

## Westinghouse Advanced Passive (AP) Technology

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### ABSTRACT

Westinghouse's Advanced Passive (AP) reactor technology has undergone a structured, evidence-based evolution over more than three decades, beginning with the AP600™ and leading to the deployment of the AP1000® Pressurized Water Reactor (PWR), and remains at the heart of the AP300™ Small Modular Reactor (SMR). This progression reflects a consistent design philosophy: leveraging natural forces - gravity, natural circulation, convection, and stored energy—to achieve safe shutdown, maintain core and containment cooling, and ensure long term heat removal without operator intervention or reliance on AC power.

The AP600 design established the foundational passive safety system architecture, validated through extensive separate and integral effects testing programs. These tests confirmed the capability of passive core cooling and containment systems to maintain safety margins under a wide variety of postulated accidents, establishing regulator confidence and enabling first-of-a-kind certification. Building upon the AP600 design, the AP1000 Nuclear Power Plant (NPP) introduced scale up efficiencies, simplified systems, improved constructability through modularization, and enhanced reliability via standardized components. With global regulatory approvals and operating experience exceeding multiple reactor years, the AP1000 PWR validated the robustness, reliability, and deployability of advanced passive nuclear technology.

The AP300 SMR represents the latest product in the Westinghouse AP family, directly inheriting its core design, major equipment, proven fuel, and safety systems from the AP1000 PWR, while scaling down to a 300–330 MWe class reactor optimized for deployment flexibility. Its passive safety systems maintain the same fail-safe, self-sufficient characteristics: automatic actuation without pumps, diesels, or operator actions; long duration passive cooling; and a containment architecture protecting all critical systems within a steel vessel and shield building. Testing needs for the AP300 SMR are largely met by the AP600/AP1000 data sets, significantly reducing first of a kind (FOAK) risk.

This paper will summarize the development and maturation of the Westinghouse passive safety systems and their integration into the AP1000 PWR and AP300 SMR designs.

**Keywords:** *scaling assessment, passive safety systems, small modular reactor, PIRT, integral effects tests, separate effects tests.*

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# 1 INTRODUCTION

The Advanced Passive technology development started in 1990s with the AP600 design with 600 MWe rated power. The philosophy at the core of the AP600 design was to keep it safe, proven and simple [1]. The key concept that made the design simpler and enhanced safety was eliminating the reliance on alternating current (AC) power sources for primary safety functions. The AP600 design introduced passive safety systems in commercial NPP designs. This was a huge improvement compared to the legacy nuclear power plants, where the safety systems were active.

Passive safety systems rely only on natural forces such as gravity, natural circulation, convection, and stored energy and do not rely on external mechanical and/or electrical power, signals or forces [2]. They are automatic and diverse from the active defense in depth and power production systems. The active defense in depth systems need AC power to operate and perform their function. This provides reliability and simplicity to the design. Moreover, the use of passive safety systems reduces the frequency of potential core damage and radiation release. The main passive safety systems introduced in the AP600 design were the Passive Core Cooling System (PXS) and the Passive Containment Cooling System (PCS). The only requirement for actuation of these safety systems is a one-time alignment of valves without operator action. Performance of those systems has been proven by extensive testing approved by the United States Nuclear Regulatory Commission (US NRC). Those systems are described in Section 2 of this paper.

The AP600 design received the US NRC Final Design Approval in 1998. At that time, it was the simplest, least expensive nuclear power plant design available [1]. However, due to the market needs and strong competition in terms of economics from gas power plants, Westinghouse realized that the cost per megawatt of installed capacity had to be even lower to be competitive on the market. Raising the power output was the only way to make the design competitive, since the design was already as simple as it could have been and still safe and reliable. The result of raising power was the AP1000 plant design. The power output was raised without negating any safety margins.

