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PREDICTIONS OF RCCA DROP TIMES UNDER CONSIDERATION OF FUEL ASSEMBLY DISTORTIONS

Mingmin Ren[1] and Claus Münch[2]

[1] Dr.-Ing., AREVA Expert, AREVA GmbH, Erlangen, Germany (mingmin.ren@areva.com)
[2] Dr.-Ing., Senior AREVA Expert, AREVA GmbH, Erlangen, Germany

ABSTRACT

A coupled RCCA (Rod Cluster Control Assembly) drop model has been developed for prediction of RCCA drop times down to full insertion under consideration of fuel assembly distortions (previously only down to dashpot). This coupled RCCA drop model takes the hydraulic resistances in control rod drive mechanism (CRDM) and in guide thimbles/dashpots into account. The mechanical friction forces between RCCA and its surroundings are also considered via a finite element model. The validations of this coupled RCCA drop model have been performed with comparison of quasi-static and dynamic RCCA drop experiments and with the RCCA drop tests under reactor operational conditions and with the in-core RCCA drop measurements.

The coupled RCCA drop model can be used to evaluate: (1) the impact of the modifications of the guide thimble design on RCCA drop time; (2) RCCA drop time over an irradiation cycle in combination with fuel assembly distortions; (3) the safe shutdown margins under accident conditions.

INTRODUCTION

The ability of RCCA in a pressurized water reactor (PWR) to be fully inserted in the core within a required time limit is one of the important safety requirements for quick shutdown. This kind of quick shutdown in a PWR is initiated by allowing the RCCA to fall in the core by gravity. During normal operation, the RCCA drop time is mainly influenced by the weight of RCCA, hydraulic resistances in the control rod drive mechanism (CRDM) and in the guide thimbles and by the mechanical friction force between RCCA and its surroundings. In the case of strong fuel assembly distortions i.e. fuel assembly bow or spacer grid deformations after seismic or loss of coolant event, RCCA drop time requirement could be violated or incomplete rod insertion (IRI) issues could occur. Therefore, it is very important to predict the RCCA drop times due to seismic or loss of coolant events and due to the evolution of fuel assembly distortion to demonstrate that the RCCA drop time requirement is fully met.

A COUPLED RCCA DROP MODEL

A coupled hydraulic and structure-dynamic model was developed for prediction of RCCA drop time down to dashpot under consideration of hypothetical fuel assembly distortions plus spacer grid crush deformations in 2009 (see reference list: Ren, M. and Dressel, B. 2009).

The governing equation of motion of the RCCA dropping can be written as follows:

$$(m + m_H)\ddot{X} = -mg + F_b + F_{DR} + F_{CR} + F_c + F_{drag} \quad (1)$$

where m is the mass of the drive line (drive rod + spider + control rodlets) and m_H is the added mass, X is the drop depth, g is acceleration of free fall. F_b is buoyancy of the drive line, F_{DR} and F_{CR} are the hydraulic resistance on drive rod and control rods, respectively. F_c is the overall friction force between the RCCA and its surroundings and F_{drag} is a drag force (flow resistance) of the spider during RCCA drop.

The buoyancy of the drive line is constant and can be calculated with its geometrical data. The drag force of the spider can be estimated by the drag coefficients. The hydraulic resistances F_{DR} and F_{CR} can be determined by the hydraulic models for CRDM and control rod in guide thimble which will be discussed in the following sections. The overall friction force F_c can be calculated by means of the structure-dynamic model which will be studied below. The governing equation of motion of the RCCA drop is solved by means of an explicit time history integration method.

Hydraulic Resistance in CRDM

A schematic sketch of hydraulic model of the CRDM in German reactor is shown in Fig. 1. The flow paths in the CRDM can be classified into the outer and inner flow paths. The outer flow path consists of three annular spaces between the drive rod and the pressure housing. The inner flow path inside the drive rod includes the inflow holes at the lower part of the drive rod, the annular spaces inside the drive rod and the outflow holes.

