
      IF (CMAT(1:4).EQ.'zirc') THEN
         CLAMB=ZLAMB (TEMP)
C>vver>
      ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
         CLAMB=ZNLAMB (TEMP)
C<vver<
      ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
         CLAMB=Z2LAMB (TEMP)
      ELSE IF (CMAT(1:5).EQ.'steel') THEN
         CLAMB=STLAMB (TEMP)
      ELSE
         WRITE(6,1000) CMAT
         STOP
      ENDIF
      RETURN
1000  FORMAT (//,10X,' no conductivity data for the clad material ',
     &        A8,//)
      END
```

A.18. Function ZNLAMB

```
C>vver>
*-----------------------------------------------------------------------
C&N     function ZNLAMB
C&N
C&F     function : calculation of the local clad thermal conductivity
C&F                unit for Zr-1%Nb: W/(mm*deg)
C&F
C&V     input arguments :
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION ZNLAMB (TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION LAMBD0
C
      TK = TEMP+273.15D0
      LAMBD0 = DEXP(0.000461843D0*TK)*15.0636D0
      ZNLAMB = LAMBD0*1.D-03
      RETURN
      END
C<vver<
```

A.19. Subroutine FLURO

```
*-----------------------------------------------------------------------
C&N     subroutine FLURO
C&N
C&F     function : driver for the calculation of the density of a fluid
C&F                (unit : g/mm3)
C&F
C&V       input arguments :
C&V          CFLUID .. type of the fluid
C&V          TFLUID .. fluid temperature (C)
C&V          PFLUID .. fluid pressure (MPa)
C&V
C&V       output arguments :
C&V          RO ..... volumic mass (g/mm3)
C&V          DROT .... d(RO)/d(T)    (g/mm3/C)
C&V
      SUBROUTINE FLURO (CFLUID,TFLUID,PFLUID,
     O                  RO,DROT)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*8 CFLUID
      DATA EPS /1.D-3/
C
      IF (CFLUID(1:5).EQ.'water') THEN
         RO=WATRO(PFLUID*1.D6,TFLUID+273.15D0)
         RO2=WATRO(PFLUID*1.D6,TFLUID+273.15D0+EPS)
      ELSE IF (CFLUID(1:6).EQ.'sodium') THEN
         RO=XNARO(TFLUID)
         RO2=XNARO(TFLUID+EPS)
C>vver> new coolant
      ELSE IF (CFLUID(1:3).EQ.'air') THEN
         T1=TFLUID+273.15
         RO=-2.883D-3+355.06D0/T1+353.527D0/T1**2
         T1=T1+EPS
         RO2=-2.883D-3+355.06D0/T1+353.527D0/T1**2
C<vver<
      ELSE
         WRITE(6,1000) CFLUID
         STOP
      ENDIF
C
C    computation of the derivative and conversion in (g/mm3/Celsius)
C    and (g/mm3) :
      DROT=(RO2-RO)/EPS
      DROT=DROT *1.D-6
```

```
      RO=RO *1.D-6
      RETURN
C
 1000 FORMAT (//,10X,' no density data for the fluid ',A8,//)
      END
```

A.20. Subroutine DEPSDT

```
C>vver>
C&N      subroutine DEPSDT
C&F      function : determine clad hoop plastic strain rate
C&V      input arguments :
C&V            NFM..... number of fuel meshes
C&V            NCM..... number of clad meshes
C&V            NSLICE... number of axial slices
C&V            EPSPL.... plastic deformation (m/m)
C&V            EPSPL0... plastic deformation from old time slice (m/m)
C&V            DT....... time step size (s)
C&V      output arguments :
C&V            EPSDOT... clad hoop plastic strain rate (1/s)
C
      SUBROUTINE DEPSDT(NFM,NCM,NSLICE,EPSPL,EPSPL0,DT)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION EPSPL(3,NFM+NCM,NSLICE),EPSPL0(3,NFM+NCM,NSLICE)
      COMMON/VVERR/EPSDOT(20,50),BSTRR,QCHFC1,QCHFC2,TWET
C
      DO  I = 1, NCM
      DO  J = 1, NSLICE
          EPSDOT(I,J)=(EPSPL(2,I+NFM,J)-EPSPL0(2,I+NFM,J))/DT
      END DO
      END DO
      RETURN
      END
C<vver<
```

A.21. Function CYS

