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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

SUMMARY RECORD OF THE EXPERTS MEETING ON THE PROPOSED OECD-IRSN STLOC PROJECT

Madrid, Spain
18-19 November 2003

English - Or. English

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Summary Record of the

Experts meeting on the proposed OECD - IRSN STLOC Project Madrid, 18 - 19 November 2003

1. Opening

Mr. Vitanza welcomed the participants on behalf of the OECD-NEA. He noticed that there had been a good response to the request of nomination for this meeting, and that the participation was large (23 experts) and very qualified. He added that the OECD-NEA has set up various experimental projects in different safety domains such as thermal-hydraulics and severe accidents. One of the criteria for starting such projects is the uniqueness of the facility where the programme is carried out, and whether the future existence of such facility needs to be ensured through international programmes. Another criterion is that the proposed programme has solid backing and substantial funding within the host country.

2. Election of the Chairman

Mr. Vitanza proposed Mr. Conde as Chairman of the meeting.
The Group approved.

3. Purpose of the meeting

Mr. Conde thanked the participants and asked if there were important changes to the Agenda. It was clarified that Mr. Waeckel of EDF, Ms. Papin from IRSN and Mr. Meyer of the US NRC had prepared a presentation each, which would be given at the appropriate point-in-time. (Waeckel's and Papin's presentation would be given after agenda point 5 and Meyer's presentation during the tour de table at agenda point 7). With this, the agenda was approved (Appendix 1).

Mr. Conde asked the participants to introduce themselves, noting that there were 23 participants representing 10 countries (Appendix 2).

He added that the purpose of the meeting was to determine the interest in member countries for the types of LOCA tests envisaged in the STLOC programme proposed by IRSN. The IRSN proposal was circulated among this Group in advance of the present meeting. The statements of interest from the Group will be made under agenda point 7. IRSN was to give their presentations and ideas under agenda point 4, 5 and 6, which the participants were asked to discuss and comment upon as they were presented.

4. Brief background of the IRSN proposal

Mr. Mailliat gave this presentation. He said Phebus is an important facility for safety studies and accident management. Amongst others, the Phebus had given fundamental contributions to the understanding of the iodine chemistry in plant accidental and post-accidental conditions.

There have been three large experimental programmes in Phebus in the past, i.e.

- Phébus LOCA
- Phebus-CSD addressing severe accident and (freshly) fuel degradation,
- Phebus-FP focusing on fission products release and severe accident progression, including H-production and I-chemistry.

The results have been largely used in the nuclear community, for instance through ISPs (International Standard Problem). Phebus results have provided relevant insights and produced substantial improvements in the knowledge of accidents and on modelling capabilities.

There are engineering, experimental and analytical teams working around the Phebus facility and on its experimental results. They do constitute and important expertise on severe accident experimentations done at realistic conditions.

Mr. Mailliat pointed out important Phebus features that make such reactor a flexible and valuable tool, including a power control system able to simulate a variety of transients. He also explained the function of specific instrumentation developed ad-hoc for Phebus experimentations.

The STLOC programme is intended to include source term (ST) and LOCA type of tests. As requested by the NEA, he gave a brief overview of the ST part before describing the details of the LOCA part.

The ST part of the programme had been discussed in the context of GAMA (Group for Accident Management and Analysis) approximately one year earlier (London 24 - 25 September 2002). In that occasion, the interest for the following two items was stressed:

- Source term in presence of air ingress. The consideration here is that Zircaloy oxidation is more violent, energy generation is greater and ruthenium is more volatile in presence of air as compared to steam.
- Source term for high burn-up fuel and/or MOX fuel. The consideration here is that structural, stoichiometric and chemistry changes due to high burn-up and in MOX fuel may affect the physico-chemical behaviour in accidental conditions and thus the fission product release.

Ruthenium was identified as an element to be addressed in these studies.

A third issue identified by IRSN was the corium quench phase. However, this subject did not receive the same level of interest as the two mentioned above.

Mr. Mailliat concluded by stating that in STLOC project the first test considered is a ST test with air ingress. Mr. Melis confirmed this and said that the STLOC1 test (i.e. the first STLOC test) would be run at end of 2007 or likely in 2008. Thus, the second test - which is envisaged to be a LOCA test - would presumably be run in 2009. Mr. Waeckel said he was informed that the Phebus PF tests had produced interesting results but had not lead to any changes in the regulation. Mr. Mailliat said that the contribution Phebus has made to code qualification and understanding of accidents is important (the Phebus results have allowed to correct the source term evaluation and are now used in PSA).

Mr. Trambauer commented on the process that was followed to identify the ST needs that were presented by Mr. Mailliat. He said that after an in-depth review of all available information, there was a consensus internationally that air ingress, high burn-up and quench were items that needed further attention. Lastly, it was proposed that the document from the Air Ingress Working Group will be sent to the participants.

5. Presentation of the STLOC proposal, LOCA part

Mr. Mailliat presented the LOCA part of the STLOC proposal, which had been circulated earlier to the meeting participants. This proposal is enclosed in Appendix 3.

Mr. Mailliat started from the DBA basic requirement that after any LOCA transient, a coolable core geometry must be ensured. This means that fuel rods shall not shatter and that the rods can be cooled even if they have been deformed and are in contact with each other. Experimental results are essential both for establishing manageable criteria and, once criteria are set, to support the verification that criteria are met.

Establishing LOCA criteria means in practice to define quantities that control the cladding residual ductility. Supporting the verification that criteria are met means in practice to perform calculations that show that the core will be below the LOCA criteria, by means of validated codes which include models for all relevant phenomena occurring in LOCA.

The issues that the STLOC programme can address are the following:

- *Fuel relocation*. This can affect the peak cladding temperature, the cladding oxidation and the hydrogen uptake.
- *MOX fuel*. The MOX microstructure and the end-of-life reactivity of MOX can exacerbate the relocation and its consequences.
- *High burn-up* : ANL tests have shown potential for greater relocation at high burn-up due to increased fuel fragmentation, It is unknown if fuel-cladding bonding delays relocation.
- *Bundle blockage*.
  - There is a more uniform cladding temperature at high burn-up, which can lead to much larger cladding deformations and thus more pronounced flow blockage.
  - New alloys have the tendency of being more ductile, which can increase ballooning size and thus increase blockage.

