CNEA-NT 19/81

REPUBLICA ARGENTINA
COMISION NACIONAL DE ENERGIA ATOMICA
Dependiente de la Presidencia de la Nación
GERENCIA DE DESARROLLO

"COMPUTATIONAL EXPERIENCE" SHOWING THE INFLUENCE OF THE FUEL-TO-SHEATH THERMAL CONDUCTANCE, IN REACTOR FUEL TEMPERATURE PREDICTIONS

Carlos A. Baigorria (*)
Santiago Harriague (**)
Klaus Lassmann (***)

BUENOS AIRES
1981

(*) Departamento Combustibles Nucleares - Gerencia de Desarrollo
(**) Departamento Materiales - Gerencia de Desarrollo
(***) Kernforschungszentrum Karlsruhe - Rep. Federal de Alemania

R E S U M E N

Mediante el empleo del Código de Combustibles BACO[1] se ha investigado la influencia que diferentes modelos de conductancia térmica Combustible-Vaina, ejercen en la predicción de las temperaturas del Combustible.

Se han utilizado cuatro modelos diferentes en la simulación del comportamiento termo-mecánico de un elemento combustible tipo Atucha, bajo un determinado ciclo de potencia.

"COMPUTATIONAL EXPERIENCE" SHOWING THE INFLUENCE OF THE FUEL-TO-SHEATH THERMAL CONDUCTANCE, IN REACTOR FUEL TEMPERATURE PREDICTIONS.

Carlos Baigorria* Santiago Harriague* Klaus Lassmann**

ABSTRACT

Through the BACO[1] code, the influence of the pellet-sheath gap thermal conductance models on temperature predictions has been investigated. Four different models have been used for simulating the thermo-mechanical behavior of a reactor fuel element.

NOMENCLATURE

d : radial gap. (cm)

h : fuel-to-sheat heat transfer coefficient or gap thermal conductance. (Watt/cm^2 °K)

k_m : thermal conductivity of the filling gas in the gap. (Watt/cm °K)

$\bar{k}$: $\frac{2 k_f \cdot k_s}{k_f + k_s}$, where k_f : thermal conductivity of the fuel

k_s : thermal conductivity of the sheat

(Watt/cm °K)

R_s, R_f : Roughness of sheath and fuel inner surfaces (mean values). (cm)

R : root mean square of the fuel and sheath roughness. (cm)

H : Sheath Meyer hardness. (MPa)

g : Sum of the temperatures jump distances of sheath and fuel. (cm)

P : contact pressure. (MPa)

* Comisión Nacional de Energía Atómica - Argentina.

** Kernforschungszentrum Karlsruhe - Germany.

h_{fg} : thermal conductance of the fuel-gas interfase. (Watt/mm^2 °K)

h_{sg} : thermal conductance of the sheath-gas interfase. (Watt/mm^2 °K)

h_g : thermal conductance of the filling gas in the gap. (Watt/mm^2 °K)

B : Burnup (MWd/MtU)

INTRODUCTION

One of the co-autors, Lassmann[2], in a recent publication has proposed a new model for the fuel-to-sheath heat transfer coefficient. Also, in that paper, current models are critically reviewed with more than 388 experimental results.

The above mentioned model, used in the URANUS[10] code, has been incorporated to the BACO code which admits, alternatively, the use of different models.

In the present work, the computational experience consists in four runs of the code, simulating the thermo-mechanical behavior of a fuel element of a reactor of the type HWPR, for a determined power cycle; each run was performed with a different model for the mentioned coefficient in order to discern the influence that this coefficient has in fuel-sheath temperature predictions.

Gap conductance models are described in section 1. Results are showed and commented in section 2.

The general input data for the runs are showed in Table I and the power cycle in Table II.

