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Fuel Modelling at Extended Burnup: IAEA Coordinated Research Project FUMEX-II

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Abstract-*The International Atomic Energy Agency sponsored a Coordinated Research Project on Fuel Modelling at Extended Burnup (FUMEX-II). Eighteen fuel modelling groups participated with the intention of improving their capabilities to understand and predict the behaviour of water reactor fuel at high burnups. The exercise was carried out in coordination with the OECD/NEA.*

The participants used a mixture of data derived from actual irradiation histories of high burnup experimental fuel and commercial irradiations where post-irradiation examination measurements are available, combined with idealised power histories intended to represent possible future extended dwell commercial irradiations and test code capabilities at high burnup. All participants have been asked to model nine priority cases out of some 27 cases made available to them for the exercise from the IAEA/OECD International Fuel Performance Experimental Database.

Calculations carried out by the participants, particularly for the idealised cases, have shown how varying modelling assumptions affect the high burnup predictions, and have led to an understanding of the requirements of future high burnup experimental data to help discriminate between modelling assumptions. This understanding is important in trying to model transient and fault behaviour at high burnup.

It is important to recognise that the code predictions presented here should not be taken to indicate that some codes do not perform well. The codes have been designed for different applications and have differing assumptions and validation ranges; for example codes intended to predict CANDU fuel operation with thin wall collapsible cladding do not need the clad creep and gap conductivity modelling found in PWR codes. Therefore, when a case is based on CANDU technology or PWR technology, it is to be expected that the codes may not agree. However, it is the very differences in such behaviour that is useful in helping to understand the effects of such internal modelling.

I. INTRODUCTION

The International Atomic Energy Agency (IAEA) has sponsored a Coordinated Research Project (CRP) on Fuel Modelling at Extended Burnup (FUMEX-II). Eighteen fuel modelling groups participated, with the intention of improving their capabilities to understand and predict the behaviour of water reactor fuel at high burnups. The Project started with the first Research Coordination Meeting (RCM) in December 2002, there was a second meeting in September 2004 and a final meeting was held in December 2005. A final collation and comparison of the results and publication of the final report will complete the Project.

FUMEX-II is a successor to the first FUMEX exercise (Reference 1) and takes the form of co-ordination between a Code Improvement Exercise and the NEA/IAEA International Fuel Performance Experiments (IFPE) Database. The dual advantages of this co-operation are:

- Exposure of code developers to a wide ranging database
- Assistance in qualification of the IFPE database, correction of errors and detection of missing data, brought about by use of the database for comparison of predictions with data by a large number of workers.

This report will discuss the modelling aspects of FUMEX-II, and briefly describe the aim and the role played by the IFPE for the project.

The participants used a mixture of data, derived from actual irradiation histories, in particular those with PIE measurements from high burnup commercial and experimental fuel, combined with idealised power histories intended to represent possible future extended dwell, commercial irradiations, to test code capabilities at high burnup. All participants have carried out calculations on the 6 priority cases selected from the 27 cases identified to them at the first RCM. The 27 cases were expected to be made available for the exercise from the IAEA/OECD International Fuel Performance Experimental Database (IFPE). The 27 cases are all now available.

At the second RCM, three further priority cases were identified and the teams have now modelled these as well. These priority cases have been chosen as the best available to help determine which of the many high burnup models used in the codes best reflect reality. The participants are using the remaining cases for verification and validation purposes as well as inter-code comparisons.

The codes participating in the exercise have been developed for a wide variety of purposes, including predictions for fuel operation in PWR, BWR, WWER, CANDU and other reactor types. They are used as development tools as well as for routine licensing calculations, where code configuration is strictly controlled. One particular feature has been the development of the European Commission (JRC Karlsruhe) TRANSURANUS code, to cover WWER operation. This code has been provided to several countries operating WWER reactors and several participants are using a WWER version in the FUMEX-II exercise.

The code results presented here were obtained by the participants and used by them in joint meetings to discuss trends and reasons for different results. This paper summarises some of this work.

II. THE CASES

Following the previous IAEA FUMEX programme (Reference 1), a questionnaire had been distributed to the 19 participants of that exercise to provide guidance as to the cases that would further benefit their code development and validation.

The key issues raised in the responses to the questionnaire were those of normal operation and transient response at high burnup, and covered questions concerned with modelling of clad dimensional changes, fission gas release (FGR), internal pressure and fission product distributions as well as fuel temperatures. Therefore, the major objective of the FUMEX-II CRP was agreed to be the improvement of the predictive capabilities of codes used in fuel behaviour modelling for extended burn-up. From the responses received, a list of potential cases was drawn up by a panel of experts at a meeting held in Vienna 26-29 November 2001; the list of cases is given here in Table 1. From this list, participants in FUMEX-II were requested to perform calculations for the six cases identified as high priority in Table 1 and a minimum of a further 4 cases at their discretion. Not all the cases identified were initially available to the IFPE, but as part of the FUMEX-II programme these were prepared and added to the IFPE for participants to use as they need.

The focus of the high priority cases is on the topics:

- Thermal performance
- Fission gas release
- Pellet to clad interaction (PCI)

at extended burn-up above 50 MWd/kgU.

In addition, the CRP was intended address the performance of codes used for transient analysis such as RIA and LOCA at extended burn-up.

One of the problems for modelling high burnup behaviour is the shortage of publicly available experimental data at burnups above 50 MWd/kgU. To help the modellers it was decided that one of the priority cases (Case 27) would comprise nominal, simplified histories specifically designed to test the capabilities of the codes at very high burnup. These simplified histories are:

27(1) to define the locus of the centre-temperature/burn-up threshold for 1% FGR;

27(2a) to calculate FGR for an irradiaton history of 15 kW/m constant power up to 100 MWd/kgU;

27(2b) to calculate FGR for an irradiation history of 20 kW/m at BOL falling linearly to 10 kW/m at 100 MWd/kgU;

27(2c) to calculate FGR for an idealized history supplied by BNFL;

27(2d) to calculate FGR for an idealized high burn-up history, prepared by FANP for which a range of FGR measurements were available

27(3a) and 3(b) to calculate FGR for idealized CANDU histories.

