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Pellet-Clad Interaction (PCI) in Water-Cooled Reactors

Workshop Proceedings
NEA Working Group on Fuel Safety (WGFS)
Lucca, Italy
22-24 June 2016

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) is responsible for NEA programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Executive summary

This report documents the proceedings of the Workshop on Pellet-Cladding Interaction (PCI) in Water-Cooled Reactors held in Lucca, Italy on 22-24 June 2016. The workshop was organised jointly by the Nuclear Energy Agency (NEA), Nuclear and INdustrial Engineering (NINE, Italy) and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN, France).

About 80 specialists representing 19 countries and 41 organisations attended the workshop. A total of 31 presentations were given, arranged in 3 technical sessions (experiments and analysis; modelling and simulation; design verification methodologies), with an introductory session and a concluding session.

The proceedings include the 27 papers received and the 31 presentations given during the meeting. They also include technical session summaries drafted by the session chairs, as well as an overall summary of the workshop taking into account the discussions that took place during the concluding session.

Regarding the role of cladding design on the mitigation of stress corrosion cracking (SCC) driven by PC(M)I, the following conclusions were derived:

- Liner fuel remains of interest to fuel designers.
- Texture controlled cladding shows improved resistance to (SCC-)PCI failure.
- Cladding design seems to be more effective than cladding material (alloy) with respect to the mitigation of the SCC driven by PC(M)I.

Regarding the role of fuel pellet design on PCI mitigation it can be stated that:

- Available experiments and analyses on pellet additive effects do not fully explain all aspects of the potential PCI benefits.
- There is some evidence that additives trap aggressive species in the fuel. However, it has been shown through multiple experimental programmes that very low concentrations of aggressive species are sufficient to drive PCI.
- The role of oxygen liberation seems important. There is some evidence that additives release oxygen to the gap and that this serves to oxidise and protect cladding ID cracks.

Today, the conventional 1.5-D and new 3-D codes remain complementary. The 1.5-D codes still form the basis of industrial applications as a result of run time constraints. Although 3-D modelling is largely progressing to address specific phenomena that are mandatory for PCI, multi-scale modelling is not yet used as a predictive tool to evaluate the PCI failure risk.

PCI risk prevention is efficiently integrated in operational rules based on mastered methodologies that include these 1.5 D fuel-performance codes in combination with technological limits. However, although they have proven to be practicable for the design, evaluation methods remain complex and time consuming. Operators expressed their strong interest in simpler and faster PCI risk assessment tools.

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List of abbreviations and acronyms

ABAQUS	Former name of the Abaqus FEA thermomechanics computer code
ADOPT	Advanced doped pellet technology
ALCYONE	Computer code for fuel behaviour (Commissariat à l'énergie atomique et aux énergies alternatives, France)
ANGE	AdvaNced Gibbs Energy – thermochemistry computer code for fuel
ANSYS	See www.ansys.com
AOO	Anticipated operational occurrence
ATF	Accident-tolerant fuel
BISON	Fuel-performance code (Idaho National Laboratory, United States)
BU	Burn up
BWR	Boiling-water reactor
CEA	Commissariat à l'énergie atomique et aux énergies alternatives (France)
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (Spain)
CsI	Caesium iodide
CSNI	Committee on the Safety of Nuclear Installations
CWSR	Cold-worked stress-relieved
DHC	Delayed hydride cracking
EDF	Électricité de France
EPMA	Electron-probe microanalysis
EPR	European Pressurised Reactor
EPRI	Electric Power Research Institute (USA)
ERPO	Extended reduced-power operation
FCT	Fuel centreline temperature
FGR	Fission gas release
FRAPCON	Steady-state fuel-performance code (US Nuclear Regulatory Commission)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH (Germany)
HBU	High burn-up

HRP	Halden Reactor Project
I&C	Instrumentation and control
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratories (United States)
JAEA	Japan Atomic Energy Agency (Japan)
LHR	Linear heating rate
LOCA	Loss-of-coolant accident
LWR	Light-water cooled reactor
MANTA	Thermal-hydraulic systems code (Framatome)
MIR	Methodology used to kinetically analyse PCI (Framatome)
MNF	Mitsubishi Nuclear Fuels (Japan)
MOOSE	Multiphysics Object-Oriented Simulation Environment (INL)
MOX	Mixed-oxide fuel
NNL	National Nuclear Laboratory (United Kingdom)
MPS	Missing pellet surface
NEA	Nuclear Energy Agency
NRA	Nuclear Regulatory Authority (Japan)
OSIRIS	Test reactor at CEA Saclay (France)
OTS	Operation technical specifications
OXIRED	Radial oxygen distribution model of the Transuranus code (Karlsruhe, Germany)
PACE	Pellet-associated cladding degradation
PCI	Pellet-cladding interaction
PCMI	Pellet-clad mechanical interaction
PIE	Post-irradiation examination
PMG	Power manoeuvring guidance
PWR	Pressurised-water reactor
RIA	Reactivity-initiated accident
SCC	Stress corrosion cracking
SCIP	Studsvik Cladding Integrity Project
SED	Strain energy density
SMART:	Three-dimensional neutronic code
SQA	Software quality assurance
TREAT	Transient Reactor Test Facility (INL)

TREQ	Fuel-rod thermal-mechanical code (European Fuel Group)
VNIINM	Scientific Research Institute of Inorganic Materials (Russia)
WGFS	Working Group on Fuel Safety
WWER	Vodo-vodianoï energuetitcheski reactor, or water-water energy reactor of Russian design

1. Introduction

This report documents the proceedings of the Workshop on Pellet-Cladding Interaction (PCI) in Water-Cooled Reactors held in Lucca, Italy, on 22-24 June 2016. The workshop was organised jointly by the Nuclear Energy Agency, Nuclear and INdustrial Engineering (NINE, Italy) and the Institut de Radioprotection et de Sûreté Nucléaire (IRSN, France).

About 80 specialists representing 19 countries and international organisations attended the workshop. A total of 31 presentations were given.

2. Background

Renewable sources of energy have an increasing share in the energy mix in a number of NEA countries. A specific feature of some of those energy sources is that their output is essentially variable in time. For example, solar and wind generation depend significantly on weather conditions. Hence, the predictability of their output with time has some intrinsic limitations.

