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Technical Note

Fractional Scaling Analysis for IRIS pressurizer reduced scale experiments

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ABSTRACT

About twenty organizations joined in a consortium led by Westinghouse to develop an integral, modular and medium size pressurized water reactor (PWR), known as international reactor innovative and secure (IRIS), which is characterized by having most of its components inside the pressure vessel, eliminating or minimizing the probability of severe accidents.

The pressurizer is responsible for pressure control in PWRs. A small continuous flow is maintained by the spray system in conventional pressurizers. This mini-flow allows a mixing between the reactor coolant and the pressurizer water, warranting acceptable limits for occasional differences in boron concentrations. There are neither surge lines nor spray in IRIS pressurizer, but surge and recirculation orifices that promote a circulation flow between primary system and pressurizer, avoiding power transients whether outsurges occur.

The construction of models is a routine practice in engineering, being supported by similarity rules. A new method of scaling systems, Fractional Scaling Analysis, has been successfully used to analyze pressure variations, considering the most relevant agents of change.

The aim of this analysis is to obtain the initial boron concentration ratio and the volumetric flows that ensure similar behavior for boron dispersion in a prototype and its model.

1. Introduction

The availability of pertinent experimental data is normally a regulatory requirement and, at the same time, a manufacturer's need to validate designed equipments and facilities. Real size test facilities are often extremely expensive and usually unpractical. Therefore, scaled experiments are a useful and practical resource to get more affordable proof of performance. They help to uncover any remaining small flaws of the design and provide a means to optimize design parameters.

The similarity of prototypes and their respective scaled models is a key issue in their wise use for the phenomena and processes of interest. The art of conceiving and designing scaled models rely on methods that normally use dimensionless groups linking the designed installation to its model.

It is the understanding of the relevant phenomena together with dimensional analysis that make possible the generalization of experimental data. Choices of which phenomenon or process should be best represented are mandatory. Sometimes more than one model has to be constructed to assure good performance and safety characteristics if the list of processes and phenomena that have to be considered is too large. Anyway the synthesizing possibilities offered by wisely scaled models together with dimensional analysis result in a well selected and reduced number of experiments capable of elucidating and validating design features, which economize time and money.

Zuber (2001) has discussed the effects of complexity, simplicity and scaling in thermal–hydraulics and has proposed a new paradigm called, at the time, "Fractional Change, Scaling and Analysis" method. The intended purpose was to: (a) ensure economy and efficiency in addressing and resolving technical problems and (b) enable a "cultural cross-pollination" between different disciplines as the method propitiates many analogies among various fields of knowledge. One of the discussed applications was the opportunity to produce a quantitative hierarchy of the important phenomena in a loss of coolant accident. This would reduce the degree of subjectiveness in ranking them according to their importance and to produce a more efficient phenomena identification and ranking table.

An integrated set of three papers presented a new scaling methodology know as Fractional Scaling Analysis. The first one (Zuber et al., 2005) put together the general theory and presented conjectures on the many possible uses of the method, while the second

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Nomenclature

Symbols		Subscripts	
C	boron concentration (dimensionless)	0	initial; reference
M	mass (kg (kilogram))	a	primary system (reactor coolant)
Q	volumetric flow (m^3/s (cubic meter per second))	E	external reservoir
q	reservoir volumetric flow (m^3/s (cubic meter per second))	f	final
S	scale factor (dimensionless)	in	inlet (entering the pressurizer)
t	time (s (second))	j	index
V	variable; pressurizer liquid volume (m^3 (cubic meter))	m	model
v	primary system volume (m^3 (cubic meter))	out	outlet (leaving the pressurizer)
w	mass flow (kg/s (kilogram per second))	p	prototype
		ref	reference
Greek letters		*Superscripts*	
δ	variation	$\times$, ^	dimensionless
ρ	fluid density (kg/m^3 (kilogram per cubic meter))	m	model
ϕ	agent of change	p	prototype
Ω	fractional change (effect metric)	$'$	primary system
ω	fractional rate of change (1/s (inverse of second))	–	average

one (Wulff et al., 2005) focused on its application at the system level to collect and synthesize results from depressurization experiments in different test facilities. Finally, the third paper focused on the application at the component level, scaling peak clad temperature (Catton et al., 2005).

With Fractional Scaling Analysis, the conditions of operation have been obtained to design a test section preserving similarity between model and prototype. A test section shall be built based upon the preceding method, providing experimental data that will help in constructing full-scale IRIS pressurizers.

