SSC "A.A.BOCHVAR ALL-RUSSIA SCIENTIFIC RESEARCH INSTITUTE
OF INORGANIC MATERIALS"

ВНИИНМ

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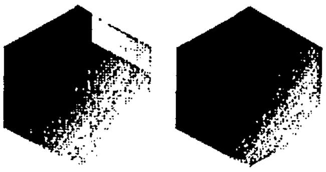
RELATION OF FUEL ROD SERVICE PARAMETERS AND DESIGN REQUIREMENTS TO PRODUCED FUEL ROD AND THEIR COMPONENTS



The Lecture Presented at the IAEA Training Courses
Bratislava
1999

1. SELECTION OF MAIN DESIGN PARAMETERS OF FUEL ROD

In the development of the fuel design and the requirements for it in the commercial production and the requirements for it's service conditions three main aspects of this problem are under consideration:

- To provide the reliable operation of fuel rod in a core during the required life-time taking account of all the design service conditions. In this case in the process of operation the updated level (for the practice all over the world) of the fuel service reliability must not be exceeded, specifically ~1,5 - $2 \cdot 10^{-5}$ failures.
- To maintain the fuel condition and the intensity of the in-fuel process in MDBA within the limits acceptable for the elimination and localization of accident effects using the available design solutions.
- The commercial feasibility of a chosen design or technological solution with the provision of an automated and comparatively inexpensive production of fuels and their components including the whole complex of control operations required for the output of high quality products having the needed characteristics.

Selection of compensation volume and initial He pressure in cladding. At the initial stage of operation prior to the rigid fuel clad contact the major load on a clad develops through a drop between the external coolant pressure and the pressure of the gas mixture (He, Kr, Xe) within the clad. The main fuel rod design parameter defining a change of this drop in a fuel cycle is the ratio between the fuel volume and the free volume for gases. This parameter is chosen on condition that by the end of the fuel cycle the gas pressure within the fuel clad should not exceed the external pressure of the coolant. This design solution ensures the fuel operation under stady-state conditions without any membrane tensile stresses developing in clads during the whole fuel life. In WWER-1000 fuel rods the volume to compensate the gas pressure consists of the free volume at the fuel rod top, the central hole in the fuel pellets, the core-clad gap, the fuel pellet porosity, the volume of the fuel pellet chamfers (fig. 1 and 2).

The requirement for the **allowable discontinuities between pellets** in a fuel column is important for fuel performance. When developing WWER-1000 fuels special experimental work was carried out using precision manufactured mock-up fuels.

The experiments were performed in the MIR reactor. They showed that in zones 15-20 mm long adjacent to the discontinuities in a fuel column a power density flash-up is observed both directly in a fuel rod with a discontinuity in the column and in the surrounding fuels (see fig. 3).The maximum flash-up amount grows with the discontinuity and is 1,3 for the discontinuity 16 mm (fig. 4).

Based on the reactor and post-irradiation examinations it is clear that discontinuities up to 16 mm did not penalize the fuel serviceability: no local clad strains at discontinuity sites, appreciable oxidation, hydrogen pick-up by Zr+1%Nb or its structural changes were revealed. However, with this discontinuity amount the fuel condition in MDBA is impaired – the temperature of a clad, the extent of its oxidation and embrittlement are increased because of the higher heat accumulation in the pellets in the discontinuities areas. Therefore, the amount of tolerable single gap (3 mm) and sums of gaps in a fuel column (8 mm) in WWER fuels were established. In this case of course account was taken of the possible appearance of additional discontinuities in a fuel column because of the re-sintering (axial shrinkage) of pellets during the initial period of operation.

The requirements placed on the design of commercially produced fuel rods as a whole and of the components (cladding, core) are worked out based on the analysis of service conditions and studies of the processes that determine the fuel rod serviceability. Account is also taken of cost effectiveness. Some requirements are established based on from the neutron physics and hydrodynamics of the reactor core.

To determine the requirements for the design of fuel rods and their components, the plans of control and the tolerable level of final product defectiveness, the initial fuel rod and component parameters are conventionally divided into three groups.

The 1-st group - most important or critical parameters of fuels, i.e., the ones that marginally affect the fuel serviceability. The non-conformity with the requirements for these parameters can be a cause of a premature fuel failure and in case of MDBA can give rise to damages that are beyond the allowable criteria that are used to estimate the safety of NPP.

The 1-st group covers the following parameters of a fuel rod and its components:

- fuel pellet contents of hydrogen, moisture, fluorine, chlorine, carbon, nitrogen;
- fuel density;
- fuel stoichiometry;
- fuel pellet outer diameter and cladding geometry;

- defects of clad and fabricated fuel rod;
- fuel leak-tightness;
- quality of welds;
- hydride orientation in clads;
- helium pressure in a fabricated fuel rod;
- fluorine contamination of inner clad surface;
- fuel column continuity;
- filler gas composition.

For the 1-st group parameters either 100% control (cladding defects, leak-tightness, fuel column continuity, quality of welds, cladding geometry) or a statistical one with the minimum level of defectiveness is selected based on the results of the output of commercial pellet batches and taking account of the importance (criticality) of a parameter. After a thorough examination of final products the control of individual fuel parameters may be rejected if they are reliably ensured in the process a commercial production.

The 2-nd group of the parameters of a fuel rod and its components usually comprises such parameters the departure from which can initiate some degradation in the technical and economical characteristics of NPP, or the possible departure of these parameters from the requirements established by the standard technical specifications can be assessed with an adequate assurance by the design and experimental investigations.

The following parameters are placed into the *2-nd group*:

- structure and properties of a cladding material, including anisotropy of properties, it's corrosion resistance;
- irradiation-induced sintering of fuel;
- microstructure of fuel
- ovality of claddings;
- fuel enrichment;
- total boron equivalent;
- pellet height;
- pellet appearance;
- mass of fuel in a rod;
- fluorine at an outer fuel rod surface.

For the 2-nd group it is recommended either to employ a statistical control or to ensure their values and tolerable departures by the process. The control of the pellet appearance is usually an exception: it is 100% due to the relatively high brittleness of sintered uranium dioxide. The choice of the allowable pellet appearance specimens is made taking account of the following factors:

- the requisite provision of the uniform fuel mass over its length per a fuel rod length unit;
- the possibility of automated methods to control the pellet appearance;
- a reduced fuel amount due to pellet chipping must not result in impermissible local power density flash-ups over a fuel rod length. In this case a conservative approach must be realized that envisages the possible direct "adjacency" of a chipped pellet and an axial gap in a fuel column;
- the requisite provision of the required margin to fuel melt-down.

All the other initial fuel parameters must be placed into the *3-d group.* The parameters of this group are established by technology or the statistical control.

Let's consider the influence of individual most important parameters of a fuel rod and its components on the serviceability.

The local hydrogenation of the clad. It is rather well known and verified by the Russian and foreign experience that one of the causes of a premature loss of the fuel tightness can be the local hydrogenation of the inner clad surfaces accompanied by a quick propagation of penetrating cracks. This takes place as a result of the action of residual and sorbed moisture and hydrogen also including hydrocarbons available in the fuel and in the internal fuel volume. Among the ways of preventing the fuel damage effected by this cause the major one is to limit moisture and hydrogen contained by the fuel core and the filler gas. Therefore the compliance with the requirements for these parameters is obligatory. The lower ultimate density limit established at 10·4 g/cm^3 for the WWER-1000 fuel made it possible to keep it with assurance in the fabrication process within 10.5-10.6 g/cm^3. This allowed the total moisture content in a fuel core to be as a rule within 0.0003-0.0004 mass.%. As a result, the probability of the commercial fuel rupture due to the local hydrogen uptake has been reduced to zero. Higher fluorine and chlorine contents in fuel can be a cause of the lower protective properties of an oxide film on the inner clad surface due to an oxyhalogen formation. With a loss of the protective properties by an oxide film the probability of local hydrogen pick-up and stress corrosion sharply increases. The aggregate contents of fluorine and chlorine equal 0,003 mass.% makes it impossible to realize during the operation this mechanism of the local cladding hydrogen pick-up. Physical and chemical properties of pellets for WWER-1000 reactor are given in the Table 1.

Cladding defects play a major role in crack nucleation and propagation. Therefore, the tolerable amount of a manufacturing defect must be minimized. For its estimation it is necessary to take a compromise solution taking account, on the one hand, of the potentialities of a commercial minimum cost tube production and, on the other, the performance and life-time of a fuel rod. Currently in Russia and other countries the amount of a tolerable defect in cladding tubes of fuels is specified to be not more than 30-35 m. This amount provides for a relatively inexpensive tube production at a rather high output of sound products. To assess the influence of such a defect on the fuel serviceability one should take into account that its evolution into a crack and further penetration occur if in a fuel clad there are tensile stresses that can arise under transient conditions or at adequately high burn-ups ~45-50 MW.day/kgU and higher due or a swelling core. Moreover in some quick transients the level of tensile stresses can be much more than those effected by a swelling core. When the action exerted by a core on a cladding is slow the stresses have time to relax through the creep of fuel and cladding. Therefore, the evolution of a manufacturing defect into a crack and its further penetration take place chiefly during transients.

Investigations of the process of a tube rupture showed that the crack evolution proceeds in a drastically non-linear mode. The slow propagation at the stage of the initial growth of a nucleated crack is replaced an avalanchelike rupture process. This fact is also confirmed by the investigations of the corrosion cracking process by the acoustic emission method. The dynamics of a crack propagation in a smooth clad and in a clad with an initial crack 50μm deep calculated by the START-3 is shown in fig. 5.