Another feature of renewable energy sources is that they are often widely distributed over the countries and operated by multiple utilities. Thus, their controllability is less than that of more centralised production means.

Finally, in some areas, the grid capacity may also be a limiting factor and the output of large production units may need to be finely and rapidly adjusted to ensure the safe operation of the grid.

With this background, some recent studies and technical meetings[1,2,3] have pointed out that an increasingly flexible operation of NPPs will probably be required in the future. By flexible mode of operations it is here meant “non-baseload”, i.e. load following, frequency control, power modulation (changes in the units’ power output on request from the grid), etc.

However, the flexible operation of NPPs has implications on the fuel behaviour as it is well known that power variations may induce strong pellet-cladding interactions with a risk of clad failures and radioactive fission product releases in the primary circuit.

The last issue of the IAEA review of fuel failures in water-cooled reactors in 2010[4] showed that PCI-stress corrosion cracking (SCC) remains one of the causes identified. One of the main solutions to reduce the number of clad failures caused by PCI-SCC consists of imposing restrictions on the power variations adopted by nuclear power plant operators. Also, fuel vendors still continue their efforts to design fuels with increasing resistance to PCI-SCC: this ranges from fuels with additives (Cr, Al, Si) to an optimisation of the pellet shape. Another option – which is already widely used among BWR fuel assemblies – is the use of a clad inner liner. Also the procedures for loading of the pellets into the fuel rod have been modified to reduce chipping of the pellet surface.

The last seminar on PCI-SCC was held more than 10 years ago.[5] In the meantime, a number of projects have been conducted and have provided updated results (e.g.

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1. Load-following operating mode at nuclear power plants (NPPs) and incidence on operation and maintenance (O&M) costs. Compatibility with wind power variability, EUR 24583 EN – 2010.
2. *The Economics of the Long-term Operation of Nuclear Power Plants*, NEA No. 7054, 2012.
3. IAEA Technical Meeting on Flexible (non-baseload) operation approaches for nuclear power plants, 2013.
4. Review of fuel failures in water cooled reactors, IAEA STI/PUB/1445, 2010.
5. *Pellet-clad Interaction in Water Reactor Fuels*, NEA No. 6004, 2005.

experimental outcomes from Halden, SCIP I or SCIP II international programmes). In parallel to this, the simulation methods have been further developed, not only by moving from one to three dimensions, but mainly by adopting a multi-scale approach in order to provide deeper understanding of the basic phenomena involved in the process. The NEA Expert Group on Multi-scale Modelling of Fuels has published a state-of-art-report on this particular topic.[6] Benchmarks have also been organised notably during the course of the SCIP programme and the IAEA FUMEX III project. In some countries, national research programmes have also produced new results.

In conclusion, since the last OECD PCI seminar, a considerable amount of new developments and results have been produced. Thus, after more than ten years, it appeared desirable to reconsider the recommendations of the last seminar in light of the new findings.

As research results have become available, specific methodologies for assessment of fuel designs in relation to flexible and more demanding modes of operations, or in order to better account for uncertainties, have been improved. With regard to the 2004 workshop, this new aspect was also addressed in the workshop.

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[6] "State-of-the-Art Report on Multi-scale Modelling of Nuclear Fuels", NEA/NSC/R/(2015)5, 2015.

3. Objectives and structure of the workshop

The main objective of the workshop was to identify the current status of experimental and analytical studies related to pellet-cladding interaction (PCI) and PCI-SCC for water-cooled reactors. Recommendations from the last NEA PCI workshop were reviewed and progresses made were summarised.

Extending the scope of the previous meetings, the workshop also addressed the methodologies used or planned for use in the member countries for the assessment and evaluation of fuel designs and safety with respect to flexible and demanding modes of reactor operations.

The workshop was organised around three technical sessions:

- experiments and analysis;
- modelling and simulation;
- design verification methodologies.

4. Summary of the technical sessions

Each technical session was summarised by the session chairpersons. These summaries are reproduced below.

4.1. Session 1 – Experiments and analysis

This session was chaired by M. Amaya (JAEA, Japan), M. Bales (NRC, USA) and W. Wiesenack (HRP, Norway). Nine papers were presented in this session.

The first paper, presented by W. Wiesenack of the Halden Reactor project, provided a summary of experimental observations related to PC(M)I from Halden Reactor fuels testing. The presentation included explanation of the unique in situ instrumentation used in Halden's experiments that allows for in-core measurement of PC(M)I effects. The author presented Halden data that indicate that the onset of PCMI shifts to higher power due to fuel – cladding accommodation. Axial ratcheting effects were not identified in the presented Halden data. One of the experiments showed a complex interaction of fission gas release and PCMI, and it was concluded that despite numerous experimental efforts on PC(M)I, there remains a lack of an integral fuel model able to explain all observations.

The second paper, presented by A. Yamauchi of NRA, provided an overview of experimental studies on hydride-induced failures during power ramps. The NRA experiments provided evidence that outside-in cracking, postulated as a hydride-induced failure mechanism during a power ramp, could be reproduced in laboratory tests. Time dependent formation of radial hydrides in the outer region of cladding, fracture of radial hydrides and crack propagation by DHC govern the process. The presented study also investigated the possibility that hydrides could reorient under AOO conditions. The study showed that BWR claddings were vulnerable to hydride reorientation at linear heat generation rates above 35 kW/m. Similar tests for PWR claddings did not show evidence of hydride reorientation. Differences in the results of BWR and PWR cladding were observed and attributed to temperature and stress effects.

The third paper, presented by F. Corleoni of Studsvik, summarised the chemical and structural characteristics of ramp tested fuel with additives. He showed that the Studsvik ramp database indicates that there is a PCI benefit using additives/dopants in the fuel. It was speculated that this PCI benefit is derived from additives trapping aggressive species in the fuel, and some PIE examinations where shown to corroborate this theory. Other observations suggest that the PCI mitigation seen in fuels with Gd or Al-Cr may be due to oxygen release from additive elements. Examination results were presented that revealed a thin oxide layer within the fresh exposed crack surface after ramp testing, suggesting that oxygen may be present in the gap and sufficient to oxide fresh crack surfaces, protecting them from aggressive species. Another important finding from Studsvik's ramp database is that Al-Si is better at retaining volatile, potentially aggressive, elements within the fuel.