2. Theory

From the early stages of IRIS design, it has been observed (Barroso and Baptista, 2004) that the IRIS integral configuration allowed a significant increase in the ratio of pressurizer volume to reactor power when compared with loop PWRs. In IRIS this ratio is more than three times greater than in the AP600 reactor (77 m^3/1000 MW for IRIS versus 45.3 m^3/1940 MW for AP600), which is actually the advanced plant design with the most favorable ratio among loop PWRs. IRIS pressurizer is located in the pressure vessel upper head, above the internal control rod mechanisms. This layout is considered optimal for the IRIS design, since it does not dictate the dimensions of the vessel, operates with closure flanges at a uniform temperature, and maximizes the overall pressurizer volume, while providing adequate space for placements of the reactor coolant pumps and internal control rod drive mechanisms.

On one hand, because of this extra capability to attenuate pressure variations, no spray was necessary, which is a very good feature, as the implementation of a pressurizer spray in an Integrated Primary System Reactor design would be very complicated. On the other hand, a pressurizer spray provides a continuous mini-flow that copes with the function to homogenize boron concentration between pressurizer and reactor coolant.

Although IRIS uses a slightly lower boron concentration than conventional PWRs, a means to minimize boron concentration difference of pressurizer and reactor coolant within acceptable bounds has to be provided. This can be done by introducing in the pressurizer basis some recirculation orifices located at points such that there is enough pressure drive between them and the surge orifices, promoting boron homogenization.

The design of a low cost "optimum" test facility intended to achieve the following objectives:

- Small size, low power and low cost.
- Good visibility (transparency) for the test section.
- Maximum similarity at a system level.
- Good flexibility to easily change a few facility parameters from one test campaign to another.

2.1. Fractional Scaling Analysis

As it has been shown by Wulff et al. (2005) and Catton et al. (2005), if one has the global equation relating the variables for which greater fidelity is required, then Fractional Scaling Analysis gives a very precise means to relate the behavior of these variables in similar purpose experiments carried out in different scaled facilities. For the purpose of this work, it will make possible to scale down a facility to fulfill the mentioned objectives and still achieve high similarity for a choice of key variables.

By using Fractional Scaling Analysis method at the system level, an effect metric considering boron concentration within the pressurizer liquid volume is derived, looking upon just one process and one agent of change – the incoming reactor coolant flow with a different boron concentration from that of the pressurizer. By imposing the same effect metric for IRIS and for the test section results in equating the product of their respective fractional rate of change by their clock time.

For a given variable, the Fractional Scaling Analysis paradigm is that systems with the same effect metric for the processes and phenomena of interest are similar. The following concepts are used to define such metric. If one considers a region of space characterized by a state variable V, that undergoes change caused by an agent ϕ, then:

$$\frac{dV}{dt} = \phi \tag{1}$$

The fractional rate of change of V is defined by:

$$\omega = \frac{1}{V}\frac{dV}{dt} = \frac{\phi}{V} \tag{2}$$

If one considers a perturbation δV from a steady state value V_0, the fractional change or effect metric is defined by:

$$\Omega = \frac{\delta V}{V_0} \tag{3}$$

which, combined with Eq. (3), may also be given by:

$$\Omega = \omega \cdot \delta t = \frac{\phi}{V_0}\delta t \tag{4}$$

Wulff et al. (2005) have used this framework to synthesize pressure–time evolution in loss of coolant accident experiments for LOFT and semiscale facilities. Catton et al. (2005) also have done a similar study for peak clad temperature.

3. Methodology

During the startup or shutdown, boron concentration must be changed by an insertion process in the reactor coolant. In Eq. (5), C', M' and w' represent instantaneous reactor coolant boron concentration, primary system bulk water mass and water mass flow entering (and leaving) the primary system, respectively, while C_E stands for a constant concentration from an external reservoir that causes change in primary water concentration. It will be admitted a homogeneous model for this analysis.

$$\frac{d(M'C')}{dt} = w'(C_E - C') \tag{5}$$

If one considers C'_0 as the initial reactor coolant concentration, Eq. (5) may be solved, leading to Eq. (6).