```
C&N      function CYS
C&F      function : calculation of the yield stress of a Zr-1%Nb clad material: MPa
C&V      input argument :
C&V         CMAT .... name of the material
C&V         TEMP .... temperature (Celsius)
C&V
      FUNCTION CYS (IM,ISL,CMAT,TEMP)
...
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERR/EPSDOT(20,50),BSTRR,QCHFC1,QCHFC2,TWET
C<vver<
      IF (IPCYS.GT.0) THEN
         NYS=NTB1(IPCYS)
         TMAX=RTBG1(NYS-1,IPCYS)
         IF (TEMP.LE.TMAX) THEN
            CYS=XILAW(TEMP,IPCYS)
         ELSE
            CYS=RTBG1(NYS,IPCYS)
         ENDIF
C>vver> account for clad hoop plastic strain rate for Zr-1%Nb
         IF (CMAT(1:5).EQ.'zr-nb'.AND.BSTRR.GT.0.D0) THEN
            T=TEMP+273.15D0
            IF(T .LE. 768.) THEN
              AM = 0.025D0
```

```
            ELSE
              AM = -5.1679D-07*T*T+1.53818D-03*T-0.852482D0
            END IF
            F=DMAX1(1.D0,(DABS(EPSDOT(IM,ISL)/BSTRR)**AM))
            CYS=CYS*F
          END IF
C<vver<
```

A.22. Subroutine IFAIL

```
C>vver>
*-----------------------------------------------------------------------
C&N     subroutine IFAIL
C&F     function : determine clad calculation failure flag
C&V     input arguments :
C&V           ISL..... axial slice number
C&V           NFM..... number of fuel meshes
C&V           NCM..... number of clad meshes
C&V           NSLICE... number of axial slices
C&V           TEMP..... node temperature (c)
C&V           RAD..... node radius (m)
C&V           PINNER... inner pressure (pa)
C&V           PFLUID... fluid pressure (pa)
C&V           CCLAD.... clad material
C&V     output arguments :
C&V           IFAIL.... clad failure flag
C&V
      FUNCTION IFAIL(ISL,NFM,NCM,NSLICE,TEMP,RAD,
     +               PINNER,PFLUID,CCLAD,T)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION TEMP(NFM+NCM,NSLICE),RAD(NFM+NCM+2,NSLICE)
      CHARACTER*8 CCLAD
C
C     find clad hoop stress due to inner gas pressure
      SIGH=(PINNER*RAD(NFM+2,ISL)-PFLUID*RAD(NFM+NCM+2,ISL))/
     +     (RAD(NFM+NCM+2,ISL)-RAD(NFM+2,ISL))
      TCAVE=0.D0
      DO  I = 1, NCM
          CYSAVE=CYSAVE+CYS(I,ISL,CCLAD,TEMP(NFM+I,ISL))
      END DO
      CYSAVE=CYSAVE/NCM
      IFAIL=0
      IF(SIGH.GE.CYSAVE) IFAIL=1
      RETURN
      END
C<vver<
```

A.23. Subroutine GMECH

```
*-----------------------------------------------------------------------
C&N     subroutine GMECH
C&F     function : driver of the mechanics calculation
...
     SUBROUTINE GMECH (IPBASE,T,DT)
...
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
...
      DO 900 ISL=1,NSLICE
C>vver>clad calculation failure criterion
        IF(CFAIL(1:3).EQ.'YES'.OR.CFAIL(1:3).EQ.'yes') THEN
        IF(JFAIL.NE.1)
```

```
     +      JFAIL=IFAIL(ISL,NFM,NCM,NSLICE,D(TEMP),D(RAD),
     +                  PINNER,D(PFLUID),CCLAD,T)
        IF(JFAIL.EQ.1) THEN
           PINNER=D(PFLUID)
           CALL TBRSTO('INNER-P','R0',1,PINNER,IPGVAL)
        ENDIF
        ENDIF
C<vver<
```

A.24. Function FEMOD

