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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Safety Significance of the Halden IFA-650 LOCA Test Results

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The committee's purpose is to foster international co-operation in nuclear safety amongst the NEA member countries. The CSNI's main tasks are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and research consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

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FOREWORD

The NEA Working Group on Fuel Safety (WGFS) is tasked with advancing the understanding of fuel safety issues by assessing the technical basis for current safety criteria and their applicability to high burnup and to new fuel designs and materials. The group aims at facilitating international convergence in this area, including the review of experimental approaches as well as the interpretation and use of experimental data relevant for safety.

Since the time of the first LOCA experiments, which were largely conducted with fresh fuel, changes in fuel design, the introduction of new cladding materials and in particular the move to high burnup have generated a need to re-examine the LOCA safety criteria and to verify their continued validity. As part of international efforts to this end, the OECD Halden Reactor Project (HRP) implemented a LOCA test series. The fourth test in this series, using a commercially irradiated segment with 92 MWd/kg burnup, exhibited strong fuel fragmentation and dispersal upon ballooning and burst at 790°C. The fact that fuel dispersal could occur at cladding temperatures far lower than the temperature entailed by the current 1200°C / 17% ECR limit caused concern. The CSNI therefore posed the question to the WGFS:

How could the Halden LOCA tests affect regulation?

This report provides a summary of the WGFS members’ evaluation related to this task.

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The report is based on the statements and opinions provided by WGFS members and experts from their respective organisations. In particular, the following persons gave valuable input to various chapters of the report or participated in the extensive review process:

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List of abbreviations

AEKI	Atomenergia Kutatóintézet / Atomic Energy Research Institute (Hungary)
ANL	Argonne National Laboratory
BWR	Boiling water reactor
CAPS	*CSNI* Activity Proposal Sheet
CEA	Commissariat à l'Énergie Atomique
CSNI	Committee on the Safety of Nuclear Installations
ECCS	Emergency core cooling system
ECR	Equivalent cladding reacted
EOC	End of cycle
EDF	Électricité de France
EPRI	Electric Power Research Institute
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
HBS	High burnup structure
HRP	OECD Halden Reactor Project
IFA	Instrumented fuel assembly
IFE	Institutt for energiteknikk (Norway)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JAEA	Japan Atomic Energy Agency
LOCA	Loss-of-coolant accident
LWR	Light water reactor
MOX	Mixed oxide
NPP	Nuclear power plant
NRI	Nuclear Research Institute (Czech Republic)
OECD	Organisation for Economic Co-operation and Development
PCT	Peak clad temperature
PIE	Post irradiation examination
PSI	Paul Scherrer Institut (Switzerland)
PWR	Pressurised water reactor
RIA	Reactivity insertion accident
RT	Room temperature
SPND	Self-powered neutron detector
TC	Thermocouple
TCCx	Denomination of cladding thermocouple in Halden LOCA tests
TCHx	Denomination of heater thermocouple in Halden LOCA tests
US NRC	United States Nuclear Regulatory Commission
VTT	Valtion Teknillinen Tutkimuskeskus / Technical Research Centre of Finland
WGFS	Working group on fuel safety

EXECUTIVE SUMMARY

Background

Since the time of the first LOCA experiments, which were largely conducted with fresh fuel, changes in fuel design, the introduction of new cladding materials and in particular the move to high burnup have generated a need to re-examine the LOCA safety criteria and to verify their continued validity. As part of international efforts to this end, the OECD Halden Reactor Project program implemented a LOCA test series. The fourth test of the series, IFA-650.4, caused particular attention in the international nuclear community. The fuel in this experiment had a high burnup, 92 MWd/kgU. The rod ballooned as intended, but the burst caused substantial fuel relocation, and PIE revealed considerable fuel fragmentation. A similar result was obtained with a later test, IFA-650.9, likewise using high burnup fuel.

The Halden LOCA test series was deliberately designed and carried out with conditions that would emphasise the occurrence of certain phenomena. Nevertheless, the fact that fuel dispersal could occur upon ballooning and burst, i.e. at cladding temperatures as low as 800°C and thus far lower than the temperature entailed by the current 1200°C / 17% ECR limit, caused concern and gave rise to the question of how the outcome of the Halden LOCA tests could affect regulation.

Objective of the report

The main safety concern is the potential for loss of coolable geometry due to fuel dispersal occurring at temperatures much lower than limited by safety criteria. In order to assess the applicability of the IFA-650.4 results to actual power plant situations and the possible impact on safety criteria, the report discusses and clarifies a number of aspects before considering a safety significance of the Halden IFA-650 series results. These are representativity for NPP cases, gas flow, fuel relocation, burnup effect, repeatability, and power history.

Assessment of key observations, influences and limitations

Representativity: The results obtained with a 50 cm long single rod enclosed in a cylindrical electrical heater do not directly represent what would happen with full-length rods in a fuel assembly. The data can therefore not be used directly to assess safety issues related to flow blockage, coolability, balloon potential over-cooling or over-heating, and drawing direct numerical conclusions for reactor incidents is not well-founded. Some differences to “real life” are the consequences of the test objectives. However, the broad range of the experimental conditions (e.g., burnup) in these tests allows interpolation into areas where no data exist.

Gas flow: The exact influence of gas flow on the LOCA fuel behaviour, both regarding ballooning propensity and fuel relocation and dispersal, is not well known. According to a LOCA fuel behaviour model with gas flow, the development of large balloons is less likely in full length high burnup rods with a peak power position sufficiently away from the plenum. A ballooning as large as the one observed in IFA-650.4 is feasible when the power peak is close to the plenum, given that the bonding is absent or broken.

Fuel relocation: The data on the filling ratio of pellet fragments in the ballooned region obtained from the Halden LOCA tests are probably the maximum possible since they were obtained with very high burn-up fuel and large balloon size. Fuel dispersal in the test is considered to be affected by the enhanced fuel relocation, and further research is needed to better understand the potential consequences of significant fuel relocation and dispersal as observed in IFA-650.4/9. There is consensus that this phenomenon is related to fuel rod burnup which was very high in the two tests (92 and 83 MWd/kgU, resp.). For burnups up to 60-65 MWd/kgU, it is believed that any fuel dispersal would be minimal. Future tests will have to address and answer important questions in this regard. At present, it is not warranted to generalise the results of IFA-650.4/9 as being typical of all cases of high burnup fuel.

Burnup effects: The burnup of the fuel segments employed in the Halden LOCA tests exceeds currently licensed burnup by some margin. No direct conclusions should therefore be drawn regarding the behaviour up to the current licensing limits. More investigations are required, and the continuation of the test series will hopefully identify a burnup threshold above which the observed fragmentation, in addition to the fragments formed by normal operation, can be expected.

Repeatability: All in all, the repeatability of the experiments seems to be good. The similar results of IFA-650.4 and IFA-650.9 emphasize the importance of the phenomena first observed in IFA-650.4. Contrary to some RIA tests, the Halden LOCA tests were not conducted under such specific conditions which could query the existence of the observed phenomena (fuel fragmentation, relocation and release of fuel fragments into the coolant) for high burnup fuel.

Power history: While some influences of the power history may be hypothesised, no special LOCA relevant features are expected apart from the important fact that a long power history leads to high burnup with all the consequences already indicated in the paragraphs above.

Assessment of safety significance

The LOCA safety criteria are defined to ensure core coolability during and after a LOCA. They consist of surrogates such as cladding residual ductility or rod quench survival. The phenomena that may play a role and therefore should be accounted for in a LOCA safety analysis must be considered thoroughly in light of the impact that the Halden tests may have on their understanding. The CSNI report attempts to assess the safety significance of the Halden LOCA tests which is summarised as follows.

Embrittlement / secondary hydriding: The Halden tests cannot be used to determine or define LOCA safety criteria related to cladding embrittlement. However, the power redistribution due to fuel relocation may impact secondary hydriding which is an additional safety concern with respect to the embrittlement of the cladding in the ballooned region. It may be assumed that the absorption of hydrogen is related to the local surface-to-volume ratio which is left by ballooning and fuel relocation on the clad inner side. Relocation of finely fragmented fuel will tend to shift the peak positions towards the burst opening, at locations where the surface-to-volume ratio is optimal for steam-starved oxidation and subsequent hydrogen pickup.

Fuel fragmentation, relocation and peak clad temperature: To a large extent, there is agreement that the extensive fuel fragmentation observed in some Halden LOCA tests is a consequence of the very high burnup of the fuel segments and not typical of lower burnup fuel. A consequence of the displacement of fuel fragments into the balloon may be a local power peak which in turn has an impact on the cladding temperature. Considering the differences in test and assembly geometry, only a refined simulation of the reactor case could elucidate the impact of fuel relocation with respect to safety limits. Such a simulation would use the necessary data for fraction of relocated fuel, fragments size distribution, balloon filling ratio, etc., as provided by the existing data base, mainly from IFA-650 test results.

An important question is whether locally increased power and temperature and thus secondary hydriding represent threats to cladding integrity that are not yet accounted for in present safety evaluation methodologies. The LOCA safety studies performed by the utilities are already based on the assumption of an axially highly peaked power profile with peak factors up to 2.0 and cover bounding situations regarding local power peaks. Depending on methodology, the relocation event does not necessarily introduce new phenomena not taken into account in the current safety analysis.

