Proceedings of the 14th International Conference of the Croatian Nuclear Society
Zadar, Croatia, June 9 – 12, 2024 *Paper No. 120*

Analysis of BEPU-Approached Multi-Physics Wall-to-Fluid Single Phase Friction Pressure Drop

HAMIDREZA YOUSEFI 1,* , VINCENZO ZINGALES 2, FRANCESCO SAVERIO D'AURIA 4
Nuclear Research Group of San Piero a Grado (GRNSPG), University of Pisa (UNIPI)
San Piero a Grado, 56100 Pisa, Italy
h.yousefi@studenti.unipi.it, v.zingales@studenti.unipi.it, francesco.saverio.dauria@unipi.it

Grégory Lefèvre 3
Chimie ParisTech, PSL Research University, CNRS, Institut de Recherche de Chimie Paris (IRCP),
Paris F-75005, France
gregory.lefevre@chimieparistech.psl.eu

HAMIDREZA YOUSEFI 1, NICOLA FORGIONE 5
DICI, University of Pisa, Largo Lucio Lazzarino 2, 56122, Pisa, Italy
nicola.forgione@unipi.it

Abstract

Over the last few decades, the aim in Nuclear Reactor Safety (NRS) research and licensing has been to transition from conservative model use, which was widely used in the early stages of the nuclear industry, to the Best Estimate Plus Uncertainty (BEPU) approach in order to increase the accuracy of results to increase reactor output power safely. Furthermore, this decision is made to cover the increase in complexity of physics (i.e. Natural Circulation (NC), Passive Safety Systems) used in nuclear reactors, despite a reduction in the number of active mechanical parts. The central pillars of BEPU which are the selection of realistic Boundary and Initial Conditions (BIC) along with the adoption of an accurate model implemented in the Best Estimate (BE) System Thermal-hydraulic (SYS TH) Code, and uncertainty quantification methodologies should provide the reference for future works.

Among the 116 Thermal-Hydraulic Phenomena (THP) for Water Cooled Nuclear Reactors (WCNRs) that are unique within the studied range of variables, the wall-to-fluid friction pressure drop (PD) as a Basic Phenomenon (BP) that can have a severe impact on the overall behavior of a thermal-hydraulic (TH) system. In fact, in normal operation conditions of NC systems, the efficiency of heat removal in the primary system is strongly dependent on PDs whereas, in off-normal scenarios, meeting Emergency Core Cooling System (ECCS) criteria may be subject to the influence of PDs along injection lines. Furthermore, this THP has an empirical origin, meaning there exists an integration domain in friction PD explicit formulas based on Re number and relative roughness, while some geometries used in Nuclear Power Plants (NPP) may not fulfill the requirements of this integration domain.

One of the main sources of uncertainty in friction factor calculations is the selection of an appropriate value for absolute roughness. The selection of the right value for roughness can become difficult because of the possible evolution of the surface of the hydraulic component concerning time. Indeed, the initial surface condition of the alloys can evolve on contact with the cooling solutions, by the growth of corrosion products, or by the deposition of particles resulting from this corrosion. Thus, roughness can change both with aging also based on different stages in subsequent time windows, and choosing a range for absolute roughness is suggested.

This work's ultimate goal is to assess the possible errors in both RELAP Mod3.2mz and RELAP-3D as candidates for the most used BE SYS TH codes in Thermal-Hydraulic analysis and to emphasize the selection of the most appropriate model for wall-to-fluid friction factor. To do so, research focused on the results obtained in single-phase PDs using subcooled water with realistic BICs, since the correlations used for single-phase calculations are fairly well developed, and enough experimental data are available. In order to use the results obtained from codes in the nuclear industry, V&V&C must be applied in core-related safety issues, as it must be able to show the capability of computational tools with a demonstration of an error. As stated, wall-to-fluid friction PDs, must not be treated as low-level objectives anymore, especially for the design of RCS that rely on NC or passive systems. In addition, wall-to-fluid friction PD must be considered as a Multi-Physical BP, since both water chemistry and wall material, as representative of coolant chemistry and material, all affect the PDs.

***Keywords**: Nuclear Reactor Safety, BEPU, System TH Code, Muti-physical Basic Phenomena, Wall to fluid friction pressure drops, Surface roughness, Oxide films, Fouling*

1 Introduction

In every industry, accidents play an important role in the development of safer and more efficient designs. In the nuclear industry, better design means increasing the safe power extraction from the core concerning material and coolant limits, while ensuring the safety of the plant in normal and off-normal operation conditions. To achieve this, the thermal-hydraulic phenomena (THP) that occur in water-cooled nuclear reactors must be identified. Therefore, the CSNI Code Validation Matrix (CCVM) by the Nuclear Energy Agency, and the Interim Acceptance Criteria (IAC) for the emergency core cooling system were initiated by the Atomic Energy Commission (AEC) in 1987. To identify the THP, one way was to directly extrapolate the TH behavior in smaller plants to the real plant. However, since some of the THPs cannot be scaled (e.g. CCFL), the possible application of a qualified version of the computer codes was chosen [1][2].

These activities lead to the selection of Best Estimate (BE) codes along with the minimum number of experiments required to establish the accuracy criteria (comparison of results with experiments, known as validation). This step was necessary because the acceptance of the results obtained with the codes was based on personal judgment [2].

For the identification of THP, the spontaneous step to be taken is the choice of the reactor of interest, i.e. the geometry of the system (can be the same for many reactors) or it can be specific to one type (i.e. orientation and height of the hot and cold leg, steam generator). The reason for this is that the geometry of a system plays by far the most important role in the behavior of the system. In other words, THP is closely dependent on the geometric configuration of the system [2].

Another reason for the use of Best Estimate (BE) System Thermal-Hydraulic (SYS TH) codes, is that when it comes to the identification of THP, due to the complexity of the system, there is a high demand to use existing computational power to reduce the time required to solve the equations. More importantly, the use of BE SYS TH codes will have a confirmatory nature of the type of THP happening in the system by allowing a clear picture of phenomena occurring during the transient. Therefore, SYS TH codes were developed in many countries (i.e. France (CATHARE), Germany (ATHLET), USA (RELAP5) [3].

One of the main issues in SYS TH codes is which (one or version) is better able to predict the phenomena. The answer lies in the availability of experimental data that will lead to the validation of models used with a reduction of compensating errors. In other words, the accuracy of codes will be highly dependent on the range of parameter change in the experiments, and sometimes they can extend the results to a certain point.

2 Pressure Drop Significance in System Design

In general, Pressure Drops (PDs) identified as part of the six Basic Phenomenon (BP), can characterized as an independent phenomenon that has a direct impact on the balance equations, directly or indirectly affecting half of the 116 THPs identified for water-cooled nuclear reactors, including CANDU and one of the six parameters described as important in scaling [2].

Among the 116 THPs, some of them have a strong relation with PD. The most compelling evidence, is the direct and strong effect of PD on the Heat Transfer Coefficient causing a direct impact on the NRS parameter, making PD have prominent repercussions on the Design Basis Accident (DBA) envelope (both in single-phase and two-phase). In addition, PDs are a type of phenomenon that is strictly geometry-dependent.

