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SUMMARY AND CONCLUSIONS OF THE CSNI SPECIALIST MEETING ON TRANSIENT BEHAVIOUR OF HIGH BURNUP FUEL

Held in Cadarache, France, from 12th to 14th September, 1995

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The CSNI Specialist Meeting on Transient Behaviour of High Burnup Fuel was held in Cadarache, France, from September 12th to 14th, 1995. It was hosted by the CEA Institut de Protection et de Sûreté Nucléaire (IPSN) at the Château located at the nuclear research centre of Cadarache. More than 125 experts from 15 OECD countries as well as experts from Russia and the IAEA attended the meeting. Thirty-two papers were presented in four sessions.

The purpose of the meeting was to bring together experts involved in the different activities related to high burnup fuel behaviour under transient conditions, and in particular during reactivity initiated accidents (RIA). The experts came from all involved parties, including research organisations, regulatory authorities, fuel designers and utilities. Information was openly shared and discussed on the integral experiments results, separate-effect tests findings and analytical assessments performed. Regulatory background and licensing implications were also included to provide the proper frame for the technical discussions.

The meeting focused on reactivity initiated accidents (RIA) because of the current interest in that subject and the significant amount of new technical information being generated. The meeting was structured around three main technical areas : integral experiments, separate effect tests and plant calculations, plus a background on the current regulatory status. Each of these areas corresponded to a separate session. The general conclusions from the meeting as well as the recommendations from the ad-hoc group to CSNI/PWG 2 together with the specific summary and conclusions from each session are included in the following points.

GENERAL CONCLUSIONS

1. Three major test programs (SPERT, NSRR and CABRI) with high burnup fuel have each found a specimen that failed at very low energy deposition.

2. These low energy failures are all believed to be caused by pellet-clad mechanical interaction, assisted by embrittlement of the Zircaloy cladding at regions with high local concentrations of hydrides.

3. Test conditions were not matching, in some parametric details, with the expected reactor conditions and the effect of these differences are not yet fully understood. Despite these aspects of non-direct-representativity, important insight is gathered from the tests on loading and resistance factors and burnup effects are revealed.

4. Tests with different cladding (Zr-1Nb) and large power pulse width conditions (~700ms) produced ductile failures at high energies in contrast to brittle failures seen in Zircaloy clad fuel rods subjected to short pulses (≤ 10ms).

5. Plant calculations are consistently showing pulse widths of 25 to 75ms and indicate that rod worth and the loading pattern are important parameters. 3D calculations reveal significant conservatism of present licensing methods using 2D/1D calculations.

6. Changes in material properties (e.g. thermal conductivity) will affect neutronic calculations. Uncertainties have to be considered in future evaluations.

7. Important materials properties at high burnup have already been measured and mechanical properties testing is just being initiated for conditions of RIA.

8. Fission gas expansion leads to grain separation and fuel fragmentation in the tests and might affect significantly the accident consequences if, after failure, finely fragmented fuel particles are ejected into the coolant water and produce violent boiling and pressure generation from fuel-coolant interactions.

9. The significance of the RIM effect is presently not fully understood or demonstrated. Its contribution to the failure phenomena is questioned. For larger pulse widths, calculations show that the thermal level reached in the RIM region is significantly decreased and associated fission gas phenomena might be mitigated.

10. Presently, there is no test facility able to perform RIA experiments under fully representative plant conditions of:

- coolant nature,
- system pressure,
- flow and temperature conditions,
- controlled pulse width,
- sufficiently high energy deposition (safety margin with regard to plant calculations).

The CEA/IPSN introduced its project to implement a pressurised water loop into the CABRI reactor to resolve this deficiency.

RECOMMENDATIONS TO CSNI/PWG 2

From the Specialist Meeting and its conclusions, the ad-hoc group recognises that:

- One of the important achievements of the CSNI meeting was to provide for the first time a forum for an extensive exchange of technical information.
- Common technical positions exist for some of the phenomena involved, but there are still technical issues under discussion.
- Several countries have on-going programs and/or are planning activities to improve the understanding of high burnup fuel behaviour under transient conditions.

Therefore the ad-hoc group proposes to CSNI/PWG 2:

1. To meet at least once more (suggested timing April 1996) to prepare a technical position paper that will:

- Consider the different options to continue providing a proper forum for exchange of technical information.
- Discuss the needs and rationale for any further work to better understand the transient behaviour of high burnup fuel.
- Consider the different options to co-ordinate and efficiently integrate OECD member countries activities on this topic.