```
*-----------------------------------------------------------------------
C&N     function FEMOD
C&N
C&F     function : calculation of the Young's modulus of the fuel of VVER type
C&F
C&V     input arguments :
C&V        POROSI .. porosity (volume of porosities per volume unit)
C&V        TSOL .... solidus temperature (C)
C&V        TEMP .... temperature (C)
C&V
C&C
      FUNCTION FEMOD (POROSI,TSOL,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<

      IF (FTYPE(1:3).EQ.'pwr') THEN
          FEMOD=UEMOD (TEMP,TSOL,POROSI)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
          FEMOD=UEMODV (TEMP,TSOL)
      END IF
C<vver<
      RETURN
      END
```

A.25. Function UEMODV

```
c>vver>
*-----------------------------------------------------------------------
C&N     function UEMODV
C&N
C&F     function : calculation of the local Young's modulus in VVER fuel
C&F
C&V     input arguments :
C&V        TEMP .... temperature (C)
C&V        TSOL .... solidus temperature (C)
C&V
      FUNCTION UEMODV (TEMP,TSOL)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DATA UEMIN /1000.D0/
C
      TK=TEMP+273.15
      IF (TEMP.GE.TSOL) THEN
         UEMODV=UEMIN
      ELSE
         UEMODV=2.0872428D+05-
     &          1.5259794D+00*TK**1.5+
     &          3.1374244D-02*TK**2-
     &          4.0357331D-06*TK**3
      END IF
```

```
      RETURN
      END
c<vver<
```

A.26. Function FNU

```
*---------------------------------------------------------------------
C&N     function FNU
C&N
C&F     function : calculation of the Poisson's modulus ofthe fuel of VVER type
C&F
C&V     input arguments :
C&V        POROSI .. porosity (volume of porosities per volume unit)
C&V        TSOL ... solidus temperature (C)
C&V        TEMP .... temperature (C)
C&V
      FUNCTION FNU (POROSI,TSOL,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
C
      IF (FTYPE(1:3).EQ.'pwr') THEN
          FNU=UNU (POROSI,TSOL,TEMP)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
          FNU=UNUV (TSOL,TEMP)
      END IF
C<vver<
      RETURN
      END
```

A.27. Function UNUV

```
c<vver<
*---------------------------------------------------------------------
C&N     function UNUV
C&N
C&F     function : calculation of the poisson's modulus for VVER fuel
C&F
C&V     input arguments :
C&V        TSOL .... solidus temperature (C)
C&V        TEMP .... temperature (C)
C&V
      FUNCTION UNUV (TSOL,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION NUEMAX
      DATA NUEMAX /0.49D0/
C
      IF (TEMP.GE.TSOL) THEN
         UNUV=NUEMAX
      ELSE
         UNUV=0.315D0
      END IF
      RETURN
      END
c<vver<
```

A.28. Function FDILAT

```
*---------------------------------------------------------------------
```

```
C&N     function FDILAT
C&N
C&F     function : calculation of the fuel thermal expansion strain of VVER fuel
C&F                The strain is 0. at 20. C
C&F
C&V     input arguments :
C&V        TSOL .... solidus temperature (Celsius)
C&V        TLIQ .... liquidus temperature (Celsius)
C&V        OSU ..... ratio (Oxygen atoms)/(Uranium atoms)
C&V        TEMP .... temperature (Celsius)
C&V
C&V
      FUNCTION FDILAT (TSOL,TLIQ,OSU,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
C<vver<
C
      IF (FTYPE(1:3).EQ.'pwr') THEN
          FDILAT=UDILAT (TSOL,TLIQ,OSU,TEMP)
C>vver>
      ELSE IF (FTYPE(1:4).EQ.'vver') THEN
          FDILAT=UDILATV (TEMP)
      END IF
C<vver<
      RETURN
      END
```

A.29. Function UDILATV