Mr. Mailliat elaborated the concept that bundle geometry is important for the LOCA assessment because:

- Bundle geometry provides the correct boundary conditions in terms of heat transfer and uniformity of the cladding temperature. The latter is essential to create realistic ballooning - which in turn can determine the extent of fuel relocation (i.e., larger ballooning are likely to induce larger relocation and the associated power generation increase).
- Bundle geometry is essential for investigating the flow blockage issue, in terms of rod-to-rod contact and co-planarity of ballooning in the rods constituting the bundle.

In Mr. Mailliat's view, there are additional issues related to coolability, e.g. the quenching may be delayed because of the largest fuel inventory and power generation in the ballooning area, if fuel relocation occurs early.

Mr. Mailliat presented then a map of ongoing LOCA investigations internationally, and the area where the STLOC tests fit-in and will provide results. This map can be synthesized as follows:

- TO DERIVE CRITERIA
  - Post oxidation ductility ⇐ Argonne National Laboratory (ANL)
  - Unconstrained quenching ⇐ TAGCIR, HYDRAZIR, CINOG, ANL
  - Constrained quenching ⇐ JAERI

- TO CHECK THAT CRITERIA ARE NOT VIOLATED (correct modelling)
  - Cladding burst ← STLOC; EDGAR, ANL, JAERI, HALDEN
  - Relocation ← STLOC; HALDEN, ANL
  - Bundle blockage geometry and heat source concentration ⇐ STLOC
  - Cladding oxidation ← STLOC; TAGCIR, HYDRAZIR, CINOG, ANL, JAERI
  - Bundle coolability: Not addressed yet. Depends on STLOC results

Two tests are envisaged at present. They are to be carried out with a 3x3 bundle of preirradiated test rods surrounded by 16 fresh rods, which would give a 5x5 arrangement in which the fresh rods fill the outer perimeter. This outer rods will operate such (choice of fuel enrichment) that they will provide the right boundary conditions for the irradiated test rods.

The first test is envisaged to cover conditions for which ballooning is maximised, including modern cladding alloys and high burn-up.

For the second test there are various options, that would need to be further discussed with participants.

Ms. Papin presented complementary calculations performed at IRSN on large break LOCA. They were performed to calculate the peak cladding temperature (PCT) for low burn-up fuel (after 1 irradiation cycle), and uncertainty related to thermo-hydraulic models only. Similar calculations were done also for high burn-up fuel, that is at 57 MWd/kg. In performing these calculations, a relocation filling ratio (of fuel into the ballooned zone) of ~65% was used. At high burn-up, the best estimate calculation led to a PCT of 970^{o}C. The uncertainties however were large: In Ms. Papin's evaluation, there is a 162^{o}C uncertainty due to thermal-hydraulics and 150^{o}C uncertainty due to relocation. These two uncertainties above would result in a PCT exceeding the 1204^{o}C criterion. The best estimate ECR would also vary between 20 and 12% depending if one takes relocation into account or not. Finally, Ms. Papin showed that blockage could exceed 90% in some assembly zone. She concluded on the need to reduce uncertainties by improving knowledge and perfecting fuel models such as for relocation and cladding deformation and ballooning.

The Group made many observations on the IRSN proposed tests. The summary of the discussion is reported only in a concise form in the following:

- Ballooning site is greatly affected by local cold spots for fresh fuel. It can be very difficult to produce large ballooning extending over a long axial distance. Hence, co-planarity is an important consideration.
- It is understood that high burn-up fuel can produce larger deformations, but evidence is scattered on this point. In the ANL tests, for instance, ballooning is rather small axially and radially in spite that the external heating used would tend to make the cladding temperature

more uniform. [This was however distorted due to experimental conditions used according to Mr. Hache].

- High burn-up fuel may fragment and relocate more than fresh or low burn-up fuel. ANL tests have shown that for BWR fuel, gas can flow to sustain ballooning. However we do not know if bonding delays relocation.
- Separate effects studies both out-of-pile and in-pile may clarify many phenomena for which only assumptions can be used today.
- The proposal focuses on improving knowledge, but one or few tests may be insufficient. It is important to determine if some phenomena may or may not occur and their relevance, before embarking on a complex testing. This determination can be done in separate effect tests.
- The IRSN strategy to address "worst" case first intends to verify the extent to which fuel relocation and bundle blockage occur in a bounding case.

The chairman summarised the discussion and said it is very important that the added value of the proposed tests clearly stands out in consideration also of other single rod tests that are being performed in different laboratories. Mr. Mailliat reiterated that bundle tests as proposed by IRSN offer a best assurance of representativity in terms of heat transfer and rod-to-rod interaction.

Mr. Waeckel summarised the EDF position. On ST EDF prefers to use well designed separate effect tests and make modelling advances before any integral test. EDF is evaluating the risk of air ingress and will decide on scenario and initial conditions based on PRA early in 2004. On this basis and on an evaluation of consequences on ST, it will determine the need in terms of R&D. This is expected to be completed in mid 2005 with a presentation of outcome in the SARNET. [For quench, separate effect test approach is preferred].

For what concerns LOCA, the compliance with PCT < 1204^{o}C and ECR < 17% has to be demonstrated. For this, the basis will be survival of quench tests. In addition, separate effect tests are made to assess ballooning and bursting as well as phase transformation and oxidation kinetics. The STLOC tests appear in Mr. Waeckel's view to be disconnected from separate effect tests where quench survival is the failure criterion - just in that the quench phase is missing in STLOC. For what concerns relocation, single rod tests would provide relevant and conservative data on irradiated fuel (conservative in that temperature uniformity is intentionally maximised). For what concerns the coolable geometry, Mr. Waeckel noted that if the ANL and Halden tests show no particular burn-up effects on deformation/ballooning, it would imply that the current flow-blockage limits for unirradiated fuel apply as well at high burn-up. He concluded that all aspects addressed in the STLOC proposal can be studied in ongoing separate effect tests and that STLOC will give only partial answers (to LOCA) in that the blow-down and the quench phase are missing. Because of the above, EDF will not support the Phebus STLOC programme but will support separate effect tests programs to address Source Term and LOCA issues.