It can be seen that the critical crack depth beyond which its accelerated propagation starts is ~60μm. Investigation results of technological defect influence to cladding stability is given in
fig. 6.

One more circumstance of importance should be also discussed. Special experiments using active species ^{131}I and ^{137}Cs showed that under isothermal conditions primarily iodine accumulates in a defect at the inner clad surface: up to ~95% of iodine evolved upon the γ-radiolysis concentrates in a defect (fig.7). With tensile stresses available this results in an accelerated rupture of clads. So the level of the tensile stresses should be limited. This can be done by setting the limits of the allowed speed of the reactor facility power increase defined by the operational specification.

The same experiments revealed that even under condition of a relatively low temperature gradient (~30-40^{0}C) iodide and cesium accumulate at a lower temperature site (fig. 8). This should be taken into account during the defining of both the allowable value for the technological defect and established value of singular gap between pellets.

Taking into account all above mentioned factors affecting the crack evolution over SCC mechanism it was defined in the technical specifications that the maximum allowed technological defect for the fuel rod cladding alloy E110 should not exceed 35 μm.

2. STRUCTURAL PARAMETERS OF FUEL PELLET

The fuel pellet structure influences complexly on a fuel rod performance and consequently its optimum parameters should be defined on the basis of the analysis of various processes inside a fuel rod. Here thermophysical as well as thermomechanical aspects of fuel rod behavior are equally important (table 2).

Experiments and calculations show that the level of gas release is increased with burn-up extension (fig. 9).

An increase of gas release at transition to fuel cycles with extended burn-up should be compensated at the expense of further improvement of fuel.

2.1. Open porosity

The optimum pellet microstructure should provide a minimum open porosity. Open porosity is harmful for technology (adsorption of gases, moisture) and promotes increased gas release, as it is visible in fig.10. The requirements to this parameter become more and more rigid: from "unlimited" for early types of fuel, to < 1 % now and to < 0.5 % in the nearest future (table 3).

2.2. Grain size

Grain size of a sintered pellet directly influence on fission gas release as it's shown in fig. 11.At early stages of fuel production this parameters was not specially limited, however practically the grain size was rather small: 7 -8 μm

The current fuel has a grain of 9 - 11μm (Elektrostal engineering plant)
and 12 -14 μm (Ust Kamenogorsk plant). The optimum size fore the high burn-up is 15 - 20 μm. The further increase of the grain size in addition to

technological problems also gives rise to the lost of ductility/creepage of pellets because the rate of the creepage is inversely proportional to the square of the grain size ($\sim 1/r^2$).

The optimization of pellets structure by the grain size and open porosity leads to the effective decrease of gas releases and can provide the good condition of a fuel rod under high burn up conditions.

2.3. Irradiation densification

The irradiation densification can render essential adverse action on a fuel rod condition.

First of all, it can result in occurrence of undesirable axial gaps in a fuel column with the power release splash.

Secondly, the densification makes worse a heat-transfer between pellet and cladding giving rise to the higher temperature of fuel and reserved energy (enthalpy), which is the important characteristic of fuel rod behavior in accident conditions. The irradiation densification is able to effect on fission gas release to some extend.

For these reasons the densification is limited now by a value of 0.4% linear and the further decrease up to 0.25-0.3% linear is supposed.

2.4. Oxide fuel with additives

In order to provide high serviceability of fuel rods the fuel pellets should have sufficient ductility, creep rate (decrease PCI), and simultaneously low gas release (large grain structure).

These two opposite requirements cannot be easily realized in standard fuel. However this problem can be solved by introduction of the special additives into a fuel. One of possible ways of ductility and creep rising of uranium dioxide is its doping by complex oxides, forming eutectics with low melting temperature on grain boundary. In this case it is possible to receive also optimized pellet microstructure concerning gas release.

Such direction now is under development. Pellets with the additives demonstrate much lower (~600°C) temperature of the brittle-ductile transition (below with fracture arises by brittle mode) and higher residual ductility (fig. 12). The creep of such pellets also is rather higher than for standard ones (fig. 13), including pellets with optimized microstructure.

2.5 The effect of the microstructure parameters on the fuel rods under high burn-up conditions

During the operation as the life time of the fuel rods grows there are different process inside fuel rods which change their initial conditions. That is why it is important to analyze the extend of the influence of the initial fuel pellets characteristics to the life time fuel rod parameters. Under thermal conditions and the burn-up of the fuel rods WWER type - the most important change of the inner state of a fuel road is the appearance of the small belt after burn-up ~ 30 - 35 MWt·day/kg U, so called "rim-layer", small outer surface pellet belt with the size ~ 100 - 150 μm. Rim-layer has the high porosity , higher concentration of plutonium and low thermal conductance. Fig. 14 shows the influence of "rim-layer" to the temperature of the fuel pellet and the gas release.

Thus the existence of a rim layer with the high burn - up makes the problem of the optimization of an initial fuel pellet structure more serious especially for the gas release reduction.

In this case the initial parameters of fuel pellets influences on the processes within the fuel rods during their whole life time of operation.

It is very important to keep the fuel rod and it's elements' parameters within the sufficient arrow interval. The more stable is main design parameters for fuel rods the more identical are fuel rods with their operational characteristics. It gives the possibility to reduce the ossification of the calculations and to optimize several operational features of a fuel rod and its life time. So while defining an interval of the allowed values of initial fuel rod parameters it is necessary to take into account this moment as well.

CONCLUSION

Based on the presented material it is possible to state that there is a very close link between the fuel operational parameters and the requirements for its design and production process. The required performance and life-time of a fuel rod can be only assured by the correctly selected design and process solutions. The economical aspect of this problem is significantly dependent on the commercial feasibility of a particular selected solution with the provision of an automated and comparative by inexpensive production of a fuel rod and its components. The operational conditions are also important for the life time of the fuel rods. If there are no special measures for the mitigation of the certain operation conditions the leakage of fuel elements can take place before the planned time.

