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Investigating the ESBWR stability with experimental and numerical tools: A comparative study☆

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ABSTRACT

In this work, the stability of the Economic Simplified Boiling Water Reactor (ESBWR) has been studied by using a Freon-134a based experimental facility (GENESIS) and two system codes, being ATHLET 2.0a and (to a lesser extent) TRACG. During setting up the GENESIS facility and the numerical calculations, a great effort has been made to approximate the ESBWR system as accurate as possible.

In general, it was found that a sufficient margin to instability exists regarding the ESBWRs nominal point. In addition, a comparison was made between the numerical and experimental results for both the thermal-hydraulic system and the reactor system. Deviations were found between the numerical and experimental results, in spite of the close similarity between the GENESIS facility and the definition of the ESBWR system in the system code. This result shows that predictions regarding real nuclear reactors, based on modeled systems, should be taken with care.

1. Introduction

In order to enhance the safety of the next generation of nuclear reactors, special emphasis is put on replacing active safety systems by passive ones. The Economic Simplified Boiling Water Reactor (ESBWR), being a next generation nuclear reactor, eliminates the need for circulation pumps and associated piping and systems since cooling takes place by natural circulation. This cooling method is simple, inherently safe, and results in reduced overall maintenance costs.

In such a reactor, the flow rate is determined by the amount of vapor present in the system. If, for some reason, the amount of vapor increases in the core section, the flow rate increases due to the increased driving heads and a cooling of the core follows. Hence, the natural circulation itself shows a negative feedback and dims any initial perturbations occurring in the reactor system. The natural circulation mechanism, however, is interwoven with other physical mechanisms such as the void/temperature-reactivity feedback, density-waves traveling through the coolant mixture and fuel rod dynamics, each of them having their own dynamics. Moreover, at very high powers, the flow rate response is reverse due to a higher friction at high void fractions. One therefore needs to study the response of the reactor *as a whole* to perturbations, i.e. the stability of the reactor needs to be investigated.

The ESBWR was designed to have large margins to instabilities, based on numerical results from the in-house system code TRACG (Shiralkar et al., 2007). Endorsement by other codes as well as experimental evidence, however, would definitely help to increase insight into the ESBWR stability performance. In the past years, a large number of authors have extensively studied natural circulation BWR systems with the help of experimental facilities and codes (e.g. Kok and Van der Hagen, 1999; Furuya et al., 2005a). This work particularly focuses on the ESBWR system, thereby aiming for the GENESIS facility and numerical models approximating the reactor system *as accurately as possible*. Such an approach reveals the similarities/differences regarding experimental facilities and numerical codes and gives more insight into the problems and, consequently, importance of modeling a complex system such as a BWR.

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Nomenclature

Nomenclature

A_c	core cross-sectional area
D_h	core hydraulic diameter
f_{TP}	two-phase friction coefficient
$G_{m,0}$	core mass flux
h_{in}, h_{sat}, h_{fg}	enthalpy (inlet, saturation, latent)
L_c	core axial length
q	core power

Greek letters

ρ_l, ρ_v	density (liquid, vapor)
σ	surface tension

2. Genesis facility

During the past decade, a number of authors performed experimental research on natural circulation BWR stability (Kok and Van der Hagen, 1999; Furuya et al., 2005a). Furuya et al. (2005a,b) performed experiments in the water-based SIRIUS-N facility, containing a single heating-rod core section, a chimney section and a digital controller for mimicking the void-reactivity feedback. Zboray et al. (2004) and Kok and Van der Hagen (1999) used the Freon-12 based DESIRE facility, representing a downscaled version of the Dodewaard-reactor (The Netherlands). This facility was equipped with a bundle geometry and a system to mimic the void-reactivity feedback.

In this work, a great effort has been made to construct an experimental facility that represents the ESBWR *as accurately as possible*. The ESBWR has therefore been downscaled to a Freon-134a based facility (GENESIS) in order to reduce the pressure, temperature and applied power to more convenient values. A brief description of the downscaling will be given first. Then, the system for implementing the void-reactivity feedback will be discussed.

2.1. Downscaling the ESBWR

A meaningful comparison between the GENESIS facility and the ESBWR can only be made when the main physics in both systems are as similar as possible. These physics comprise the flow regime, the friction distribution, the axial quality and void-fraction profiles and the inertia of the coolant throughout the system. Although an extensive description of the scaling can be found in Marcel et al. (in press), a brief description will be given here. The scaling rules are partially based on the work of Van de Graaf and Van der Hagen (1994) and are further refined in order to increase the similarity between the ESBWR and the GENESIS facility.

First, the governing equations describing the physical phenomena need to be made dimensionless. These equations are the mass balance for each section, the momentum balance for each section, the heat balance for each section and a model that describes the two-phase flow in the core section. As a result, a range of dimensionless numbers is found (see Table 1).

Table 1
Dimensionless numbers used in the scaling

Equation	Dimensionless number
Mass balance	N_ρ, χ
Momentum balance (HEM assumed)	N_ρ, N_g, N_f, N_{Fr}, χ
Heat balance (HEM assumed)	N_{Zu}, N_{sub}
Flow profile two-phase flow	N_{We}, N_{Fr}

HEM refers to the Homogeneous Equilibrium Model; both vapor and liquid have the same velocity and are in thermal equilibrium.

The dimensionless numbers are the density number N_ρ (the ratio between the densities of the vapor and liquid phase), the quality χ, the geometry number N_g (the ratio between the hydraulic diameter and the length of the core), the friction number $N_f = fN_g$ (f is the friction factor), the Froude-number N_{Fr}, the Zuber number N_{Zu}, the subcooling-number N_{sub} and the Weber number N_{We}.

