

EFFECTIVENESS OF CORE EXIT THERMOCOUPLE (CET) INDICATION IN ACCIDENT MANAGEMENT OF LIGHT WATER REACTORS

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Abstract

The working group on Analysis and Management of Accidents (WGAMA) of the Committee on the Safety of Nuclear Installations (CSNI) of OECD-NEA had a task on the effectiveness of CET indication in accident management (AM) of light water reactors (LWR). The task collected and reviewed the design basis of CET application for AM procedures through a survey of the CET use in the NEA member countries, and reviewed pertinent experimental results from such test facilities as LOFT, ROSA/LSTF, PKL and PSB-VVER focusing on the time delay in CET from core temperature rise. Scaling issues were discussed considering extrapolation of experimental results to LWR. This paper summarizes major outcomes of the task and indicates possible future work.

1. Introduction

The CET indication plays an important role for initiating the AM measures. The safety concern is that such measures could be so delayed that recovery actions would be less effective.

Historically, the idea of using CET for AM emerged after the TMI-2 accident. The TMI-2 reactor had been equipped with CETs, but the CETs were not used or tested during the accident. This accident triggered a number of actions from the regulatory side. The USNRC developed an action plan to implement the lessons learned [1], and determined that an instrumentation system for detection of inadequate core cooling (ICC) consisting of upgraded subcooling margin monitors, CETs, and a reactor coolant inventory tracking system is required for PWRs [2]. A regulatory guide [3] was developed further to define the requirements on the ICC conditions with a detailed list of required instrumentation that in fact became a standard and a basis for backfitting existing plants.

The issue was relaunched, when the Test 6-1 performed in the OECD ROSA/LSTF project simulating a PWR vessel head small break loss-of-coolant accident (SBLOCA) had to be terminated prematurely in order to avoid excessive overheating of the core. The test results showed that the core uncover had started well before the CET detected superheating and that the temperature increase rate was significantly higher in the core than at the CET. The results suggested that the response of CET could be inadequate to initiate the relevant AM actions [4].

Four LOFT experiments [5] have been analyzed further. They confirm that there may be scenarios in which CET indications would be inadequate to initiate the corresponding AM actions. Moreover, examples of CET response compiled from data obtained earlier in BETHSY, LSTF, PKL and PSB-VVER facilities seem to confirm this observation.

Possible reasons and hypothesis to explain this observation have been proposed; they are mainly related to a possible cooling of the CETs by steam generators reflux water, persistence of liquid film on the CET surface combined with low steam velocities, or thermodynamic non-equilibrium between steam and water droplets.

In order to address the CET reliability and effectiveness in AM and the main physical phenomena that may explain CET indication, the WGAMA proposed late 2007 an activity which was approved by the OECD-NEA CSNI with the objective to prepare a status report covering the following items:

- collection and review of the design basis of CET application for AM procedures in different countries;
- review of pertinent experimental results focusing on delay times between CET and core temperature rise;
- conclusions and recommendations for further work, if needed.

The present paper summarizes the WGAMA activity on CET effectiveness in AM which was completed in June 2010 and highlights the main conclusions and recommendations drawn-up from that activity.

2. Role and Current Way of Use of CET

2.1 General use of CET

One of the important activities of the WGAMA was to gather information on how the CET indication is used within AM Programs. It should be noted that the scope of the WGAMA includes use of CET during response to an accident or incident, in the context of plant stabilisation and recovery (management of an accident situation). It includes both “preventive” AM (normally, the response to an event in which core damage has not occurred), and “mitigative” AM (response to “severe accidents” – those in which core/fuel damage has occurred). The investigation does not include the use of CET during normal operation.

Information was gathered by use of a questionnaire. Seventeen responses representing thirteen different countries were received. To assess the general use of CET in different countries, participants were asked whether CETs are used for AM in their country, and if so,

for which purposes. Considering all the responses, the following areas of use of CET within accident management were identified by the participants:

- The CET is used within Emergency Operating Procedures (EOPs) (i.e. within the preventive AM regime, before core damage has occurred). All responses indicated that this is the case in their country.
- The CET is used as the primary indication to initiate the transition from EOPs to Severe Accident Management Guidance (SAMG) (i.e., the transition from preventive to mitigative AM). 12 of the 13 countries represented responded that this is the case in their country.
- The CET is used within SAMG (i.e. within the mitigative AM regime, after core damage has occurred) in order to cue certain checks and/or actions. This is the case in 9 of the 13 countries.
- The CET is used as one of the inputs to categorise an emergency (assign an Emergency Action Level or EAL) by emergency planning staff. This was the case for 4 countries,
- The CET is used as one of the inputs used to perform a Core Damage Assessment or CDA by Emergency Planning staff. (This is an evaluation of the degree of core damage which may be used as an input to the source term used to identify appropriate off-site protective actions (PAs)). This was the case for 2 countries.

