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Uncertainty Propagation from Experiment Measurements to Modeling Approaches: A Case for SMR Steam Entrainment Testing

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ABSTRACT

To license new and advanced reactor designs, regulators must be convinced that their unique safety cases—relative to existing large-scale reactors—have been adequately addressed by the designed reactor protection systems. In water-cooled small modular reactors (SMRs), droplet entrainment in steam flow has significant implications on the progression of accident scenarios due to its compact design features, which requires representative test data applicable to SMR designs. Computer code, modeling and simulation (M&S) tools and models require adequate verification, assessment, and qualification. This includes M&S results validation against scaled empirical data within allowable uncertainty bands to gain regulatory approvals during the various stages of reactor system design, demonstration, and commercialization. However, measurement uncertainty within the empirical datasets and test data applicability ranges requires careful consideration of M&S inputs (i.e., boundary conditions, and initial conditions), and verification and validation efforts. This study focuses on uncertainty quantification in designing scaled test facilities for SMR applications with appropriate measurements and a standard data-reduction method to estimate thermal hydraulics characteristics parameters that incorporate physics phenomena of interest. In addition, this study supports the evaluation model development and assessment process using M&S that interfaces with advanced computing tools and digital twin capabilities. This will allow synchronization between experiment and modeling approaches for droplet entrainment testing and analysis, improving diagnostics, prognostics, and decision-making to accelerate regulatory approval.

Keywords: small modular reactor, experimental uncertainty, verification and validation, droplet entrainment, Generation III reactors

1. INTRODUCTION

Small modular reactors (SMR) are typically promoted as the next nuclear revolution, speeding up nuclear power plant (NPP) deployment while driving down costs. This has not yet come to fruition, but the industry and government agencies have collectively poured in tens of billions of dollars to bring the technologies to a commercial reality. To reach a commercial deployment in the United States (U.S.), the reactor design and construction plan must pass the scrutiny of the U.S. Nuclear Regulatory Commission (NRC). This is a lengthy process requiring computer and probabilistic modeling, which is verified and validated (V&V) with empirical data from test facilities. Before this process begins, an evaluation team will undergo what is known as the phenomenon identification and ranking table (PIRT) process. This is a systematic collection of information toward a relevant decision-making objective, followed by a ranking of the information's importance [1]. The PIRT process for a reactor design may be used to identify potential accidents that could challenge the reactor's safety systems, along with an insufficient state of knowledge (SOK) for important

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phenomena determined by the PIRT conclusion. One such phenomenon that has been proposed for Gen III+ reactors is droplet entrainment.

Droplet entrainment occurs when liquid droplets are carried by the gas/vapor phase in a two-phase flow regime. In light water nuclear reactors, this can result from several possible design-basis and beyond-design-basis accidents, with potentially great impacts on the accident progression. The ultimate priority of reactor safety is to prevent the release of radionuclides to the environment which could harm the public, and the entrainment can challenge this prime objective. Scenarios potentially impacted by droplet entrainment include a steam generator tube rupture (SGTR) or a main steam-line break (MSLB). An SGTR can cause the steam generator (SG) of a pressurized water reactor to overfill, increasing the rate of entrainment into the main steam line as the pool height gets closer to the vessel exit [2]. While droplet entrainment may not be the most concerning factor in this accident, the phenomenon would require investigation. At the smaller scale of SMR components compared to existing large-scale reactors, less water would be needed to raise the level of feedwater in the SG. Since previous work has identified pool height proximity to the vessel exit as an important parameter in predicting entrainment rate [2], a certain amount of primary fluid leaking into the secondary side of the SG may cause a greater and faster increase in entrainment than is seen in large-scale systems. An MSLB can be a severe accident accelerated by the resulting droplet entrainment. Subsequent system depressurization after the initial break causes rapid boiling of coolant in the loop as the saturation temperature drops. As superficial gas velocity increases, the rate of entrainment increases [3], causing the liquid fraction in the break flow to go up. Droplet entrainment during this accident would therefore have a two-fold impact on nuclear safety maintenance. A greater rate of coolant inventory loss risks an overheat of the fuel and potential failure of the cladding, but this is also a direct challenge to the containment structure integrity. As high-temperature-entrained droplets enter the lower pressure environment inside the containment, they will flash to steam until the pressure inside the containment reaches the saturation conditions of the coolant, which may occur beyond the design-basis pressure. On the smaller scale of SMRs, the containment volume may afford less coping time to over-pressurization due to a coolant release inside the containment, especially if the liquid fraction in the release is greater because of increased entrainment.

