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Use and Development of Coupled Computer Codes for the Analysis of Accidents at Nuclear Power Plants

Proceedings of a technical meeting held in Vienna, 26–28 November 2003

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International Atomic Energy Agency

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FOREWORD

Computer codes are widely used in Member States for the analysis of safety at nuclear power plants (NPPs). Coupling of computer codes, a further tool for safety analysis, is especially beneficial to safety analysis. The significantly increased capacity of new computation technology has made it possible to switch to a newer generation of computer codes, which are capable of representing physical phenomena in detail and include a more precise consideration of multidimensional effects. The coupling of advanced, best estimate computer codes is an efficient method of addressing the multidisciplinary nature of reactor accidents with complex interfaces between disciplines.

Coupling of computer codes is very advantageous for studies which relate to licensing of new NPPs, safety upgrading programmes for existing plants, periodic safety reviews, renewal of operating licences, use of safety margins for reactor power uprating, better utilization of nuclear fuel and higher operational flexibility, justification for lifetime extensions, development of new emergency operating procedures, analysis of operational events and development of accident management programmes.

In this connection, the OECD/NEA Working Group on the Analysis and Management of Accidents (GAMA) recently highlighted the application of coupled computer codes as an area of "high collective interest". Coupled computer codes are being developed in many Member States independently or within small groups composed of several technical organizations. These developments revealed that there are many types and methods of code coupling. In this context, it was believed that an exchange of views and experience while addressing these problems at an international meeting could contribute to the more efficient and reliable use of advanced computer codes in nuclear safety applications.

The present publication constitutes the report on the Technical Meeting on Progress in the Development and Use of Coupled Codes for Accident Analysis. It includes summaries of the presentations made during the meeting, of the discussions, and the conclusions and recommendations put forward for further work. A CD, which contains the entire collection of papers submitted for the meeting, is provided as a supplement to this report.

The IAEA wishes to thank all participants for their contributions to this publication. The IAEA officer responsible for the organization of the meeting and the compilation of this publication was Y. Makihara of the Division of Nuclear Installation Safety.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Complex computer codes are used for the analysis of the performance of NPPs. They include many types of codes. For the analysis of anticipated transients and design basis accidents (DBAs), these codes can be categorized into the following six groups:

— Reactor physics codes;
— Fuel behaviour codes;
— Thermal-hydraulic codes, including system codes, subchannel codes, porous media codes and computational fluid dynamic (CFD) codes;
— Containment analysis codes;
— Atmospheric dispersion and dose codes;
— Structural codes.

Historically, these codes have been developed independently, but have been mainly used in combination with system thermal-hydraulic codes. By increasing the capacity of computation technology, safety experts thought of coupling these codes in order to reduce uncertainties or errors associated with the transfer of interface data and to improve the accuracy of calculation. The coupling of primary system thermal-hydraulics with neutronics is a typical example of code coupling; other cases include coupling of primary system thermal-hydraulics with structural mechanics, fission product chemistry, computational fluid dynamics, nuclear fuel behaviour and containment behaviour. Problems that need to be addressed in the development and use of coupled codes include ensuring adequate computer capacity and efficient coupling procedures, validation of coupled codes and evaluation of uncertainties, and consequently the applicability of coupled codes for safety analyses.

1.2. OBJECTIVE OF THE MEETING

The objective of the meeting was to assess the progress made and identify outstanding issues in the development and use of coupled computer codes in the area of deterministic safety analysis for NPPs.

1.3. SCOPE OF THE MEETING

The coupling of computer codes modelling different engineering disciplines has been implemented in various technical fields. In order to concentrate the discussions, it was decided that the scope of the meeting would focus on the application of coupled codes to accident analysis in NPPs. Participants were requested to give presentations and provide written material on the following topics:

— the present status and future plans for the development and validation of coupled computer codes;
— the lessons learned and results obtained in the application of coupled computer codes to accident analysis for NPPs;
— the benefits and limitations of using coupled codes in comparison with traditional codes.