6. Project organisation

Mr. Melis clarified that a test will be run in Phebus in September 2004 (FPT3) and that it will take 3 to 4 years to de-contaminate the reactor extension (so-called “caisson”) thereafter. This means that the STLOC1 test (ST + air ingress) is to be run in 2007 or - more realistically - in 2008. The first LOCA test would then be run not earlier than 2009 (18 months after STLOC1). He explained that IRSN is thinking of performing 3 ST and 2 LOCA tests and of alternating between ST and LOCA tests. He gave a rough indication of costs, which were 30 million € per each ST test and 20 million € per each LOCA test, plus an additional 20 million € to update the Phebus facility. He also said that for STLOC1 [and only for this one] the EU will contribute with financing of ~5 million €. A decision as to the performance of STLOC1 will be taken in 2004.

The chairman asked whether it would be possible to support the STLOC1 test first - separately from the rest of the STLOC programme. Mr. Melis said this would be feasible as it would not add any complication on the planning of the work foreseen on the feasibility. The Group appeared to favour the idea of taking more time and waiting for the outcome of current single rod tests before deciding on the LOCA test and supported the idea of trying to establish STLOC1 first on its own basis. Mr. Trambauer added that there are already rather clear ideas on how STLOC1 should be carried out.

There was a brief discussion on how financing of STLOC1 would be pursued. The chairman concluded that this was not for the Group to discuss in depth and that IRSN and NEA will need to work together with the EU to try to find a satisfactory financing solution.

7. Statement of interest (tour de table)

Mr. In de Betou [SKI, Sweden] said that there had been some confusion at SKI because it was thought the STLOC programme would be on ST only. SKI does support the ST part, whereas the LOCA part has not been discussed yet. However, he feels that there can be an SKI and Swedish interest on the LOCA part also.

Mr. Hatala [VUJE, Slovak Rep.] observed that Slovak power plants and fuel types are substantially different than PWRs. He said that in relation to the Phebus testing, ST is of greater interest to them than LOCA.

Mr. Conde [CSN, Spain] said the Spanish parties agree on the value of the LOCA part of STLOC as proposed by IRSN. However, he felt that waiting for the outcome of ongoing tests was the right thing to do.

Mr. Meyer [US NRC] made a presentation stating that there is NRC support for all 5 tests intended in STLOC, with the understanding that the test specification need to be defined. There is support for STLOC1 run first and in his view it is wise to see the outcome of separate effect and single rod tests before proceeding with the LOCA tests. He stated that bundle issues were thought to be resolved, but there are questions arising now on high burn-up effects. Fuel relocation is an issue that is not resolved at NRC. Information will be obtained from ANL and Halden tests but there are shortcomings with both tests. The first because of external heating, the second because the heating may be too large [which can enhance cladding temperature gradients and reduce deformations at burst]. He supports the IRSN plans but is in favour of waiting before deciding on the tests after STLOC 1.

Mr. Hache replied that thinking that bundle issues were resolved is based on a data base that is now obsolete, even for fresh cladding.

Mr. Trambauer [GRS, Germany] said that, according to the conclusions of Final Colloquium of Project Nucleare Safety (June 1986) "the long-term coolability is not hindered in LOCA due to a maximum blockage of 70%". Based on the presentations at the meeting, this statement has to be re-evaluated. It seems that the rationale of the test definitions is plausible - this has to be proved by in-house discussions [at GRS].

It is questionable whether the integral test will yield sufficient information [due to lack of on-line measurements] for model verification and code validation (i.e., time - resolution of ballooning and fuel relocation - post-test examination only seems not sufficient).

Out-of-pile and separate effect tests are necessary for successful interpretation of the integral experiments. The examination of "new" cladding material with higher ductility might possibly be out of scope of the German government. Detailed examination of fuel elements used in Germany may be necessary.

Mr. Trambauer concluded that the German position is close to that of the US NRC. His view is that STLOC1 should be performed with air ingress as proposed by IRSN.

Mr. Zimmermann [PSI, Switzerland] said that integral test should be done after Halden and other tests. He believes there is a need for a deeper rationale for the coolability tests. He added that MOX issues are generally important in Switzerland. For STLOC1, he needs to discuss it with experts at PSI. He supports postponing the decision on the rest of the programme.

Mr. El-Shanawany [HSE-NII, UK] expressed the view that there is a lot to be gained from other programmes and that one would need to see those results before taking the step of integral tests. Considering that the UK has only one PWR, the STLOC is an expensive programme and there is no UK funding available at the moment for such type of tests - in addition to those indirectly provided through the EU [for STLOC1].

Mr. Kelppe [VTT, Finland] said there is interest for LOCA bundle tests. The industry in his country is in a very dynamic situation and VTT needs to discuss with potential payers when the test conditions and instrumentation are better defined. In his view, instrumentation is important to avoid that a test generates more questions and to provide clear-cut information [on e.g. time of relocation]. He agrees we should wait to make a decision on the LOCA tests.

Ms. Yang [EPRI, USA] observed that ST experts in US industry are more focused on prevention of accidents and not so much interested in more specific data. On LOCA, it is premature to make commitments about bundle tests. Costs are high and the tests seem to be exploratory. There would be many "what if"-type of questions left after the proposed tests. She understands the issue of maintaining the facility, but noticed that there have been many instances of facilities shutdown in the US. It is premature to decide on LOCA and does not support using the STLOC1 test to buy time.

Mr. Fuketa [JAERI, Japan] said there are no urgent licensing requirements and - in his view - it is not clear how the data can be used. He expressed no opinion about ST. On LOCA, he believes one should wait until the outcome of other programmes becomes available. The cost is high and the issue is as to whether the proposed tests will provide definite answers or will generate more questions. In his view there is no urgency - from a technical viewpoint - on integral bundle tests at this stage.

Mr. Waeckel [EDF, France] reiterated the position expressed earlier, especially that the tests are exploratory and would raise more questions than provide answers. Fuel relocation is the key rationale for the IRSN proposal, but just this is being addressed in single rod tests. Upon a question from the chairman, he agreed that it is appropriate to wait until single test data are available.

Mr. Paradis [CEA, France] said CEA is the owner and operator of the Phebus reactor. He was present mainly to hear what position the international community has on the facility and on the proposed programme. He underscored that international support is needed to keep Phebus in operation in the future. Besides these observations, he had no specific recommendation on the proposed project as such.

