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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

NEA/CSNI/R(2005)1
Unclassified

PROGRESS MADE IN THE LAST FIFTEEN YEARS THROUGH ANALYSES OF THE TMI-2 ACCIDENT PERFORMED IN MEMBER COUNTRIES

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), Korea (12th December 1996) and the Slovak Republic (14 December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 28 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

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 friendly and economical use of nuclear energy for peaceful purposes, as well as
- 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 policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, 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.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA) is an international committee made up of senior scientists and engineers. It was set up in 1973 to develop, and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety among the OECD Member countries.

The CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of the programme of work. It also reviews the state of knowledge on selected topics on nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus on technical issues of common interest. It promotes the co-ordination of work in different Member countries including the establishment of co-operative research projects and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences and specialist meetings.

The greater part of the CSNI's current programme is concerned with the technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment, and severe accidents. The Committee also studies the safety of the nuclear fuel cycle, conducts periodic surveys of the reactor safety research programmes and operates an international mechanism for exchanging reports on safety related nuclear power plant accidents.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

GAMA

The Working Group on the Analysis and Management of Accidents (GAMA) is mainly composed of technical specialists in the areas of thermal-hydraulics of the reactor coolant system and related safety and auxiliary systems, in-vessel behaviour of degraded cores and in-vessel protection, containment behaviour and containment protection, and fission product release, transport, deposition and retention. Its general functions include the exchange of information on national and international activities in these areas, the exchange of detailed technical information, and the discussion of progress achieved in respect of specific technical issues. Severe accident management is one of the important tasks of the group.

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FOREWORD

The TMI-2 accident keeps providing unique full scale data giving opportunities to check the ability of the codes to model overall plant behaviour and to perform many sensitivity and uncertainty calculations. Some countries continue improving their system codes using the TMI data. The objective of this status report is to summarise on-going activities on TMI-2 analysis in NEA member countries, and progress made in this area, and to find out to which extent current advanced codes are able to model later phases of the TMI-2 accident.

The work started in early spring 2003 under the lead of IRSN (Institut de Radioprotection et de Sûreté Nucléaire). The participating organisations and their codes used were as follows:

- ENEA (Ente per le Nuove tecnologie, l'Energia e l’Ambiente, *Italy*) : ASTEC, ICARE/CATHARE V1 and SCDAP/RELAP5
- GRS (Gesellschaft für Anlagen- und Reaktorsicherheit, *Germany*) : ATHLET-CD
- IRSN (Institut de Radioprotection et de Sûreté Nucléaire, *France*) : ICARE/CATHARE V2
- NRC (Nuclear Regulatory Commission, *United States of America*) : MELCOR
- Univ. Pisa (Università di Pisa, *Italy*) : SCDAP/RELAP5
- PSI (Paul Scherrer Institute, *Switzerland*) : MELCOR

The draft report generated by the Group was reviewed at the GAMA meeting in September 2004, and finally approved at the CSNI meeting in December 2004.

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1. Introduction

The experimental database on core degradation and melt relocation (and their consequences on hydrogen production, vessel rupture, etc.) is limited to small-scale experiments which are only partially representative of what could occur in a reactor. As a consequence, codes are used to describe core degradation transients in real nuclear reactors without a clear idea of their predictive capabilities.

The GAMA has recommended starting a common action, in order to find out to which extent the current advanced codes are able to predict core degradation in a nuclear reactor. The TMI-2 accident sequence was chosen for comparisons because it is a reference scenario that has been calculated by most of the code users and code developers throughout the world. It was decided to write a status report about on-going activities and the progress made in the area of TMI-2 analysis in members Countries. This would help to check the consistency in the choice of physical models and plant description between different code users.

In this report, several experts in using severe accident codes have provided their views about the progress made during the last fifteen years in the calculation of the TMI-2 transient. The results obtained with several codes are presented in tables, with a reference to the results, where possible, of the last OECD TMI-2 Analysis Exercise Final Report NEA/CSNI/R(91)8.

The main improvements are listed and a conclusion is drawn in order to prepare a future benchmark exercise on a TMI-2 alternative transient.

2. Summary of the contributions

A few member Countries have designated experts able to analyse the progress made in the predictions of one or several codes. Each expert is either a code developer or a code user, with a long experience. The operational sequence of events during the TMI-2 accident is well known by all of them. The modelling of the circuits and reactor core has been rather well assessed by all experts. The main uncertainties in the sequence are the boundary flows, which were not recorded and have been adjusted by each expert independently. All the participants in this analysis are briefly introduced below, with a mention of the code(s) they have used.

2.1 ENEA (Ente per le Nuove tecnologie, l'Energia e l'Ambiente, Italy)

ENEA has been involved in several studies of the TMI-2 transient with different codes, since the last OECD benchmark. An important step was the complete transient calculation with SCDAP/RELAP5, which showed significant progress in the capabilities of a severe accident code. More recently, ENEA particpated in a benchmark exercise in the frame of the COLOSS European Project and calculated the first phases of the transient with ASTEC V1 (developed by GRS and IRSN) and ICARE/CATHARE V1 (developed by IRSN).

2.2. GRS (Gesellschaft für Anlagen- und Reaktorsicherheit, Germany)

GRS has oriented the development of ATHLET-CD with the aim of calculating reactor applications, and a particular interest for TMI-2 transient. A recent calculation of the complete transient provides a clear illustration of the progress made since the last OECD benchmark.

2.3. IRSN (Institut de Radioprotection et de Sûreté Nucléaire, France)

IRSN has released the first version of the ICARE/CATHARE V1 code in 1999, which was able to calculate severe accident transients in reactors (including the primary circuit). Previoulsy, calculations of the TMI-2 transient had been performed only with CATHARE (limited to phase 1 and early phase 2) or with ICARE (limited to phase 2 in the vessel, with imposed thermalhydraulic boundary conditions).

2.4. NRC (Nuclear Regulatory Commission, United States of America)

The main computational tool for the NRC studies is MELCOR. Since this code did not exist at the time of the last OECD benchmark, the observation of the progress made in the last decade was done by reviewing the papers that have been regularly issued about the calculation of TMI-2 transient with MELCOR.

2.5. Univ. Pisa (Università di Pisa, Italy)

The University of Pisa was regularly involved in severe accident studies, mainly with SCDAP/RELAP5. The experience gained from these studies helped to achieve a calculation of the complete TMI-2 transient.