Regarding the last two points, which relate to the use of CET within the Emergency Plan, the information was volunteered, and so it is not possible to conclude that this is not done in the other nine participating countries. Use of CET in the Emergency Plan is not discussed since it is outside the scope of this investigation.

2.2 Specific usage of CET and Setpoint Basis

The survey also collected information on the more detailed usage of CETs and in particular the basis and values of set-points used.

From the responses received, a summary of the basis for EOPs and SAMGs in the different countries was made, and also of the detailed uses of the CET, which are presented in the main report.

The basis for EOP and SAMG packages in use in participating countries fell into two main classes:

- a plant or design specific basis, or
- a package based on a vendor or owners group generic approach which has been adapted to the specific plant.

Detailed uses of the CET within these EOP and SAMG packages identified by the responding participants were:

- to quantify subcooling margin,
- to detect loss of subcooling margin (or, onset of saturation conditions),
- to detect onset of superheated conditions (temperature rising above saturation temperature at prevailing pressure),
- to quantify amount of superheat (or, detecting that superheat has exceeded a certain

value),

- to determine that core has been successfully re-covered (reflooded) and cooled following an event in which core damage has occurred.

It should be noted that not all participants use CETs for all these functions.

3. Possible Issues with CET

3.1 Relation between CET readings and PCT

While it is generally accepted that the CET do not provide a direct measurement of the parameter of interest (the highest cladding temperature, since this affects geometry, coolability and oxidation/hydrogen generation concerns), it is also generally the case that the CET provide the “most direct” measurement of fuel temperature status. Of interest is how (or if) the relation between actual cladding temperature and core fluid channel exit temperature is addressed in the accident management procedures, and in case this is investigated via analyses (simulations) how this is done and to what extent the models used are validated.

The questionnaire addressed these issues, and the responses revealed a wide range of approaches. At one end, using a thoroughly validated model to calculate set-points, or applying suitably conservatively estimated margins to the nominal set-point value appear to be the techniques which address the CET issue the most in current AM approaches. At the other, some approaches do not consider specifically the performance of the CET, or provide simple warnings within the guidance.

Some approaches do not attempt to identify any narrow range of core conditions, but simply try to detect a “gross” loss of core cooling. This response indicated that in some approaches, response actions could be adequately taken over a wide range of degraded conditions.

Answers to questions regarding modelling and calculations of CET response indicated that the CET issue is of importance, since a significant fraction of respondents indicated that calculations are performed. However, it is also notable that only two organisations felt that the associated models were adequately validated. Results of calculations presented at working group meetings clearly indicate the sensitivity of the results, and particularly the timing, to the modelling assumptions.

3.2 Technical basis for CET set-points

Detailed uses of the CET within EOP and SAMG packages which were identified by the responding participants were listed above, and a further activity of the working group was to consider each of these, and provide a discussion, together with examples, of the technical basis used to calculate the set-point values. Space does not permit this review to be presented here, but reference is made to the main Working Group report [6].

Many set-point technical bases are developed by the reactor vendor as part of a generic AM package. The plant specific values of the set-points are then adapted for the specific plant application during an AM implementation phase. (An additional conservatism is sometimes added during this phase as a utility checks uncertainties in its specific parameters / instrumentation against the vendor's generic values but usually does not change the vendor's values).

3.3 Specific issues with using CET in AM

The survey asked participants if there were any aspects of using CET in AM procedures which raised any specific issues and what these were. Concerns fell into the following categories:

“*No concern*”: the organisation has no specific concern with the use of CET in AM, or a concern exists but was resolved by use of appropriate guidance (for example, not using CET above temperature at which their survivability/reliability is doubtful). There were 8 such responses from a total of 23 for this issue.

“*Survivability*”: CETs are used, but there is a concern over the survivability of the thermocouples in a severe accident environment. 4 responses identified this as a concern.

“*Accuracy*”: The accuracy of thermocouples is known to decrease as temperature increases, and within harsh environments. These respondents felt that more should be understood about this aspect. 4 responses identified this as a concern.

“*Delayed response / representativeness*”: The concern is that either the thermocouples respond with a certain delay compared with the heatup rate in the core during a severe accident, potentially leading to late diagnosis or decision to take actions, and/or, that the thermocouple readings do not represent adequately the conditions in the core which are required to be known. 4 responses identified this as a concern.

“*Reliability, availability, power supply*”: Responses essentially related to concerns over the availability of the instrumentation are grouped under this heading. 3 responses identified this as a concern.

Qualification of CET instrumentation was not mentioned in responses, though survivability is clearly an issue for some. This may be because most responses concerned existing plants where (in general) no equipment is qualified for severe accident conditions.