Together with the mentioned points, PDs will be a more sensitive subject for systems that work based on Natural Circulation (NC). This is because, in active systems, the design of the pump is such that the head given by the pump will overcome the whole head loss in the circuit, causing a suitable range of HTC in the core and SG, while in these systems, due to lack of mechanical systems to control the flow, the gravity and PDs will determine the flow rate in the circuit. To put it in another way, in passive systems, the driving forces (e.g. driving pressure) are 10-100 times lower than the equivalent driving forces in active systems, and the irreversible PDs that are friction and local PD terms will determine the effectiveness of NC in heat removal (i.e. lower value of pressure drop will allow the higher flow rate to the core, causing a strict and shorter temperature spread), therefore, uncertainties that will affect the PD will have a direct impact on Core Damage Frequency (CDF), while in active systems, the contributing term to CDF will be minimal cut-set of the pump [4][5].

The purpose of this article, in general, is to complete the assessment of SYS TH codes in single-phase PD in compliance with the Best Estimate Plus Uncertainty (BEPU) approach. To put it another way, since the irreversible PDs (i.e. friction and local) have an empirical basis, some discrepancy between SYS TH code and experimental data may exist. Going into detail of wall to fluid friction PD term, the friction factor may be the main parameter that contributes to discrepancies. Therefore, the foremost focus was selected to investigate BE models for friction factor in the whole Reynolds region, considering the possible effect of geometry along with the identification of possible uncertainties that may become important in passive systems. To fulfill this task, two different Best Estimate SYS TH codes (RELAP5 Mod3.2mz and RELAP5 3D) were used, to verify the results set of parallel hand calculations was made and finally comparison of the result obtained was done.

2.1 Pressure drop BP effect on system behavior

As a principle of thermo-dynamics, for a closed system, the direction of the spontaneous process will be such that for the system will have less Gibbs energy. Therefore, it can be said that:

$$\int_{initial}^{final} dG = \int_{initial}^{final} VdP\ ^{1} \quad \text{at constant Temperature} \tag{1}$$

therefore, the basis of the principle of mathematics can be said:

$$\Delta G = V(P_f - P_i) \quad \text{at constant V (In-compressible flow)} \tag{2}$$

Therefore, for a phenomenon, to occur spontaneously, $P_i > P_f$ or $H_i > H_f$.

In this case, it can be said that the driving force for a fluid is the head difference between two different points. This head difference can be created by many ways such as gravity and active systems. are important as a resisting part, that is the principle of passive systems (e.g. ancient systems) or can be created by active systems (addition of mechanical components e.g. pump). Going into the design

---

[1] G is the total Gibbs energy of the system composed, P is the pressure and V is Volume.

of a system, it is prominent that viscosity is the characteristic of the fluid that will cause the creation of many different consequences in the flow, one of the famous consequences is friction PD. After the extension of the Bernoulli equation, many scientists were involved in the process of understanding the friction PDs, and among them, Henry Darcy, the French scientist, could demonstrate experimentally that in different pipes (surface roughness and diameter) the hydraulic gradient that is defined as $\frac{h_f}{L}$ is proportional to the flow rate [6][7].

2.2 Wall-to-Fluid Friction Factors

The development of friction factors for In-compressible, Fully Developed, Adiabatic Flow (IFDAF), can be considered in two different major time steps. First, in 1845, Julius Weisbach defined a dimensionless friction factor unique for round tubes, and then in 1883, Osmond Reynolds introduced Reynolds dimensionless number as a number to identify the flow regimes (for single-phase flow). Therefore, the dependency of friction head loss to the roughness and Re number is shown below:

$$h_f = f\left(\frac{\varepsilon}{D}, Re\right)\frac{L}{2D}\frac{\overline{V}^2}{g} \tag{3}$$

This formula[2] has been implemented in many different forms of balance equations such as the Homogenous Equilibrium Model (HEM), Un-even Velocity Un-even Temperature (UVUT), and many others used in different SYS TH codes[3].

2.2.1 Laminar Friction factor

Given the peculiarities of friction factor in different geometries, the friction factor formula in the laminar region (Re[4]≤2000), will only function of Re number and geometry and it can be calculated by: 1) With direct impact of Geometry: $f = \frac{K_i}{Re}$, that K_i depends only on geometry (varying between $48 \leq K_\mathrm{i} \leq 96$ when K_i=64 is for round tube).
2) Based on equivalent hydraulic diameter: $f = \frac{64}{Re}$ and the head loss will be: $h_f = \frac{32\,L\,\overline{V}}{{D_h}^2\,g}$

This simplification will also determine the fact that the head loss in the laminar region is not a function of density and shows the dependency on the diameter is way more than the other parameters. In the first method, the constant K_l is defined for particular geometries such as channels with specified aspect ratio, in SYS TH code of RELAP5 Mod3.2mz, to simulate the desired geometry of channel geometry, the modified formula of friction factor for round is used[5].

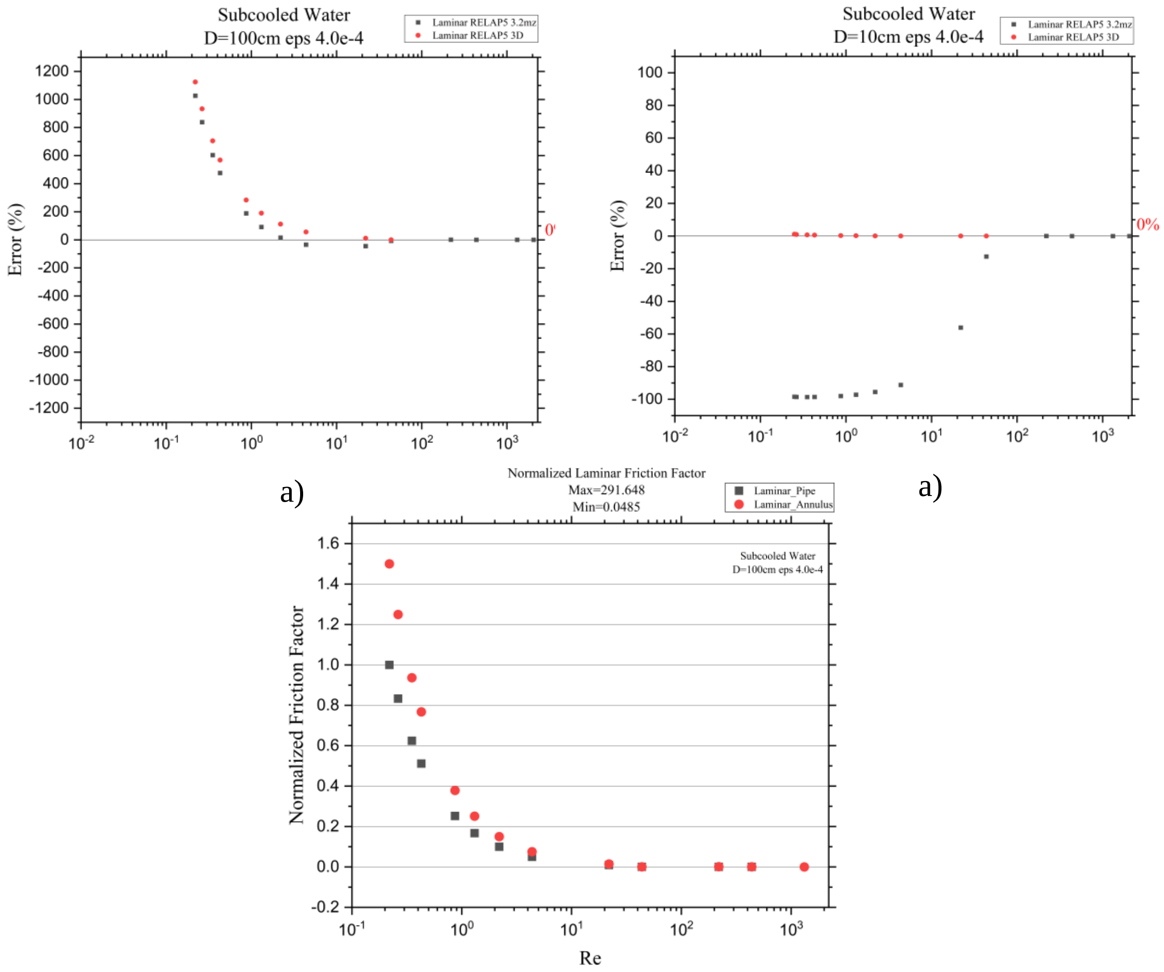
$$h_f = \frac{32\,L}{\Phi_{s\times}{D_h}^2}\frac{\overline{V}}{g} \tag{4}$$