Mr. Melis [IRSN, France] stated he understands the need of separate effects - as well as of integral tests. In addition to trying to perform the STLOC1 test, he proposed to make the outcome of IRSN separate effect tests on LOCA [denominated CHIP, out-of-pile] available to interested parties. He also proposed to activate an expert group aimed to follow-up the technical discussion on the LOCA reactor studies .Mrs Papin presented a proposal for a mandate of such an expert group which could aim at a better definition of the current lack of knowledge on safety margins assessment and of the needs for performing tests in bundle geometry. Mr. Melis concluded that it will be essential to try to get sufficient funding for STLOC1. This is essential for the future LOCA tests and essential for the future of Phebus. He reiterated that Phebus is indeed the only facility of its kind in the world and that its continued operation will depend on international co-operation.

The chairman concluded the tour de table and observed that there was no consensus for deciding a Phebus-LOCA programme at this time. He added that the Group advises to try to establish the source-term STLOC1 test first, which likely is to be run in 2008. The LOCA issue would be re-assessed in 2006. The experts group proposed by IRSN could be integrated in the NEA SEG FSM [Special Experts Group on Fuel Safety Margins].

The participants agreed.

8. Conclusions and recommendations

On behalf of the chairman, Mr. Vitanza summarised the Group recommendations as follows:

- Different views were expressed as to the need to perform the LOCA integral tests.
- There was an understanding that the results of separate effect tests (ANL, JAERI, Halden) would need to be obtained before deciding on the intended LOCA tests proposed in STLOC.
- IRSN and the OECD-NEA should explore the possibility to run the first ST test with air ingress (STLOC1), for which partial funding already exists. This test is foreseen for 2008.
- The need of LOCA tests as envisaged in STLOC should be re-assessed in about three years time (2006).
- Analytical and experimental progress on LOCA tests should be monitored until then, through for instance the SEGFSM.

These recommendations will be communicated to the CSNI at its next meeting on 3 December 2003.

9. Closure

The chairman thanked IRSN for the quality and completeness of the presentations, and the participants for their active participation in the discussion. Mr. Melis expressed on behalf of the Group his gratitude to Mr. Conde for the excellent conduct of the meeting.

Appendix 1

Experts Meeting on the Proposed
OECD-IRSN STLOC Project

Madrid 18-19 November 2003

Agenda

1. Opening - welcome

2. Election of the Chairman

3. Purpose of the meeting

4. Brief background of the IRSN proposal for the STLOC project
   - General outline of the project (SA part and LOCA part)
   - Complement to other undertakings
   - Relevant Phebus experience/expertise
   - Unique Phebus features

5. Detailed presentation and discussion of the proposed STLOC project
   - Background
   - Objective and motivation
   - Areas of interests and issues to be addressed
   - Tests methods to investigate the issues above
   - Options on fuel to be tested
   - Outline of scope of work

   Presentation by Mme Papin (agreed upon at the meeting)
   Presentation by Mr Waeckel (agreed upon at the meeting)

6. Proposed OECD project organisation
   - Project schedule
   - Umbrella Agreement and Bilateral Agreement
   - Steps to establish a possible OECD Agreement

7. Participants' statements of interests (round table)

   Presentation by R.. Meyer (agreed upon at the meeting)

8. Recommendations and actions (chair summary)

9. Closure

Appendix 2

List of participants

Name	Organ.	Country
Kelppe, Seppo	VTT	Finland
Bardelay, Joël	IRSN	France
Mailliat, Alain	IRSN	France
Melis, Jean-Claude	IRSN	France
Papin, Jöelle	IRSN	France
Hache, Georges	IRSN	France
Paradis, Luc	CEA	France
Tricot, Nicolas	IRSN	France
Waeckel, Nicholas	EdF	France
Trambauer, Klaus	GRS	Germany
Fuketa, Toyoshi	JAERI	Japan
Hatala, Branislav	VUJE	Slovak Rep
Conde, José M.	CSN	Spain
Mendizábal, Rafael	CSN	Spain
Pérez, Julio	CSN	Spain
Herranz, Luis E.	CIEMAT	Spain
Quecedo, Manuel	Enusa	Spain
In De Betou, Jan	SKI	Sweden
Zimmermann, Martin	PSI	Switzerland
El-Shanawany, Mamdouh	NII	UK
Meyer, Ralph O.	NRC	USA
Yang, Rosa	EPRI	USA
Vitanza, Carlo	OECD-NEA	

Appendix 3

IRSN SOURCE TERM LOCA PROGRAM

LOCA PART

EXECUTIVE SUMMARY

Alain Mailliat, Georges Hache,

Claude Grandjean, Bernard Clément, Joëlle Papin, Jean Claude Mélis.

Prepared for the Experts Meeting on The OECD-IRSN STLOC Project
To be Held in Madrid, 18-19 November 2003

Abstract

Studies performed in IRSN and elsewhere pointed out that modern alloys used for rod cladding and high burn up fuels induce specific effects under LOCA conditions. This paper is devoted especially to those related with bundle flow blockage geometry and accumulation of heat sources induced by fuel relocation. Uncertainties exist regarding how much these effects affect the evolution of the accident transient and the applicability of the current LOCA regulatory safety criteria. The main question marks are related with increases of peak cladding temperature and of equivalent cladding reacted and whether the resulting flow blockage geometry is coolable. In addition to the existing or planned programmes related to several pending LOCA issues, IRSN proposes to address the points which are not explored elsewhere through two in pile bundle tests of the LOCA part of its STLOC program. The test objectives are to produce data for realistic flow blockage geometry using a multirod configuration and to determine the accumulation of heat source associated to both fuel relocation and the balloon size variability due to rod interactions at burst. Such a piece of information is required for answering the main issues: will the resulting flow blockage with fuel accumulation be still coolable, when using modern clad alloys and high burn up fuel. IRSN is proposing this program to the main partners of the nuclear community in a consistent way with the present effort of both in pile and separate effects experimental programmes for strengthening power plant operations with high burn up and MOX fuels and the associated safety.