$$N_\rho = \frac{\rho_v}{\rho_l}$$

$$N_g = \frac{D_h}{L_c}$$

$$N_f = f_{TP} N_g$$

$$N_{Fr} = \frac{G_{m,0}^2}{\rho_v^2 g D_h}$$

$$N_{We} = \frac{G_{m,0}^2 D_h}{\rho_l \sigma}$$

$$N_{sub} = \frac{h_{in} - h_{sat}}{h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$

$$N_{Zu} = \frac{q}{G_{m,0} A_{core} h_{fg}} \frac{\rho_l - \rho_v}{\rho_v}$$

It is found that the density number for Freon-134a is the same as for water at a saturation point of 11.4 bar and 317 K. The facility was therefore designed for these conditions. The correct scaling of the flow pattern (churn-bubbly flow is assumed (Marcel et al., in press)), is attained by keeping the Weber and Froude numbers in the two systems the same. This results in the ratio for the hydraulic diameter of the ESBWR and the GENESIS facility being a function of the surface tension and density of the two coolants. This ratio turns out to be

$$\frac{D_{h,GENESIS}}{D_{h,ESBWR}} = 0.47 \tag{1}$$

As the geometry number N_g should be kept constant for proper scaling, the ratio of the length of the ESBWR and the facility is determined by the same ratio

$$\frac{L_{C,GENESIS}}{L_{C,ESBWR}} = 0.47 \tag{2}$$

The relative contribution of buoyancy to the total pressure drop over the core and chimney sections is kept the same since the geometry number, the axial quality profile and the density number are the same. In addition, the relative contribution of inertia in each section is kept the same, as the geometry number is kept the same for both the ESBWR and the GENESIS facility. Regarding the operational conditions, the Zuber number should also be kept the same for both the ESBWR and the facility, hence the ratio between the applied powers per rod is

$$\frac{q_{GENESIS}}{q_{ESBWR}} = 0.0244, \tag{3}$$

showing a significant reduction of power required. Finally, the ratio of the time turns out to be

$$\frac{t_{GENESIS}}{t_{ESBWR}} = 0.69, \tag{4}$$

which implies that phenomena taking place in the GENESIS facility proceed 1.45 times faster than in the ESBWR.

It is impossible to *ab initio* preserve the local frictions caused by the core inlet, the spacers, the steam separators and wall friction. The friction distribution is, therefore, slightly different from the original one. The spacers in the GENESIS facility, for example, cause more friction due to the fact that it is impossible to exactly scale the real spacers (which, on a larger scale, are already designed to minimize the friction). Moreover, the diameter of the heating rods is larger than the scaling permits (60 mm instead of 47 mm). On the other hand, the friction at the inlet of the core is lower than in the ESBWR. In general, it is found that the total friction in the GENESIS core is about 8% higher than the friction in the ESBWR core. The friction at the outlet of the chimney was therefore increased by 8% in order to keep the same friction ratio, keeping the dynamics similar (Marcel et al., in press).

A summary of the scaling results can be found in Table 2 and a schematic of the GENESIS facility can be found in Fig. 1.

2.2. Void reactivity feedback system

Besides the thermal-hydraulics, void-reactivity feedback needs to be introduced in order to study reactor stability. As the rods in the GENESIS facility are electrically heated, the electrical power applied to the rods needs to be adjusted according to the amount of vapor present in the core section. Several authors have used different techniques (Kok and Van der Hagen, 1999; Furuya et al., 2005a), based on pressure drop measurements and local void-fraction determination by a gamma source/detector combination. Since the

Table 2
Summary of the scaling results

Parameter	ESBWR	GENESIS	Ratio
Power per rod (kW)	43	0.98	0.023
Pressure (bar)	71	11.4	0.16
Saturation temperature (K)	560	317	Not meaningful
Number of fuel bundles	1132	1	0.00083
Fuel rods per fuel bundle	92	25	∼0.25
Heating rods diameter (m)	0.01026	0.006	0.58
Water rods per fuel bundle	2	0	–
Water rods diameter (m)	0.02489	–	–
Pitch (m)	0.01295	0.006	0.47
Chimney cell hydraulic diameter (m)	0.6	0.04	0.07
Number of fuel bundles per chimney cell	16	1	–
Subcooling temperature (K)	12	5	0.42
Fuel bundle area (m^2)	0.009	0.002	0.22
Bypass area (m^2)	0.0009	–	–
Core mass flux (max) (kg/m^2 s)	1187	1242	1.047
Core hydraulic diameter (m)	0.009	0.00423	0.47
Heated length (m)	3.0	1.41	0.47
Chimney length (m)	6.61+2.0	4.05	0.47
Steam separator length (effective) (m)	4.2	1.97	0.47
Downcomer length (m)	16.4	7.71	0.47
Core exit quality	0.169	0.169	1