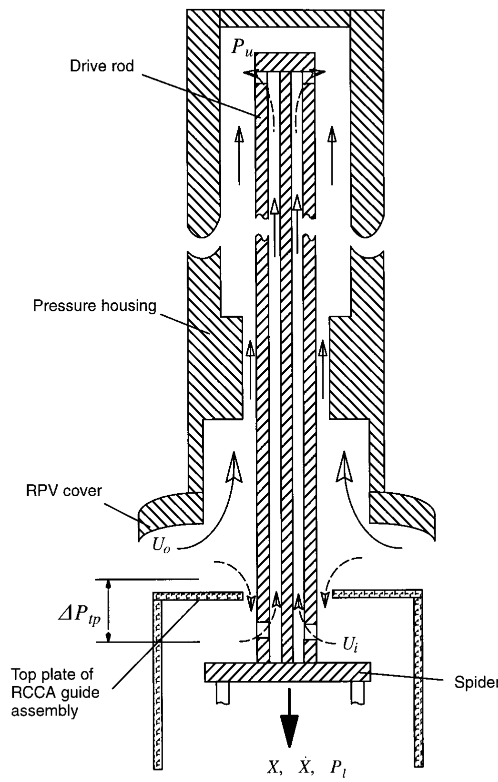

Figure 1. Schematic sketch of CRDM hydraulic model

During the RCCA drop, the fluid flows through the inner and outer flow paths upwards to fill the space generated by RCCA dropping. By applying the equation of continuity and ΔP-equation (the pressure loss through the inner flow path must be equal to the one through the outer flow path), the flow velocities U_o in the outer flow path and U_i in the inner flow path can be determined as a function of the RCCA drop depth and drop velocity. By applying the equation of momentum, the fluid resistance acting on the drive rod in the CRDM can be calculated.

In the hydraulic model, it is very important to determine the local pressure loss coefficients over flow paths correctly. For this purpose, CFD simulations have been applied and the local pressure loss coefficients over the flow paths in CRDM and control rod in guide thimble were determined individually as a function of local flow velocity.

Hydraulic Resistance in guide thimbles

The hydraulic model of control rod dropping in a guide thimble of a fuel assembly is shown schematically in Figure 2. The control rod drop down to the dashpot is considered analytically in the hydraulic model while the dynamic characteristics are determined empirically within the dashpot. Above the dashpot, the flow path inside the guide thimble can be divided into the inflow holes at the lower part of the guide thimble, a cylindrical region below control rod and an annular space between control rod and guide thimble.

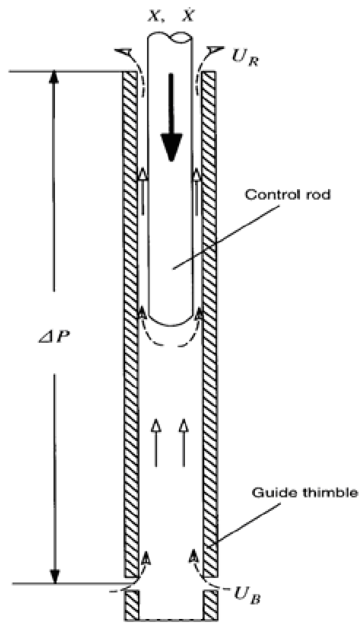

Figure 2. Schematic sketch of guide thimble hydraulic model

During the control rod dropping, fluid will be pushed out of guide thimble. By applying the equation of continuity and ΔP-equation (The pressure loss through the inner flow path in the guide thimble must be equal to the one outside the guide thimble), the flow velocities U_R can be calculated as a function of the RCCA drop height and drop velocity. By applying the equation of momentum, the fluid resistance acting on the control rod in the guide thimble can be determined.

An empirical dashpot hydraulic model for control rod movement within the dashpot is added to the coupled RCCA drop model. The parameters of the empirical dashpot hydraulic model are determined by fitting the measured RCCA drop curve from RCCA drop experiments in a test loop or in-core measurements. With this dashpot hydraulic model, the RCCA drop down to full insertion can be completely simulated.

Structure-dynamic model

In the structure-dynamic model, the drive rod and control rods are considered as 3D beams which are connected to the spider. The spider is modeled as a rigid body. The whole drive line (drive rod, spider and control rods) can move down in vertical direction and move and bend in horizontal direction. The CRDM, control rod guide assembly and fuel assembly guide thimbles are modeled as 3D beams separately, but can only move and bend in horizontal directions. Annular gap elements are used to describe the contact mechanism between the RCCA and its surroundings. These gap elements become active, if the gap between the RCCA and its surroundings is closed. During the RCCA dropping, the axial position of the RCCA is calculated transiently and the coupling nodes of the gap elements are newly reordered and the impact and friction forces of these gap elements are then evaluated.