3.4 Ideal development of AM procedure set-points

In order to assure that the AM measure selected for the given situation be successful the developer has to select a method to define an appropriate set-point for initiating the action. If the cladding temperature was directly measurable, it would be relatively easy to select a set-point, such that the time taken to initiate the action plus the time taken for the action to have the desired effect, are allowed for. An example is primary system depressurisation, where the time allowance would be based on (a) the time needed to perform the action to open the pressuriser valves, plus (b) the time taken for the system to depressurise to a particular pressure allowing primary injection to occur, plus (c) the time required for the injection to be effective in arresting the clad temperature increase. This total time allowance would then be combined with an expected cladding heatup rate to obtain the temperature margin.

However, since the cladding temperature is not known directly, and must be inferred from CET readings, this introduces a further “allowance” into the set-point - so it should be reduced further to account for all the known contributors to the difference between indicated CET and true clad temperatures. One of the contributors to this additional allowance will be due to the fact that core exit fluid temperature will always be less than highest clad temperature – for physical reasons. This contributing factor is caused by physical reasons that are understood and can in principle be modelled – so the AM developer should take it into

account. Another contributor may be due to instrumentation accuracy/bias concerns which need to be addressed. Finally, there are apparently some mechanisms which lead to a delayed response and, if the temperature is increasing, we obtain an under-prediction (at any given time) due to this response delay.

So, ideally, the AM developer should calculate his set-point by applying margin to cover each of these identified effects. In order to better understand the nature of the allowances, the group investigated experimental results focusing on the differences between core cladding temperatures and CET signals, as described in following sections.

4. Review of CET Performance Found in Experiments

4.1 Background and history

A review was made of pertinent experimental results focusing on discrepancies between CET readings and core temperature measurements during conditions that can be addressed by AM. Beyond the collection of experimental data showing significant core superheat from different integral-effect test (IET) facilities the focus was also to supply physical explanation on the CET response by reviewing the physical phenomena playing an important role. Obviously, location of CETs may be very different in test facilities as compared to plants and the scaling ratio of the facilities may lead to distortions: these effects have to be assessed as well. After screening the availability of experimental data, LOFT, ROSA/LSTF, PKL have been selected to review the results in detail.

A CL SBLOCA experiment at the Russian test facility PSB-VVER performed in the framework of an OECD/NEA project was roughly reviewed further. It then confirmed that a significant delay appeared both in time and temperature in the CET readings from the heater rod surface temperature. Blowdown of the SG as a postulated AM procedure then effectively quenched the dry out. A French facility BETHSY was not examined because it was reported that the design of upper core support plate is not representing any NPP-typical geometry.

4.2 LOFT

The LOFT facility simulated a typical 4-loop PWR [7]. Of particular interest for the present study is the monitoring of cladding and fluid temperatures. For most of the experiments the exit thermocouples were located just 1 inch above the top of the fuel rods. This arrangement is expected to respond quicker to core uncovering than CETs for typical commercial PWRs.

The LOFT test program was in the beginning focused on large break LOCA but was redirected after the TMI-2 accident, and a first series of 26 nuclear tests were performed from May 1979 until end of 1982. Thereafter, an OECD project was formed. Two large breaks and three small breaks and one with loss of feedwater were simulated. The project was terminated by two experiments with fission product release; the last one was carried out July 3, 1985 [7].

In order to assess the function of CETs under conditions that are typical for an AM situation, all the selected experiments had a significant core uncovering. An excellent compilation and analysis of the CET functionality, based on four experiments in the first series (L2-5: a large break LOCA in the cold leg (CL) with rapid pump coastdown, L8-1: a 4 inch SBLOCA in the CL, L5-1: an intermediate size (14 inch) CL break LOCA with low head accumulator (ACC) injection, and L8-2: a 14 inch LOCA in the CL with delayed ACC injection), was done in [5].

The experiment that first raised the question of the reliability of measured core exit temperatures as an indicator of ICC was a large break LOCA (L2-5) which exhibited a second core uncover. Although the core was in dryout conditions, the CETs did not show superheat, but started to show superheat at about the same time as the quench began.

In a SBLOCA test (L8-1) as well as in two intermediate break tests (L5-1 and L8-2) the CETs showed significantly delayed response compared to time of core dryout and demonstrated that CET responded more to saturated conditions or cladding temperatures near the core exit rather than the hottest temperatures in the core.

The general conclusion in [5] is that any procedure that relies on the response of the CETs to monitor core uncover should take delayed response and that the CET could be much lower than core temperatures, into account. There may be accident scenarios in which these thermocouples would not detect ICC that precedes core damage.