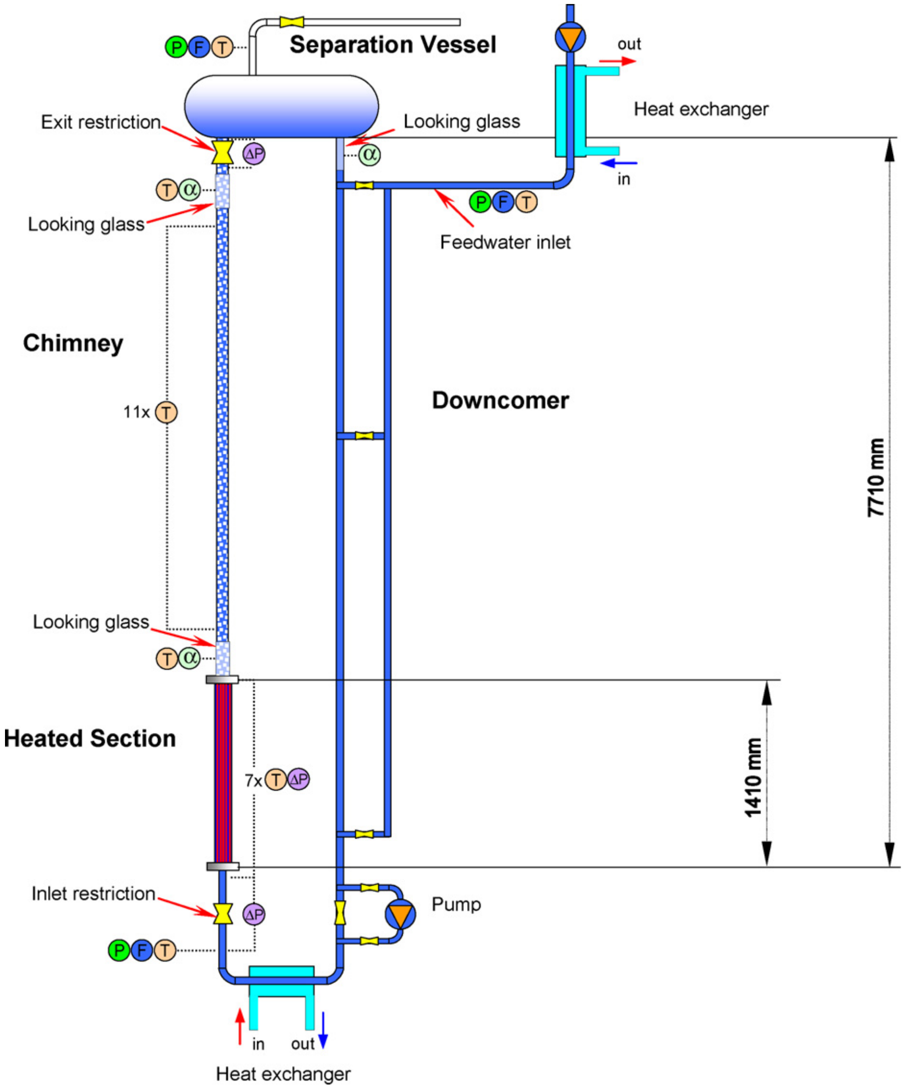


Fig. 1. Schematic (not to scale) of the GENESIS facility (Marcel et al., in press).

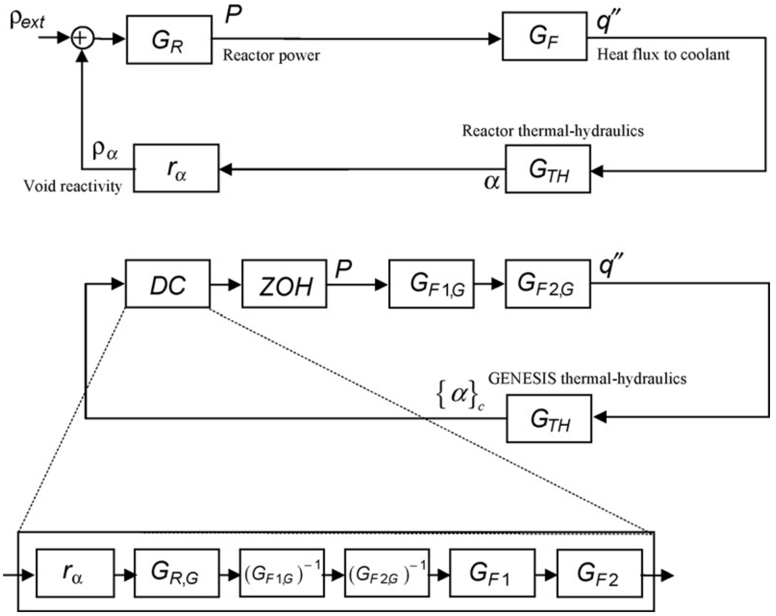


Fig. 2. Schematic overview of the void-reactivity feedback in the ESBWR (top) and in the experimental setup (bottom).

dynamics of a reactor is very sensitive to the void-reactivity feedback, existing techniques have been refined in order to reduce the uncertainty of the results as much as possible. Such refinements comprise the use of very fast sensors (pressure, flow), boiling boundary dynamics and the application of higher-order dynamics regarding the heat transfer taking place inside the ESBWR fuel rods.

2.2.1. *The digital controller*

The digital controller adjusts the applied heat to the heating rods according to the average void fraction as measured in the core section. A schematic overview of the system is shown in Fig. 2.

The boxes in Fig. 2 represent transfer functions that relate physical input and output quantities present in the system. The top figure in Fig. 2 shows that a perturbation in the reactivity perturbs the power (G_R), the heat flux (G_F), the average vapor in the bulk of the coolant (G_{TH}) and, again, the reactivity (r_α). In the GENESIS facility, a perturbation in the power perturbs the heat flux, where $G_{F1,G}$ and $G_{F2,G}$ represent the transfer functions of the heat transport within the rod and the heat transport from the rod surface to the bulk of the coolant, respectively. The thermal-hydraulics in the facility then determines the perturbation in the core averaged void fraction $\{\alpha\}_c$ (G_{TH}), which finally determines the response to the applied power. Note that the void-fraction signal is corrected by the digital controller in such a way that the heat transfer dynamics of the GENESIS heating rods is replaced by the dynamics of the ESBWR fuel rods. Finally, the dynamics of the thermal-hydraulics in both the GENESIS facility and the ESBWR are assumed to be the same, as this has been the purpose of the downscaling as described in Section 2.1.

2.2.2. *Determination of the average core void fraction $\{\alpha\}_c$*

The average void fraction in the core is determined by measuring the pressure drop over the core and by applying an iteration step regarding the momentum balance, thereby adjusting the core exit quality step by step. The different terms in the momentum balance are

- Single-phase regime (below the boiling boundary)
  - Friction due to the walls, $f_1 = 0.079Re^{-0.25}$ (Zhang and Webb, 2001)
  - Friction due to the spacers, $k_{sp} = 1.5$ (experimentally determined)
  - Gravitation
- Two-phase regime (above the boiling boundary)
  - Friction due to the walls (Zhang and Webb, 2001),

$$f_1 = 0.079Re^{-0.25},$$

$$\phi_{LO}^2 = (1-\chi)^2 + 2.87\chi^2\left(\frac{p}{p_c}\right)^{-1} + 1.68\chi^{0.8}(1-\chi)^{0.25}\left(\frac{p}{p_c}\right)^{-1.64},$$

where $p/p_c = 0.26$

  - Friction due to the spacers, $k_{sp} = 1.5$, $\phi_{LO}^2 = \left(1 + \left((1/N_\rho) - 1\right)\chi\right)$ (Todreas and Kazimi, 1990)
  - Acceleration
  - Gravitation,

where f_1 is the liquid wall friction factor, k_{sp} the friction coefficient for the spacer and ϕ_{LO} is the two-phase multiplier and p/p_c the reduced pressure (p_c is the critical pressure). The inertial term has been neglected, since this term is small compared to the others. The assumptions with respect to the momentum balance are (i) application of the Homogeneous Equilibrium Model, (ii) a linear quality profile starting from the boiling boundary, (iii) no void accumulation near the spacers and (iv) no sub-cooled boiling region in the core section.

