XA0053645

HIGH TEMPERATURE STUDY OF THE CONTROL ROD BEHAVIOUR UNDER ACCIDENT CONDITIONS

V. TROYANOV, A. POMESCHIKOV, V. SOUGONJAEV
Institute of Physics and Power Engineering,
Obninsk

V. PONOMARENKO, A. SCHEGLOV
Moscow Polimetal Plant,
Moscow

Russian Federation

Abstract

Control rod behaviour under accident conditions is considered. A comparative assessment of various types of absorbers is carried out in this respect. It was found that the best absorbers are dysprosium based absorbers. Dysprosium based control rods show no failure at temperatures below 1300°C. Boron based control rods may be liquefied at a temperature of 1150°C. Besides, the cladding may burst at lower temperature, due to the released helium. Experiments indicate that the absorber materials may initiate severe core damage under severe accidents. The beginning of core structure degradation is caused by the boron control rod liquefaction.

1. THE MAIN CORE DEGRADATION PROCESSES UNDER UNCONTROLLED TEMPERATURE INCREASE

The temperature range of core material liquefaction for WWER is between 650°C (melting point of burnable absorber based on aluminium, MPA) and 2700°C (melting point of uranium oxide and zirconium). This range may be divided conditionally to the low temperature range (not more 1500°C) and high temperature range (up to 2700°C). Let us consider the stainless steel melting point as the conditional border.

In the study considered the low temperature phenomena have been mostly analyzed. Just in this temperature range, the core degradation processes occur under severe accident conditions. These processes are fuel rod ballooning and failure, control rod failure and liquefaction, liquid eutectic formation, chemical interaction of differential types of materials, melt flow down, etc. Several schemes of core structure degradation are presented in chapter 2. These schemes are based on the experimental study of the phenomena analyzed.

2. EXPERIMENTAL STUDY OF THE CORE STRUCTURE DEGRADATION, ABSORBER CONCERN

2.1. Methodological approach

Contact interactions as well metallurgical liquefaction have been studied. Mock-ups of spacer grids, fuel rods, guide tubes have been used. Standard fuel, absorber and cladding materials have been applied for mock-up fabrication. A gamma facility and furnaces are used for testing. The gamma facility is a high temperature steam loop with steam pressure of 1 - 2 bar and test temperatures up to 1900°C. The temperature rise is approximately 1.5°C/sec. Mock-ups have been surveyed after testing and cutting and are examined metallographically by micro X-ray phase analysis. Mechanical material tensile testing has been carried out as well.

2.2. Fuel cladding/spacer grid interaction

A comparative assessment of the fuel cladding (FC) and spacer grid (SG) interactions in vacuum and in a steam environment has been done (see Table I).

TABLE I. FUEL ASSEMBLY DEGRADATION; INTERACTIONS OF THE FUEL RODS (FR) AND SPACER GRIDS (SG)

Temperature range, approximately °C	Phenomena
600-800	Fuel cladding ballooning
800-900	Fuel cladding failure Fission gas release Beginning of internal cladding oxidizing
1200 and higher	Cladding oxidizing acceleration Hydrogen release
1450	Melting of spacer grids Melt flow down Blockage formation
1900	Cladding melting

Remark: no eutectic formations are observed up to stainless steel melting.
FR cladding - Zr,1%Nb; Fuel - UO_2; SG - stainless steel

There are no visible interactions after 15 min testing at 980°C in vacuum. Metallography shows a 15-60 micrometer interaction layer. After 15 min testing at 1030°C in vacuum, the interaction zone is increased up to 25-360 micrometers in spite of the fact that no visible interactions are observed. At 1100°C and higher temperatures, significant interaction and liquefaction is observed. It was expected that liquefaction would happen approximately at 950°C, since the liquid eutectic temperature would be exceeded. Nevertheless, it did not happen, the initial oxide film on the zirconium cladding prevents it from liquefaction.

In the steam environment, the oxidation of zirconium is higher. A thick zirconium layer prevents the chemical interaction with steel up to 1500°C. This phenomenon is illustrated in Figs. 1 and 2.

2.3. Control rod cladding/absorber interaction

2.3.1. CRC/boron carbide

Pressurized mock-ups have been studied at a temperature range of 800-1200°C (see Table II).

