Project Report

Deterministic Safety Technology for RBMK Reactors

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The present paper deals with the description of the technical activities conducted within the TACIS Project R2.03/97, 2 EC Contract no. 30303, related to RBMK. The project activities are focused toward the setting-up of a chain of computational tools suitable for the analysis of transients expected in the RBMK nuclear power plant (NPP). The accident leading to the rupture of one pressure channel, with fuel melting or high temperature damage, creep and brittle failure of the pressure tube and of graphite bricks with possibility of rupture propagation, constitutes the reference scenario for the project. However, a series of expected scenarios has been selected to prove the capability of the individual codes or chains of code in simulating the envisaged phenomenology. The paper summarizes the activities performed at NIKIET in Moscow and at University of Pisa (UNIPi) in Pisa. A top-down approach is pursued in structuring the executive summary that includes the following sections: (i) the safety needed for the RBMK NPP, (ii) the roadmap, (iii) the adopted computational tools, (iv) key findings, (v) Emphasis is given to the multiple pressure tube rupture (MPTR) issue and the individual channel monitoring (ICM) proposal.

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1. INTRODUCTION

The present paper deals with the description of the technical activities conducted within the TACIS Project R2.03/97, EC Contract no. 30303, related to RBMK [1]. The project activities are focused toward the setting-up of a chain of computational tools suitable for the analysis of transients expected in the RBMK nuclear power plant (NPP). The accident leading to the rupture of one pressure channel, with fuel melting or high temperature damage, creep and brittle failure of the pressure tube and of graphite bricks with possibility of rupture propagation, constitutes the reference scenario for the project. However, a series of expected scenarios has been selected to prove the capability of the individual codes or chains of code in simulating the envisaged phenomenology.

The result of 30 man-years effort is summarized hereafter including activities performed at NIKIET in Moscow and at University of Pisa (UNIPi) in Pisa. A top-down approach is pursued in structuring the executive summary that includes the following sections.

- (i) The safety needed for the RBMK NPP is described first: this includes the overview from the starting

tasks and the key findings from the execution of the project.

- (ii) The roadmap is discussed that gives an idea of the interdisciplinary nature of the project and of the related complexity.
- (iii) The adopted computational tools are presented in the third paragraph including codes and input decks or nodalization. In this section, the transient scenarios established for proving the validity of the code and code chains are discussed.
- (iv) Key findings are presented per each logical block of activities planned within the roadmap.
- (v) Emphasis is given to the multiple pressure tube rupture (MPTR) issue and the individual channel monitoring (ICM) proposal.

2. RBMK SAFETY NEEDS, STATUS, AND KEY CONCLUSION ABOUT SAFETY

RBMK safety technologists in Russia are well aware of safety needs and their expertise took benefit by international cooperation involving EC, US DOE, and IAEA in the last

twenty years. The state-of-the-art in the area has been summarized and was used to identify the priorities of the project and to orient the conduct of activities. The RBMK safety technology was found as well as established and no remarkable deficiency could be identified from the review process. However, related to the development and the improvement of computational tools, systematic procedures are described that brought to the characterization of priority areas, where further efforts from the research side can be concentrated. Examples of this, related to the KORSAR code (see below), are the modeling of headers and of pump performance as well as the need for a three-dimensional thermalhydraulic model.

The main difference from the safety standpoint, primarily in the domain of deterministic analyses, between RBMK and other water-cooled reactor lies in the allowance in the case of RBMK, for even limited amount of molten fuel within design basis conditions (design basis accident (DBA)), to break the safety barrier constituted by the primary circuit pressure boundary. In facts, the rupture of fuel channel caused by fuel overheating is part of DBA. This implies contamination of parts of the confinement system, but no real harm for the environment where estimated releases are not expected to overpass the thresholds applicable to other water-cooled reactors. The following additional notes apply.