For each of these cases the modellers were provided with details of how the case should be constructed; for example, for Case 27 (2d) the following guidelines were set:

- The reactor should be a 15x15 design, modern PWR

- The fuel rod has 22 bar helium fill gas
- There is a standard UO_2 pellet, 4% enriched, 10 micron mli grain size, low densification
- The cladding is low corrosion Zr-4 cladding with standard creepdown
- The irradiation history provided comprises 49 steps with 12 axial zones to a burnup of 100 MWd/kgU
- FGR data is provided as shown in Table 2

For Case 27 the participants were expected to carry out calculations where possible, noting that the differences between the reactor types included made prediction problematic for some codes. The CANDU cases do not extend to the same level of burnup as do the LWR cases, but the cases are intended to cover advanced CANDU operation at up to 35MWd/kgU. Many of the LWR codes were not able to model the CANDU cases adequately due to the collapsible cladding and high powers, whilst the CANDU codes had problems with clad creep, gap conductance and fuel thermal conductivity degradation which are features of LWR codes.

The remaining priority cases are well-described and documented experiments, Cases 3 and 4 are Halden experiments based on instrumented fuel rods. The data available for modelling includes cladding elongation, fuel centre temperatures as a function of power and fission gas release at burnups over 50 MWd/kgU. The two Risø-3 tests (Cases 14 and 15) are at lower burnup, but provide detailed temperature and fission gas release data during power ramps for different fill gas, whilst the REGATE data (Case 7) covers fission gas release and cladding diameter measurements during and after a transient at around 45MWd/kgU.

The three additional prioritised cases were chosen to try to help the modellers discriminate between the various models used for fission gas release at high burnup. Cases 1 and 2 were chosen to compare similar rods with differing grain size and case 17 from the High Burnup Effects Programme (HBEP) was chosen as the highest available burnup, even though the measured fission gas release was not large. Most modellers also completed all three of the HBEP rods (Cases 16, 17 and 18)

III. THE PARTICIPANTS

Table 3 lists the participants of FUMEX-II, their affiliations and the main codes they are using. The table includes teams who are working in association with FUMEX-II, without formal contractual arrangements, but who are nevertheless participating using the same data and priorities and sharing their results. There is also close cooperation between the IAEA and the OECD/NEA who are custodians of the IFPE. Occasionally other codes were used by some participants, or results were provided with more than one variant of the main code.

IV. THE IFPE

The aim of the International Fuel Performance Experimental Database (IFPE Database) is to provide, in the public domain, a comprehensive and well-qualified database on zircaloy-clad UO_2 fuel and recently MOX fuel for model development and code validation. The data encompass both normal and off-normal operation and include prototypic commercial irradiations as well as experiments performed in Material Testing Reactors. To date, the Database contains over 1200 individual cases, providing data on fuel centreline temperatures, dimensional changes and FGR either from in-pile pressure measurements or PIE techniques, including puncturing, Electron Probe Micro Analysis (EPMA) and X-ray Fluorescence (XRF) measurements. This work in assembling and disseminating the Database is carried out in close co-operation and co-ordination between OECD/NEA and the IAEA and the IFE/OECD/Halden Reactor Project.

The data sets are dedicated to fuel behaviour under thermal reactor irradiation, and every effort has been made to obtain data representative of BWR, PWR, WWER, CAGR and PHWR conditions. In each case, the data set contains information on the pre-characterisation of the fuel, cladding and fuel rod geometry, the irradiation history presented in as much detail as the source documents allow, and finally any in-pile or PIE measurements that were made. Special emphasis is given to data relevant for current issues such as behaviour at high burn-up. The database contains besides the compilation and evaluation of the experimental data also the detailed primary documents from which the data were derived. The compilations contain for user convenience a synthesis with the data required for model development and validation. The IFPE contains all cases investigated both in the FUMEX-I and FUMEX-II exercises. Through the FUMEX exercises, feedback from modellers could be used to improve the content by removing some inconsistencies or errors. The IFPE database is now widely used in about 100 institutions in more than 30 countries. Feedback from users has been essential to ensure that the database improves with its use.

V. THE MODELLING

Results from the modelling teams are presented in Figures 1 to 13. The results are presented so that there is no identification of an individual code and in many case, only a selection of the results has been shown. This is due to the large number of participants and results and also due to the recognition that poor prediction in a particular case outside a code's normal prediction range may have no relevance to that code's performance for its intended use. The figures, therefore, show a representative selection of predictions, showing trends that were noted during the second RCM. The trends appear to reflect the modelling assumptions made in the codes. The results presented here are focussed on fission gas release with some dimensional modelling included.

A compendium of the main modelling assumptions made in the codes was drawn up and considered at the Coordination Meetings to help in the identification of some of the reasons why the codes can produce diverse predictions, particularly at high burnups.

The cases which were intended to test the thermal modelling capability of the codes, priority cases 4 and 15, were well predicted by most of the codes and it is clear that overall the modelling of fuel centre temperature at this high burnup has been very successful.

V.A. Case 7: Transient FGR and dimensional change

Figure 1 shows the results for the REGATE experiment. This experiment provided a base irradiation to 47MWd/kgUO_2 with a measurement of the fission gas release and test transient where rod diameter and fission gas release were also measured. The figure compares the fission gas release measurements with the predictions of all the codes that attempted this case. In the figure each code has been allocated a number and the experimental data are shown towards the right of the figure, as code 25. It is clear that most codes predict both base and transient release quite well. An example of an exception to the general trend is code 6, which is a CANDU code, and this example shows the problems that such codes have with difficult PWR histories.

V.B. Case 27 (1): Threshold release (idealised)

This Case required the teams to reproduce the experimental result of a burnup dependent, threshold centre temperature for fission gas release (the Vitanza threshold, Reference 2) and extend their predictions to 100 MWd/kgU. This empirical line was first developed from experimental data at the Halden Reactor Project and is widely used as an indicator of the conditions required for significant FGR (>1%). There has been recent evidence that the Vitanza threshold is showing too high temperatures at high burnups where there are little data, and beyond the reasonable validation range of around 50 MWd/kgU. What evidence that exists strongly suggests an enhancement of FGR at high burnup where a"rim effect" of enhanced porosity at the pellet surface has developed. (eg Reference 3)

The modelling results are shown in Figures 2 and 3. The first Figure gives some indication of the difficulties encountered at high burnup. For many codes an FGR in excess of 1% is predicted, regardless of temperature above a limiting burnup. This behaviour appears as a vertical line in the plot, and the points shown represent variations of modellers' assumptions to see where this limit might be. Figure (3) is a simplified version of Figure (2), highlighting the modelling trends and indicating where additional data would be useful in determining what effects are occurring at these high burnups.

