FUMAC: IAEA'S COORDINATED RESEARCH PROJECT ON FUEL MODELLING IN ACCIDENT CONDITIONS

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ABSTRACT

The Coordinated Research Project (CRP) T12028 on "FUel Modelling in Accident Conditions (FUMAC)" has the objective to better understand the fuel behaviour in accident situations through the identification of best practices in the application of relevant physical models and computer codes, used by different Member States, and the enhancement of their predictive capacities. For this purpose, collection of well checked results of accident simulation experiments and their analyses with advanced fuel performance codes, were carried out in the CRP. Three Research Coordination Meetings (RCMs) were held from 2014 to 2017, where results of the CRP participants were presented and thoroughly discussed. The main activities and results of the CRP are overviewed in the current paper.

1. Introduction

Fuel modelling is a recurrent priority in the IAEA sub-programme "Nuclear Power Reactor Fuel Engineering". Development and verification of computer codes are possible only on the basis of good experimental data that requires very durable and expensive in-reactor and post-irradiation studies. That is why international cooperation in this area is highly desirable, and the IAEA traditionally supports interested Member States in their efforts to enhance the capacities of their computer codes used for predicting fuel behaviour.

Since the 1980's, a series of four Coordinated Research Projects (CRPs): D-COM (1982-84) [1], FUMEX (1993-1996) [2], FUMEX-II (2002-2007) [3] and FUMEX-III (2008-2012) [4], targeted nuclear fuel modelling in normal operational conditions. Those projects were highly appreciated by Member States, and the proposed CRP T12028 on "Fuel Modelling in Accident Conditions" (FUMAC) has continued the series with the focus on fuel behaviour in design basis and severe accidents.

The CRP FUMAC was initiated in light of the Fukushima accident under the umbrella of the IAEA Action Plan on Nuclear Safety, following a recommendation of the 2012 meeting of the IAEA Technical Working Group on Fuel Performance and Technology (TWG FPT) to launch a new fuel modelling CRP focusing on accident conditions. Preliminary ideas were brainstormed during the Technical Meeting on "Fuel Behaviour and Modelling under Severe

Transient and Loss of Coolant Accident (LOCA) conditions" that took place in Japan in October 2011, agreed with NEA/OECD in 2012 and finalized through more detailed discussions during the Technical Meeting on "Modelling of Water-Cooled Fuel Including Design Basis and Severe Accidents", organized in China in 2013, and at the International QUENCH Workshop in Germany the same year.

This paper describes the objectives (§2), the participants and used codes (§3), the organisation (§4), the main outcomes and achievements (§5) of the FUMAC project.

2. Objectives

The CRP FUMAC (Fuel Modelling in Accident Conditions) has been launched by the IAEA in 2014 and will end in 2018. The objectives of the CRP are:

- Analysis and better understanding of fuel behaviour in accident conditions, with a focus on LOCA (DBA), in line with the early stage of the scenario of the Fukushima accident (BDBA);
- Collection of well checked results of accident simulation experiments, and dissemination of experience in the organizations of Member States;
- Identification of best practices in the application of physical models and computer codes used in different Member States for modelling of fuel in accident conditions, and enhancement of predictive capacities of these models and codes.

The project FUMAC followed the FUMEX-III project [1] with the new focus on modelling of fuel behaviour in design basis and severe accidents that is particularly demanding after the Fukushima accidents. The CRP FUMAC was planned with the well-proven organizational approach used in FUMEX-III, which presumes cross-comparisons of computer codes used in different Member States and close collaboration with the OECD/NEA. Selected sets of accident simulation experimental results, provided by the CRP participants, will be integrated into the International Fuel Performance Experiments (IFPE) Database (developed in close co-operation and co-ordination between OECD/NEA, the IAEA and the IFE/OECD/Halden Reactor Project) and used for codes verification. The codes involved ranged from fuel performance codes (DIONISIO, FRAPTRAN, FTPAC, RAPTA, TRANSURANUS) to system or severe accident codes (ATHLET-CD, MELCOR, SOCRAT) as well as multi-dimensional fuel performance codes (ALCYONE, BISON).