WWER-1000 FUEL ROD

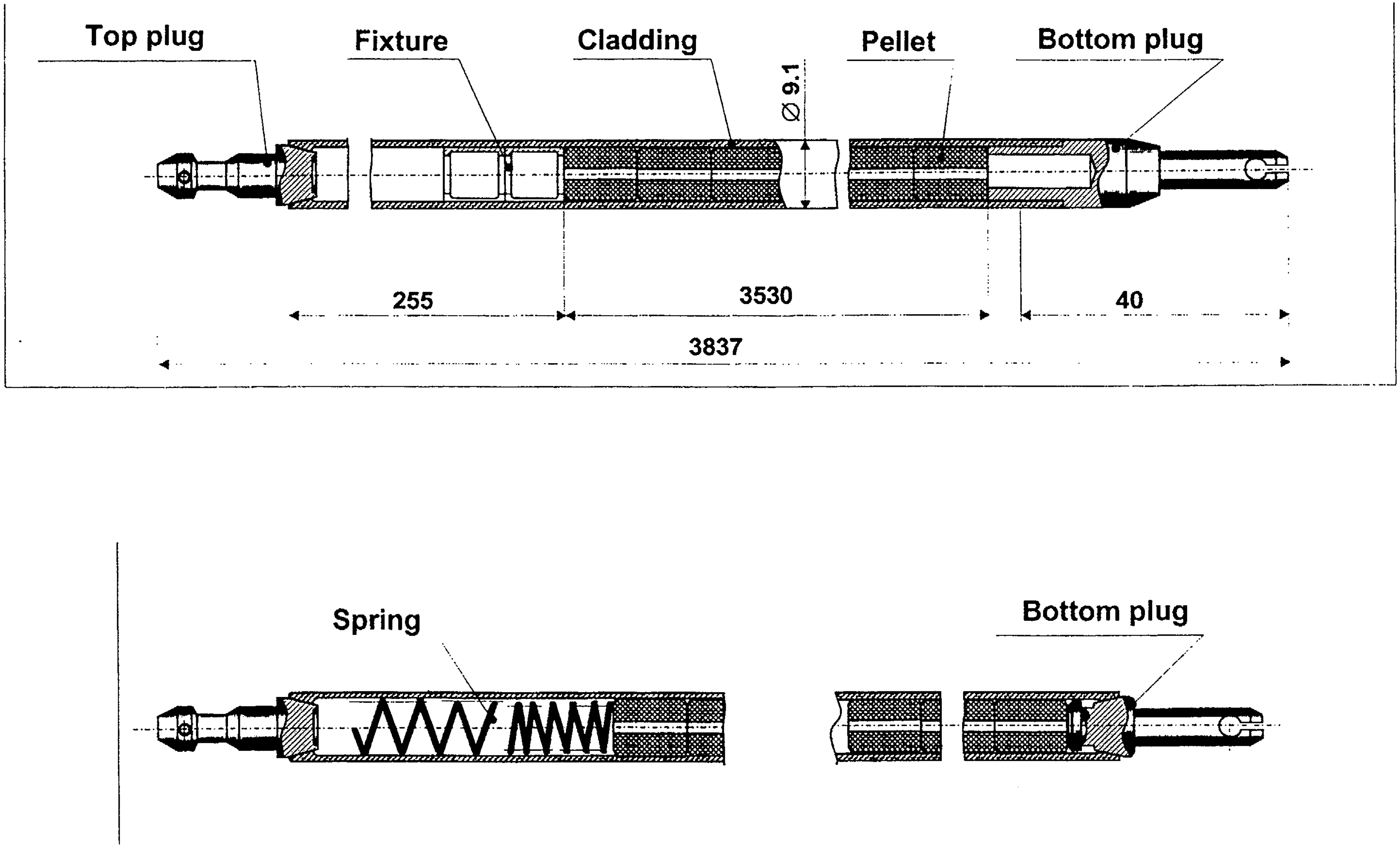


Fig.1

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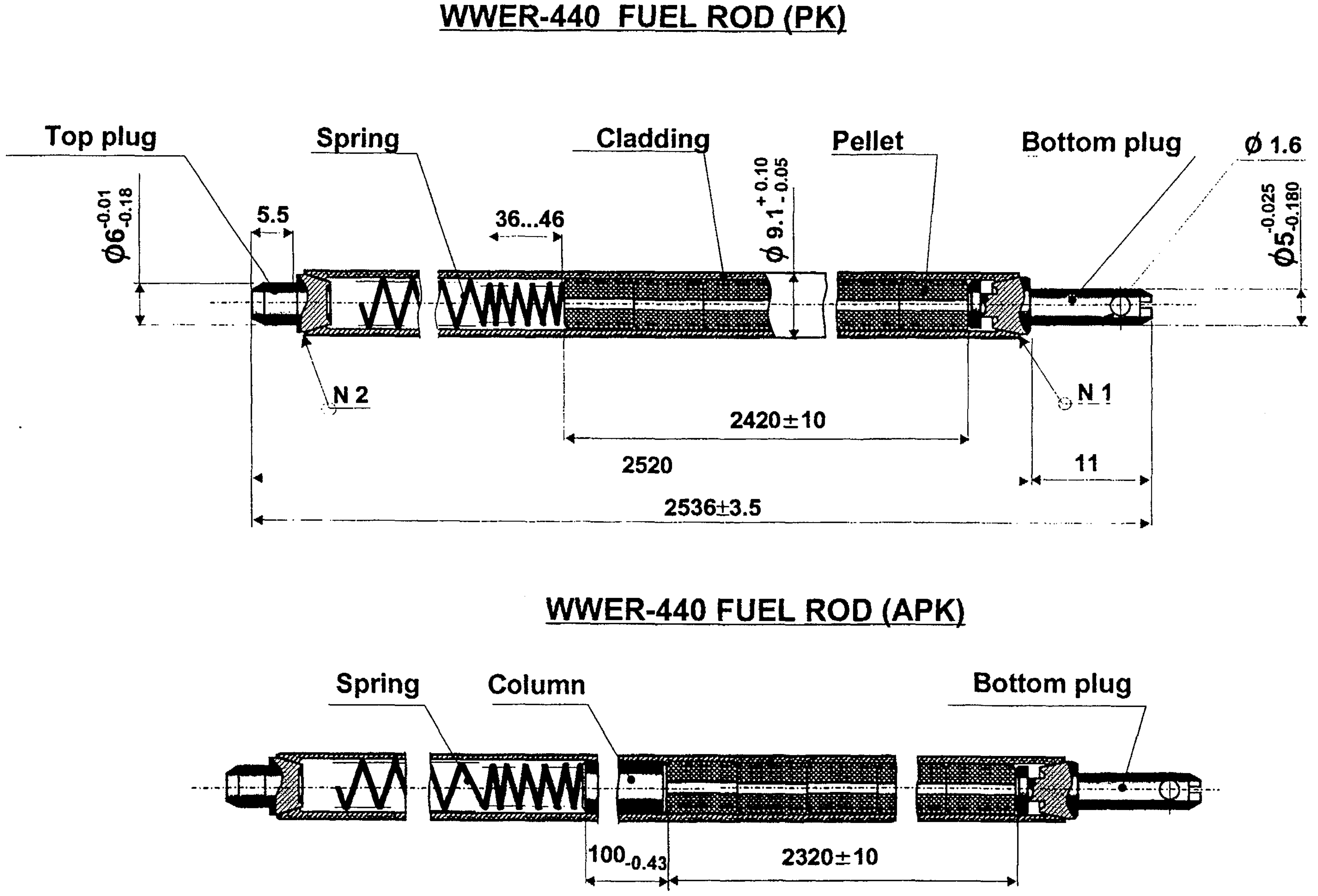
WWER-440 FUEL ROD (PK)
Top plug
Spring
Cladding
Pellet
Bottom plug
Ø 1.6
$\phi 6^{-0.01}_{-0.18}$
5.5
36...46
$\phi 9.1^{+0.10}_{-0.05}$
$\phi 5^{-0.025}_{-0.180}$
N 2
N 1
2420±10
2520
11
2536±3.5
WWER-440 FUEL ROD (APK)
Spring
Column
Bottom plug
$100_{-0.43}$
2320±10

Fig.2

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Distribution of power density in fuel rod along fuel pellet height with different ruptures

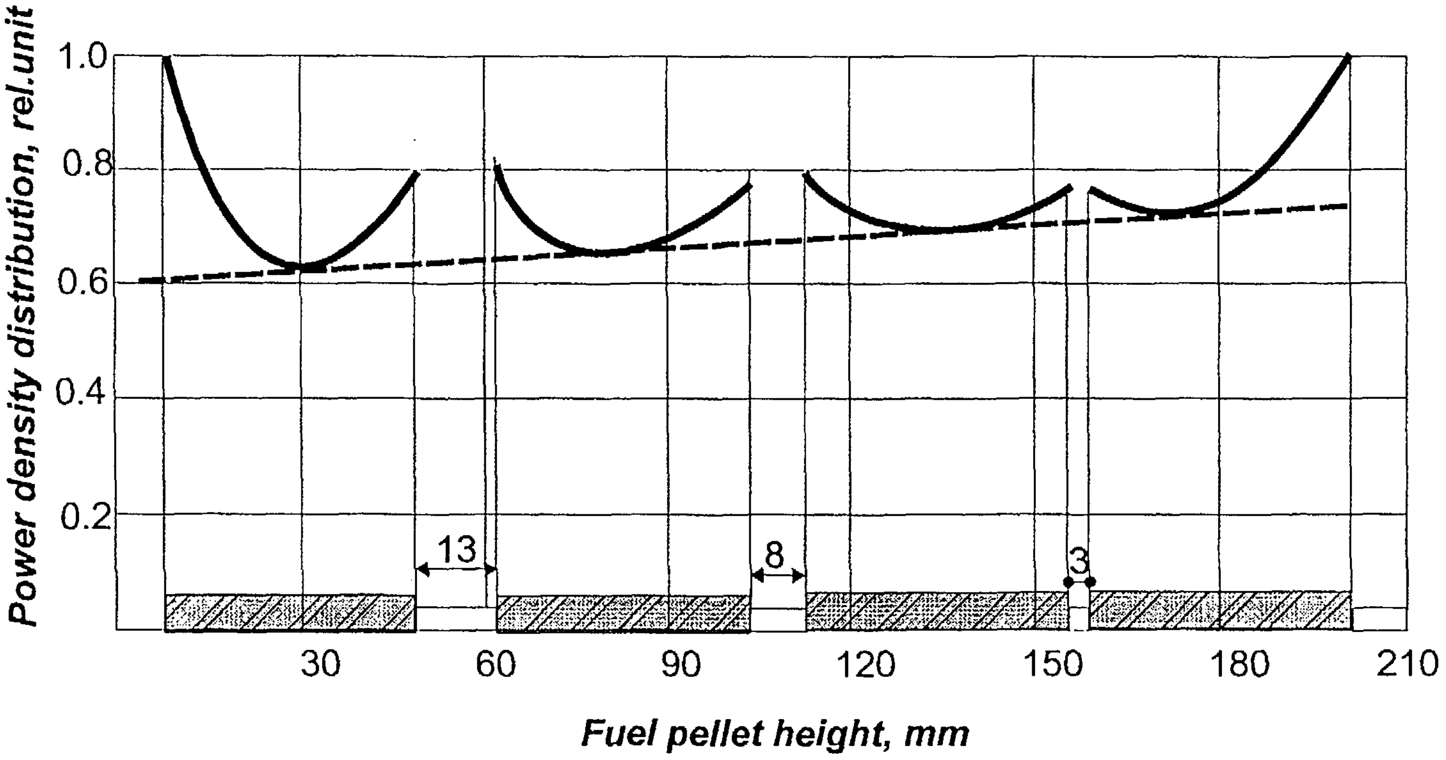

Fig.3

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POWER PEAKING CHANGE AT THE PELLET ENDS VERSUS RUPTURE VALUE IN FUEL CORE