```
C>vver>
*-----------------------------------------------------------------------
C&N     function UDILATV
C&F     function : calculation of the thermal strain in VVER UO2 unit
C&F                The strain is set to 0. at 20. C
C&V     input arguments :
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION UDILATV (TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION EXPVVR(30)
      DATA EXPVVR/293.15, 0.00000D0,
     &            600.D0, 0.46800D0,
     &            800.D0, 0.71200D0,
     &           1000.D0, 0.95800D0,
     &           1200.D0, 1.22400D0,
     &           1400.D0, 1.49520D0,
     &           1600.D0, 1.78560D0,
     &           1800.D0, 2.09160D0,
     &           2000.D0, 2.41400D0,
     &           2200.D0, 2.75220D0,
     &           2400.D0, 3.10560D0,
     &           2600.D0, 3.47620D0,
     &           2800.D0, 3.86400D0,
     &           3000.D0, 4.26600D0,
     &           3080.D0, 4.43212D0/
C
      TK=TEMP+273.15D0
      UDILATV = XITAB (14,TK,EXPVVR)/1.D2
      RETURN
      END
C<vver<
```

A.30. Function CEMOD

```
C&N     function CEMOD
C&F     function : calculation of the Young's modulus of a Zr-1%Nb clad material
C&F                unit : MPa
C&V     input arguments :
C&V        CMAT .... name of the material
C&V        TSOL .... solidus temperature (C)
C&V        TEMP .... temperature (C)
C&V
      FUNCTION CEMOD (CMAT,TSOL,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*(*) CMAT
C
      IF (CMAT(1:4).EQ.'zirc') THEN
         CEMOD=ZEMOD (TEMP,TSOL)
C>vver>
      ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
         CEMOD=ZNEMOD(TEMP)
C<vver<
      ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
         CEMOD=Z2EMOD ()
      ELSE IF (CMAT(1:8).EQ.'steel-Vq') THEN
         CEMOD=STVQE (TEMP)
      ELSE IF (CMAT(1:8).EQ.'steel-Vi') THEN
         CEMOD=STVIE (TEMP)
      ELSE IF (CMAT(1:8).EQ.'steel-Vs') THEN
         CEMOD=STVSE (TEMP)
      ELSE
         WRITE(6,1000) CMAT
         STOP
      ENDIF
      RETURN
1000  FORMAT (//,10X,' no Young's modulus data for the clad material
     &        A8,//)
      END
```

A.31. Function ZNEMOD

```
C>vver>
C&N     function ZNEMOD
C&N
C&F     function : calculation of the local Young's modulus in the Zr-1%Nb
C&F                unit : MPa
C&F
C&V     input arguments :
C&V        TEMP .... temperature (C)
C&V
      FUNCTION ZNEMOD (TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DATA ZEMIN /1000.D0/
C
      TK=TEMP+273.15D0
      IF(TK .LE. 1073.D0) THEN
         ZNEMOD=11.21D4-64.38D0*TK
      ELSE IF(TK .LE. 2133.D0) THEN
         ZNEMOD=9.129D4-45.D0*TK
      ELSE
         ZNEMOD=ZEMIN
      ENDIF
      IF (ZNEMOD.LT.ZEMIN) ZNEMOD=ZEMIN
      RETURN
      END
C<vver<
```

A.32. Function CNU

```
*-----------------------------------------------------------------------
C&N      function CNU
C&N
C&F      function : calculation of the Poisson's modulus of a Zr-1%Nb clad material
C&F
C&V      input arguments :
C&V         CMAT .... name of the material
C&V         TSOL ... solidus temperature (C)
C&V         TEMP .... temperature (C)
C&V
       FUNCTION CNU (CMAT,TSOL,TEMP)
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
       CHARACTER*(*) CMAT
C
       IF (CMAT(1:4).EQ.'zirc') THEN
          CNU=ZNU (TSOL,TEMP)
C>vver>
       ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
          CNU=ZNNU (TSOL,TEMP)
C<vver<
       ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
          CNU=Z2NU ()
       ELSE IF (CMAT(1:5).EQ.'steel') THEN
          CNU=STNU ()
       ELSE
          WRITE(6,1000) CMAT
          STOP
       ENDIF
       RETURN
1000   FORMAT (//,10X,' no Poisson's mod. data for the clad material ',
      &        A8,//)
       END
```

A.33. Function ZNNU