The fuel behaviour during LOCAs have been extensively studied during the last decades. Recent LOCA tests, performed in Halden, Norway, and Studsvik, Sweden, have revived interest in the fuel relocation and dispersion phenomena. Indeed, the test results suggest that high burnup fuel pellets may pulverize into very fine fragments, with a higher potential for axial relocation and subsequent dispersal, than observed for low to medium burnup fuel in early tests. This issue is a current research area, which was being addressed by the Working Group on Fuel Safety (WGFS) of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI). It was also identified as a key issue in the ongoing IAEA coordinated research project FUMAC.

3. Participants and used codes

26 organizations from 18 Member States participated in the CRP. A list of the participating organizations and the codes they used is given in Table 1.

TABLE 1. PARTICIPANTS OF THE CRP FUMAC

Country	Organization	Code	Experiment
Argentina	CNEA	DIONISIO-2.0	-
Belgium	Tractebel	FRAPTRAN-TE-1.5	-
Brazil	IPEN-CNEN	FRAPTRAN	-
Bulgaria	INRNE	TRANSURANUS	-
China	CIAE	FTPAC	-
China	CNPRI	FRAPTRAN-1.5	-
Germany	JRC	TRANSURANUS	-
Germany	KIT	-	QUENCH-LOCA1, CORA-15
Finland	VTT	FRAPTRAN-1.5 & 2.0	-
France	CEA	ALCYONE-1D	-
Hungary	MTA EK	FRAPTRAN-2.0	Clad ballooning tests
Italy	POLIMI	Modelling	-
Korea	KAERI	FRAPTRAN-1.5/ S-FRAPTRAN	-
Norway	IFE	-	IFA-650.9/10/11
Russian Federation	IBRAE	SOCRAT	Boundary conditions for IFA-650.9/10/11
Russian Federation	Bochvar Institute	RAPTA-5.2	-
Spain	CIEMAT	FRAPTRAN-1.5	-
Sweden	Quantumtech	FRAPTRAN-QT-1.5	-
Ukraine	Energorisk	MELCOR	-
Ukraine	SSTC NRS	TRANSURANUS	-
USA	Battelle INL	BISON-2D	-
USA	Westinghouse	MELCOR	-
USA	US NRC	-	Studsvik 192, 198
Germany	GRS (Acting observer)	ATHLET-CD	-
International	OECD/NEA	Observer	-

Many of the participants used the CRP to provide or extend a validation database for their codes or to help in development. Some were using commercial codes and used the CRP to help develop an understanding of the code and to train young professionals. The wide range of participants and their needs contributed to informative discussions and widespread cooperation between the participants.

4. Organisation

4.1 The preparatory Consultancy Meeting

The preparatory Consultancy Meeting was held in March 2014 in Vienna, the outcome of the consultancy group along with the survey of potential participants by means of a questionnaire were presented and discussed in order to structure and define the scope of the CRP. A preliminary list of available experiments for the benchmark were proposed for consideration. It was recommended to organize the CRP in four main topic areas:

- Design basis accidents (DBA):
  - experiments,
  - single rod LOCA studies,
  - separate effects tests,
  - uncertainties,
  - codes.
- Beyond design basis accidents (BDBA):
  - experiments,
  - assembly/single rod studies,
  - separate effects tests,
  - uncertainties,
  - codes.
- Fuel code integration:
  - experiments,
  - multi-physics, multi-dimensional analysis,
  - sensitivities,
  - coupled codes.
- Experimental support:
  - data preparation and QA,
  - define new experiments.

4.2 The first Research Coordination Meeting

The first Research Coordination Meeting (RCM) of the CRP was held on November 11-14, 2014 in KIT (Karlsruhe, Germany) in conjunction with the 20th QUENCH Workshop. 27 participants from 21 organizations representing 18 MSs attended the meeting.

The RCM was designed to introduce the participants, their simulations tools and interests. In addition, the consultancy group proposed experiments for the benchmark were presented and discussed. Finally, a common understanding of priorities for the group was reached and a roadmap, including set of priority cases that would be modelled has been identified.