1. Description of the gap conductance models.

The following models have been selected for the comparative study:

a) Ross-Stoute[3] (with modifications due to Godesar[4] - Tobbe[5] and Kaiser[6]

b) Campbell et al[4]

c) Lassmann[2]

d) Broughton - McDonnald[8]

The Ross-Stoute model

The heat transfer coefficient within the model generally known as Ross-Stoute model is:

$$h = h_f + h_s \qquad (1)$$

where $h_f = \dfrac{k_m}{2{,}5\ (R_s+R_f) + g + d}$ is the heat transfer coefficient corresponding to the conduction through the gas filling the gap

and $h_s = \dfrac{\bar{k}\ P}{0{,}5\ R^{1/2}\ H}$ is that corresponding to the conduction through the solid-solid contact spots.(*)

In the present paper k_m and g are calculated according to Godesar - Tobbe and Kaiser (Appendix 1).

The Campbell model

This model is based in the Ross-Stoute model, with some modifications introduced in order to fit in reactor measurements.

(*) In the present work radiation terms are neglected.

Within this model the coefficient is:

$$h = \frac{k_m}{1.5\ (R_f + R_c) + g + d} + \frac{\bar{k}\ p^{1/2}}{8{,}6\ .\ 10^{-2}\ R^{1/2}\ H}$$

The Lassmann model.

This model is extensively explained in Ref.2. Within it the first term of equation (1) is obtained from:

$$1/h_f = 1/h_{fg} + 1/h_{sg} + 1/h_g$$

where

$$h_{ig} = \frac{k_m\ (1 + 115\ R_i)}{2{,}55\ R_i} \left(\frac{\text{Watts}}{\text{mm}\ ^\circ\text{K}}\right) \quad i = s,\ f$$

$$h_g = \frac{k_m}{g + d} \left(\frac{\text{Watts}}{\text{mm}\ ^\circ\text{K}}\right)$$

The second term arises from the following correlation:

$$\frac{h_s}{\bar{k}\ R} = 0.312 \left(\frac{P}{R^2\ H}\right)^{0.7} \qquad h_s \text{ in } \left(\frac{W}{\text{mm}\ ^\circ\text{K}}\right)$$

k_m and g are given according to Godesar-Tobbe and Kaiser, (Appendix 1).

The Broughton - McDonnald model[8]

This model considers fuel-sheath geometries ranging from an open gap with partial contact zones to a closed gap with strong contact. The size of the contact zone depends of the burnup.

For zero contact pressure, the thermal conductance is

given by:

$$h = (1 - F)\, h_f + F\, h_s \qquad (6)$$

where

$$h_f = \frac{k_m}{d + R}$$

k_m : as determined by Brokaw[9] and Dean[11], Appendix 1.

$$h_s = \frac{k_m}{R}$$

The fraction of pellet circumference in contact with the cladding, F, is assumed to be an inverse power low function of the ratio between the radial gap and the pellet radio.

$$F = \frac{1}{a \left(\frac{100\ d}{r}\right)^b + 1{,}429} + 0{,}3 \qquad (7)$$

where

r : pellet radio

a : 100 - 98 F'

b : 4 - 0,5 F'

with $$F' = 1 - \frac{1}{\left(\frac{B - 600}{1000}\right)^4 + 1}$$

When the fuel and sheath are in strong contact (contact pressure larger than zero), the conductance is given by:

$$h_s \left(\frac{W}{cm^2 °K}\right) = C\, P^n + \frac{k_m}{R}$$

where $C = 5 \times 10^{-2}$ and

$n = 1$ for $0 \leqslant P \leqslant 6,8$ MPa

and $n = 1/2$ for $P > 6,8$ MPa

RESULTS

By using the general input data of Table I and the power history of Table II, four runs of the BACO code have been performed, each one with a different model for the gap thermal conductance described in section 1. The results of interest from the point of view of BACO temperature predictions are shown in Figs.1 to 4.

The label in each curve means: 1) Run with Ross-Stoute 2) with Lassmann, 3) with Campbell and 4) with Broughton - McDonald models.

In figure 1 the gap width and the contact pressure are plotted. For the cycle described in Table 1 which has a sudden power increment after 50 days of irradiation, the four models predict the pellet-sheat contact to occur at the second power ramp. A slight larger gap is predicted by the model 4.