The evaluation model development and assessment process (EMDAP) is a major component of gaining license approval for commercial nuclear reactors in the U.S. The Chapter 15 safety analysis of the NRC's Standard Review Plan requires development or use of evaluation models and analysis codes which are sufficient to assess system performance after being subjected to several transient and accident scenarios [4]. The EMDAP should give reactor designers confidence that the system will behave as expected outside of the normal operating envelope while also instilling regulators with confidence that all aspects of the Code of Federal Regulations are being complied with. The evaluation models (EMs) will likely include a combination of systems-level code such as the Reactor Excursion and Leak Analysis Program (RELAP), as well as higher fidelity component-level simulation with any number of computational fluid dynamics (CFD) programs. The core requirement of the EMs is that they are representative of reality, capturing the effects of real phenomena in a reasonable window of uncertainty. The model assessment process of the EMDAP involves validating the model results with a database of the experimental programs directly applicable to the phenomena and scenarios under consideration. Model assessment centers on the key phenomena identified in the PIRT process and whether the model adequately predicts the results of the experiments selected for comparison. The empirical database can be compiled from existing sources, but new experiments may be required if previous testing cannot adequately cover the conditions of a novel design [4]. When considering the phenomenon of droplet entrainment in SMRs, there is a severe inadequacy of data that will soon be needed to enable commercial deployment. A major area of research being pursued by the NRC further ties empirical data with computational models in a concept called a digital twin. This uses advanced sensing and instrumentation to collect information on the physical phenomena occurring in a nuclear facility and transmits this information in real-time to the digital twin, which models the system based on actual conditions. Combined with artificial intelligence and machine-learning tools, the digital twin will be able to provide detailed physics models, diagnostics, operational recommendations, and even manage control signals [5].

Previous droplet entrainment experiments are a valuable resource for gaining basic knowledge on the mechanisms of entrainment and de-entrainment or their impact on system development during a transient scenario. Many of these have made use of a two-phase flow of air and water to simulate pool boiling and droplet entrainment in a pipe carrying steam. This approach to two-phase experimentation is simpler to perform, and more easily allows for direct visualization of the phenomena, but it lacks consideration of the significant impact of heat transfer between the phases and condensation of the gas. For this reason, air and water testing is most applicable to identifying the mechanisms which cause droplet entrainment on a fundamental level, as shown in [3] and [6]. A condensable gas phase, therefore, is more useful for direct quantitative investigation of specific system designs and their progress through a transient. Steam and water testing focusing on the impact of droplet entrainment has been used for safety analysis of large-scale NPPs. However, the phenomenon of droplet entrainment has been shown to heavily depend on the specific geometry of the vessel, with significant differences shown between the inclusion and exclusion of vessel internals [7]. For this reason, these steam and water experiments inform the coarse expectations of different NPP designs, such as greater entrainment results from closer pool proximity to the vessel exit [8], but one of the most significant improvements for future experiments will be in understanding instrumentation applicability in this challenging environment. A summary of major previous droplet entrainment empirical work is given in Table I, which includes the instrumentation sensitivity and experiment conclusions. These are also described based on the gas phase used and whether they were designed as integral effect tests (IET) or separate effect tests (SET) [9]. *An important gap in the literature is droplet entrainment-affected accident scenarios for SMR-scale nuclear reactors. Another major impact of entrainment absent from the identified previous experimental programs is the effect on containment pressure and integrity from droplet entrainment flashing to steam inside the containment volume. This will be an important consideration for future licensing analysis and should be addressed in future empirical research on an SMR design.*