The important feature of the experimental data that is informing the modelling is that there is enhanced fission gas release at high burnup compared with that expected using normal modelling assumptions. Three main approaches to deal with the high burnup effect have been used by the modelling teams:

- Contribution of FGR from the pellet rim – release from the restructured region
  - Magnitude of the effect was variable
- Burnup dependent diffusion parameters
  - Diffusion coefficient
  - Irradiation induced re-solution
- Limiting saturation concentration of gas in the UO_2 matrix.

In the majority of cases, explicit consideration was also taken for the thermal effect of the rim porosity.

The two general trends A and B shown in the figure are a result of these assumptions, where release is assumed to come from a restructured region, the type B behaviour is found, and release is initiated at a burnup limit, with little temperature dependence. Where the modelling has burnup dependence of diffusion parameters, a more continuous extrapolation of the existing Vitanza curve is seen, this is type A behaviour.

V.C. Case 27 (2a, 2b): Simplified Histories

A selection of the calculated results for one these simplified cases (Case 27 (2a)) is shown in Figure 4. The codes give a very wide range of predictions for the histories, which are again designed to challenge high burnup predictive capability. The results for Case 27 2(b) are very similar. The codes generally predict low FGR below 1% for normal burnups, to 50 MWd/kgU, but at higher burnups the predictions vary, in a similar manner as seen for Case 27 (1), those codes that model release from a rim or gas saturated region tend to give the highest FGR at extremely high burnups.

V.D. Case 27 (2c, 2d): Notional HBU Histories

These cases were provided by fuel vendors, to illustrate possible fuel irradiations that are proposed for advanced fuel cycles. Figure 5 shows the power profile of a single axial zone from a notional history provided by BNFL, the actual case was a 12 axial zone history with a final rod average burnup of 103MWd/kgU. The predictions shown in the figure are typical of the results achieved, and again show low levels of FGR predicted at normal burnup, up to around 60 MWd/kgU However, despite a drop in power as burnup proceeds, the FGR is expected to increase significantly.

The history provided by FANP (now Areva) in Figure 6 was more onerous than the BNFL history at low burnups, but did not extend to the same extreme burnup. The power history was representative of test irradiations of FANP fuel, and the case was also provided with details of the expected range of FGR up to 70 MWd/kgU. It was good to see that the codes tended to give a good representation of the release, showing excellent agreement up to 60 MWd/kgU, and still giving good agreement at 70 MWd/kgU. Due to the power history in this case, it seemed to be less sensitive to details of the high burnup modelling, the majority of the FGR was well described by normal models and significant release had already occurred at low burnups.

V.E. Cases 16, 17 and 18: HBEP Programme

Three rods from the High Burnup Effects Programme (HBEP) were included in the CRP, and Rod BK 365 was selected as a priority following the second RCM. Most participants attempted all three rods and the results are shown in Figure 7. The codes have been allocated a number along the X-axis of the figure and the experimental results are shown by the large symbols as Code 27. Generally the codes reflect the low fission gas release from these rods, due to the low power operation, however there is a general over-prediction of the prioritised case Rod BK365, and few of the modellers reproduced the experimental result of lower release from this rod than from rod BK 370.

V.F. Cases 1 and 2: Grain Size Effect

Two refabricated rods from IFA 534.14 were modelled. The intention was to determine the effect of grain size on the code predictions. Rod 18 (Case 1) had a grain size of 22 microns whilst Rod 19 (Case 2) had a grain size of 8.5 microns. Figure 8 compares the measured and predicted results for Rod 19 (the experimental result is shown as the large symbol for code 27). The code predictions generally give both the base irradiation FGR and the FGR during the Halden irradiation. The experimental result is only for the FGR during the Halden irradiation and is therefore best compared with the incremental FGR calculated from the code predictions, which is plotted as “transient” release. The majority of PWR codes provide a good estimate of the incremental release, but there is an under-prediction from others.

The effect of grain size on the code results is best seen by comparing the ratio of the FGR predictions for the two rods (Figure 9). It is expected that the release from the large grain size Rod 18 should be smaller than Rod 19 and the experimental ratio (Rod 19/Rod 18) was found to be 1.85, roughly proportional to the grain size ratio. It is good to see that most codes gave a ratio close to the experimental value, not only for the transient release, but also for the base irradiation predictions as well, indicating that the modelling of this effect is appropriate..

V.G. Summarised fission gas release results

Figures 10 and 11 give the results of an overall comparison of the code predictions and the experimental measurements. Thee results include all the reported code predictions, not only the priority cases described above. The results are shown as a plot of predicted to measured fission gas release in Figure 10 and as a ratio of predicted to measured as a function of burnup in Figure 11.

The results show that, whilst some codes give excellent results, there is a general under-prediction of the high release measurements (above approximately 10% FGR). However, when the results are plotted as a function of burnup there is no particular trend, and even where there is a systematic under-prediction of the high release experiments, the codes are generally within the usual factor of ×÷2 in predictive capability.

VI. DIMENSIONAL CHANGES

Figures 12 and 13 show the results of some of the dimensional modelling. Figure 12 shows rod diametral changes following ramp testing. Not all codes have the capability to model this effect, but those that do were reasonably successful. The figure shows the predictions of one code along the whole rod length, showing the axial profile, on the right of the figure are the simplified results from the other codes that attempted the case. Several predicted the swelling during the transient reasonably well, and one code gave predictions that bounded the measurements by altering input parameters (these results are shown as code 4 and code 5 in the figure). This code was very sensitive to details in the pellet cracking model.

The priority case 3, IFA 597 rod 7, was intended to test codes handling of the mechanical treatment of fuel pellets and PCMI. The results of four codes are presented in Figure 13. The codes had to calculate the pre-test irradiation, and there were variations in the calculated burnup which caused some difficulties. Only one of the presented codes can be seen to have performed well and predicted the initial extension and subsequent shrinkage noted in the measurements. However the overall predictions of extension were reasonably satisfactory.

VII. DISCUSSION

The modelling of the FUMEX-II priority cases has been carried out by the participating teams of fuel modellers. The modelling results show good agreement with fuel centre temperature measurements for both normal operation and during power ramps.