- (i) The potentially involved core inventory is less than 0.1% of the total inventory.
- (ii) The radioactivity is expected to remain primarily in the reactor cavity with minor contamination of the accident localization system and basically no contamination for the environment.
- (iii) Notwithstanding the above, the expected breaking of the pressure barrier that already occurred in the events Leningrad NPP 1 and 3 (1975 and 1992) and Chernobyl NPP 1 (1982) might be considered (by the public or by the regulatory authorities) as a lack of capability of controlling the system.
- (iv) The individual channel monitoring (ICM) proposal and the possible implementation of the system, see below, might substantially contribute in preventing the possibility of the pressure tube rupture event.

The deterministic analyses performed within the project did not show weak areas from the safety viewpoint or situations that can harm the public or the environment to an extent different from other NPP types (it was not the purpose of the project to evaluate the RBMK safety, however that is the results of the wide range of performed calculations). Nevertheless, computational tools are the outcome of the project that can be used to assess the above conclusion and the ICM proposal has been formulated in the attempt to improve the safety (see also below).

3. THE ROADMAP OF THE PROJECT

The roadmap of the project has been finalized based on two main steps that consisted in the setting-up of (a) two

matrices, where the computational tools are related to the safety barriers, the materials and components of the RBMK NPP and the technological areas, Figure 1, (b) the flow diagram of activities that starting from the assigned NPP and accident scenarios goes through the technological subjects and ends to the deliverables and products of the project.

Matrices of activities

Two matrices have been developed for codes adopted by NIKIET and by UNIPI, respectively. Three topological subjects, relevant to the nuclear technology, were distinguished in each matrix:

- (i) five barriers (5Bs) to the release of fission products to the environment, not necessarily in series: pellet, clad, pressure boundary, reactor cavity, ALS, and (various) reactor buildings,
- (ii) sixteen RBMK system (16S) hardware or material parts: UO₂ pellets, gas fuel gap, Zr-Nb clad, fuel assembly, coolant in power channel (high pressure) and in CPS (low pressure), Zr-Nb pressure tube, control rod absorber and displacer tube, graphite of power channels and of reflector, gas gaps inside graphite, main circulation circuit, reactor cavity, accident localization system and (various) reactor buildings, and source term,
- (iii) seven nuclear technology (7T) sectors or computational areas relevant for NPP safety and design: system thermalhydraulics in main circulation circuit (including fuel cooling) and in confinement, application of CFD, structural mechanics including fuel behavior, three-dimensional neutron kinetics, generation of cross-sections, and fission product release and transport.

Nine and eight codes, 9C and 8C, were selected by NIKIET and UNIPI, respectively.

Diagram of activities

The first level of the diagram (not given here) is constituted by the objective and the boundary conditions. The second level of the diagram is constituted by the disciplines and the related activities. The third level of the diagram is constituted by the main outcomes from the project.

4. THE COMPUTATIONAL TOOLS AND THE ESTABLISHED SCENARIOS FOR PROVING CODE CAPABILITIES

The correspondence between the seven nuclear technology (7T) sectors and the codes adopted by UNIPI and NIKIET constituted the background for identifying the classes of accidents and the challenging phenomena to prove the capabilities of the codes. The classes of accidents, the selected transient scenarios, nine (i.e., 9 TS), and the adopted codes are given in Table 1.

FIGURE 1: Connection between topological subjects in nuclear technology and codes adopted for the conduct of the project by NIKIET.

TABLE 1: Transient scenarios relevant to RBMK safety and design that are reference for the project and correspondence with adopted code or chain of codes.