The presentations addressed the application of coupled codes to accident analysis and the comparison with previously used system codes. In particular, the use of coupled codes in analysis for licensing was of interest. Less emphasis was placed on numerical methods and computer code interfaces, which might be the subject of other specialized meetings. In addition, the scope of the meeting was limited to analyses for design basis accidents and beyond design basis accidents before core degradation. Thirty-three participants from sixteen Member States and two international organizations (IAEA and OECD/NEA) participated in the meeting.

1.4. STRUCTURE OF THIS PUBLICATION

Section 2 lists the papers presented by the participants and provides examples of the applicability of coupled codes. Section 3 summarizes the discussions of the meeting and reviews the following topics: the time needs of code coupling; categorization of coupled codes; status of development; transients to be analysed by coupled codes; example of complex phenomena; application of coupled codes; coupling of various codes; and expectations of the industry and licensing authorities. Section 4 provides the main conclusions of the meeting.

2. RESULTS OF THE MEETING

2.1. PAPERS PRESENTED AT THE MEETING

Altogether 20 papers were presented at the meeting. These were:

(1) Use of Coupled Codes for Best-Estimate Analysis at University of Zagreb
D. Grgić, T. Bajs, S. Spaji, Croatia

(2) The Role of Coupled Codes in Accident Analysis at Paks NPP
J. Elter, Hungary

(3) Simulation of Coupled Phenomena for Advanced Heavy Water Reactor (AHWR): Approaches, Methodologies and Application
H.G. Lele, S.K. Gupta, H.S. Kushawaha, V. Venkat Taj, India

(4) The Status of Development and Use of Coupled Codes for Accident Analysis in Korea
C.S. Jang, Republic of Korea

(5) Standardization of Code Coupling for Integrated Safety Assessment Purposes
R. Herrero, J.M. Izquierdo, M. Sanchez, E. Melendez, Spain

(6) Development of MARS Coupled Code System
W.J. Lee, B.D. Chung, J.J. Jeong, K.D. Kim, Republic of Korea

(7) Current Status of Deterministic Sensitivity Analysis of Coupled Core Physics/Thermal-hydraulics/Heat Structures Codes Systems
D.G. Cacuci, M. Ionescu-Bujor, X. Jin, Germany

(8) Overview of Coupled 3D System Thermalhydraulics Neutron Kinetics Code Applications
A. Bousbia Salah, F. D'Auria, G.M. Galassi,W. Giannotti, A. Lo Nigro, C. Parisi, A. Spadoni, Italy

(9) Simulation of a Power Pulse during Loss of Coolant Accidents in a CANDU 6 Reactor by Coupling the Neutronic Code PUMA and the Thermohydraulic Code CATHENA
P.U. Serrano, A. Parrando, M. Higa, Argentina

(10) Development, Qualification and Application of the Coupled RELAP5/PANTHECOBRA Code Package for Integrated PWR Accident Analysis
J. Zhang, C. Schneidisch, Belgium

(11) Analysis of the OECD MSLB Benchmark Using the Coupled 3-D Neutronics and Thermal-hydraulics Code SKETCH-INS/TRAC-P
T. Nakajima, A. Kanda, F. Kasahrara, Japan

(12) Neutronic and Thermal-hydraulic Modeling of HTR-10 via VSOP Code
S. Köse, I. Kilic, Turkey

(13) Capability of the Coupled Code System ATHLET-QUABOX/CUBBOX for Safety Analysis
S. Langenbuch, Germany

(14) Development of Combined Complex DKM for Calculation of Local Parameters in WWER Core Considering 3-D Kinetics
G.V. Alekhin, Yu.V. Belyaev, S.I. Zaitsev, M.A. Bykov, Yu.N. Nadinsky, O.V. Kudryavtsev, Russian Federation

(15) Results and Experience from the Analysis of the OECD PWR MSLB and BWR TT Benchmarks by the Coupled Code System ATHLET-QUABOX/CUBBOX
K. Velkov, Germany