```
C>vver>
*-----------------------------------------------------------------------
C&N      function ZNNU
C&N
C&F      function : calculation of the Zr-1%Nb Poisson's modulus
C&F
C&V      input arguments :
C&V         TSOL ... solidus temperature (C)
C&V         TEMP .... temperature (C)
C&V
       FUNCTION ZNNU (TSOL,TEMP)
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
       DOUBLE PRECISION NUEMAX
       DATA NUEMAX /0.49D0/
C
       TEMPK = TEMP+273.15
       IF (TEMP.GE.TSOL) THEN
          ZNNU=NUEMAX
       ELSE
          ZNNU = 0.42628-5.556D-5*TEMPK
       ENDIF
       RETURN
       END
C<vver<
```

A.34. Function CDILAT

```
C&N     function CDILAT
C&F     function : calculation of the thermal expansion strain for clad material
C&F                The strain is 0. at 20. C
C&V     input arguments :
C&V        CMAT .... name of the material
C&V        TEMP .... temperature (Celsius)
C&V
      FUNCTION CDILAT (CMAT,TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*(*) CMAT
      IF (CMAT(1:4).EQ.'zirc') THEN
         CDILAT=ZDILAT (TEMP)
C>vver>
      ELSE IF (CMAT(1:5).EQ.'zr-nb') THEN
         CDILAT=ZNDILA (TEMP)
C<vver<
      ELSE IF (CMAT(1:4).EQ.'ZrO2') THEN
         CDILAT=Z2DILA ()
      ELSE IF (CMAT(1:5).EQ.'steel') THEN
         CDILAT=STDILA (TEMP)
      ELSE
         WRITE(6,1000) CMAT
         STOP
      ENDIF
      RETURN
1000  FORMAT (///,10X,' no dilatation data for the clad material ',A8,//)
      END
```

A.35. Function ZNDILA

```
C>vver>
C&N     function ZNDILA
C&F     function : calculation of the thermal expansion strain for Zr-1%Nb
C&F                The strain is 0. at 20. C
C&V     input arguments : TEMP .... temperature (Celsius)
C&V
      FUNCTION ZNDILA (TEMP)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)

      T=TEMP+273.15D0
      IF(T.LE.393.D0) THEN
         STR11=5.7D-6*(T-293.D0)
         STR33=5.3D-6*(T-293.D0)
      ELSE IF(T.LE.573.D0) THEN
         STR11=5.70D-4+5.9D-6*(T-393.D0)
         STR33=5.30D-4+5.4D-6*(T-393.D0)
      ELSE IF(T.LE.773.D0)THEN
         STR11=16.32D-4+6.3D-6*(T-573.D0)
         STR33=15.02D-4+5.5D-6*(T-573.D0)
      ELSE IF(T.LE.923.D0)THEN
         STR11=28.92D-4+6.8D-6*(T-773.D0)
         STR33=26.02D-4+5.6D-6*(T-773.D0)
      ELSE IF(T.LE.1153.D0)THEN
         STR11=-17.95D-2+0.0549D-2*T-5.4D-7*T**2+1.74D-10*T**3
         STR33=-17.28D-2+0.0533D-2*T-5.3D-7*T**2+1.72D-10*T**3
      ELSE
         STR11=-0.886D-2+9.7D-6*T
         STR33=-1.038D-2+9.7D-6*T
      ENDIF
      ZNDILA=(2.D0*STR11+STR33)/3.D0
      RETURN
      END
C<vver<
```

A.36. Subroutine FGEOM