---

[2] For wall to fluid friction pressure drop
[3] Based on that, the results obtained from this analysis may also be subjected to other SYS TH codes
[4] In SYS TH code of RELAP5, Laminar region is considered as Re<2200.

Φ_S is a geometry correction factor used for channel geometry. This approximation has a maximum error of 1.7% with the exact solution, therefore, results obtained from RELAP5 Mod3.2mz will have at least the error band of 1.7% for the laminar and transition region [8].

As for annulus, the laminar friction factor will be calculated with equivalent hydraulic diameter conditions. In this case, the friction factor will be at least 50% more than the friction factor obtained for the smooth round pipe, with the same hydraulic diameter [9]. Markedly, considering the effect of corrosion and other phenomena may lead to an increase in the roughness[6].



a) a)

b)

[7]Figure 1: a) Results obtained for Laminar region Re<2200 for the round pipe (both node lengths of 10 cm)
b) Friction factor comparison in different geometries obtained from hand-calculation

Figure 1, obtained from the verification of the SYS TH code, shows that not only at Reynolds below 50 the friction PD is not verified, but also shows a different behavior of the SYS TH code in reporting the value of the error. In addition, it shows that the influence of $\frac{L}{D} \geq 1$ has a different behavior in the results of the SYS TH codes. Finally, the overprediction and underprediction of PDs at different diameters.

---

[6] In this case, will affect the velocity distribution.

To summarize, the influence of geometry on the friction factor is unavoidable and the laminar friction factor is more susceptible to these changes. The laminar friction PDs in different geometries (i.e., round tube, channel, and annulus) can become important for the laminar transients of Light Water Reactors (LWRs), Liquid Metal Reactors (LMRs), start-up in any type of reactors, especially those designed based on NC, also in Research Reactors (RRs). In addition, it can have a significant effect on the active systems, especially on the Design Basis Accident (DBA) Envelope, the Large Break Loss of Coolant (LB-LOCA), and the Flow Reversal Point. For more than two decades, attempts have been made to move the flow reversal (FR) point from the core to the steam generator (SG) tubes by reducing the diameter. This is mainly done to increase the safety margin of the nuclear reactor fuel (possible impact on the NRS parameter and the thermomechanical operating limit (TMOL) of the fuel).

2.2.2 Turbulent and Transition Region

In the Turbulent and transition regions, the friction factor for different geometries is calculated by a series of correlations. The reference correlation is Colebrook (sometimes called Colebrook-White 1939) with an implicit numerical scheme.

$$f = \left(-2 \times log\left[\frac{\varepsilon}{D \times 3.7} + \frac{2.51}{Re\sqrt{f}}\right]\right)^{-2} \tag{5}$$

In general, to calculate the friction factor, three possible ways can be mentioned:
1) Implementation of Iterative procedure;
2) Use of Explicit numerical schemes.
3) Graphical Approach (i.e. Rouse (1943), Moody (1944));

To begin with, the first method will allow us to reach a desirable degree of precision based on the sensitivity of the system we are analyzing. Furthermore, the implementation of this method will allow us to keep the integration domain the same as the reference correlation [10].

In brief, all the explicit correlations are obtained by changing the numerical scheme from Colebrook implicit to explicit. This method is widely used in SYS TH codes (in RELAP 5 is Zigrang-Sylvester 1985) and usually comes with some consequences; namely, the introduction of:
1) Integration domain meaning a range of parameters in which the correlation is validated
2) Introduction of an Error (with the reference of Colebrook)
3) Increasing the computational power needed to solve the correlation

Although the absolute value of this error is small, it is misleading in the sense that the main cause of the discrepancy with the realistic friction factor obtained from the experiment could be the reference correlation itself. To support that, as Haaland mentioned, "It [is] worth keeping in mind that the Colebrook-White formula…. Itself maybe 3-5 percent, if not more in error compared to experimental data"[10].

Secondly, it must be clear that the use of graphical approaches must be considered an obsolete method in modern times due to the interpolation and correlation used to obtain them. These methods were only developed due to the lack of computing power and after almost 80 years need to be replaced by exact correlations. To back this up, White (1994) has mentioned that the Moody diagram is only accurate to (-/+)15%. As a matter of fact, it is puzzling that these methods are not updated even after almost 80 years [6][12] [13].

Henceforth, until new experimental data is available or a better correlation in terms of accuracy based on the existing data proposed, it is suggested that only Colebrook implicit with iterative procedure must serve as the reference chiefly in systems where PDs are more sensitive.

Table 1: Typical friction factors formula used for Transition and Turbulent regime

Friction factors formula	Absolute Error %	Integration Domain
$f = (-2 \times \log\left[\frac{\varepsilon}{D \times 3.7} + \frac{2.51}{Re\sqrt{f}}\right])^{-2}$ 1) Colebrook 1939	0	Re>2300
$f = (-2 \times \log[\frac{\varepsilon}{3.7D} + \frac{2.51}{Re}[1.14 - 2\log\left[\frac{\varepsilon}{D} + \frac{21.25}{Re^{0.9}}\right]])^{-2}$ 2) Zigrang-Sylvester 1985 (used in RELAP 5Mod3.2mz and RELAP 3D)	+0.5	$2500 \leq Re \leq 10^7$ $10^{-5} \leq \frac{\varepsilon}{D} \leq 0.05$
$f = (-2 \times [\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)])^{-2}$ 3) Swamee & Jain 1967 as Iterative initial guess (Miller)	User-defined	Same as Colebrook
$f = (-2\log\left[\frac{\varepsilon}{3.7 \times D} - \frac{4.518}{Re} log\left[\frac{6.9}{Re} + \left[\frac{\varepsilon}{3.7 \times D}\right]^{1.11}\right]\right])^{-2}$ 4) Zigrang-Sylvester 1985	+0.4	Same as Colebrook

2.3 Roughness Effect

A point often overlooked is that the predominant source of uncertainty of the friction factor in the hydraulic system is the value of the absolute roughness of the component. Given this point, when it comes to the importance of uncertainty in the roughness, the first thing to ponder is the kind of system considered. Figure 2 will address this issue.