Fuel dispersal, radiological consequences and coolability: Fuel dispersal as observed in the high burnup Halden LOCA tests may have two significant consequences for the evaluation of reactor safety during LOCA. One is related to the radiological source term. According to current practice, the activity release from fuel rods during LOCA is limited to some percentage of fission products. The Halden LOCA tests showed that large amounts of fuel can be released from ruptured cladding with limited corresponding release of radionuclides.

An iodine inventory balance was conducted for the test IFA-650.9, and it was concluded that much less iodine was released than commonly assumed (e.g. USNRC Regulatory Guide 1.183) despite the fine fragmentation of the fuel. Hence, based on current information, there is no need to alter assumptions related to radiological consequences up to the licensed burnup limits.

The other consequence concerns core coolability. The fuel fragments released from the fuel rods may accumulate on the spacer grids and impair the penetration of cooling water into some sections of the core. Many different configurations can be imagined depending on fragment size and bundle/core geometry, and it cannot be excluded that some of these configurations may cause coolability problems.

The Halden tests cover extremes and may not be appropriate for drawing direct conclusions on fuel behaviour in the core of a commercial nuclear power station. For burnups up to 60-65 MWd/kg, it is believed that fuel relocation and dispersal would be minimal, but the question will need to be addressed prior to approving increases in licensed burnup.

Recommendations and conclusions

The concern primarily addressed in the CSNI report is the fuel relocation and dispersal observed in the Halden LOCA tests. While the tests have clearly identified the phenomenon, they also raise questions. The recommendations therefore include gaining more insight through more experimental work, in particular to perform tests on fuel segments with burnup representative of bounding industrial situations. Such tests, together with appropriate separate effect tests, can provide the industry with relevant results aiming at increasing the robustness of the LOCA safety studies.

Further, a sufficient number of Halden LOCA tests should be performed at high temperature in order to address secondary transient hydriding and in this way provide a basis for assessing the significance of the phenomenon for the embrittlement of the ballooned region.

It is also recommended to improve the predictive capabilities of LOCA analysis codes, e.g. to model the occurrence of fuel relocation and related consequences and to include the effect of restricted gas transport on ballooning and possibly on fuel expulsion.

The Halden tests raise questions regarding core coolability under LOCA conditions at high burnups. Assessment of these data under other, more prototypic conditions may require a detailed, core-wide and rod by rod analysis providing realistic rod powers (high burnup rods run at low power both due to their peripheral position and fuel depletion) as input to LOCA analysis codes. Under these conditions, the expectation is that only a small number of high burnup rods would reach conditions and consequences as observed in the Halden tests. It is therefore recommended to consider basing the analysis of the LOCA event on detailed calculations of the core power and temperature distribution and to assess the behaviour of high burnup fuel with realistic conditions assuming appropriate uncertainty margins.

The Halden tests have identified possible fuel behaviour not previously seen. The results cannot be ignored even though they are, to some extent, produced and amplified by conditions and features deliberately introduced into the test series. The recommendations take this into account. In turn, regulators and the industry should take them into account in a way appropriate for their respective countries and fuels.

1. INTRODUCTION

The safety criteria for loss-of-coolant accidents were defined to ensure that the core would remain coolable. Since the time of the first LOCA experiments, which were largely conducted with fresh fuel, changes in fuel design, the introduction of new cladding materials and in particular the move to high burnup have generated a need to re-examine these criteria and to verify their continued validity. As part of international efforts to this end, the OECD Halden Reactor Project program implemented a LOCA test series. Based on recommendations of a group of experts from the USNRC, EPRI, EDF, IRSN, FRAMATOME-ANP and GNF, the primary objective of the experiments were defined as

1. Measure the extent of fuel (fragment) relocation into the ballooned region and evaluate its possible effect on cladding temperature and oxidation.

2. Investigate the extent (if any) of "secondary transient hydriding" on the inner side of the cladding above and below the burst region.

The fourth test of the series, IFA-650.4 conducted in April 2006, caused particular attention in the international nuclear community. The fuel used in the experiment had a high burnup, 92 MWd/kgU, and a low pre-test hydrogen content of about 50 ppm. The test aimed at and achieved a peak cladding temperature of 850^{o}C. The rod burst occurred at 790°C. The burst caused a marked temperature increase at the lower end and a decrease at the upper end of the system, indicating that fuel relocation had occurred. Subsequent gamma scanning showed that approximately 19 cm of the fuel stack were missing from the upper part of the rod and that fuel had fallen to the bottom of the capsule. PIE at the IFE-Kjeller hot cells corroborated this evidence of substantial fuel relocation.

The fact that fuel dispersal could occur upon ballooning and burst, i.e. at cladding temperatures as low as 800°C and thus far lower than the temperature entailed by the current 1200°C / 17% ECR limit, caused concern. The CSNI therefore posed the question to the Working Group on Fuel Safety (WGFS):

How could the Halden LOCA tests affect regulation?

The WGFS agreed that the main safety concern would be fuel dispersal (and hence the potential for loss of coolable geometry) occurring at relatively low temperature, i.e. 800°C. In order to assess the applicability of the IFA-650.4 results to actual power plant situations and the possible impact on safety criteria, a number of aspects should be clarified before considering a safety significance of the Halden IFA-650 series results:

- Representativity for NPP cases
- Gas flow
- Relocation
- Burnup effect

- Repeatability
- Power history

These items will be discussed one by one in this CSNI report.

On April 17, 2009, test 650.9 was carried out with 650.4 sibling fuel. The target cladding peak temperature was 1100°C in this case, but otherwise the experimental conditions were very similar. In many respects, 650.9 repeated the 650.4 experiment, e.g. by showing clear signs of fuel relocation which was confirmed by gamma scanning later on. The WGFS therefore decided that 650.9 should be considered as well for this CSNI report. Mention is also made of IFA-650.3, which failed with a small crack in a weak spot induced by thermocouple welding, and IFA-650.5 which involved ballooning and fuel ejection under conditions of restricted gas flow.

2. HALDEN REACTOR PROJECT LOCA TEST DETAILS

The OECD Halden Reactor Project LOCA test series supplements other national and international programs aimed at LOCA fuel behaviour and safety criteria. The experiments are implemented as in-core tests and focus on integral effects that are different from those obtained in out-of-reactor set-ups. Heating is provided internally by simulating the decay heat through a low level of nuclear power. This feature was expected to influence axial gas flow, maintaining/breaking fuel-clad bonding and fuel axial relocation.

The fuel for IFA-650.4 was provided by Framatome ANP. The segment had been irradiated in a commercial PWR to very high burnup, 92 MWd/kgU. The experiment was conducted on April 25, 2006. The instrumentation worked well, the target peak cladding temperature of 850 °C was achieved, and cladding burst with fuel relocation occurred at 770-780 °C.

2.1 Rig structure and instrumentation

A single fuel rod is inserted into a pressure flask connected to a water loop. A low level of nuclear power generation in the fuel rod is used to simulate decay heat, whereas the electrical heater surrounding the rod is simulating the heat from surrounding rods.

The rod instrumentation consisted of two cladding thermocouples at the upper part of the rod, two heater thermocouples (at two different axial elevations), a cladding extensometer and a rod pressure sensor. The rig contained coolant thermocouples (two at rig inlet and two at outlet), three axially distributed vanadium neutron detectors to measure the axial power distribution, and two fast response cobalt SPNDs to monitor rapid flux and power changes.

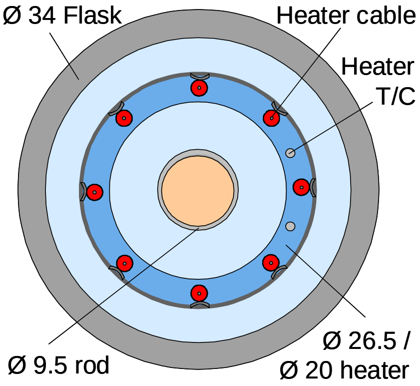


Figure 1 – Cross section of fuel pin, heater and pressure tube used in HRP LOCA studies

2.2 Test execution and results

Before the test execution, the reactor was operated for 7-8 hours at 15 MW (fuel average linear heat rate 85 W/cm). After power calibration, the LOCA test was performed at a reactor power of 4 MW, and the rod power was about 10 W/cm. The axial power profile was nearly symmetric with an axial peak-to-average power factor of 1.05.

The test was initiated by opening the blow-down line at the bottom of the rig. After about 5 minutes at target temperature, the test was terminated by a reactor scram. The fuel heat rate during the test was 9.3 W/cm. Excess decay heat from the operation at higher power during power calibration increased the total linear heat rate to 10 W/cm. The heater power was adjusted to 15 W/cm. The measured cladding and heater temperatures and heater power are shown in Figure 2.

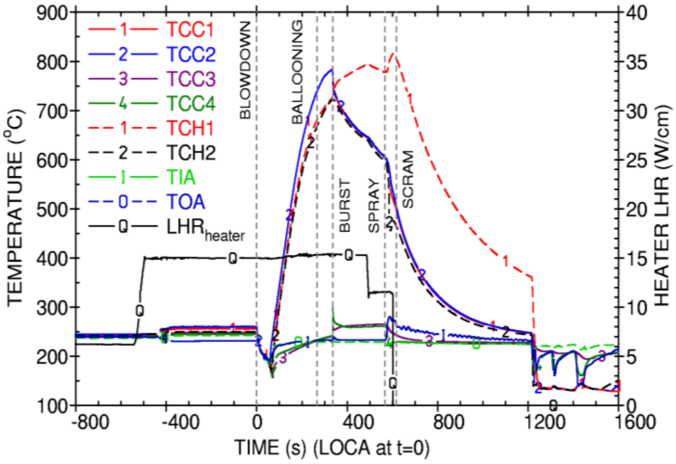


Figure 2 – Overview of LOCA test execution

2.3 Cladding temperatures

After the blow-down was completed, the cladding temperature increased with an initial rate of 3.5ºC/s, decreasing towards the end when approaching the target PCT of 800°C. The maximum temperature measured at the time of burst, 336s after blow-down, was 786°C. After the burst, the cladding cooled gradually to about 600°C. Then, spraying enhanced the cooling, and the cladding temperature dropped to about 500°C until the test was terminated by scramming the reactor.