The fourth paper, presented by R. C. O'Brien of INL, provided an update of TREAT capabilities and experimental planning activities. TREAT is a power pulse reactor which can produce pulse widths typical of LWRs. Transient testing of ATF concept fuels in TREAT is scheduled for 2018. The planned transient tests include RIA, LOCA, AOOs (fuel melting, ramps, reduced flow), and possibly beyond design-basis accident scenarios. Continuation of LWR fuel transient testing is also expected in the TREAT reactor.

The fifth paper, presented by V. I. Arimescu of Areva, discussed the possible mitigating effects of slow power ramps and speculated whether these effects were mechanical or chemical in nature. The presentation provided evidence that ramp speed influences peak cladding stress, that both slow and stepwise ramps show PCI benefits. The presentation also argued that oxide formation and healing can win over chemical attack. The presentation concluded that both mechanical and chemical effects played a role and called for the development and use of a multiple-parameter PCI threshold combined with uncertainty analysis.

The sixth paper, presented by P. Frankel of University of Manchester, provided an overview of the Pellet-Associated Cladding Degradation (PACE) programme. PACE is a collaborative research consortium to investigate pellet-cladding interaction designed to bring together capabilities of leading academic institutions and industry based knowledge and experience. The presentation highlighted that the collaboration enables systematic study of possible PCI mechanisms and noted that a number of PACE associated projects have already started. The PACE programme has been designed to keep modellers and experimenters working closely together to design better experiments and fine-tune models to support improved understanding of PCI phenomena.

The seventh paper, presented by N. Murakami of MNF, discussed the possibility that texture controlled cladding material could offer improved PCI performance. The presentation provided experimental evidence showing that that texture controlled cladding is more PCI failure resistant. The experimental results suggest that it is possible to operate with higher PCI failure threshold of 2 kW/m applicable to burn-up up to 80 MWd/kg.

The eighth paper, presented by D. Le Boulch of CEA, summarised testing and modelling efforts related to iodine-induced stress corrosion cracking (I-SCC) in zirconium alloys. The CEA research indicated that pressurised iodine vapour showed an I-SCC threshold of ~240 MPa for fresh CWSR Zry4 and ~150 MPa for irradiated CWSR Zry-4. The Kachanov-Miller model was presented, which simulated I-SCC initiation and the stress intensity factor k_{SCC} for irradiated CWSR Zry-4. The model was shown to well predict time to failure under iodine exposure.

The ninth paper, presented by A. Casagranda of INL, focused on 3D Modelling of PCMI with a missing pellet surface (MPS) defect. In preparation of an MPS in-pile test, BISON predicted measureable clad deformations (> 20 microns) at MPS. This work showed that the fuel/cladding contact model (glued or sliding) significantly influences certain cladding results and that higher fuel temperatures are predicted in MPS pellets.

4.2. Session 2 – Modelling and simulation

This session was chaired by C. Delafoy (Areva, France), T. Forgeron (CEA, France) and P. Van Uffelen (ITU, UE). Ten papers were presented in this session.

The first paper, presented by N. Waeckel (EDF), gives an overview of the efforts to address the PCI-SCC issue for more than 30 years in the French Nuclear R&D community. Industrial robust “PCI design approaches” were developed and licensed in order to calculate the corresponding margins available in a core at any time, in each fuel rod, for various fuel reload patterns in normal and AOOs conditions. In these approaches, a failure threshold is defined based on the interpretation of a power ramp test database using a validated fuel-performance code. The same fuel-performance code is then used to quantify the in-reactor PCI-SCC margins and to define the operation restrictions. Independently, a “Multi-scale R&D approach” is considered to shed light on the PCI-SCC phenomena, from the pellet centre to the clad inside surface. The aim is to provide the industry with insights on various SCC mechanistic scenarios based on promising hypotheses as pellet thermal chemistry and oxygen radial thermal diffusion. Such an R&D approach is well suited to explain why specific fuels (e.g. Cr_2O_3-doped or MOX fuel pellets) exhibit better PCI-SCC resistance or to confirm that the fuel-performance code used in the design approach includes relevant models to assess the PCI-SCC failure risk.

The second paper, presented by H.G. Sonnenburg (GRS) deals with a modelling approach deduced from Studsvik Hardening-RelaXation (HRX) tests to predict the creep of Zry-2 and then clad peak stress under load-follow operation, which may induce PCI failures. The TESPA-ROD code applies a Norton creep law with parameters developed to predict the thermal creep of a-Zr material under LOCA transient conditions. Applying this creep model to HRX tests gives good predictions for the first load cycle. However, it turns out that this approach is inappropriate when the strain hardening mechanism becomes obvious, i.e. when long-term creep is to be considered. The Norton creep law was therefore modified with a reset of the creep rate reduction when the stress reaches zero, hence the reduction progresses with a doubled velocity. This relative complex algorithm applies for Zry-2, for stress levels ranging from zero up to plasticisation and for temperatures between 310-360°C. Nevertheless, the application of the same approach for M5 and Zirlo turned out to be unsuccessful.

The third paper, presented by J.Y.R. Rashid (Anatech, United States), describes a generalised failure model for the BISON fuel-performance code in normal conditions, AOOs and accident situations. In all these situations, the cladding failure emanates from service-induced inner or outer cladding surface flaws acting as nucleation sites for fracture initiations. Therefore, the premise of the model is to use a simple measure that recognises the presence of a flaw without the explicit representation of the flaw geometry. To that end, the path-independent J-Integral methodology of elastic-plastic fracture mechanics was adapted. The purpose is to have a direct evaluation of the J-integral as a function of the strain energy density only. For a discrete notch-type form of damage either at the outside or inside diameter of the cladding, the far-field strain energy density is calculated with respect to an un-cracked body. The resulting disturbance function is a measure of how the local strain energy field is modified by the notch. The disturbance function depends on the sharpness of the notch. Relatively large disturbance would characterise a PCI-MPS mode whereas small values would characterise RIA and LOCA. Relationships are established between the critical strain energy density and the fracture toughness which is a function of the material, the fluence/BU, the temperature, the hydrogen content, etc. OverRamp and TransRamp tests as well as some CABRI RIA REP Na tests were analysed with the BISON code. In all cases very good agreement is found between the calculations of the strain energy density and the model’s critical (failure) strain energy density. According to these evaluations it is concluded that this development is analytically robust.