In Fig.2 the gap conductances are plotted. Until 50 days approximately the models 1 to 3 show no differences and the model 4 predicts higher values when the gap is open due to the assumption of the pellet fraction to be in soft contact (zero contact pressure) with the sheath.

From 50 days up the four thermal conductances increase quickly because of the sharp increment in the contact pressure.

The later decrease is due principally to the release of fission gases into the gap. Despite the increment in gas density as the irradiation evolves, fission products normally reduce

the thermal conductivity.

The fuel central temperatures are shown in Fig. 3. Before the contact time, a difference of about 300°K exists between the values predicted by using the model 4 and those predicted by using the other three.

After the contact a difference of less than 150°K exists between the four predictions. That is, when the pellet and sheath are in contact a difference of approximately 60% in the thermal conductance values produces a difference less than a 10% in the calculated values for the fuel central temperature.

In Fig. 4 the calculated inner sheat and fuel surfaces temperatures are shown.

As expected, the sheat surface temperature does not depend of the gap conductance.

In addition, at the fuel surface a difference of less than 100°K between the predictions resulting for different models of the gap conductance is obtained; this value amounts to about 15% of the fuel temperature values.

By the end of the power cycle the differences in predictions are less than 5% of the temperature values.

CONCLUSIONS

The BACO code has been used for simulating the thermal-mechanical behavior of a fuel element of a HWPR under a given power cycle.

Four models of fuel-to-sheath conductances have been used for differents runs of the code in order to compare the thermal predictions.

For the cycle proposed we have found that different models lead to no important differences in fuel temperatures.

Then, we concluded that stablishing trustable models for the fuel-to-sheat thermal conductance could be relevant for predicting fuel temperatures for high burnup elements or during transients, but not for fuel pins under normal operating conditions.

REFERENCES

1) S. Harriague, G. Coroli y E. Savino: BACO (Barra combustible), a computer code for simulating a reactor fuel rod performance. Nuclear Engineering and Design, 56, (1980).

2) K. Lassmann: Zum Wärmedurchgang im Bereich zwischen Hülle und Brennstoff eines Brennstabes. Warme - und Stoffübertragung, 12, (1979), 185-202.

3) A.M. Ross and R.L. Stoute: Heat transfer coefficient between UO_2 and Zircaloy-2. AECL-1552 (1962).

4) R. Godesar: Untersuchungen des Einflusses des Wärmeübergangskoeffizienten im Spalt zwischen Brennstoff und Hülle auf die sicherheitstechnischeAuslegung von stabförmigen Brennstäben für Schnelle Brutreaktoren. Diss. TH Aachen (1972).

5) H. Többe: Das Brennstabrechenprogramm IAMBUS zur Auslegung von Schnellbrüter-Brenn-stäben. Interatom, Technischer Bericht, ITB 75.65 (1975).

6) K. Kaiser: Untersuchungen zum Wärmedurchgang im Spalt zwischen Hülle und Brennstoff eines Brennstabs. Diplomarbeit im Fachgebiet Reaktortechnik, TH Darmstadt (1978).

7) F.R. Campbell, L.R. Bourque, R. Deshaies, H. Sills and M.J.F. Notley: In - reactor measurement of fuel-to-sheath heat transfer coefficients between UO_2 and stainless steel. AECL 5400 (1977).

8) J.M. Broughton and P.E. MacDonald: MATPRO, Version 09, Appendix C (1976).

9) R.S. Brokaw: Alignment charts for transport properties, viscosity, thermal conductivity and diffusion coefficients for nonpolar gases and gas mixtures at low density. Lewis Research Center, NASA-TR-R-81 (1960).

10) K. Lassmann: Uranus - A computer programme for the thermal and mechanical analysis of the fuel-rods. Nuclear Eng. Design, 45, (1978), 325-342.

11) R.A. Dean: Thermal contact conductance between UO_2 and Zircaloy-2. Westinghouse Electric Co., CVNA-127, (1962).