This study identifies a research gap in the literature relating to droplet entrainment in SMR systems, considering previous experimental and empirical efforts toward this phenomenon in separate and integral effects testing. Due to unique design characteristics compared to existing light water reactors, such as geometric compactness, steam flow requirements, and advanced integral pressurized water reactors (PWRs), PIRT studies have identified entrainment in steam flow as a high-ranked phenomenon of interest with a low SOK [10], [11]. A recommended approach is discussed to improve the licensing case for SMRs, which would utilize both testing facilities and computational modeling and simulations to improve the EM. Reactor system design licensing, for example, through the U.S. NRC is gained by adequate EMDAP, which is supported by a qualified test dataset with detailed measurement strategies. This dataset then supports qualified computer code modeling and analysis by prioritizing measurement accuracy with a detailed best-estimate-plus-uncertainty assessment. Such experiment measurement-to-modeling approaches ensure better understanding of the physics phenomena, corrections of the underlying physics approximations, and applicability of specific correlations for the targeted reactor systems. *These improvements reduce measurement and modeling uncertainties of postulated transients and accident scenarios, such as an MSLB, SGTR, and other loss-of-coolant accidents (LOCAs)*. This study scope is limited to horizontal pipe flow because the physics and behavior of droplet entrainment of the targeted SMR's main steam line is relevant to horizontal pipe flow and differs greatly with the vertical pipe flow.

Table I. Previous entrainment experiments with application to nuclear facilities.

Test Program	Instrumentation Standard Deviation	Author Remarks
AP1000 Hot Leg Air SET [12], [13]	• Weight transducers for entrainment: ±4 kg • Ultrasonic for pool level: ±10 mm • Vortex meters for fluid: ±0.5%	Significant differences in entrainment amount between side and top upper plenum exits.
ADETEL, Steam SET [7]	• Weight transducers for entrainment: ±0.02% • Capacitance meter for pressure vessel liquid level: ±0.2% • Differential pressure for collapsed liquid level: ±0.2%	Net droplet entrainment increases when vessel internals are included in the RPV.
Stratified-Horizontal, Air SET [3]	• Thermal mass flow meter for air mass flow rate: ±0.78 kg/m^2s • Coriolis flow meter for liquid mass flux: ±1.99 kg/m^2s • Single channel optical fiber probe and laser doppler anemometry for droplet flow rate: *NP	Increase in droplet entrainment from greater superficial liquid or vapor velocity.
CCTF, Steam IET [14]	• Local impedance probe and gamma densitometer for void fraction: *NP • Conductivity meter and optical liquid level detector for liquid level: *NP	During recovery from a severe accident, droplet entrainment from the core vaporizes in the steam generator.
INKA, Steam IET/SET [15]	• Gamma densitometer for void fraction: *NP • Thermo needle-point probes for water level: *NP • Mass spectrometer for drywell composition: *NP	Test findings not presented.

*NP = Not provided by the authors

2. UNCERTAINTIES AND INSTRUMENTATION SENSITIVITY

Computational models have been discussed in conjunction with empirical data, but models are only as accurate as the underlying data used to build them. For fluid and thermal hydraulic properties, such as the Reynold’s or Nusselt numbers, the multiple non-exact inputs to their calculation result in final uncertainties which can have significant impact on the model results. A simple flowchart of all the parameters going into the calculation of Nusselt numbers is given in Figure 1 and shows how uncertainty propagation magnifies initial error in instrumentation. These uncertainties derive from fluid properties and the limits of instrument sensitivity. The numerical analysis in [16] determines that the standard deviation of a derived Nusselt number can be between 13–18% propagated from reasonable errors in measurements of pressure, temperature, velocity, two-phase mixture characteristics, and power. This underscores the importance of increasing measurement sensitivity in experimental facilities if the results are to be useful for informing an integrated effort with computational models.

