Proceedings of the Seminar on

THERMAL PERFORMANCE OF HIGH BURN-UP LWR FUEL

3-6 March 1998
Commissariat à l'Énergie Atomique (CEA)
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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

FOREWORD

The deregulation of electricity markets is leading to increased pressure on nuclear energy to stay competitive. The economic performance of nuclear energy can be improved by extending plant life and combining this with an increase of ^{235}U enrichment and a higher discharge burn-up of fuel. An additional benefit of this strategy is a decrease in the amount of discharged spent fuel. High burn-up does, however, place stricter demands on fuel performance, although the nuclear fuel burnt in today's reactors is extremely reliable and has a very low failure rate.

Nuclear fuel is licensed in reactor-operating countries for discharge burn-up below the level forecast for future fuel cycles. Before such licensing is approved, the performance of fuel in the burn-up range beyond that used today needs to be investigated and the predictive models benchmarked with experiments. Five countries have licensed the loading of mixed-oxide (MOX) fuel in some of their reactors. Specificity and similarity of this fuel with UO_2 when considering higher burn-up is also being addressed and is becoming of interest to countries considering reactor-based, excess weapons plutonium disposal.

A number of high burn-up experiments have been carried out, and one area considered to be of great importance is the degradation of fuel thermal conductivity as burn-up increases. The need for an international seminar reviewing recent progress and aiming to improve the models used in codes predicting thermal performance was expressed by several national and international institutions. The Commissariat à l'énergie atomique (CEA) agreed to organise the seminar from 3-6 March 1998 at the Château de Cadarache. The seminar was co-organised by the OECD Nuclear Energy Agency (NEA), in co-operation with the International Atomic Energy Agency (IAEA), and hosted by the Département d'études des combustibles (DEC). The general chairman of the seminar was Clément Lemaignan; the co-chairman was Carlo Vitanza of the Halden Reactor Project; and the secretary was Pierre Chantoin, assisted by Régine Bousquet. The organising committee, which reviewed the presentations proposed by participants and shaped the technical programme, was made up of the following people:

- Daniel Baron, EDF;
- Pierre Beslu, CEA;
- Patrick Blanpain, Framatome;
- Pierre Chantoin, CEA;
- Yannick Guérin, CEA;
- Clément Lemaignan, CEA;
- Patrick Menut, IAEA;
- Enrico Sartori, OECD/NEA;
- Maria Trotabas, Cogema.

Sixty-six experts from nineteen countries and four international organisations attended the seminar. The current proceedings provide a summary of the discussions and conclusions of the seminar, together with the text of the presentations made.

The text is published on the responsibility of the Secretary-General of the OECD. The views expressed do not necessarily correspond to those of the national authorities concerned.

Acknowledgements

We would like to express our thanks to the organising committee, the technical programme chairs and all those who contributed to the success of the seminar by presenting their work and competent views. Our gratitude goes to CEA for hosting the seminar and to CEA, Cogema, EDF and Framatome for their generous hospitality. Special thanks go to Régine Bousquet for taking care of the burdensome local arrangements and contacts as well as to Amanda McWhorter for her dedication in editing these proceedings.

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EXECUTIVE SUMMARY

M. Pierre Beslu opened the seminar and welcomed participants. He stressed the great importance of understanding fuel performance in view of using higher enrichment fuel, achieving higher burn-up and for introducing innovative fuel cycles. He announced that the CEA envisages to hold a series of three such seminars, the present one addressing thermal fuel performance, a second fission gas release and a third concerned with pellet clad interaction.

Thermal performance occupies the most important aspect of the fuel performance modelling. Not only is it extremely important from a safety point of view, but also many of the material properties of interest and behaviour, such as transport properties like fuel creep and fission gas release are thermally activated processes. Thus, in order to model these processes correctly, it is critical to calculate temperatures and their distribution as accurately as possible.

In recent years, considerable progress has been made in the understanding of fuel rod thermal performance. This is primarily due to the development of suitable in-core instrumentation and its application to the measurement of fuel centreline temperature during irradiation. There is now a substantial database on in-pile thermal performance covering a wide range of design parameters and material characteristics at both the beginning of life and at high burn-up. In addition post irradiation examination (PIE) techniques have been developed to measure thermal diffusivity and heat capacity on previously irradiated UO_2 fuel, thus allowing a measurement of fuel thermal conductivity at high burn-up.