A P P E N D I X 1

MODELS FOR THERMAL CONDUCTIVITY OF GAS MIXTURES AND FOR EXTRAPOLATION LENGTH

a) Godesar-Tobbe-Kaiser

Thermal conductivity

$$k_m = \sum_i \frac{k_i}{1 + \sum_{j \neq i} B_{ij} \, c_j / c_i} \qquad (1)$$

where k_i : thermal conductivity of gas i

c_i : mole fraction of gas i

$$B_{ij} = \left\{ 1 + \left[\frac{u_i}{u_j} \left(\frac{M_j}{M_i} \right)^{3/4} \frac{(T+S_i)}{(T+S_j)} \right]^{1/2} \right\}^2 \cdot \left(\frac{(T + S_i S_j)}{(T + S_i)} \right)$$

$$u_i / u_j = \frac{k_i \, c_{pj} \, (9 - 5 \, c_{vj}/c_{pj})}{k_j \, c_{pi} \, (9 - 5 \, c_{vi}/c_{pi})}$$

u_i : gas viscosity of gas i

c_{pi}; c_{vi} : specific heats at constant pressure and at constant volume respectively of gas i

M_i : molecular weight of gas i

S_i : Sutherland constant of gas i

T : temperature (°K)

Extrapolation length or temperature jump distance

$$g = 1{,}875 \frac{(2 - 0{,}827\ a)}{a} \cdot 1$$

where

a : average accomodation factor

1 : average mean free path

$$a = \frac{\sum_i \frac{c_i a_i}{M_i}}{\sum_i \frac{c_i}{M_i}}$$

$$1 = \frac{1_o\ (273 + S)}{P_g\ (T + S)} \cdot \frac{T}{273}$$

a : accomodation factor of gas i

$1_o = \sum_i c_i\ 1_{oi}$: average mean free path at 273°K and 0.1 MPa.

1_{oi} : mean path of gas i

P_g : gas pressure (bar)

$S = \sum_i c_i\ S_i$: average Sutherland constant

b) Brokaw - Dean

Thermal conductivity

The relationship for calculating the thermal conductivity is given by equation (1) in a), with the B_{ij}^* as :

$$B_{ij} = A_{ij}\left[1 + 2{,}41\,\frac{(M_i - M_j)(M_i - 0{,}142\,M_j)}{(M_i + M_j)^2}\right]$$

where

$$A_{ij} = \frac{\left[1 + (k_i/k_j)^{1/2}\,(M_i/M_j)^{1/4}\right]^2}{2{,}83\,(1 + M_i/M_j)^{1/2}}$$

For very diluite gases, that is, when the ratio of the mean free path to the characteristic dimension of the gap exceeds about 0,01, the thermal conductivity of the light gases should be divided by the factor (Dean[11]).

$$f = 1 + 0{,}002103\,\frac{k_i\sqrt{T}}{P\,R}$$

where all the symbols have the previous meaning.

Table I

General input data

Fuel inner radius	: compact
Fuel outer radius	: 0,531 cm
Sheath inner radius	: 0,540 cm
Sheath outer radius	: 0,595 cm
Active length	: 530 cm
Sheath material	: stress-relieved Zry-4
Fuel material	: UO_2 (Staichometric natural)
Fuel density	: 95% TD
Coolant pressure	: 12 MPa
Outer sheath temperature	: 578°K (constant during calculations)
Filling gas composition	: He
Filling gas initial pressure	: 1.7 MPa at room temperature
Fuel surface roughness	: 2μm
Sheath inner surface roughness	: o,7μm

Table II

Power Cycle

	Initial time (d)	Final time (d)	Linear power (w/cm)	Accumulated final burnup (Mwd/MtU)
Power up ramp	0	0.5	0 to 300	25
Constant linear power	0.5	50	300	2500
Power up ramp	50	50.5	300 to 500	2524
Constant linear power	50.5	150	500	7000

FIGURE CAPTIONS

Figure 1: Gap width and contact pressure as function of the irradiation time.