The fourth paper, presented by F. Feria (CIEMAT), focuses on the use of version 3.5 of the FRAPCON 1.5-D code for assessing the gaseous swelling effect on PCMI for a Zirlo cladded 16x16 fuel rod up to a burn-up of 75 GWd/tU. The code uses purely empirical correlations supported by slow ramp tests to simulate the effect of gaseous swelling without increasing computational costs. The cited modelling is expressed in terms of strain, which is calculated as a linear triangular function of fuel temperature, leading to an effect initiated from ~1 000°C and reaching a maximum at about 1 400°C. Moreover, the model is phased in between 40 and 50 GWd/tU by applying a factor that varies linearly from 0 to 1. Accordingly, the gaseous swelling strongly affects the fuel surface displacement during base irradiation from 40 GWd/tU, whereby the actual contribution of this mechanism is controlled by the decreasing fuel temperature. Under ramp conditions the calculations point out implications on safety margins related to the activation of gaseous swelling. The stress margin shows a decrease during start-ups from 33 to 50 GWd/tU and lower power increment is allowed from 65 GWd/tU. Considering this significant effect, a critical review of the gaseous swelling model used in FRAPCON is recommended in order to derive a better description of this phenomenon with possibly a mechanistic approach.

The fifth paper, presented by E. Federici (CEA), synthesises the knowledge acquired from the co-operative R&D programme between CEA, EDF and Areva NP about the PCI I-SCC mechanisms, and provides an overview of the corresponding modelling in the ALCYONE application. More precisely, the authors summarised the effects caused by thermal expansion and cracking, fuel creep and swelling, as well as the iodine release, and how these mechanisms are integrated in the ALCYONE code. Some details were provided about the smeared pellet cracking model, which relies on two physical parameters: critical stress and fracture energy. These have been fitted on the basis of bending and indentation tests, as well as post irradiation examinations of the cracking patterns. A second model that was highlighted deals with fuel creep, consisting of two stationary temperature-activated mechanisms (diffusion and dislocation creep). Compression tests in combination with finite element modelling are used to infer the creep model parameters for fresh fuel, along with an inverse analysis of the dishing filling ratio on longitudinal metallographic examinations for assessing their burn-up dependency. In the final part, the authors outlined the validation process that is based on 50 ramp tests on UO_2 and MOX fuel with both Zry-4 and M5 cladding carried out in the OSIRIS test reactor. The post irradiation examination data used are the cladding average outer diameters and the heights of the ridges, and could be simulated satisfactorily. Finally, an overview of ongoing developments has been given concerning the possibility to model the thermo-chemistry of irradiated UO_2 fuel in transient conditions, and the development of a damage model for the cladding to be used in PCI I-SCC conditions.

The sixth presentation provided an overview of the R&D activities at VNIIM for PCI in WWER fuel. The modelling activities involved both the 1.5D START-3A code, as well as the 2D and 3D calculations using the ANSYS finite element code. The former code is applied for the design and interpretation of ramp tests in test reactors, and provides input parameters (e.g. about gaseous swelling) for the subsequent analysis with the ANSYS code. The multi-dimensional finite element code is also applied for the design and interpretation of separate-effect laboratory experiments by means of the mandrel test. The combination of these analyses has led to define the stress limits. In particular, the maximum tensile stresses in the fuel were found to be 568 MPa, while the corresponding limit in the cladding was found to be 190 MPa in front of the fuel cracks. An example was provided of a mandrel test as well as for a ramp test, in which it was shown that the multi-dimensional analysis by means of ANSYS was able to reproduce the detrimental effect of a missing chip, and the START-3A calculations were shown to be in good agreement with the finite element results without consideration of the pellet defect.

In the seventh paper, preliminary thermo-chemical-mechanical simulations of power ramps were presented by J. Sercombe (CEA). The simulation tool includes the fuel-performance code ALCYONE coupled with the radial thermo-diffusion of oxygen based on the OXIRED model and fission product chemistry modelled by means of the ANGE software. The main purpose was to assess the impact of the oxygen redistribution on the fission products thermo-chemistry and on corrosive fission gas release, which is considered to play a major role in PCI-SCC. This was triggered by observations made on fuel rods after a power ramp. More precisely, the pronounced reduction of molybdenum oxides and chromium oxides at the pellet centre, highlighted by EPMA measures, are considered to result from the oxygen depletion at the pellet centre. The latter is considered to result from the small hypostoichiometry of irradiated UO_2 fuels in combination with the high thermal gradient across the pellet. This thermo-diffusion of oxygen is found to modify greatly the concentration of the gas species of interest for I-SCC, i.e. I_2, CsI and TeI_2. The coupled simulations showed that the release of iodine presents two steps that are related to the kinetics of the oxygen redistribution. During the first step TeI_2 would be released, which is considered to form ZrI_4 and to initiate I-SCC. In the second step, iodine is released in the form of CsI along with some minor quantity of Cs. Because these are considered to be non-corrosive to zirconium alloys, the simulations indicated a limited time window for I-SCC during power ramps. Nevertheless, further work is ongoing with respect to the model of gaseous release for the 60 species considered, as well as on the thermo-diffusion of oxygen in slightly hypostoichiometric UO_2.

The eighth paper, presented by R. Daum (EPRI), presented the statistic approach developed by EPRI in order to improve the Power Maneuvering Guidance (PMG) for PWR and BWR operators, taking into account the statistical distribution of the size of the missing pellet surface (MPS) fuel type defects. Based on the feedback experience of fuel failures root causes analysis and established PCI-SCC and PCMI assessment thresholds derived from integral tests, the methodology uses the FALCON fuel-performance code 2-dimensionnal capabilities in (R-z) for localising the maximum hoop stress zone and (R-q) for the evaluation of the stress concentration factor induced by the MPS defect. 3-dimensional ABAQUS analysis completed the evaluation of the impact of the axial extension of the defect. Based on the knowledge of the operational environment (distribution of nodal peak power, delta power and burn-up) on the one hand and on the MPS size distribution data from the fabrication process on the other hand, the probabilistic approach allows to better evaluate the risk of the duty-related failure assuming the impact of MPS defects and to adapt the PMG for a better operational efficiency (compared to those derived from conservative deterministic approaches).