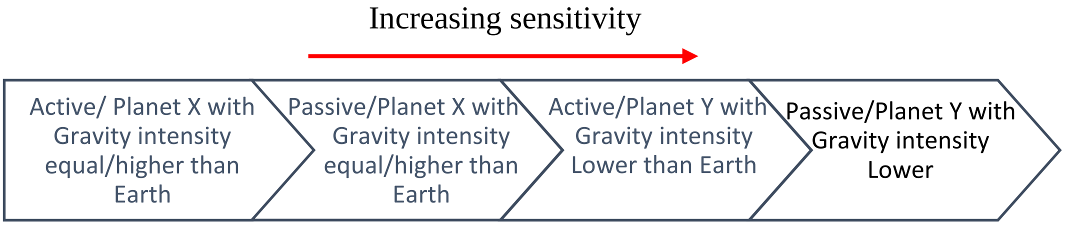


Figure 2: Sensitivity of the roughness in consideration of uncertainty based on the design[8]

This is simply because of the balance of driving and resisting forces that will determine the amount of the flow rate.

$$\Delta p_{driving} = \Delta p_{res} \tag{6}$$

$$\Delta p_{res} = \sum(\Delta p_{local} + \Delta p_{distributed}) \tag{7}$$

---

[8] This part is mainly for future designs, maybe spaceships where meticulous study of roughness is needed.

Therefore, figure 2 suggests that this issue in the environment with gravity like Earth, will be more tangible in passive systems, and the most significant case will be in nuclear reactors used for space programs. In the lifetime of a component, the subsequent time windows at which surface roughness will change are:

1) Production;
2) Welding ;
3) Service-induced changes.

As for production, most of the components in NPP will be produced by cold rolling. In this case, there is a high chance of creating valleys and peaks. Another option for the production of components is hot rolling however, since the probability of segregation, additional chemical reaction (with the environment), and diffusion of gases in the metal layers is high in this way, the Acceptance Quality Level (AQL) obliges the seller to use cold working methods.

The welding is an unavoidable process in the components of the primary circuit, to retain the integrity of the primary coolant system and avoid releasing radioactive material. Due to the welding process, primarily the morphology/orientation of the crystals will change. This effect may lead to a change in the surface roughness of the pipes. For example, in the primary system of the EPR, the nozzle is connected to the hot leg made of Inconel 50 by a sleeving process.

At the same time, welding of two different materials will cause a stepwise change in the value of roughness.

Finally, the service-induced changes may play the dominant role among others. In this case, multi-engineering disciplines, mostly structure mechanics, will affect these changes.

Based on the chemical phenomenological point of view, it can be categorized in:

1) Corrosion and Flow Acceleration Corrosion[9] (FAC);
2) Particle Deposition ;
3) Precipitation (Retrograde[10] or Normal).

As shown above, the roughness of the surfaces is the dominant source of uncertainty that will affect the friction pressure drop calculations. Thus, it is important to document both the value and the evolution during operation time, however, such an action requires a good understanding of the phenomenon affecting the changes. In NPP, the material selection rules (i.e. SSG-30 IAEA [14], US NRC RG 1.26[15], ASME BPV Code Sec III [16]), along with regulations defined by EPRI will underline the Acceptance Quality Level (AQL) for the initial value of absolute roughness, yet sometimes, in the reality, this rule may not be fulfilled. This is the first source of uncertainty in the production stage of a component, and it has a strong relation with the quality control of the element.

To begin with, the first reported values for the roughness can be found for pristine alloy surfaces, before possible corrosion or fouling occurs during the operation phase. In the guidelines for alloy 690 published by EPRI, considering AQL [17][18], the roughness should be less than 6.35 µm for reactor vessel nozzles, less than 1.6 µm for outside of steam generators tubes and less than 0.5 µm for the inside surface. In complement to these requirements, an analysis of as-received alloy 690 SG tubes has been performed, leading to values between 0.19 and 0.71 µm (Ra) of the inner surface [20].

In contact with the primary solution in experiments done in representative conditions, the corrosion of alloys has been documented. Images obtained by Scanning Electron Microscopy analysis

---

[9] FAC is predominant in pipes made of C.S i.e. steam-line.

[10] Mostly in the core of reactor.

have shown iron-rich micro crystallites up to 500 nm after 400 h on the surface of alloy 690, while micro crystallites from 40 to 1200 nm have been found on alloy 800 after 150 h [20]. Another study on Inconel 600 has shown that crystals from ~200 nm to ~700 nm depending on the dissolved oxygen content have grown after two to six days in simulating LWR primary water [21]. A last example of the growth of microcrystals during aging in primary water conditions was done on SS304 after 336 h, where sizes of 70 to 557 µm were measured, with a decrease to ~100 nm in the presence of 400 ppb of zinc [22]. Beyond these laboratory experiments, interesting results have been obtained with flow-through cells installed on Finish BWR and PWR for around 6 to 18 months [23].

The thickness of the oxide layer measured on several alloys was consistent with the laboratory experiments described above, from 0.3 to 2 µm, with a standard deviation of 0.5 µm in the latter case, depending on the alloy and its pre-treatment. In conclusion, the alloys in contact with primary water consist of a metallic surface of around 0.5 µm, textured with valleys resulting from the shaping by cold Pilger rolling [21], with a layer of micro crystallites coming from the corrosion, with sizes up to around 1 µm after aging of a dozen of days. Thus, these corrosion products could roughly multiply by a factor of 3 the initial roughness if they do not fill the valleys initially present at the surface of the cold-rolled alloys. Later in the operational phase, these surfaces may become fouled by the colloidal particles present in the cooling water. This phenomenon is a major problem on the secondary side of the SG tubes, where the deposition may lead to the clogging of quatrefoil-shaped holes [24].

Without reaching this extreme case, dissolved and colloidal corrosion products can create a particle layer on heat exchanger surfaces, in sub-cooled boiling conditions, or absence of bubble formation. In the case of the deposit of particles derived from the Beal model [25], calculations of the sticking probability have shown that the deposition of the small particles (< 1 µm) is favored. The roughness coming from deposited particles is close to their size, since in this work, a multi-layer is not considered. This latter possibility has been theoretically evaluated in another work [26] and would lead to an uneven deposit, with a difference in height equal to several times the size of an individual particle.

In boiling systems conditions, several works to characterize the deposition of magnetite particles have been published by Lister's group, whose one micrograph of the ring formed at a bubble nucleation site, shows a deposit thickness difference of ~10 µm between the lowest level and the top of the deposit formed by 0.4 µm magnetite particles [27]. Furthermore, the total roughness should be a combination of the oxidized surface possibly covered by a deposit of colloidal corrosion products. It would evolve with time, from a surface whose roughness comes from the cold rolling to the growth of microcrystals during the early stages of corrosion, and finally the deposit of colloid particles, as a monolayer or a multilayer.