4.3 The 2nd Research Coordination Meeting

The 2nd Research Coordination Meeting took place in Vienna International Centre on May 30 – June 3, 2016. 27 participants from 21 organizations represented 18 MSs at the Meeting. The main objectives of this meeting consisted in presenting individual status reports on the work done during the 1st phase of the project and to discuss and agree on actions and work-plan, both individual and joint, for the 2nd phase of the project. For this purpose, three sessions were organized:

- Session 1: DBA Experiments and Data Sets;
- Session 2: Modelling of Fuel Behaviour under DBA;
- Session 3: Severe Accidents and ATF Materials.

Well-checked experimental datasets from separate-effect tests (clad ballooning tests PUZRY from MTA EK), out-of-pile single rod LOCA tests (Studsvik 192, 198), in-reactor LOCA tests with single rods IFA 650.9-11 from the Halden Project, out-of-pile bundle LOCA test QUENCH-L1 and bundle SA test CORA 15 (KIT) were chosen for benchmark exercises, as outlined in Table 2.

TABLE 2. TEST MATRIX FOR BENCHMARK EXERCISES

IFA 650.9	IFA 650.10	IFA 650.11	Studsvik 192, 198	MTA-EK	QUENCH LOCA1	CORA 15	Uncertainty analysis
With dispersal	PWR	VVER	Out-of-pile Single fuel rod	Fuel rod segments	Out-of-pile Bundle	Out-of-pile Bundle	DAKOTA, URANIE, etc.

In particular, discussions related to the T/H boundary conditions (BC), new tests, new cases, as well as the proposed planning for the second phase were carried out. It was agreed to apply improved and common BC to IFA650.9, 10 and 11 to be calculated by the integral severe accident code SOCRAT. Besides, the IFA-650.2 test with new PIE data about the hydrogen uptake were proposed for analysis in view of the preparation of new licensing criteria in various MSs.

It has been also proposed that the available severe accident codes would be compared with experimental data for CORA15, the IFA-650 cases and the QUENCH-LOCA1 test in order to provide a common basis for the different types of codes involved in the CRP.

Finally, the participants also agreed to extend the analysis by means of an uncertainty and sensitivity analysis as in the detailed specifications prepared by one of the participants (Tractebel).

4.4 The 3rd Research Coordination Meeting

The 3rd Research Coordination Meeting took place in Vienna International Centre on 13-17 November 2017. 24 participants from 22 organizations and 3 observers from 2 organizations represented 18 MSs at the Meeting; the meeting was organized similarly to the 2nd RCM in three Sessions.

The main objectives of this meeting were to present individual status reports on the work done during the 2nd phase of the project; to compare/analyse results of the CRP benchmark exercises including uncertainty/sensitivity analyses; to evaluate the final results of the CRP and to discuss the path forward for their publication, and to agree on actions and work plan, both individual and joint, for the publication of the CRP results.

During the meeting, assessment and comparison of calculation results of eight benchmark exercises against the various datasets were carried out, results of uncertainty and sensitivity analyses in application to fuel modelling under DBA conditions were analysed, and Table of contents (TOC) of the first draft of TECDOC was prepared. The main outcome of the different cases will be outlined in separate contributions to this conference.

4.5 The final Consultancy Meeting

The final Consultancy Meeting to Finalize the Final Report of the Coordinated Research Project on Fuel Modelling in Accident Conditions was held on 21–23 February 2018 in Vienna.

The consultancy group members compared/analysed results of the benchmark exercises and related uncertainty/sensitivity analyses carried out during the CRP, drew preliminary conclusions and prepared these results for publication in the CRP final report (IAEA TECDOC).

Furthermore, the group evaluated contributions of the CRP participants to the TECDOC, prepared the TECDOC for publication, discussed details for the publication of results as scientific papers in specialised journals by individuals or all participants of the CRP, in line with the new publication guidelines/policy of the IAEA.