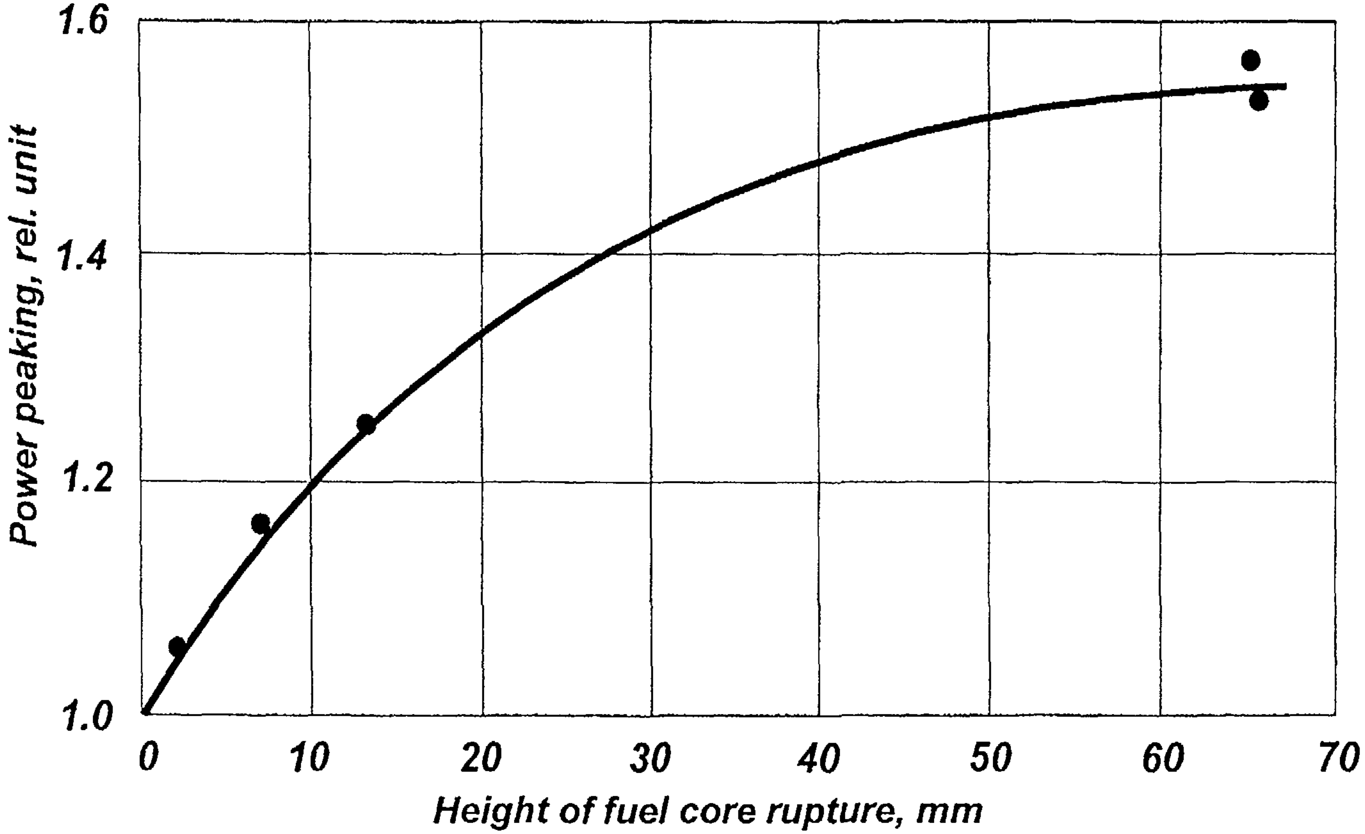
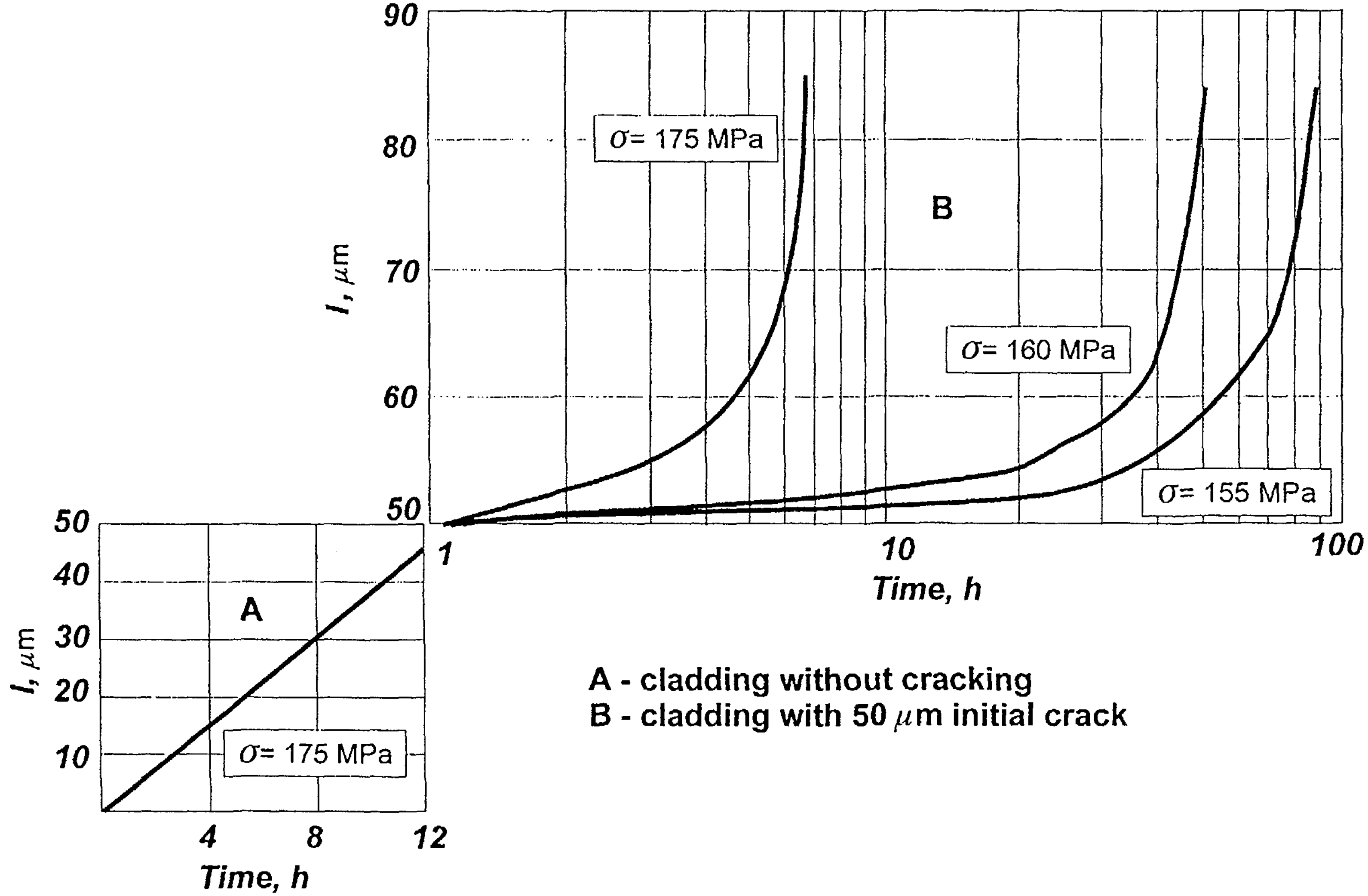


Fig.4

STRESS CORROSION CRACKING PROPAGATION OF Zr+1%Nb ALLOY CLADDING



A - cladding without cracking
B - cladding with 50 μm initial crack

Fig.5

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THE CALCULATED AND EXPERIMENTAL RESULTS of SCC INVESTIGATION of Zr+1%Nb ALLOY CLADDING (IODINE INSIDE)

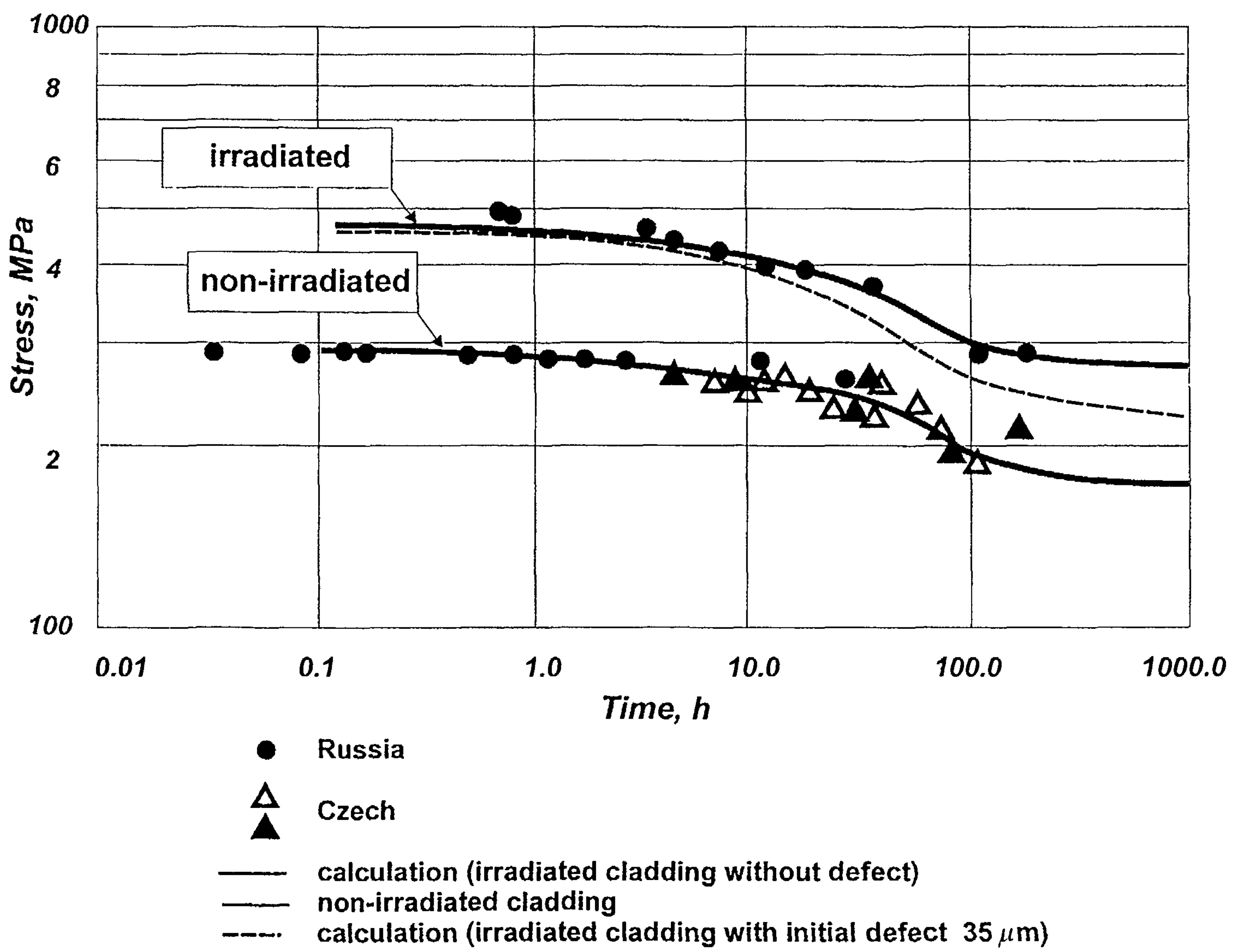

Fig.6

Measurement of γ- counting along the height of simulator containing 20 mg CsI (I^{131} included)