Class no.	Identification	Codes ⁺	Reference accidents for the RBMK accident analysis
A	ESF & ECCS design	KORSAR RELAP5	A1 LOCA-PH-FIGDH A2 LOCA-SL A3 LOOP-ATWS A4 GDH-BLOCKAGE
B	Confinement (RC, ALS, and RB)	KORSAR, COCOSYS CONTAIN, RELAP5	B1 GDH-BLOCKAGE-SA B2 LOCA-PH-FIGDH B3 LOCA-SL
C	3D NK-TH*	UNK, BARS, KORSAR HELIOS, RELAP5-3D, NESTLE	C1 FC-BLOCKAGE C2 GDH-BLOCKAGE C3 CR-G-WITHDRAWAL C4 CPS-LOCA
D	PT rupture and MPTR	RAPTA, STAR-CD, KATRAN, U-STAK FRAP, FLUENT, RELAPS, ANSYS	D1 FC-BLOCKAGE D2 FC-LOCA
E	FP generation and transport	VICTORIA, COCOSYS MELCOR	E1 FC-BLOCKAGE E2 GDH-BLOCKAGE-SA
F	ICM proposal	RELAP5	F1 FC-BLOCKAGE

⁺The codes used at NIKIET are reported in bold characters.

*The coupled 3D NK-TH codes require derivation of proper cross-sections (or functions). The codes needed for this are also listed.

FIGURE 2: Evolution of the RBMK FC blockage event.

5. KEY FINDINGS WITHIN THE IDENTIFIED SAFETY TECHNOLOGICAL SECTORS

Reference is made to the seven safety technological (7T) sectors and to the results from the application of codes and chain of codes to the identified accident scenarios. The capability of calculating reference scenarios was shown in all cases.

Thermalhydraulics in primary cooling circuit

Relap (primarily) and Korsar codes were found capable of simulating RBMK transient scenarios. No severe limitation was found that prevents the application of those codes. Typical results from the “scoping” accident analysis can be summarized as follows.

- (i) Instabilities in parallel channels may originate critical heat flux and consequent rod surface temperature excursions during the operation of the emergency core cooling system- (ECCS-) bypass lines.
- (ii) As a consequence of the group distribution header blockage and after the break of one or a few pressure tubes, flow reversal may be sufficient to cool the remaining channels keeping them intact. However, this result appears a function of the adopted calculation hypotheses including channel grouping and initial thermalhydraulic conditions.
- (iii) The comparison between system performance in Ignalina and Smolensk NPP shows that innovations introduced in Ignalina NPP in the recent past create the conditions for substantial improvements in system dynamic response.

The best estimate analysis of the RBMK primary circuit requires a huge modeling and related qualification efforts.

Thermalhydraulics in confinement

The passive function of mitigating the radioactivity release to the environment following the occurrence of a hypothetical accident in RBMK is performed by a number of buildings among which the reactor cavity and the accident localization system (ALS) constitute the important ones. Suitable pressure resistance characteristics is part of the design of reactor cavity and ALS.

Application of CFD

Two main applications were completed within the framework of the project by NIKIET and UNIP, respectively. The former focused on the modeling of a valve located in the inlet region of the fuel channel. It was found that leakage steam superheating, due to pressure drop in the flow reversal with the valve in the close conditions, could be a trigger event for the Chernobyl 4 accident. The latter application focused on determining the hydraulic loads of fuel rods following the break of the pressure tube.

Structural mechanics including fuel behavior

Clad ballooning was found as the most important mechanism for rod damage in the case of loss of coolant accident from any channel. A damage map for fuel rods derived in the plane initial/nominal bundle power versus percentage of channel blockage was derived. In the case of flow blockage, significant events are summarized in Figure 2.

The graphite rings and the bricks have been modeled by finite elements together with the pressure tube to calculate failure conditions. The important role of graphite rings has been found together with the expected high influence of the radiation damage (fluence) upon the conditions for graphite brick failure.

FIGURE 3: Results from calculating mechanical loads on neighboring channels due to the rupture of an assigned pressure tube.

Three-dimensional neutron kinetics

A pioneering effort has been made in relation to the application of the coupled Korsar-Bars to the RBMK safety technology. Bars, allowing the 3D representation of the RBMK core uses a special approach based on the derivation of suitable “ λ -functions” to calculate the local system performance. The codes capability, in predicting overall system response following local perturbations like the control (and) protection system (CPS) emptying or the withdrawal of an individual control rod, was demonstrated.

Generation of cross-sections

The Helios and the Unk codes were adopted to calculate the macroscopic cross-sections or the “ λ -functions,” respectively.