TABLE II. FUEL ASSEMBLY DEGRADATION; INTERACTIONS OF BORON CARBIDE AND CONTROL ROD CLADDING GUIDE TUBE

Temperature range, approximately, °C	Phenomena
650 and higher	Diffusion of C and B into the cladding
800 and higher	Control Rod Cladding ballooning He released from B_4C Steel - B_4C interaction
1080 1174 1150 and higher	Ni/B eutectic formation Fe/B eutectic formation CR cladding liquefaction Guide tube liquefaction Melt flow down, blockage formation He released H2, CO, B203 released

Remark: pressurized control rod cladding is not failed by the guide tube protection and guide tube strength.
Control rod cladding - stainless steel; Guide tube - stainless steel

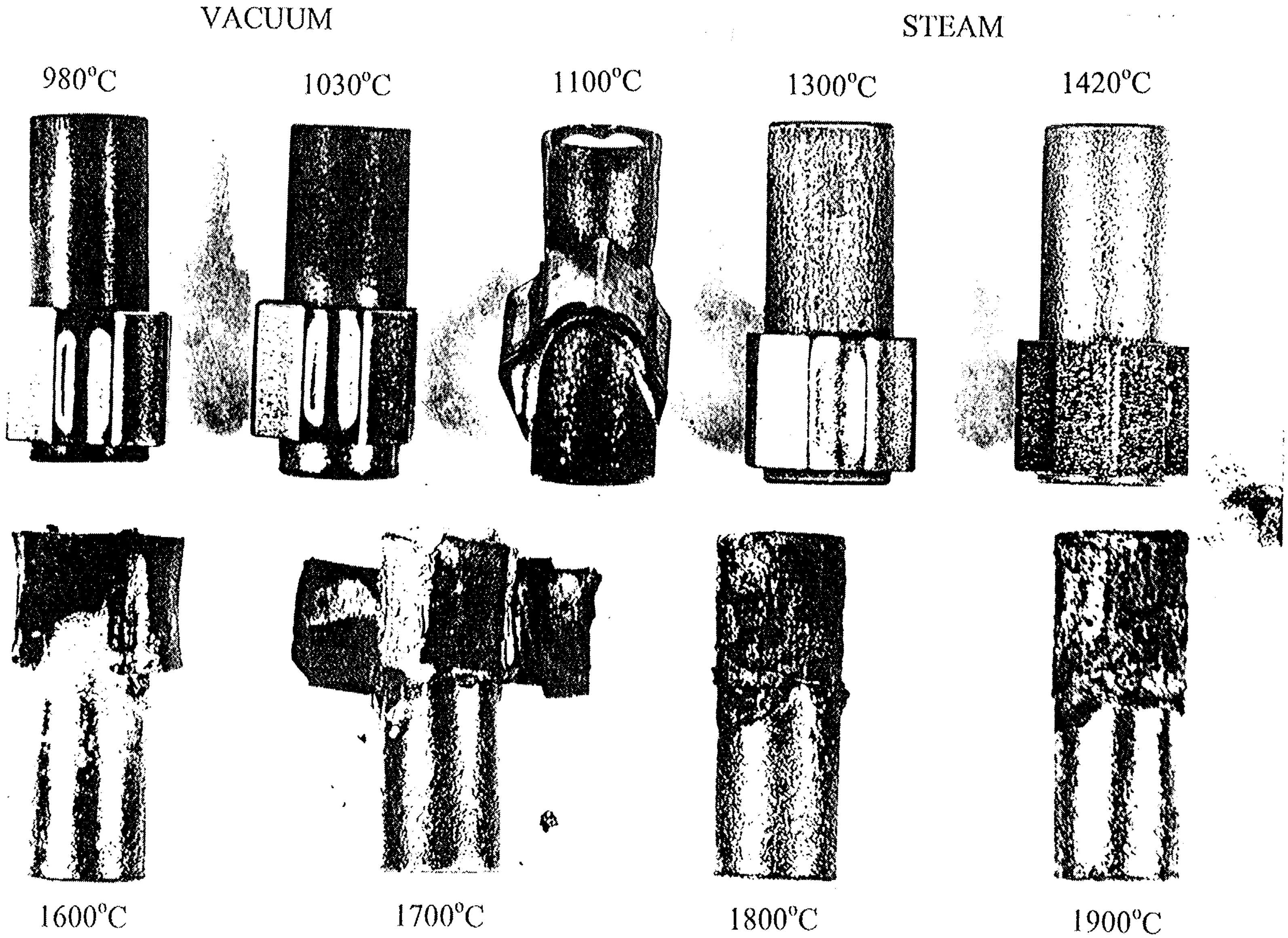

FIG. 1. Spacer grid/fuel rod cladding interaction

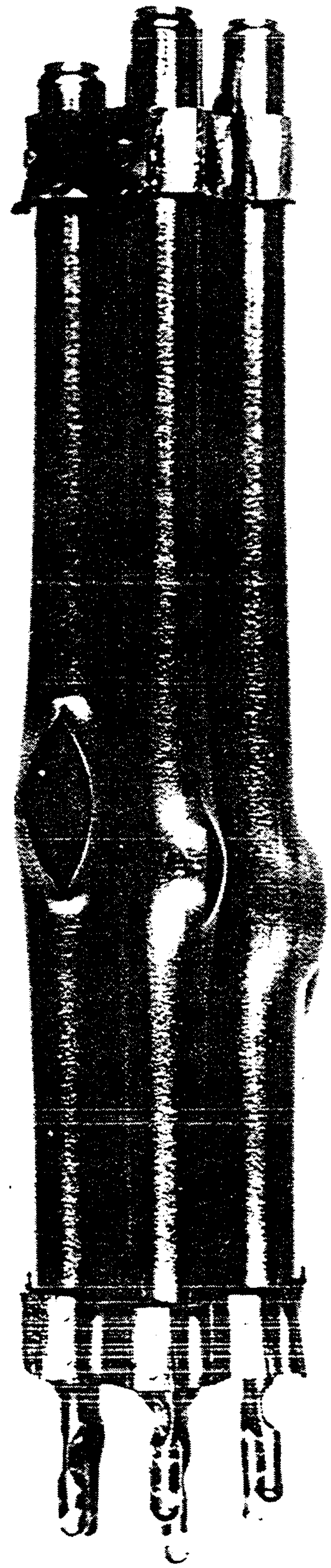

FIG. 2. Fuel assembly mock-up

There are no significant chemical interactions in the temperature range between 800-1150°C. This can be explained by the short period of temperature increase at the temperature rise rate of 1.5°C/sec. The beginning of liquefaction is observed at temperatures above 1150°C. Penetration of carbon and boron into the austenitic through diffusion is observed. Complex carbides type Me_7C_3 and borides type Me_2B is found. Fatal liquefaction occurs above 1200°C. Views of the mock-up are shown in Figs. 3-6, before and after testing at 1200°C and 1350°C.

2.3.2. CRC/dysprosium titanate

Non-pressurized mock-ups were tested at temperatures up to 1800°C (see Table III).

TABLE III. FUEL ASSEMBLY DEGRADATION; INTERACTIONS OF THE DYSPROSIUM TITANATE AND CONTROL ROD CLADDING GUIDE TUBE

Temperature range, approximately, °C	Phenomena
1200 and higher	Guide tube oxidizing acceleration