2.6. PSI (Paul Scherrer Institute, Switzerland)

The PSI has extended the NRC (SNL) model of the TMI-2 transient for MELCOR version 1.8.5 to properly accommodate boundary conditions (RCP restarts, HPI and letdown flows, bleed functions) for phases 3 and 4. Parts of the model have been modified to suit the conditions after phase 2, and to reduce analysis time. The simulation has been integrated and is performed from the start of the accident to five hours. Details and findings for phases 1 and 2 are the same as those provided by the NRC contribution. Details provided do not include current improvements, since this was the first integrated MELCOR simulation of accident conditions from phase 1 to the end of phase 4 since the first OECD benchmark.

3. Physical modelling improvements

The understanding of physical processes has improved significantly and new models were developed, providing more accurate predictions. The increase of computing power also allowed code developers to introduce more detailed and CPU-consuming models, especially for thermal-hydraulics and corium relocation.

The main progress made since the last OECD-CSNI benchmark comes from this better physical understanding and modelling.

3.1. Thermalhydraulics

- The use of six equations models (different velocities and temperatures for steam and water) appeared to improve several results in the case of ATHLET-CD.

- The modelling of cross-flows to simulate natural convection has a significant influence on the results (MELCOR, ATHLET-CD, ICARE/CATHARE V2) and appears to be necessary to all experts.

3.2. Cladding Oxidation

- Models for cladding oxidation were improved in all the codes, as a result of the assessment which was done on many integral tests (e.g. CORA, PHEBUS, QUENCH,) over several years.

- Models for relocated mixture oxidation have been introduced in some codes and have a strong influence on the hydrogen production in the late phase of the accident, and during the reflooding phase.

- Models for cladding failure depending on the oxide shell thickness have been introduced in most codes and have a strong influence as well. They also result from the assessment which was done on many integral tests (e.g. CORA, PHEBUS, QUENCH) over several years.

3.3. Material Properties

- The effects of materials interactions leading to a lower melting temperature for the fuel pellets have been introduced in all the codes (between 2650 and 2850K). This has a significant impact on melt progression. However, this issue is still under investigation because it is usually modelled with user parameters instead of relevant phase diagrams.

3.4. Molten Corium Progression

- Improved models for melt relocation (1D or 2D) and freezing have been introduced in all the codes. They are especially important to predict the extent of the in-core molten pool and the characteristics of corium relocation in the lower plenum. The limitation of melt progression by water ingression through cracks and porosities is generally not well modelled and needs further improvements. In most codes, the slumping of materials from the core down to the lower plenum is more parametric than mechanistic. Some mechanistic descriptions have been introduced, but they have to be assessed.

3.5. Debris Beds

- Most codes have specific models to deal with debris beds and molten pools, in particular in the lower plenum. For some codes, these models must be activated separately from the core degradation calculation. Parametric studies of the lower plenum debris in phases 3 and 4 have been done with the COUPLE module of SCDAP/RELAP5.

- This is an area where improvement is still needed for all codes, in particular to model the transition between core debris and lower plenum debris. Such models are under development in most of the codes.

4. Plant and transient description improvements

The accurate prediction of the TMI-2 transient relies on the proper definition of boundary conditions and plant characteristics. Some of these data are either unknown or difficult to estimate. In particular, the data for the make-up and let-down flows were not recorded during the accident. Although these data do not bring any improvements in the understanding of severe accident processes, they have required important efforts from code users who have tried to estimate them.

The main improvements made since the last OECD/CSNI benchmark are listed below. They constitute a prerequisite for any TMI-2 calculation.

- Adjustments of the assumed make-up and let-down flows were necessary for all of the codes in order to fit the primary pressure history.

- Refined modelling of the pressurizer and surge line to avoid pressurizer draining after closure of the vent valve.

- Adjustment and proper modelling of the auxiliary feedwater injection to control the SG water level.

- Other adjusted data were sometimes necessary : pump characteristics, behaviour of some valves, etc.

- Some parameters describing the secondary circuit have been imposed in some cases (SG water level or pressure).

In future, a new benchmark exercise is planned among OECD member countries. The objective is to do it on a well-defined plant (similar to TMI-2, for convenience) and with prescribed boundary conditions, so as to avoid additional and unwanted sources of discrepancies between code predictions.

5. Comparison with last benchmark conclusions

The conclusions of the last OECD/CSNI benchmark are summarized in the following table. A comparison with present codes capabilities is also presented to quantify the progress made in the last fifteen years. A significant improvement in the understanding of the physical processes has led to a more accurate and reliable prediction of the transient, except for the debris bed behaviour in the lower plenum which is still difficult to predict.

Table 1: **Comparison of the last OECD/CSNI benchmark conclusions and present codes capabilities**

	Last benchmark conclusions[12]	**Present codes capabilities**
Phase 1	All the participants were able to end Phase 1 with reasonable estimates of the the initial conditions (mass inventory and RCS pressure) for the initiation of Phase 2. Phase 1 is a relatively simple thermal-hydraulic transient which requires only mass and energy balance calculations.	Most of the current severe accident codes, are also able to calculate Design Basis Accidents. They all provide good estimates of the RCS pressure and mass inventory at the end of phase 1. No significant progress was done, since the results were already satisfactory.
Phase 2	The prediction of Phase 2, up to the beginning of repressurization was adequately estimated by the participants. After the start of core heat-up and degradation, the codes predictions diverge on their estimates of RCS pressure and hydrogen generation (even after sensitivity studies). Model improvement was required. Several codes predicted the drainage of the pressurizer after closure of the PORV valve. This lead to core quenching, contrary to what happened in the transient.	All codes now include new (and similar) models for cladding oxidation. This constitutes a significant improvement and leads to a correct prediction of the hydrogen generated during Phase 2. The modelling of the pressurizer was improved by several code users, avoiding the unrealistic drainage after PORV closure. This is another significant improvement which is compulsory to be able to calculate Phase 2 and the rest of the transient. Other improvements were made on thermalhydraulics (cross flows) and melt relocation.
Phase 3	None of the codes were able to predict the significant hydrogen production during the pump transient. Model deficiencies were identified for the following phenomena: reflood oxidation, relocation of Zr before reflood and more generally the spatial distribution of oxidation during core heat-up.	Some codes include improved models for cladding oxidation during reflood. Although this phenomenon is still under study in several countries, the development of these new models constitute a significant progress, leading to a better prediction of the total amount of hydrogen produced during the transient. Improvements and extensions of thermal-hydraulics models to deal with damaged fuel rods and blocked areas have been developed. This has helped to calculate the good pressure evolution during reflood.
Phase 4	None of the codes demonstrated the ability to model the phenomena such as formation of crusts, retention of liquid corium in the core region and corium relocation in the by-pass.	Some codes are able to calculate corium relocation down to the lower plenum and the subsequent evolution of lower plenum debris. However, some of the models are very parametric or uncomplete and the quality of predictions is questionable, in the code users' opinion. No code is actually able to predict the melt retention in the vessel without a proper tuning of model parameters. Nevertheless, the development of such models constitutes an outstanding improvement.