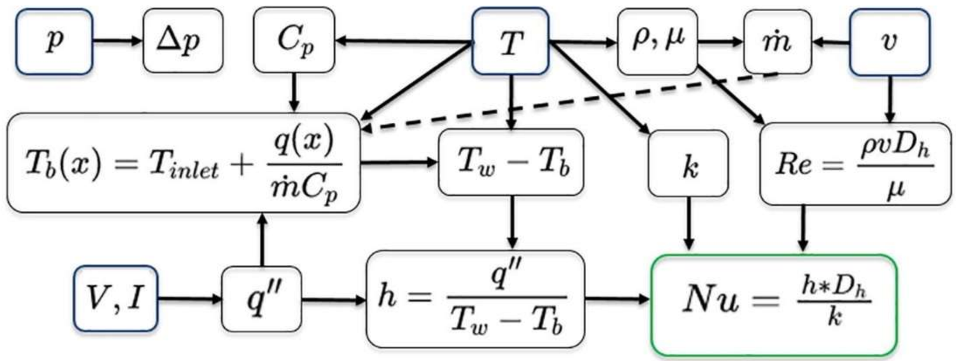

Figure 1. Uncertainties compound from fundamental measurements to thermal hydraulic calculation parameters. Reprinted from [16].

Mitigating uncertainty should be a prime objective for the collection of empirical data because of the uncertainty magnification that occurs in every calculation using a measured parameter. To this end, the main strategy is simplifying the measurement regime by attempting to capture less detailed phenomena in physical measurements. This approach coarsens measurements to collect more accurate information on bulk data to best inform the computational models. These are then used for insight into more complex phenomena, while the instrumentation methods and placement are selected for that which will be least disruptive to flow and cause little departure from a realistic scenario. One such example from employing this strategy is in the measurement of void fraction and droplet entrainment amounts in a pipe. A high-fidelity device previously used extensively for this purpose is the wire mesh sensor (WMS). These are composed of a 2D or 3D array of metallic wires which operate on the principle of capacitance or conductance in each grid cell. They are calibrated while immersed in the liquid phase, and the difference in measured quantities during a two-phase test can be interpreted to calculate the void fraction mapped over the pipe cross section, or simply used to calculate an average void fraction. However, these devices can be disruptive to the flow inside the pipe, potentially causing liquid holdup in the sensor and an underprediction of void fraction. The inverse can also occur if the gas superficial velocity is low [17]. Another aspect of WMS disruption is that the flow resistance can cause sudden expansion and contraction in the pipe, altering flow characteristics. *Despite these effects, the WMS has been assessed as being accurate to within 10.5% of validation data for void fraction measurement [17] and comes with the benefits of real-time measurement and some spatial details of flow characteristics.* This can be compared with a more traditional method of gamma densitometry, which has shown uncertainties of 15% on average [17] and which loses applicability as pipe size increases and void fraction decreases, as both increase radiation attenuation. Comparison is also made between the WMS and quick-closing valve approaches to show that the WMS results only deviate by 1.5% [17]. The quick-closing valve technique would not be desirable for the scenarios discussed because it requires pausing and restarting testing for every measurement made. Selection of appropriate control valves is pivotal for reactor system thermal hydraulics experimentation—specifically simulating pipe break(s) and a LOCA analysis [18]. Another promising method for void fraction measurement in this application is through separation of the liquid and gas phases to measure each independently. Whether this is through collecting the entrained liquid in a holding tank and measuring the total mass change over time, or by measuring flow rates with Coriolis or vortex flowmeters, the moisture separators cause their own flow disruption through significant pressure drop across the inlet and outlets. A specific analysis would be needed for the specific system being modeled, but scenarios with higher liquid fractions may require use of multiple separators to improve the separation efficiency but would also enhance the pressure disruption.