(16) The SIMMER-III and SIMMER-IV Code Family: 2-D and 3-D Mechanistic Simulation Tools for Reactor Transients and Accidents
W. Maschek, A. Rineiski, T. Suzuki, X. Chen, Mg. Mori, S. Wang, Y. Tobita, Sa. Kondo, H. Yamano, S. Fujita, T. Cadiou, P. Coste, presented by A. Rineiski, Germany

(17) Fuel Performance during a LBLOCA in Angra 1 Nuclear Power Plant
G. Sabundjian, T.N. Conti, C.J. Morandini, D.A. de Andrade, Brazil

(18) PTS Procedure, Analysis and Results by Coupled Thermalhydraulic, CFD and Structure Mechanics Codes
D. Araneo, M. Beghini, F. D'Auria, B. Di Maro, D. Mazzini, C. Sollima, Italy

(19) Qualification and Application of Coupled Primary System and Containment Nodalisation
F. D'Auria, G.M. Galassi, W. Giannotti, A. Petruzzi, K. Moussavian, F. Pierro, A. Lo Nigro, N. Muellner, Italy

(20) Fluid Structure Interaction Analysis by FLAVOR Code with Coupling of Single-phase Flow and Structural Vibration
M. Naitoh, Japan

The papers are provided on the CD-ROM included with this report.

2.2. TYPICAL RESULTS OBTAINED FROM COUPLED CODES

One of the main objectives of coupling computer codes is to model the interactions and hence the feedback effect of the different physical phenomena during the course of the simulated accident analysis. The following papers showed the results of analyses for this objective:

— The effectiveness of coupled codes was demonstrated in the analysis of very complex phenomena expected during the LOCA at CANDU reactors (Serrano, et al., Paper No. 9);
— The realistic analysis for KRSKO MSLB showed no return to power for HFP calculation (Grgić, et al., Paper No. 1);
— Coupled codes are applied in the steam generator replacement and power up-rate project in Doel 2 (Zhang et al., Paper No. 10).

Taking into account the interactions between the different phenomena would produce a more accurate analysis. Accordingly, the performed analysis would provide a more realistic results and a better understanding of the accident progression. The following papers demonstrated the results of this kind with respect to innovative/advanced reactors:

— Successful results were obtained from a thermal-hydraulic (TH) – containment coupled code for SBLOCA analyses for IRIS plant (Grgic et al., Paper No. 1);
— A coupled code was applied to calculate the steady state core behaviour of a gas cooled reactor (Köse, et al., Paper No. 12);
— Coupled codes were applied to the transients without core disruption for advanced reactors (ADS, SCFR and MSR) (Maschek et al., Paper No. 16).

The coupling is done not only by combining neutronic and thermal-hydraulic codes, but also the thermal-hydraulic code with the codes of various disciplines such as the structural code or the containment code. The following papers illustrated various combinations of code coupling:

— A coupled code between single phase flow and structural vibration was validated by the analyses of tests (Naitoh et al., Paper No. 20);
— The capability of a system thermal-hydraulic code (RELAP5) to calculate coupled transients involving primary system and containment was demonstrated, based upon the comparison with experimental data (Araneo et al., Paper No. 18).

The reduction of the computational time is an important issue when coupling computer codes. A new method to significantly reduce the calculation time was developed and presented at the meeting. In addition, status of the development of advanced methodology of uncertainty assessment was also presented (Cacuci, et al., Paper No. 7).

The validation of the results of coupled codes needs to be carried out by comparison with experimental data and with the results of the other codes. The reports (Nakajima et al., Paper No. 11, Velkov, Paper No. 15) show the results of OECD MSLB benchmark.

3. SUMMARY OF DISCUSSIONS AT THE MEETING

3.1. NEEDS OF CODE COUPLING

3.1.1. Code coupling and code integration

The multi-disciplinary nature of reactor transients and accidents, which include neutronic, thermal-hydraulic, structural and radiological aspects can generally be addressed in two different ways: either by code coupling or code integration. In general, an integrated code means a new code, in which two or more codes are merged and a new structure is created. Therefore, the development of integrated codes requires a relatively long time.