6. Conclusions

It appears that some progress has been made since the last OECD/CSNI benchmark on TMI-2. Progress results partly from a better definition of the transient conditions but mainly from significant improvements of the physical modelling in the codes. It is important to mention that several processes that occurred during the TMI-2 transient have led to starting experimental programs worldwide to achieve a better understanding. Among these processes, the most remarkable are the peak of hydrogen production which occurred during the reflood phase and the fact that the vessel did not fail despite the flow of 30 tons of high temperature corium in the bottom head.

Thanks to those experimental programs, a lot of experience was gained by code developers and users, and most of the physical processes that occurred during the TMI-2 transient are now understood. They are also, more or less, calculated by the codes (at least, some of the codes). However, there are still remaining uncertainties and some physical processes are not quite understood even now. The main items that need further improvements are:

- The impact of natural circulation in the vessel, in particular after melt relocation and reduction of the porosity in some parts of the core. This has a strong influence on hydrogen production.

- The impact of a more detailed modelling of the thermalhydraulics, heat transfers and oxidation during reflooding. This has an influence on hydrogen production and on melt relocation.

- The processes governing melt progression in the core, and the release of molten corium to the lower plenum. This is essential to determine the initial configuration of the lower plenum debris (particles, compact crust, pool, etc.). This includes a possible debris bed collapse (transition from early to late phase degradation). This has a strong influence on the determination of pipes or vessel failure due to a pressure peak or steam explosion.

- The behaviour of debris in the lower plenum (coolability, oxidation, etc.). At present, models are very parametric. Detailed models are not tightly coupled with the thermalhydraulics and core degradation calculation. Some processes, such as water ingression between the corium and the vessel, are not understood, despite the existence of experimental results. This has a strong influence on the determination of vessel failure (timing, location and released melt properties).

To get an estimation of current codes capabilities, benchmark reactor calculations constitute a pertinent (but not exclusive) way. It helps participants (code developers and users) to share their understanding of the physical processes and therefore it may open the way to improvements. It is also a good opportunity to draw conclusions about the quality and relevance of code results for safety analysis. Hence, the GAMA group has proposed a new benchmark exercise on TMI-2 plant.

To prepare this new benchmark, the first step would be to check the consistency between the boundary conditions and hydraulic components modelling chosen by all the code users. Despite the differences due to the different code structures, the "critical" data are the same for each code and are well known by the experts. Therefore, a first task will be to propose a set of common data to be included in each input deck. It is very likely that the plant description will be limited to the primary circuit. The secondary circuit conditions will be imposed, as it was done by several contributors to this report. After that first step, the participants would define an alternative transient, different from the TMI-2 accident. The scenario should be built to cover the largest range of physical processes (e.g. a starvation phase, a large amount of molten materials, a late quenching, etc.). The aim of the benchmark will be to compare the different code results obtained for that specified transient and to draw conclusions from that comparison.

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Appendix: Comparative tables for each code

1. Description of the tables

Each participant has filled a table and expressed the level of satisfaction with the calculated results for the respective codes that they have used. The accident sequence was divided into the four classical main phases:

- Phase 1: between scram and stop of pumps (up to 100 minutes)
- Phase 2: between stop of pumps and first reflooding (up to 174 minutes)
- Phase 3: reflooding (up to 200 minutes)
- Phase 4: end of the sequence (up to 300 minutes)

Several physical parameters were chosen as the most important to characterize the evolution of the accident transient. They correspond either to indicators of the reactor state (pressure, water inventory, etc.) or indicators of the degree of degradation (relocated mass, etc.) or measures of the impact of degradation on the containment safety (hydrogen production, FP release, etc.). The parameters used in the previous OECD benchmark were also selected for consistency.

In the same table, an opinion about the progress made during the last 10-15 years is expressed, considering the last OECD TMI-2 standard problem as a reference, when possible. The reasons for improvements are given. The progress may be related to a better modelling and discretization of the reactor and circuit, a better knowledge of the accident sequence and operator actions (improvement of input data, better modelling of the circuits, etc.), or an improvement of important models (correction of errors, better correlations, more sophisticated modelling). Some possibilities for further improvements are also presented.

2. Rating of the tables

Participants have either written a personal comment or used a rating to fill the tables. The signification of the ratings is explained below.

<u>*Quality of prediction*</u>

- N: Not calculated
- 0: Bad quality of the prediction
- 1: Acceptable prediction (some discrepancies with available data or no possibility of comparison with measured data)
- 2: Satisfactory quality of the prediction (reasonable agreement with available data)

<u>*Improvements*</u>

- N: Not calculated
- 0: No improvement
- 1: Noticeable improvement, but some discrepancies remain
- 2: Significant improvement leading to satisfactory results

ASTEC (ENEA)

PHASE 1 (< 100')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(2)	(N)		
Water inventory	(2)	(N)		
Water level in pressurizer	(2)	(N)		
Secondary pressure	(2)	(N)		
Water level in SG	(0)	(N)		Improvement of SG water level control by auxiliary feedwater injection
Pump behaviour	(1)	(N)		Characteristics of pump according to TMI-2 data

SCDAP/RELAP5 (ENEA)

PHASE 1 (< 100')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(2)	(0)		
Water inventory	(2)	(1) Slight improvements	Better definition of boundary conditions and PORV valve behaviour	
Water level in pressurizer	(2)	(0)		
Secondary pressure	(2)	No comparison		
Water level in SG	(2)	No comparison		
Pump behaviour	(1)	No comparison		Better definition of TMI-2 pump characteristics

SCDAP/RELAP5 (ENEA)