1450	Melting of the CR cladding Melt flow down within guide tubes No Di_2TiO_5 relocation due to its densification
1900	Guide tube material melting and flow down

Control rod cladding - NiCr alloy; Guide tube - Zr,1%Nb.

No significant chemical interaction has been observed up to 1400-1450°C. The views of mock-ups tested at 1200°C and 1400°C are shown in Fig. 7 and at 1800°C in Figs. 8-10.

2.4. Burnable absorber rod behaviour

The absorber alloy MPA is based on an aluminium/boron mixture. MPA is molten at temperatures higher than 650°C (see Table IV). The specific volume of MPA increases when melting by about 7%. The melt interacts with the zirconium cladding. Intermetallic compounds are formed, but the solubility of Al in Zr is not significant.

TABLE IV. FUEL ASSEMBLY DEGRADATION; BURNABLE ABSORBER ROD BEHAVIOUR

Temperature range, approximately, °C	Phenomena
650	MPA melting
650 and higher	Cladding - MPA melt interaction
700 and higher	Intermetallic compounds Zr/Al protect from further chemical interaction Cladding oxidizing
800 and higher	Cladding failure for pressurized BAR Molten absorber extraction and flow down **No failure for unpressurized BAR**

Burnable absorber - aluminium based boron alloy, MPA; Control rod cladding - Zr,1%Nb.
BAR - burnable absorber rod

The intermetallic layer is formed on the inner surface of the cladding. This is a barrier for further aluminium penetration into the cladding. The reaction rate depends on the diffusion through this layer. The fatal liquefaction of zirconium cladding does not occur. The failure of BAR cladding takes place for pressurized BARs only. For failed BAR's, the gas pressure pushes the MPA melt through the hole and the melt flows down.