In the OECD LP-SB-3, a small break in the cold leg, it was a significant spread in CET indicating that they could have been affected by runback from the hot leg. Also in the first part of the fission product release experiment (LP-FP-2) there was a significant spread. The core temperatures were in excess of 2100 K for several minutes.

There was no evidence of a large delay in the response. The heatup rate of the fluid temperatures was much slower than in the cladding and some temperatures reached a maximum of about 1000 K when typical core clad temperatures were in the order of 1500 K. During the rapid oxidation phase the CET were actually disconnected from core temperatures. The fluid temperatures showed a sudden peak of about 2000 K when quenching started.

Findings from the experiments in the LOFT facility indicate that the concerns for the functionality of the CETs in AM situations are well-founded.

4.3 PKL

For over 30 years, investigations of the thermohydraulic system behavior of pressurized-water reactors under accident conditions have been carried out in the PKL test facility [8] at AREVA NP in Erlangen, Germany. The PKL facility models the entire primary side and significant parts of the secondary side and other relevant operational and safety systems of a pressurized water reactor at a height scale of 1:1. Volumes, power ratings and mass flows are scaled with a ratio of 1:145. The experimental facility consists of 4 primary loops. The maximum pressure on the primary side is 45 bar. The investigations carried out encompass a very broad spectrum from accident scenario simulations with large, medium and small breaks, over the investigation of shutdown procedures after a wide variety of accidents, to the systematic investigation of complex thermohydraulic phenomena [9, 10].

Differences between CET temperature and maximum cladding temperature were observed in several PKL experiments, three out of them, representing relevant accident scenarios have been selected to analyze in detail these differences and to provide information on physical phenomena responsible for the CET performance:

- Loss of feed water transient as consequence of station blackout (SBO) with primary and subsequent secondary side bleed-and-feed and hot leg ACC injection
- SB-LOCA transient with additional system failures (no HPSI, no automatically initiated secondary side cool down, hot leg ACCs only), late secondary side depressurization

- Parameter study on heat transfer following loss of RHRS transients, with additional coolant inventory reduction in the RPV

The three tests are characterized by a significant loss of inventory in the core leading to a pronounced core uncover for a longer period of time. As the existing boundary conditions (e.g. upward steam flow, water back-flow) are of high significance for the CET performance, the experiments or individual test phases within the experiments have been categorized as follows:

- Phases with no water back-flow from the top with decreasing coolant inventory in the core at constant primary pressure or with depressurization in parallel (flashing)
- Phases with water backflow from the top, e.g. from hot leg ACC or from the SGs due to reflux condensation

In the PKL test facility the reactor core is modeled by a bundle of 314 electrically heated rods. The core geometry is constructed as an „actual section“; that is, the individual heated rods have the actual geometry, but the number of heated rods in the core are reduced by the volume scaling factor as compared to the original plant. The heater rods are arranged in three concentric zones which can be heated independently of another to enable radially variable power profiles across the test bundle to be simulated. The core simulator used in the experiments described below was designed with a uniform axial power distribution.

The PKL III test facility features a detailed set of thermocouples (TC) used to acquire temperature signals from different locations within the RPV including heater rod wall temperatures (at different radial and axial positions), sub-channel fluid temperatures (at elevations in-plane with the corresponding cladding temperatures) and additional fluid temperatures (just below and above the upper core plate and in the upper plenum). The fluid temperature, which is in the following defined as CET, is measured directly (15 mm) above the upper core plate and close to the center position. The upper core plate in PKL represents the fuel assembly top nozzle in the PWR plant (in PWRs the CET measurements are typically also installed above this fuel assembly top nozzle). As an example, Fig.1 shows the evolution of the measured wall temperature (in the center of the upper core region) in comparison with the CET and with the fluid temperatures in the upper core region for the SBO-experiment, indicating an important delay in CET response.

In general, the results from the described PKL tests concerning CET performance can be summarized as follows:

- Significant temperature differentials between CET temperature and maximum cladding temperature (delay in start of superheating and difference in maximum measured temperature) were observed even in situations without water backflow. The following main reasons for this have been identified:
 - Rather poor heat transfer from the rod cladding to the ambient steam due to low steam flow velocities, to some extent a possible entrainment of water (made evident by comparison of wall and fluid temperatures in the core at the same elevations).
 - Impact of heat exchange with colder structures above the upper end of the heated lengths. Cold structures (e.g. unheated lengths of rods, upper core plate, core barrel) located in the steam flow path from the heated lengths towards CET measurement positions influence the maximum temperature differential measured between CET and maximum cladding temperatures.
- Higher differences occurred between the fluid temperatures in the upper plenum (or RPV

outlet) and the maximum cladding temperature in the core because of the additional cooling effects of the structures in the upper plenum.