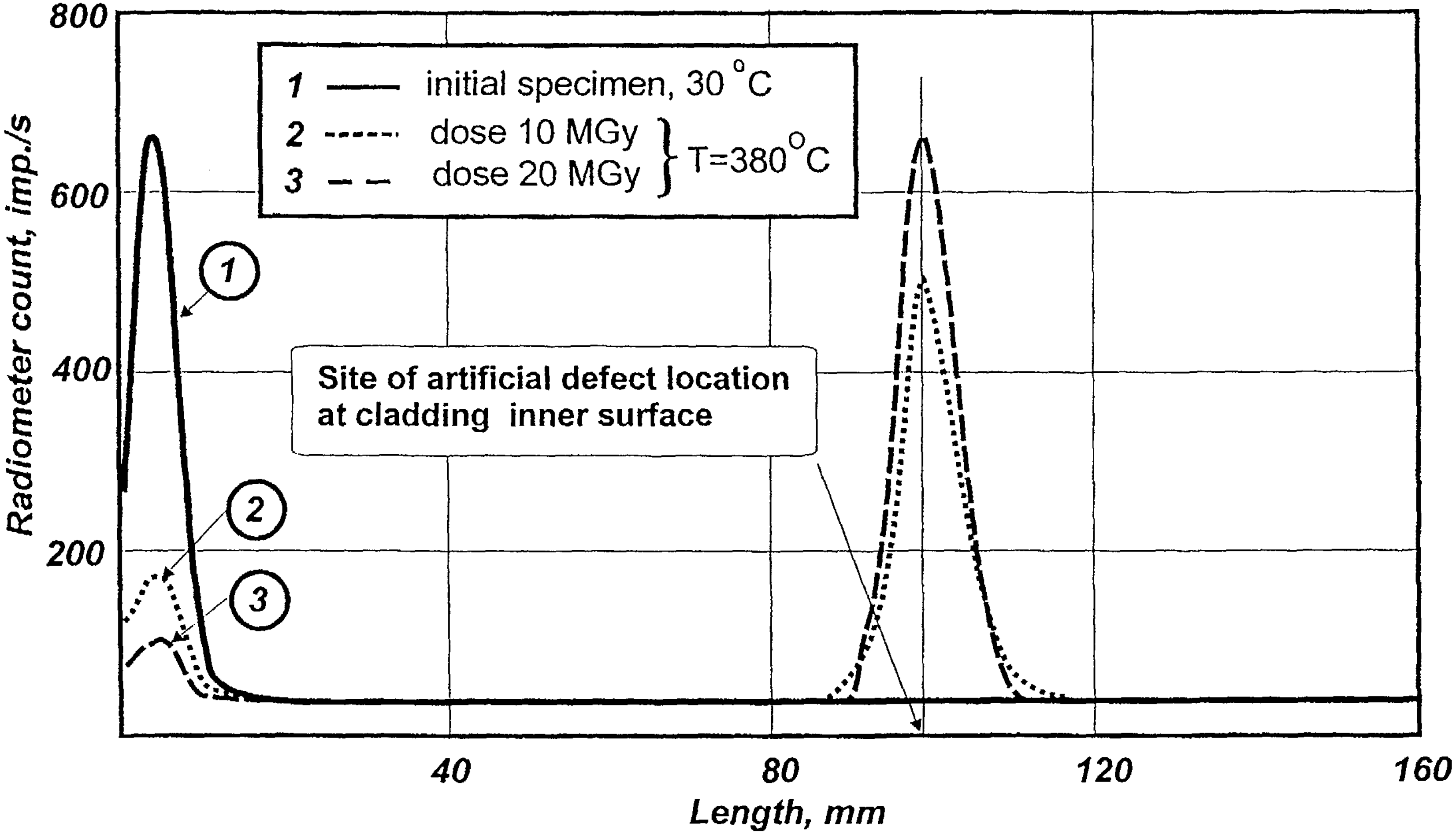

Fig.7

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Influence of γ-irradiation on iodine accumulation in the lower temperature region under radiothermal CsI decomposition