2.4 Cladding burst

Cladding burst was detected 336s after the start of blow-down. The indications of cladding burst can be seen in Figure 3 as an instantaneous rod pressure drop at 336s, accompanied by a fast increase of the elongation signal. The two cladding thermocouples, TCC1 and TCC2, reacted to the cladding burst and subsequent fuel slumping with a drop in temperatures. The gamma monitor on the blow-down line reacted to the burst 50-60s later.

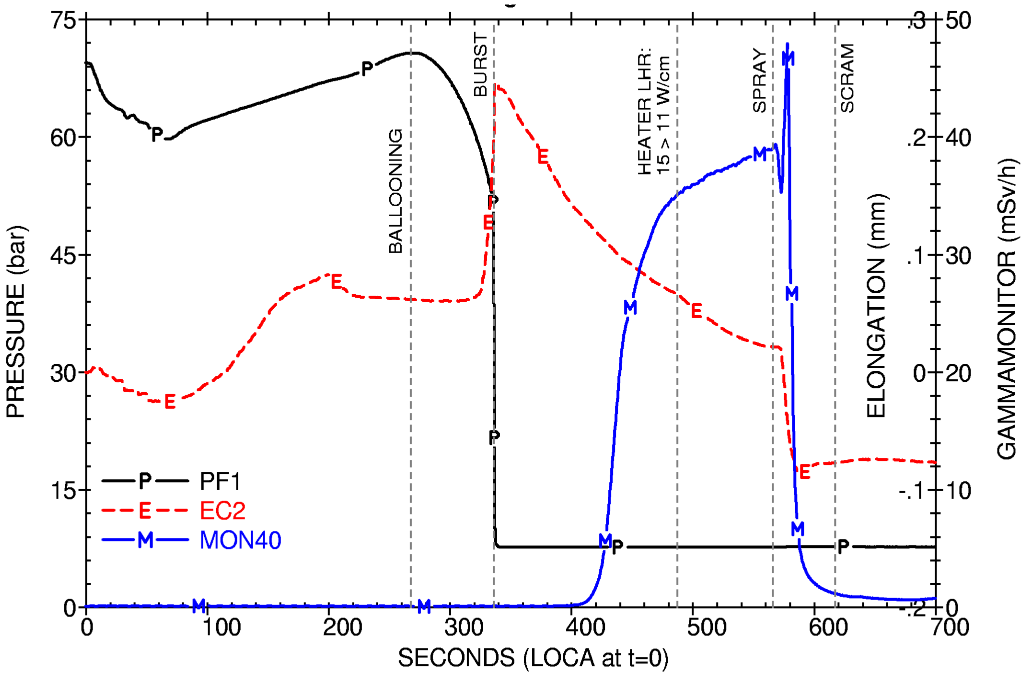


Figure 3 – Cladding burst indications

The measured maximum rod internal pressure prior to ballooning and burst was 70.7 bar corresponding to a hoop stress of 51 MPa. The pressure maximum was measured 264-267 s after LOCA, i.e. ballooning started around this time, about 70 seconds before burst.

2.5 Termination of the experiment

Termination criteria of the experiment, as agreed beforehand, were:

- reaching the 17% ECR limit;
- having run the experiment for about 5 minutes after ballooning (a LOCA would normally not last longer than that if the ECCS responds as foreseen);
- detecting signs of secondary degradation after ballooning, e.g. breaking of the fuel rod.

The experiment was terminated by switching off the electrical heating and scramming the reactor such that the fission heat generation in the fuel rod ceased. The test rod was allowed to cool down relatively slowly with the reactor. Quenching, although included in the experimental possibilities of the system, was not applied. This was a deliberate choice with the purpose to avoid any disturbances, e.g. vibrations, that might influence a possible fuel relocation that had developed during the experiment.

2.6 Fuel relocation indications

The question if and when fuel relocation occurs as well as the consequences for the cladding was central when the Halden LOCA test series was discussed and designed. Care was therefore exerted to run the test at conditions that would not impede relocation.

2.6.1 Evidence of relocation at the time of test execution

The strongest indication of in-core fuel relocation was the cladding and heater thermocouple response. As there was no more fuel producing heat at the top of the rod, the temperatures measured with the upper thermocouples TCC1, TCC2, and TCH2 started to decrease, whereas the lower heater thermocouple TCH1 showed increasing temperature after the burst. This is clearly seen in Figure 2.

2.6.2 Post irradiation examination

After the test, the fuel relocation was verified by gamma scanning which showed that about 19 cm of the original fuel stack were missing from the top of the rod. Fuel had dropped to the ballooned region at half height of the rod (Figure 4). Some fuel was also detected at the bottom of the flask. Fuel fragmentation and redistribution was also verified by cutting through the heater and fuel cross section after fixing with epoxy (Figure 5).

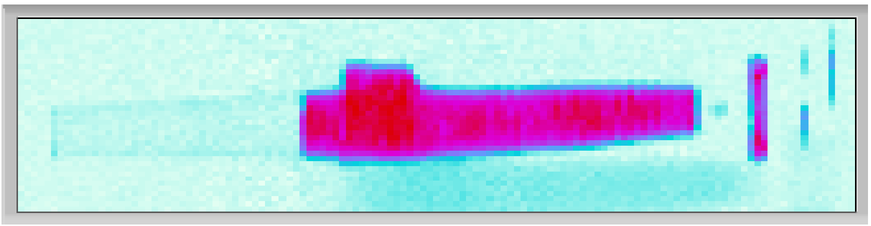


Figure 4 – Gamma scanning of LOCA fuel rod from IFA-650.4. Fuel is missing at the top (left), ballooning at half height. Some fuel has fallen to the bottom of the flask (right).

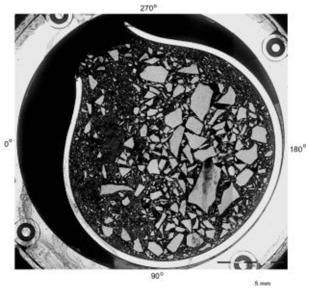


Figure 5 – Cross-section showing fuel relocation. Filling ratio 38%

3. TEST ISSUES AND RELATED WGFS OPINIONS

An experiment run in a test reactor or in a device installed in a laboratory will by necessity differ from the “real” situation it is supposed to address. An important issue is therefore how differences can be accounted for or whether they are so considerable that the applicability to the real case must be questioned.

The Halden LOCA test series is no exception in this regard. The tests were deliberately designed and carried out with conditions that would emphasise the occurrence of certain phenomena instead of trying to exactly reproduce the reactor conditions expected during a LOCA. It must also be kept in mind that there is no unique LOCA case that would be representative for all LWR reactors – not even for a given principal type like PWR or BWR.

In the following sections of this chapter, the issues and concerns as formulated in the report proposal to the CSNI are repeated in *italics* as an introduction to the respective section and then discussed in more detail.

3.1 Representativity for NPP cases

Concern:

The single rod configuration and the very uniform boundary conditions in the IFA-650 series might have favoured the occurrence of large ballooning due to very uniform cladding temperatures, more than in real cases. Moreover, extremely low corrosion layer, due to special external liner, should also be considered as a lack of representativity.

In accordance with the test objectives stated in the introduction, the rod configuration and test boundary conditions as well as the characteristics of some irradiated rods may be non representative of the configuration, conditions and characteristics of an actual LWR rod. The differences between a multi-rod fuel assembly and its components and the single rod experimental set-up in the Halden LOCA tests can be categorised as related to outer geometry, rod design, cladding material, and fuel.

3.1.1 Outer geometry

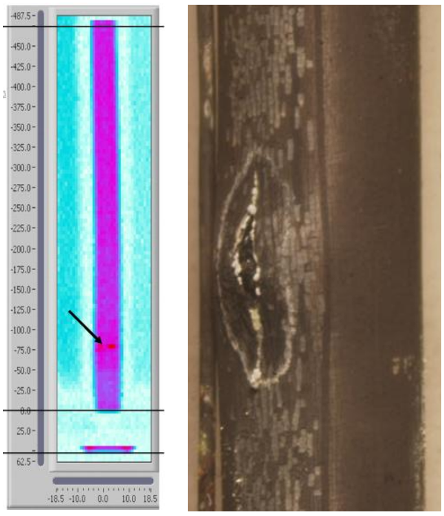
A fuel assembly consists of an N x N array of fuel rods in contrast to the single rod employed in the Halden tests. One of the consequences of the heating of a fuel rod in an assembly within a commercial reactor is the presence of azimuthal temperature gradients. Experimental data show that a uniform azimuthal temperature in the cladding promotes larger ballooning [1].

The presence of neighbour rods in an assembly also gives rise to rod-to-rod contact during and after ballooning which contributes to the further development of an inhomogeneous temperature distribution. The consequences may be early burst and limited ballooning.