Coupled codes are codes produced by inter-connecting existing codes with clear code boundaries, points of data exchange and with separation of I/O and restart parts and data files. They have been mostly developed for coupling thermal-hydraulics system codes with 3D neutronics or thermal-hydraulic system codes with containment codes.

3.1.2. Benefits of code coupling

The major purposes of the development of coupled code are to be capable of representing the results of interactions between different physical phenomena in more detail. Since the calculation method of each code is not changed, reduction of computational time or necessary computer memory volume is not expected. Nevertheless, many additive benefits are expected as follows:

(1) Since the interface data are easily, automatically and frequently exchanged between codes, the results of calculation would be obtained faster than the combination of individual codes and also be more reliable;
(2) Since the development works are limited to the interface part, the cost and time for development can be minimized;
(3) Since the interface data between each code would be adjusted to meet the specifications (e.g. noding of the system or time increment of calculation) of each code at the development stage, additional assumptions or data averaging and reductions are not required when performing the calculation;
(4) Minimum code V&V works (coupling parts only) are required since in general the well-established codes are coupled. Code users must be careful if each part of the coupled code is well validated;
(5) Those who have the knowledge of the existing codes are not necessary to study the coupled code from the beginning, because the existing knowledge is applicable to the coupled code.

3.2. COUPLED CODES

The coupling of codes is usually done by coupling of a thermal-hydraulic code and other disciplines according to the objective of the coupling. The coupled codes presented at the meeting are grouped to the following three broad groups:

(1) Codes for calculating in further detail the interaction between neutronics and thermal-hydraulics. This includes 3D neutron kinetics/thermal-hydraulic coupled codes which

take into account of the effect on neutronics of 3D moderator conditions (density, boron concentration) and fuel temperature distribution in detail;

(2) Codes for calculating the system behaviour and local behaviour simultaneously. This includes:

- System TH/core TH (subchannel) coupled codes. The boundary conditions of each code are given at the boundaries of core region;
- TH/fuel behaviour coupled code. The boundary conditions of each code are given at the fuel surface;
- TH/CFD coupled code. The boundary conditions of CFD codes are provided by TH codes.

(3) Codes for calculating in further detail the interaction between thermal-hydraulic behaviour and mechanical behaviour. This includes:

- TH/Structure mechanics coupled code (e.g. effect on component vibration characteristics of fluid dynamics).
- Thermal-hydraulic behaviour and containment behaviour simultaneously after LOCA).

3.3. STATUS OF THE DEVELOPMENT OF COUPLED CODES

Table I lists the coupled codes which were discussed at the meeting. Various combinations of coupling have been attempted by many organizations.

Table I. Coupled Codes Discussed at the Meeting

Coupled Code	Function	Organization/Presentation No.(PN)
RELAP5/QUABOX/COBRA RELAP5/PARCS/COBRA	1-D System/3-D Kinetics/Subchannel	U. of Zagreb/PN-1
RELAP5/HT-MOD4	1-D System/3-D rod bundle	BARC/PN-3
RELAP5/PARCS	1-D System/3-D Kinetics	KINS/PN-4
MARS/MASTER/COBRA/ CONTEMPT_CONTAIN/VISA	3-D System/3-D Kinetics/Subchannel/Containment/ GUI	KAERI/PN-6
RELAP5/PANBOX	1-D System/3-D Kinetics	FZK/PN-7
RELAP5-3D/NESTLE RELAP5/PARCS RELAP5/ANSYS RELAP5/TRIO-U	3-D System/3-D Kinetics 1-D System/3-D Kinetics 1-D System/structure-mechanics 1-D System/CFD	U. of Pisa/PN-8,18,19
CATHENA/PUMA	1-D System/3-D Kinetics	NASA/PN-9
RELAP5/PANTHER/COBRA	1-D System/3-D Kinetics/Subchannel	TRACTEBEL/PN-10
TRAC-P/SKETCH-INS	3-D System/3-D Kinetics	JNES/PN-11
VSOP	1-D System/3-D Depletion	TAEA/PN-12
ATHLET-QUABOX/CUJBBOX/BIPR8/DYN3D/KIKO3D	1-D System/3-D Kinetics	GRS/PN-13,15
DKM	1-D System/3-D Kinetics	Gidropress/PN-14
SIMMER-III/IV	3-D Fluid Dynamics/3-D Neutronics/Structure	JNC/FZK/CEA /PN-16
RELAP4/FRAP-T	1-D System/Fuel	IPEN/CNEN/PN-17
FLAVOR	Fluid Dynamics/Structure	NUPEC/PN-20