After discussion of the impact that droplet entrainment can have on accident progression, and after a review of the previous experiment programs that considered the effect of entrainment, there is still a severe lack of knowledge on this phenomenon at the SMR scale. These data are necessary to validate the results from computational models, ensuring they are accurate for both regulators and system designers, as well as to confirm the safety arguments that favor smaller NPPs. The sizes of individual components and systems are much lower at the SMR scale, so it is unclear how entrainment will change to reflect this. One example of a likely exacerbation of entrainment in SMRs comes from previous SET testing taken from the literature. This testing determined that the vertical distance to the vessel exit piping from the water pool is a large driver of the rate of entrainment [2]. Since the SG is one such two-phase component in a PWR, an SMR design will likely reduce the height difference on the secondary side between liquid and the main steam line. An MSLB in an SMR will likely have a greater entrainment fraction in the fluid flow during depressurization relative to the large-scale NPPs, due to the closer proximity of the pool surface to the vessel exit. The effect in an accident is dependent on numerous additional factors. However, factors such as the presence of non-condensable gases, fluid flow rates, break size, and vessel swell rate further underscore the need for facility testing at the scale of a representative SMR. The process of building the case for licensing approval of a new reactor is illustrated in Figure 2 and ends with computational models and correlations qualified to accurately represent actual conditions. This process is described further in the next section.

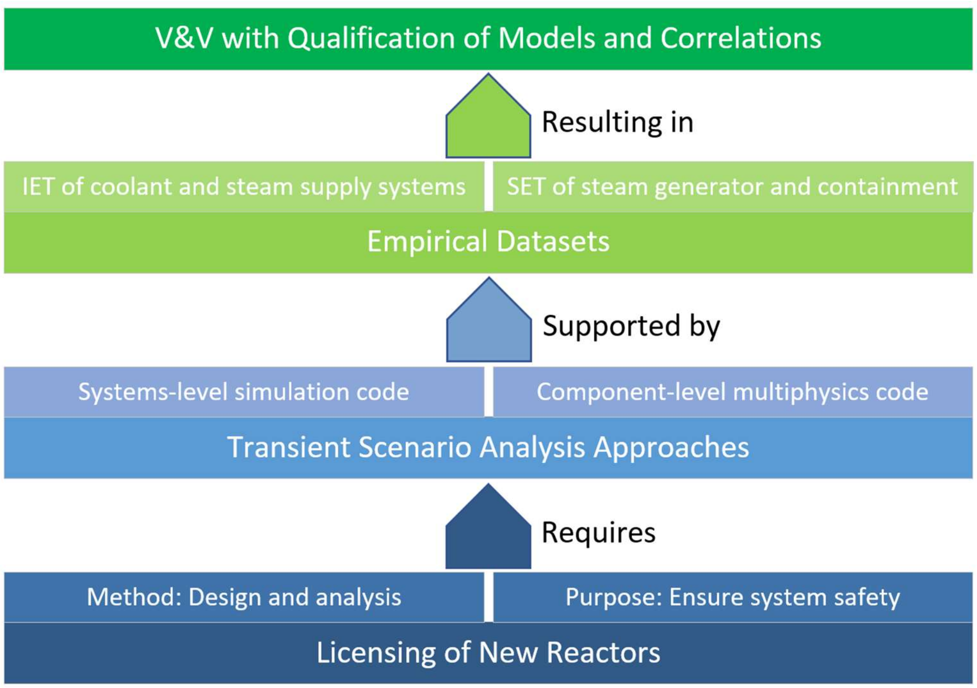

Figure 2. The licensing process requires safety analysis supported by experimental and computational results.