In an assembly, most of the fuel rods are also physically restricted in the possibility of ballooning due to the presence of their neighbours. Only fuel rods in the outermost row of the fuel assembly have somewhat more space for developing a bigger ballooning. However, contact with neighbour rods may promote the axial development of ballooning if the contact occurs prior to burst.

All in all, if the ballooning is small due to the reasons stated above, there is less fuel relocation into the ballooned area. Consequently, the change of the axial power profile caused by this redistribution would be less significant. In addition, a smaller burst opening can be expected which in turn would limit, but not entirely prevent a loss of fuel from the rod as another test, IFA-650.5, has shown (see Figure 6).

In contrast, the experimental rig uses a single fuel rod in an axisymmetric geometry leading to an azimuthally uniform temperature of the test rod. This would favour large ballooning – as intended with the rig design in order to maximize ballooning and increase the potential for fuel pellet axial relocation, and as in fact observed in the Halden tests.



Fuel at bottom of flask

Small burst opening

Figure 6 – Post-test appearance of rod in LOCA test IFA-650.5

3.1.2 Rod design

There are some deliberately chosen and to some extent unavoidable differences between the test rods and commercial fuel rods. They differ in two major respects, namely the shorter length of about 50 cm and the considerably larger free volume to fuel ratio. The latter combined with the rod pressure provides for relatively more gas to drive the ballooning, fuel relocation and expulsion.

When discussing the design of the experiment, the Halden Programme Group gave careful consideration to the free volume in the test segment. Should the fuel-to-volume ratio be about the same as for a commercial fuel rod (meaning that the absolute free volume would be quite small due to the shorter length of the test rod) or should the absolute volume be about the same? It was concluded that it was more important to keep the absolute volume (and the number of gas moles) comparable to the values of commercial fuel rods. In the alternative, the pressure in the rod would drop very quickly due to the volume increase by ballooning which in turn would have a negative impact on the ability of the test to produce a good balloon. However, there are no experimental data or models available to assess the exact consequences of the choice that was made. (IFA-650.5 with restricted gas flow offers some clue, though.)

The rod pressure, 40 bar at RT, was chosen to maximise ballooning according to the objectives of the experiments. The initial internal pressure in commercial fuel rods is lower than this pressure, but the pressure will increase to higher values because of fission gas release as shown in Figure 7 [2]. For a distribution as shown in the figure, most of the rods will not be at “optimum” pressure and produce smaller balloons. However, there are probably always at least some fuel rods in a reactor core which have the appropriate pressure to produce a large ballooning.

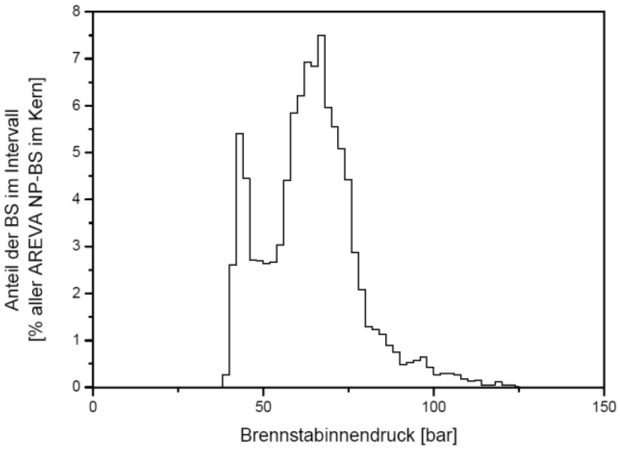


Figure 7 – Distribution of best-estimate rod internal pressure values of a typical reactor core

Another difference is the location of the plenum relative to the spot of ballooning and burst. In the test set-up, the plenum is closer to the balloon, and the gas can impact the ballooning and burst process more directly than in a typical high burnup commercial fuel rod where the plenum is at a greater distance from the peak cladding temperature location. This, combined with reduced gas transport caused by reduction of the pellet-cladding gap or even bonding commonly observed at high burnup, will reduce or delay the ballooning and burst process. In this situation, the driving force due to rod depressurisation following burst is much higher in Halden cases. A higher driving force is expected to lead to more fuel fragment movement and an increased potential for fuel dispersal.

3.1.3 Cladding material

As the cladding material was a Duplex type, the fuel rod showed very small oxidation: the outer oxide layer was no more than 10 μm and the estimated hydrogen content was around 50 ppm. Consequently, this material is believed to be particularly ductile for a very high burnup fuel. On the other hand, the thin corrosion layer and low hydrogen content in the test sample of IFA-650.4 should not be atypical for modern corrosion-resistant fuel cladding. Achieving such features is actually the objective of the development of modern cladding alloys. A cladding with low corrosion and high ductility will produce a large ballooning.

3.1.4 Fuel

The fuel, while being standard by design, achieved a burnup of more than 90 MWd/kgU. Many phenomena are known that are progressively affected by exposure, and the burnup of the Halden LOCA test segments is clearly above today’s LWR discharge burnups. The consequences will be discussed in detail in section 3.4.

3.1.5 Test conditions

The Halden LOCA test power distribution is not more uniform than a real one. The situation simulated in Halden test rods (short rod and small distance from the balloon to the plenum) is conceivable in an integral fuel rod at EOC. According to calculation, the largest balloon corresponds to the “flattest” power profile in the integral rod, showing the high relevance of Halden LOCA to the EOC-power-profile in the integral rod.

The forth test result is at least regarded to be relevant to PWR high burnup fuel with high fission gas release, given that the peak power position is shifted to the upper end and a breach or absence of fuel-cladding bonding develops there. All of the above-mentioned conditions seem to be feasible.

3.1.6 Conclusion on representativity

The Halden LOCA tests were not designed for a 1:1 representation of industrial cases. It is clear that the results obtained with a 50 cm long single rod enclosed in a cylindrical electrical heater do not directly represent what would happen with full-length rods in a fuel assembly which is around eight times longer. Also, single rod test conditions usually lead to bigger balloons than if the rod were tested within a bundle, which usually generates azimuthal temperature gradients known to impair the ballooning. The results can therefore not be used directly to assess safety issues related to flow blockage, coolability, balloon potential over-cooling (droplets impact effect) or over-heating (quantification of relocation, fuel fragments relocation effect), etc. Drawing direct numerical conclusions from the tests for reactor incidents is not well-founded.

A direct representativity of the IFA-650 LOCA tests for nuclear power plant cases is not an important criterion regarding the overall usefulness for gaining insight in the potential behaviour of high burnup fuel in LOCA conditions. Some differences to “real life” are the consequences of the test objectives as listed in the introduction. However, the differences also allow interpolation to more benign real conditions rather than extrapolation, and which gives more confidence in analyses of actual events.

3.2 Gas flow

Concern:

There is a need for better understanding the gas flow in an actual fuel rod under LOCA transient conditions. The gas transport from the plenum to the ballooning-burst position is important for sustaining the ballooning and the fuel ejection after burst. Gas flow data are needed, including burnup and fuel type effects. Straightforward hot cell data on gas transport along commercial fuel rods can be of great help in this context.

3.2.1 Effect of gas flow

Axial gas flow in a fuel rod during a LOCA is a complicated function of the pre-transient state of the fuel (burnup, irradiation history) and the course of the transient itself where fuel and cladding are heated up differently and exhibit a differential thermal expansion. The axial gas flow, even if limited by the closed gap between pellets and cladding, could obviously affect the pellet relocation process (as an additional driving force). This driving force is important and influences the timing of relocation as well as the amount of relocated fuel. Conservatively, it can be assumed that due to this force the relocation takes place right after cladding burst and that the total mass of fragments in the ballooned area is equal to the volume of the ballooned section multiplied by fuel density. However, it is questionable whether fast gas flow and a rapid pressure drop can occur in a 4 m long high burnup fuel rod.

The Halden test conditions, with a plenum located close to the balloon-burst location, suggest that the plenum gas will be directly (and quickly) involved in the cladding ballooning-burst process. In reactor conditions, a larger distance between the plenum and the location of the axial cladding temperature peak, together with the impaired axial gas transport commonly observed at high burnup, may reduce or delay this ballooning-burst process. As a consequence, the driving force due to rod depressurisation is potentially much higher in Halden cases, leading to more fuel fragment movement and more fuel dispersal.

3.2.2 Conclusion on gas flow

The exact influence of gas flow on the LOCA fuel behaviour, both regarding ballooning propensity and fuel relocation and dispersal, is not well known. According to a LOCA fuel behaviour model with gas flow [3], the assumption of strong pellet cladding bonding over the whole stack length suggests no balloon. However, the results change if it is assumed that bonding is either initially absent or locally breached early during the heat-up. The conclusions are:

1. Because of reduced gas permeability, the development of large balloons is less likely in full length high burnup rods with a peak power position sufficiently away from the plenum.
2. No flow (after all the gas has come out) or weak flow means no further fuel ejection.
3. A ballooning as large as the one observed in IFA-650.4 is feasible when the power peak is close to the plenum, given that the bonding is absent or broken.

3.3 Relocation

Concern:

The mechanism for relocation needs to be better characterised as related to its occurrence during the ballooning phase or after the cladding burst.

The possibility to observe fuel relocation is a unique feature of LOCA tests under operational conditions and therefore a particular characteristic of the Halden test series which has had special impact on the test goal definitions. The tests have shown that fuel relocation is coincident with the burst of the fuel rod.