INTRODUCTION

Since the seventies, a permanent evolution of the light water reactors (LWR) is observed. The evolution deals with the reactor designs. It is also related to the fuel management and burn up increase. This evolution affects the fuel itself (UO_2, MOX, Gd fuel), the cladding (Zircaloy, Zirlo, M5, MDA, NDA etc…). As a consequence of these modifications, there is a permanent need to reassess the reactor safety studies which implies improving the associated knowledge and upgrading the corresponding calculation tools. For the studies associated with the continuous evolution of the reactor operation, the safety authorities requirements are both related to the design basis accidents and the severe accidents. They have to appreciate to which extent their analyses and criteria might be modified by the burn up increase and the type of fuel. In France e.g, under safety considerations, it was requested prior to any generic authorisation of discharge burn-up extension, that the high burn-up fuel behaviour be validated, with the support of appropriate R&D tests results, under accidental conditions, particularly under Loss-of-Coolant-Accident (LOCA) conditions.

The current regulatory safety criteria for LOCA, still in use in most countries, are derived from the ECCS acceptance criteria that were issued by USAEC in December 1973 and published in the Code of Federal Regulations (10.CFR50, part 50.46) as "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water-Cooled-Nuclear Power Reactors". The criteria are stated as 5 requirements, concerning the calculated performance of the cooling system under the most severe loss-of-coolant accident conditions. The first two requirements address : the peak cladding temperature (PCT) which shall not exceed 1204°C and the maximum cladding oxidation rate, defined through an equivalent cladding reacted (ECR), which shall nowhere exceed 17% of the cladding thickness before oxidation but after cladding swelling with or without rupture. The third request addresses the maximum hydrogen generation, the total amount of which shall not exceed 1% of the hypothetical amount generated by the reaction of all the metal in the cladding surrounding fuel. Finally the last two requirements are related with core cooling. The calculated changes in core geometry shall leave the core amenable to cooling and after any operation of the ECCS, the core temperature shall be maintained at an acceptably low value and decay heat removed for the extended period of time required by long-lived radioactivity.

UNCERTAINTIES AND PENDING ISSUES

In the aftermath of the AEC LOCA criteria release, numerous studies were undertaken world-wide in order to improve the basic knowledge of the physical phenomena intervening in LOCA transients, so as to allow a better prediction with realistic models. Beyond the numerous experimental investigations that were conducted on unirradiated rods or cladding, either in-pile or out-of-pile, there exists a few number of available results of such experiments with irradiated material. Following is a very short review of the current knowledge on clad and fuel rod behaviour gained from experiments on irradiated material, that will introduce the pending questions and critical issues for irradiated fuel behaviour in LOCA.

UNCERTAINTIES

CLAD BEHAVIOUR

A progress in knowledge relative to irradiated clad behaviour has been obtained from the results of the EDF/IRSN, ANL, JAERI programs [1,2,3,8], addressing the oxidation kinetics and quench bearing capability of irradiated zircaloy. The main outcome concern:

- the non protective effect of corrosion oxide scale formed during irradiation;
- the oxidation kinetics of irradiated zircaloy ;
- the resistance to quench loads of irradiated zircaloy ;
- the effect of high hydrogen content on ductility, as a result of internal hydriding during LOCA transient.

Relative to oxidation kinetics and quench behaviour, a comprehensive understanding of all involved phenomena and of their inter-related influences is not yet achieved and leaves still pending questions, most of them being not specific to high BU fuel. One important question is the influence on clad quenching resistance of axial constraints that may result from differential contractions upon quench between guide tubes and a fuel rod blocked in spacer grids as a result of ballooning or metallurgical interaction. Such blockage consequences had been evidenced on past tests at JAERI [3] on unirradiated rods and should therefore be expected to some extent on irradiated rods.

ROD BEHAVIOUR

There exists a few number of available results from experiments with irradiated fuel rods under LOCA conditions. The main outcome were found in results from the PBF-LOC tests[4,5] in the USA, the FR2 tests[6] in Germany, and the FLASH5 test [7] in France. They concern the fuel relocation process and an increased cladding deformation.

FUEL RELOCATION

All the available tests performed with irradiated fuel rods experiencing LOCA conditions have shown an accumulation of fuel debris in the swollen region –called balloon- of the burst cladding which resulted from fuel fragments slumping from upper locations (see figures 1 and 2 below from FR2 results [2]). This process, here after called fuel relocation, is initiated at the time of the cladding burst, as demonstrated by the FR2-E3 and E4 tests. It is thought that the driving forces are both gravity and the pressure difference between the rod upper plenum and the channel.

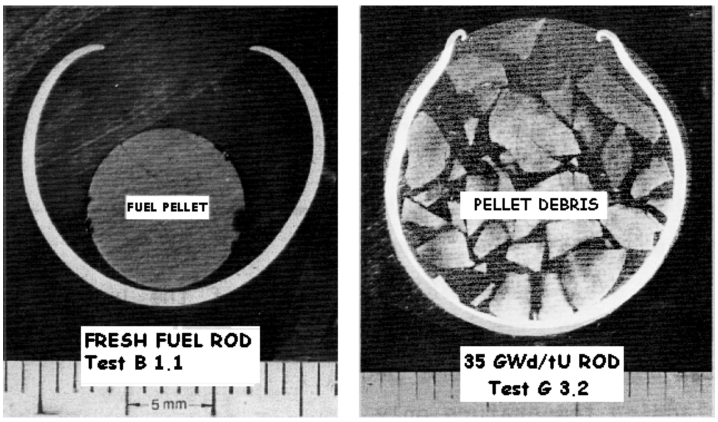

Figure 1

This fuel relocation is not counteracted by the fuel-clad tight bounding which exists at the beginning of the LOCA transient with high burn up fuel. Indeed, the process was observed in the FLASH-5 test with 50GWd/t fuel in spite of a rather low clad strain (not higher than 16%). Fuel relocation was observed more recently in the ANL program [8]. It is thought that the cladding temperature increase combined with its ballooning suppress –at least partly- the bounding making possible the fuel relocation.