Pre-defined fuel assembly deformations (bow, torsion and spacer grid deformations) can be applied in the structure-dynamic model to take its influence on RCCA drop time into account.

VALIDATION

First, the coupled RCCA drop model was validated by simulations of quasi-static and dynamic RCCA drop tests with a pre-deformed fuel assembly at ambient temperature in AREVA's DISTU test facility. In the quasi-static DISTU RCCA tests, the fuel assembly skeleton is pre-deformed with a fuel assembly bow in a C-shape of up to 20 mm or in an S-shape of up to -7.5/+5.0 mm, the control assembly is periodically moved upwards and downwards with a slow velocity and the acting friction forces on control assembly are measured. For each test configuration, the quasi-static tests were repeated 5 times and the results are very good reproducible. The simulations of these quasi-static RCCA tests with the coupled RCCA drop model show a good agreement with experiments.

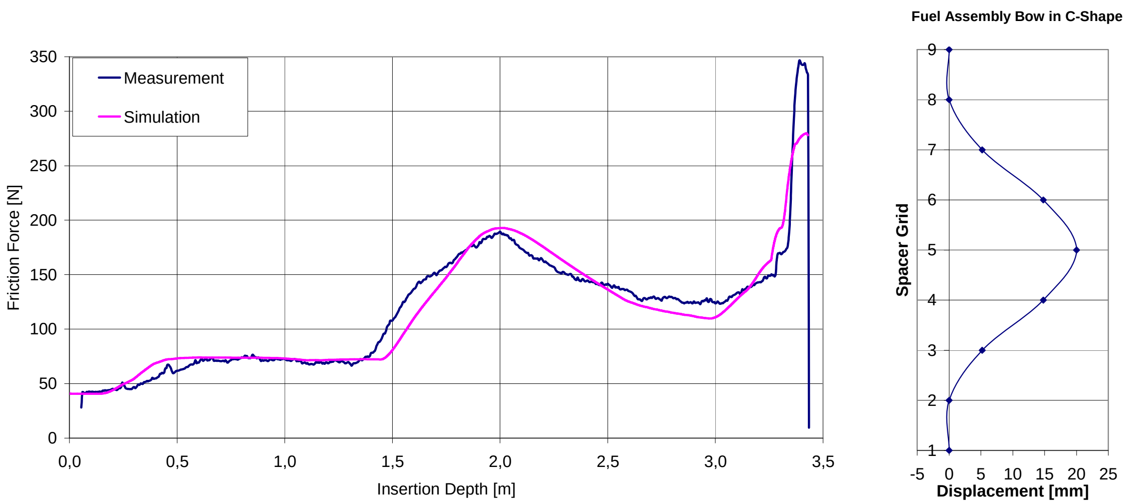

Figure 3. DISTU quasi-static test with a FA bow of 20 mm in C-shape

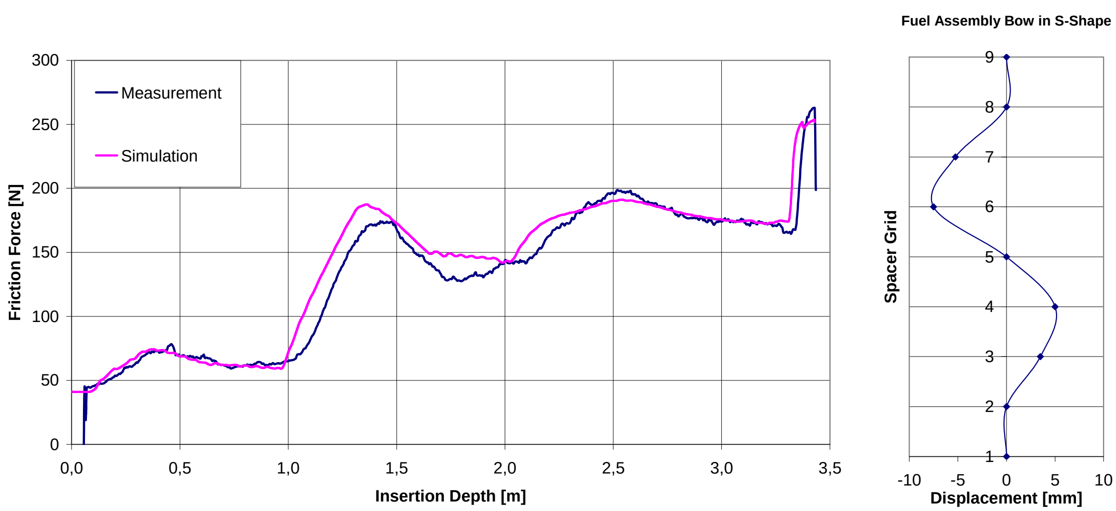

Figure 4. DISTU quasi-static test with a FA bow of -7.5/+5.0 mm in S-shape