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(2)	(1) Slight improvement	Better prediction of core uncovery, heatup and hydrogen generation	
Water inventory	(2)	(1) Slight improvement	Better definition of boundary conditions (makeup flow rate reduction during phase 2)	
Water level in pressurizer	(1) Underprediction of level in phase 2	(2) Avoiding pressurizer draining after PORV closure	Better prediction of core heatup and primary pressure behaviour (pressure increase before PORV closure prevents pressurizer draining)	
Secondary pressure	(2)	No comparison		
Water level in SG	(2)	No comparison		
Water level in the core	(2) Well predicted towards the end of phase 2	(1)	Better definition of boundary conditions (makeup flow rate reduction during phase 2)	
Cladding burst	(1) about 5 minutes earlier than TMI-2 data (initial core heatup likely overpredicted)	No comparison		Model improvements to better account for in-vessel gas natural circulation during initial core heatup
Hydrogen production	(2)	(2) Significant improvement	Improved modelling for clad oxidation and oxidation of relocating mixtures. Use of suitable clad failure criteria. No double-side clad oxidation after clad burst	
Material melting and relocation	(2-) Reasonably well predicted at the end of phase 2	(2)	Better prediction of core uncovery and heatup. Improved modelling of late phase degradation and use of suitable clad failure criteria	
FP release	(N) Not closely examined			
Temperature in the hot leg	(1) Significant overprediction of gas temperature during core heatup	No comparison		Take into account heat losses to the environment through primary circuit structures

SCDAP/RELAP5 (ENEA)

PHASE 3 (< 200')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	(1) Pressure increase during reflood well predicted. Primary pressure after reflood underpredicted	(2) Significant improvement	Good prediction of total hydrogen release during reflood (simple quenching model)	Improvement of core quenching model (core thermalhydraulics and oxidation of mixtures under reflood)
Water inventory	(2) Depends mainly on boundary conditions (small water loss through re-opened PORV)	No comparison		
Water level in pressurizer	(1-)Pressurizer water level increase largely underestimated	No comparison		Better prediction of core and primary circuit thermalhydraulics under reflood
Secondary pressure	(2-)SG-B pressure is underpredicted	No comparison		Better prediction of core and primary circuit thermalhydraulics under reflood
Water level in SG	(2)	No comparison		
Water level in the core	(2-)Water entering the vessel at pump restart quite well predicted	No comparison		Better prediction of core and primary circuit thermalhydraulics under reflood
Hydrogen production	(2-)Total hydrogen release after reflood well predicted	(2)	Code model improvement for clad embrittlement and oxidation during quenching	Improvement of modelling of oxidation of mixtures under core reflood
Material melting and relocation	(2-)Heatup and spreading of the in-core molten pool is computed by the code	No comparison	Improvement of the late phase degradation modelling	Improvement in the computation of heat transer mechanisms between molten pool and surrounding core structures
FP release	(N) Not closely examined			
Fuel rod collapse,Debris formation	(1) Transition to debris bed but not debris bed collapse computed by the code	No comparison	Improvement of the late phase degradation modelling	Modelling of debris bed collapse

PHASE 3 (< 200')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Molten pool progression	(2-)Heatup and spreading of the in-core molten pool is computed by the code	No comparison	Improvement of the late phase degradation modelling	Improvement in the computation of heat transer mechanisms between molten pool and surrounding core structures
Temperature in the hot leg	Not closely examined			
Quenching of rods ans debris	(1) Simple clad oxide shattering model used	No comparison		More mechanistic quenching model (including oxidation of mixtures)

SCDAP/RELAP5 (ENEA)

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(1) primary pressure peak at core slumping is overpredicted	(N)		Improvement of molten material-coolant interaction and heat transfer modelling during core slumping into the lower head
Water inventory	Not closely examined	(N)		
Water level in pressurizer	(2-) Filling of pressurizer is computed with some delay	(N)		Better prediction of core and primary circuit thermalhydraulics under reflood (HPI actuation)
Secondary pressure	(2-) SG-B pressure is underpredicted as in phase 3	(N)		
Water level in SG	(2)	(N)		
Water level in the core	(2) Completely covered as expected	(N)		
Hydrogen production	No significant hydrogen generation in phase 4 (no model for hydrogen release during core slumping)	(N)		Modelling of molten material quenching and oxidation during slumping
Quenching of rods and debris	(1) No debris bed collapse modelling	(N)		Modelling of debris bed collapse
FP release	Not closely examined	(N)		
Failure of the baffle	(N) Not computed	(N)		
Corium relocation to lower plenum	(2-) Total amount of relocated material quite well predicted. Slumping slightly anticipated	(N)		Improvement of molten pool crust failure and molten material relocation models

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Temperature in the hot leg	Not closely examined	(N)		
Quenching of relocated corium	Not closely examined	(N)		Difficulties in applying the COUPLE bottom head vessel model which should be improved
Steam production after relocation	(1) It seems overestimated during relocation on the basis of overpredicted primary pressure peak	(N)		Improvement of molten material-coolant interaction and heat transfer modelling during core slumping into the lower head

References cited:

Bandini G. (May 2001), *TMI-2 Accident Calculations with ICARE/CATHARE and SCDAP/RELAP5 Codes, ENEA IT-SBA-00011, SAM-COLOSS-P011 (Part B*).

SCDAP/RELAP5 (Univ. Pisa)

PHASE 1 (< 100')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	Current RELAP5/SCDAP Mod. 3.2 prediction is good compared with available data: pressures are into the uncertainty of measured values, and levels are coincident with measured data	The good prediction is due to a good improvement of the steady s9tate before scram.	Due to the uncertainty about data in the systems before scram, it is necessary to drive the reactor for at least 100 s before the start of the accident to reach the starting levels of the different parameters.	
Water inventory				
Water level in pressurizer				
Secondary pressure				
Water level in SG				
Pump behaviour	Imposed mass flow rate	Many parametric calculations have been performed to obtain at the scram time the right available system parameters.	Due to the great uncertainty about pump characteristics, the mass flow rate has been imposed	Better definition of TMI-2 pump characteristics

SCDAP/RELAP5 (Univ. Pisa)

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	Current RELAP5/SCDAP Mod. 3.2 prediction is good compared with available data: the predicted pressure is into the uncertainty of measured values, except for 300 s at about 150 min. during which the pressure is underpredicted of 0.5 MPa			
Water inventory				
Water level in pressurizer	Underprediction of the PRZ level in Phase 2 (the difference is about 2.5 m)	Noticeable improvement, but some discrepancies remain	The improvements have been imposed to avoid the PRZ draining	
Secondary pressure	Current RELAP5/SCDAP Mod. 3.2 prediction is good compared with available data	Boundary conditions imposed	Imposed conditions due to the uncertainty about data to obtain the right degradation of the primary system	
Water level in SG				
Water level in the core	RELAP5/SCDAP Mod. 3.2 prediction is good comparing the next degradation	Many calculations have been performed to obtain the best prediction of the core degradation	Better definition of boundary conditions.	Improved modelling for clad oxidation and oxidation of relocating mixtures. Use of suitable clad failure criteria.
Cladding burst	Good prediction with available data, even if it starts about 300 s later than TMI2 data.			