Finally, the position of the boiling boundary is needed to be able to determine the core averaged void fraction. The simplest way of determining the position of the boiling boundary would be by assuming that the length of the single-phase region instantaneously changes with the applied heat via $z_{bb} = (T_{sat} - T_{in})\dot{m}c_p(q')^{-1}$. In reality, however, the dynamics of the boiling boundary follows the dynamics of transfer of heat from the inside of the rod to the bulk of the coolant and is assumed to be described by the single time constant τ_{FG} (see Section 2.2.5).

2.2.3. *From average void fraction to reactivity*

Although the power profile in the ESBWR is far from axially homogeneous, the profile of the heating rods in the GENESIS facility is. With such an axially flat profile the reactivity effect of void produced somewhere in the core is independent of the axial position

Table 3
Data on the delayed neutron groups

i	β_i	λ_i (s^{-1})
1	0.03	1.25×10^{-2}
2	0.21	3.06×10^{-2}
3	0.19	1.15×10^{-1}
4	0.39	3.11×10^{-1}
5	0.13	1.21
6	0.05	3.20

Neutron generation time Λ (s): 50 μs; effective delayed neutron fraction β: 0.00562 (MOC). MOC refers to Mid-Of-Cycle.

of production. Void traveling from one position to the other leads to no reactivity change; the void reactivity effect is purely determined by the integral void fraction in the core. The reactivity was therefore calculated according to $\rho = r_\alpha \delta\alpha$, where $\delta\alpha$ represents the deviation from the average void fraction (for a critical reactor) in the core and r_α the reactivity coefficient for a MOC profile ($r_\alpha = -1.03 \times 10^{-3}$) (Rohde et al., 2006).

2.2.4. From reactivity to power

The power is calculated by using the point-kinetic equations for the neutron density and the six neutron precursor densities. The data for the delayed neutrons can be found in Table 3. Note that the decay constants λ_i for the delayed groups are adjusted to the time scaling as described by Eq. (4).

2.2.5. From power to heat flux to the bulk of the coolant

Since electrically heated rods have been used, the dynamics of heat transport within the rods is different from the dynamics of the ESBWR fuel rods. Moreover, the dynamics of the heat transport from the surface of the rods to the bulk of the coolant differs, because of the different (thermal) properties of water and Freon-134a. We therefore have to artificially apply the ESBWR heat transfer dynamics and 'eliminate' the corresponding dynamics taking place in the GENESIS facility. By doing so, the dynamical behavior of the reactor can be approached.

It is found that the dynamics of power to heat flux regarding the GENESIS facility can roughly be described by a first-order process and, consequently, with one time constant. In the Laplace-domain, we have

$$G_{F1,G}G_{F2,G} = \frac{1}{\tau_{FG}s + 1}, \tag{5}$$

where $\tau_{FG} \approx 0.5$ s for the Freon-12 based DESIRE facility (Kok and Van der Hagen, 1999).

The dynamics of the power to the rod surface heat flux (indicated by G_{F1}) taking place in the ESBWR rods cannot be described by a first-order system. The analytic solution for the temperature response within the rod due to a step in power can be described by an analytic relation (Van der Hagen, 1988).

$$T'(r', t') = \sum_{n=1}^{\infty} \frac{2Bi}{\lambda^2(\lambda^2 + Bi^2)} \frac{J_0(\lambda_n r')}{J_0(\lambda_n)} (1 - \exp(-\lambda^2 t')), \tag{6}$$

where all quoted quantities are dimensionless. $Bi = hR/k$ is the Biot number, λ_n the nth root of geometry characteristic equations and J_0 is the zeroth-order, first kind Bessel function. The heat transfer coefficient is denoted with h, R is the rod radius and k is the conductivity of the rod material.

Table 4
Heat resistances in a typical ESBWR fuel rod and the boiling water layer

Material	Heat resistance (m^2K/W)
Fuel pellet	1.67×10^{-3}
Gap	1.40×10^{-4}
Cladding	5.62×10^{-5}
Convective, boiling water boundary layer (Chen, 1963)	2.95×10^{-5}
Total resistance	1.88×10^{-3}

Thermal properties were obtained from General Electric.

From this relation, the heat flux at the surface of the rods can be calculated for this specific case. The heat flux can be approximated with a second-order system within the range of $t = 0, \ldots, 4$ (s) and can be described by the next transfer function

$$G_{F1} = \frac{1}{\tau^2 s^2 + 2\zeta\tau_F s + 1}. \tag{7}$$

where $\tau_F = 1.01$ s and $\zeta = 2.78$ (corresponding to the two time constants $\tau_1 = 5.42$ s and $\tau_2 = 0.188$ s).

The process of heat transfer from the surface of the rods to the bulk of the boiling water is much faster than the heat transfer within the rods. A simple analysis of the heat resistance of each material (fuel pellets, gap, cladding, flowing boiling water boundary layer) shows that most of the heat resistance can be found in the fuel pellet (see Table 4). The transfer function G_{F2} can therefore be neglected. Hence,