To sum up, until suitable tools to calculate the best estimate value for the roughness of a component are not used, it is advised to select a range for the absolute roughness, based on existing data for BOL and EOL of the component.

2.3 Roughness Measurement Methods

Taking changing of pipe roughness as granted, there are many methods to measure the changes that can be classified as follows:

1-Non-Destructive Examinations (NDE)

NDE can be used to track the changes in the pipe roughness. One of the methods in particular used is the Ultrasonic method. This method requires the determination of the velocity of sound waves in the material since it works based on the propagation and reflection of the sound waves. With some modifications obtained from the experiment (changing from time-based to depth-based). High cost and low precision level can be mentioned as a disadvantage of this method [28][29].

2- By Codes

Some codes (i.e. OSCAR) were originally designed for the measurement of Activated Corrosion Products (ACP), originating from Corrosion Products (CP), that are responsible for 85% of the total collective dose of workers. ACP is also undesirable for system integrity since due to the deposition in touch with hot surfaces (retrograde deposition) may cause Crud Induced Power Shift (CIPS), which can be modeled in some dedicated codes (i.e. ChemCrud) [30].

In general, considering the material of the whole Primary System (PS), Ni and Iron are the dominant elements. The corrosion in the elements of the PS due to contact with PS coolant (290<T<325, presence of Li and Boron) will lead to the formation of double-layer oxide, located at the interface of metal with coolant. The releases from this layer be categorized into two main categories: 1) Ions 2) Particles.

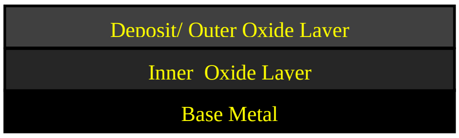


Figure 3: Surface Evolution of material in NPP with time

In this code, the deposition of particles onto a surface with iso-thermal condition is modeled by considering two main steps that are:
1) Transport;
2) Attachment.

The working principle of OSCAR is out of the scope of this paper; however, it is important to realize that this code, is a result of over 50 years of data collection under the EMECC project and not only can be used for Sodium Fast Reactors (SFR) and Fusion but also has been validated in CIRENE experimental facility. By proper means, these codes may be able to provide information regarding the roughness evolution, during the lifetime of a component, from the attachment of individual particles to the growth of a fouling layer [25].

2 Validation of SYS TH Codes, Wall to Fluid Friction PD THP

In general, when it comes to validating the SYS TH codes, the first thing that needs attention is to utilize data obtained from highly precise instrumentation[11]. This is mainly because some of this data will be used for simulating the plant itself (i.e. local pressure loss coefficient) which is vital for Accident Analysis (AA). With this in mind, at the beginning of the validation process, experimental data was obtained from a facility designed to carry out tests related to the nuclear industry. Therefore, the instrument used for the measurement had a high precision level in measuring fluid properties and the setup of measuring devices was done carefully to ensure the reliability of the experiment data. This way it is possible to exclude other reasons that may contribute to the existence of discrepancies in the validation process. The test section setup consisted of a horizontal smooth pipe (in terms of roughness), and subcooled demineralized water with different BIC and flow rates would pass through the pipe.

---

[11] Obviously, it is suggested to continue the validation at the Separate Effect (SE) level with other data as well, yet, in the case of possibility, the use of data obtained from nuclear-related experiments is suggested.

To begin with, the nodalization was selected such as the pressure tap position of the facility, which was at the center of the node. Moreover, the nodalization used to obtain the results was such that the $\frac{L}{D}$ rule of RELAP5 Mod3 is fulfilled all along the components [8].

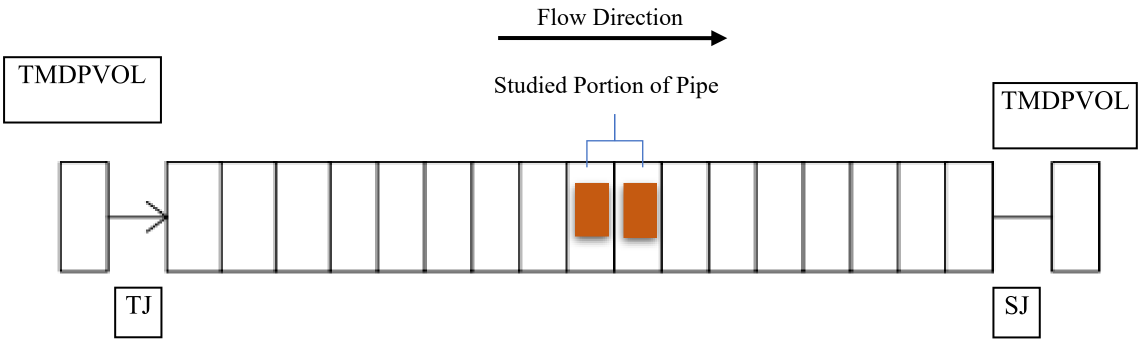


Figure 4: Nodalization of the component in SYS TH code

Furthermore, SYS TH codes were run with two different computers with different nodalizations to exclude the uncertainty due to the Complier and nodalization effect. For a horizontal geometry, the total pressure drop will be calculated based on the following formula:

$$\Delta P_{tot} = \Delta P_{gravity} + \Delta P_{acc} + \Delta P_{loss} \tag{8}$$

Considering the orientation of the pipe and the absence of local geometrical discontinuities, the local PD with the gravity term can be removed. Also, the flow was in Fully Developed Flow (FDF) and steady-state conditions, the time acceleration term can also be pulled out from the calculations. Therefore, PDs reported in the facility can be only due to friction term.

First, the verification process is completed to complete the assessment of SYS TH codes. To do so, the first step was the selection of the BE model for friction factor since it is one of the pillars of the BEPU approach. Therefore, based on the reasons mentioned in section 2.2.2, the iterative procedure was selected. The degree of precision was selected based on the following formula:

$$\frac{f_{n+1} - f_n}{f_n} < 10^{-4} \tag{9}$$

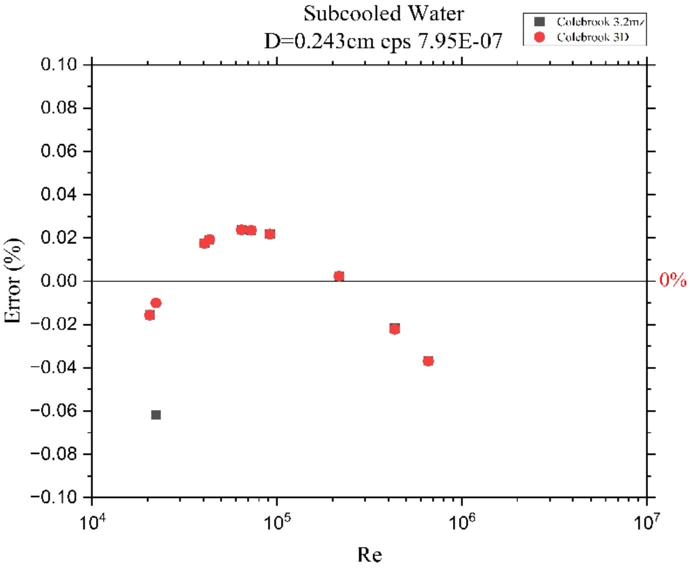


Figure 5: Preliminary analysis of Verification of Friction PD in SYS TH code

Figure 5 shows that the friction PD in the RELAP5 Mod3.2mz matches very well with the hand-calculated friction PD using Colebrook with an iterative procedure. In the verification procedure, the error value of the friction pressure drop was calculated from the following equation.