Due to seismic or loss of coolant events, the spacer grids could be plastically deformed. Such spacer grid deformation mode (disturbance of guide thimble matrix) is depending on the spacer grid designs. For one of AREVA's spacer grid design, the spacer grid deformation mode shows a shear deformation orthogonal to the impact direction between the upper and lower guide thimble blocks with the half guide thimbles of each, respectively.

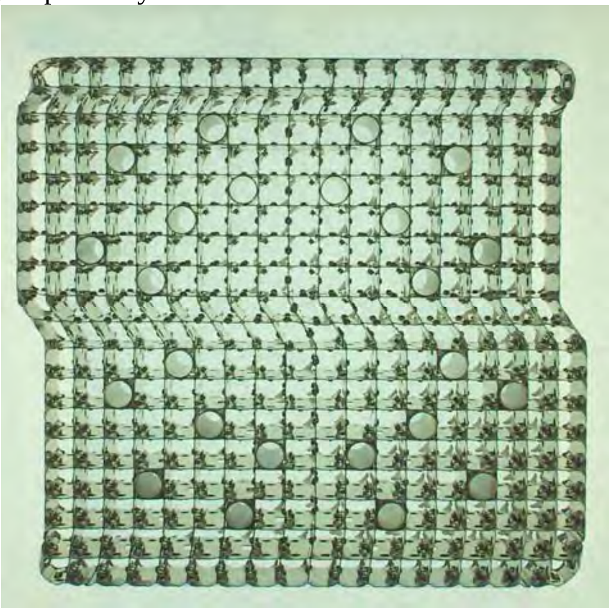

Figure 5. Spacer grid deformation mode

In the DISTU test facility, spacer grid deformation modes can be flexibly prescribed in such a manner that each spacer grid can have different deformation mode. In a validation case, the 5th spacer grid is set to have a shear deformation of +/-X mm while the 4th and 6th spacer grids have a shear deformation of -/+0.5*X mm (the half shear deformation but applied in the opposite direction as the one in the 5th spacer grid). The simulation with the coupled RCCA drop model shows an overall good agreement with the experiment, except the friction force at the 6th spacer grid elevation is slightly underestimated compared to the experiment.

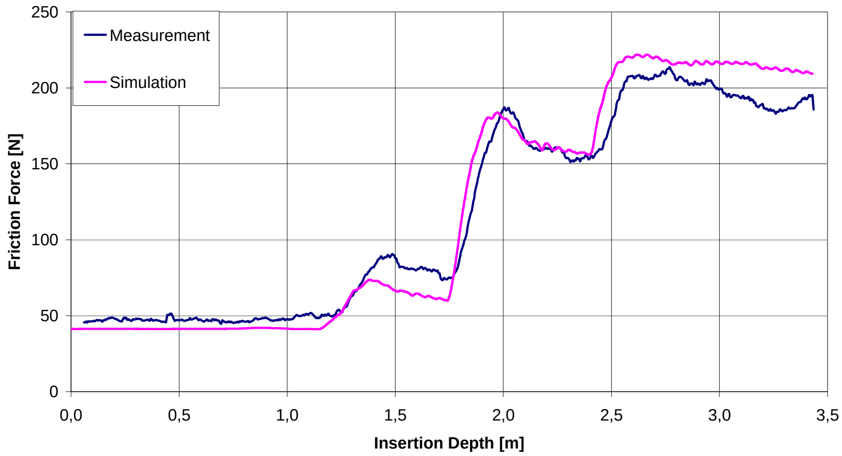

Figure 6. DISTU quasi-static test with spacer grid deformations

The dynamic DISTU RCCA drop tests are initiated with RCCA free drop by gravity. The RCCA drops through the control rod guide assembly into fuel assembly. There is no CRDM in DISTU RCCA quasi-static or drop tests, therefore it can only be used for validation of the hydraulic model for the control rod movement in guide thimble/dashpot.