```
C&N     subroutine FGEOM
C&N
C&F     function : initialization of the geometrical data.
...
      SUBROUTINE FGEOM (NSLM,NMESHM,IPDATA,
     M                  IPRVAL,IPGVAL,
     O                  NSLICE,NFM,NCM,NZRO2M,CCLAD,XZ,XRAD)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      CHARACTER*8 CGNAME,COPT,CCLAD,CTBGET
      DIMENSION XZ(NSLM+1),XRAD(NMESHM+2,NSLM)
C>vver>
      CHARACTER*8 CGAS,CHT,CPLENUM,FTYPE,CFOPT,CFAIL
      COMMON/VVERC/CGAS,CHT,CPLENUM,FTYPE,CFAIL
      COMMON/VVERR/EPSDOT(20,50),BSTRR,QCHFC1,QCHFC2,TWET
C<vver<
...
C>vver>
C     base strain rate
      IPGPR=ITBGET('CLAD',1,IPDATA)
      BSTRR=RTBGET('STRRATE ',1,IPGPR)
C
C     option for fuel type
      IPFUEL=ITBGET('FUEL',1,IPDATA)
      CFOPT=CTBGET('FUELTYPE',1,IPFUEL)
      FTYPE='pwr'
      IF ((CFOPT(1:3).EQ.'pwr').OR.(CFOPT(1:3).EQ.'PWR')) THEN
         FTYPE='pwr'
      ELSE IF ((CFOPT(1:4).EQ.'vver').OR.(CFOPT(1:4).EQ.'VVER')) THEN
         FTYPE='vver'
      ELSE
         WRITE(6,*)'WRONG FUEL TYPE'
         STOP
      ENDIF
C
C     option for clad failure model
      IPFAIL=ITBGET('CLAD',1,IPDATA)
      CFAIL=CTBGET('CFAIL',1,IPFAIL)
      IF(CFAIL(1:1).EQ.' ') CFAIL(1:2)='no'
C
C     option for heat transfer package
      IFLUID=ITBGET('FLUID',1,IPDATA)
      CHT=CTBGET('CHT',1,IFLUID)
      IF(CHT(1:1).EQ.' ') CHT(1:4)='cht0'
C
C     tuning factors for critical heat flux of 1st and 2nd types
      QCHFC1=RTBGET('QCHFC1',1,IFLUID)
      QCHFC2=RTBGET('QCHFC2',1,IFLUID)
      IF(QCHFC1.EQ.0.D0)QCHFC1=1.D0
      IF(QCHFC2.EQ.0.D0)QCHFC2=1.D0
C
C     time of rewetting
      TWET=RTBGET('TWET',1,IFLUID)
      IF(TWET.EQ.0.D0)TWET=1.D30
C
C     option for fission gas behavior calculation
      IPIL=ITBGET('PILOT',1,IPDATA)
      CGAS=CTBGET('CGAS',1,IPIL)
      IF (CGAS(1:1).EQ.'n'.OR.CGAS(1:1).EQ.'N') THEN
         CGAS='not'
      ELSE
         CGAS='yes'
      ENDIF
C
C     option for gas plenum model
      IPGAP=ITBGET('GAP',1,IPDATA)
      CPLENUM=CTBGET('CPLENUM ',1,IPGAP)
      IF(CPLENUM(1:1).EQ.' ') CPLENUM='S'
```

```
C<vver<
C clad :
C
C     clad material :
       IPC=ITBGET('CLAD',1,IPDATA)
       COPT=CTBGET('MATERIAL',1,IPC)
       IF ((COPT(1:4).EQ.'zirc').OR.(COPT(1:4).EQ.'ZIRC')) THEN
          CCLAD='zirc'
C>vver>
       ELSE IF ((COPT(1:5).EQ.'zr-nb').OR.(COPT(1:5).EQ.'ZR-NB')) THEN
          CCLAD='zr-nb'
c<vver<
...
       RETURN
       END
```

APPENDIX B. Sample input deck of the adopted SCANAIR/VVER version