Figure 2: Fuel-to-sheath thermal conductance as function of the irradiation time.

Figure 3: Fuel central temperature as function of the irradiation time.

Figure 4: Surface fuel and inner sheath temperature as function of the irradiation time.

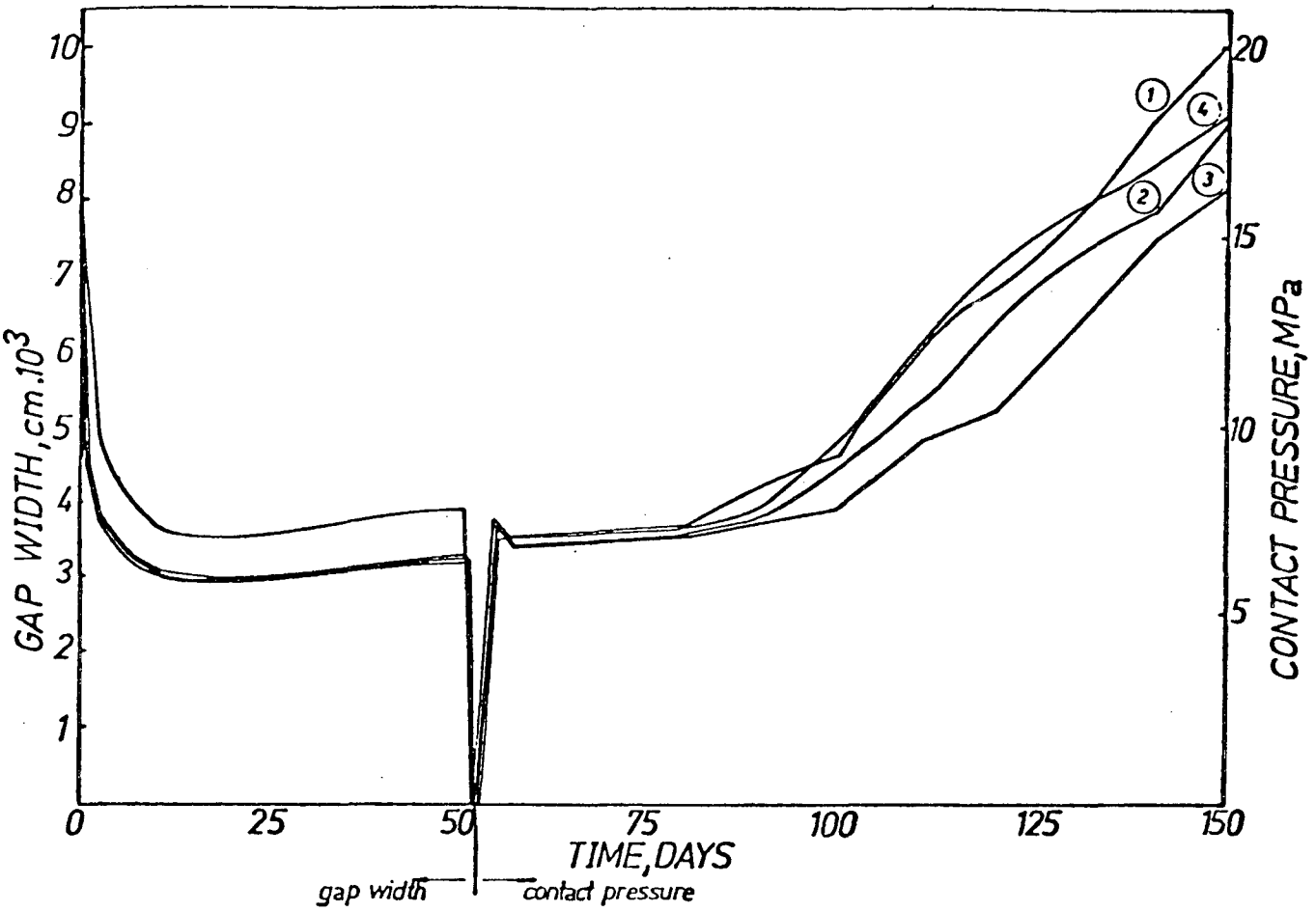
GAP WIDTH, cm.10³
CONTACT PRESSURE, MPa
TIME, DAYS
gap width
contact pressure
1
2
3
4