The ninth paper, presented by R. Williamson (INL), dealt with the Verification and Validation of the INL finite element fuel-performance code BISON, for the PCMI application. Due to multiple and interdependent complex phenomena involved, the simulation of the nuclear fuel behaviour is a challenging topic and post irradiation measurements give global parameters issued from path-dependent complex histories. After having recalled the main features of the BISON Code (multi-dimensional, multi-physics, etc.), the essential importance of the verification work that must precede the validation step was pointed out. Based on an original software quality assurance (SQA) programme and taking advantage of the methodology set up for the development of the open-source MOOSE software, the BISON team uses the Gitlab repository allowing version management with detailed information, total traceability and secured archives. The Verification process also includes unit testing based on specially designed cases with analytically known solutions and classical non-regression testing. The verification of solutions is then carried out by comparison of simulation results with available data in terms of fuel centreline temperature (FCT), fission gas release (FGR) and rod diameter profiles over a data base of typical well-characterised PWR fuel rods. The accuracy is given as a function of the mesh refinement and time discretisation. For the Validation of the PCMI application, BISON code results have been compared with the measurements of about 50 integral rod LWR experiments (FCT, FGR, diameters before and after tests). If the temperatures and FGR appear to be reasonably well predicted, many questions arise from the analysis of the rod diameter evolution during the transients and several hypotheses are proposed. The necessity to take into account the separate effects tests (e. g. clad creep tests IFA-685) in the validation process was also pointed out. Parametric studies and comparisons of predicted and measured data at different stages of power ramp experiments are presented and discussed. Priorities for future developments are derived towards a better simulation of PCMI, including more realistic mechanical models such as smeared cracking, creep and relocation recovery for oxide fuels.

The tenth paper presented the first results of the OECD/NEA benchmark on the pellet-clad mechanical interaction modelling with various fuel-performance codes. The benchmark started in June 2015 and involves 18 organisations in 12 NEA member countries. A detailed status of the benchmark, achieved and expected results, was presented by G. Rossiter (NNL). The participants use various codes (fuel-performance codes 1.5-D, 2-D, 3-D, alone or in conjunction with general thermomechanical finite element method based codes). Four cases were selected: the two first cases are hypothetical beginning of life cases on short segment (10 pellets) and full length typical PWR rods, the third one is the IFA-118 experiment carried out in the frame of the Halden Reactor Project (1969-70) and the fourth one the end of life experiment IFA-629 (2004). Cases 1 and 2 computations are achieved. The case 1 detailed results (fuel stack and clad elongations, rod diameter and hoop stress profiles) exhibited significant discrepancies for some participants for initial step of calculation (zero time). The first elements of analysis were presented. Questions concerning the implementation of very basic physical data such as thermal dilatation parameters may arise, among other. First conclusions were derived from case 1: fuel pellet cracking pattern, fuel-clad friction, fuel relocation are key modelling assumptions; similar behaviour in terms of stack elongation or outer diameter during the power transient are generally observed; the predicted peak hoop stress, often considered as a key parameter for PCMI can vary from 100 to 300 MPa.

4.3. Session 3 – Design verification methodologies

This session was chaired by C. Anghel (Westinghouse Electric, Sweden), N. Waeckel (EDF, France) and J. Zhang (Tractebel, Belgium). Four of the five papers foreseen for this session were presented (i.e. one paper was never received).

In the first paper, Christine Delafoy (Areva) presented some fuel manufacturing improvements and a PCI resistant fuel design. Effective hardware solutions have been successfully implemented in Areva manufacturing plants to eradicate MPS occurrences. Areva developed and optimised Cr_2O_3 doped fuel pellets to enhance PCI-SCC resistance of the fuel in LWRs, such allowing significant upgrade of flexible operation. During the development of various types of doped fuels, Areva noticed the detrimental effect of other dopants such as Nb, Si or Ti. Cr_2O_3 doped fuel pellets bring direct relief of peak cladding stress by virtue of enhanced creep deformation and of the presence of more numerous and smaller outer pellet radial cracks, which reduce stress concentration at the cladding inner surface. In addition, evolution of chemical state of chromium during ramp test and induced effect on oxygen potential may contribute to SCC mitigation. Areva mentioned that Cr doped fuel has been successfully commercialised for BWR. It must be noted that Areva BWR doped fuel rods do not include a cladding liner, such increasing the cladding bearing capacity. The PWR version includes Cr doped fuel pellets with high performance M5 cladding. According to the ramp tests data base, PWR and BWR Cr doped fuel rods exhibit similar performances. Regarding doped fuel behaviour at HBU, higher fission gas retention of Cr_2O_3 doped fuel allows lower end of life rod internal pressure which is beneficial for LOCA and possibly for RIA transients. Regarding reprocessing, comprehensive scoping analysis has shown there is no significant difference with standard UO_2. The assistance asked if the “short pellets” concept is still under investigation. Areva said yes, mechanistic multi-scales models which are still under development are usefully used to analyse the experimental results obtained so far.

In the second paper, Clara Anghel (Westinghouse) presented the new Westinghouse BWR fuel concept with HiFi cladding + liner + ADOPT pellets to minimise waterside corrosion/ hydriding and maximise PCI and PCI-SCC margins. Westinghouse developed lined cladding for BWR applications. Inner liner provides a 15 to 20 kW/m gain on the PCI-SCC failure threshold and the benefits remain under all types of fuel operation conditions and temperatures. Since this gain is derived from stepwise power ramps, Westinghouse convened that it should be confirmed using more prototypical test conditions. According to Westinghouse, significant benefit of the liner cladding is obtained in the case of fuel relocation or pellet defects such as missing pellet chips. One example of a fuel rod with liner cladding and ADOPT fuel that showed significant resistance to fuel relocation was presented. According to Westinghouse, “doped” fuel (i.e. ADOPT) doesn’t exhibit any benefit in normal operation (no creep benefit below 1 300°C) but generate more dense peripheral radial cracking (which is beneficial for PCI and PCI-SCC). Other possible beneficial effects such as the changes of the oxygen potential and formation of alternate/modified fission product secondary phases as a result of the dopants in the pellets are under investigation. Westinghouse is ready to develop a lined cladding for PWR applications, too.