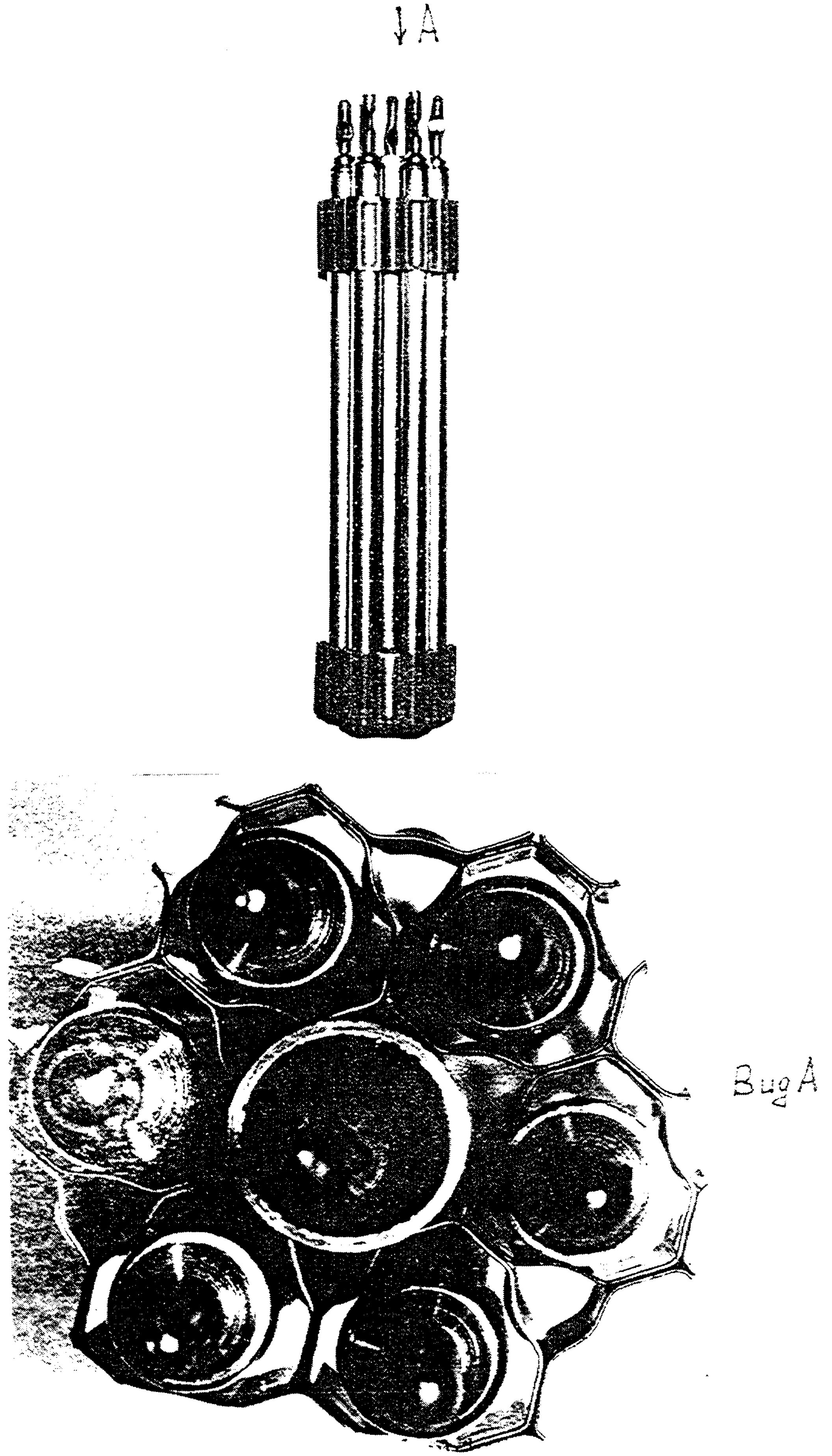

FIG. 3. Fuel assembly mock-up before testing

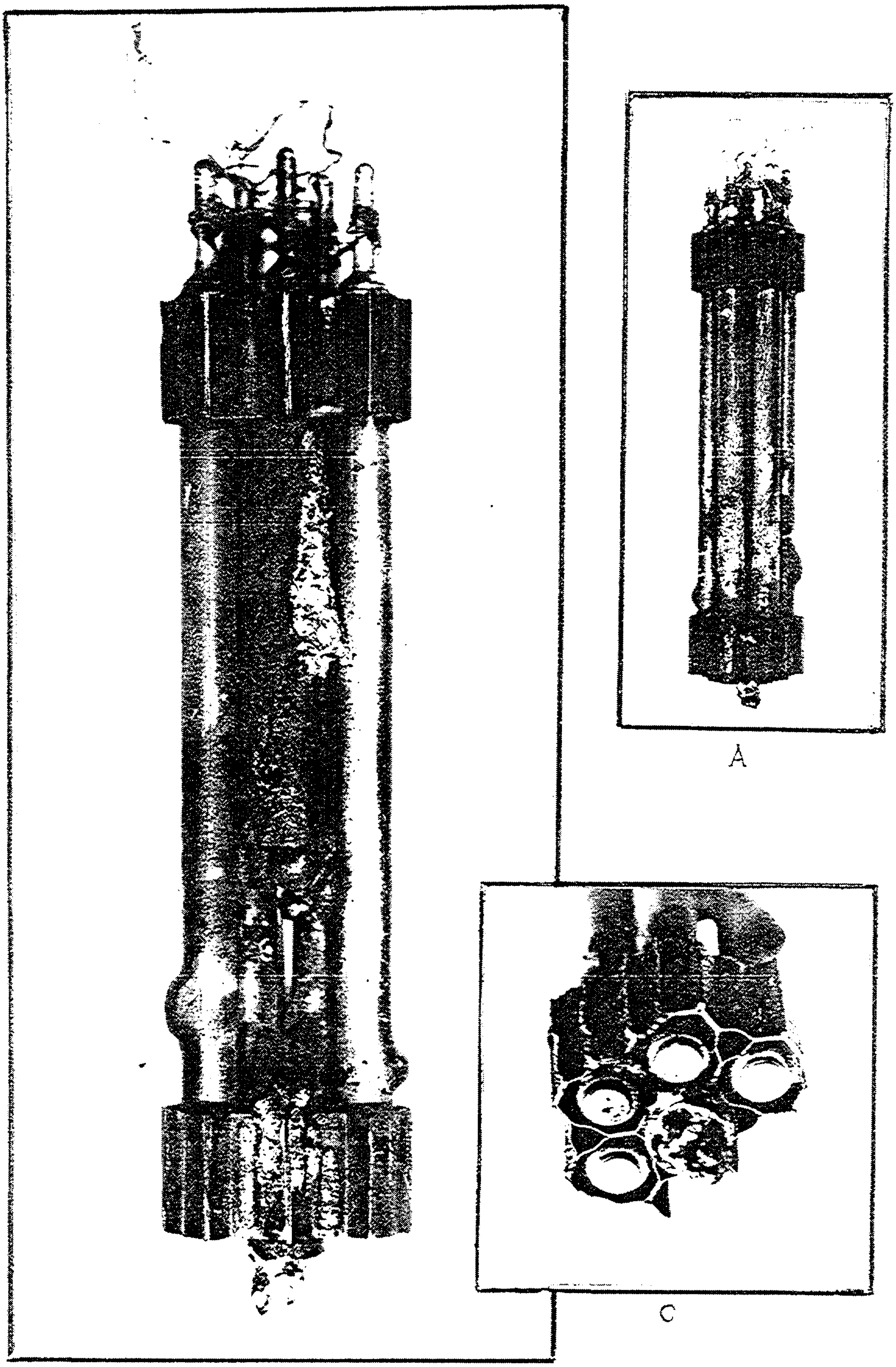

FIG. 4. Boron contained