$$C' = C_E + (C'_0 - C_E)e^{-\alpha t} \tag{6}$$

$$\alpha = \frac{w'}{M'} \tag{7}$$

As occurred with the reactor coolant concentration, the bulk liquid inside the pressurizer will be modified by a small circulation flow whose concentration, C_{in}, is equal to that given by Eq. (6) (inasmuch it is originated from the primary system). Thus:

$$\frac{d(MC)}{dt} = w(C_{\text{in}} - C) \tag{8}$$

In Eq. (8), M, C and w represent pressurizer bulk liquid mass, pressurizer bulk liquid concentration and circulation flow, respectively. In this last equation, once M and w are constant, only C_{in} and C will be dimensionless by dividing them by their respective maximum value, ensuring dimensionless terms of unity order. In the case of boron dilution, the maximum concentrations are the initial value. The first step is to obtain dimensionless terms:

$$C^\times = \frac{C}{C_0} \tag{9}$$

$$C^\times_{\text{in}} = \frac{C_{\text{in}}}{C_{\text{in},0}} = \frac{C_{\text{in}}}{C'(0)} = \frac{C_{\text{in}}}{C'_0} \tag{10}$$

Inserting Eqs. (9) and (10) into Eq. (8):

$$\frac{dC^\times}{dt} = \frac{w}{M}\frac{C'_0}{C_0}C^\times_{\text{in}} - \frac{w}{M}C^\times \tag{11}$$

Eq. (11) may be written in the following form:

$$\frac{dC^\times}{dt} = \omega_{\text{in}}\phi^\times_{\text{in}} + \omega_{\text{out}}\phi^\times_{\text{out}} \tag{12}$$

in which:

$$\phi^\times_{\text{in}} = C^\times_{\text{in}} \quad \phi^\times_{\text{in}} = -C^\times \quad \omega_{\text{in}} = \frac{w}{M}\frac{C'_0}{C_0} \quad \omega_{\text{out}} = \frac{w}{M} \tag{13}$$

To scale time correctly, Eq. (12) must be divided by the absolute value of the aggregate fractional rate of change, given by Eq. (14):

$$\overline{\omega} = \omega_{\text{in}} + \omega_{\text{out}} = \frac{w}{M}\left(\frac{C'_0 + C_0}{C_0}\right) \tag{14}$$

Thus, Eq. (12) becomes:

$$\frac{dC^\times}{dt^\times} = \hat{\omega}_{\text{in}}\phi^\times_{\text{in}} + \hat{\omega}_{\text{out}}\phi^\times_{\text{out}} \tag{15}$$

in which:

$$\hat{\omega}_{\text{in}} = \frac{\omega_{\text{in}}}{\overline{\omega}} \quad \hat{\omega}_{\text{out}} = \frac{\omega_{\text{out}}}{\overline{\omega}} \quad t^\times = \overline{\omega}t \tag{16}$$

Fractional Scaling Analysis states that each fractional change metric, defined by:

$$\Omega_j = \omega_{j,0}t_{\text{ref}} \tag{17}$$

must be common to all scaled facilities. In the following equations, the m and p indexes refer to model and prototype, while S_t and S_v represent time and volumetric scales, respectively. Then:

$$(\omega_{\text{out}}t)_m = (\omega_{\text{out}}t)_p \quad \therefore \ \frac{t_m}{t_p} = S_t = \frac{\omega_{\text{out},p}}{\omega_{\text{out},m}} \tag{18}$$

By using Eq. (13), Eq. (18) may be written as:

$$S_t = \frac{\left(\frac{w_p}{M_p}\right)}{\left(\frac{w_m}{M_m}\right)} = \frac{\rho^p_{\text{in}}}{\rho^m_{\text{in}}}\frac{\rho^m}{\rho^p}\frac{V_m}{V_p}\frac{Q^p_{\text{in}}}{Q^m_{\text{in}}} = \frac{\rho^p_{\text{in}}}{\rho^m_{\text{in}}}\frac{\rho^m}{\rho^p}S_v\frac{Q^p_{\text{in}}}{Q^m_{\text{in}}} \tag{19}$$

Eq. (19) can be turned to Eq. (20):

$$Q^m_{\text{in}} = \frac{\rho^p_{\text{in}}}{\rho^m_{\text{in}}}\frac{\rho^m}{\rho^p}\frac{S_v}{S_t}Q^p_{\text{in}} \tag{20}$$