$$G_{F2} \approx 1 \tag{8}$$

3. Numerical tools

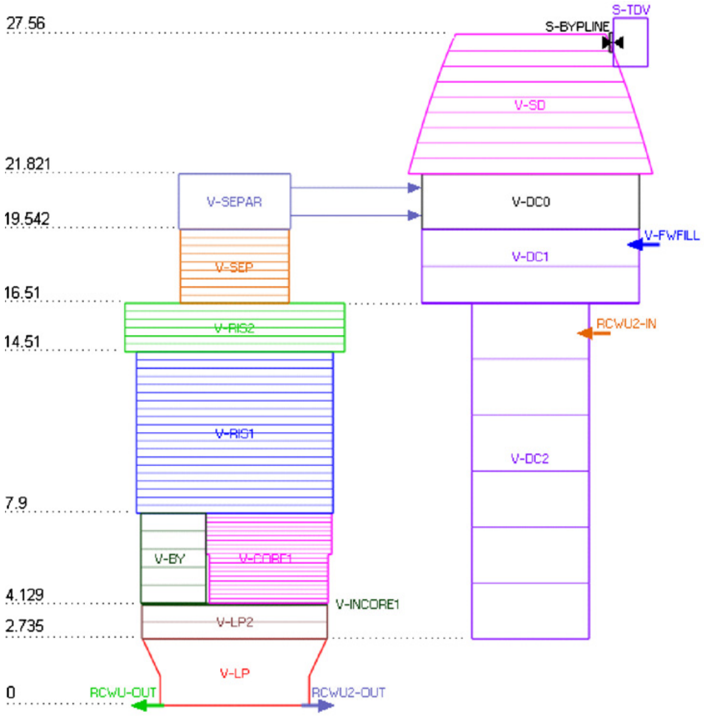
3.1. Athlet

3.1.1. Model description

A nodalization of the ESBWR reactor has been developed for the ATHLET 2.0A code (Austregesilo et al., 2003). The core is modelled with a single fuel channel and a single bypass channel. A constant pressure boundary condition (set to the nominal value of 7.171 MPa) is imposed. A controller is added to adjust the feed-water flow rate in order to match the steam flow rate and to keep the water level in the steam separators at the prescribed nominal value. The power produced in the core is modelled by means of point-kinetic neutronics with six groups of delayed neutrons. The guide tubes present in the lower plenum are not modelled since they are characterized by stagnant water and therefore have no role in density wave instabilities and power-flow performances. A scheme of the nodalization is shown in Fig. 3.

The five-equation model is used for the simulation, which consists of separate mass and energy balances for liquid and vapor phase and a common momentum balance combined with a drift-flux model. A multi-purpose drift-flux model package is used in ATHLET (Sonnenburg, 1991), which provides different models for different geometries as vertical pipes, vertical bundles, vertical annuli, horizontal pipes. A mixture level-tracking model is used for the evaluation of the boundaries between single- and two-phase regions. Such a model reduces numerical diffusion and produces therefore more accurate results, especially with regards to the estimation of stability characteristics.

The Martinelli–Nelson correlation is selected for the evaluation of the friction pressure drops. A special model (ATHLET steam separator component) is adopted to model the steam separator. Such a component consists of two parts, the first (V-SEPAR) simulating the steam separator pipes and the latter (V-DC0) simulating the volume containing the water level. The model forces the steam upward towards the steam dome and the liquid below the water level, in the downcomer section.



Component	Name	Nodalization
Lower plenum	V-LP	Branch
	V-LP2	Pipe (N=2)
Core section	V-INCORE	Pipe (N=1) N_{chan}=1132
	V-CORE	Pipe (N=20) N_{chan}=1132
Core bypass	V-BY	Pipe (N=5)
Partitioned riser	V-RIS1	Pipe (N=20)
Common riser	V-RIS2	Pipe (N=6)
Separator	V-SEP	Pipe (N=9) N_{chan} = 371
	V-SEPAR	Separator N_{chan} = 371
Downcomer	V-DC2	Pipe (N=6)
	V-DC1	Pipe (N=2)
	V-DC0	Branch
Steam dome	V-SD	Pipe (N=9)

Fig. 3. Nodalization of the ESBWR with ATHLET 2.0A. Elevations are reported in meters. N denotes the number of axial nodes and N_{chan} is the number of parallel channels.

The k-factor for the inlet of the bypass section was tuned in order to achieve a bypass flow of about 12% of the core flow, according to specifications.

3.2. TRACG

The TRACG computer code is used by GE for the analysis of ESBWR stability margins. TRACG is a General Electric (GE) proprietary version of the Transient Reactor Analysis Code (TRAC) (U.S. NRC, 2007). TRACG uses advanced one-dimensional and three-dimensional methods to model the phenomena that are important in evaluating the operation of BWRs. TRACG has been approved by the USNRC for ESBWR stability analysis.

TRACG has a multi-dimensional, two-fluid model for the reactor thermal-hydraulics and a three-dimensional reactor kinetics model. The models can be used to accurately simulate a large variety of test and reactor configurations. These features allow for realistic simulation of a wide range of BWR phenomena, and are described in detail in the TRACG Model Description Licensing Topical Report (Andersen et al., 2001).

TRACG uses a fully implicit integration technique for the heat conduction and hydraulic equations when integrating from time step n to time step $n+1$. In the implicit formulation, the convective terms are calculated based on the new properties at time step $n+1$. For time domain stability calculations, a semi-explicit integration technique is employed for the fuel channel component. To minimize numerical damping, the semi-explicit scheme evaluates the convective terms at time step n instead of the new time step $n+1$. For this numerical scheme, the Courant limit sets the maximum time step size based on the fluid velocity and length of the nodes in the core. Typical node lengths are of the order of 15 cm, with smaller nodes at the bottom of the fuel channel.

TRACG has been extensively qualified against separate effects tests, component performance data, integral system effects tests and operating BWR plant data. The TRACG thermal-hydraulic instability modeling using the semi-explicit integration scheme has been evaluated for adequacy by comparison to experimental data from the FRIGG facility (Andersen et al., 1989). Plant data from operating BWRs (e.g. LaSalle 2, Leibstadt, Peach Bottom) have been used to validate TRACG predictions of core-wide and regional stability.

4. Results

In the experiments as well as in the simulations, the decay ratio and resonance frequencies have been determined for a range of operational points. In order to obtain this data, the response of the core inlet flow-rate to a perturbation of the pressure (ATHLET) or reactivity (GENESIS) was fitted to the response of a third-order model. The operational points can be indicated with a specific point in the stability map (N_{Zu}, N_{sub}), where N_{Zu} is proportional to power/flow and N_{sub} is proportional to $h_{sat}-h_{inlet}$. The nominal point of the ESBWR can be found at

$$(N_{Zu}, N_{sub}) = (5.5, 0.9), \tag{9}$$

where N_{Zu} is based on the power and flow rate related to a bundle without by-pass. Both the thermal-hydraulic system (i.e. without any reactivity feedback) and the reactor has been studied.

4.1. The power to flow and power to heat flux maps

It is important to investigate whether for each applied power, the appropriate mass-flux/mass-flow occurs. If it does so, each point in the $N_{Zu}-N_{sub}$ plane represents both the ESBWR and the GENESIS facility/ATHLET description at equal conditions. The power to heat flux map and the power to flow maps are given in Fig. 4.