mock-up after testing at 1200°C

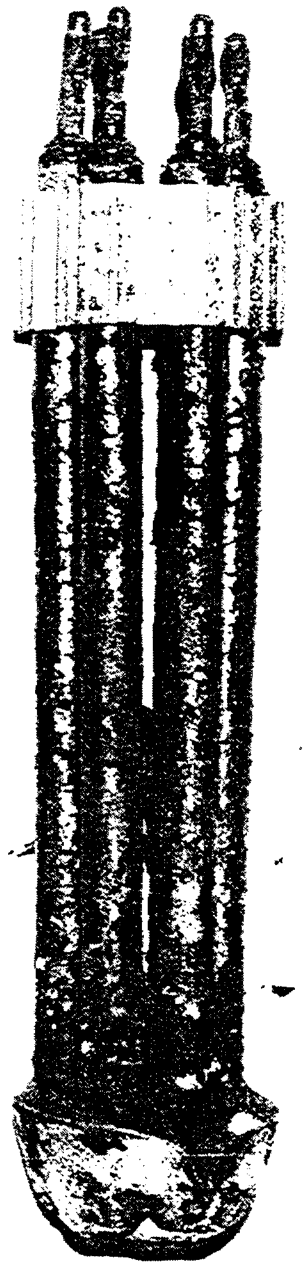

FIG. 5. Boron contained mock-up after testing at 1350 °C

FIG. 6. Boron contained mock-up