3.3.1 Consequences of fuel relocation

As evidenced in IFA-650.4 and later in IFA-650.9, the slumping of fuel fragments may involve a significant amount of fuel, with partial relocation in the ballooned region and partial dispersal outside the cladding. As indicated by the measurements, in particular the temperature drop at the upper end, the slumping coincides with the burst.

The important parameters associated with fuel relocation and dispersal are:

- fraction of fuel escaping the rod,
- filling ratio of the relocated fuel in the balloon.

The relocation of fuel fragments into the balloon and fuel dispersal have several consequences.

Change of power profile

Fuel accumulating in the balloon will create a local power peak. Although a preliminary evaluation indicates that this local power peak will not cause coolability problems in the investigated range of parameters, it is clear that under specific conditions the local power peak can delay the cool-down of the assembly after the LOCA. The effect of fuel relocation on the local power peak can be taken into account in the current design approaches and tools through an additional peaking factor (the axial power profile calculations already include various sources of power peaking), together with a reduction or closure of the fuel-clad gap in the ballooned section.

Release of fine pellet fragments through the burst opening

According to the current evaluation methods, the activity release during LOCAs is limited to a rather small fraction of fission products (this approach was based on earlier tests with fresh or low burnup fuel). The release of fuel fragments in the high burnup Halden LOCA tests was very significant. In the case of a reactor LOCA, the fuel release will be much lower due to smaller ballooning deformation, but cannot be neglected in the future analyses of high burnup fuel. In this case, the amount of released gaseous and volatile fission products in a LOCA involving high burnup fuel will increase due to the large surface of fuel pellet fragments that will be in contact with the coolant after reflooding the assemblies.

Possible accumulation of ejected fuel on grids or structures

If a significant amount of fuel is released into the assembly structure, this may impair the coolable geometry.

3.3.2 Conclusions regarding fuel relocation

The conditions of the Halden LOCA tests were chosen to support the development of a large balloon and fuel relocation. However, the test IFA-650.5 has shown that small differences (in this case the shift of the peak axial power position by some 10 cm to the lower end) can considerably influence the outcome. It is therefore not warranted to generalise the results of IFA-650.4 (or the later 650.9) as being typical of all cases of high burnup fuel. Rather, the development of models is required aiming at the estimation of the ejected amount of fuel. Members of the WGFS participating in the associated LOCA benchmark are therefore pursuing related ideas:

- Incorporate gas flow in the model calculations taking into account the axial burnup and temperature distribution that may produce a plug of fuel between the plenum and the ballooning (as observed in IFA-650.5);
- Estimate fuel particle pull-out by the gas flow through rupture;
- Consider axial fuel slumping driven by gravity before the burst (observed earlier at KfK in rods which ballooned but did not burst) as well as by gravity and gas-friction (drag) after the burst has occurred.

Valuable information on the filling ratio of pellet fragments in the ballooned region is obtained from the Halden LOCA tests. However, the data are probably the maximum possible since they were obtained with very high burnup fuel and large balloon size. Fuel dispersal in the test is considered to be affected by the enhanced fuel relocation.

Further research is needed to better understand the potential consequences of significant fuel relocation and dispersal as observed in IFA-650.4/9. There is consensus that this phenomenon is related to fuel rod burnup which was very high in the two aforementioned tests (92 and 83 MWd/kgU, resp.). Currently licensed burnup limits vary between countries. Fuel rod average burnup values of 60-70 MWd/kgU are not only licensed, but also reached in some of them. For the lower number of this range, it is believed that any fuel dispersal would be minimal. Future tests will have to address and answer important questions in this regard:

- Is there a burnup above which the observed fragmentation and relocation behaviour becomes typical?
- What are the respective roles of the high burnup rim and the temperature re-distribution for fuel fragmentation?

In summary, the IFA-650 experiments are relevant for investigating some aspects of fuel relocation during LOCA. However, the results should not be extrapolated to other issues (such as the impact of the fuel relocation on the peak cladding temperature) for which industrial safety codes are needed.

3.4 Burnup effects

Concern

The IFA-650.4 had extremely high burnup, which might affect porosity, susceptibility to fragmentation and thus relocation. (A similar fragmentation was also observed in IFA-650.5 using very high burnup fuel as well, but fuel relocation or expulsion was limited due to a much smaller ballooning and burst opening.)

The issue is closely linked to relocation already addressed in the previous section.

When burnup is quoted, it may be important to also state what it refers to: 1) average batch discharge burnup, 2) average assembly burnup, 3) rod average burnup or 4) local rod burnup. Regulation limits often refer to assembly burnup, but even in an assembly, the rod average burnups may have a ±10% spread or more. The burnups quoted for the Halden tests is the local rod burnup which is the highest of the four burnup references listed above. While the (local) burnup of the fuel employed in IFA-650.4 is certainly very high, it is not necessarily far away from what may be achieved locally by the rod with highest burnup in an assembly, considering that in some cases actual assembly discharge burnups are reaching 70 MWd/kgU.

Many phenomena are known to occur in (UO_2) nuclear fuel as burnup proceeds. The following ones may be considered to be of particular relevance for LOCA and the interpretation and application of the Halden test results:

- Development of pellet – clad bonding which is an important factor for axial gas mixing in an intact rod and for gas flow to the point of rupture in a failed one.
- Grain boundary embrittlement caused by fission product migration to the grain surface, making the grain matrix more susceptible to cracking.
- Accumulation of fission gas in the pores as a driving force for fuel fragmentation.
- Structural changes in the pellets (first of all the formation of a high burnup structure layer) possibly affecting the fragmentation and relocation process.

These phenomena do not necessarily develop proportional to burnup, but rather exacerbate when a threshold is exceeded. Two observations, namely high burnup structure formation and fuel fragmentation, will be discussed in more detail in the following sections.

3.4.1 Development of high burnup structure

The formation of the so-called high burnup structure (HBS) depends on local burnup and temperature. A fully developed HBS has been found to be present when the local burnup exceeds 70 MWd/kgU. Figure 8 shows that this limit is exceeded for the entire pellet when the average burnup exceeds 80 MWd/kgU. But HBS formation also requires that temperatures stay lower than 1000 °C [4]. The latter is not given for all parts of a pellet during irradiation, but towards end-of-life when the fuel is operating at low power, the conditions for HBS formation are present in the entire pellet cross section. The amount of HBS can therefore only be estimated if the power and temperature history is evaluated with a fuel modelling code having the required models for HBS formation.

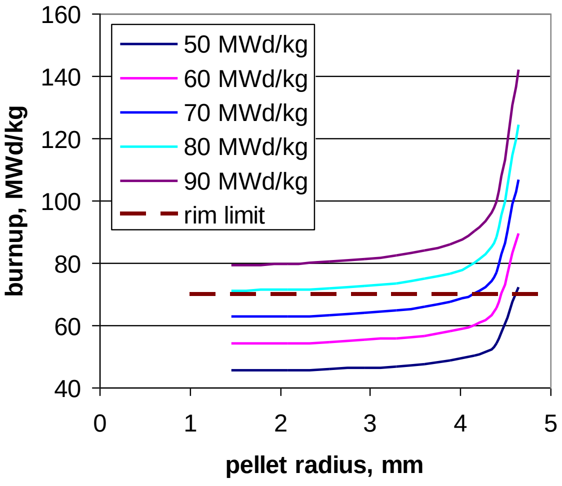


Figure 8 – Radial burnup distribution

For the segment used in IFA-650.4, the irradiation to 92 MWd/kgU induced a very wide rim area, estimated in the post base irradiation examinations to be larger than 1100 μm. The high burnup structure, which is characterised by high porosity and small grain size, represents more than 42% of the fuel volume of the IFA-650.4 segment. Such ratio has not been observed in any of the high burnup fuel rods EDF has examined so far. High burnup UO_2 pellets with burnup ranging from 72 to 82 GWd/tU have been analysed after base irradiation in EDF PWRs, and maximum rim widths of 80 μm (~4%vol) and 150 μm (~7%vol) respectively have been measured.

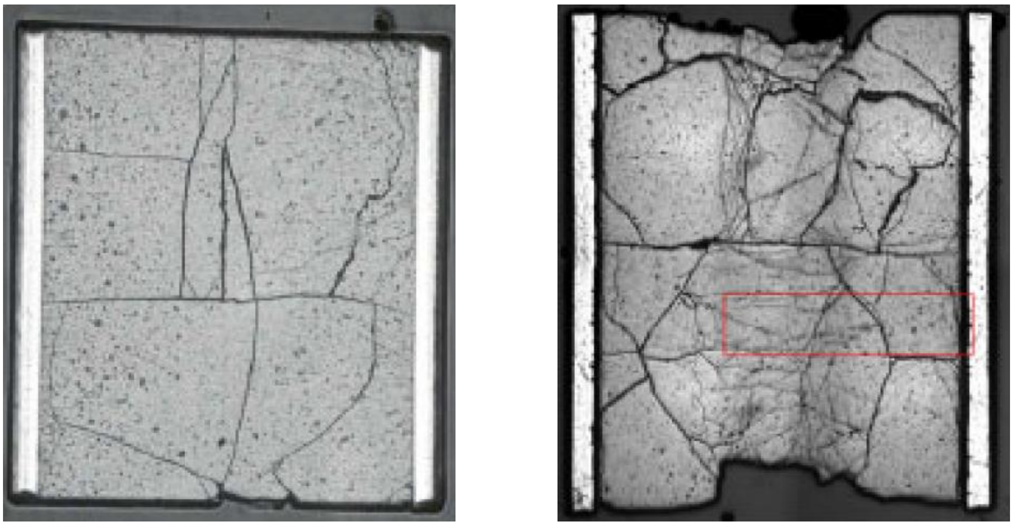
As the rim mechanical properties strongly differ from those of the standard UO_2 matrix, the high fraction of HBS in the IFA-650.4 segment may have modified the whole fuel column mechanical behaviour during the test and favoured fuel particle displacement and fuel dispersal out of the cladding.