As an introduction to the seminar, J.A. Turnbull reviewed the thermal behaviour of nuclear fuel and addressed the factors affecting gap conductance and fuel pellet conductivity. This review is the first paper in these proceedings.

The first two sessions were devoted to *Fuel Thermal Conductivity Data* and *Thermal Conductivity Modelling*. This was followed by a first panel discussion, chaired by Hubert Bairiot and Louis-Christian Bernard addressing *Solving and Emerging Thermal Conductivity Questions*. The third session covered *Fuel Clad-Gap Evolution Modelling* followed by a second panel discussing *Gap Evolution and Heat Transfer Questions*, chaired by Gary Gates and Marc Lippens. The two final sessions covered *Experimental Databases* and *Advances in Code Development on Thermal Aspects*.

A final panel, chaired by J.A. Turnbull and Daniel Baron, reviewed the conclusions of the two panels on thermal conductivity and gap conductance and summarised – after discussion among all participants – the key conclusions of the seminar. These conclusions immediately follow this Executive Summary.

Clément Lemaignan closed the seminar thanking participants for their valuable and competent contributions.

CONCLUDING PANEL SUMMARY

J.A. Turnbull, Daniel Baron

Fuel thermal conductivity

Fuel thermal conductivity correlations

The initial thermal conductivity correlations are well established for almost all fuel oxides loaded in commercial reactors. The influence of parameters such as temperature, stochiometry, plutonium content and gadolinium content are relatively well known. Some models are able to account for all these parameters simultaneously.

MOX fuels

The non-homogeneity of MOX fuel can be accounted for, using mathematical homogenisation techniques. However, even for high Pu content the fuel thermal conductivity is close to the uranium oxide fuel conductivity providing O/M close to 2.000. Participants seem to agree on a degradation of 4 to 5% per 10% Pu. However, it was shown that a deviation from stochiometry has a stronger effect.

The burn-up effect

The burn-up effect on fuel thermal conductivity has been assessed up to 80 MWd/KgU, thanks to in-pile centreline temperature measurements and out-of-pile thermal diffusivity measurements. There is some agreement between these two methods.

Cp variation with burn-up

Analysing shut-down temperature records in the Halden reactor, a slight increase of the Cp with burn-up is likely to happen. Nevertheless the discussion outlined that the Cp variation with burn-up could be neglected. The experimental data expected in the near future will certainly allow checking this assumption.

Further needs

A lack of data is identified on the burn-up degradation at temperatures higher than 1800 K. A decrease of the conductivity improvement due to the electronic heat transport is likely to happen with burn-up. This effect was already observed when increasing the gadolinium content.

Heat transfer in the rim

The rim thermal conductivity evolution is not yet clearly known. The thermal degradation due to the onset of numerous micrometer porosities could be balanced by the cleaning of the matrix subsequent to this porosity build-up. In order to investigate the net effect of the rim structure, samples irradiated to high burn-up and temperatures lower than 800 K are required. Other questions are still open about the rim fission gas release and the rim volume variation during the porosity build-up.

Gap conductance

Pellet fragmentation and relocation

The stochastic nature of this phenomenon prohibits analytical modelling of gap conductance. Reliance must be placed on benchmarking models against in-pile data. There is no general consensus as to a definitive formulation for gap conductance. Fortunately a large database exists and providing this is employed, there are limited difficulties in formulating an adequate gap conductance model which correctly reflects the effects of gap dimension, fill gas composition and pressure.

Surface roughness

In principle this should be an important contributor to gap conductance by its effect of inhibiting heat flow. In practice, at both the beginning of line and at high burn-up, there appears to be a little effect on heat transfer between the fuel pellet and the cladding.

Formation of inner clad oxide layer

At high burn-up, when the fuel and clad have been in intimate contact for some time, an inner oxide layer is formed, 6-10 microns thick. It has been shown that this has a complex structure, which can include ZrO_2, uranium and caesium, depending on the heat rating and burn-up. It is supposed that its contribution to gap heat transfer is small and if anything, beneficial, as it would tend to eliminate effects due to surface roughness and misaligned pellet fragments.

Closed gap conductance

There is evidence to suggest that under these conditions, heat transfer is good and substantially independent of the fill gas composition and pressure, since it corresponds to a solid bound between fuel and cladding. There is some debate as to whether or not the conductance depends on interfacial pressure.