In Eq. (20), Q_{in}, ρ_{in} and ρ represent the circulation volumetric flow, its inlet density and the pressurizer bulk liquid density, respectively. As occurred for the outlet effect metric, the inlet change metric must be the same for model and prototype:

$$(\omega_{\text{in}}t)_m = (\omega_{\text{in}}t)_p \tag{21}$$

By combining Eqs. (13), (20), and (21), one has:

$$\frac{t_m}{t_p} = \frac{\omega_{\text{in},p}}{\omega_{\text{in},m}} = \frac{\left(\frac{w_p}{M_p}\right)\left(\frac{C'_{0,p}}{C_{0,p}}\right)}{\left(\frac{w_m}{M_m}\right)\left(\frac{C'_{0,m}}{C_{0,m}}\right)} = \frac{\rho^p_{\text{in}}Q^p_{\text{in}}}{\rho^m_{\text{in}}Q^m_{\text{in}}}\frac{\rho^m}{\rho^p}\frac{V_m}{V_p}\frac{C'_{0,p}}{C_{0,p}}\frac{C_{0,m}}{C'_{0,m}} \tag{22}$$

After simplifying some terms, Eq. (22) turns to Eq. (23):

$$\frac{C'_{0,p}}{C_{0,p}} = \frac{C'_{0,m}}{C_{0,m}} \tag{23}$$

Eq. (23) demands the equality of initial inlet to ambient concentration in the pressurizer for the model and for the prototype. Usually, these concentrations have very close values before a disturbance in concentration starts, making both sides of Eq. (23) nearly equal to one. So, from the physical and analytical points of view, Eq. (23) satisfies the similarity between a prototype and its model.

Another condition established by Fractional Scaling Analysis is the equality of each normalized $\phi^\times_j$. By combining Eqs. (13) and (16), subjected to the initial condition $C^\times(0) = 1$, Eq. (15) may be written as:

$$\frac{dC^\times}{dt^\times} = \frac{\omega_{\text{in}}}{\overline{\omega}}\left[\frac{C_E}{C'_0} + \left(1 - \frac{C_E}{C'_0}\right)e^{-\frac{\alpha t^\times}{\overline{\omega}}}\right] - \frac{\omega_{\text{out}}}{\overline{\omega}}C^\times \tag{24}$$

Since it can be reasonably assumed that evaporation and condensation flows carry no boron content, the total amount and distribution of boron in the pressurizer liquid region is affected only by the circulating flow.

The condition of equality for $\phi^\times_{\text{in}}$ and $\phi^\times_{\text{out}}$ in the model and prototype demands thus:

$$\left[\frac{C_E}{C'_0} + \left(1 - \frac{C_E}{C'_0}\right)e^{-\frac{\alpha t^\times}{\overline{\omega}}}\right]\Bigg|_m = \left[\frac{C_E}{C_0} + (1 - \frac{C_E}{C'_0})e^{-\frac{\alpha t^\times}{\overline{\omega}}}\right]\Bigg|_p \tag{25}$$

$$C^{\times}|_m = C^{\times}|_p \tag{26}$$

No additional comment is necessary for Eq. (26), once the dimensionless terms must be equal due the own nature of scaling. In Eq. (25), the model and prototype will be only described by the same differential equation at any dimensionless time if the respective terms have the same value, i.e.:

$$\left(\frac{C_E}{C_0'}\right)\bigg|_m = \left(\frac{C_E}{C_0'}\right)\bigg|_p \tag{27}$$

$$\left(1-\frac{C_E}{C_0'}\right)\bigg|_m = \left(1-\frac{C_E}{C_0'}\right)\bigg|_p \tag{28}$$

$$\left(-\frac{\alpha}{\varpi}\right)\bigg|_m = \left(-\frac{\alpha}{\varpi}\right)\bigg|_p \tag{29}$$

While Eqs. (27) and (28) establishes the same relation for external reservoir and initial reactor coolant concentrations for maintenance of similarity, Eq. (29) provides the external reservoir flow to keep an identical behavior for the prototype and its model. By using Eqs. (7) and (10), Eq. (29) turns to:

$$\frac{w_m'}{M_m'}\frac{M_m}{w_m}\left(\frac{C_{0,m}}{C_{0,m}'+C_{0,m}}\right) = \frac{w_p'}{M_p'}\frac{M_p}{w_p}\left(\frac{C_{0,p}}{C_{0,p}'+C_{0,p}}\right) \tag{30}$$

But due to Eq. (23), even for different initial inlet and ambient concentration in the pressurizer, Eq. (30) becomes:

$$\frac{w_m'}{M_m'}\frac{M_m}{w_m} = \frac{w_p'}{M_p'}\frac{M_p}{w_p} \tag{31}$$

In Eq. (31), each mass flow from the external reservoir, w', primary system water mass, M', water mass in the pressurizer, M, and circulation water mass flow, w, may be written in terms of appropriate densities, volumes and volumetric flows:

$$w = \rho_{\text{in}} q \quad M = \rho_{\text{in}} v \quad M = \rho V \quad w = \rho_{\text{in}} Q_{\text{in}} \tag{32}$$