3. INTEGRATED APPROACH WITH SCALED EXPERIMENTS AND M&S

The benefits garnered from integrated system modeling with computational models and experimental facilities are greater than each individually. This is because the results from each iteration of testing can be used to improve the simulation with the other. An example of this principle being applied successfully comes from AP1000 testing of entrainment in the hot leg during automatic depressurization system operation. Using RELAP5/MOD3.4, the researchers successfully reduced the error in the entrainment estimate from 30 to 5% when compared with empirical data [19]. Through a process of selecting the entrainment correlation of best-fit, the systems-level code became much more accurate for accident analysis in the specific geometry and operating conditions of concern. The first iteration used only the two-fluid, six-equation model with no special upper plenum entrainment model and resulted in discrepancies of under

30% with experimental data. The next two attempts for the researchers were to create entrainment models specific to the upper plenum. The dimensionless model exacerbated error up to 50%, and the complex mechanistic model only revised this down to 40%, which were both still unacceptable to the researchers. The final approach was to simplify the entrainment model into a liquid mass conservation, using only feedwater flow rate in, phase enthalpies of the water and steam, and power input. This most accurately modeled the empirical data, fitting well within a 5% margin of error.

There are many instances of how tandem efforts like this one can be utilized in the simulation of an SMR, some of which are discussed in this section. The first of these comes from systems-level computer models aiding the design phase of a scaled test facility. Due to the inherent inaccuracy that comes with scaling down a system, certain parameters are prioritized to maintain important thermal hydraulic phenomena. Some of the scaling methodologies may include 1:1 model-to-prototype scaling of the power-to-volume ratio, component height, and pressure drops, as well as similar ratios between system or vessel volume, and fluid flow rates with flow areas that maintain velocities and pressure drops with the prototype [20]. Computer modeling can be used before the test facilities are constructed to potentially identify significant distortions or negative dimensionless parameter ratios (i.e., evaporation instead of condensation) between the model design and the prototype to minimize these distortions [20]. The steps for use of CFD simulation in an integrated effort with experimental data are outlined in Figure 3. The first effort in validation occurs on a single empirical dataset, where the model parameters are adjusted to fit the experimental data. The wider the range of test parameters and results to validate a model, the closer it comes to general validation.

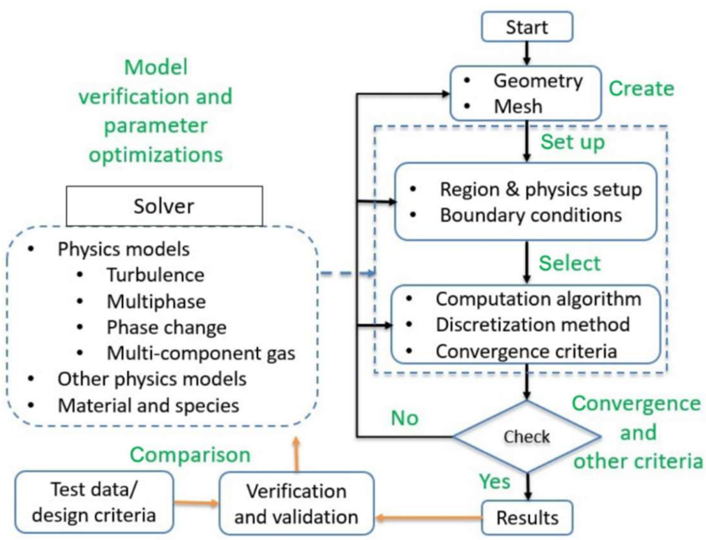

Figure 3. Process of simulating with CFD to produce data for comparison with empirical data. Reprinted from [21].

Once the experimental facilities are operational and empirical data are being collected, these datasets are used to improve the correlations and assumptions that are inherent in computational models. A sample of the empirical correlations identified in literature and developed from experimental programs or applied in computational modeling is shown in Table II. These will be checked for applicability to SMR droplet entrainment once the empirical data are collected. This is applicable to both high-fidelity multiphysics and CFD simulation, and systems-level control volume codes like RELAP where parameters such as the heat transfer correlation can be corrected based on empirical results from an SET facility. In this way, the experimental simulations also improve the data which are used to build the computational models to improve the applicability of results garnered from these. Another way computational results improve the applicability of the empirical data to safety analysis is by informing the initial conditions of SET scenarios. An SET of containment can use the break flow rate and entrainment fraction produced by the computer modeling to create a realistic scenario for assessing how the containment structure copes under the accident conditions. For the purpose proposed here, the computational modeling and experimental program will be limited to an integrated approach of iterative improvement in both, rather than digital twin real-time interfacing. However, this is an important step to support a future effort since reducing uncertainty in modeling correlations can enable a more accurate digital twin.