For qualification of coupled codes, two benchmark problems of OECD/NEA/NRC have been mainly performed, e.g., PWR main steam line break for code-to-code comparison and BWR turbine trip for comparison with measured plant data. It is emphasized that the coupled codes, which simulate the plant behaviour during transients need to be more broadly validated by comparison with the plant data, though it is recognized that available plant transient data will represent only mild transient that will not cover the ranges of application in accident analysis. On the basis of this meeting, it was suggested that the transient data obtained from operating plants should be actively utilized to validate the coupled.

3.4. TRANSIENTS IN LWRs TO BE ANALYSED BY COUPLED CODES

Coupling of computer codes would improve the quality of accident analyses for transients where either a strong or uneven feedback effect exists or different solution domains have to be taken into account.

Typical examples of such transients are:

- Inadvertent control rod withdrawal (uneven feedback);
- Control rod ejection (strong local feedback);
- Start-up of a cold or boron free loop (uneven feedback);
- External asymmetrical boron dilution (uneven feedback);
- Transients with potential for inherent boron dilution (uneven feedback);
- Anticipated transients without scram (uneven feedback);
- Cool-down transients with re-criticality potential (steam or feed lines break (uneven feedback);
- LOCA with strong influence from containment processes (different solution domains);
- Severe accident progression and radioactive material transport in the containment (different solution domains).

3.5. EXAMPLES OF MODELLING OF COMPLEX PHENOMENA WITH THE AID OF COUPLED CODES

Examples of complex phenomena that need to be addressed with the aid of coupled codes are:

(1) In the analysis of main steam line break (MSLB) accident for a PWR, two phenomena that affect the core power transients are identified. One is the break flow from the secondary side that affects the total amount of reactivity feedback, and the other one is the coolant temperature distribution at core inlet and outlet, which would cause the three-dimensional power distribution in the core. Therefore, the treatments of heat removal from the broken loop and thermal mixing in lower RV plenum and core outlet are essential. A more accurate modelling and also validation by tests are required in the MSLB analysis.

(2) In the analysis of loss of coolant accident with TH/containment coupled code, flow reversal through the break may occur when the primary system pressure decreases to the same level as the containment pressure. Since the system codes are not normally able to treat multi-species of gas components, modification of the code models may be required so that they can properly take into account multi-species of gas.

(3) Additional complex phenomena and problems can be encountered when modelling new advanced passive systems. For such calculations, delicate mass, momentum and heat balances control the system behaviour. Therefore, the application of coupled codes may require additional user training or the introduction of special models.

3.6. APPLICATION OF NEUTRONIC/THERMAL-HYDRAULIC COUPLED CODES

3.6.1. Application to non-LWR reactors

For analyses of non-LWR reactor designs, employment of coupled codes (T/H, neutronics, structure, etc.) is of importance due to:

- Possible significant variation of material, temperature, density distributions during the transient;
- Specific design features that may require use of additional complicated models;
- The fact that new reactor designs have not yet been studied extensively and understood in detail, and therefore there is a possibility that some important phenomena may be missed in the early stage of design if simplified calculation models are applied only.