2. To enlarge the ad-hoc group with additional industry representatives and a Russian expert to properly take into account the various activities and technical points of view. This extension should be limited to those institutions currently performing a significant work in this area in to keep the size of the group reasonably small.

3. To endorse the publication of the Proceedings of the Specialist Meeting as a general distribution document. This document consists of the papers presented, the main facts from the discussion that took place and the summary and conclusions prepared by the session chairmen and the Programme Committee.

SUMMARY OF SESSION 1 : REGULATORY BACKGROUND

The introductory session provided background information and established the safety relevance of the research papers presented in the meeting. The meeting focused on the behaviour of high burnup fuel during reactivity initiated accidents (RIAs). In the session, burnup levels licensed and achieved to date were described. Expected burnup extensions, current fuel damage criteria and regulatory actions taken in response to recent high burnup test data were discussed by members of regulatory authorities from USA, France, Japan and Germany. Similar information for Switzerland was presented in a paper in Session III and is included in this summary.

Licensed burnup limits, burnup levels achieved to date and expected burnup extensions

The following licensed burnup limits have been reported :

- a maximum rod-average burnup of 60 GWd/t in USA
- a generic limit for the assembly average burnup of 47 GWd/t in France
- generic limits for the assembly average burnup of 48 GWd/t for PWRs and of 50 GWd/t for BWRs in Japan
- Examples of maximum assembly average burnups are 65 GWd/t for PWRs and 53 GWd/t for BWRs in Germany.
- assembly average burnups of 48 to 60 GWd/t for different reactors in Switzerland.

In the US, assembly average burnup levels up to 52 GWd/t have been achieved and requests for a peak rod average burnup up to about 75 GWd/t have been proposed to the USNRC. In France, Japan and Germany, the utilities aim to increase the maximum assembly average burnup from 42-50 GWd/t to 52-55 GWd/t with a corresponding peak pellet average burnup of about 65 GWd/t in the near future. In Switzerland, peak pellet average burnups up to 66 GWd/t have been attained.

Current fuel damage criteria

There is general agreement that a control rod ejection accident in a PWR or a control rod drop accident in a BWR must not result in a loss of core coolability or mechanical damage to the primary system. Based on earlier experiments, it was assumed that this design goal can be satisfied if fuel fragmentation and dispersal is prevented and corresponding radially-averaged peak pellet enthalpy limits of 280 Cal/g in USA and Switzerland, 230 Cal/g in Japan and 200 Cal/g in France have been prescribed. As cladding failure threshold for burnup fuel radially-averaged peak pellet enthalpy limits of 170 Cal/g (in USA, Germany and Switzerland) or of 85 Cal/g (in Japan) have been defined. In Germany, a RIA must not cause any damage to the reactor core and is classified as an event without radiological impact and so cladding failures must be avoided.

Regulatory actions taken in response to high burnup test data

In response to the recent high burnup RIA test data, the following regulatory actions have been taken in some countries:

- Decisions on requests for extension of burnup limits beyond the maximum value previously approved were suspended until sufficient supporting transient performance data were available.

- The industry was asked to evaluate the significance of lower enthalpy thresholds for cladding failure and fuel dispersal on the safety of the plant and the radiological consequences. It was found that, if the present burnup limits were respected, no immediate threat to the safe operation of LWRs was posed.

- In several countries, a detailed evaluation of the transient test data for high burnup fuel was initiated and a co-ordinated effort between the industry, international experimenters and regulatory representatives is being pursued to develop appropriate fuel damage criteria for use in safety analyses.

- A new provisional licensing criterion for fuel cladding failure that is burnup dependent is being used in Switzerland :

ΔE (Cal/g) = 125 - 1.6B (GWd/t)

In summary :

(a) Different licensing procedures are used in different countries.
(b) Several presenters suggested that additional technical information is needed before regulatory positions are modified.

SUMMARY OF SESSION II : INTEGRAL TESTS AND ANALYSIS

Presentations

Nine (9) papers on integral tests and analysis including unexpected transient in an inpile experiment were presented.

Two (2) papers on NSRR test results and their interpretation were presented by JAERI. Results of pulse irradiation of 4 PWR rods irradiated to 50 GWd/MtU (HBO-1~4) and irradiated PWR type segment rods were introduced, and the failure mechanism was discussed.