- A radial temperature profile (fluid and wall) in the core and above the core (CET) was observed in all the tests due to the radial power profile superposed by the effects of the core barrel and of the heat losses.
- Tests at low primary pressures (shut down conditions) also revealed pronounced differences/delay between CET and maximum cladding temperatures. A tendency is visible in the test results: The faster the evolution of the transient towards core uncover, and the colder the structures in the UP the larger $\Delta T_{\text{clad,max-CET}}$.
- Despite the delay and the difference in the measured temperatures, the time evolution of the CET signal readings in the center section seem to reflect the change of the cooling conditions in the core and thus the tendency of the maximum cladding temperatures quite well.

The PKL test results and the identified phenomena relevant for the CET performance can be qualitatively extrapolated to the PWR. The thermal hydraulic conditions present in the different phases of the tests under investigation are typical for the relevant PWR accident scenarios.

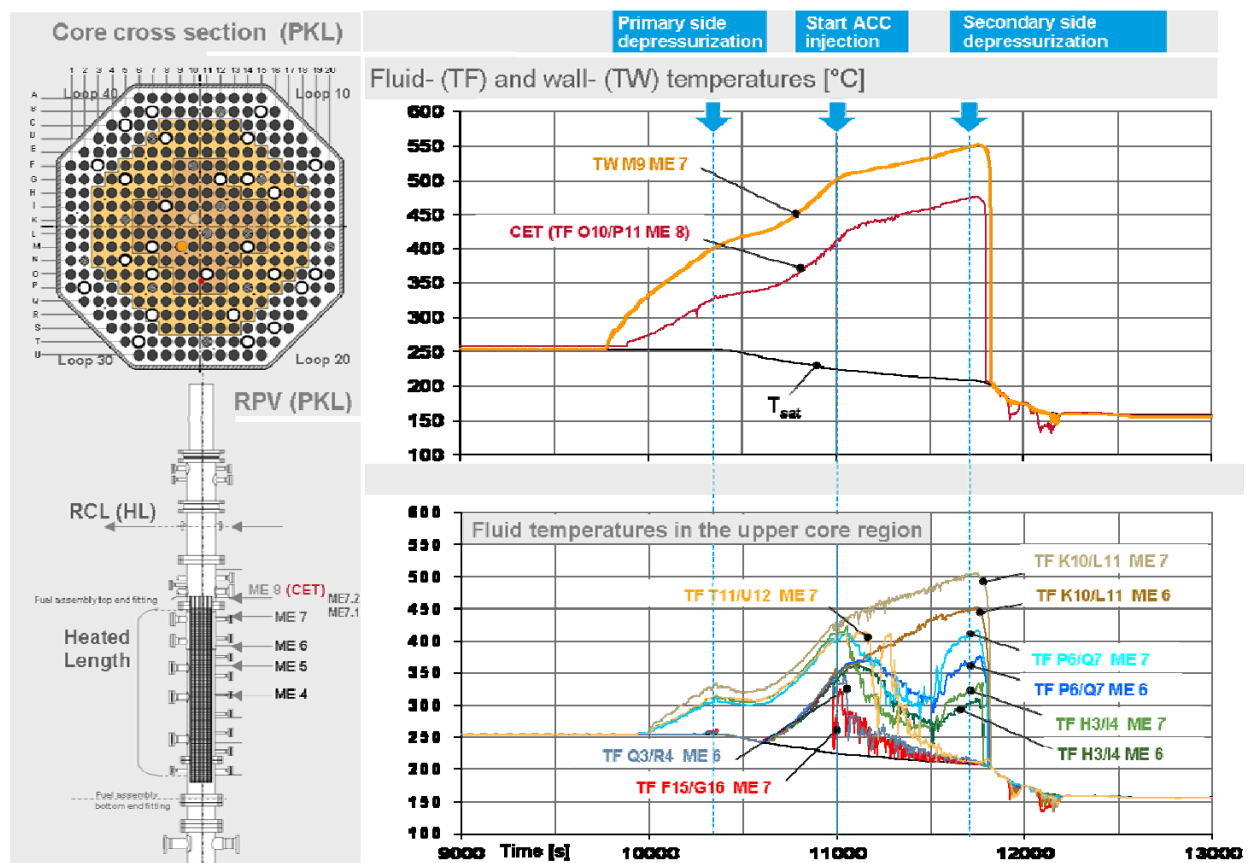


Fig. 1: Results from PKL station black out experiment

Because of the diversity of influential parameters and the test facility design features (e.g. overall geometry, heat structures, uniform axial power profile, location of CET) the PKL test

results cannot be directly extrapolated to PWR in quantitative terms. Furthermore, the CET performance (i.e. the difference between CET and maximum cladding temperature) strongly depends on the accident scenario and the flow conditions in the core and around the CET measurements and may also vary between different PWR types (due to different design). Nevertheless, the clear boundary conditions present for different quasi-stationary heat transfer states in the PKL tests, in particular for the SBO experiment (phases of pool boiling without and with depressurization in parallel, no coolant backflow) contribute to a better understanding of the T/H phenomena associated with the issue in general on one hand and represent a good data base for the validation of codes and models on the other hand.