```
--------------------------------------------------------------------------------
(nsl=1)(nzmesh=1)(nrmesh=20)(hz=150.)(energy=256./0.24)
STRUCTURE PILOT
   TM-COUPLING 'explicit'
   CRACKS 'yes'
   STICKING-OPTION 'noslip'
   PORO-EQ 'no'
   CGAS 'yes'
   T-END 10.
   SR1 TIME-STEP
      0.005  5.0
      0.010  10.0
   TERM
   SC1 STEADY-LIST
      'RADII'
   TERM
   SC1 TRANS-LIST
     'T&DT'     'ABSTRACT'   'FMASSES'   'FTEMP'    'CTEMP'   'S-TEMP'
     'FSTRESS'  'FTHSTR'     'FPLSTR'    'F-VM-EPS' 'FSWSTR'
     'CSTRESS'  'CTHSTR'     'CPLSTR'    'C-VM-EPS' 'F-VM-EPS'
   TERM
   STRUCTURE PRINT-TIMES
      EVERY 5
   END
END
$
STRUCTURE POWER
   ST-POWER 0.0
   INJECTED-ENERGY (energy)  TIME 580.
   SR1 TIME-LAW
       0.0    0.00E+00
...
    580.00    3.23E-04
   TERM
   PROFILES  'cab+tos'
END
$
STRUCTURE MESHING
   GEOMETRY 'tosura'
   STRUCTURE AX-SLICES
      U-SPLIT (nzmesh)
   END
   STRUCTURE F-MESHES
   END
   STRUCTURE C-MESHES
      CLAD-M 7
   END
END
$
STRUCTURE FUEL
   FUELTYPE 'VVER'
   RGRAIN    0.003       % mm %
   POROSITY 'porosity'   % ratio %
   PU-C      'Pu-c'      % ratio %
   BURN-UP   'burn-up'   % atom per-cent %
   STOECHIO  2.0
   GAS-C     'gas-c'     % mm3/g %
   INTER-OC  0.5         % ratio %
   DENSITY   'density'   % g/mm3 %
   RB-INTRA  10.         % Angstroems %
   RB-INTER  100.        % Angstroems %
   EOL-TEMP 'eol-temp'   % C %
   EOL-PRES  9.48        % MPa %
   DP-LIMIT  50.         % MPa %
   K-PERMEA  1.D+12      %  %
   PORO-PRE  1.7         % MPa %
   PORO-TEM  20.         % Celsius %
END
STRUCTURE GAP
```

```
   CPLENUM  'L'
   RUGOSITY 0.010                                  % mm %
   HE-C     1.0   FP-C 0.0   AIR-C 0.0            % molar fraction %
   N-GAS    82000.                                % mm3 %
   INNER-P  1.7                                   % MPa %
   L-PLENUM 0.    U-PLENUM 4500.                  % mm3 %
END
$
STRUCTURE CLAD
  MATERIAL 'zr-nb'
  STRRATE  2.D-3
  CFAIL    'yes'
  SR1 CYS
  20.     503.0506
...
  2000.     1.
  TERM
END
$
STRUCTURE FLUID
   CHT         'CHT1'
   FLUID-CALC 'no'
   FLUID-TYPE 'water'
   H-CLAD-FL  'yes'
   TIME        0.0     TFLUID      20.0
   TIME        580.0   TFLUID      20.0
   PFLUID      0.1
   QCHFC1      0.80D0   % W/m2 %
   QCHFC2      0.50D0   % W/m2 %
   TWET        4.5D0    % s    %
END
$
STRUCTURE WALL
   WALL-CALCULATION 'no'
   RADIUS    30.
END
$
$---------------------------- geometry (mm)
STRUCTURE GEOMETRY   NAME 'tosura'
   SR1 ELEV    0.000 (hz)    TERM
   SR2 FUEL-RAD  (nsl)  (nrmesh+1)
    1.20000 1.47957 1.69126 1.87900 2.04944 2.20665 2.35331 2.49129 2.62197 2.74641
2.86542
    2.97966 3.08966 3.19588 3.29868 3.39838 3.49526 3.58953 3.68144 3.77117 3.79000
   TERM
   SR2 CLAD-RAD   (nsl)   2   % gap (um)      %
    3.82000 4.57500           %  30.00        %
   TERM
END
$
$---------------------------- porosity
STRUCTURE FIELD   NAME 'porosity'  TYPE 'RZ'   % volumic ratio %
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'no'
   SR2 VALUES           (nsl) (nrmesh)
    2.94550D-02 2.94550D-02 2.94540D-02 2.94540D-02 2.94520D-02 2.94490D-02 2.94460D-02
    2.94420D-02 2.94390D-02 2.94350D-02 2.94320D-02 2.94290D-02 2.94260D-02 2.94250D-02
    2.94230D-02 2.94210D-02 2.94190D-02 2.99990D-02 2.99920D-02 2.99880D-02
   TERM
END
$
$---------------------------- Pu concentration
STRUCTURE FIELD   NAME 'Pu-c'  TYPE 'RZ'
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'no'
   SR2 VALUES           (nsl) (nrmesh)
       1.11487D-02 1.11617D-02 1.11787D-02 1.12007D-02 1.12035D-02 1.11889D-02 1.11856D-02
       1.11974D-02 1.12296D-02 1.12898D-02 1.13892D-02 1.15449D-02 1.16891D-02 1.18565D-02
       1.22075D-02 1.28709D-02 1.41226D-02 1.54295D-02 1.80717D-02 2.16568D-02
   TERM
END
$
$---------------------------- burn-up (at%)
STRUCTURE FIELD   NAME 'burn-up'  TYPE 'RZ'
```