The modelling also shows good agreement for fission gas release at burnups close to current commercial limits (around 50 MWd/kgU). However, it is recognised that standard models do not account for an increase in fission gas release rates observed at high burnups and the teams have used various options and additional modelling in their codes to try to account for this phenomenon. Three distinct approaches have been tried:

1. Allowing fission gas release directly from the rim structure seen at the periphery of pellets at high burnup. Modelling choices include varying the retentive capacity of this region and in determining how to define the extent of the rim region. Evidence for this mechanism comes from the existence of the rim structure, which seems to initiate at the same time as the additional release.

2. Allowing release of additional gas from saturated regions of the fuel, where the saturation is temperature dependent and the additional release comes from the pellet interior. Modelling choices here lie in determining the saturation level and the temperature dependence of this effect.

3. Allowing an additional burnup dependence on the diffusion and resolution parameters used in standard models. Release of fission gas is enhanced in the pellet centre with this approach.

Experimental data on fission gas distributions in high burnup have not been sufficiently clear to allow the teams to be able to positively distinguish between these models, though each approach would predict different distributions of retained fission gas. The reason why release from the rim is excluded in the latter two approaches is due to the fact that the available data seem to show significant retention of fission gas in this region. Difficulties in interpretation arise from determining the concentration of fission gas retained in bubbles in the rim structure, which are not well measured by standard electron optical techniques. Additional data together with further interpretation and detailed examination of existing data will help in this regard.

The modellers noted several important issues for high burnup modelling which were addressed during the later stages of the FUMEX-II CRP. These included:

- Accurate calculations of the burn-up dependent radial power profile, i.e., Pu build-up at rim.
- What is the effect of the High Burnup Structure (HBS) at the rim? What is its impact on the thermal performance and FGR behaviour of the fuel rod?
- Is a separate treatment of this region required for successful modelling?
- What are appropriate conditions for the formation of the HBS?
- At what burnup does the enhanced release begin
- What temperature limits should apply to the models.
- What are the effects of pressure, grain size, dopants or other details of fuel rod manufacture?

The additional priority cases allowed the participants to attempt a consensus on some of these issues. In particular the modelling of the grain size effect would appear to be reasonably in agreement with the scale of the effect in the experimental data.

The modellers found difficulty with the Risø data in particular, with most under-predicting the measured FGR, however it has not yet been possible to discriminate between the models for high burnup release, though detailed examination of the results is continuing. The overall results show no trend in the predictive capability of the codes with burnup, it would appear that all of the modelling approaches tried to date are adequate to explain the high burnup releases available in the CRP list of cases. Whilst some modellers rely heavily on the rim structure to enhance release at high burnup, others do not, and so far there has been no experimental data available to allow discrimination between the competing models in their release predictions, though there exists experimental evidence of fission gas retention at the rim.

Not many codes have good mechanical modelling capabilities, and the results that were obtained were limited. Diametral swelling was a difficult area for many codes and their models for this were often very sensitive to small changes in the modelling assumptions. The initial rod elongation in a transient due to PCMI was reasonably well predicted by a few codes, but relaxation of the rod growth was rarely modelled.

VIII. CONCLUSIONS

The modelling carried out for the FUMEX-II Coordinated Research Project has been completed, but detailed analysis of the code predictions, including fission product distributions and rod mechanical behaviour, is still in progress.

Results of code predictions against a set of priority cases show that fuel temperature modelling is much improved since the previous FUMEX-1 CRP. Fuel centre temperature predictions are now generally good, and match the data well, up to burnups of around 60 MWd/kgUO_2.

Fission gas release measurements are also generally satisfactory within normal operating burnups, up to around 50 MWd/kg UO_2, but accurate modelling of the release of fission gas at higher burnups is problematic, particularly in the absence of data that could help to discriminate between the various modelling options currently being used by the different teams. These different options lead to different release behaviour when the available burnup range is extrapolated, but within the current database the codes generally fit the measurements.

Mechanical interaction is not well developed and further work in this area would be useful.

REFERENCES

1 IAEA TECDOC-998 Fuel Modelling at Extended Burnup. A Report of the Co-ordinated Research Programme on Fuel Modelling at Extended Burnup – FUMEX. January 1998
2 Vitanza C, Kolstad E and Graziani U, Fission Gas Release From UO_2 Pellet Fuel at High Burnups; ANS Topical Meeting on LWR Fuel Performance, Portland 1979
3 Kinoshita M et al, International Meeting On LWR Fuel Performance, Orlando, Florida, 2004

TABLE I

FUMEX-II cases

Note: the original 6 high priority cases are in **bold** typeface, the additional priority cases are in ***bold italic***

No.	Case identification	Measurements made for comparison
1.	***Halden IFA 534.14, rod 18***	***EOL FGR and pressure, grain size 22 μm, Bu ≈ 52 MWd/kgUO₂***
2.	***Halden IFA 534.14, rod 19***	***EOL FGR and pressure, grain size 8.5 μm, Bu ≈ 52 MWd/kgUO₂***
3.	**Halden IFA 597.3, rod 7**	**Cladding elongation, at Bu ≈ 60 MWd/kgUO₂**
4.	**Halden IFA 597.3, rod 8**	**FCT, FGR at Bu ≈ 60 MWd/kgUO₂**
5.	Halden IFA 507, TF3	Transient temperature during power increase
6.	Halden IFA 507, TF5	Transient temperature during power increase
7.	**REGATE**	**FGR and cladding diameter during and after a transient at Bu ≈ 47 MWd/kg**
8	HATAC	FGR and cladding diameter during and after a transient at Bu ≈ 49 MWd/kg
9.	Kola-3, rod 7 from FA222	FGR, pressure and creepdown at Bu ≈ 55 MWd/kgUO₂
10.	Kola-3, rod 52 from FA222	FGR, pressure and creepdown at Bu ≈ 46 MWd/kgUO₂
11.	Kola-3, rod 86 from FA222	FGR, pressure and creepdown at Bu ≈ 44 MWd/kgUO₂
12.	Kola-3, rod 120 from FA222	FGR, pressure and creepdown at Bu ≈ 50 MWd/kgUO₂
13.	Riso-3 AN2	Radial distribution of fission products and FGR-EOL, Bu ≈ 37 MWd/kgUO₂
14.	**Riso-3 AN3**	**FGR and pressure-EOL, FCT, Bu ≈ 37 MWd/kgUO₂**
15.	**Riso-3 AN4**	**FGR and pressure-EOL, FCT, Bu ≈ 37 MWd/kgUO₂**
16.	HBEP, rod BK363	FGR-EOL, Bu ≈ 67 MWd/kgUO₂
17.	***HBEP, rod BK365***	***Fission products and PU distribution, FGR-EOL, Bu ≈ 69 MWd/kgUO₂***
18.	HBEP, rod BK370	Fission products and Pu distribution, FGR-EOL, Bu ≈ 51 MWd/kgUO₂
19.	TRIBULATION, rod BN1/3	Pressure, FGR, cladding creepdown, Bu ≈ 52 MWd/kgUO₂
20.	TRIBULATION, rod BN1/4	Pressure, FGR, cladding creepdown, Bu ≈ 51 MWd/kgUO₂
21.	TRIBULATION, rod BN3/15	Pressure, FGR, cladding creepdown, Bu ≈ 51 MWd/kgUO₂
22.	EDF/CEA/FRA, rod H09	Fission products and Pu distribution, FGR-EOL, Bu ≈ 46 MWd/kgUO₂
23.	Kola-3 + MIR test	Temperature during ramp, FGR-EOL, Bu ≈ 55 MWd/kgUO₂
24	Kola-3 + MIR test	Pressure-EOL, Bu ≈ 55 MWd/kgUO₂
25.	RIA	to be specified (real data or simplified case)
26.	LOCA	to be specified (real data or simplified case)
27	**Simplified case**	**(1) Temperature vs Bu for onset of 1% FGR**
		(2a) FGR for constant 15 kW/m to 100 MWd/kgU
		(2b) FGR for 20 kW/m at BOL decreasing linearly to 10 kW/m at 100 MWd/kgU
		(2c) FGR for idealized history supplied by BNFL
		(2d) FGR for idealized history supplied by FANP
		(3a) FGR for CANDU idealized history
		(3b) FGR for CANDU idealized history