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Hydrogen production	The hydrogen production starts about 300 s later than TMI2 data, but the shattering model allows to predict the measured pressure in the primary system.	Significant improvements		
Material melting and relocation	Reasonably well predicted at the end of phase 2		Better prediction of core uncovery and heatup. Improved modelling of late phase degradation and use of suitable clad failure criteria	
FP release	Not examinated			
Temperature in the hot leg	Satisfactory quality of the prediction			

SCDAP/RELAP5 (Univ. Pisa)

PHASE 3 (< 200')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	Good agreement is obtained between the code simulation and the system pressure measured during the accident (difference less then 1MPa).	Significant improvement on make up flow rate up to 200 min have been assumed.	Make up flow rate has been parametrised to obtain good prediction on water level in the core, which has great effect on pressure, cladding oxidation and degradation.	
Water inventory	The mass inventory is imposed by setting the make up flow rate	Parametric calculations with different make up flow rates have been performed.	Make up flow rate has been parametrised to obtain good prediction on water level in the core, which has great effect on pressure, cladding oxidation and degradation.	
Water level in pressurizer	Underprediction of the PRZ level in Phase 3 (the difference is about 2.5 m)	Many parametric calculations on surge line pressure drops have been performed.	The improvements have been imposed to avoid the PRZ draining.	
Secondary pressure		Boundary conditions imposed	Imposed conditions due to the uncertainty about data to obtain the right degradation of the primary system	
Water level in SG		Boundary conditions imposed	Imposed conditions due to the uncertainty about data to obtain the right degradation of the primary system	
Water level in the core	Good agreement is obtained between core level and material relocation during accident.	Parametric calculations with different make up flow rates have been performed.		
Hydrogen production	The total amount calculated by the code (490 kg) is in a quite agreement with the estimation of the hydrogen production during the accident (460 kg)	Significant improvement on make up flow rate and on oxidation (DCMN models) have been assumed. Moreover the shattering model has been imposed.	The improvements have been imposed to obtain the good prediction during reflood.	

PHASE 3 (< 200')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Material melting and relocation	Good behaviour of the in vessel relocation and molten pool formation is observed.	Significant improvements about cladding failure criteria and relocation temperature have been imposed.	The improvements have been imposed to better predict the core uncovery and heatup. Moreover, have been improved modelling of late phase degradation and have been used suitable cladding failure criteria	
FP release	Not examinated			
Fuel rod collapse,Debris formation	The fuel rod collapse and debris bed formation is well predicted by the code: results are in a good agreement with experimental studies.	The significant improvements to obtain a good prediction of the degradation result by the previous parametric calculations.		
Molten pool progression	The molten pool spreading is well predicted by RS5, but Mod3.2 overexstimes the limit of the crust failure.			
Temperature in the hot leg				
Quenching of rods ans debris	Rods quenching is predicted: good behaviour of the material fragmentation and of hydrogen production.	The good prediction is the effect of the used models		

SCDAP/RELAP5 (Univ. Pisa)

PHASE 4 (< 300’)	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	Up to MP relocation, good prediction of pressure; after the calculation with integral nodalisation is influenced by the presence in core of MP and data are not significant. In the vessel calculation (Couple model) the pressure is imposed to study LP bheaviour.	See Note	See Note	
Water inventory	Up to MP relocation the water inventory is influenced by previous make up flow rate; after 224min. the inlet mass flow is imposed.	See Note. The inlet mass flow rate after MP relocation has been imposed in accord with previous integral calculations (4 kg/sec)	See Note	
Water level in pressurizer	As in the Phase 3, the PRZ level is underpredicted due to the draining.			
Secondary pressure	Imposed			
Water level in SG	Imposed			

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Water level in the core	Up to MP relocation, the core level is well predicted, and degradation results have good agreement with experimental and best estimated calculations. In the vessel calculation, the level in the core was assumed to be 0.	During vessel calculation only LP is full of water	See Note	
Hydrogen production				
Quenching of rods and debris	The behaviour of remaining rods and debris is well predicted by the code up to MP relocation. After 224 min the attention was focused on LP behaviour.	See Note	See Note	
FP release	Not examinated			
Failure of the baffle	The starting failure of the baffle has been imposed	See Note	See Note	Improvement of molten pool crust failure and molten material relocation models
Corium relocation to lower plenum	The total amount of relocated material has a good agreement with experimental data (about 2.4 m3)	Parametric calculations have been performed on slumping duration and temperature, on debris status at relocation (fragmented or coesive), on porosity and diameter of debris particles, on presence or absence of a gap between debris bed and LH walls.	The improvements have been imposed to study the behaviour of COUPLE model, and to verify the LH walls behaviour.	

PHASE 4 (< 300')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Temperature in the hot leg	Not examinated			
Quenching of relocated corium	The corium behaviour in the vessel lower head has been examinated by the finite elements model of COUPLE code. The corium and wall temperatures are well predicted, even if temperature is initially higher than 2200 K and overcomes the melting temperature of the steel for about 10 minutes (even though in a limited fraction of the inner vessel surface).	Parametric calculations on slumping duration and temperature.		
Steam production after relocation	The steam production after relocation has been calculated: the steam production starts at high melting temperature materials slumping and finishes 1 min later, with different production based on parametric calculation (the total calculated amount is in the the range between 700 and 1100 kg) .	Parametric calculations on slumping duration and temperature.	See Note	

Note:
The phase 4 is characterised by material relocation in the LP:the calculations performed by R5S Mod3.2 do not predict the molten pool relocation, due to the overextimation of the failure limit of the MP crust. Therefore it was imposed to calculate lower head behaviour by COUPLE model: to study Couple predictions, only vessel region has been modellised and parametric calculations have been performed starting from MP relocation (at about 224 min).