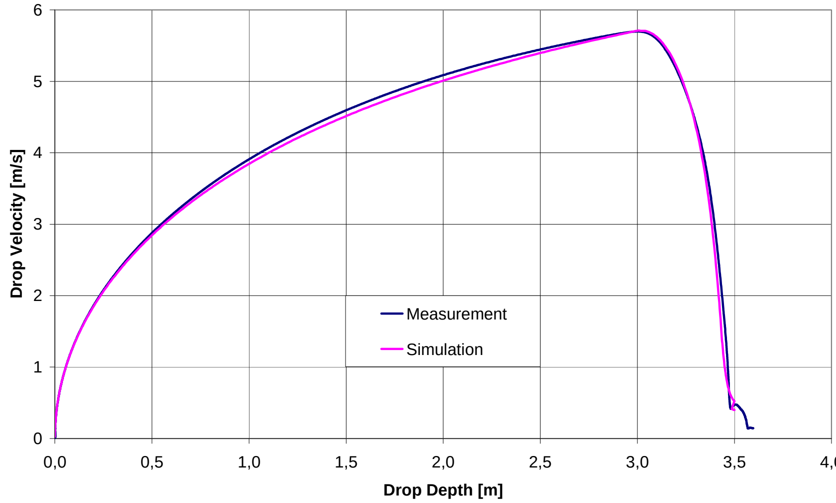

Figure 7. DISTU RCCA dynamic drop test

The RCCA drop curves (RCCA drop velocity versus drop depth) are compared between the simulation and measurement. As shown in the figure above, the RCCA drop curve from the simulation agrees well with the one from the measurement.

Further validations of the coupled RCCA drop model were performed with KOPRA RCCA drop tests under reactor hot conditions (T = 320 °C and P = 156 bar) for different flow rates. In the KOPRA test loop of AREVA, the whole drive line is represented full scale with the original components including a non-bowed fuel assembly. The RCCA drop depth and velocity are recorded as a function of time for each RCCA drop test. In addition, the drop time down to the entry of dashpot (T5) and drop time down to full insertion (T5+T6) are measured. For the purpose of the validation, two mass flow rates are considered.

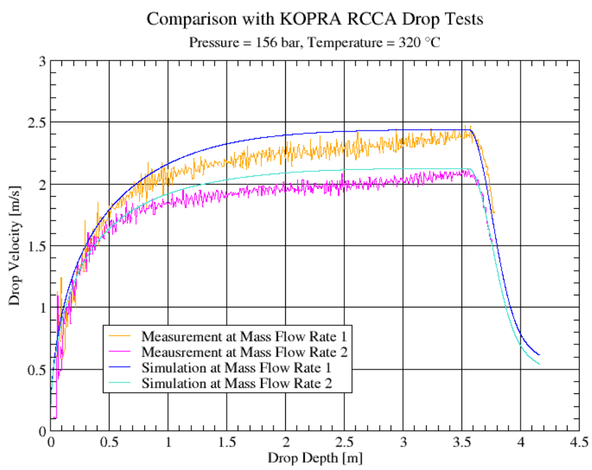

Figure 8. KOPRA RCCA drop tests

Figure 8 shows agreement between the measured and calculated drop curves for the two mass flow rates. The corresponding drop times are listed in Table 1.

Table 1. Comparison of measured (KOPRA loop) and calculated drop times

	T5		T5+T6	
	measurement	simulation	measurement	simulation
Mass flow rate 1	1.80 s	1.81 s	2.36 s	2.35 s
Mass flow rate 2	2.00 s	2.02 s	2.64 s	2.65 s

Not only the RCCA drop curves, but also the drop times agree well between the simulations and experiments.

VALIDATION WITH IN-CORE MEASUREMENTS

In the German reactors, the RCCA drop time measurements are performed at the beginning and end of each cycle. For the validation, one reactor has been selected, where all FA distortions in the core have been measured during the outage at the end of one cycle. The recalculations of the RCCA drop times have been performed for specific positions and compared with the measurements.

First, the recalculation was performed for a core position with a fuel assembly with small bow amplitude. In this case, the RCCA drop curve is similar to the one from the laboratory (KOPRA) RCCA drop tests. As shown in Figure 9, there is a good agreement between the calculated and in-core measured drop curves and drop times (slightly lower values of calculation).