Since no by-pass has been applied in the experimental work, a direct comparison between the numerical and experimental results should be made with the help of the power-mass flux map instead of the power-flow map. For completeness, however, the power-flow map is also given. When the flow rate is corrected for the relative contribution of the by-pass flow to the total flow rate (being a multiplication or division by a factor of 1.1, since the by-pass flow is

Table 5
Derivation of the nominal Zuber-number and the upscaling of operational parameters from GENESIS scales to ESBWR scales

	TRACG	ATHLET	GENESIS	GENESIS upscaled
Linear power per rod (kW/m)	14.4	14.4	0.740	14.3
Latent heat (kJ/kg)	1.50×10^3	1.50×10^3	1.58×10^2	1.50×10^3
Liquid density (kg/m^3)	7.38×10^2	7.38×10^2	1.13×10^3	7.38×10^2
Vapor density (kg/m^3)	37.1	37.1	56.5	37.1
Core length (m)	3.00	3.00	1.41	3.00
Bundle cross-sectional area (m^2)	8.895×10^{-3}	8.895×10^{-3}	4.95×10^{-4}	8.98×10^{-3}
Core mass-flux (kg/m^2 s)	993	1012	1040	993
Core mass flow (kg/s)	10,003	10,193	0.5148	10,009
By-pass mass flow (kg/s)	1200	1272	–	–
Zuber-number	5.61	5.47	5.58	5.58

10% of the total flow rate), it can be seen that the power-flow maps match each other also.

Fig. 4 shows that the mass-flux and flow match for all powers, hence, via the scaling rules $q_{\mathrm{GENESIS}}/q_{\mathrm{ESBWR}} = 0.0244$ and $G_{\mathrm{m,GENESIS}}/G_{\mathrm{m,ESBWR}} = 1.047$, the nominal conditions with respect to the Zuber-number are the same for both systems (see Table 5).

4.2. Results for a thermal-hydraulic system

The decay ratios and resonance frequencies are shown in Fig. 5 for a large range of operational conditions. The values for the nominal point are given in Table 6. Note that the GENESIS frequencies are rescaled to ESBWR scales in order to facilitate the comparison.

It is clear that the numerical results show a less stable system than the experimental results; within the overlapping range, the decay ratio in the upper left figure varies in the range of DR ≈ 0.1–0.5, whereas the decay ratio in the upper right figure is roughly constant (DR ≈ 0.1). The resonance frequency appears to be rather constant for the overlapping region in the $N_{Zu} - N_{\mathrm{sub}}$ plane. The numerical and the experimental values correspond well and amount to $f \approx 0.1$ Hz.

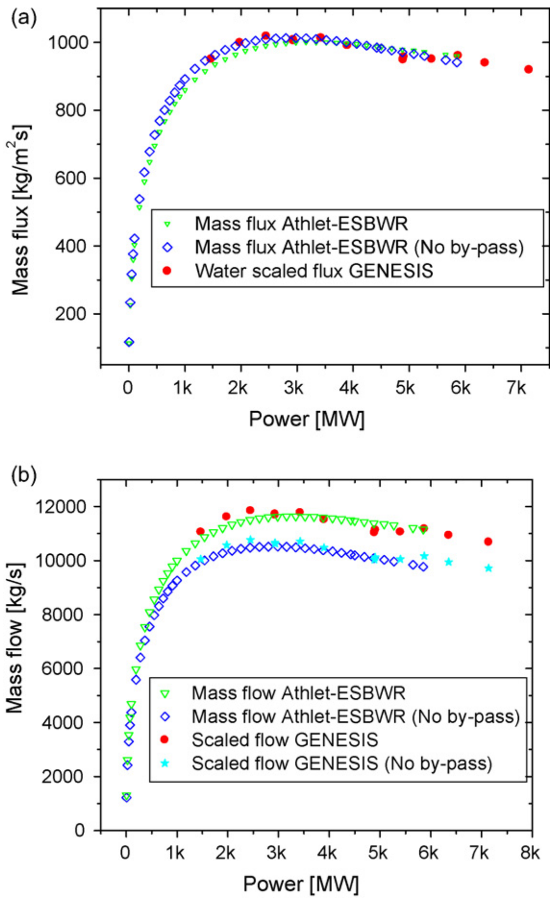


Fig. 4. Power to mass flux (a) and power to flow (b) as found in the numerical and experimental studies. The experimental results have been converted to ESBWR scale. In the right figure, a fixed by-pass flow of 10% of the core mass flow is used. In reality, the by-pass flow varies between 8.9% and 14% in the 1.5–5.9 GW range.

Table 6
Thermal-hydraulic stability characteristics for the nominal operational point

	ATHLET	GENESIS
Decay ratio	0.11	0.12
Resonance frequency (Hz)	0.13	0.11

The GENESIS values are obtained by applying a linear interpolation in the stability map.

The measured and calculated stability characteristics for the nominal operational point correspond very well. Since a purely thermal-hydraulic system is considered here, the resonance frequency is much lower than the frequency in the reactor system and is determined by the residence time of density waves in the upward flow sections. As expected, the oscillation period is roughly twice the traveling time through the core and chimney sections (about 5 s) (Rizwan-uddin, 1994; Zboray, 2002).

4.3. Results for the reactor system

The decay ratio and resonance frequency are given in Fig. 6. Again, the GENESIS frequencies are rescaled to ESBWR scales in order to facilitate the comparison. In general, the numerical as well as the experimental results show that the ESBWR is stable. It can also be seen that also for the reactor system, the ATHLET calculations predict a less stable system than the experiments do. The ATHLET stability boundary is situated around the sub-cooling-number $N_{\mathrm{sub}} \approx 1.5$ (corresponding to a margin for inlet temperature of 6 K) for the largest range of Zuber-numbers, whereas no decay ratio higher than 0.9 was found in the experiments (margin for the inlet temperature >30 K). From both studies, however, the trend of the iso-decay ratio lines is roughly the same. This trend is to be expected, as can be seen in numerous stability studies (e.g. Van Bragt et al., 1998a,b; Zboray et al., 2001). The resonance frequencies are roughly the same for both the numerical and the experimental studies. The frequency should be much higher than in the case of a system without void-reactivity feedback, since the oscillations are merely driven by the friction in the core section.

The values for the nominal operational point are shown in Table 7. Since TRACG results were available for this specific point, these results are added to the table. The frequencies correspond to the rule that the oscillation period should be between 1.5 and 2 times the traveling time through the core section (being about 1 s) (Rizwan-uddin, 1994; Zboray, 2002). Note the excellent agreement between the GENESIS results and the TRACG results.