after testing at 1350 °C

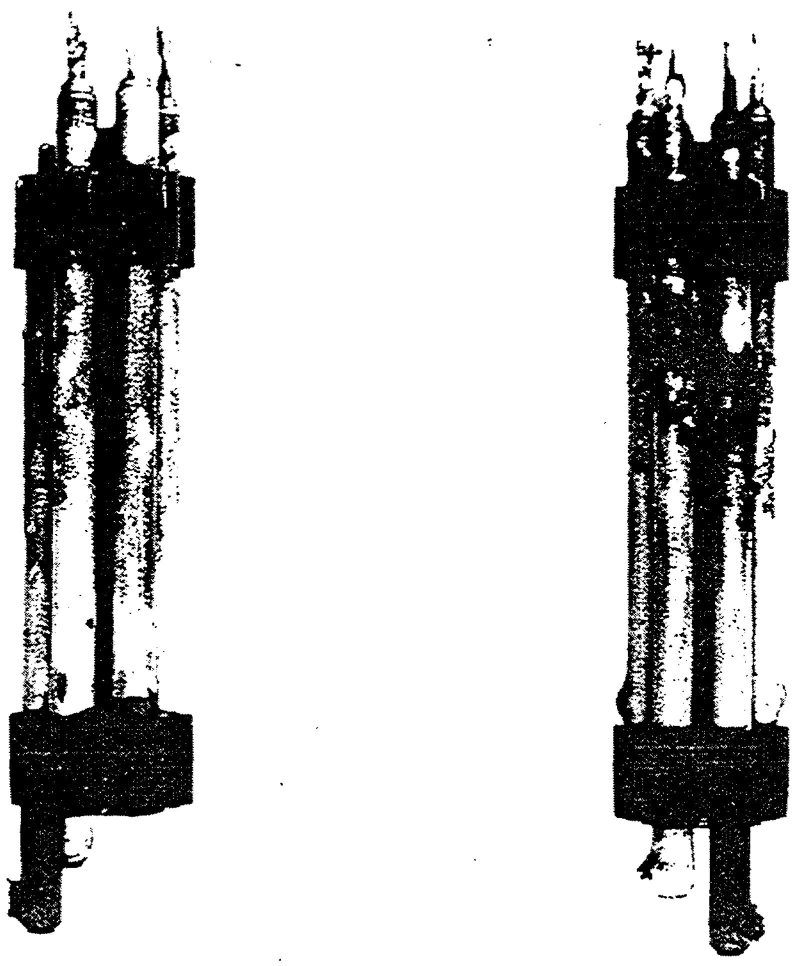

FIG. 7. Dysprosium contained mock-up after testing at 1200℃ (left) and 1400℃ (right)