TABLE II

Fission gas release values for Case 27 (2d)

End of Cycle	2	3	4	5
Full Power Days	673.3	1007.3	1349.0	1689.8
FGR (%)	6-8	6-8	9-13	18-20

TABLE III

Participants and the main codes used:

Code	**Country**	**Name of Chief Scientific Investigator**	**Institute**
BACO	Argentina	Mr. M. Armando	CNEA
FEMAXI-PLUTON FRAPCON 3.2 MACROS-2	Belgium	Mr. V. Sobolov	Nuclear Research Center SCK CEN
TRANSURANUS (WWER)	Bulgaria	Mr. D. Elenkov	Institute for Nuclear Research and Nuclear Energy
FEMAXI–V PIN/PIN2FRAS	Czech Republic	Mr. M. Valach	Nuclear Research Institute, Rez
METEOR	China	Mr. P. Chen	China Institute of Atomic Energy
TRANSURANUS	EC	Dr P. van Uffelen	JRC Institute for Transuranium Elements
FANP Development code (COPERNIC-3)	Germany/France	Mr. F. Sontheimer	FRAMATOME ANP GmbH
INFRA	Korea Republic, of	Mr. Chan Bock Lee	Korea Atomic Energy Research Institute
TRANSURANUS DCHAIN5V	Romania	Ms. A. Paraschiv	Institute for Nuclear Research
START-3	RF	Mr. G. Khvostov	A.A. Bochvar Res. Institute of Inorganic Materials
ELESTRES	Canada	Mr. M. Tayal	AECL
FAIR FUDA PROFESS	India	Mr. H.S. Kushwaha	BARC
	UK	Mr. T. Turnbull	Consultant
FEMAXI JINS	Japan	Mr. K. Kamimura	NUPEC
ENIGMA IMAGE	Finland	Mr. K. Kelppe	VTT
PIN W99	Bulgaria	Ms S. Stefanova	INRE
PSI version TRANSURANUS	Switzerland	Mr A. Nordstroem	PSI
ENIGMA-B 7.7	UK	Mr G. Rossiter	BNFL

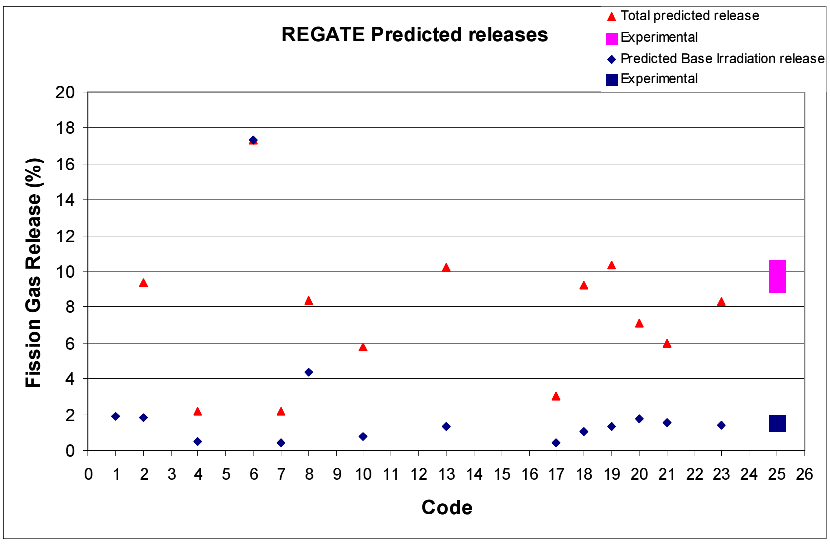

Fig.1 Case 7, REGATE. In this figure each code is identified by a number and their predictions for base and transient fission gas release are shown. The experimental results are shown as Code 25.

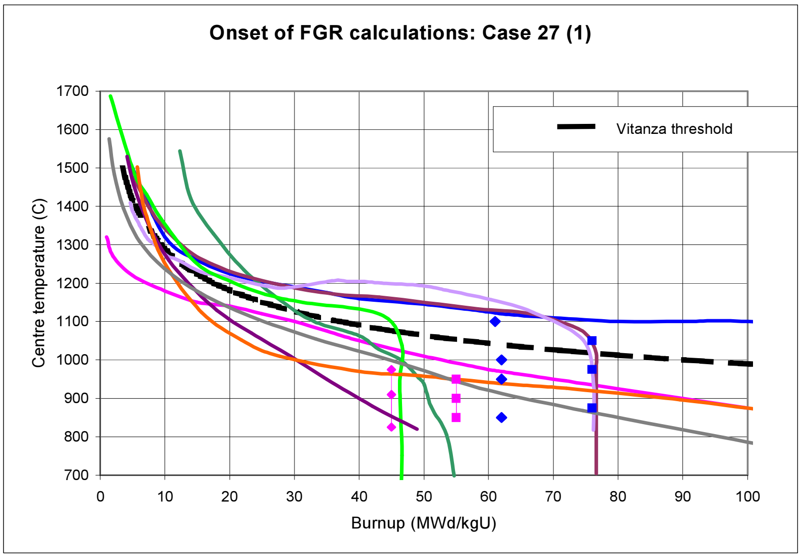

Fig. 2. Modelling results for Case 27 (1), Fission Gas Release Threshold. Representative code predictions are shown.