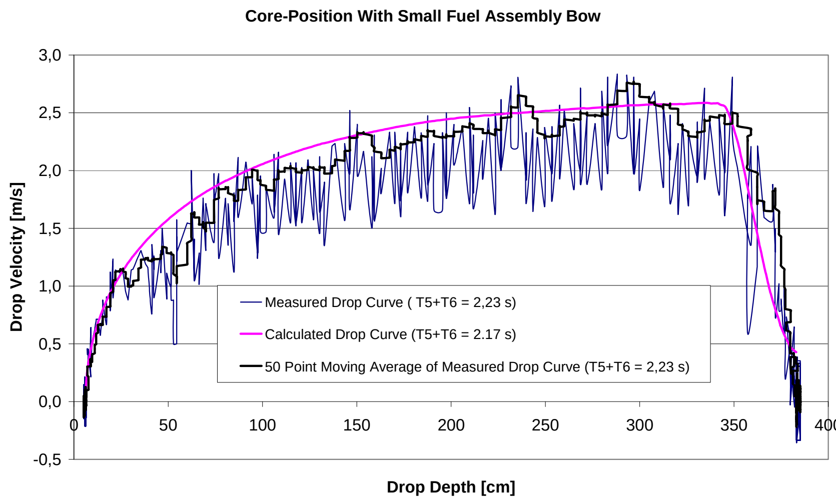

Figure 9. In-core RCCA drop behavior by a fuel assembly with small bow

Then, the recalculation was performed for a core position with a fuel assembly with large S-bow amplitude. The measured RCCA drop time delay was well simulated analytically, as shown in Figure 10. The calculated RCCA drop velocity and drop time agree well with the in-core measurements.

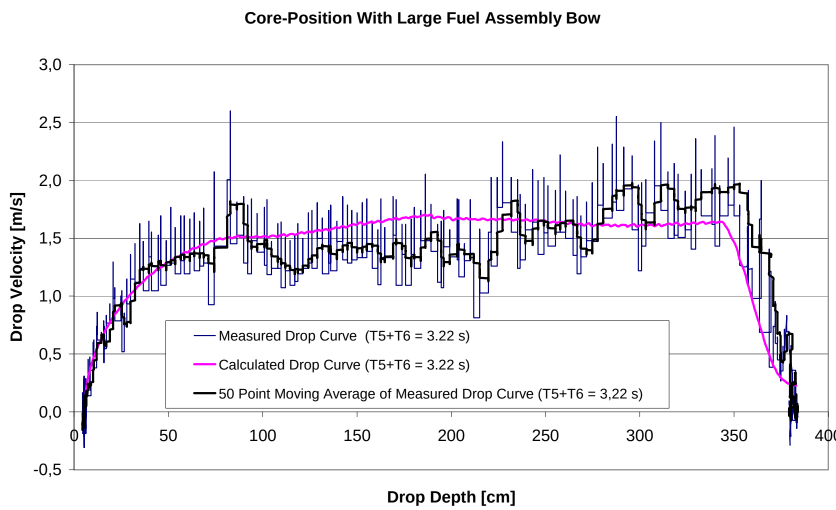

Figure 10. In-core RCCA drop behavior by a fuel assembly with large S-bow

The RCCA drop time predictions are very sensitive to the input hydraulic and mechanical parameters of the coupled RCCA drop model, i.e. bending stiffness of the control rods, bending stiffness of the guide thimbles and rotational stiffness of spacer grid/guide thimbles, and thus these parameters must be well defined.

CONCLUSION

A coupled RCCA drop model has been developed for prediction of RCCA drop times down to full insertion under consideration of fuel assembly distortions. This coupled RCCA drop model takes the hydraulic resistances in control rod drive mechanism and in guide thimbles/dashpots into account. The mechanical friction forces between RCCA and its surroundings are also considered via a finite element model. The validations of this coupled RCCA drop model have been performed with comparison of out-of-core quasi-static and dynamic RCCA drop experiments and with the RCCA drop tests under reactor operational conditions in addition to in-core RCCA drop measurements.

The coupled RCCA drop model can be used to evaluate the effects on RCCA drop time behavior of: (1) the impact of the modifications of the fuel assembly guide thimble design and/or RCCA design; (2) fuel assembly distortion evolution over an irradiation cycle and (3) dimensional changes to the fuel assembly under accident conditions.

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Ren, M. and Stabel, J. (1999). "Analytical Modeling of Control Rod Drop Behavior," the 15th International Conference on Structural Mechanics in Reactor Technology, Seoul, South Korea.

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