5. Overall outcomes and achievements

5.1 DBA Experiments and Data Sets

MTA-EK provided six ballooning tests (separate effect tests) conducted with unirradiated, unoxidized 5 cm long Zry-4 tube specimens. The selection criteria of these tests from a larger set were clear balloon shapes and burst openings as well as the highest-pressure increase rates in order to be most representative of LOCA conditions. The time of burst is well correlated with specimen temperature at burst.

IFE-HRP presented in-core measurements and PIE related to the experiments provided for FUMAC by the Halden Reactor Project. The three tests from the IFA-650 test series have increasing burnups of 56, 61, and 89.9 MWd/kg for IFA-650.11, IFA-650.10 and IFA-650.9, respectively. The tests show a clear progression in the severity of LOCA-induced changes as burnup increases. For example, IFA-650.11 shows mainly large fuel fragments (too large to pass through the burst opening) and no sign of dispersed fuel, while IFA-650.9 exhibits extensive fragmentation (many particles down to less than 20 µm in size) and fuel dispersal. IFA-650.10 is between these two in its LOCA performance.

KIT provided the results of the LOCA reference bundle test QUENCH-L1 with Zircaloy-4 claddings. The test, available from a series of QUENCH-LOCA experiments, reached a maximum cladding temperature of about 1100°C, simulating a large break PWR LOCA. Cladding temperatures were measured at evenly spaced axial positions. All rods in the bundle test experienced burst; no strong orientation of the burst position towards the bundle centre was observed. The average burst temperature was estimated as 860±30°C.

US NRC provided the Studsvik out-of-pile LOCA tests 192 and 198.

The above selected sets of accident simulation experimental results will be integrated into the joint NEA-IAEA International Fuel Performance Experiments (IFPE) Database.

5.2 Modelling of Fuel Behaviour under DBA

Detailed comparison of the simulation results with the experimental data will be performed and documented in the final TECDOC and separate papers for the most simulated cases:

- MTA- ET burst tests [5];
- Halden LOCA tests (IFA-650.9, 10, 11), Studisvik LOCA tests (NRC-192), QUENCH L1 [6];
- KIT Bundle Test CORA-15 [7];

- Uncertainty and sensitivity analysis on Halden LOCA test IFA-650.10 [8].

The main outcomes can be summarized as follows:

- A good prediction of the time-to-burst could be observed, especially in the separate effect cladding tests that are best controlled and for which experimental uncertainties are minimal. Moreover, the trend of the burst time as a function of both temperature and internal pressure seemed to agree well with the experimental observations, although an increasing deviation was noticed with decreasing temperatures.
- A large uncertainty exists on the predicted cladding strains (both in the hoop as well as in the axial direction). Part of this can be attributed to the fact that all codes – regardless of the number of dimensions in the mechanical analysis (1D versus 3D) – rely on the small deformation approximation or a second order approximation thereof.
- The large uncertainties pertaining to the experimental failure thresholds (hoop stress and strain) as a function of param The outcome of a specific axial relocation model tested in the FRAPTRAN code, as well as the simplified axial power profile adopted in SOCRAT indicated a substantial improvement in the reproduction of the experimental observations of IFA-650.9eters such as the local temperature and composition seem to affect mostly the predicted strains rather than the predicted burst times.
- There is a very strong impact of the boundary (coolant) conditions on the predicted parameters such as the axial profile of the cladding radial deformation. The simulation of the thermal hydraulic conditions (including the plenum gas temperature) and axial distribution is very important in explaining the discrepancies. It was acknowledged to IBRAE for providing the common thermal hydraulic boundary conditions for IFA-650.9-11 with SOCRAT.
- There is a need to revise the plenum temperature models and their validation, and to implement models for axial gas transport, especially in high burnup fuel rods.
- The testing of a specific axial relocation model, developed by Quantum Technologies and tested in the FRAPTRAN code, as well as the simplified axial power profile adopted in FRAPTRAN and SOCRAT, indicated a substantial improvement in the reproduction of the experimental observations of IFA-650.9 .
- The uncertainty and sensitivity analysis based on the IFA-650.10 and 11 were consistent with the observations above and provided some more insights on the variations of the simulation results and the important physical parameters and models.