Three (3) papers on the CABRI program, test results and analysis were presented by IPSN and CEA/DRN. Transient and PIE results of pulse irradiation of a 64 GWd/MtU PWR rod, failed at the fuel enthalpy of about 30 Cal/g (REP Na1) were introduced. Failure mechanism was discussed based on the interpretation of PIE results and code analysis of REP.Na1 and also of other 4 tests followed (REP.Na2~5).

Results and interpretation of high burnup Russian PWR rods irradiated at IGR pulse reactor were presented by NSI RRC-KI. Through the IGR tests, 13 WWER-1000 rods irradiated to 48 GWd/MtU, 10 rods with irradiated cladding and 20 fresh rods were irradiated in IGR by relatively slower pulse power than NSRR or CABRI tests. Failure mechanism and threshold were discussed.

Interpretation of major fuel failure mechanisms and the effects of cladding materials were introduced by INEL/USNRC, based on the interpretation of SPERT, PBF, NSRR, CABRI, IGR and other test results. Experience of fuel failure in an unexpected transient in experimental capsule of BR2 reactor, and that of ramping experiments for high burnup rods in Studsvik were introduced.

Main conclusions

Main conclusions obtained through the presentations and the discussion can be summarised as follows :

(1) ***Fuel Failure Mechanism***

Common understanding is that the hydride-assisted PCMI failure mechanism is responsible for the failure of high burnup fuel rods under fast power transient of an RIA.

This type of failure has been observed for burnups higher than about 20 GWd/MtU in NSRR, CABRI, SPERT and PBF experiments.

The cracks in the cladding are initiated at the spots of local pre-existing hydriding, spot hydriding by spalling off of oxide layer and/or radially localised hydriding, at the surface during very early phase of the transient (few to some ten ms). The strong loading to the cladding may be enhanced by expansion and liberation of fission gas at grain boundaries by quick temperature rise, in addition to thermal expansion of the pellets.

Different type of failure of high burnup fuel has been observed in IGR tests. Low level of oxidation (5~6μm) and absence of significant effects of cladding hydriding prevents PCMI failure. All the test rods failed by high temperature rupture of cladding, at the peak fuel enthalpy of 240 Cal/g for 48 GWd/t. However, direct comparison of the results is rather difficult due to large difference of power pulse width between IGR and other tests in NSRR, CABRI, SPERT and PBF.

Studies of the effects of power pulse width should be performed through experiments and analysis.

For much slower transient power rise of some ten seconds or larger, the failure mode will change to cladding oxidation or melting after DNB or by PCI failure, as were seen in BR-2 transient.

(2) ***Effects of major parameters***

- Fuel burnup

One of the dominant factors to control loading to the clad by fission gas expansion and by clad hydriding. The effects become more evident for over 40 GWd/MtU.

- Power Pulse Shape

There may exist the effects of pulse width to fuel failure mode and threshold. Strain rate in the pellet may become lower with wider pulse and milder grain boundary separation, resulting in milder loading to the cladding, for example.

Different understanding that the effect will be minor compared with clad hydriding is also presented.

- Cladding hydriding/oxidation

Local hydriding at cladding surface is thought to be important as the initiation sites of cracks. Spalling off of the oxidation layer at high burnup is one of the important causes of local heavy hydriding.

Embrittlement of the cladding with increase of average hydriding and high strain rate will also enhance the propagation of the cracks and may decrease the failure thresholds.

- Cooling conditions

For the failure mode of cladding rupture after DNB, high system pressure might have some influences due partly to suppressing DNB initiation and partly to decreasing pressure difference across the cladding . But no experimental evidence exists yet to quantify this effect.

(3) ***Failure thresholds***

Fuel failure enthalpy decreases with burnup, especially above 40 GWd/MtU. The lowest value of failure enthalpy obtained in the integral tests are 85 Cal/g at 32GWd/MtU (SPERT), 60 Cal/g at 50 GWd/MtU (NSRR) and 30 Cal/g at 64GWd/MtU (CABRI).

Plots of fuel failure enthalpy vs. burnup are often used to indicate the effects of burnup. But one should be careful when applying in a quantitative manner without consideration of the experimental conditions.

These values are dependent on the experimental conditions i.e. fuel design, irradiation conditions, system pressure and temperature, pulse width, etc.