$$\frac{(\Delta P(RELAP)-\Delta Pacc)-\Delta Pfriction}{\Delta Pfriction}\times 100 \tag{10}$$

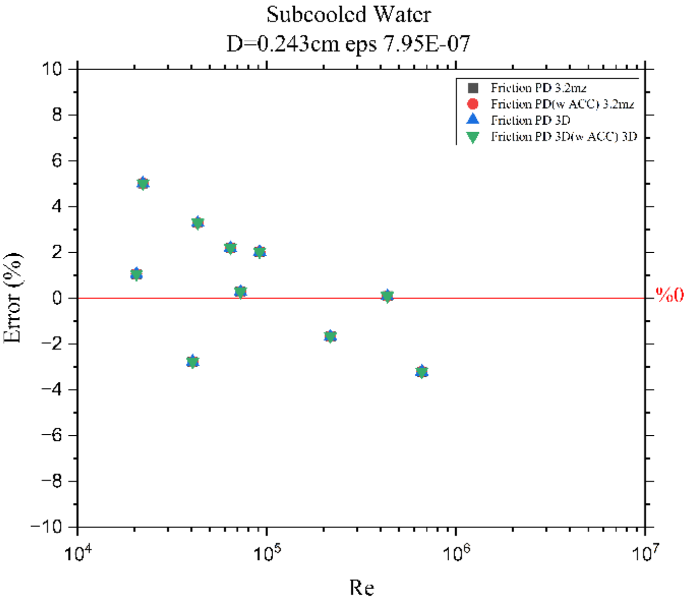


Figure 6: Preliminary results of Accuracy analysis of SYS TH code with Experimental data[12]

The formula used for the error is the following:

$$\frac{(\Delta P(Exp)-\Delta P(RELAP5))}{\Delta P(Exp)}\times 100 \tag{11}$$

$$\frac{(\Delta P(Exp)-\Delta P(ACC))-\Delta P(RELAP)}{\Delta P(Exp)}\times 100 \tag{12}$$

The preliminary result obtained from the comparison of SYS TH codes and experimental data shown in figure 6 shows a perfect match with what is mentioned in section 2.2.2 regarding the possible error in the reference correlation (Colebrook) since both codes use Zigrang-Sylvester (1985) correlation which is an explicit form of Colebrook [8]. Moreover, for the sake of increasing the precision level, the acceleration pressure drop was considered, although no significant changes have been noted.

To be sure of the consistency of error varying the diameter, the same procedure was repeated with different pipe diameters, and as mentioned some discrepancies were noted. In addition, the possible error due to the utilization of different thermo-dynamical properties by SYS TH codes and the experiment is excluded. This was just to show that the discrepancies shown in figure 6 are solely due to errors in the reference model used.

Another important key is that based on the preliminary results obtained, flow instabilities may occur due to the signs of errors. In other words, the friction PD is underestimated in some regions while it is overestimated in other regions. As for the importance of the magnitude of errors, it should be clear that this importance depends on the type of system (i.e. passive or active).

Given these points, in NPP, rarely the flow will be in steady-state and fully developed condition, henceforth it is estimated that the value of absolute error will be higher, especially in the sections where also heat transfer phenomenon will change the thermo-dynamical property (e.g. viscosity) of the coolant with spatial gradient.

3 Possible Uncertainties and BEPU

In general, since Uncertainty Evaluation (UE) is an important pillar of the BEPU approach, the uncertainty sources can be distinguished into two parts:
1) Uncertainties originated from Experiments;
2) Uncertainties in the SYS TH codes.

As for the first one, since possible instrumentation error with coolant thermo-dynamical parameter variation will strongly affect the uncertainties, especially in the laminar region, until advanced techniques such as Magnetic Resonance Spin Echoes (MRSE) are fully developed [31], it is suggested to use “Input Error Propagation” method by defining a suitable range of parameters. The MRSE method may also have the capability of measuring the droplet's spin in a two-phase flow overcoming the difficulties in the conventional measurements. Table 2 will summarize the instrumentation error of the facility.

Table 2: Instrumentation Error of the facility

Quantity	Limits of Error
Pressure	+/- 34473.8 Pa
Mass flow rate	+/- 2%

As mentioned, the possible effects due to uncertainty are considered in the analysis, however, they still couldn’t justify the values of error obtained from the accuracy analysis. As for the latter terms, the source of uncertainty in SYS TH codes related to this analysis will be the following:(among them, some will be addressed)

1) Uncertainty of Average Velocity[13] (due to the use of the quasi1-D method).

2) Use of Numerical Methods.

Since in SYS TH codes, the partial differential equation is solved by proper numerical methods, to be sure of numerical methods utilized by SYS TH codes, all of the analyses were run with MATLAB as a complementary separate code.

3) Integration domain of correlations used in balance equations (i.e. like for Zigrang-Sylvester mentioned in Table 1).

4) Use of FDF correlation for complex systems such as NPP.

---

[13] The roughness will have a shadow effect in this term.

5) Code user effect and Nodalization.

Since Nodalization is one of the major sources of uncertainty, a sensitivity study on the effect of nodalization was performed. The selection of nodalization was with respect to the $\frac{L}{D}$ rule, nonetheless there was a negligible change in the value.

6) Compiler effect

Although nowadays most of the computers in the market have almost the same computational power, however, to be sure of the results, a separate set of analyses was performed to exclude this effect.

4 Discussion and conclusion

In light of using the BEPU approach, the selection of BE models accompanied by using BE codes to simulate the phenomenon occurring in the real NPP was considered a top priority. Also, since uncertainty is an inseparable part of BEPU, the effort was to take the possible effect along with the identification of possible uncertainty terms for future analysis. In this paper, the assessment of two BE SYS TH codes of RELAP5 Mod3.2mz and RELAP5 3D was performed.

The first and probably foremost point is the formulas, correlations obtained for friction factor are for steady-state, FDF, adiabatic, and in-compressible flow, yet it is clear that in the NPP, these conditions especially the FDF and steady-state will never be seen. Therefore, even higher values of error can occur for both geometric discontinuities and friction pressure drops. On the other hand, the difficulties in the measurement of the TH properties in the laminar region make it somewhat burdensome to validate the SYS TH codes in the laminar region, unless new methods of measurement are applied.

Together with the first point, based on investigations performed, against what is expected, even in the laminar region, single phase friction pressure drops, the situation is highly geometry[14] dependent. As has been noted, a combination of different geometry and the presence of temperature gradient may increase the complexity and error in the laminar flow [9] [32].