The following are the examples where the analyses of non-LWR reactors by coupled 3D neutron kinetics/TH codes are recommended:

- For CANDU reactors, the asymmetric behaviour caused by LOCA or a single pump failure requires employment of 3D neutron kinetics;
- Advanced Heavy Water Reactors (AHWR) have a large number of parallel channels. These channels have dissimilar thermal hydraulics and physics characteristics. Hence there is a need for coupled 3-D neutron kinetics thermal hydraulics techniques for these reactors;
- For the coupled codes used in the transients and accident analysis of the HTGRs, especially concerning the pebble bed type reactors, the deficiencies arising from both neutronic and thermal-hydraulic standpoints (such as qualification of nuclear cross section data, absence of a core bottom mixture plenum model, passive decay heat removal modelling, etc.) need to be identified. It is necessary that their contributions to the uncertainties in fuel temperatures be determined based on the calculations using coupled codes;
- For innovative reactor designs as Accelerator Driven System (ADS) or Molten Salt systems, coupled systems offer a good basis for extension due to their generality and flexibility. Particular features as dependence of the power shape on subcriticality level in ADS or dependence of the residence time of delayed neutron precursors upon complex flow patterns can be treated in most accurate manner if coupled neutronic/TH models are employed.

On the other hand, non-LWR analyses may and most probably will profit from the expertise and codes developed for LWR. In particular, standard interfaces between different computation modules may facilitate implementation of tools developed for one type of reactors for other designs.

3.6.2. Validation of coupled codes based on NPP data

As discussed in Section 3.3, it is necessary to obtain transient data from operating reactors to qualify the coupled codes. In this section, an attempt for the validation of coupled 3D kinetics and TH codes was carried out against data generated from the operating plants.

In order to implement the analysis, careful treatment is needed as shown below:

- All necessary input data for the NPP are defined and checked;

— NPP input data include design characteristics and experimental data;
— Data from NPP are available also for the comparison with calculations;
— To ensure quality of the data to be used in coupled codes, these data including uncertainties are selected from or confirmed by tests performed at operating NPPs or in test facilities; typical data to be selected or confirmed include thermal-hydraulic characteristics, neutron physics characteristics, coolant mixing characteristics, etc.;
— Both steady state and transient NPP data obtained are used; it is important to compare results of calculation and experiments for such data as fuel burn-up, core power distribution, reactivity feedback, control rod worth, etc.;

The collection of operating plant data has been started in the other project such as:

— The VALCO Projects [1] collected and used NPP data related to WWER440 and WWER1000 that are suitable for assessing coupled neutron kinetics thermal-hydraulic techniques.
— The CRISSUE-S Project [2] collected and used NPP data related to PWR and BWR that are suitable for assessing coupled neutron kinetics thermal-hydraulic techniques.

3.6.3. Uncertainty and sensitivity calculations

The coupled codes have been developed to perform realistic calculations describing fundamental physical processes. The model equations and the numerical procedures contain approximations that compare with the laws of physics. Therefore it is necessary to investigate the uncertainty of the results and the sensitivity on most of the effective parameters. Various methods have been developed to perform quantified uncertainty and sensitivity studies for instance adjoint sensitivity method presented by Cacuci (Paper No. 7) and others UMAE [3] and CIAU [4] used by the University of Pisa and the SUSA method used by GRS [5].

In general it is difficult to apply best-estimate codes for conservative calculation. Tractebel has proposed such a deterministic bounding approach, and has applied successfully to the SLB analysis using best estimate coupled code package (Zhang et al., Paper No. 10). The bounding study of sensitivity and uncertainty was performed in the ANGRA-1 LB LOCA analysis (Sabundian et al., Paper No. 17).

Cacuci et al. (Paper No. 7) have also summarized the current status of the ongoing work devoted to the implementation of the Adjoint Sensitivity Analysis Procedure (ASAP) into the multi-physics code system RELAP5/MOD 3.2. To illustrate the results that can currently be obtained by using the newly developed ASM-REL/TFH coupled adjoint model, time-dependent sensitivities have been presented of the cladding temperatures of the heated rods belonging to the inner ring in the QUENCH-4 experiment.

The two features (i.e. the dimensionally adaptive, automatic switching algorithm and the adjoint sensitivity analysis capability in RELAP5/MOD3.2) have not been coupled to each other yet. Such a coupling would involve augmenting the ASM-REL/TF adjoint system by applying the ASAP to the neutron kinetics model in PANBOX.