Fig. 1

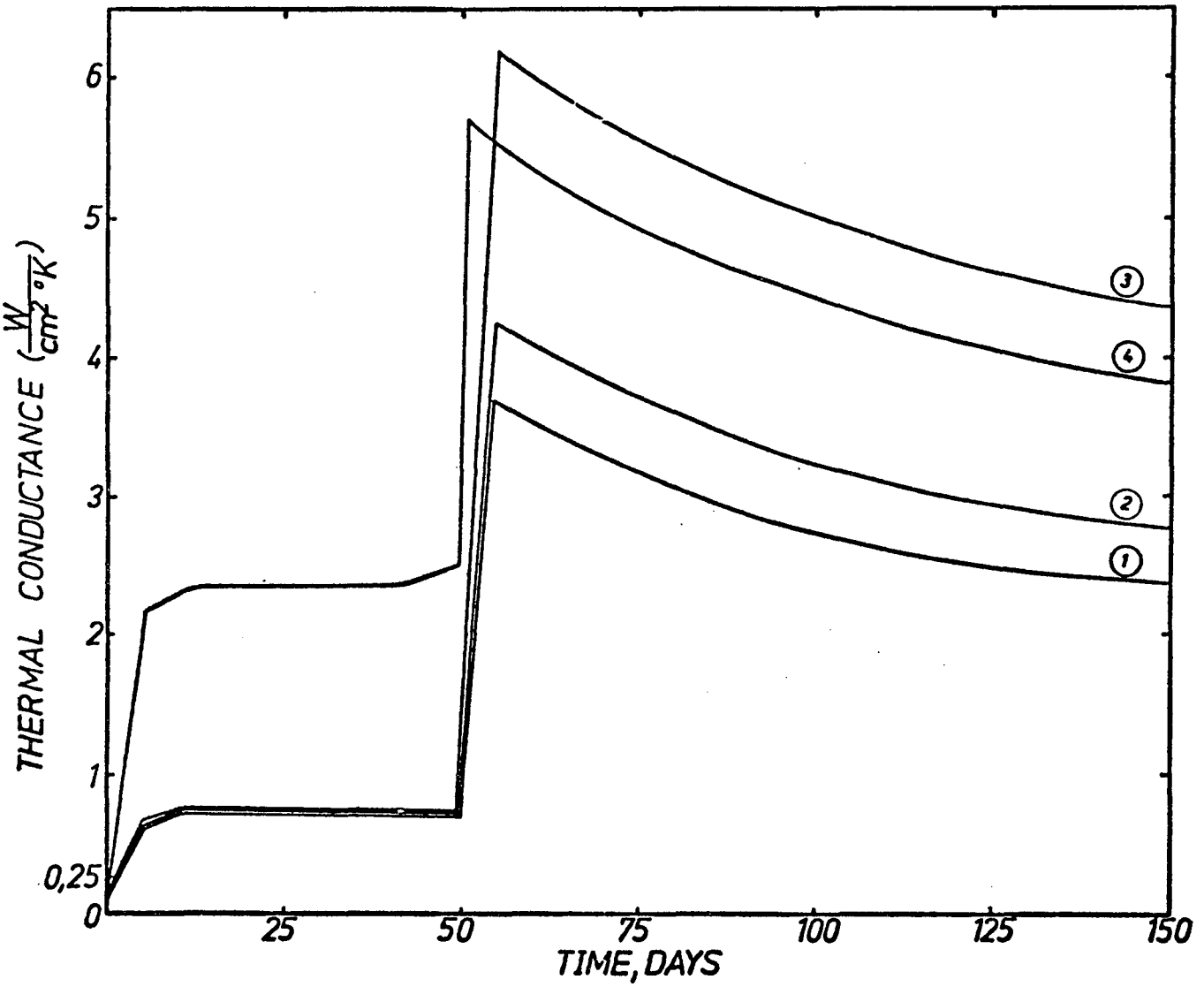
THERMAL CONDUCTANCE ($\frac{W}{cm^2 \cdot °K}$)
6
5
4
3
2
1
0,25
0
25
50
75
100
125
150
TIME, DAYS
①
②
③
④