Table II. Entrainment correlations developed from experimental programs or included in computational models.

Reference	Correlation Formula	Application of Correlation with Uncertainty
AP1000 Hot Leg, Air SET – [13]	$E_{fg} = 1.0(10^{25})(\frac{j_g^*}{h^*})^{10.05}$ where, E_{fg}: droplet entrainment amount j_g^*: dimensionless superficial gas velocity h^*: dimensionless height above pool	Horizontal upper plenum exit, where: $\frac{j_g^*}{h^*} \geq 3.34(10^{-3})$ Uncertainty: Not provided.
Stratified-Horizontal, Air SET – [3]	$S_E = 9.18(10^{-6})\frac{\mu_l}{D}We_g^{2.107}Re_l^{0.7}(D^*)^{-1.652}$ where, S_E: droplet mass flux μ_l: dynamic liquid viscosity D: inner pipe diameter We_g: Weber number for the gas Re_l: Reynold's number of the liquid D^*: dimensionless inner pipe diameter Re_g: Reynold's number of the gas	Horizontal pipe net-entrainment, where: $65{,}500 \leq Re_g \leq 571{,}400$ and $170 \leq Re_l \leq 11{,}000$ Uncertainty: Mean absolute uncertainty of 14.3%.
REGARD, Air SET – [6]	$\Gamma_E = \frac{\rho_l V_E}{\lambda_c^2 \tau_C}$ where, Γ_E: entrainment rate ρ_l: liquid density V_E: entrained volume sub correlation (SC) λ_c: critical wavelength SC τ_C: characteristic time SC	Validity only in regime of stratified-horizontal flow, and droplet entrainment assumed to result from wave fragmentation exclusively. Uncertainty: Propagated from six probes with error of 3 mg/s each.
RELAP5/MOD3 Code Manual – [22]	$E = \tanh(7.25 * 10^{-7} We^{1.25} Re_l^{0.25})$ where, E: fraction of liquid as flowing as droplets We: Weber number for entrainment j_g: superficial gas velocity	Annular liquid film, where: 1 atm < Pressure < 4 atm 0.95 cm < D < 3,2 cm $370 < Re_f < 6400$ $j_g < 100$ m/s Uncertainty: Claimed to be satisfactory.

4. CONCLUSIONS

Droplet entrainment has been discussed for its impact in accelerating possible accident scenarios, marking this phenomenon as vitally important for understanding how it affects system development. The literature contains many important details about these potential effects, as well as insight into the fundamental mechanisms for how entrainment and de-entrainment occur. As far as the author could identify, data for specific nuclear reactors were all collected to replicate the conditions or geometry of large-scale systems. There are notable gaps in the knowledge as the industry looks forward to licensing small-scale power plants, including:

- Droplet entrainment effects on accident progression in a system scaled to represent an SMR power system, recognizing the impact of geometric compactness and unique design characteristics.
- Empirical data from SMR separate and integral effects testing which can be used to validate computational models for EMDAP.
- Droplet entrainment effects on containment temperature and pressure from a simulated depressurization inside containment.

This future experimental program can build confidence in the arguments put forward by SMR designers that these reactors are better equipped to cope with departures from normal operation. The effect of droplet entrainment on reactor safety will likely be significant, but properly measuring the phenomenon for improving system software modeling will enable the industry to progress through this burgeoning frontier in clean power. Licensing through the NRC is the biggest challenge to overcome for many designs, and an experimental program which addresses the literature gaps will crucially improve the case for approval.

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Conflicts of Interest: The authors declare no conflict of interest.

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