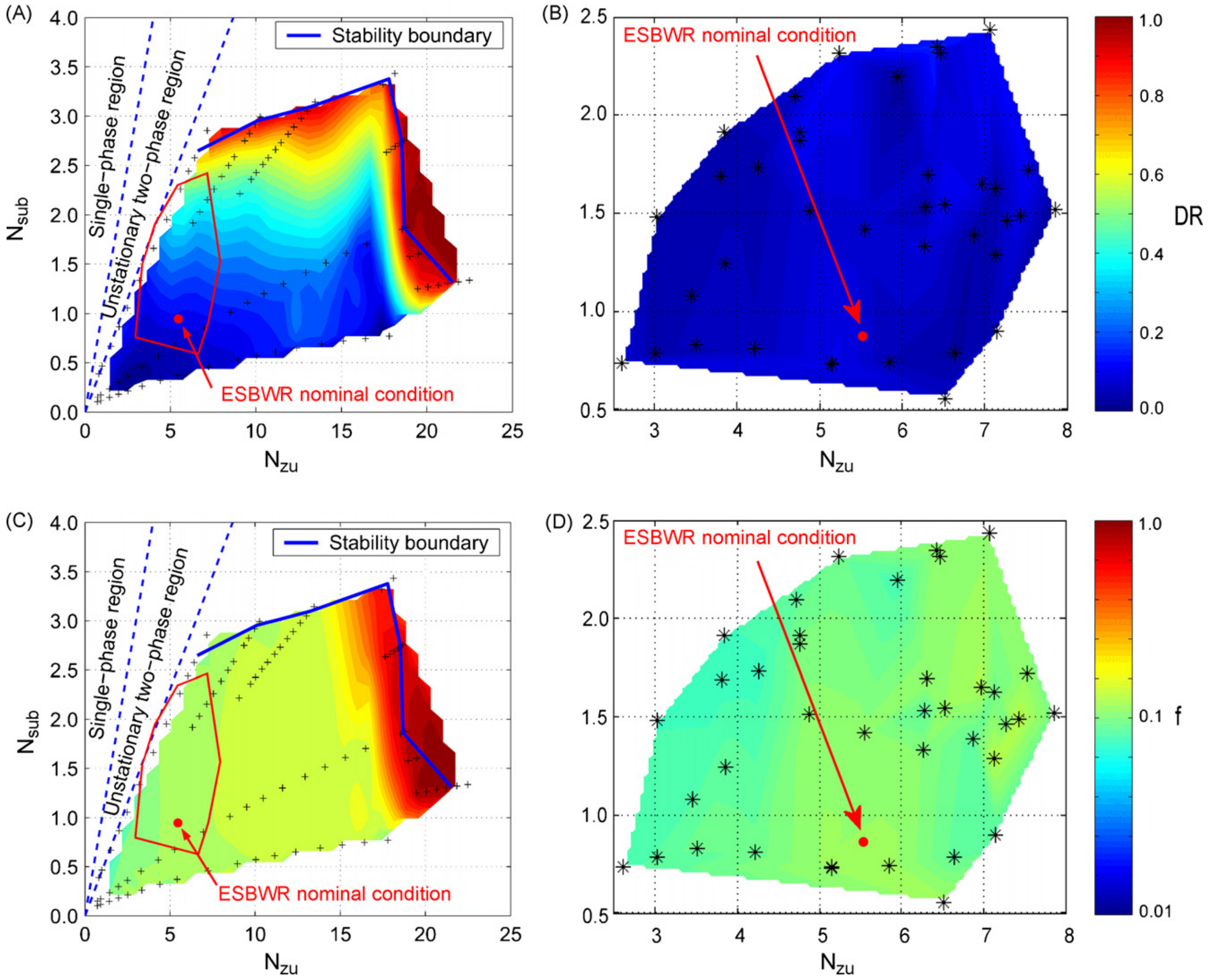


Fig. 5. The decay ratio (numerical A, experimental B) and the resonance frequency (numerical C, experimental D) without reactivity feedback, represented in a stability map. The smaller, experimental region is shown in the numerically obtained stability map.

5. Final considerations and conclusions

In this paper, great care has been taken to approximate the ESBWR and its conditions as close as possible so that

- the stability of the ESBWR can be studied by both a numerical and an experimental tool,
- a comparison between different tools simulating the same complex system can be made.

First of all, drawing clear-cut conclusions from the stability study is a very difficult task since a large number of aspects needs to be considered. Moreover, most uncertainties are unknown in the quantitative (or even in the qualitative) sense. In spite of the uncertainties, however, the data obtained by the experiments as well as the ATHLET and TRACG calculations clearly show margins to stability for the ESBWR at the nominal point.

Table 7
Reactor-kinetic stability characteristics for the nominal operational point

	ATHLET	GENESIS	TRACG
Decay ratio	0.64	0.30	0.33
Resonance frequency (Hz)	0.66	0.75	0.74

The GENESIS values are obtained by applying a linear interpolation in the stability map.

Table 8 shows a list of aspects that introduce uncertainties with respect to the real ESBWR system, which will be discussed in the following.

Regarding the GENESIS uncertainties, the following can be said:

- It has been shown that the scaling distortions induced by the friction can be compensated by adjusting the chimney exit friction (Marcel et al., in press).
- Regarding the void-reactivity feedback system, the HEM approximation tends to overestimate the void fraction in the core section. Since we are only concerned with the void fraction *perturbations*, however, we think that the influence on the stability is small. Besides, the spacers tend to homogenize the two-phase mixture, making the HEM assumptions more valid.