Fig.2

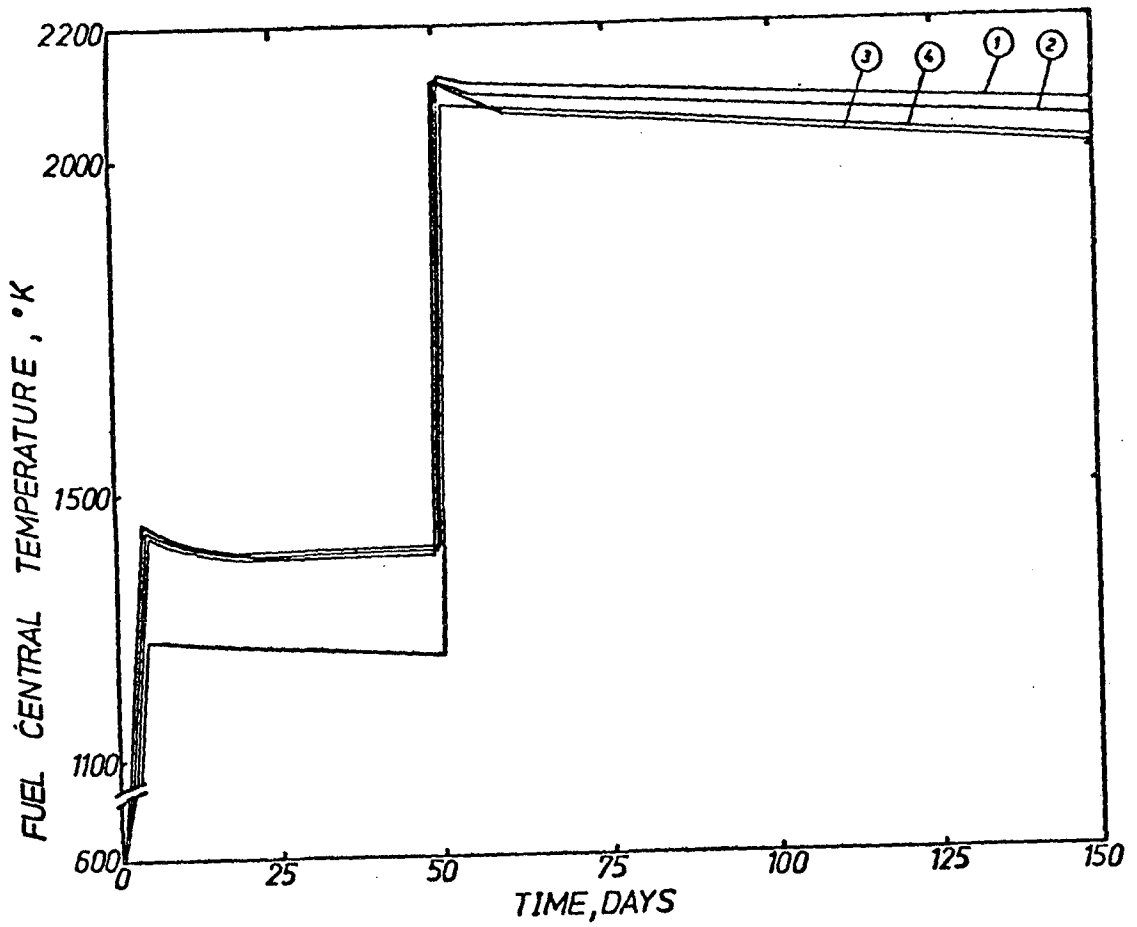
2200
2000
1500
1100
600
FUEL CENTRAL TEMPERATURE, °K
0
25
50
75
100
125
150
TIME, DAYS
3
4
1
2