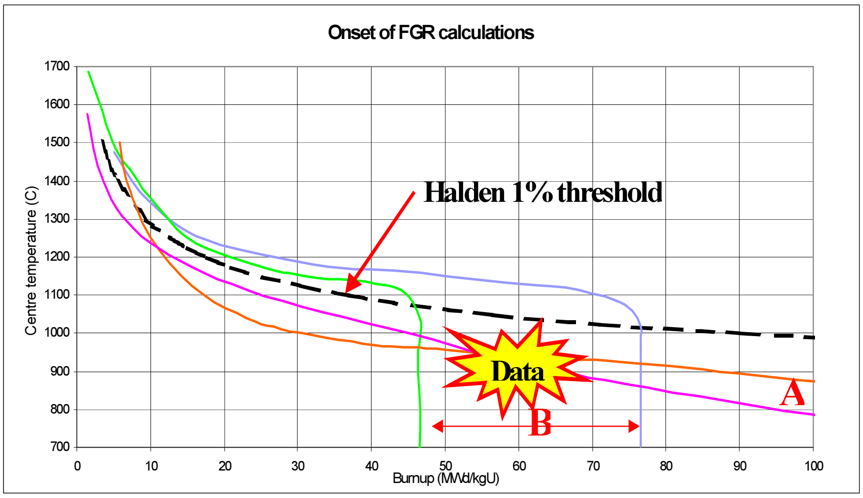

Fig. 3. Simplified diagram of the fission gas threshold calculations, indicating two distinct types of predictive behaviour at high burn up. The region where additional data would be most useful is highlighted

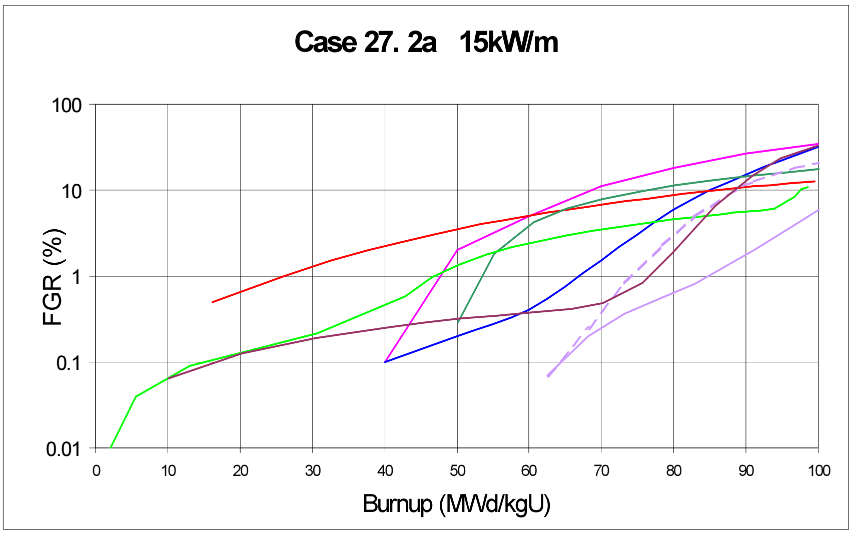

Fig. 4. Predicted fission gas release from standard PWR fuel at a constant rating of 15kW/m. Eight representative code predictions are shown.

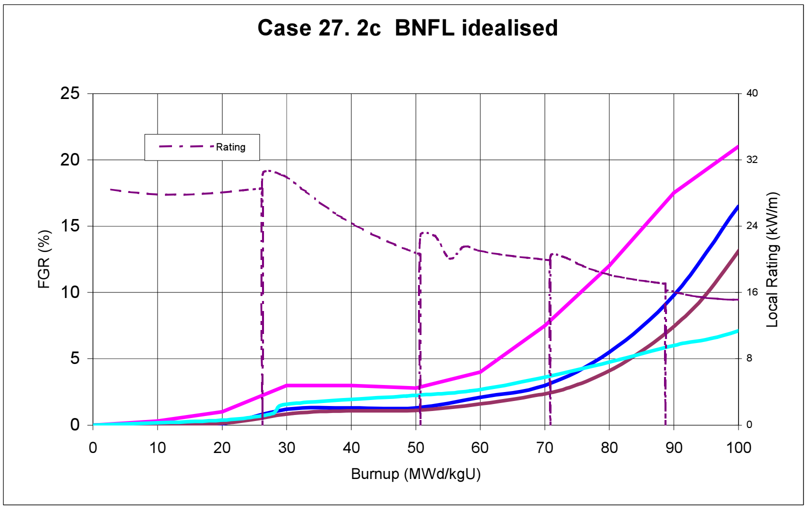

Fig. 5. Case 27 (2c): Fission gas release predictions for an idealised operational history to 100 MWd/kgU provided by BNFL. The rating history of a single axial zone is given. Four representative code results are shown.

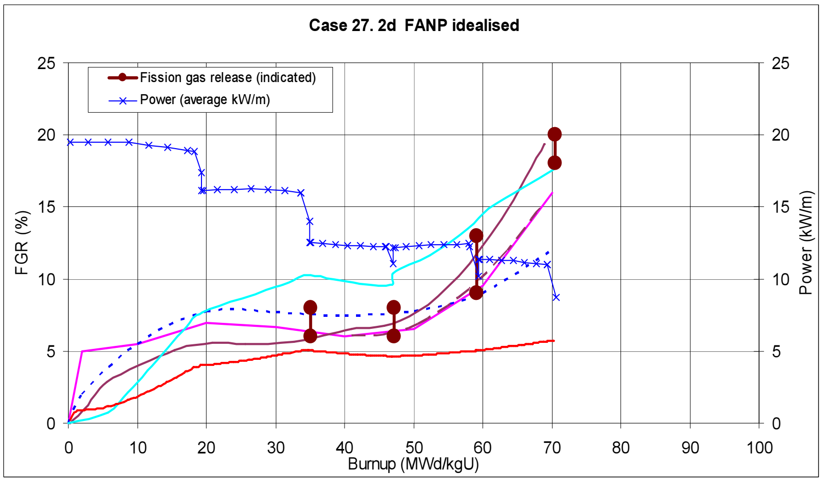

Fig. 6. Case 27 (2d): Fission gas release predictions from five codes for an idealised operational history to 70 MWd/kgU. The history was provided by FANP and the indicated FGR measurements and rod average power are shown.. Five representative codes predictions are shown.