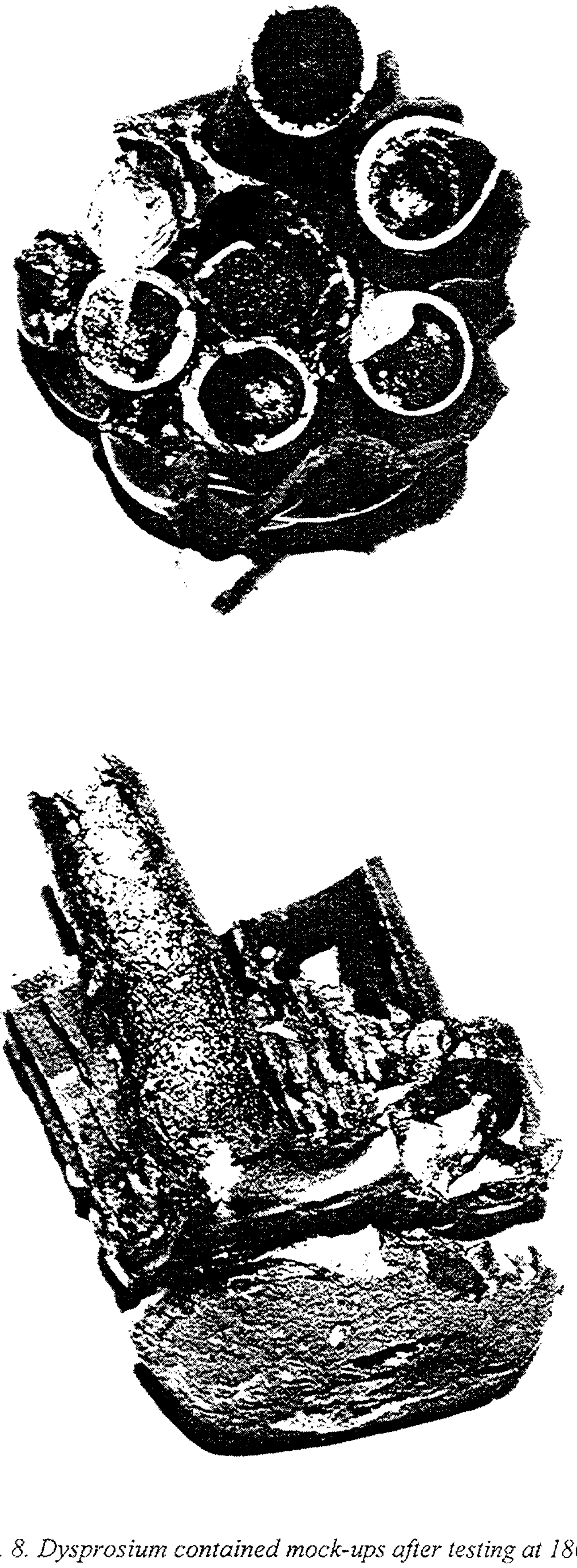

FIG. 8. Dysprosium contained mock-ups after testing at 1800℃

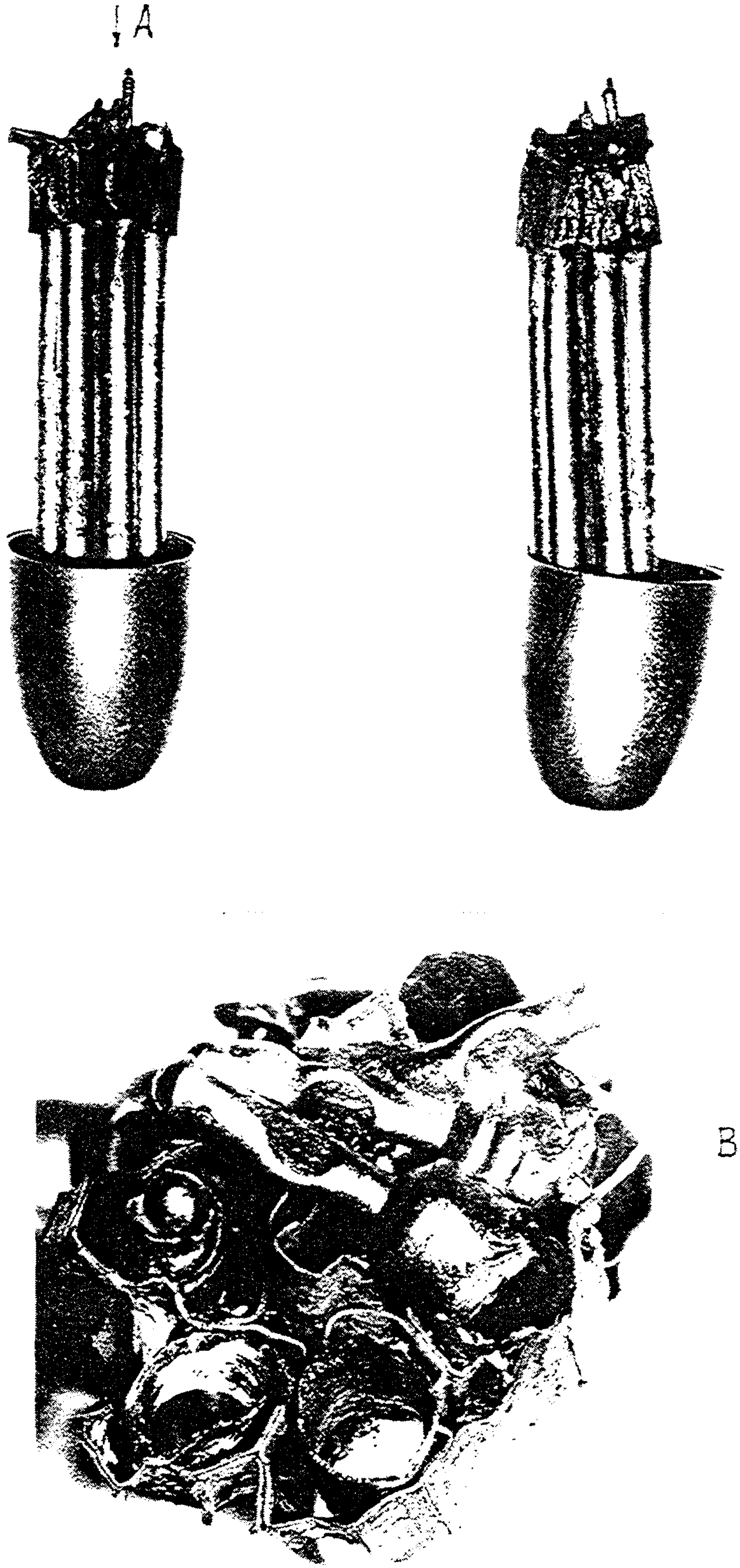

FIG. 9. Dysprosium contained mock-ups after testing at 1800 °C

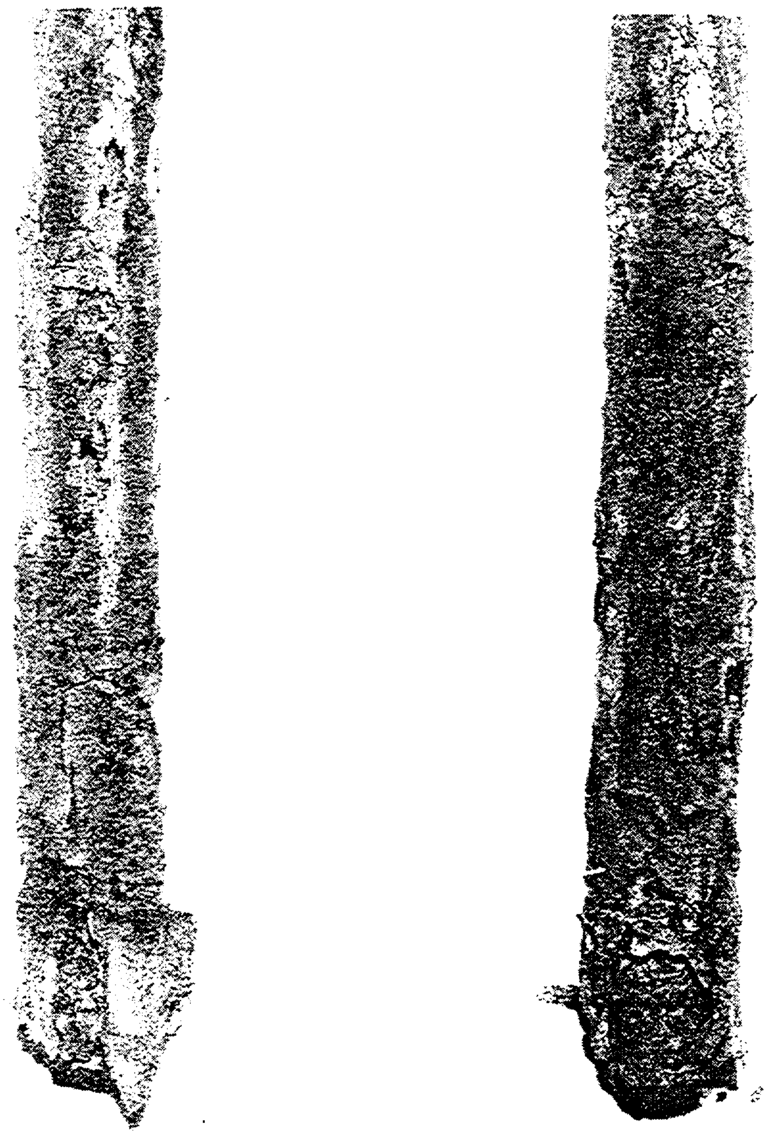

FIG. 10. Dysprosium control rod after testing at 1800 °C

SUMMARY

1. The liquefaction of boron absorber rods may happen between 1150-1200°C. It leads to liquid eutectic formations, flow down of melt and blockage formations mainly near the spacer grids.

2. Control rod liquefaction initiates core degradation in the melt formations observed. The temperature of absorber liquefaction is about 200°C less than fuel rod liquefaction.

3. Absorber relocation within the core may happen while the core structure is not destroyed.

4. Dysprosium absorbers are much more firm. Dysprosium absorber rods are not destroyed up to 1450°C. Only the bottom part of the absorber rods of the new Russian control rod design is made of dysprosium absorber.

5. It is supposed that under severe accident conditions, the control rods are inserted into the core. The most heated part of the core is the central cross-section. Thus, the unirradiated absorber is heated more.

Therefore, previous irradiation of absorbers before carrying out tests is not necessary for the above discussed experiments.