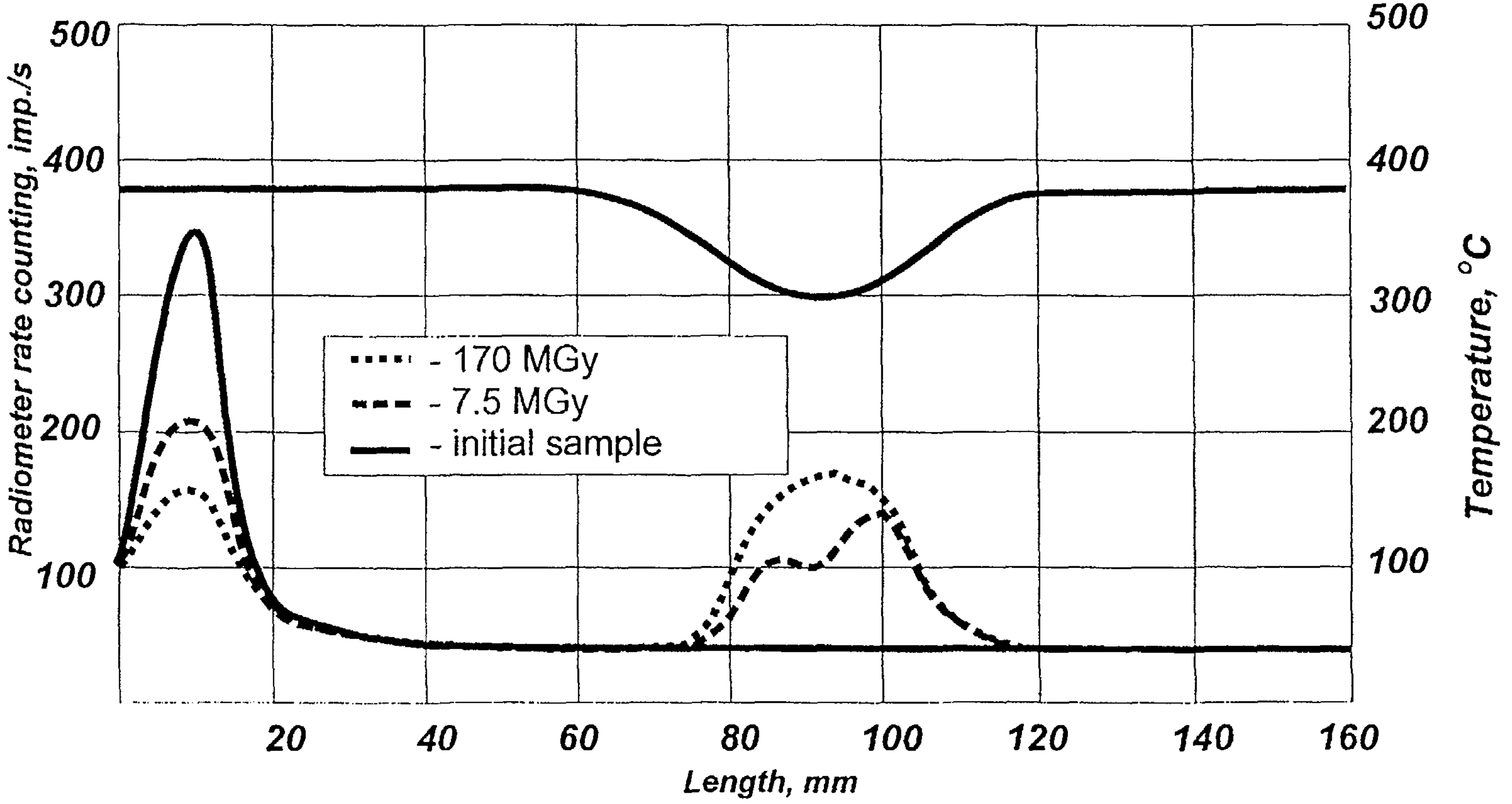

Fig.8

VK
Design'99

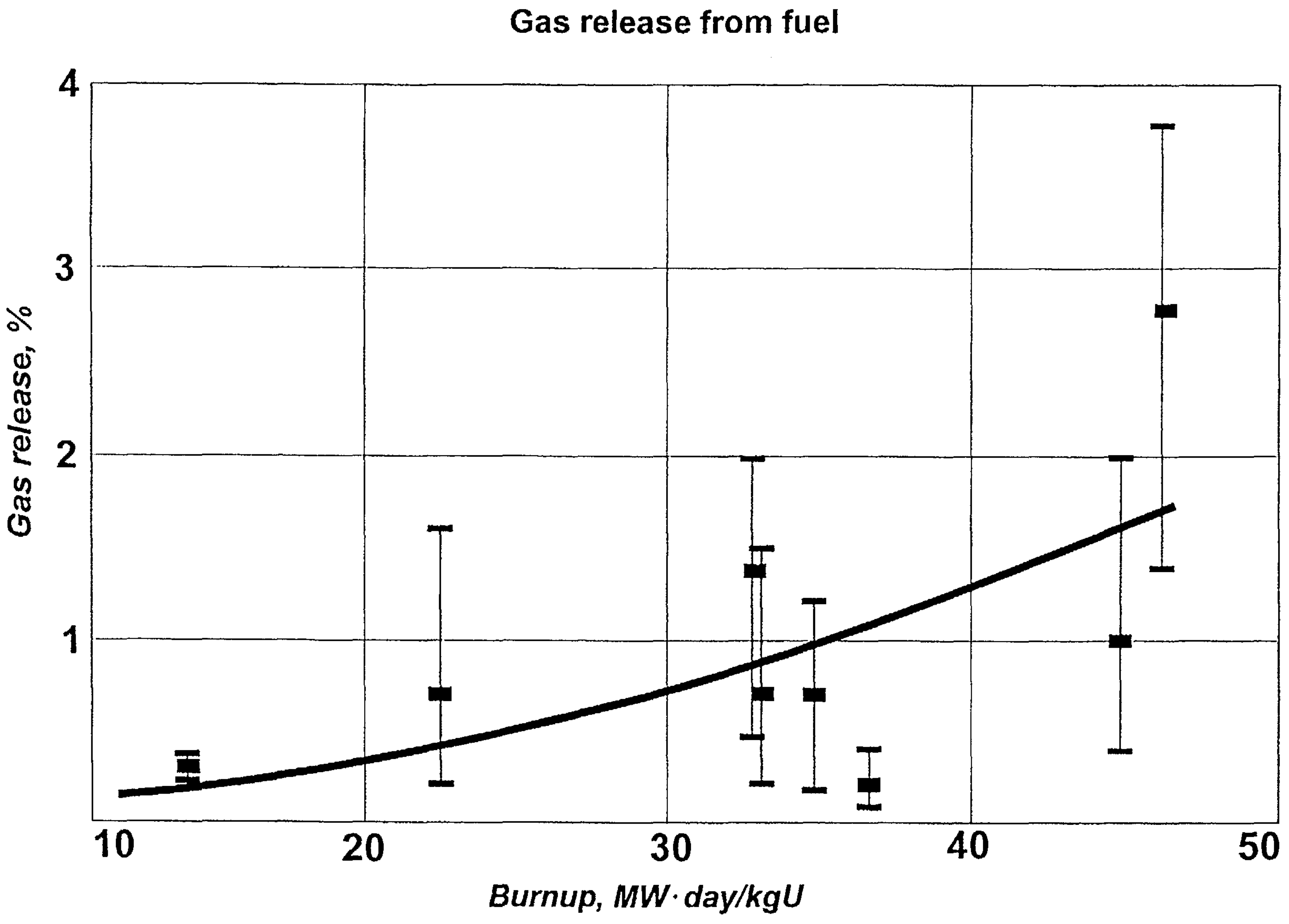
Gas release from fuel
4
3
2
1
Gas release, %
10
20
30
40
50
Burnup, MW·day/kgU

Fig.9

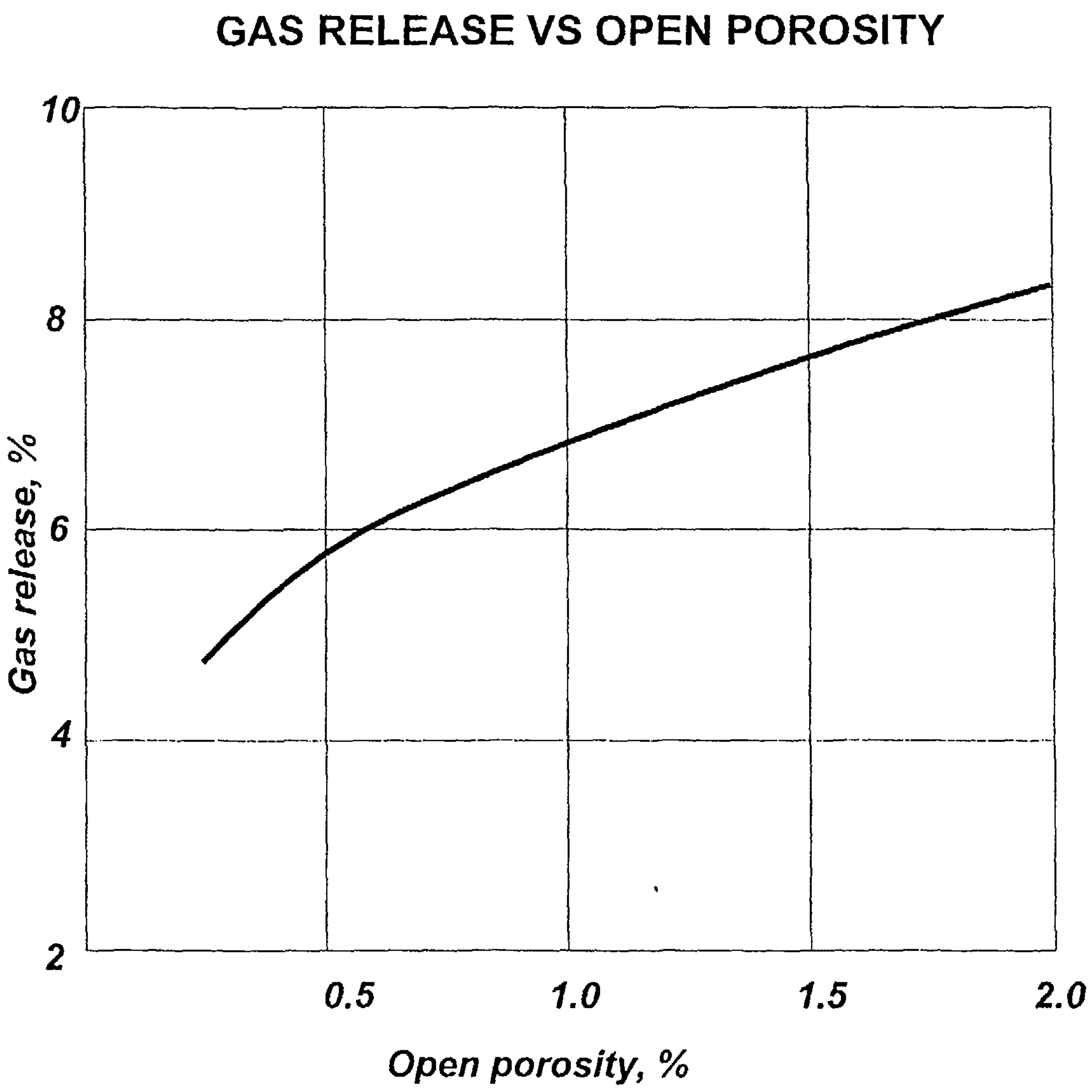
GAS RELEASE VS OPEN POROSITY
10
8
6
4
2
Gas release, %
0.5
1.0
1.5
2.0
Open porosity, %