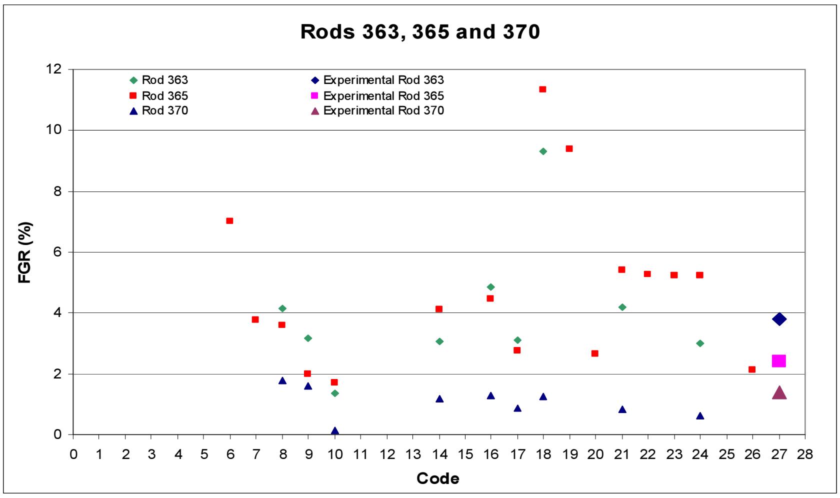

Fig. 7. Cases 16, 17 and 18: High Burnup Effects Programme rods BK363, BK365 and BK370. The code predictions of fission gas release are shown (each code has been allocated a number, and not all codes were able to predict these cases). The experimental results are shown as Code 27.

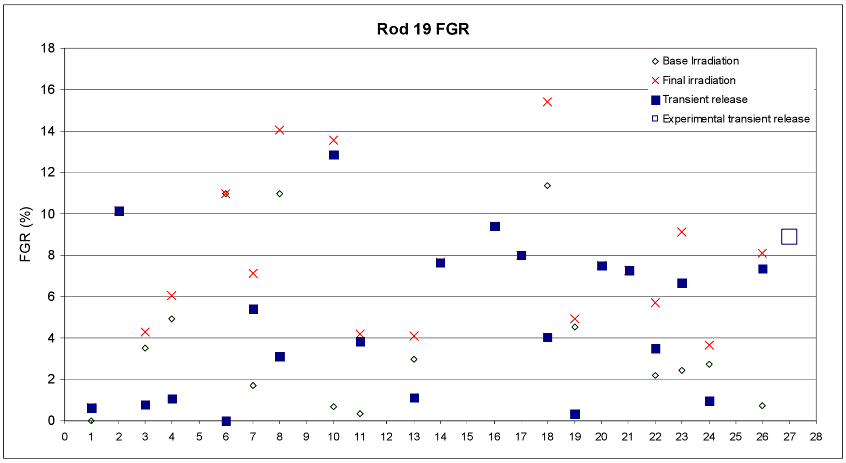

Fig. 8.Case 2: Predicted fission gas release (FGR) from IFA 534.14 rod 19. The code predictions of FGR are shown (each code has been allocated a number, and not all codes were able to predict these cases). The code results give FGR at the end of the base irradiation and at the end of the test irradiation in Halden. The measurement (shown as code 27) is for the release during the Halden irradiation, and should be compared with the "transient" release (final FGR – base FGR) for the code predictions.

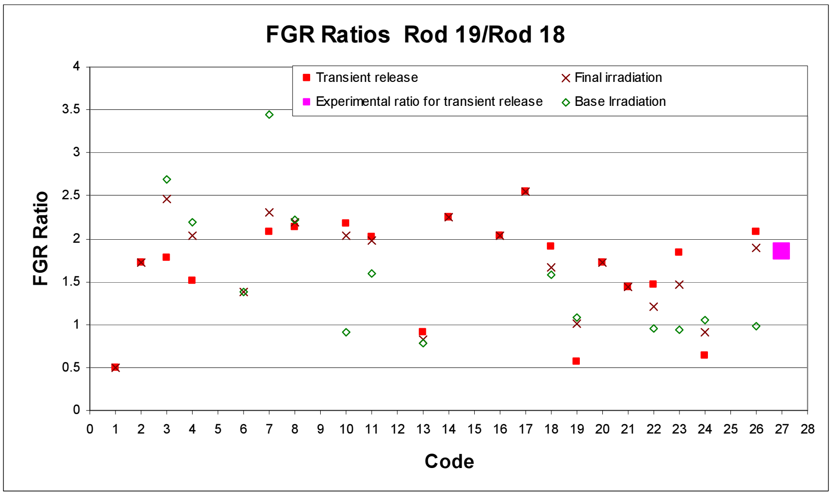

Fig. 9. Cases 1 and 2, Halden IFA 534.14, rods 18 and 19. Grain size effect comparison: Rod 18 had a grain size of 22µm and rod 19 had a standard grain size of 8.5µm. The code predictions of the ratio of fission gas release from the rods are shown (each code has been allocated a number, and not all codes were able to predict these cases).The experimental results are only available for the transient release in the Halden reactor and are shown as Code 27.