```
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'no'
   SR2 VALUES           (nsl) (nrmesh)
        5.0959  5.0959  5.0958  5.0958  5.1130  5.1474  5.1818  5.2162  5.2505  5.2847
        5.3189  5.3529  5.4330  5.5593  5.6850  5.8100  5.9336  6.4715  7.4199 10.5796
   TERM
END
$
$--------------------------- density (g/mm3)
STRUCTURE FIELD   NAME 'density'  TYPE 'RZ'
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'yes'
   SR2 VALUES           (nsl) (nrmesh)
    1.01352D-02 1.01564D-02 1.01708D-02 1.01817D-02 1.01888D-02 1.01939D-02 1.01986D-02
    1.02025D-02 1.02049D-02 1.02076D-02 1.02095D-02 1.02113D-02 1.02109D-02 1.02111D-02
    1.02102D-02 1.02078D-02 1.02073D-02 1.02013D-02 1.01945D-02 1.01704D-02
   TERM
END
$
$--------------------------- gas concentration (mm3 TPN/g)
STRUCTURE FIELD   NAME 'gas-c'  TYPE 'RZ'
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'yes'
   SR2 VALUES           (nsl) (nrmesh)
    1.30502D+03 1.30501D+03 1.30500D+03 1.30499D+03 1.30935D+03 1.31809D+03 1.32682D+03
    1.33554D+03 1.34424D+03 1.35292D+03 1.36157D+03 1.37019D+03 1.39050D+03 1.42245D+03
    1.45425D+03 1.48582D+03 1.51703D+03 1.65219D+03 1.88760D+03 2.59464D+03
   TERM
END
$
$--------------------------- fuel temperatures at the end of irradiation (Celsius)
STRUCTURE FIELD   NAME 'eol-temp'  TYPE 'RZ'
   GEOMETRY 'tosura'   INTERPOL 'linear' NORM 'no'
   SR2 VALUES           (nsl) (nrmesh)
        840.05  829.74  816.18  800.56  783.51 765.41  746.50  726.94  706.84  686.30
        665.35  644.05  622.36  600.20  577.52 554.27  530.39  505.09  477.32  441.74
   TERM
END
$
$--------------------------- axial and radial power profiles
STRUCTURE PROFILES   NAME 'cab+tos'
   XP-TYPE 'law'
   SR1 AX-PROF
    0000D+00    1.D+0
    (hz)        1.D+0
   TERM
   GEOMETRY 'tosura'
   SR2 RAD-PROF           (nsl) (nrmesh+1)
       0.83553 0.83553 0.83553 0.83553 0.83877 0.84525 0.85173 0.85821 0.86468 0.87116
       0.87764 0.88412 0.90385 0.93683 0.96981 1.00279 1.03578 1.17907 1.43268 2.30548
       2.30548
   TERM
END
END
```

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(See instructions on the reverse)

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11. ABSTRACT *(200 words or less)*

The IPSN's transient fuel rod code SCANAIR, has been modified to analyze pulse tests with high-burnup VVER fuel rods in the Impulse Graphite Reactor (IGR). New and modified models of separate phenomena have been developed, including models for gas plenum temperature, heat transfer from the cladding to the stagnant coolant, the effect of the cladding strain rate on the yield stress, and interruption of the cladding mechanical calculation. Thermal and mechanical properties for the VVER's fuel and Zr-1%Nb cladding were added to the SCANAIR data base on material properties. Changes in the input data file are described, and a sample calculation is presented with the modified code. A FORTRAN listing for the new and modified models is given in an Appendix A.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*
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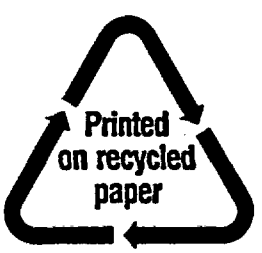

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