The third paper was not presented at the meeting, but N. Doncel (ENUSA) sent the presentation. ENUSA developed a methodology to evaluate the risk of fuel rod failure due to PCI mechanism throughout the development of an effective stress limit, called “PCI Technological Limit” (PCI-TL) based on the analysis of experimental power ramps to discriminate between failed and non-failed rods. Using this PCI-TL ENUSA developed a specific methodology to determine the maximum allowable ERPO duration with no restriction on the ramp rate when coming back to full power. This methodology was tested with a demonstration case and is available for its licensing and future applications.

In the fourth paper, Lucile Daniel (Areva) presented the two primary PCI methodologies at Areva: the MIR methodology and the Allowable Power methodology. Both approaches are based on thermal-mechanics computations of class-II transients, at each time step and for various BU. The margin to rod failure is given by the comparison of the cladding strain energy density (SED) to a threshold previously determined using a representative experimental power ramp tests database. The two approaches use different way of calculating the neutronic class-II transients: MIR methodology includes full core 3D kinetics calculations (SMART code) coupled with a system code (MANTA) to account for I&C and safety systems, while Allowable Power methodology uses 3D steady-state (SMART) with bounding loop parameters. The comprehensive analysis using MIR methodology allows defining the plant Operating Technical Specifications. However, this detailed approach implies a significant number of computational cases, such limiting its use to the equilibrium cycle. On the other hand, the Allowable Power approach proposed by Areva NP, is efficient enough to perform cycle-by-cycle analysis. To take advantage of the strong points of both approaches in order to cover extended flexible operations (so-called flexibility cycles), a coupled methodology is developed: a generic PCI study on the equilibrium cycle is carried out with both MIR and Allowable Power methodologies whereas studies on flexibility cycles are performed with the Allowable Power methodology. In the near future, extended manoeuvrability of the nuclear power plants will imply using additional features such as:

- the Gliding Threshold methodology specifically considered for EPR reactors;
- an evolution of the Core Monitoring System.

The fifth paper was presented by Philippe Paulin (EDF). He first indicated the main operational constraints related to PCI-SCC at EDF:

- Potential reduction of manoeuvrability, if the margins between the normal operation conditions (including load follow and frequency control) and protection thresholds are insufficient;
- Limitation of Extended Low Power Operation durations;
- Limitation on core reloads variability.

Examples of industrial needs regarding manoeuvrability and operation at intermediate power are presented. The best way to address these operational requirements consists in using high PCI-SCC performance fuel designs. In addition, a simplified "PCI with variability" approach is being licensed to improve the robustness of the current generic PCI studies which is focused on the “equilibrium cycle”. EDF has defined "variable" Operation Technical Specifications (OTS), including a "penalty" on PCI margins while maintaining a generic design approach. EDF recalled that OTS are rather complex and suggested to ask for experienced operators on both primary and secondary sides of the Nuclear Power Plant (human factors should not be neglected).

In the sixth paper, R. Daum (EPRI) presented the industrial initiative for PCI mitigation. EPRI has provided a 4-step PCI failure risk assessment procedure: this helps utilities to perform an independent PCI margins evaluation. This procedure needs to be adapted to mixed cores.

The seventh paper was given by Jinzhao Zhang (Tractebel). He indicated that due to the expansion of renewable energy sources in Europe, power modulations are requested for certain Belgian NPPs at 50%NP during 72h during Week-Ends, then back to normal power at 1%NP/min max (this ramp rate is related to operational constraints rather than to PCI limitation). A load pattern PCI risk assessment tool is developed to enhance the loading pattern fuel reliability and design assessment. Load pattern PCI risk assessment is based on the use of simple PCI correlations to assess the PCI margins to be comparable to the previous cycle and to the fuel vendor analysis. Analysis can be performed within a few hours (rather than 4 weeks by the fuel vendor). It is hoped to define simpler “all included” operational or design limits to avoid time-consuming analysis, but these design limits may lead to unbearable operational constraints.

Finally, in the eighth paper, Laureline Barbié (EDF) confirmed that the MIR approach (see Areva's paper above) is comprehensive but rather time and resources consuming. As mentioned by Philippe Paulin earlier, EDF is developing a new promising "static approach" to cover variable reload patterns, while reducing the calculation time to less than 4 weeks, without unbearable restriction as compared to the comprehensive MIR approach. One potential option to simplify PCI-SCC design and reduce operational constraints could be to implement on line automatic systems (like for EPR), but this imply additional on-site modifications and heavy licensing work.

5. General conclusions and recommendations

On the basis of the discussions that took place during the conclusion session, the chairpersons formulated general conclusions and recommendations.

Regarding the role of cladding design on the mitigation of SCC driven by PC(M)I mitigation, the following conclusions were derived:

- Liner fuel remains of interest to fuel designers.
- Texture controlled cladding shows improved resistance to (SCC-)PCI failure.
- Cladding design seems to be more effective than cladding material (alloy) with respect to the mitigation of the SCC driven by PC(M)I.

Regarding the role of fuel pellet design on PCI mitigation it can be stated that:

- Available experiments and analyses on pellet additive effects do not fully explain all aspects of the potential PCI benefits.
- There is some evidence that additives trap aggressive species in the fuel. However, it has been shown through multiple experimental programmes that very low concentrations of aggressive species are sufficient to drive PCI.
- The role of oxygen liberation seems important. There is some evidence that additives release oxygen to the gap and that this serves to oxidise and protect cladding ID cracks.

PCI benefits seen in modern “PCI resistant fuel”, as well as further developments in PCI resistance will likely not be explained through mechanical effects alone; chemistry effects also play an important role. This means that fuel-performance models must also deal with chemistry effects if they seek to make accurate predictions of PCI failure limits. In general, however, it appears that mechanical aspects are better understood than chemical aspects of PCI benefits.

Experimental programmes and analyses focused on identifying the relevant parameter to characterise the clad failure risk (linear heat rate, cladding strain, cladding stress, strain energy density, etc.) still present a complex picture. LHR appears to be the primary driver, but insufficient to discriminate failure/non-failure in detail. Experiments therefore largely address LHR (RTL) and ΔLHR, even though time appears to play a role as well.

There are encouraging active research programmes that have a clear objective to co-ordinate and create links between separate effects modelling and experiments. These programmes have already provided important insights into some phenomena at play in PCI, including missing pellet surfaces, crack growth in the presence of iodine, and fission gas migration. They also reveal a finer level of refinement that could be illuminated with future experiments.