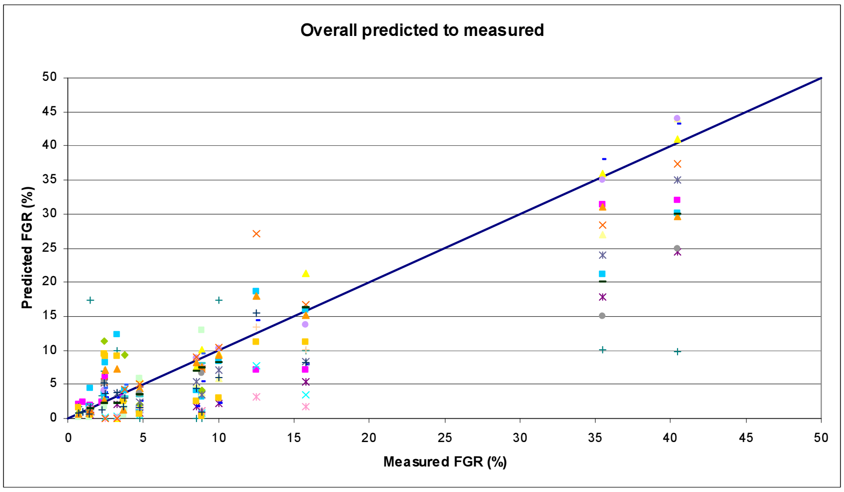

Fig. 10. All results for the fission gas release predictions from the codes compared with the measurements. There is a general under-prediction of the high release measurements from the Risø AN3 and AN4 tests.

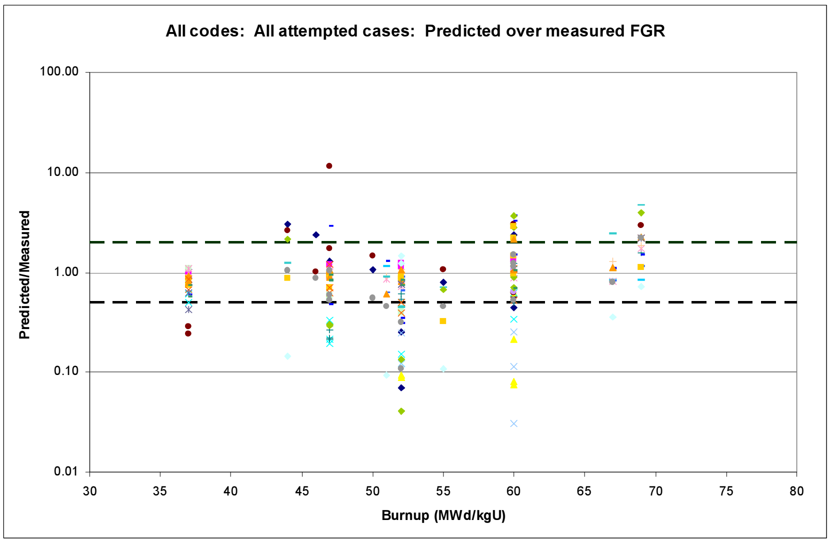

Fig. 11. Predicted to measured fission gas releases for all the cases and all the codes. The bounds shown as dotted lines are a factor of times-divide 2. There is no discernable trend for under-prediction at high burnup.

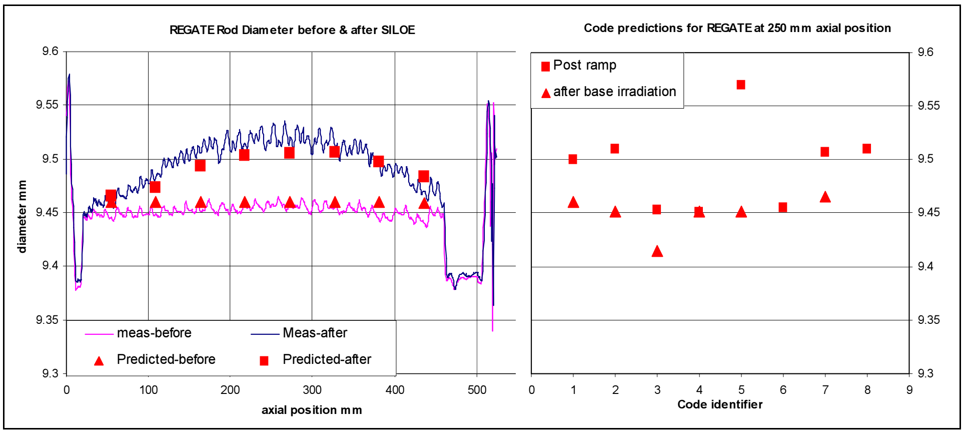

Fig. 12.Case 7 REGATE: Rod diameter predictions following the SILOE ramp. The diameter measurements are shown with one code predictions superimposed. Other code predictions for the maximum deformation near the centre of the rod are shown to the right of the figure.

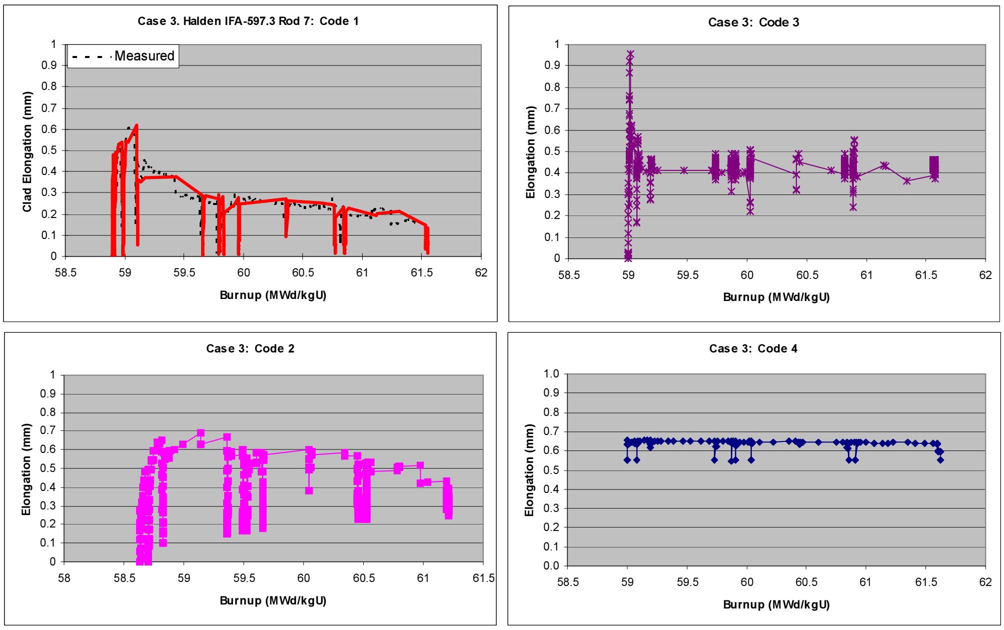

Fig. 13 Predicted and measured length changes of IFA 597 (Case 3).