3.4.2 Fuel fragmentation

Oxide fuel (UO_2, MOX) cracks into many pieces during normal operation. The question is whether high burnup and the temperature changes experienced by the fuel during a LOCA will increase the degree of fragmentation and then impact fuel relocation and dispersal.

Increasing burnup entails grain boundary embrittlement by fission product migrating to the grain surface, making the grain matrix more susceptible to cracking. Further, the accumulation of fission gas in the pores builds up a driving force for fuel fragmentation.

In a LOCA transient, temperature changes within a few seconds in parallel to radial temperature redistributions in the pellet of several hundreds of Kelvin. This induces enough temperature stresses to promote fragmentation. Annealing tests on high burnup fuel have shown that the pellets in fact develop cracks in the pellet surface region in addition to those stemming from normal operation. An example is shown in Figure 9 [5].



before after

Figure 9 – Influence of LOCA-like temperature increase on fuel fragmentation (GASPARD)

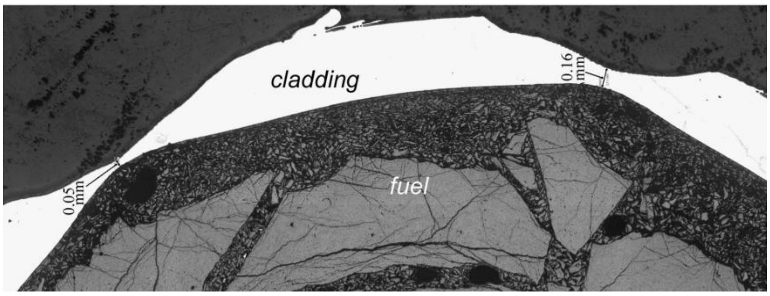


Figure 10 – Fuel fragmentation in IFA-650.3

While more cracks are present at the end of the test in this example, the pieces are still quite large in contrast to the Halden LOCA tests where fragmentation resulted in a fraction of fine powder (about 50 µm) and a fraction of larger pieces which, however, were smaller than the fragments typically found after normal operation exposure. This is evident from Figure 5 (IFA-650.4) and also from Figure 10. The latter is from a cross section pertaining to IFA-650.3 (with premature failure) showing fine fuel powder and larger, cracked fragments even in that case.

IFA-650.5 is even more interesting in this regard. The test achieved a peak clad temperature of 1050 °C, and the rod ballooned and failed at about 750 °C. Figure 11 shows that the pellet cracking is influenced by the constraint exerted by the cladding at the moment of failure. At the upper half (strong contact), the cracking from normal operation prevails. Where the cladding distended (lower half), the sudden drop of pressure on burst caused additional pellet cracking.

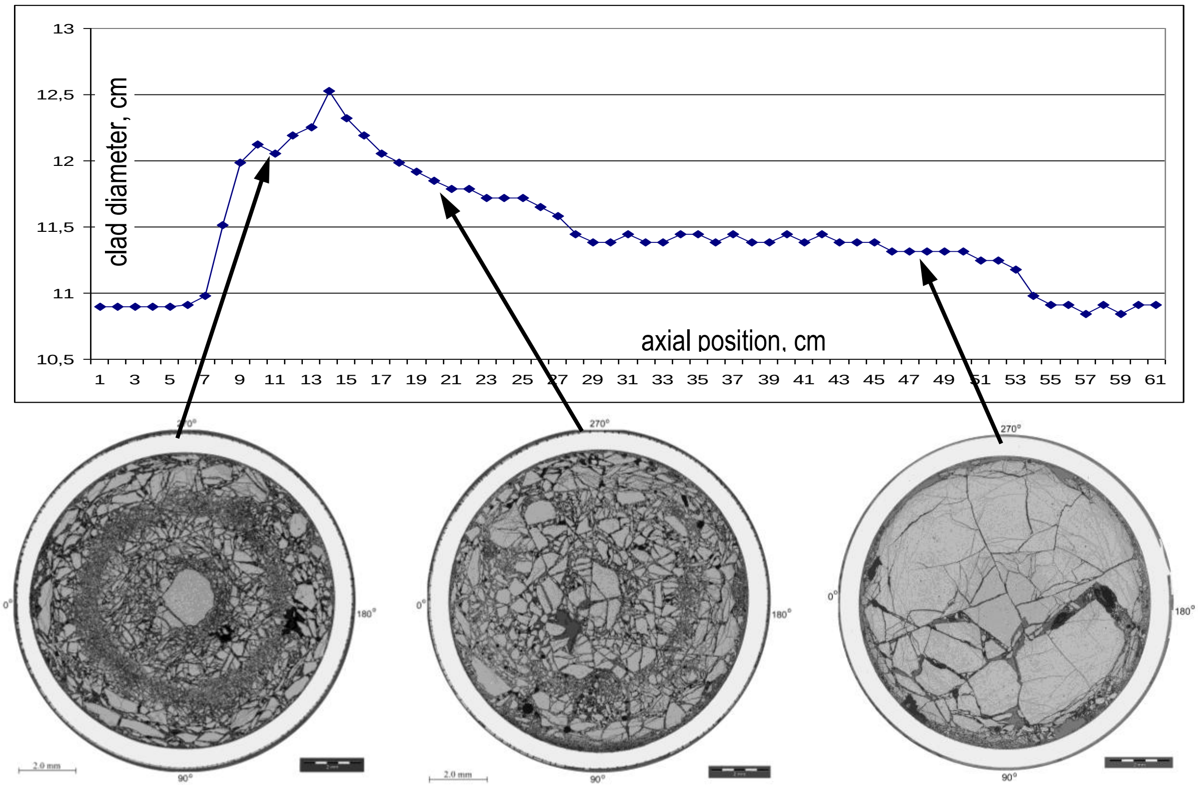


Figure 11 – Different cracking patterns obtained in IFA-650.5 (PCT 1050 °C).
The diagram shows the change of cladding diameter along the length of the rod.

All these observations combined indicate that fuel fragmentation is a function of several parameters. In any case, the Halden LOCA tests IFA-650.3/4/5/9 all exhibited more extensive fragmentation than shown by, e.g., the GASPARD test fuel depicted in Figure 9.

3.4.3 Conclusions on burnup

The burnup of the fuel segments employed in the Halden LOCA tests exceeds currently licensed burnup by some margin. No direct conclusions should therefore be drawn regarding the behaviour up to the current licensing limits. More investigations are required, and the continuation of the test series will hopefully identify a burnup threshold above which the observed fragmentation, in addition to the fragments formed by normal operation, can be expected.

3.5 Repeatability

Concern:

As the IFA-650.4 results have not yet been reproduced in other Halden tests, the question on repeatability should be addressed in one or another way.

(It should be noted that this statement was formulated in the CAPS at a time when IFA-650.9 had not yet been executed.)

3.5.1 Considerations

The significance of IFA-650.4 is increased if test results can be reproduced in a controlled way. Repeatability concerns several aspects of the test series: a) fuel fragmentation; b) ballooning (size and axial location); and c) fuel relocation and dispersal. Because of the stochastic nature of the phenomena and unavoidable differences in the test specimens, some variations of the outcome have to be expected and must be accepted as inevitable.

Taking a closer look at the test results (four tests with very high burnup fuel), the following can be stated:

Fuel fragmentation was observed in all tests, even in IFA-650.3 where failure occurred at the onset of ballooning due to a weak spot introduced by the thermocouple welding. (See 3.4.2 for more details.)

Ballooning occurred in IFA-650.4 (large), 650.5 (small) and 650.9 (large). The latter is essentially a repetition of IFA-650.4 with a higher target temperature and hence a higher heating rate and demonstrated the repeatability of the tests. (However, since all four available segments of the high burnup type have been used, no further test is possible.)

Fragment dispersal was observed in three of four tests. Not surprisingly, the amount depends on the size of the burst opening, and the unintended outcome of IFA-650.5 (small balloon and burst opening) has given valuable additional information on the range of the phenomenon.

Fuel relocation was observed in the two tests, IFA-650.4 and 650.9, which developed sufficient ballooning.

If hydrogen uptake in the balloon is an objective of investigation, repeatability compared to IFA-650.4 is not given anyway, because it was run at low peak clad temperature and consequently very little oxidation, and there was no hydrogen measured (and no significant increase expected). Argonne tests with increased statistics as planned should give a good basis for modelling of this phenomenon.

3.5.2 Conclusion regarding repeatability

All in all, the repeatability of the experiments seems to be good - especially when the outcome of the recent IFA-650.9 is considered. The similar results of IFA-650.4 and IFA-650.9 emphasize the importance of the phenomena first observed in IFA-650.4. Contrary to some RIA tests, the Halden LOCA tests were not conducted under such specific conditions which could query the existence of the observed phenomena (fuel fragmentation, relocation and release of fuel fragments into the coolant) for high burnup fuel.