Despite a number of research programmes highlighting separate effects and concerted efforts to model the existing PCI experimental database, it appears that the existing PCI models are not able to distinguish “failure” from “non-failure” points in code predictions.

This is probably because the existing PCI experimental database, while very large, is extremely heterogeneous, and because of the stochastic nature of some phenomena involved (e.g. cracking pattern). This may result in residual retention of conservatism for PCI prevention thresholds. Separate effects studies are proving to be more valuable in discerning the impact of various PCI variables for modellers, and promising collaborations between PCI experimental programmes and PCI modelling programmes are taking place all over the world.

In response to the question of whether experiments, in-pile or out-of-pile, on fresh or irradiated material, are still needed to investigate PCI, the audience and session chairs unanimously confirmed that they are necessary. However, it was also noted that the number of PCI failures is nowadays very limited in the existing nuclear fleet, diminishing the safety concerns due to PCI.

Today, the conventional 1.5-D and new 3-D codes remain complementary. The 1.5-D codes still form the basis of industrial applications as a result of run time constraints. The PCI risk prevention is efficiently integrated in operational rules based on mastered methodologies that include these 1.5 D fuel-performance codes in combination with technological limits.

It remains more challenging to explain why some rods did not fail under power transient conditions or why some fuel pellet types exhibit a higher PCI resistance with respect to standard UO_2 fuel. Multi-dimensional modelling is needed to understand experimental PCI failures because these occur at pellet interfaces, where local deformations develop that cannot be reproduced by 1.5-D codes. Although 3-D modelling is largely progressing to address specific phenomena (temperature, gaseous swelling, mechanics, etc.) that are mandatory for PCI, multi-scale modelling is not yet used as a predictive tool to evaluate the PCI failure risk. Computational material science, which typically considers smaller scales, might also be useful but is still at an embryonic state in the PCI field.

A prerequisite for further progress is the definition of a PCI failure criterion. It is considered that PCMI must be evaluated before PCI, and several parameters that can be model-dependent are still candidates (stress, strain, strain energy density, damage parameter, etc.) although some of them cannot be measured directly.

With respect to modelling and simulation, a number of recommendations were therefore identified:

- More effort is needed to integrate and to analyse the effect of uncertainties in the verification and validation of codes. Several statistical approaches are being considered, but need to be consolidated.
- Out-of-pile separate-effect tests generally lead to a relevant model for one phenomenon but they are not straightforward in deriving a relevant global failure threshold when applied in a fuel-performance code. Comprehensive advanced multi-physics modelling has to be continued for better quantitative analysis.
- 3-D modelling should be more systematically involved in the design and interpretation of discriminant experiments (for example to study MPS adverse effects).
- In order to validate a significant step in modelling PCI such as 3-D calculations coupling thermal-mechanical and thermo-chemistry, dedicated experiments should be carried out. Examples could include assessing oxygen thermo-migration during power transient conditions or characterising in-pile fuel creep.

- It is generally well accepted that iodine is the cladding corrosive agent for PCI but further work is necessary to consolidate the carrier species (i.e. Te, Cs, etc.) and the migration kinetics from the pellet centre to the cladding inner surface.
- Within the NEA, different groups are involved in multi-scale and multi-physics benchmarks. PCMI analysis by means of 1.5-D codes is being considered. However, since various modelling capabilities were presented during the seminar in order to address the specific impact of MPS on PCI, this could be the subject of a benchmark for 3-D codes as follow-up to the current PCMI benchmark.

Fuel vendors are proposing various fuel concepts to mitigate PCI-SCC failures risks. The first approach is the use of additive fuels. For BWR and PWR, Areva proposes a Cr_2O_3 doped fuel concept with no lined cladding recovering the thermal-mechanical design margins of the standard cladding. Westinghouse showed that the benefit of the ADOPT pellet is a high temperature effect: it would not bring benefits at normal operating conditions but would bring significant benefits in case of transients or accident conditions. The second approach is the use of advanced cladding materials. Areva proposes high performance Zry-2 claddings with or without liner for BWR and M5® alloy for PWR. Westinghouse proposes as BWR fuel the combination of ADOPT pellets with liner cladding for improved PCI performance and corrosion resistance for all operation conditions gaining significant margins in demanding operation conditions, which include transients and accident scenarios that could occur in commercial nuclear power plants.

To address PCI, operators have developed operational limits and PCI risk assessment guidance and methods. EDF identified the main operational constraints related to PCI-SCC. To complement the comprehensive but time-consuming kinetic methodology (MIR method), a new simpler “static PCI” methodology has been developed to cover variable reload patterns and improve the overall robustness of the PCI-SCC design studies. Licensing of the simplified "PCI with variability" approach is ongoing. EPRI has provided a 4-step PCI failure risk assessment procedure: this helps utilities to perform an independent PCI margins evaluation. Tractebel-ENGIE has developed a tool for fast evaluation of the PCI risk of a loading pattern for flexible core design.

Various PCI design analysis methodologies were developed by fuel vendors. ENUSA proposes a methodology to evaluate the risk of fuel rod failure due to PCI mechanism throughout the development of an effective stress limit, called “PCI Technological Limit” based on power ramps to discriminate failed from non-failed rods. Areva proposes a set of different PCI methodologies for PWR reactors to support utilities for a more flexible nuclear energy production.

In order to respond to the needs of the safety authorities and the industry, it is still important to improve our mechanistic understanding of the complex mechanisms and phenomena that take place in the fuel and in the pellet-clad interface during normal and AOOs conditions. In particular, the following SCC “mitigators” phenomena need further investigations:

- Assess oxygen potential variations, oxygen thermal diffusion and oxygen availability at the cladding/liner inner surface (and quantify their impact on SCC).
- Assess the crack pattern development in the pellet periphery and quantify its influence on PCI crack initiation at the cladding/liner inner surface.
- Confirm fission products retention in additive fuel is beneficial in normal operation and in transient conditions.

- Measure high temperature creep of the different doped pellet variants – are differences between the effects of different dopants significant?
- Develop representative ramp testing and improved modelling to define reliable PCI-SCC failure limits and to compare various cases (e.g. Stair-case vs. single ramp – what are the differences and what would be generated in terms of margins to PCI clad failure).

Although they have proven to be practicable for the design, evaluation methods remain complex and time consuming. Operators expressed their strong interest in simpler and faster PCI risk assessment tools.