Fission product release and transport

The technological area of fission product generation, release and transport in RBMK, including the deposition in various surface does not present special features compared with the same area in LWR.

5.1. The MPTR issue and the ICM proposal

The MPTR issue

A methodology was proposed for investigating the realism in the propagation of one pressure tube break to neighboring pressure tubes, that is, addressing the MPTR issue. Significant results can be derived from Figure 3.

The study emphasized the importance of

- (i) modeling the RBMK core channels one-by-one (i.e., the difficulty to identify symmetry conditions),

ICM instrumentation:
TC at FC outlet,
flow-meter at FC inlet

Ranges for ICM instrumentation:
Temperature: (300–650) K
Flow: (10–200) %Gnom
Response time: < 1 s for
the entire measure ranges
(both cases)

ICM scram signal:
Simultaneous occurrence
of high temperature
and low flow at FC
outlet and inlet,
respectively

ICM scram set-points:
TC value > ($T_{sat} + 10$ K),
flow value < (Gnom
– 30%)

ICM scram delay:
2.2 s following scram
signal generation

FIGURE 4: The ICM and the predicted working modalities.

namely, considering the geometric position within the array, the material composition, the initial stack temperature, and the fluence,

- (ii) the stiffness of the tank that constitutes the ultimate constraint preventing excessive channel deformation, again depending upon the position of the channel in the core.

As a key conclusion (the generic warning about the applicability of the current results to safety evaluation of RBMK scenarios will be considered), it was found that only a limited number of channels in the periphery of the core are prone to cause the propagation of the fuel channel rupture.

The ICM proposal

The RBMK safety issue connected with the hydraulic blockage (i.e., loss of cooling) of one core channel has been deeply considered within the project. Notwithstanding the recent evidence that the risk of propagation of one channel rupture to a multiple pressure tube rupture is negligible, the break of one pressure tube causes (a) a cost for the NPP associated with stop of electricity production for cleaning and structural controls (several weeks), (b) radiation doses to

personnel (unquantified), and (c) a “residual risk” for MPTR (unquantified) and, as already mentioned, a critical subject for public acceptance and for regulatory bodies.

The individual channel monitoring (ICM) system has the capability to prevent the pressure tube rupture following the channel blockage. The system generates a devoted scram signal from simultaneous occurrences of low flow and high coolant temperature at FC inlet and outlet, respectively. The performed thermalhydraulic analyses demonstrate that scram can be actuated early enough to prevent the PT rupture. See also [2–7].

REFERENCES

- [1] F. D’Auria, S. Soloviev, O. Novoselsky, et al., “Deterministic Safety Technology in RBMK,” University of Pisa, Pisa, Italy, 2005.
- [2] F. D’Auria, B. Gabaraev, V. Radkevitch, et al., “Thermal-hydraulic performance of primary system of RBMK in case of accidents,” *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 904–924, 2008.
- [3] F. D’Auria, O. Novoselsky, V. Safonov, et al., “Thermal-hydraulic performance of confinement system of RBMK in case of accidents,” *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 925–939, 2008.

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- [4] F. D'Auria, B. Gabaraev, S. Soloviev, et al., "Deterministic accident analysis for RBMK," *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 975–1001, 2008.
 - [5] F. D'Auria, S. Soloviev, V. Malofeev, K. Ivanov, and C. Parisi, "The three-dimensional neutron kinetics coupled with thermal-hydraulics in RBMK accident analysis," *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 1002–1025, 2008.
 - [6] F. D'Auria, B. Gabaraev, O. Novoselsky, et al., "The multiple pressure tube rupture (MPTR) issue in RBMK safety technology," *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 1026–1061, 2008.
 - [7] F. D'Auria, M. Cherubini, F. Pierro, and W. Giannotti, "The individual channel monitoring (ICM) proposal to improve the safety performance of RBMK," *Nuclear Engineering and Design*, vol. 238, no. 4, pp. 1062–1079, 2008.