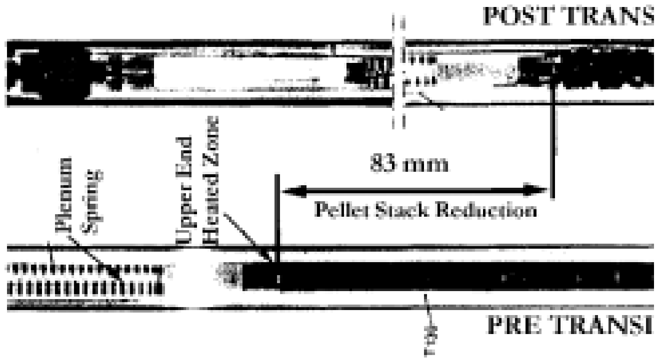

Figure 2

Finally, fuel relocation process is not specific of high burn up fuel. It was also observed for fuel rod having a burn up as low as 48MWd/t (LOC5-7B test [4]).

BUNDLE BLOCKAGE GEOMETRY

One important uncertainty is the bundle coolability which is associated to both the geometry of the bundle at burst and the accumulation of heat source in the balloons due to fuel relocation. Five different phenomena affect the bundle geometry after the burst of the rods and therefore the flow blockage geometry. Their main aspects are summarized hereafter.

CLAD CREEPDOWN

In PBF-LOC experiments [4-5], 2 couples of rods (2 unirradiated + 2 irradiated) were simultaneously tested in the same test train. Available data for comparison, although in very limited number due to technical problems, clearly indicate significant differences in the deformation behaviour of irradiated versus unirradiated rods. A higher circumferential rupture strain for irradiated rods (a factor greater than 2 relatively to unirradiated rod strain for maximum values) and more axially extended . A wall thinning affecting almost all the circumference of irradiated rods, thus indicating low azimuthal temperature differences as compared to unirradiated rods despite cold shrouds .

These differences in behaviour have been attributed to the lower temperature differences on the clad of irradiated rods, circumferentially and axially, as a result of the pellet-clad gap reduction due to clad creepdown during rod irradiation already at about 11 GWd/t.

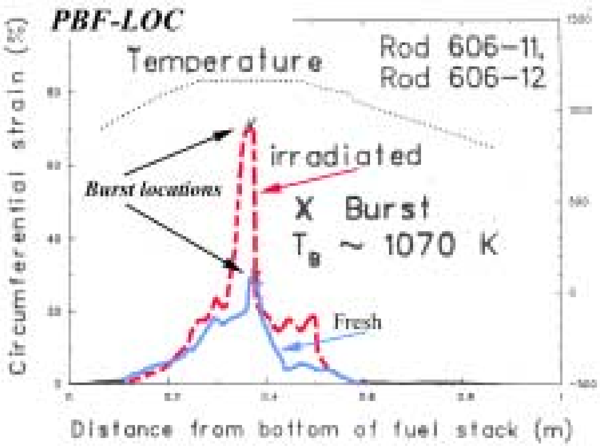

Figure 3

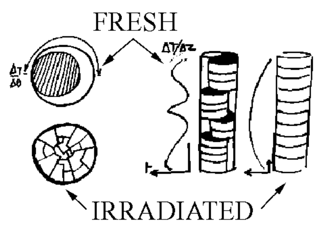

Figure 4

DUCTILITY

New alloys based of low tin content or niobium, called hereafter modern alloys, were developed for a lower corrosion during reactor operations. Due to this lower corrosion, hydrogen uptakes during irradiation are reduced, e.g. for a burn up of 60 GWd/tU the H content of a Zr-4 cladding is around 600 ppm but the M5^{TM} alloy H content is well below 100 ppm [9]. Due to this low hydrogen uptake, this modern alloy keeps a higher ductility than a Zr-4 cladding after the same reactor operation time. This tendency can be seen clearly on the two following figures (5-6) for low tin and a niobium alloy.

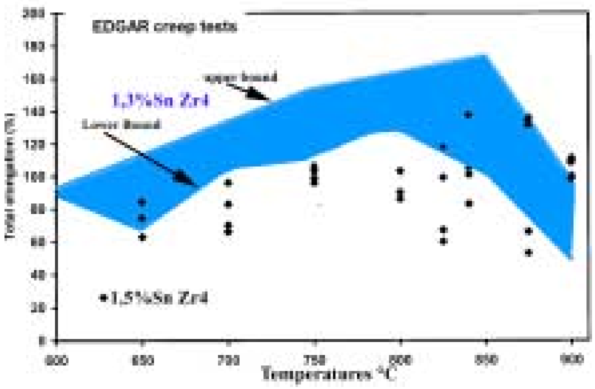

Figure 5

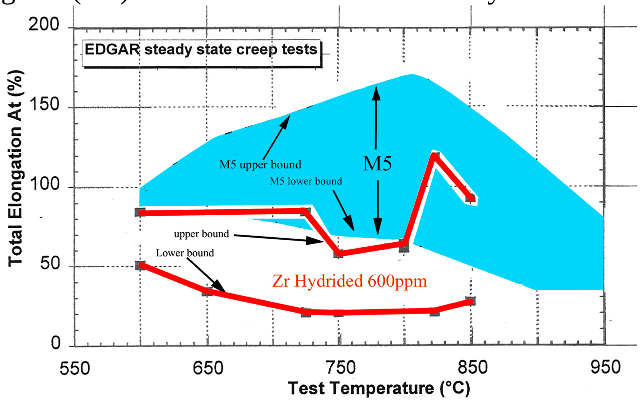

Figure 6

On figure (5) is presented a comparison of the ductilities of fresh Zy4 (from unpublished IRSN data) and fresh low tin Zr-4 alloy [11]. Clearly, it is seen that such a low tin alloy has a better ductility than the traditional Zy4. Right figure (6), deduced from [10-11] provides the same ductility information for two alloys. A Zy4 with 600 ppm hydrogen (red curves) corresponding to a burn up around 60GWd/tU and a fresh niobium alloy cladding. According to the low hydrogen uptake during base irradiation for this kind of alloy [9], its ductility for 60GWd/tU would present a ductility close to the fresh one presented on this figure (6).

Therefore, it can be anticipated, due to this better ductility that, for modern alloys, the rod balloons will be bigger and the resulting flow blockage geometry at burst higher with more radial and axial extension than for Zy4 rods when experiencing the same conditions at burst.