5.3 Severe Accidents and ATF Materials

Results, provided by GRS, Germany (ATHLET-CD code) and IBRAE, Russia (SOCRAT code) for the modelling of the CORA-15 test, were compared among each other and with experimental data. The main outcomes of this benchmark are the following:

- The effect of the pressurized rods in CORA-15 has been taken adequately into account by both codes. The calculated rupture time, the elevation and the cladding temperatures at burst are within the experimental ranges.
- Both codes predict the total hydrogen mass at the end of the test well within the measurement uncertainties of one of the mass spectrometers.
- The blockage formation due to melt relocation and solidification match to experimental data for SOCRAT and axially shifted for ATHLET-CD due to the lacking modelling of melt retention by the spacer grids.
- In general, the analysis performed by two system severe accident codes, ATHLET-CD and SOCRAT, reveal a good compliance with the measured data as well as with each other.

The concept of accident tolerant fuels (ATF) includes various combinations of fuel/cladding materials: UN/SiC, U_3Si_2/SiC, UN/Coated Zircaloy, and U_3Si_2/Coated Zircaloy. Two participants were involved in the corresponding simulation work: Westinghouse (USA) with the MAAP code and IPEN/CNES (Brasilia) with the FRAPCON and FRAPTRAN codes. The following activities took place in the framework of the FUMAC project: 1) Modelling (with the MAAP code) of station blackout accidents and Fukushima accidents for both Zr/UO_2 and ATF systems (in the latter case, with improved SiC material properties and models); 2) Modifications of the FRAPCON and FRAPTRAN codes in application to stainless steel AISI-348 tubes (instead of Zry tubes). Sensitivity and uncertainty analyses were performed.

6. Conclusions and perspectives

Within the FUMAC project, the following achievements were made:

- Verified experimental data set on fuel characteristics in accident conditions, supporting codes development and validation for potential extension of the IFPE database.
- Better predictive capacities of fuel modelling codes: improved models, material properties and codes for the simulation of nuclear fuel under DBA and severe accident conditions, with consideration of uncertainties.
- Extended collaboration between some MS organisations (examples: INL-POLIMI-JRC collaboration agreement; IFE-IBRAE collaboration and joint presentation at the Enlarged Halden Programme Group Meeting, 2017) beyond the FUMAC project timeframe.

Many participants have acknowledged the IAEA for organising this CRP, which provided an ideal platform to compare their code results with others and especially with experimental data, to which they otherwise would not have had access.

All experimental data analysed reveal a relatively large spread of the measured burst strains, which is not only determined by the local conditions of temperature and pressure, but also by heterogeneities and composition or micro-structural variations in the materials under investigations. An uncertainty analysis of the experimental data was therefore recommended, including those data that have been used for the development and validation of the codes applied.

It has been reiterated that this coordinated research project triggered new collaborations, leading for example to the common development of improved models, in particular for those that are used by a larger user group (e.g. FRAPTRAN, TRANSURANUS). It has also enabled to point out differences in the interpretation of some experiments and therefore in the use of the codes, the so-called user effect.

The constant participation of the organisations providing the experimental data has also been very instrumental in clarifying various questions raised during the project.

The following recommendations were made:

- More analysis and cases for VVER fuel would be needed, especially in view of recent advanced fuel developments;
- A general interest has been expressed to consider a similar analysis for advanced fuels and cladding materials, including some of the so-called accident tolerant fuels;
- For a successful CRP that involves so many cases and participants, the duration of the project meetings may be extended, enabling for instance to analyse better model details and code changes as well as their comparison with more detailed experimental data.;

- Deeper analysis of failure criteria with advanced tools, and uncertainty analysis on experimental data is needed;
- Need more quantitative information about fuel fragmentation.

It is also recommended to focus the future CRP in fuel modelling on more practical applications to support the sustainability of nuclear technology, diversification of fuel supply, and innovation in fuel technology development.

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7. References

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