3.6 Power history

Concern:

IFA-650.4 had a particular power history in that the mother rod was transferred from one assembly to another three times, in order to have high power rating and relatively rapid burnup build-up.

3.6.1 Possible influences

The power history during the irradiation period in the commercial reactor influences the pellet microstructure and the gas distribution within the pellet before the LOCA test. It can be relevant for estimation of the actual burnup of the tested fuel samples and, possibly, the local conditions of bonding and HBS in the pellet after base irradiation. In the case of high power rating, some pellet fragmentation takes place during normal operation. This may have some consequences on fuel relocation during LOCA, but the effect is not clear today.

The fuel rods at high burnup are characterised by low linear heating rate in a power reactor. The maximum temperature reached during LOCA depends on the decay heat and so on the power rate before the accident. The low power results in low maximum temperature, so it is possible that ballooning of high burnup fuel rods will not take place at all in the real case.

3.6.2 Conclusion on power history

While some influences of the power history may be hypothesised, no special LOCA relevant features are expected apart from the important fact that a long power history leads to high burnup with all the consequences already discussed in previous sections.

4. BENCHMARK REVIEW

The assessment of the consequences of a LOCA transient is to a large extent based on calculations carried out with codes especially developed for addressing the phenomena occurring during the transient. The Halden LOCA series contains test cases well suited for checking the ability of the codes to predict or reproduce the measurements and for providing clues as to where they need to be improved.

A first benchmark series was carried out on data obtained from the Halden test IFA-650.3. Since this test did not produce the expected ballooning and fuel relocation, it was decided to continue the benchmarking efforts with tests 650.4 and 650.5. The benchmark is in detail described in [6]. The main results for IFA-650.4 are repeated below.

Four codes participated in the benchmark on IFA-650.4: Athlet (GRS), Fraptran-Genflo (VTT), Icare-Cathare (IRSN), and Meteor (CEA). They also participated in the first phase and contain modifications and improvements to render the Halden experiments in a better way.

4.1 Rod pressure and time of failure

The comparison, Figure 12, indicates various degrees of agreement with the measured data (the Athlet-CD results are identical with the measured pressure which was used as input).

- The pressure decrease during the blow-down phase and the following increase due to heating up the system is not rendered by Fraptran-Genflo.

- All codes are in satisfactory agreement with the evolution of decreasing pressure after onset of ballooning until rupture which is an indication of correct calculation of the balloon size.

- The time of rupture, 336s, is best rendered by Meteor (340s), but the other results (Icare-Cathare 316s, Fraptran-Genflo 308s) are within an acceptable range of deviation.

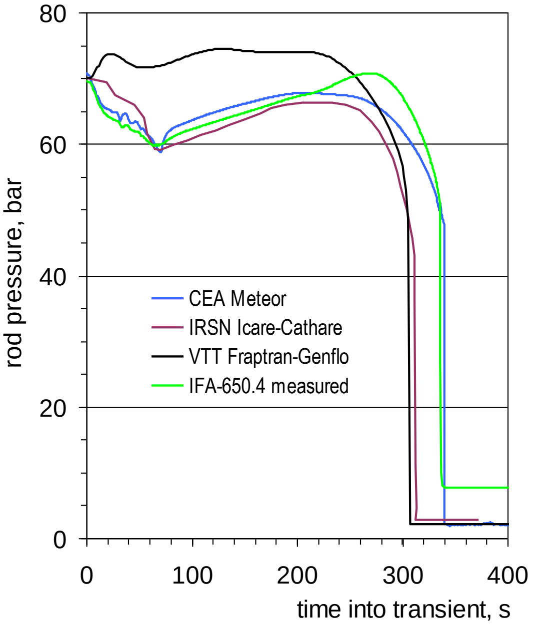


Figure 12 – Rod pressure evolution in IFA-650.4 - measured and calculated

4.2 Cladding temperature

Figure 13 shows the comparison of the measured and calculated cladding temperatures at the position of the upper cladding thermocouple in IFA-650.4.

- All codes predict the initial, steep temperature rise after end of blow-down, although Fraptran-Genflo does not render the cooling associated with the blow-down.
- The peak temperature at the upper TC position, occurring at rupture, is reproduced well by all codes and agrees with the measurement within 35 degrees C (Meteor).
- All codes introduced a feature to consider the missing (relocated) fuel after clad rupture. The calculated temperature decreases are in overall agreement with the measurements, but the decrease calculated by Icare-Cathare is on the high side.

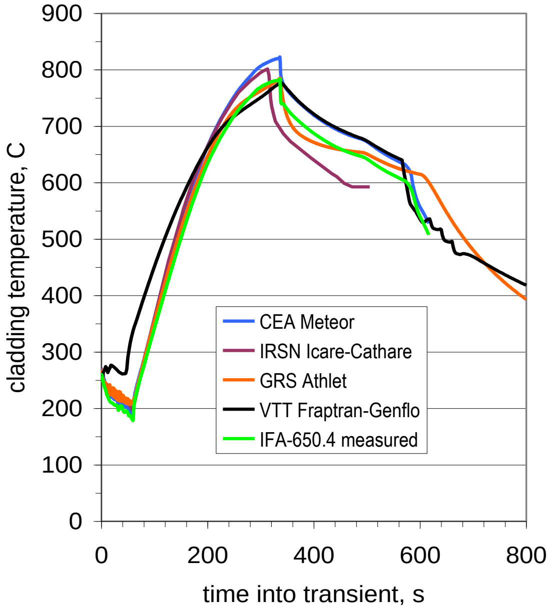


Figure 13 – Cladding temperature evolution in IFA-650.4 - measured and calculated

4.3 Ballooning strain

IFA-650.4 is characterised by quite large ballooning of the cladding, as intended according to the objectives of the test. This is mainly brought about by the uniform heating and circumferential temperature distribution. The calculated and measured cladding strain at the ballooning location is shown in Figure 14.

- The code results are in good agreement with the measured maximum strain of 62%.
- Meteor and Fraptran-Genflo agree in their prediction of the onset of ballooning at approximately 200 seconds into the transient.
- A comparison with the development of the rod pressure (Figure 12) indicates that this onset is probably too early (the measured pressure starts deviating from the increase at about 260 seconds).

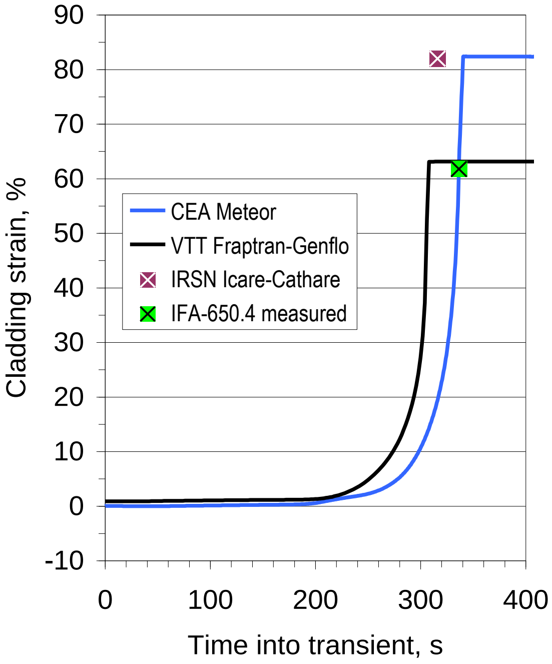


Figure 14 – Cladding strain evolution in IFA-650.4 - measured and calculated

4.4 Conclusions on code benchmark

On average, the codes agree reasonably with the experimental results.

Regarding rod pressure, the effect of ballooning causing the pressure to decrease is well calculated by the codes, implying that also the ballooning strain is calculated with a similar degree of agreement with the measured maximum strain of about 62%.

Also regarding time to failure at measured 336s, the results are within an acceptable range of deviation (308 – 340 s).

The most critical calculation is the cladding temperature since it is directly linked to the safety criterion limit of peak clad temperature and has a strong influence on cladding oxidation which is limited by the ECR safety criterion. The peak temperature as measured at the upper thermocouple position in IFA-650.4 is reproduced well by all codes and agrees with the measurement within 35 degrees C. The codes are conservative in that the results are slightly higher than measured.

As an improvement, the codes introduced the effect of fuel relocation on cladding temperature. The principal effect seems to be well described as evidenced by Figure 13. However, improvements regarding details of the temperature response to fuel relocation should still be sought since the codes will be used to judge a potentially critical part of a safety assessment.

5. ASSESSMENT OF SAFETY SIGNIFICANCE

The LOCA safety criteria are defined to ensure core coolability during and after a LOCA. They consist of surrogates such as cladding residual ductility or rod quench survival. The Halden LOCA tests are performed while the renewal of LOCA safety criteria is discussed in several countries including the United States and France. In this context, the phenomena that may play a role and therefore should be accounted for in a LOCA safety analysis have been considered thoroughly, and it is expected that the Halden tests provide the community with relevant experimental information on certain aspects of fuel behaviour during LOCA.

Some unexpected outcomes of the Halden LOCA tests, which were conducted with fuel segments having very high burnup, have attracted the attention of the international nuclear community. For example, the status of the current discussions on LOCA including statements on the Halden test IFA-650.4 has been presented to the German reactor safety commission at the end of 2008. Requests for further clarifications are to be expected since licensing in Germany has to be performed according to the state-of-the-art of science and technology.

In the following sections, an assessment of the safety significance of the Halden LOCA tests will be attempted based on the material and opinions presented in the previous chapters.