AZIMUTAL TEMPERATURE FIELD

Since the REBEKA program [12], it is well established that exists for fresh cladding a very clear relationship between the size of the rod balloon and the azimuthal temperature variation around the rod as presented on this figure (7). As a consequence, the first condition to produce realistic data for flow blockage geometry will be to use a bundle geometry in order to get the complex azimuthal temperature field structure which will produce correct balloons sizes.

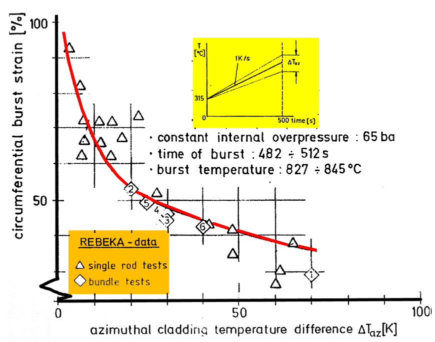

Figure 7

RADIAL INTERACTIONS AND AXIAL DISTRIBUTIONS

Two other important aspects affect the rod geometry at burst and the resulting flow blockage geometry.

The first one is related to radial interaction betweens balloons and can be seen clearly on the right side figure (8) from the ORNL MRBT B5/B3 tests. It can be observed that there is a rather large variability of the balloon sizes at burst which results of their radial interactions. It means that the flow blockage cannot be deduced directly from a simple addition of a balloon size measured in a single rod test. In general, such a method will prognosticate more than 100% flow blockage !

In a bundle geometry, radial interactions tend to prevent too large balloons and tend to prevent, by this way, a total blockage of the bundle flow area, but enhance the length of the balloons.

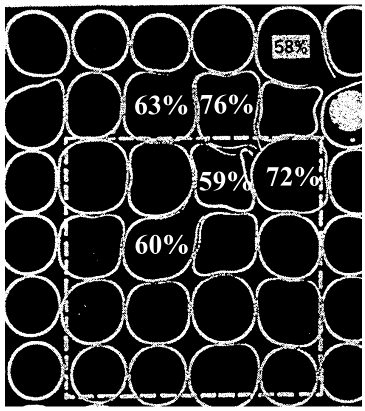

Figure 8

The second important aspect is related to the fact, that, in realistic bundle conditions, there is some axi-radial variability in the flow and thermal conditions. Therefore, all the rod bursts do not take place exactly in the same plan at the same elevation. The result of this axial variability is an axi-radial distribution of the balloons along a certain length of the bundle. Such a situation is shown on the right side figure (9) from [12] where it can be observed that bursts are distributed over 15 cm.

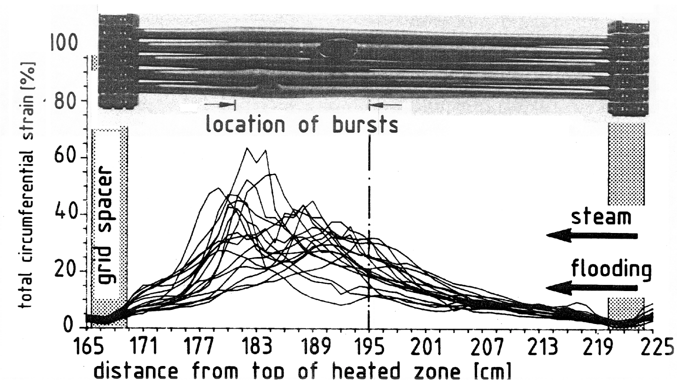

Figure 9

THE PENDING ISSUES

A better understanding of the specific phenomena shortly mentioned above leads to raise a list of some complementary questions related with rod behaviour, fuel relocation process and coolability issue during LOCA transients.

ROD BEHAVIOUR

The question mark about rod behaviour is related to the influence of hydrogen pick-up and other irradiation effects on ballooning, burst behaviour and embrittlement during reflooding which were not considered when 10CFR50, part 50.46 was released.

FUEL RELOCATION

Several questions are induced by the relocation process. The first ones concern the process itself. The needed data are the following ones.

- Instant of fuel movement at high burn-up, with possible delay due to fuel-clad bonding.
- Filling ratio of clad balloon at high burn-up, with fragmentation of UO2 rim or MOX agglomerates
- Impact of the relocated material on steam access inside the balloon and hydrogen uptake rate.

The second set of question marks concerns the consequences of the relocation process.

- What are the effects on peak clad temperature and final oxidation ratio of the local increase in lineic and surfacic powers and of the local decrease in fuel-clad gap resulting from fuel accumulation ?

Note that these last issues are particularly important for end-of-life MOX fuel for which power generation is not reduced, unlike for UO2 fuel.

COOLABILITY

Related questions should be considered additionally, relative to flow blockage behaviour of highly deformed cladding with possibly relocated fuel and the embrittlement potentials associated to fuel fragmentation. The 90% value for flow blockage still coolable, as derived from results of flooding experiments (FLESH/SEASET, SEFLEX et al) on unirradiated rods arrays is questionable since these experiments did not take account of any fuel relocation and associated effects. The needed information are the following.

- What is the flow blockage geometry that leaves coolable an irradiated rods bundle ?
- Does the flow blockage geometry attainable with an irradiated rods array remain below the maximum coolable value indicated above ?

THE STLOC- LOCA PART EXPERIMENTAL PROGRAM

For many years, IRSN and several other safety organisations have applied a three-tier method for their reactor safety researches. The first step consists of computer code developments from the existing data bases. The second step involves small-scale, out-of-pile experiments, which provide the additional data bases requested by the code developments and their preliminary assessments. But, as the reactor phenomenology is complex and cannot be totally reproduced in such small scale experiments, a third step consisting of integral in-pile experiments using real materials is essential for comprehensive accident analyses. Their results allow the final code assessment in terms of reactor applicability and simulation completeness. This in-pile part of a programme assures that the investments done for code developments and small scale experiments will produce profits in terms of reactor safety.

Regarding the LOCA issue, the current testing programmes dealing with irradiated material mainly involve out-of-pile experiments : separate effect unconstraint quench tests on irradiated cladding (TAGCIR tests) in France ; tests on irradiated cladding and integral type experiments (ballooning / burst / oxidation / quench) on irradiated rods at ANL (USA) [8] and JAERI (Japan) [13] with the support of an important programme of mechanical tests. In addition , there is the OECD in-pile programme [14] consisting of some single rod geometry tests with irradiated fuel. The programme is conducted in the Halden reactor and should provide information about the relocated fuel characteristics. Clearly, the issues related to the flow blockage geometry and the accumulation of heat sources induced by fuel relocation are not addressed up to now. Nevertheless such information is required to conclude on the coolability issue.