Nevertheless, the core friction distribution, the uniform flow profile and the point-kinetic neutronics, could give a significant contribution to the experimental uncertainty:

- It is well-known that a top-peaked power profile results in a more stable system than a bottom-peaked profile (Zboray, 2002). A uniform power profile, being an intermediate between those two

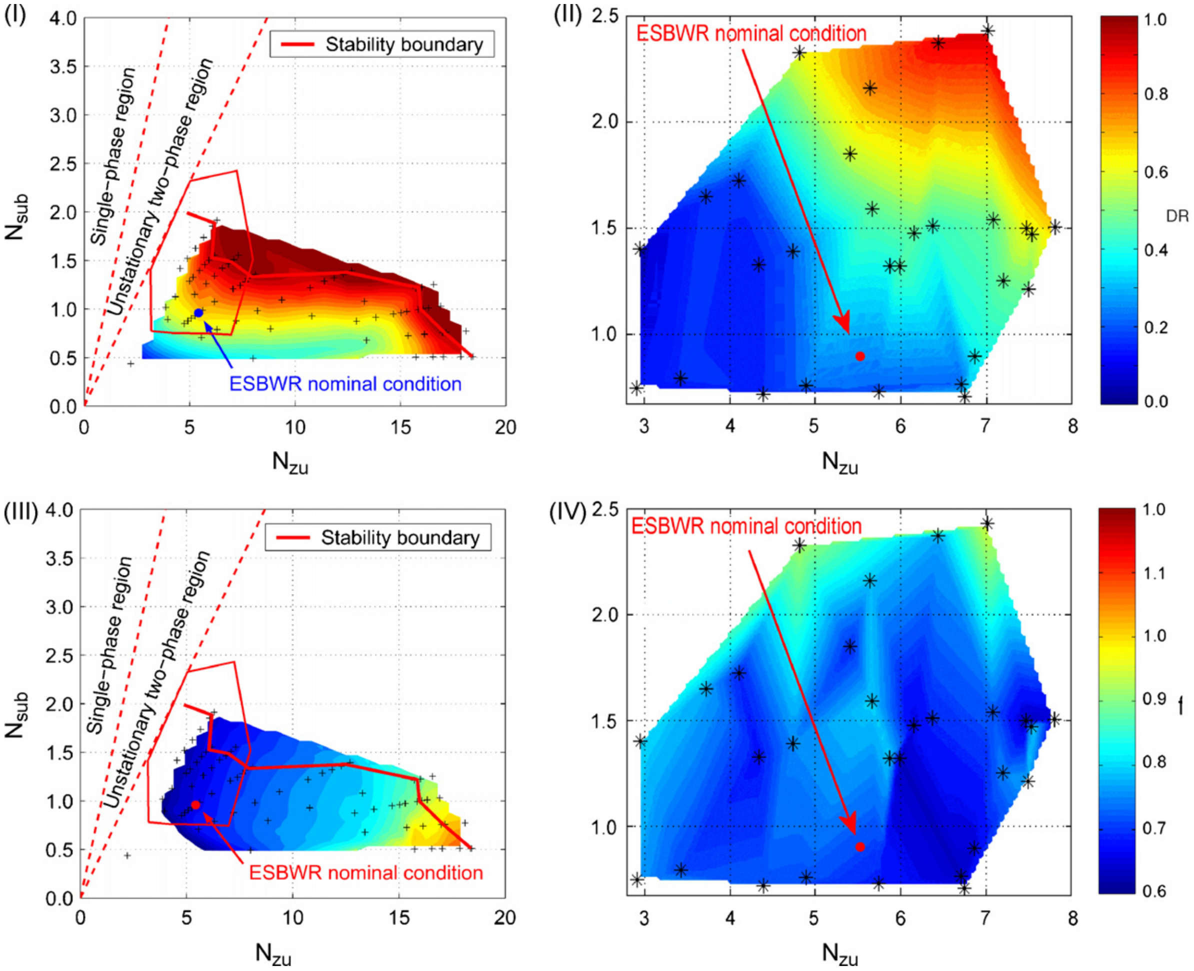


Fig. 6. The decay ratio (numerical I, experimental II) and the resonance frequency (numerical III, experimental IV) with reactivity feedback, represented in a stability map. The smaller, experimental region is shown in the numerically obtained stability map.

Table 8
Uncertainties of numerical and experimental tools used with respect to the real ESBWR system

GENESIS	ATHLET	TRACG
Uniform power profile	Single-channel approximation	
Scaling distortions: more wall friction due to 5 × 5 bundle instead of 10 × 10 bundle; higher friction due to Freon-134a (N_f not scaled)	Fixed pressure in the steam dome	
Point-kinetics neutronics	Point-kinetics neutronics	
Core friction distributed along the core instead of friction condensed at the inlet		
No core by-pass channels		
Void-reactivity feedback: lumped core void fraction; HEM approximation used; no sub-cooled boiling; no void accumulation near spacers; linear quality profile		
DR: unknown	DR: unknown	DR: ±0.1 (Shiralkar et al., 2007)

'DR' refers to decay ratio.

extremes, is therefore expected to give non-conservative results since the ESBWR has a bottom-peaked profile.

- As the friction is uniformly distributed along the core section instead of concentrated at the core entrance, conservative results are to be expected.
- The influence of the absence of the core by-pass channels is conservative from the thermal-hydraulic point of view, as the chimney contains a bit more void, which is destabilizing. From the neutronic point of view, no difference is to be expected since the void reactivity coefficient used includes the presence of core by-pass channels (strictly speaking, this reasoning only holds when the corresponding r_α is taken for each operational point in the $N_{Zu} - N_{\mathrm{sub}}$ plane. In the experiments, however, a constant coefficient has been used for all operational points).

The ATHLET code is a general system code that has been validated for a number of cases (see e.g. Krepper, 1999). Unfortunately, no quantitative data exists regarding uncertainties in the decay ratio. Sources of uncertainties are the single-channel approximation (the conditions in all 1132 parallel channels are the same), the fixed pressure boundary condition and the point-kinetic neutronics. Due to the fixed pressure boundary in the steam dome, the ATHLET results are conservative, since the feedback due to the compression of the steam cushion in the steam dome has not been taken into account. This feedback would provide a stabilizing effect.

The uncertainties in the TRACG calculations have been quantified through extensive validation, and Monte–Carlo analysis yields an uncertainty of the order of 0.1 in the core decay ratio (Shiralkar et al., 2007). Hence, even with a very detailed description of the ESBWR and its physical phenomena taking place (e.g. multi-channels, three-dimensional neutronics, component-specific thermal-hydraulics models), a certain, non-negligible uncertainty has to be taken into account.

The comparative study shows that, even though great attention has been paid to modeling the ESBWR system as accurate as possible (numerically as well as experimentally), predicting the stability of a boiling water reactor remains a challenge. Results from such stability studies should therefore be taken with care.

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