ICARE/CATHARE V1 (ENEA)

PHASE 1 (< 100')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(2)	(0)		
Water inventory	(2)	(1) Slight improvements	Better definition of boundary conditions and PORV valve behaviour	
Water level in pressurizer	(2)	(0)		
Secondary pressure	(2)	No comparison		
Water level in SG	(2)	No comparison		
Pump behaviour	(2)	(1) Slight improvements		

ICARE/CATHARE V1 (ENEA)

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	(2-) Slight discrepancy towards the end of phase 2	(2) Significant improvement	Better prediction of core uncovery and heatup, and material oxidation and hydrogen generation. Coupling between ICARE and CATHARE codes	Better prediction of timing of hydrogen release
Water inventory	(2)	(1) Slight improvement	Better definition of boundary conditions (makeup flow rate reduction during phase 2)	
Water level in pressurizer	(1) Underprediction of level in phase 2	(2) Avoiding pressurizer draining after PORV closure	Better prediction of core heatup and primary pressure behaviour (pressure increase before PORV closure prevents pressurizer draining)	
Secondary pressure	(2-) SG-B pressure slightly overestimated towards the end of phase 2	No comparison		
Water level in SG	(2)	No comparison		
Water level in the core	(2) Well predicted towards the end of phase 2	(1)	Better definition of boundary conditions (makeup flow rate reduction during phase 2)	
Cladding burst	(2-) About 1-2 minutes earlier than TMI-2 data	No comparison		
Hydrogen production	(2) Total hydrogen release at the end of phase 2 is well predicted	(2) Significant improvement	Improved modelling for clad oxidation and oxidation of relocated mixtures. No double-side clad oxidation after clad burst	The timing of hydrogen release could be improved
Material melting and relocation	(2-) Reasonably well predicted at the end of phase 2	(2)	Better prediction of core uncovery and heatup. Decanting and candling of molten material in rod-like geometry and use of suitable fuel rod melting temperature (2830 K) according to SCDAP/RELAP5 code	Use of debris bed and mgma models for the late degradation phase need more validation

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
FP release	(N) Not computed			
Temperature in the hot leg	(1) Overprediction of gas temperature during core heatup	No comparison		Take into account heat losses to the environment through primary circuit structures

References cited:

Bandini G. (May 2001), *TMI-2 Accident Calculations with ICARE/CATHARE and SCDAP/RELAP5 Codes, ENEA IT-SBA-00011, SAM-COLOSS-P011 (Part B*).

Bandini G. (May 2003), *TMI-2 Accident Analysis: 2nd Set of ICARE/CATHARE and ASTEC V1 Calculations, ENEA FIS-P127-024, SAM-COLOSS-P037 (Part A, B*).

ICARE/CATHARE V2 (IRSN)

PHASE 1 (< 100')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	Good agreement	No significant improvement since last benchmark		
Water inventory	Good agreement	No significant improvement since last benchmark		
Water level in pressurizer	Good agreement	No significant improvement since last benchmark		
Secondary pressure	Good agreement	Slight improvement	Improvement of the SG modelling	
Water level in SG	Good agreement	Slight improvement	Improvement of the SG modelling	
Pump behaviour	Satisfactory	No significant improvement	Updated characteristics of the pumps.	

ICARE/CATHARE V2 (IRSN)

PHASE 2 (< 174')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	Good prediction up to 7500s.	No significant improvement since last benchmark		
Water inventory	Stabilised around 1m, which in rather good agreement with TMI2 data	Slight improvement with respect to last benchmark		
Water level in pressurizer				
Secondary pressure	Good prediction up to 7500s.	No significant improvement since last benchmark		
Water level in SG	Good prediction up to 7500s for GV A. Overestimation in GV B after 6000s.	No significant improvement since last benchmark		
Water level in the core	Stabilised around 1m, which in rather good agreement with TMI2 data	Slight improvement with respect to last benchmark		
Cladding burst		No calculation of cladding burst in previous benchmark	Modelling of cladding deformation and failure	
Hydrogen production			Modelling of Zircaloy cladding oxidation	
Material melting and relocation			Modeling of molten material relocation	

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
FP release	Not examined			
Temperature in the hot leg	Over-estimated	A similar over-estimation was observed in previous benchmark exercise.		

References cited:

Dumaz P. (December 1989), Three *Mile Island Unit 2 analysis exercise: CATHARE computations of phases 1 and 2 of the accident*, Nuclear Technology, Vol. 87.

Fichot F., R. Gonzalez, P. Chatelard, B. Lefèvre and N. Garnier (May 1995), ICARE2 *Late phase degradation models: Application to TMI-2 accident, Int. Seminar on Heat and Mass Transfer in Severe Reactor Accidents, Cesme (Turkey).*

Mélis S., V. Guillard, F. Camous and F. Fichot, (November 1998), *Analysis of the TMI-2 accident using* the ICARE/CATHARE *code, Workshop of Severe Accident Research held in Japan, Tokyo (Japan).*

MELCOR (NRC)

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	Current MELCOR 1.8.5 prediction is good through end of Phase 2.	Latest improvement gives correct pressure during boiloff and pressurization transient at end of phase 2.	Improvement in latest analyses traces back to adjustments in assumed makeup and letdown rates. Improvement over Version 1.8.4 gained from improvement in melt progression modeling, now avoiding a too-soon melt relocation to lower plenum in Phase 3.	Any further improvements are likely to come from refinement of boundary conditions and not from model improvement.
Water inventory	Current analyses are believed to be as good as is attainable.			
Water level in pressurizer	Pressurizer water level currently correctly predicted (i.e. pressurizer doesn't drain too soon.)	Pressurizer water level currently correctly predicted. Earlier representations of TMI encountered problems with draining pressurizer partly reflooding core and producing clearly wrong accident signature.	Present model avoids draining of pressurizer in Phase 2 owing to correct prediction of primary system pressure and accounting of hydraulic heads in surge line.	No significant improvements anticipated.
Secondary pressure	Not closely examined.			
Water level in SG	Present water levels reasonably well predicted.	Present predictions reasonable consistent with available data. Improvement mainly on heat transfer to secondary side.	Heat transfer improvements due to accounting for spatial incoherencies in feedwater contact with congested tube bundle.	We presently seek to improve the physical representation of the feedwater spray onto the upper tube region of the SG making use of MELCOR draining film model for heat structures.