3.7. COUPLING OF CODES ON THERMAL-HYDRAULIC/STRUCTURE MECHANICS

3.7.1. Coupling of codes for the analysis of pressurized thermal shock

The reactor pressure vessel is considered one of the components that may limit the extension of the lifetime operation of old plants. Several design criteria (i.e. material toughness, operational conditions, end of life neutron fluence, etc.) allow preventing the possibility of its failure, but the risk of brittle propagation due to pressurized thermal shock (PTS) may threat the integrity of reactor pressure vessel. In recent years, important progresses have been made in the development of methods for the best estimation of loads and stresses on the vessel wall. In order to perform the PTS analysis in detail, three different phases are taken:

- The thermal-hydraulic analysis of the entire plant in order to define the boundary conditions for the analysis of next step (system thermal-hydraulic (TH-SYS) code);
- The detailed analysis of the downcomer fluid flow (CFD code);
- The evaluation of the total stresses in the RPV (structure mechanics (SM) code).

The proposed procedure (Di Maro et al., Paper No. 18) makes use of specialized codes to obtain a great accuracy in the phenomena prediction, employing assessed numerical models for each of them. On the contrary, a right coupling technique has to be employed in order to minimize the numerical error in the data transfer between the codes. The conclusions are:

- The sophistication of the TH-SYS and SM tools is sufficient;
- The CFD qualification is necessary especially in heat transfer between the fluid and the vessel wall;
- Weight Function technique allows performing fracture mechanics (FM) parametric analyses in the limit of its validity;
- Although the coupling of the tools has been made, qualification is needed.

3.7.2. Coupling of codes for the analysis of fluid-structure interaction

Some operating nuclear power plants had experienced troubles due to structural damages caused by flow-induced vibration (FIV). It is essential to clarify the causes and to establish countermeasures timely order to avoid prolonged plant shutdown. A fluid-structure interaction analysis code must be a good tool for design, clarification of the cause of trouble and establishment of the countermeasures against the flow induced vibration. The FLAVOR code (Naito, Paper No. 20), a coupled code of fluid flow analysis and structure displacement analysis, was presented at the meeting.

A computational fluid dynamics (CFD) code and a structure displacement analysis code were coupled by the Message Passing Interface (MPI), which is a standard library to send and receive messages between processors, and integrated into a single code “FLAVOR”. A moving boundary was taken into account in the fluid flow analysis by the Arbitrary Lagrangian Eulerlian (ALE) method. The FLAVOR runs on a parallel computer and a workstation with plural processors. The results obtained using structural-TH coupled code are as follows:

- The pressure loads on structure surface were analysed by the 3-D load analysis module;
- The fluid-structure interactions in a single-phase cross flow were analysed using the 2-D cross flow module;

— Test results for the “lock-in” phenomena and single tube FIV were well reproduced by the analysis.
— It was shown that FLAVOR was capable to calculate pressure load on a core barrel of PWR and stress on the in-core monitor housing in the lower plenum of ABWR as examples.

3.8. INDUSTRY AND LICENSING AUTHORITIES EXPECTATIONS FROM THE USE OF COUPLED TECHNIQUES

The benefits associated with the development and the use of coupled codes have been discussed in Section 3.1.2. It is expected that these benefits can contribute to the improvement of activities carried out by both licensing authorities and industries.

Expectations for licensing authorities can mainly be derived from the features of coupled codes such as more accurate calculation than the combination of individual codes. These are summarized as follows:

— Improvement of the understanding of the phenomena of interest for safety;
— Better assessment/demonstration of the conservatisms (versus historical approaches such as the use of point kinetics or evaluation models);
— Extension of the capabilities of the codes for safety analysis and training/simulators;
— Better assessment of uncertainties associated with the use of best estimate coupled codes.

Many benefits are expected with the use of coupled codes for industries. These are:

— Faster turnaround of calculation allows the users to perform more precise analysis and more sensitivity or case studies. This would contribute in more detail to understand the features of the plant, systems or components.
— More accurate calculation would contribute to remove unnecessary uncertainties and to identify margins available to use for sophistication of the plant;
— Uncertainties due to user effects would be minimized because the existing knowledge of individual codes is applicable to the coupled codes.