(4) ***Application to reactor conditions***

Integral tests are not fully representative of the actual reactor conditions. Ample consideration should be taken when applying the test results to actual reactor conditions. Major conditions to be considered are :

- System conditions (coolant pressure, temperature and flow)
- Transient power history (power pulse width)
- Fuel conditions (fuel design, irradiation conditions).

Since the crack initiation in the cladding is strongly influenced by local hydriding, it is expected that modification of clad material against oxidation (low tin, Nb addition, etc.) may largely improve the strength against PCMI failure, but no firm experimental evidence yet exists.

(5) ***Fission product release***

FP release from the failed rod to the coolant is important for the estimation of environmental impact. NSRR and CABRI test results indicated that FP release is a strong function of fuel burnup. The correlation is to be further developed for higher burnup region for better estimation.

(6) ***Fuel fragmentation and consequences***

Release of finely fragmented fuel particles at fuel failure has been observed in CABRI and NSRR tests. As a consequence of the fuel dispersal, partial blockage of the flow channel occurred in the CABRI test, but no significant mechanical energy generation has been detected at the energy deposition range reported. It is suggested, however, that vigorous steam generation resulting in significant mechanical energy may occur when fine fuel fragments are released into the coolant especially at high temperature at higher energy deposition.

Remaining issues

From the safety point of view, the two more important aspects of fuel behaviour are fuel cladding failure and the resulting fission product release, and fuel fragmentation which may threaten core coolability and the integrity of the reactor primary system.

(1) Fuel failure

- Quantify uncertainties
    - . Experiments : measurements
      probabilistic reliability of test data
    - . Analysis : code validation, input qualification

- Application to reactor conditions
    - . Coolant conditions
    - . Fuel design
    - . Burnup range
    - . Power shape, etc.

(2) Fuel fragmentation and consequences at high energy depositions

- Experimental data from integral tests and interpretation.

SUMMARY OF SESSION III : PLANT CALCULATIONS

For BWRs and PWRs, the design basis RIAs have been reviewed to determine the effect of the presence of high burnup fuel on the accident consequences. Results of analyses for rod ejection accident (PWR) and control rod drop accident (CRDA), (BWR) have been presented. The main objective was to perform more realistic evaluations and to compare results with licensing approaches. Realistic evaluations start from the specification of core loadings of operating plants and use 3D neutron kinetics methods. Additional conservative assumptions were taken for some analyses presented: these included e.g. conservative assumptions on initial conditions of the plant and sensitive parameters such as rod worth, peaking factors, feedback mechanisms, etc.

The comparison of calculations by refined 3D neutronics and thermohydraulic models and licensing approaches using zéroD- or 1D-neutronics shows a reduction of enthalpy rise of approximately a factor of 2 to 3. For many PWRs, the control rod worth is below prompt-critical conditions under realistic assumptions. For BWRs results were presented which show that the reactivity insertion of CRDA reaches prompt-critical values of 1.3$ to 1.5$. Higher values such as 2 to 3$ may be reached under conservative assumptions.

The most important parameter for RIA analyses is the inserted reactivity by the control rod. The consequences are localised to the nearest fuel assemblies of the dropping or ejecting control rod , typically 2 to 3 rows.
The core loading pattern influences the results in two aspects :

- it affects the control rod reactivity worth
- it determines the location of fresh and burnt fuel assemblies in the neighbourhood of the dropping or ejecting rod.

The dependence of enthalpy rise on burnup is evaluated in most contributions by detailed scatter plots. Generally, these figures show a decrease of enthalpy rise with increase of burnup. Analyses of RIA for both reactor types were presented which showed that based on realistic evaluations, the number of failed rods was small or even zero. In some contributions, preliminary burnup-dependent fuel failure limits have been used, including CABRI-REP Na1 test, to determine the number of failed fuel rods during RIA.

Questions remain as how to systematically consider uncertainties in sensitive parameters and issues like the effect of burnup on fuel rod parameters (e.g. heat conductivity and capacity, gap resistance and radial power distribution in the fuel rod).

A controversial discussion is about the importance of the RIM-effect on the fuel rod failure mechanism. Some experts argue that thermal expansion is sufficient to explain fuel rod responses without assuming additional fission gas release from the RIA area.

Based on the comparison of reactor transient time-behaviour and the pulse width of RIA experiments, concerns have been expressed whether test conditions are really representative for reactor transients. Typical values of pulse-width from RIA reactor calculations are in the range of 25ms to 75ms and even greater values for some BWR rod drop cases, whereas RIA experiments are performed with fast pulses in the range of 4-9ms. The consequences of this difference for the fuel rod failure mechanism should be determined.