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Water level in the core	Current water level well predicted.	Better water level predicted during second half of phase 2. Results in improved timing for hydrogen production and system pressure.	Adjustment of makeup and letdown rates and inclusion of 2D flow representation in core and upper plenum. Natural circulation moves more heat to upper plenum, delays core degradation, and thereby avoids too-soon melt relocation to lower plenum and accompanying level swell.	No significant improvements anticipated.
Cladding burst	Not closely examined.	MELCOR model parametric based on temperature threshold.	Any improvements would be due to improved core heat up predictions resulting from multi-dimensional treatment of in-vessel circulation.	We should review timing insofar as this data is known.
Hydrogen production	Present H2 predicted during Phase 2 is reasonably well predicted. We predict ~350kg prior to B-loop transient at 174+ minutes.	Current hydrogen production signature in Phase 2 is improved both with respect to timing of onset and total amount produced.	Improvement in timing of hydrogen onset is due to correct prediction of water level and due to including 2D natural circulation in-vessel which transports core energy to the upper vessel internals, delaying core heat up and initiation of oxidation. Total hydrogen produced is due to improvements in modelling of oxide shell retaining molten Zr and to improvements in core melt progression modelling.	We continue to improve melt progression modelling in the area of oxidation of relocating materials and in late-phase melt progression. We expect further improvements in late phase 2 and phase 3 aspects of the TMI-2 accident.
Material melting and relocation	Overall melt progression signature is reasonable through end of Phase 2.	Correct overall core debris formation, peak temperatures and molten pool formation.	Improvements made in the area of molten zr retention behind cladding oxide, and fuel rod degradation near 2650K owing to non-equilibrium material interactions and irradiated fuel effects produce improved signatures.	We expect significant future improvements in the area of molten pool formation, crust formation in-core pool growth to core boundaries, and relocation of melt into the lower head, and subsequent formation of the molten corium pool in the lower head.

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
FP release	Not closely examined.			
Temperature in the hot leg	Not closely examined.	We assume significant improvements here.	We expect that modelling in-vessel natural circulation, which transports significant heat from core to upper plenum and ultimately to hot legs, is of principal importance. We would expect our current model to be significantly improved in this respect.	Future improvements in this area assumed to be due to improvements in representation of the TMI-2 input and not so much due to improvements in modelled physics.

References cited:

Gauntt, Ross and Wagner (2002*), MELCOR 1.8.5 Simulation of TMI-2 Phase 2 with an enhanced 2-D In-Vessel Natural Circulation Model, ICONE10-22321*.

Gauntt *et al*, *MELCOR Demonstration Problems*, NUREG/CR 6119, Vol 3.

Boucheron, E. and J. Kelly (1989), *MELCOR Analysis of the Three Mile Island Unit 2 Accident*, Nuc. *Tech.* Vol 87, pp. 1050.

MELCOR (PSI)

PHASE 3 (< 200')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	Current MELCOR 1.8.5 underpredicts the pressure escalation at the restart of the RCP. The trend throughout the phase is correct.			Oxidation models for debris and submerged debris.
Water inventory	Current analyses are believed as good as is attainable.			
Water level in pressurizer	Pressurizer water level is not shown to increase as in the accident during this phase.			If pressure predictions (due to increase in oxidation) better approximate accident data, it is likely that the level will recover due to increased hydraulic heads.
Secondary pressure	Not closely examined.			
Water level in SG	Not closely examined.			
Water level in the core	Current water level appears to be well predicted according to other accident signatures.			
Hydrogen production	During reflood the code predicts about fifty additional kilograms bringing the total to about 350-400 kg.			Due to improvement in models for oxidation of relocating materials, further improvements are expected.
Material melting and relocation	Melt progression signature appears reasonable through phase 3.			
FP release	No closely examined			
Fuel rod collapse, Debris formation	Collapse appears to be accelerated.			Sensitivity analyses can be performed for the criteria of rod break-up and debris formation.

PHASE 3 (< 200’)	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Molten pool progression	No closely examined.			
Temperature in the hot leg	Not closely examined.			
Quenching of rods and debris	The quenching model appears not to account for some physical phenomena, such as water ingression in debris beds.			It is recommended that the MELCOR quench model be revisited.

MELCOR (PSI)

PHASE 4 (< 300’)	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	The relevant signatures are in fair agreement with accident data.			No further modelling improvements are expected beyond sensitivity studies to boundary conditions.
Water inventory	Water inventory appears to follow all relevant accident signatures.			No further modelling improvements are expected beyond sensitivity studies to boundary conditions.
Water level in pressurizer	Correctly predicted.			
Secondary pressure	Imposed			
Water level in SG	Imposed			
Water level in the core	The water level is recovered to the top within the second stage of feed and bleed. Follows the imposed HPI flow boundary conditions.			No further modelling improvements are expected beyond sensitivity studies to boundary conditions.
Hydrogen production	Very limited production by submerged unquenched debris.			Oxidation models for debris and submerged unquenched debris.
Quenching of rods and debris	The quenching model appears not to account for some physical phenomena, such as water ingression in debris beds.			It is recommended that the MELCOR quench model be revisited.
FP release	Not closely examined.			
Failure of the baffle	Not included in the model.			

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Corium relocation to lower plenum	The current MELCOR capabilities do not include models for relocation other than due to core support plate failure. This is predicted during phase 4, even though it was not observed in the accident. Failure is due to stress and creep rupture.		.	The next version of MELCOR will include additional modes for relocation of debris.
Temperature in the hot leg	Not examinated			
Quenching of relocated corium	The quenching model appears not to account for some physical phenomena, such as water ingression in debris beds.			It is recommended that the MELCOR quench model be revisited.
Steam production after relocation	Not closely examined, however, pressure trends are similar to accident data.			

References:

Gauntt, Ross and Wagner (2002), *MELCOR 1.8.5 Simulation of TMI-2 Phase 2 with an enhanced 2-D In-Vessel Natural Circulation Model, ICONE10-22321*.

Gauntt et al, *MELCOR Demonstration Problems*, NUREG/CR 6119, Vol 3. *Tech.* Vol 87, pp. 1050.

Boucheron, E. and J. Kelly (1989), *MELCOR Analysis of the Three Mile Island Unit 2 Accident*, Nuc. Tech. Vol 87, pp. 1050.

Gaunt, Ross, MELCOR 1.8.*5 Integral Calculation of Phase 1 and 2 of the Three Mile Island Unit 2 Accident*

Cazzoli, Vitázková, (Draft August 2004), *Modification of the TMI-2 input model to allow changes to boundary conditions on restart and extension to include Phases 3 and 4. First analysis of the entire sequence. Identification and first corrections of modelling deficiencies. Stage 4 of the TMI/2 analysis*.