4.4 ROSA/LSTF

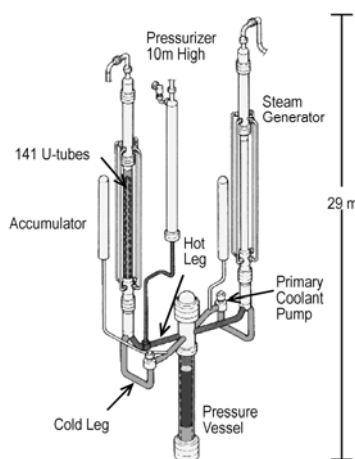


Fig.2 LSTF

The LSTF (Large Scale Test Facility, Fig. 2) [11] of ROSA Program in JAEA simulates the Westinghouse-type 4-loop 3423 MWt PWR, Tsuruga Unit-2 of the Japan Atomic Power Company (JAPC) by a full-pressure full-height 2-loop system with a volumetric scaling of 1/48 (1/21 for 2-loop PWR). Test 6-1 [4] of the OECD/NEA ROSA Project was conducted in 2005 to simulate a SBLOCA with a break at the pressure vessel (PV) top head (1.9% cold leg (CL) break equivalent). Total failure of the high pressure injection (HPI) system was assumed. The steam generator (SG) relief valves were opened as an AM action when CET temperature reached 623 K. Steam flow going to the break at PV top through the control rod guide tubes (CRGTs) was then considered to enhance the steam flow around CET locations outside the CRGT, resulting a smooth detection of superheat. However, the CETs detected superheat

with a time delay of about 230 s from the core heat-up, and indicated a large temperature difference from the over-heating core as shown in Fig. 3, causing too high core temperature to safely continue the experiment. Three-dimensional (3D) steam flow in the core and core exit regions were suggested further from the measured temperatures, even enhanced by the steam flow towards the break through CRGTs, which was called as “chimney effects”.

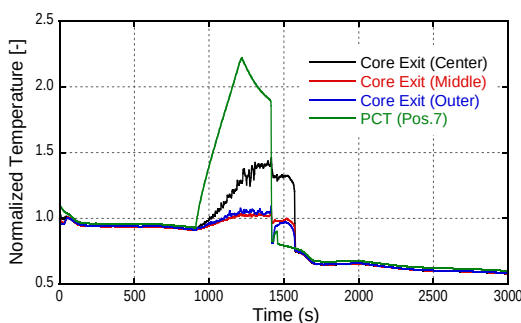


Fig.3 CET response and PCT

(TMI-type) with or without AM actions, and two abnormal transient tests: station blackout (TMLB') scenario and loss of residual heat removal (RHR) system under mid-loop operation, respectively under extremely high or low pressures. From these LSTF experiments including OECD ROSA Project Test 6-1, it was found that the CET response depends on such parameters as core radial power profile, 3D steam flow around core exit with large temperature variation, cooling by cold structures and fall-back water. Followings specific results are obtained;

- (1) General CET responses (time delay and temperature discrepancy relative to heating-up

core)

Following two relations were found, which are applicable to most of the examined LSTF tests including few tests with limited fall-back water effects.

(1-1) The relation between the time to start core heat-up (t_{ICC} [s]) and the time to start CET heat-up (t_{CET} [s]) is expressed by the following equation within an uncertainty of $\pm 6\%$ as

$$t_{\text{ICC}} = a \times (t_{\text{CET}})^b, \quad \text{where } a = 0.7603 \text{ and } b = 1.027.$$

(1-2) Temperature discrepancy of CET from the core top region is expressed in terms of average superheat ($\Delta T = T - T_s$ [K]) between the CETs (ΔT_{CET}) and core top region (ΔT_{P9}) as

$\Delta T_{\text{P9}} = C_1 \times \Delta T_{\text{CET}} + C_2$, where C_1 varies from 1.4 to 2.8 and C_2 from 0 to 40 K, and P9 is the thermocouple position 9 at simulated fuel cladding. In the Loss-of-RHR low-pressure transient particularly, values of C_1 and C_2 were exceptionally large: 3.9 and 120 K respectively.