Fig.10

FG release vs grain size and UO_2 densification

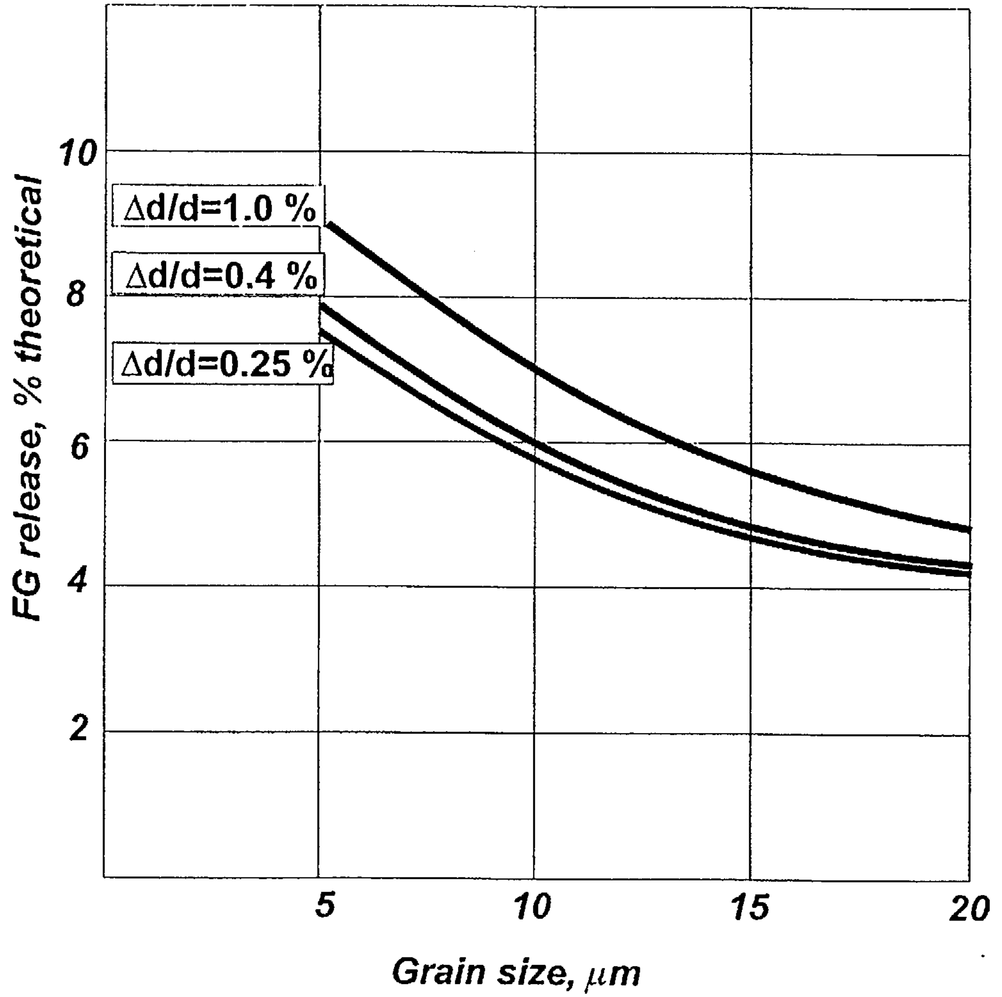

Fig.11

PLASTIC STRAIN OF URANIUM DIOXIDE FUEL PELLETS

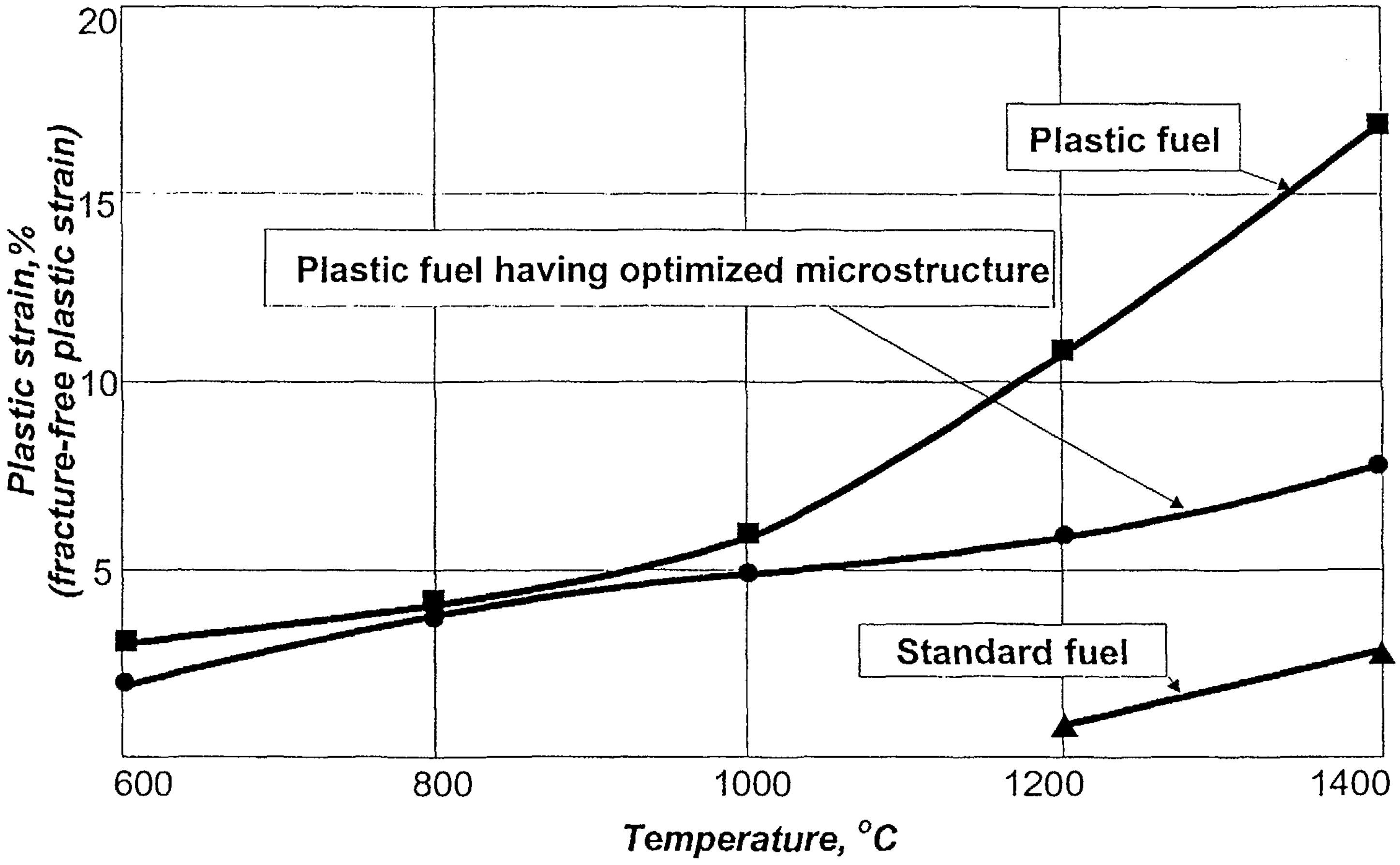

Fig.12

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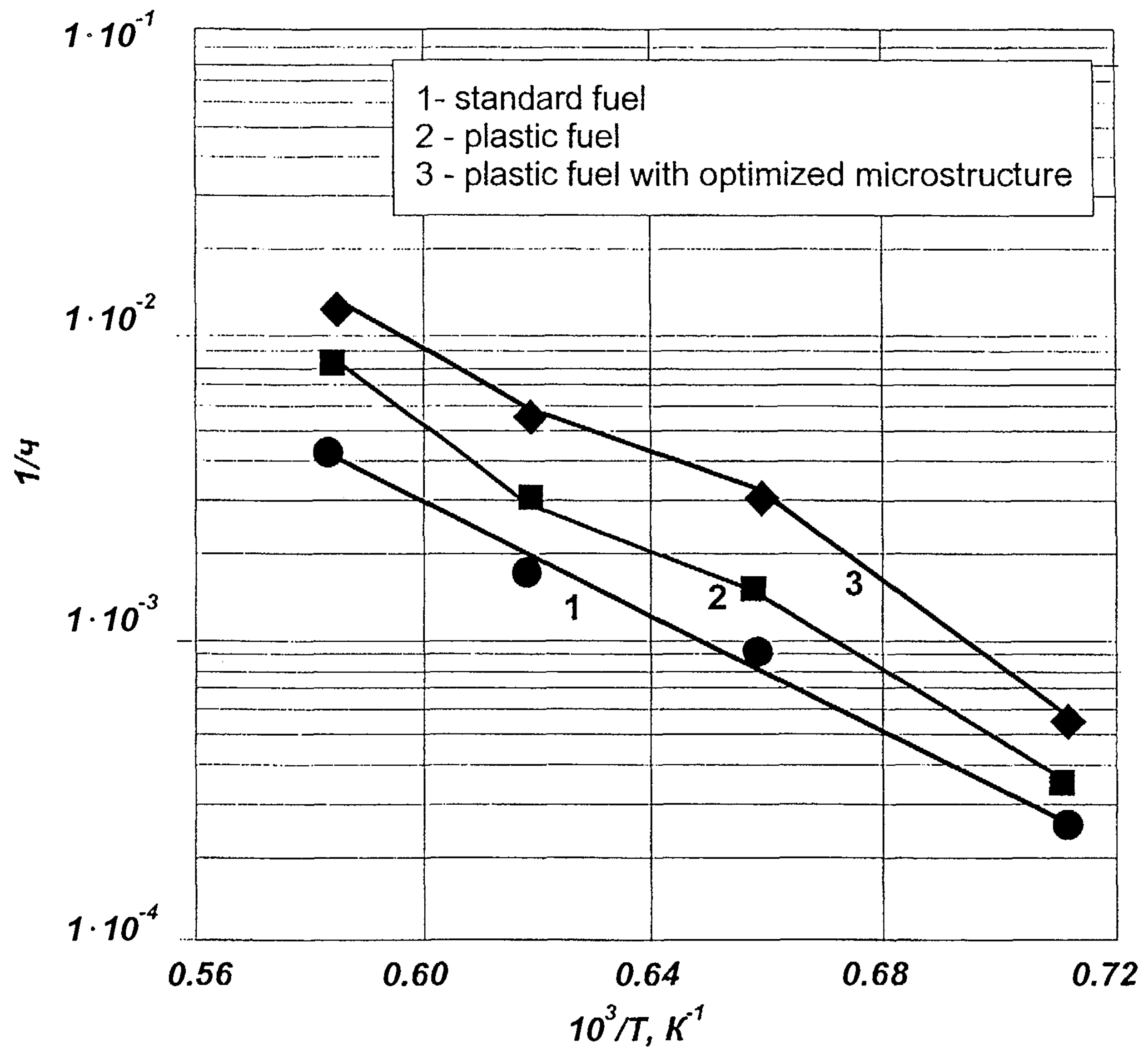