Taking this as granted, the miscalculation of laminar friction pressure drop may directly affect the system behavior, especially in normal operation conditions of RRs, laminar transients, NC systems start-up, in the components like Down Comer of LWRs, Bayonet tubes of LMR SG, and many other locations in the primary circuit.

Surface roughness is the parameter that not only has the highest importance in the calculation of friction factor but also is the main source of uncertainty. Taking these points as a fact, friction PD will be considered a multi-physical subject for more sensitive systems, and an appropriate system code shall be developed to address its effect on system behavior. (Figures 7 and 8 will address this issue).

In other words, in a well-designed active system, the whole pressure drops along the circuit will be overcome by the pump; in this way, also, a suitable range for the Heat Transfer Coefficient will be ensured. However, changing the design of the system, (i.e. going to passive systems),

---

[14] This issue was also the subject of the International Agreement Report (IAR) and benchmarking [9][32].

although the mechanical components involved in flow control of the system is decreased, causing in reduction of the minimal cut-set of failure in the system, but it will increase both quantity and complexity of physical phenomena (the thermo-physical parameters may change widely that sometimes in experimental facilities, they can't be reproduced). Keeping these in mind for the applicable use of SYS TH codes for low flow NC, it is suggested to perform a set of experiments, since as it is mentioned, for NC, RELAP5 Mod3 underpredicts the frictional pressure drops at least 45% [9]. In fact, with the advent of new designs such as integral PWRs (iPWRs), the quality of safety assessments may fall short compared to conventional LWRs. One of the reasons that may cause some discrepancy arises from limitations in experimental data available for ITFs with BIC close to the new reactor design, resulting in fewer analyzed scenarios and a smaller archive of system code benchmarks.

Moreover, preliminary results obtained from the assessment of both SYS TH codes for wall-to-fluid friction pressure drops suggest that the main model used, which in this case in Colebrook, in some cases, may cause notable discrepancy. These discrepancies may be even higher in NPP.

Chiefly, this shows that even for phenomena that are well understood like single phase, new models shall be used. Besides, since wall-to-fluid friction pressure drop is one of the important parts of 6 BP it directly will affect the two-phase model [2].

Foremost, since some discrepancies are present in the two-phase friction PD, plus taking into account that in the AA of current conventional reactors, mainly two-phase flow will determine the evolution of the system with a direct effect on NRS parameters (e.g. Peak Cladding Temperature), a realistic model for two-phase flow is essential. To achieve that, first the single phase shall improve.

This is because, not only in the equation of two-phase friction PDs, is the only part that will show the effect of roughness in the single-phase model but also, the errors in the single-phase model will act as a residual error in two-phase friction PDs. Therefore, this may come with great importance, especially in boiling systems where the value of surface roughness will increase due to bubble formation on the heated surface. To sum up, "a good way to obtain a two-phase model, is to go through the model for single-phase".

Last but not least, figure 7 proposes some of the changes that may need to be applied in future designs to obtain better predictions of system behavior.

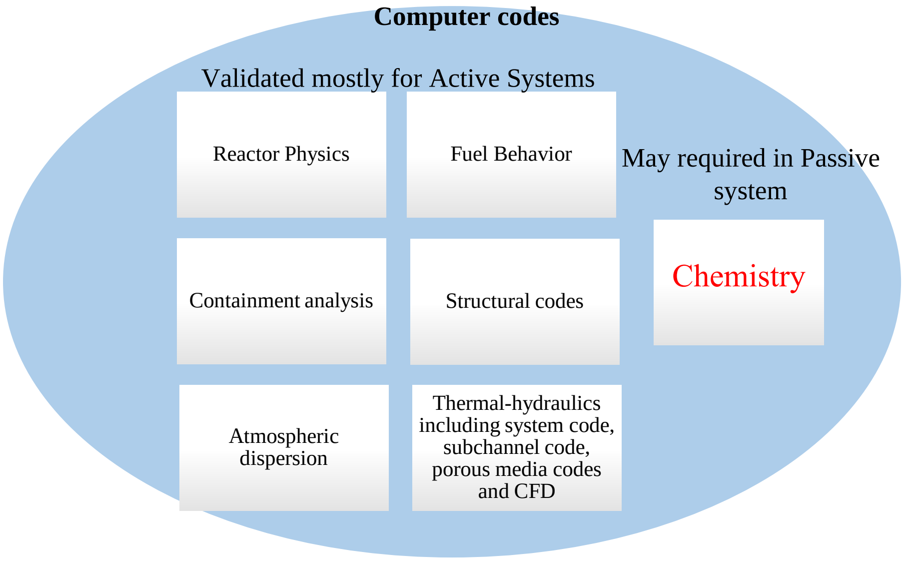


Figure 7: Venn diagram of Computer codes with the proposal for the addition of chemistry-related code

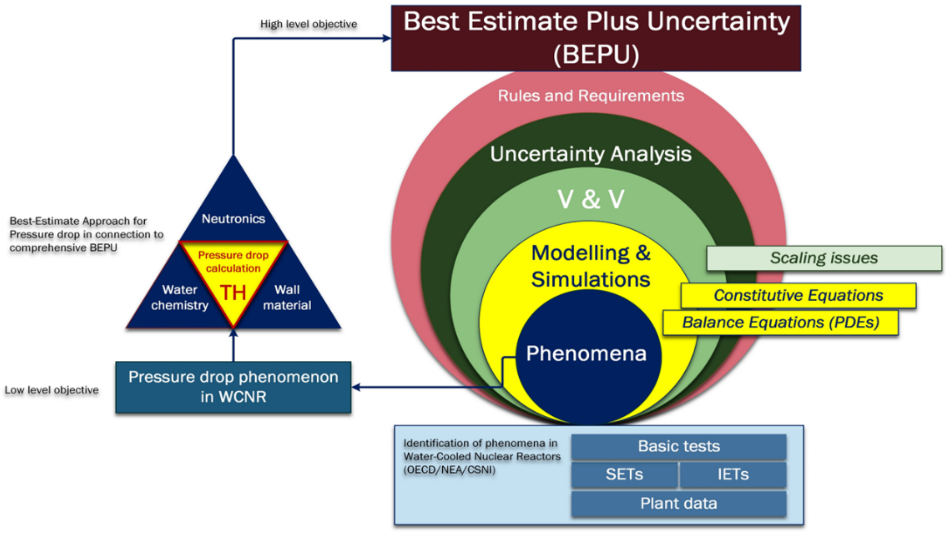


Figure 8: Proposal for consideration of wall-to-fluid friction PD as a Multi-physical phenomenon

References

[1] S. R. Aksan et al., "CSNI code validation matrix of thermo-hydraulic codes for LWR LOCA and transients," 1987.

[2] N. Aksan, F. D'Auria, and H. Glaeser, "Thermal-hydraulic phenomena for water cooled nuclear reactors," *Nuclear Engineering and Design*, vol. 330, pp. 166-186, 2018.

[3] C. CD, "Use and Development of Coupled Computer Codes for the Analysis of Accidents at Nuclear Power Plants," 2007.