(2) Steam flow conditions at core exit

Average steam velocity at upper core plate (UCP) of LSTF during core boil-off was found to be very small; typically around 10 to 30 cm/s and less than 0.6 m/s, in most of LSTF tests except for the loss-of-RHR test at low pressure and 10% CL break LOCA test with significant coolant fall-back. The 3D steam flow may have appeared in the core and core exit due to the following factors as; (a) radial power profile, (b) cooling effect by low-temperature structures and (c) CRGT-chimney effect for PV top break LOCA, (d) the longer delay time with the smaller break for small-break LOCAs including PV top break, because of lower core power and slower level drop in the core during core boil-off, (e) high speed steam flow in a loss-of-RHR transient under atmospheric pressure, which causes low steam superheat leaving large temperature discrepancy between core top and steam at the CETs.

(3) Exceptional but important cases

(3-1) As a criterion to start AM action, steam superheat ΔT would be preferable than constant criterion value in case of extremely high or low pressure boil-off such as the station blackout and loss-of-RHR transients respectively with high/low saturation temperature. The superheat indication by CET should be helpful to operators to notice the core heat-up.

(3-2) No CET heat-up was observed in the two LOCA tests: (i) 10% CL break and (ii) 0.2% PV bottom break under SG depressurization action. In the case of (i), fall-back water significantly limited the CETs to detect steam superheating. In the case of (ii), the core temperature excursion started even after the SG depressurization operation as an AM measure. The CETs then started to detect superheat when the uprising steam flow was significantly enhanced in the core by opening the PORV at the pressurizer.

(4) PV structures of LSTF influential to CET responses

The PV internal structures at and above the active core region such as UCP, upper nozzle (End-box), No.9 spacer and core barrel in the core periphery are almost correctly simulated in the LSTF at the same elevation with 1/48-scaled flow areas. Instead of gas plenum of each fuel rod, the LSTF heater rod has non-heating part above the heating region. Steam flow area in each structure per one fuel rod is almost equivalent to those of the reference PWR. The LSTF has no core bypass (baffle) region around the core. The scaled metal capacity around the core shroud is thus even smaller than in a PWR. The cooling effect of colder structures

on superheated steam flow in the LSTF would be qualitatively comparable to that for the reference PWR.

The installation of CETs is plant-specific. Meanwhile, the reference PWR has 50 CETs (about 1 CET per 4 fuel bundles with 17x17 rod array), while the LSTF has 20 (almost 1 CET per 1 bundle with 7x7 rod array).

Diameter of LSTF PV upper plenum is about 1/12 of that of the reference PWR. This difference may influence the coolant conditions around CETs when water fall-back happens from HLs. When CETs are wet, they indicate saturation temperature especially at certain area under HLs while the other region free from coolant splashing may detect superheat. There is no systematic information on the splashing spreading area. However, it is expected that the dry region around core exit and over UCP with CETs would be far larger in the reference PWR than in LSTF.

(5) Applicability to PWR

The LSTF correctly simulates the steam generation rate and the average velocity in the core, because core power and PV coolant inventory are volumetrically scaled. The CET responses in LSTF may thus be applicable to PWR if the following conditions are taken into account; the 3D steam flows depending on core power profile, effects of cool structures around core exit and CET location relative to the CRGTs. The effects of different upper plenum configuration should be carefully estimated when the influences of water fall-back including detection/non-detection of superheat are estimated in the case of limited fall-back water.

4.5 Synthesis and the applicability to reactor scale

Based on the relevant experiments performed in LOFT, PKL and ROSA/LSTF, following conclusions were suggested:

- CET measurements have some limitations in detecting ICC and core uncover: the superheating in CET reading is always significantly lower (up to several 100 K) than the actual maximum cladding temperature, and appears in all cases with a certain time delay (ranging from 20 to several 100 s).
- CET performance strongly depends on the accident scenarios and the flow conditions in the core.
- The main causes affecting CET delays for most of the scenarios are (a) radial temperature profiles (both in and above the core), (b) cooling effect of the unheated structures in the upper part of and above the core, (c) poor heat transfer from the rod surface due to low steam velocities during core boil-off and (d) water backflow from hot legs during core heat-up due to steam condensation in SG tubes, pressurizer water fall down or from hot leg ECC injection.
- There are other relevant aspects specific to the facility design like the actual CET location, or the steam behavior that is scenario-dependent such as hot steam chimney effect in RPV Top Head breaks and downward core flow in the case of RPV bottom head break.
- The number of experiments for scenarios starting from shutdown and/or low reactor water level conditions such as loss-of-RHR is limited. However, PKL and ROSA tests have shown that CET delays in these conditions can be even more pronounced than in tests starting from nominal power due to colder structures in the upper part of the core.

These conclusions deal with the consequences of CET delays for the effectiveness of the AM strategies included in the different EOP/SAMG packages existing in the nuclear industry.