In Eq. (32), ρ_{in}, ρ, q, v, V and Q_{in} represent reactor coolant density, pressurizer water density, external reservoir volumetric flow, primary system water volume, pressurizer water volume and circulation flow inside the pressurizer, respectively. Inserting these terms into Eq. (31), one obtains:

$$\frac{q_m}{v_m}\frac{\rho^m V_m}{\rho_{\text{in}}^m Q_{\text{in}}^m} = \frac{q_p}{v_p}\frac{\rho^p V_p}{\rho_{\text{in}}^p Q_{\text{in}}^p} \tag{33}$$

By taking the value of from Eq. (20), Eq. (33) can be put in terms of volumetric and time scales, providing the relation for the external reservoir volumetric flow between model and prototype:

$$q_m = q_p \frac{S_v}{S_t} \tag{34}$$

From Eq. (24), one could think that beyond equality of the terms for ensuring similarity, their respective coefficients should have the same value when comparing a prototype with its model. And they do. From Eqs. (13) and (14):

$$\frac{\omega_{\text{in}}}{\varpi} = \frac{C_0'}{C_0'+C_0} \qquad \frac{\omega_{\text{out}}}{\varpi} = \frac{C_0}{C_0'+C_0} \tag{35}$$

But from Eqs. (13) and (35) have the same value for the model and prototype. Finally, to keep similarity between model and prototype under the same volumetric and time scales used for the external reservoir, the volumetric flow inside the primary system (reactor coolant flow) of the model, $Q_{a,m}$, must obey a similar expression as that of Eq. (34), in which $Q_{a,p}$ represents the volumetric flow inside the primary system of the prototype.

$$Q_{a,m} = Q_{a,p}\frac{S_v}{S_t} \tag{36}$$

4. Application of Fractional Scaling Analysis methodology

An application of Fractional Scaling Analysis will be shown in this section. For IRIS project, the primary system volume, v_p, and volumetric flow, $Q_{a,p}$, are equal to 400 m^3 and 7.18 m^3/s, respectively. While reactor coolant density for IRIS has a value close to 656 kg/m^3, the water density inside the pressurizer approaches 594 kg/m^3. The total circulation flow between primary system and pressurizer and the external reservoir flow are equal to 5.04×10^{-4} m^3/s and 6.3×10^{-3} m^3/s, respectively. For this analysis, it will be supposed, for instance, that the initial boron concentrations in primary system/pressurizer and external reservoir are equal to 1500 ppm and 500 ppm, respectively, indicating a dilution process.

It is desired to build a model by adopting a volumetric scale equal to 1:200. In IRIS project, there are eight surge orifices and eight recirculation orifices connecting the primary system to the pressurizer. Thus, by using one-eighth symmetry and the volume scale factor already mentioned, the model shall have approximately 0.25 m^3 for primary system representation. If a time scale equal to 1:5 is adopted, then, according to Eq. (20) and one-eighth symmetry, a circulation flow close to 1.7×10^{-6} m^3/s must be provided when considering primary system model water with a temperature close to 333 K (60 °C).

According to Eqs. (34) and (36), dilution/boration rates from the external reservoir and primary system flow in the model will be equal to 1.97×10^{-5} m^3/s and 0.0224 m^3/s, respectively, when one-eighth is considered once more. Finally, if one uses an initial boron concentration in primary system/pressurizer for the model equal to 150 ppm, an external reservoir concentration equal to 50 ppm must be utilized to fulfill what is established by Eq. (27).

With these values, the following equations describe boron concentration of the pressurizer for IRIS and its test section during a transient process, even though different conditions of temperature, pressure, time and size are found for these two systems:

$$\frac{dC^{\times}}{dt^{\times}} = 0.5[0.333 + 0.667\exp(-1032t^{\times})] - 0.5C^{\times} \tag{37}$$

$$C^{\times}(0) = 1 \tag{38}$$

5. Conclusions

By utilizing a new method of scaling systems (Fractional Scaling Analysis), three volumetric flows (circulation, external reservoir and reactor coolant) and a concentration relation to design a test section for simulating boron dispersion inside IRIS pressurizer were stated.

It was shown that the operation conditions for the most important physical parameters of the test section can be obtained, supplying reliability for prototype construction. For a future work, fixing a volumetric scale, the time scale and inlet water temperature in the model pressurizer can be obtained by an optimization process.

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