Appendix A: Workshop programme

Wednesday 22 June 2016			
Introduction Session – Chairs: M. Cherubini – M. Kissane – M. Petit			
09:30	Introductory remarks	M. Cherubini/M. Kissane	N.IN.E/OECD
09:45	Recall of the conclusions and recommendations from the 2004 OECD seminar on PCI	M. Petit	IRSN
10:10	Electric system & Flexible Power Operation : Economic Issues	M. Moatti	EDF
10.40 – Break			
11:00	A regulator's perspective	M. Bales	NRC
11:30	Ramp Testing at the Studsvik R2 Reactor 1969-2005	J. K.-H. Karlsson, F. Corleoni	STUDSVIK
12.00 – Lunch			
Session 1: Experiments and Analysis, Part 1 – Chairs: M. Amaya, M. Bales, W. Wiesenack			
13:30	Experimental observations related to PC(M)I in Halden Reactor fuels testing	W. Wiesenack	HRP
13:55	An Overview of Experimental Studies on the Hydride-Induced Fuel Failure during Power Ramp	A. Yamauchi et al.	S/NRA
14:20	Chemical and structural characterisation of ramp tested fuel with different additives	D. Jädernäs et al.	STUDSVIK
14:45	Resumption of Transient Testing at the Idaho National Laboratory TREAT Reactor: Development of Experimental and Analytical Capabilities in Support of the Accident Tolerant Fuels Campaign	R.C. O'Brien et al.	INL
15.10 – Break			
Session 1: Experiments and Analysis, Part 2 – Chairs: M. Amaya, M. Bales, W. Wiesenack			
15:30	Slow Power Ramps: Are the Mitigating Factors Mechanical or Chemical in Nature?	V.I. Arimescu, J. K-H. Karlsson	AREVA/STUDSVIK
15:55	Pellet-Associated Cladding Degradation (PACE) A collaborative research consortium to investigate pellet-cladding interaction	P. Frankel	U Manchester
16:20	Improving PCI performances of texture 26 controlled cladding material	N. Murakami, Y. Kameda	MNF/KEPCO
16:45	Testing and Modeling Iodine-induced Stress Corrosion Cracking (I-SCC) in Zircaloy alloys	D. Le Boulch et al.	CEA/EDF/AREVA
17:10	Analysis of Experimental Fuel Rod Parameters using 3D Modeling of PCMI with MPS Defect	A. Casagranda et al.	INL
17.35 – Adjourn			

Thursday 23 June 2016			
Session 2: Modeling and simulation, part 1 – Chairs: C. Delafoy, T. Forgeron, P. Van Uffelen			
09:00	General overview of the French effort to address the SCC- PCI issue	N. Waeckel	EDF
09:25	Modeling Approach in TESPA-ROD Code Deduced from Studsvik HRX tests for Cladding Creep of Zry-2 under Operational Condition	H.-G. Sonnenburg	GRS
09:50	A Generalised Multi-Regime Failure Model for BISON Fuel-Performance Code	J. Y. R. Rashid et al.	ANATECH
10:15	Gaseous swelling and PCMI under ramping conditions: an analytical insight	F. Feria, L.E. Herranz	CIEMAT
10.40 – Break			
11:00	PCI simulations with ALCYONE V1.4: modeling description and validation assessment	E. Federici et al.	CEA/EDF/AREVA
Session 2: Modeling and simulation, part 2 – Chairs: C. Delafoy, T. Forgeron, P. Van Uffelen			
11:30	3D-modelling of fuel pellets and cladding interaction for WWER rods	A.V. Kupkin et al.	VNIIM
11:55	Simulations of power ramps with ALCYONE including fission products chemistry and oxygen thermo-diffusion	J. Sercombe et al.	CEA/EDF
12.20 – Lunch			
13:45	Parametric Studies of Duty-related Fuel Failures Using Falcon Fuel- Performance Code	R. Daum et al.	EPRI
14:10	Verification and Validation of the BISON Fuel-Performance Code for PCMI Applications	R. L. Williamson et al.	INL
14:35	NEA benchmark on Pellet-Clad Mechanical Interaction modeling with fuel- performance codes	G. Rossiter	NNL
Session 3: Design and verification methodologies, part 1 – Chairs: C. Anghel, N. Waeckel, J. Zhang			
15:05	Developments in fuel design and manufacturing in order to enhance the PCI performance of AREVA NP'S fuel	C. Delafoy, I. Arimescu	AREVA
15.30 – Break			
15:50	Towards an Increased Understanding of Fuel Pellet and Cladding Features Enhancing the PCI Resistance of LWR Fuel	J. Wright et al.	Westinghouse
16:15	PCI analysis during ERPO with thermal mechanical TREQ code	N. Doncel, C. Muñoz-Reja	ENUSA
16:40	AREVA NP's PCI methodologies for PWR enhanced plant manoeuvrability	L. Daniel et al.	AREVA
17.10 – Adjourn			

Friday 24 June, 2016			
Session 3: Design and verification methodologies, part 2 – Chairs: C. Anghel, N. Waeckel, J. Zhang			
09:30	~~Primary research analysis of PCI in CGN's NPPs~~	~~Y. Deng et al.~~	~~CGN~~
09:55	Operational constraints related to SCC-PCI	P. Paulin	EDF
10:20	Guidance and Risk Assessment for Mitigating Duty-related Fuel Failures	R. Daum et al.	EPRI
10.45 – Break			
11:10	Development and applications of a loading pattern PCI risk assessment tool for flexible core design	J. Zhang et al.	ENGIE
11:35	Safety requirements for Pellet-Clad Interaction in France – New approach developed by EDF	L. Barbié et al.	EDF
12.15 – Lunch			
Concluding Session – Chairs: M. Cherubini – M. Petit			
13:45	Summary of session 1	Session chairs: M. Amaya, M. Bales, W. Wiesenack	
14:05	Summary of session 2	Session chairs: C. Delafoy, T. Forgeron, P. Van Uffelen	
14:25	Summary of session 3	Session chairs: C. Anghel, N. Waeckel, J. Zhang	
14:45	General discussion	All	
15:30 – End of the Workshop			

Appendices B and C:

The Papers (Appendix B) and the PowerPoint files (Appendix C) presented during the workshop can be found on the NEA website.