The opinion was expressed that if burnup-dependent fuel failure limits were to be imposed, the analysis methodology used to demonstrate compliance to these limits should use realistic evaluation methods

However, it is understood that assumptions on accident conditions and analysis methodology used in licensing evaluations will be determined by the licensing requirements.

SUMMARY OF SESSION IV : SEPARATE-EFFECT TESTS AND ANALYSIS

A significant body of experimental work, both separate- and integral-effect tests, and analytic work, has been presented which relates to the behaviour of high burnup LWR fuel during rapid power pulses such as those in Reactivity Initiated Accidents (RIAs). It would appear that all of the important phenomena and factors, affecting this behaviour, have been identified. These important phenomena and factors are as follows:

1. The transient thermal/mechanical behaviour of highly irradiated clad. Factors of importance include the :

    I. material type and fabrication route ;
    ii. degree and characteristics of oxidation, with emphasis on the extent of spallation;
    iii. degree and orientation of hydriding with a focus on hydride gradients ; and
    iv. strain rate sensitivity of the clad.

2. The transient thermal/mechanical behaviour of the high burnup « rim » region of the fuel (i.e. enhanced rate of fuel heatup, grain-boundary gas bubble pressurisation, fuel microcracking, transient gas-release to the free volume and fuel swelling).

3. The characteristics of the RIA power pulse (i.e. pulse width, gross energy deposition into the fuel, transient heat removal to the coolant and consequent fuel enthalpy).

4. The fuel conditions immediately prior to the accident (i.e. the degree of fuel/clad gap closure, the fuel radial power profile, the radial variation in fuel thermal conductivity and porosity, and the resultant fuel radial temperature distribution).

5. Longer term (i.e. post-DNB) transient fission gas/volatiles release and consequent fuel swelling.

In order to quantify the fuel energy deposition required to result in high burnup fuel clad failure, the major considerations are the loss of clad ductility and the factors which determine the transient thermal behaviour and loading of the clad. This first point (listed previously) related to the loss of clad ductility. The latter four points relate to the transient thermal behaviour and loading of the clad.

It would appear that if extended burnup fuel has clad characterised by high hydrogen contents (i.e. localised hydride formations such as « sunbursts »and/or hydride distribution gradients), then clad failure will occur at reduced energy depositions. Thus, from the point-of-view of clad failures during RIAs, obtaining quantitative information on the range of conditions that lead to a significant loss of clad ductility is of primary importance. It is apparent, from the papers presented, that this information has been, is being, and should continue to be obtained through well-characterised separate-effects tests in various countries.

Existing programs that provide insight into the previously discussed factors include :

i. ex- and in-reactor investigations of the burnup dependence of fuel thermal conductivity, and the conductivity of « rim structure » fuel :
ii. ex-reactor tests on the mechanical properties of clad from high burnup rods as a function of corrosion, hydriding, fast neutron fluence and strain rate ;
iii. neutronic and thermal-hydraulic code calculations to assess realistic energy depositions and pulse widths for RIAs ; and
iv. detailed post-test examinations of failed and intact RIA-tested rods, including measurements of the radial distributions of fission gas release and fuel swelling and clad strains and cracking.

Additional insight into the behaviour of highly irradiated fuel rods in RIAs would be obtained via further work on :

i. The definition of radial power peaking in high burnup fuel ;
ii. Analysis of thermal diffusivity/thermal conductivity measurements ;
iii. Further correlation between oxide layer spallation, hydride concentration and distribution, and clad ductility loss under prototypical RIA conditions, including recovery of clad ductility as a function of time at temperature ; and
iv. in-reactor RIA tests at prototypic neutronic, coolant and pre-transient conditions.

It is a more complex problem to quantitatively assess the potential for, and/or extent of, dispersion of highly irradiated fuel as a function of energy deposition in an RIA. In this case, it is important to understand the interplay between all the various factors affecting the transient, thermal/mechanical behaviour of the high burnup UO_2 fuel.

If a more representative, less restrictive understanding of the potential for high burnup fuel dispersion during RIAs is desired for LWR licensing analyses, then further, more prototypic in-reactor tests would contribute to this understanding and licensing code validation. If required, these more prototypic in-reactor tests should be performed under conditions more representative of those expected in LWR RIAs (i.e. wider power pulse widths, representative pre-transient fuel and transient coolant conditions).