The following table provides a rational for the LOCA researches. The table summarises the issues for which additional LOCA researches are needed and the corresponding programs from which data are existing or will be available. According to this rational, IRSN is proposing to the nuclear community to collaborate on the STLOC program addressing one of the important issue for which there is no alternative program.

ISSUES TO ADDRESS	AVAILABLE OR PLANNED PROGRAMS
Post oxidation ductility	ANL
Unconstraint Quenching	TAGCIR HYDRAZIR CINOG
Quenching with constraint	JAERI
Cladding burst	EDGAR, ANL, JAERI, HALDEN
Relocation	HALDEN in Pile ANL out of pile
Bundle Blockage Geometry and Heat source Accumulation	STL-LOCA Part
Cladding oxidation	TAGCIR HYDRAZIR CINOG ANL JAERI
Bundle Coolability	If necessary according to STLOC results

THE MAIN EXPERIMENTAL OBJECTIVES

The main objectives of the in-pile experiments in STLOC-LOCA part will be to investigate the behaviour of fuel and cladding with conditions representative of the reactor during LOCA sequences in order to produce data for the bundle geometry at burst and for the total amount of fuel relocated in the balloons. Such data will provide the flow blockage geometry and the heat source accumulation allowing to appreciate what could be their importance on core coolability issue. According to such a piece of information from STLOC results it will be possible also to rule on the needs for thermal-hydraulic additional studies for coolability.

TEST DEFINITION RATIONALE

The following analysis provides the rationale for the STLOC-LOCA part programme characteristics. It is shown that the conditions for having representative data for reactor applications are both in-pile tests and a bundle geometry.

NEEDS FOR IN-PILE TESTS

Neutron flux provides the unique way to produce the correct heat generation in the fuel fragments, corresponding to the residual power, whatever are the relocations induced by the ballooning and/or the burst of the rod. Both the exact amount of heat generation in the balloon and the heat exchanges with the rod channel depend on the characteristics of the relocated fuel fragments, their size, shapes, compaction ratio. This heat generation correctness is one of the main conditions for having realistic estimates of the relocation consequences in terms of equivalent clad reacted, peak clad temperature and hydrogen uptake inside the balloon.

NEEDS FOR BUNDLE GEOMETRY

In addition to the requirement associated to heat generation mentioned above, a multirod geometry is an second important condition to produce realistic data. Relocation being closely associated with the volume which is made free by the rod burst, it is clear that a correct amount of relocated fuel will be produced only if the sizes of the balloons are representative of the reactor conditions. Such correct balloon sizes which are driven by five different processes, as explained previously, impose a bundle geometry. This is the reason why these tests are essential and complementary of single rod tests.

EXPERIMENTAL CONFIGURATIONS

The main factors that we have to consider for defining the tests conditions are mainly the nature of fuel -UO2, MOX and the burn-up range –low, medium, high-, the nature of the cladding -Zirlo, M5, MDA, etc- and the test geometry.

TEST GEOMETRY

Regarding this last point, it was shown previously that the most useful data will be those related to a bundle geometry with the objectives to determine the geometry at burst. Therefore the ST-LOCA part test bundle consists of 9 irradiated fuel rods re-fabricated from irradiated commercial fuel rods surrounded by a ring of 16 fresh fuel rods which provides a correct thermal environment in order to ensure representative strains and subsequent phenomena. This ring of 16 fresh fuel rods has two functions.

First, it will contribute to reduce the heat losses to the shroud -through an adjustment of their fuel enrichments- and provides, by this way, a correct radial temperature field inside the bundle. Secondly, the pressures inside the fresh fuel rod will be defined for having a behaviour in terms of balloon size and burst time comparable to the 9 irradiated rods providing the radial and axial interactions from which depends a realistic flow blockage geometry.

In addition, a cylindrical borated absorber will be installed in the test train at the bundle elevation to produce a more flat neutron flux, providing an axial heat generation comparable to the reactor axial residual power at the burst elevation.

TEST RODS

As it is hardly conceivable to carry out a program of experiments that will address in a systematic way the effects of the various kinds of fuels, their burn up and several cladding alloys, it appears more appropriate to perform in-pile tests having the objectives to produce results which can be regarded as envelop conditions but still being realistic conditions of reactor ones during a LOCA.

According to such a strategy of a realistic envelope of the reactor conditions a preliminary program of two tests is considered.

For the first one the cladding is determined in order to maximise the flow blockage geometry. With regard to the fuel, its burn up has to be high enough for having a large amount of rim microstructure, enhancing by this way –in principle- the amount of relocated material and the heat source accumulation in the balloons. A possible fuel rod having such characteristics can be a M5^{TM} rod with UO2 local burn up above 60 GWd/tU.

The second test is still open, two main possibilities can be considered.

- The first one is a UO2 rod at the end of first cycle. The cladding is a low tin Zr-4 for which the hydrogen uptake at this stage is low and its ductility high enough for having a large flow blockage ratio. The fuel burn up is low enough maximize clad ductility and high enough to trigger clad creepdown. In addition, in terms of interest for LOCA issues, this test configuration corresponds to a reactor phase for which the fuel linear power is high. Having in mind that the fraction of the residual power which affects the fuel temperature during a large break LOCA transient is mainly associated to short lives fission products roughly proportional to the linear power, it means that the energy stored in the fuel fragments is higher than for subsequent time periods during reactor operations. Therefore, for such first cycle conditions, it is important to have a precise estimate of the amount of relocated fuel.
- An other candidate for the second test can be a MOX fuel around 50 GWd/tU, the objective being to appreciate the impact of this specific fuel structure on the relocation process.The objective of having an envelop for the flow blockage geometry is no more possible, according to the reduction of ductility of this kind of material.

Finally, in case of need, this second test can be also a back-up test devoted to relocation per se study. In this case, the test bundle will include only one irradiated fuel rod surrounded by a ring of 9 fresh fuel rods to produce the right azimuthal temperature field.

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