Qualitative application/extrapolation of the CET response to reactor scale is possible. Direct extrapolation in quantitative terms to the reactor scale, however, should be avoided in general or done with special care due to limitations of the experimental facilities in terms of geometrical details, unavoidable distortion in the scaling of the overall geometry, and of the heat capacity of structures.

5. Conclusions

5.1 Lessons learned

The evaluation of the experimental results provided a consistent picture regarding the CET response in relation to the maximum core cladding temperature by clarifying the relevant physical phenomena and improved their understanding related to the CET responses.

According to the results of the experiments and the subsequent analysis, it seems that the observed delays should not affect severely the effectiveness of most existing AM actions at least for scenarios starting at power conditions, but it must be underlined that concerns about CET functionality for general use in AM are well founded. It should be realised that superheat detection by the CET is the ultimate indication of an ICC and of an already started core heat-up.

No superheat detection by the CET does not guarantee adequate core cooling. In some specific cases (in particular with water fall back from the hot legs), core heat up may not be detected by the CET, depending on CET positions to be affected by the fall back water. It should be emphasized that test results from transients with a significant amount of fall-back water are difficult to transpose to the reactor scale because the upper plenum cannot be correctly scaled. It can be expected that in a test facility, due to the smaller scale, the water fall-back is more likely to affect the CET response than in the reactor case.

Review of the different international approaches to AM has suggested that it is not possible to *a priori* fully discard the possibility of having a similar response in LWRs as the one observed in OECD/NEA ROSA Project Test 6.1, if the applicable AM action initiation rely only on CET readings, which is not always the case though.

In this sense it is interesting to remark that most of the AM strategies analyzed here rely on a combination of CET readings and other instrumentation indications (normally, RPV and/or SG water level) to define the initiation of the different AM recovery actions. This approach makes the AM more reliable because the specific drawbacks of each individual instrumentation system do not use to be coincident for a particular scenario. However, it is worth recognizing that not all the identified potential problems would be completely addressed by just using this type of multi-instrumentation AM approach, by the contrary specific validation for each foreseeable scenario should be carried out. Full understanding on the response of each instrumentation against the “expected” phenomena may form a basis for the validation.

Nevertheless, taking into account the delay and the temperature difference in the CET

response, a CET superheat indication, in particular in combination with other measurements, is well capable to detect a core heat up and is therefore an important element in the context of AM procedures.

5.2 Impact on and from computer code analysis

Existing models used to calculate time delays and the temperature difference in CET readings from core temperature may not be fully validated – this is also evident from the responses received to the questionnaire referred in Section 3. Based on the responses to the questionnaire, it can be assumed that in most cases of AM procedure development the supporting analyses may have not gone into detail. Computer code models normally used for this type of analysis may not have enough “spatial resolution” to accurately calculate some relevant phenomena affecting this particular issue, considering that complicated multi-dimensional steam flow is involved. As a result, it can be expected that the estimation of the cooling conditions in the reactor core may include relevant uncertainties.

Degree of detail in the noding representation of the reactor geometry and the applicability of calculation method and models to the phenomena of interest is important when the calculated CET response or steam superheating at the CET location is judged whether it properly represents the actual conditions including the core cooling conditions. Detailed measurement on the steam temperature around the core exit and in the core is then necessary to validate the applicability of computer codes and models with respect to the CET response for both best-estimate codes and CFD codes. Definition of correct AM set points can only be expected by the use of codes and models validated in this way.

5.3 Recommendations

The following activities related to the CET effectiveness in AM could be recommended for the future:

- The importance of dealing appropriately with the discussed phenomena and uncertainties is evident when performing analytical studies in support of AM strategies. It is then recommended to verify whether or not state-of-the-art codes and their underlying models applied in support of AM procedure development are able to reproduce the delays and differences in CET readings from rod surface temperatures.
- The above activity could take the form of an international standard problem (ISP) based on one or two pertinent experiments. PKL or ROSA/LSTF tests reviewed here could be candidates. The activity could have the following objectives:
 - ✧ To assess physical models to predict heat transfer modes affecting CET behavior.
 - ✧ To develop a “best practice guideline” for the nodalisation approach of the uncovered core section up to the point of CET location.
 - ✧ To assess the possible impact of 3D effects, not modeled in these codes based on comparison with test results.
 - ✧ To investigate, how these effects can be modeled e.g. by the help of CFD codes, if the 3D effects turn out to have an important contribution to the time delay and/or temperature difference from the core.
- To investigate the “scaling” problem as CET issue: method(s) of extrapolation from

experimental facilities size, like PKL and ROSA/LSTF, to commercial PWR reactors. The investigation could include both experimental and analytical aspects and would focus on the influence of reflux water from hot legs onto CETs as well as on the 3D flow behaviour in the upper part of the core. Large-scale experiments to address prototypical conditions are preferable for phenomena investigation and data preparation for code validation.

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