It is requested to use qualified codes in licensing calculations. Nevertheless, for coupled codes, it is usually not so easy to qualify the codes using data from operating plants, because very limited transient data, which can be obtained from operating plants are available. To reduce the effort for the qualification of the coupled codes, code developers are requested to use only validated revisions of codes. In addition, the code developers are requested to:

— Design the coupling so that auditing is easy and feasible;
— Provide guidelines to minimize user effects;
— Allow provisions for reasonable conservatisms;
— Structure the code so that coupling is easy and feasible;
— Standardize the coupling procedures;
— Integrate as much as possible the existing approved calculation methodologies.

3.9. SUMMARY OF THE MEETING

On the basis of the 20 presentations and discussions at the meeting, the following main points were made:

- Coupled codes are applied for the analyses of complex phenomena where the strong feedbacks between different disciplines are expected.
- The major benefit of code coupling is the increased capability of performing more realistic and detailed calculations with a minimum of work for further code development.
- The application of coupled codes in licensing is expected to improve the reliability of licensing. Some expectations and recommendations for both licensing authorities and industries were summarized.
- The coupled codes discussed at the meeting were grouped into 3 groups:
  - To calculate in more detail the interaction between neutronics and thermal-hydraulics;
  - To calculate the system and local behaviours simultaneously;
  - To calculate in more detail the interaction between thermal-hydraulics and other disciplines.
- The validations of coupled codes are carried out based on comparison between codes. It is desirable to obtain transient data from operating plants for the qualification of coupled codes.
- Coupled codes are applied to confirm the existence of safety margin in the operating plants.
- Coupled codes are used to predict the realistic phenomena in innovative or advanced reactors.
- Examples where analyses by coupled codes are desirable were summarized for the application to both LWRs and non-LWRs.
- Development of coupled codes is in progress not only in the area of neutronics/thermal-hydraulics but also for combining thermal-hydraulics and various other disciplines such as containment and structure mechanics.
- The needs for the development of thermal-hydraulic/structure mechanics codes were discussed. The results of thermal-hydraulic/structure displacement coupled code showed a good agreement with the results of the experiment.
- The implementation of an efficient method of calculation, such as ASAP, would represent a positive step towards a comprehensive analysis of transients.

4. CONCLUSIONS

It was confirmed that taking into account the interactions between the different physical phenomena by coupling computer codes represents a very useful tool for safety analysis of existing and new reactor design. The use of coupled codes has expanded not only to the area of neutronics/thermal-hydraulics but also to thermal-hydraulics and other disciplines. It is expected the wide variety of code coupling including more than 3 codes will be achieved with the advancement of calculation methods and with the increase of computer capacity.

The coupled code can reduce the uncertainties associated with the code interface and improve calculation turnaround with minimum efforts for code development and V&V. The coupled code is efficient when it is applied to calculate the complex phenomena such as 3D phenomena in core. It was also shown that the coupled codes were useful tools for the development of future reactors.

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ABBREVIATIONS

ADS	Accelerator Driven System
AHWR	Advanced Heavy Water Reactor
ASAP	Adjoint Sensitivity Analysis Procedure
ALE	Arbitrary Lagrangian Eulerlian
BWR	Boiling Water Reactor
CFD	Computerized Fluid Dynamics
CIAU	Code with Internal Assessment of Uncertainty
FIV	Flow Induced Vibration
FM	Fracture Mechanics
HFP	Hot Full Power
HTGR	High Temperature Gas Reactor
IRIS	International Reactor Innovative and Secure
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MPI	Message Passing Interface
MSLB	Main Steamline Break
NPP	Nuclear Power Plant
PN	Presentation Number
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
SBLOCA	Small Break Loss of Coolant Accident
SUSA	Software System for Uncertainty and Sensitivity Analysis
TH	Thermal-Hydraulic
TH-SYS	System Thermal-Hydraulic
UMAE	Uncertainty Methodology based on the Accuracy Extrapolation
V&V	Verification and Validation
WWER	Water Cooled and Water Moderated Power Reactor

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