5.1 Embrittlement / secondary hydriding

The primary embrittlement characteristics of cladding materials are determined in special tests, e.g. ring compression tests. Their assessment is not part of the experimental program in Halden. The transient applied during the Halden tests represents the ballooning and burst phase of the LOCA (more specifically, one ballooning and burst scenario among many other possibilities), and the Halden tests cannot be used to determine or define LOCA safety criteria related to cladding embrittlement.

Secondary hydriding is an additional safety concern with respect to the embrittlement of the cladding in the ballooned region, since hydrogen influences the oxygen solubility in the remaining ductile phase of the cladding together with an intrinsic effect on embrittlement at low temperature.

High hydrogen pickup may be obtained upon clad inside oxidation under stagnant steam conditions after cladding burst. The axial distribution of hydrogen content shows a typical M-shape with two peaks away from the burst opening. However, it has been observed in ANL and JAEA integral tests that the peak concentrations and locations may vary considerably between fresh and irradiated rods, depending on fuel burnup. It may be assumed that the absorption of hydrogen is related to the local surface-to-volume ratio which is left by ballooning and fuel relocation on the clad inner side. Relocation of finely fragmented fuel will tend to shift the peak positions towards the burst opening, at locations where the surface-to-volume ratio is optimal for steam-starved oxidation and subsequent hydrogen pickup.

5.2 Fuel fragmentation, relocation and peak clad temperature (PCT)

To a large extent, there is agreement that the extensive fuel fragmentation observed in some Halden LOCA tests is a consequence of the very high burnup of the fuel segments employed and not typical of lower burnup fuel. Fuel relocation is emphasised by the fragmentation as well as by the driving force provided by the amount of gas available in the experiments. Neither such extensive fuel fragmentation nor fuel relocation has been observed in Halden LOCA tests conducted at low (e.g., zero) or moderated burnups.

A technical concern frequently evoked while analysing the Halden results is the effect of fuel relocation on the peak cladding temperature (PCT) in the ballooned area. The displacement of fuel fragments into the balloon may generate extra sources of heat and produce a local power peak (depending on filling ratio and residual power of the relocated fuel fragments).

The cladding temperature history in the ballooned region is obviously impacted by the relocation of fuel, but is also widely dependent on the thermal environment provided by the neighbouring structure (heater in Halden tests or rods in a fuel assembly). Therefore, the response observed in IFA-650 tests cannot be directly transposed to the reactor case with respect to the safety limits on peak clad temperature (PCT) and total oxidation rate (ECR) accumulated in the high temperature transient. Only a refined simulation of the reactor case, taking account of the radiative and possibly conductive heat transfers with neighbouring rods, could elucidate the impact of fuel relocation with respect to safety limits. Such a simulation would use the necessary data for fraction of relocated fuel, fragments size distribution, balloon filling ratio, etc., as provided by the existing data base, mainly from IFA-650 test results. However, the measured filling ratio in the order of 50% in IFA-650.4 indicates a rather moderate effect on PCT.

An important question is whether locally increased power and temperature and thus secondary hydriding represent threats to cladding integrity that are not yet accounted for in present safety evaluation methodologies. The LOCA safety studies performed by the utilities are already based on the assumption of an axially highly peaked power profile with peak factors up to 2.0. These safety studies cover bounding situations regarding local power peaks. The peak is usually confined to the ballooned and burst area (which is the axially hottest point of the rod). Qualitatively, the relocation event (if any) does not bring any new real physical phenomena not taken into account in the current safety analysis. Due to the relocation of fuel fragments, the numerical value of the maximum local power might be higher. This impact of fuel relocation on PCT and oxidation will depend on the fuel management scheme and on the reactor type.

5.3 Fuel dispersal, radiological consequences and coolability

One specific safety issue has been raised by the IFA-650.4 results. Even if not identified as an initial objective of the IFA-650 series, concerns related to fuel fragment dispersal have been evoked after the IFA-650.4 test results were released. Such fuel dispersal as observed in the high burnup Halden LOCA tests may have two significant consequences for the evaluation of reactor safety during LOCA:

Radiological consequences. According to the current practice, the activity release from fuel rods during LOCA is limited to some percentage of fission products accumulated in the gap and washed out by water from fragmented fuel surfaces of the ballooned and failed fuel rods. The Halden LOCA tests showed that large amounts of fuel can be released from ruptured cladding with limited corresponding release of radionuclides.

Core coolability. The fuel fragments released from the fuel rods may accumulate on the spacer grids between the fuel rods and impair the penetration of cooling water into some sections of the core (e.g. if the assemblies are covered by a shroud). Many different configurations can be imagined depending on fragment size and bundle/core geometry, and it cannot be excluded today that some of these configurations may cause coolability problems.

When judging these questions, the atypical fuel pellet microstructure of the fuel rod used in IFA-650.4, the significant free volume and amount of gas inside the tested rod, and the specific Halden LOCA test conditions, which were intended to produce a large balloon, have to be taken into account. The Halden tests cover the extremes that can be expected and may not be appropriate for drawing direct conclusions with respect to fuel behaviour in the core of a commercial nuclear power station. Fuel dispersal has not been observed in Halden LOCA tests conducted at low (e.g., zero) or moderated burnups.

At the current burnup limit licensed in the US (62 MWd/kgU peak rod average), it is believed that any fuel dispersal would be minimal. Fuel relocation and dispersal will need to be addressed prior to approving increases in licensed burnup. In the meantime, the planned Halden LOCA tests with fuel in the 55-65 MWd/kgU range will shed more light on the fragmentation and dispersal behaviour of fuels with relevant discharge burnups.

For the US, none of the current research adversely impacts current LOCA radiological assessments because of conservative assumptions related to core damage and isotopic inventories for purposes of dose analysis. The Halden Reactor Project conducted an iodine inventory balance for before and after the last test (IFA-650.9) and concluded that much less iodine was released than commonly assumed despite the fine fragmentation of the fuel [7]. Hence, based on current information, there is no need to alter any assumptions related to radiological consequences up to the licensed burnup limits.

6. RECOMMENDATIONS

The concern primarily addressed in this CSNI report is the fuel relocation and dispersal observed in the Halden LOCA tests. While the tests conducted so far have clearly identified the phenomenon, they also raise questions. Recommendations related to gaining more data and insight through more experimental work are:

1. Perform tests on fuel segments which have a burnup representative of bounding industrial situations (around 60 GWd/tU rod average) and whose in-reactor power history is representative of a standard commercial nuclear power plant; apply test conditions that produce a significant, but realistic balloon size (i.e. reasonably demonstrative).
2. Account for regulatory needs by incorporating segments with up to 70 MWd/kgU burnup in the experiments.
3. Determine the impact of axial gas transport on ballooning, e.g. by including a spacer grid between the upper plenum and the balloon area that would act as a prototypical distension restriction and cooling improvement similar to what can be expected in the real situation.
4. Investigate fuel relocation as influenced by fragmentation and the driving force provided by the amount of gas available in the experiments. Further tests on more prototypical fuel segments should be performed to document these phenomena.

Such tests, together with appropriate separate effect tests, can provide the industry with relevant results aiming at increasing the robustness of the LOCA safety studies.

An objective of the Halden LOCA tests is to investigate secondary transient hydriding in the balloon area. Although this is not the primary concern addressed in this CSNI report, the objective should not be entirely overshadowed by the fuel dispersal issue. It is therefore important and recommended to

5. Perform a sufficient number of Halden LOCA tests at high temperature in order to address secondary transient hydriding and in this way provide a basis for assessing the significance of the phenomenon for the embrittlement of the ballooned region.

The LOCA safety analysis is carried out with specialised codes. Some of them participated in the benchmark organised by the WGFS where the Halden test data were provided as input for the simulation. It is recommended to

6. Improve the predictive capabilities of LOCA analysis codes – among others:
    - model the occurrence of fuel relocation and related consequences (e.g. power redistribution and secondary hydriding);
    - assume realistic filling ratios, e.g. as observed in IFA-650.4 where the product of lower fragment density and increased volume results in about the same power density as before

ballooning and relocation (unless new tests performed on more prototypical fuel segments show different filling ratios);

- include the effect of restricted gas transport on ballooning and possibly on fuel expulsion.

The Halden LOCA tests have exhibited fuel expulsion, in the tests 650.4 and 650.9 to a considerable extent. The data raise questions regarding core coolability under LOCA conditions at high burnups. Assessment of these data under other, more prototypic conditions may require a detailed, core-wide and rod by rod analysis providing realistic rod powers as input to LOCA analysis codes. Such a procedure could take into account that in modern, low leakage core loading schemes the assemblies with the highest burnup are placed in the periphery of the core and are running at low power both due to their position and fuel depletion. Under these conditions, the expectation is that only a small number of high burnup rods would reach conditions and consequences as observed in the Halden tests. It is therefore recommended to

7. Consider basing analysis of the LOCA event on detailed calculations of the core power and temperature distribution and assess the behaviour of high burnup fuel with realistic conditions assuming appropriate uncertainty margins.

7. SUMMARY AND CONCLUSION

The Halden tests have identified possible fuel behaviour not previously seen. The results cannot be ignored even though they are, to some extent, produced and amplified by conditions and features deliberately introduced into the test series. The recommendations given in this CSNI report take this into account. In turn, regulators and the industry should take them into account in a way appropriate for their respective countries and fuels.

8. REFERENCES

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