[4] F. D’Auria, "Scaling, Passive Systems, and the AP-1000," *Nuclear Science and Engineering*, vol. 197, no. 5, pp. 987-999, 2023.

[5] K. Umminger et al., "Status, needs and perspectives in measuring of pressure drops," *Nuclear Engineering and Design*, vol. 354, p. 110218, 2019.

[6] G. O. Brown, "Henry Darcy and the making of a law," *Water Resources Research*, vol. 38, no. 7, pp. 11-1, 2002.

[7] H. Darcy, *Recherches expérimentales relatives au mouvement de l'eau dans les tuyaux*, Vol. 2. Mallet-Bachelier, 1857.

[8] C. D. Fletcher and R. R. Schultz, *RELAP5/MOD3 code manual*, No. NUREG/CR-5535-Vol. 5; EGG-2596-Vol. 5. Nuclear Regulatory Commission, Washington, DC (United States). Div. of Systems Research; EG and G Idaho, Inc., Idaho Falls, ID (United States), 1992.

[9] R. P. Martin and B. K. Taylor, *Benchmarking assessment of RELAP5/MOD3 for the low flow and natural circulation experiment*, No. WSRC-TR-92-088; CONF-9209172-4. Westinghouse Savannah River Co., Aiken, SC (United States), 1992.

[10] D. J. Zigrang and N. D. Sylvester, "A review of explicit friction factor equations," 1985.

[11] S. E. Haaland, "Simple and explicit formulas for the friction factor in turbulent pipe flow," 1983.

[12] H. Rouse, "Evaluation of boundary roughness," in *Proc. 2nd*, June 1942.

[13] L. F. Moody, "Friction factors for pipe flow," *Transactions of the American Society of Mechanical Engineers*, vol. 66, no. 8, pp. 671-678, 1944.

[14] International Atomic Energy Agency, *Safety classification of structures, systems and components in nuclear power plants (Specific Safety Guide No. SSG-30)*. International Atomic Energy Agency, 2014.

[15] U.S. Nuclear Regulatory Commission, "Quality Group Classifications and Standards for Water-, Steam-, and Radioactive-Waste-Containing Components of Nuclear Power Plants (Regulatory Guide 1.26)," U.S. Nuclear Regulatory Commission.

[16] American Society of Mechanical Engineers, "ASME Boiler and Pressure Vessel Code, Section III: Rules for Construction of Nuclear Facility Components," American Society of Mechanical Engineers.

[17] EPRI, "Materials Reliability Program: Guidelines for thermally treated alloy 690 pressure vessel nozzles (MRP-241) (Report No. 1015007)," Electric Power Research Institute, 2008.

[18] Electric Power Research Institute, "Guidelines for PWR steam generator tubing specifications and repair: Volume 2, Revision 1: Guidelines for procurement of alloy 690 steam generator tubing (EPRI Report No. TR-016743-V2R1)," Electric Power Research Institute, 1999.

[19] C. Ribière et al., "Multi-scale characterization of the inner surface of as-received steam generator tubes and correlation with the Ni release in primary water," *Corrosion Science*, vol. 218, p. 111205, 2023.

[20] A. Machet, "Etude des premiers stades d’oxydation d’alliages inoxydables dans l’eau à haute temperature," Ph.D. dissertation, Université Paris VI, 2004.

[21] S. Y. Park et al., "Preparation of Oxide Layer on Inconel-600 for a Decontamination Performance Test," 2012.

[22] H. Wei et al., "Influence of Zn injection on corrosion of 304SS under PWR primary side conditions," *Frontiers in Materials*, vol. 9, p. 833291, 2022.

[23] M. Bojinov et al., "Correlating activity incorporation with properties of oxide films formed on material samples exposed to BWR and PWR coolants in Finnish nuclear power plants," 2002.

[24] H. Bodineau and T. Sollier, "Tube support plate clogging up of French PWR steam generators," in *Eurosafe Forum*, Paris, France, Nov. 2008, pp. 3-4.

[25] C. Cherpin and F. Dacquait, "Modeling particle deposition in the primary circuit of pressurized water reactors for the OSCAR code," *Annals of Nuclear Energy*, vol. 199, p. 110364, 2024.

[26] C. Henry, J. P. Minier, and G. Lefèvre, "Towards a description of particulate fouling: From single particle deposition to clogging," *Advances in colloid and interface science*, vol. 185, pp. 34-76, 2012.

[27] N. Arbeau, W. Cook, and D. Lister, "The early stages of deposition of magnetite particles onto alloy-800 heat exchange surfaces under subcooled boiling conditions," 2003.

[28] Y. Hou et al., "Assessing the efficacy of non-destructive testing methods to detect pitting corrosion," *Nondestructive Testing and Evaluation*, vol. 38, no. 3, pp. 373-393, 2023.

[29] American Society of Mechanical Engineers, "ASME Boiler and Pressure Vessel Code, Section V: Nondestructive Examination," American Society of Mechanical Engineers, 2019.

[30] B. Lockamon et al., "Advancements in the Framatome crud and corrosion risk assessment process for pressurized water reactors," in *Top Fuel Conference*, 2019.

[31] Jiangfeng Guo et al., "Laminar flow velocity profile measurement from magnetic resonance spin echoes at incomplete polarization," *Physics of Fluids*, 2022.

[32] Validation of RELAP5/MOD3.3 Friction Loss and Heat Transfer Model for Narrow Rectangular Channels," *NUREG/IA-0508*, U.S. Nuclear Regulatory Commission, Washington, D.C., 2020.

Acknowledgment

1) This paper is devoted to **my parents**, especially my mother, she may rest in peace.

2) This work has been partially supported by the ENEN2plus project (HORIZON-EURATOM-2021-NRT-01-13 101061677) founded by the European Union.

Funded by European Union

Disclaimer:

HPC standard acknowledgment

This research made use of Idaho National Laboratory's High Performance Computing systems located at the Collaborative Computing Center and supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facilities under Contract No. DE-AC07-05ID14517.

Letter to the dear reviewers

Reviewer 1
Comments for the Authors

An excellent paper but before publishing it should be formatted to match the template format.
Dear Reviewer 1,
Thank you very much for your comments. In the newly submitted file, I have addressed the changes that are aligned with the paper corresponding to the format of the conference. Please kindly let me know if the changes are applied correctly and if there are no issues regarding the format of the paper.

Reviewer 2
Comments for the Authors

The list of references (32) is too long. It can be considered reasonable to have only the most relevant references.

Acknowledgment should be on the last page below references not separate.

Maybe some format change is needed also the footer should be corrected.
Dear Reviewer 2,
I appreciate your cordial reviews sir, regarding the references, I would like to ask you to keep the referencing since this activity is still going on and further analysis are done. This will ease us in further papers and avoid too many references in the future. Also, not to mention that having an error in a single phase is hard to believe since the idea is that the formulas are fairly developed. Our recent analysis shows about a 20% error.

I have corrected the acknowledgment and checked the footers, however since in the template, there is no example of a footer, It's hard to find where I have made a mistake. Please kindly address me.
+ all the changes are highlighted in the new pdf version.

My best regards
Hamidreza Yousefi
GRNSPG, Pressure drops leading engineer