ATHLET-CD (GRS)

PHASE 1 (< 100')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	In fair agreement considering the uncertainty of boundary conditions; in this calculation the aim was to get the proper core uncovery after pump trip at 100'	None; this phase has been exhaustively investigated in the frame of the OECD TMI2 analysis exercise (1)	None	Not expected unless more precise boundary conditions allow better simulation
Water inventory	See above			
Water level in pressurizer	See above			
Secondary pressure	Imposed as boundary condition			
Water level in SG	See first row			
Pump behaviour	See above			

ATHLET-CD (GRS)

PHASE 2 (< 174’)	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	In excellent agreement with measured data 105’ - 147’, in fair agreement for the rest	Simulation of oxidation, rod failure and blockage formation	Model extension for severe accidents (2,3)	Exchange from rod model to debris model for highly degraded core regions
Water inventory	Correct simulated, indicated by pressure history and freezing of metallic melt at elevation 0.6 - 1.6 m	Thermal hydraulic models with separated energy and momentum equations as well as simulation of non-condensables	General model developments	Not expected, unless more precise boundary conditions allow better simulation
Water level in pressurizer	Collapsed level qualitative in good agreement with measured data, after 120‘ underestimated by approximately 2 m	Correct nodalisation of surge line	consideration of user guide lines	Not expected, deviation possibly due to uncertainty of level measurement
Secondary pressure	Imposed as boundary condition			Complete simulation of secondary cooling system is not in the scope of severe accident simulation and questionable due to unknown boundary conditions
Water level in SG	In fair agreement, considering problem of level measurement in SG_B			Not expected, unless more precise boundary conditions allow better simulation
Water level in the core	After pump trip separation of steam and water results in a water level below middle of core with subsequent decrease due to evaporation. Water level in inner ring lower than in outer ring due to blockage formation	Feed back between blockage formation and flow distribution	Model extension for severe accidents	Benchmark to CFD code under consideration of blockage formation

PHASE 2 (< 174')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Cladding burst	Clad failure due to melting well predicted 146' - 153'	Simulation of oxidation and rod failure	Model extension for severe accidents	Not expected
Hydrogen production	In fair agreement according to primary pressure; use of Prater-Courtright results in faster pressure increase, heat-up and melting in the beginning and too slow pressurization after 150'.	See comment in first row	See comment in first row	See comment in first row
Material melting and relocation	First control rod melt relocation at 140' and refreezing at 1.2 m; first metallic fuel rod melt at 148' and refreezing at 1.6 - 2.3 m; first ceramic fuel rod melt at 160' and refreezing at 1.7 m accompanied by melting of metallic melts. Accumulated melt mass possibly underestimated.	See above and melt relocation model for control rod and fuel rod (candling model with freezing and remelting)	See above	Further model development for debris bed and slumping of decladded fuel
FP release	Not simulated in this calculation			Activate model FIPREM with rate equation approach for rod like structure, development of FPPOOL for release from molten pool

PHASE 2 (< 174')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Temperature in the hot leg	Qualitative in good agreement. Under super heated conditions overestimated up to 50 K considering upper limit of measurement range (400°C). Loop A: temperature rise after pump trip and cooling periods due to water from pressuriser well captured. Loop B: temperature rise with start of loop flow due to feed water injection in SG_B and cooling due to start of MCP_B2 well captured	Thermal hydraulic models with separated energy and momentum equations as well as simulation of non-condensables	General model developments	Not expected

ATHLET-CD (GRS)

PHASE 3 (< 200')	Quality of prediction	Improvements	Reasons for improvements	Further possible improvements
Primary pressure	Initial pressure increase due to quenching well captured, ensuing pressure decrease possibly due to too less heat generation due to oxidation or to high heat losses to secondary system	Simulation of oxidation, rod failure and blockage formation and thermal hydraulic models with separated energy and momentum equations as well as simulation of non-condensables	Model extension for severe accidents and general model developments	Exchange from rod model to debris model for highly degraded core regions and simulation of rod collapse during quenching
Water inventory	Correct simulated due to well known boundary conditions			
Water level in pressurizer	In good agreement with measured data considering constant deviation of appr. 2 m	See comment phase 2	See comment phase 2	See comment phase 2
Secondary pressure	Imposed as boundary condition			See comment phase 2
Water level in SG	In good agreement with measured data considering constant deviation			See comment phase 2
Water level in the core	Pump restart causes fast level increase and ensuing level decrease due to evaporation	See comment phase 2	See comment phase 2	See comment phase 2
Hydrogen production	No significant hydrogen generation is calculated due to the fact that all metallic material is in cooler core regions	Simulation of oxidation, rod failure and blockage formation	Model extension for severe accidents and general model development	Oxidation of metallic crust, ceramic fuel and melt, based on analyses of quench experiments (SET, QUENCH, LOFT)

PHASE 3 (< 200')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Material melting and relocation	No further fuel melting (metallic and ceramic) is calculated possibly due to too high heat transfer to coolant; absorber material crust is remelting, but melt is captured by crust below	See comment in first row	See comment in first row	See comment in first row
FP release	Not simulated in this calculation			See comment phase 2
Fuel rod collapse, Debris formation	Model not yet available			See comment in first row
Molten pool progression	Model not yet available			See comment in first row
Temperature in the hot leg	Qualitative in good agreement, see phase 2	See comment phase 2	See comment phase 2	See comment phase 2
Quenching of rods and debris	Quenching of intact, damaged and degraded rods is calculated with the same model considering reduced heat transfer in and reduced water ingression into blocked regions. Debris model not yet available	See comment in first row	See comment in first row	See comment in first row

ATHLET-CD (GRS)

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
Primary pressure	Pressure decrease due to injection of cold water until 220', then due to opening of pressurizer valve. Simulation not adequate after 224' due to the fact that core melt slump into lower plenum is not modelled yet. Comments below reflect only the time until 224'.	Simulation of oxidation, rod failure and blockage formation and thermal hydraulic models with separated energy and momentum equations as well as simulation of non-condensables	Model extension for severe accidents and general model developments	Exchange from rod model to debris model for highly degraded core regions and simulation of rod collapse during quenching as well as modelling of core melt slump into lower plenum
Water inventory	Plausible behaviour			
Water level in pressurizer	In good agreement with measured data considering constant deviation of appr. 2 m; with opening of pressurizer valve step level increase			
Secondary pressure	Imposed as boundary condition			
Water level in SG	In good agreement with measured data considering constant deviation			
Water level in the core	Plausible behaviour			
Hydrogen production	No significant hydrogen generation calculated			
Quenching of rods and debris	Limited cool-down due to refill of RPV and further remelting of absorber material			

PHASE 4 (< 300')	**Quality of prediction**	**Improvements**	**Reasons for improvements**	**Further possible improvements**
FP release	Not simulated in this calculation			
Failure of the baffle	Model not yet available			
Corium relocation to lower plenum	Model for coarse melt slumping into lower plenum not available			
Temperature in the hot leg	Qualitative in good agreement as in phase 2 & 3			
Quenching of relocated corium	Model not yet available			
Steam production after relocation	Model not yet available			

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