Fig.13

Table 1

Physicochemical indices of the WWER pellets when accepted

Index	Requirement according to TU9ts S.I 823-95		Batch		
	value	acceptance value	№ 850572	№ 850573	№ 850574
1. Mass part of uranium isotopes mixture, °o, minimum	87.8	88.0	88.0	88.0	88.0
2. Conditional mass part of U^{235}, %	4.34 - 4.45	4.37-4.43	4.39	4.39	4.39
3. Conditional mass part of U^{236}, %, maximum	0.1		0.04	0.04	0.04
4. Oxygen coefficient	2.000-2.015	2.000-2.014	2.001	2.001	2.001
5. Conventional mass part of impurities, %, maximum:					
nitrogen	0.007	0.005	0.003	0.003	0.003
aluminium	0.02	0.015	0.003	0.003	0.003
boron	0.00004	0.00002	0.00002	0.00002	0.00002
vanadium	0.01	0.007	0.003	0.003	0.003
iron	0.05	0.036	0.013	0.016	0.012
cadmium	0.00006	0.00004	0.00003	0.00003	0.00003
calcium	0.015	0.011	0.01	0.01	0.01
silicon	0.02	0.014	0.003	0.003	0.003
magnesium	0.005	0.004	0.001	0.001	0.001
manganese	0.002	0.0015	0.0003	0.0003	0.0003
copper	0.005	0.004	0.0004	0.0004	0.0005
molybdenum	0.01	0.007	0.003	0.003	0.003
nickel	0.015	0.011	0.003	0.003	0.003
phosphorus	0.02	0.015	0.01	0.01	0.01
chromium	0.01	0.007	0.003	0.003	0.003
carbon	0.01	0.008	0.003	0.003	0.003
tungsten	0.01	0.007	0.005	0.005	0.005
fluorine	0.00i5	0.0011	0.0005	0.0005	0.0005
fluorine + chlorine	0.003	0.002	0.001	0.001	0.001
gadolinium	0.000005	0.000004	0.000001	0.000001	0.000001
6. Mass part of total hydrogen, %, maximum	0.00006	0.00004	0.00002	0.00002	0.00002

FUEL TEMPERATURE RADIAL DISTRIBUTION FOR DIFFERENT SECTION BURN-UP (CURRENT FUEL, W_l= 22 kW/m)

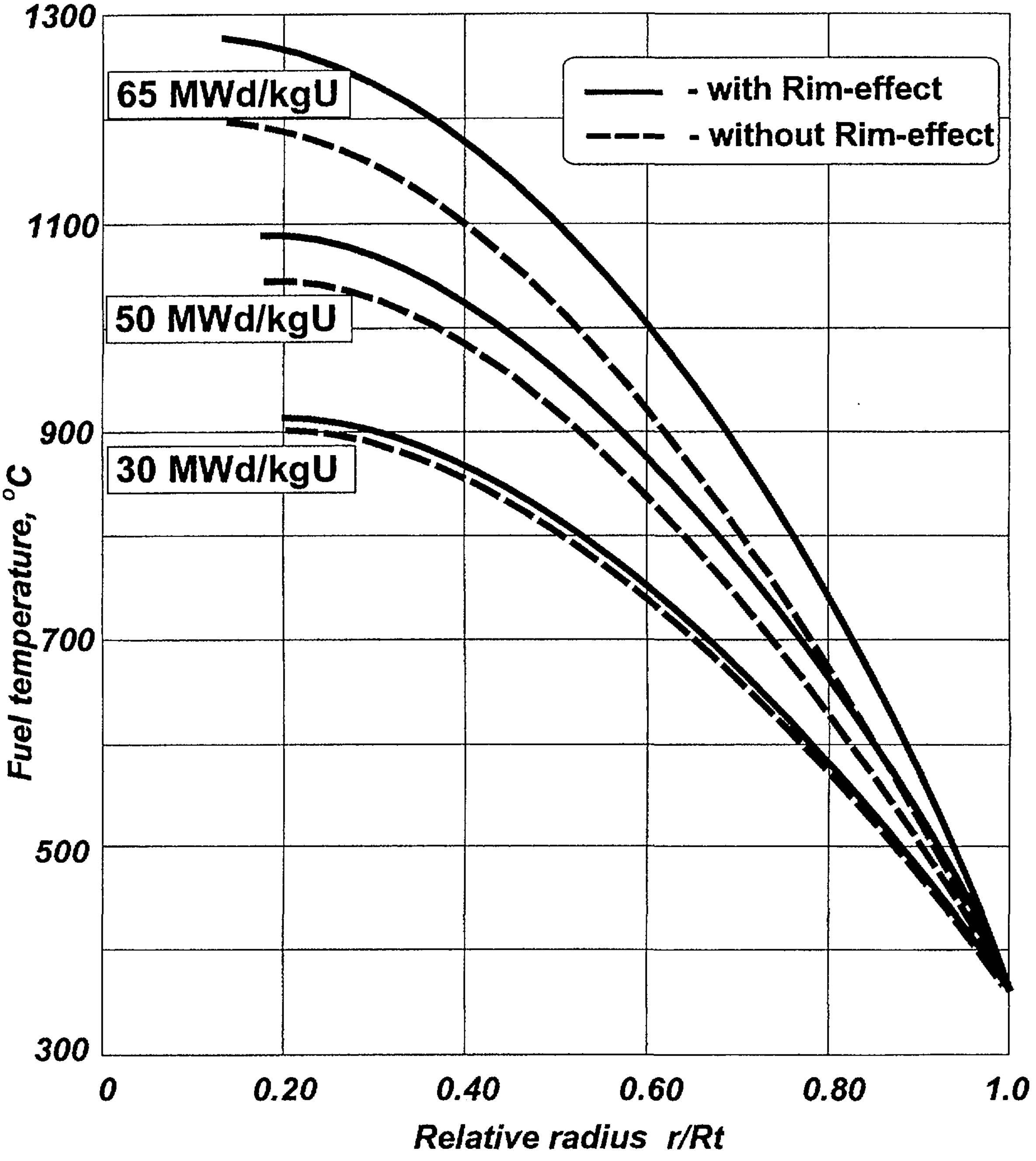

Рис.14

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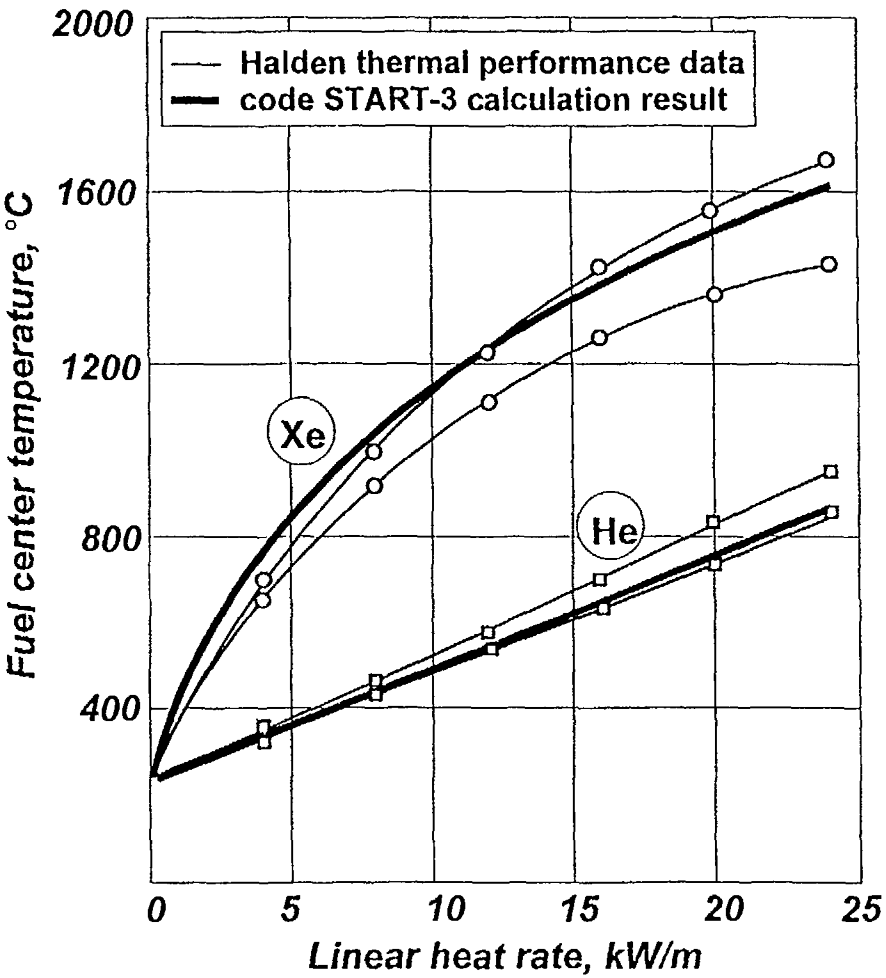
Halden thermal performance data
code START-3 calculation result
Fuel center temperature, °C
2000
1600
1200
800
400
Xe
He
0
5
10
15
20
25
Linear heat rate, kW/m

PROVISION OF CONSERVATISM OF DESIGN ANALYSIS

THE GUARANTEED IMPLEMENTATION OF THE LICENSING ACCEPTANCE CRITERIA IS PROVIDED BY

- INTRODUCTION OF CONCERVATIVE ASSUMPTIONS INTO DESIGN ANALYSES;
- STANDARD FACTORS OF MARGIN FOR THE ASSUMED DESIGN CRITERIA

$$K_{STAND}=[R]/R_P$$

WHERE
$[R]$ - STRENGTH PARAMETER AT WHICH THE STRUCTURE IS POSTULATED TO FAIL;
R_P - STRENGTH PARAMETER AT WHICH THE PROBALITY OF THE INEQUALITY $R>R_P$ IS EQUAL TO THE RELIABILITY P.