Fig.3

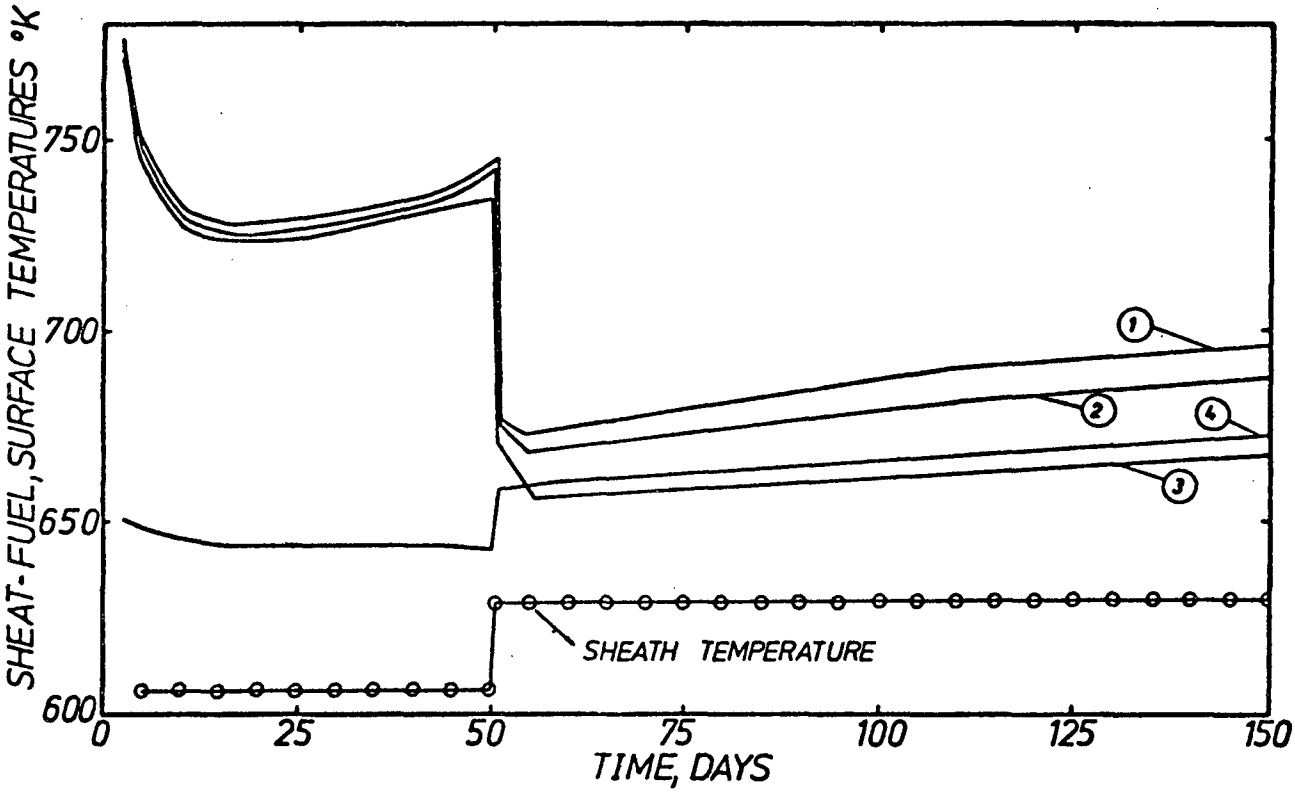
SHEAT-FUEL, SURFACE TEMPERATURES °K
750
700
650
600
0
25
50
75
100
125
150
TIME, DAYS
1
2
3
4
SHEATH TEMPERATURE

Fig.4