The AP1000 NPP is safe, simple and standard. The PXS and PCS remain the heart of the passive safety design solutions. The design uses standardized proven components, which provide enhanced reliability. The AP600 testing basis along with testing and scaling results for AP1000 design have been further confirmed from the operating AP1000 units worldwide through pre-operational and routine testing of the safety systems. Westinghouse is a pioneer in developing standardization for nuclear power plant designs with demonstrated capabilities to deploy standardized plants design. This means that the current AP1000 operating plants serve as the reference plant or starting point for specific project development. The site-specific portion is aimed at the integration of the standard plant with the local site geography and characteristics, without any major changes to the design. To ensure the full benefits of the standardization in terms of optimizing fleet operation, it is imperative to maintain unchanged nuclear island design basis for all plants delivered. This results in benefits for procurement, construction, licensing, operation, and maintenance of the plant.

The AP1000 NPP has undergone significant licensing effort worldwide. In the US, the Design Certification under 10 Code of Federal Regulations (CFR) Part 52 was issued in 2011 for the standard design. Beyond the US, National Nuclear Security Administration (NNSA) in China issued construction license for the first-of-a-kind AP1000 plant in 2009, with a fuel load permit in 2018. Westinghouse has also successfully completed the Generic Design Assessment (GDA) process in the United Kingdom (UK), and the UK Office for Nuclear Regulation (ONR) issued a design acceptance confirmation and statement of design acceptability for the AP1000 plant design in March 2017. In 2013, the pre-project design review, which is an optional service provided by the Canadian Nuclear Safety Commission (CNSC), concluded that there are no fundamental barriers to licence the AP1000 plant in Canada [3]. Currently, the licensing process is ongoing in both Poland and Bulgaria, with Vogtle Unit 4 as the reference plant. Vogtle Units 3 and 4 are the two AP1000 plants currently operating within the US. These international approvals demonstrate that the standard AP1000 plant as approved by the US NRC, can be successfully applied to international applications with a high level of licensing certainty.

Another key feature of the AP1000 plant is the simplified construction by modularization. By using prefabricated, predesigned modules that fit smoothly into the overall layout, the AP1000 plant seeks to minimize onsite construction work and accelerate project deployment. Figure 1 presents the installation of the biggest module (CA20) at Vogtle site construction. Modularization supports construction logistics, which are one of the biggest challenges during the NPP deployment. It also helps with lowering the overall cost of construction. Modularization and the use of digital design tools played a key role in deployment of six AP1000 reactor units worldwide – two units in the US and four units in China [4]. First unit in China – Sanmen 1 entered commercial operation in September 2018. Vogtle Units 3 and 4 entered commercial operation in 2023 and 2024, respectively. With global regulatory approvals and operating experience exceeding multiple reactor years, the AP1000 PWR validated the robustness, reliability, and deployability of advanced passive nuclear technology.



Figure 1: Installation of the CA20 module at Vogtle site (© Georgia Power Company All Rights Reserved)

The most recent product of the AP technology family is the AP300 SMR. This design retains all safety features of the AP1000 plant, while scaling down to the 300 MWe class range to allow deployment flexibility and to respond to worldwide market needs. Although the AP300 SMR's primary mission is to deliver clean and safe electric power, it can equally be deployed for other energy applications such as district heat supply and for meeting energy needs in off-grid environments. The AP300 SMR is a one-loop design that uses proven AP1000 plant components. Using the same passive safety systems as the AP1000 plant ensures that the reactor can maintain safe shutdown conditions without the need for active intervention. The AP300 SMR is the only SMR design that is based on a constructed and operating advanced reactor technology [5][6]. Testing needs for AP300 SMR are largely met by the AP600/AP1000 data sets, significantly reducing FOAK risk.

The purpose of this paper is to help the reader familiarizing with the AP technology, the passive safety systems and the scale test program characterizing all three AP designs.

## 2 PASSIVE SAFETY SYSTEMS

In the AP technology plants, all safety functions are fulfilled by passive safety systems. The AP technology passive safety systems function entirely without operator intervention, relying solely on natural driving forces—gravity, natural circulation, and compressed gas—to perform their safety functions. Aside from a small number of automatically actuated valves, the design philosophy eliminates the need for pumps, fans, diesel generators, chillers, or other active equipment. To provide high reliability, these automatically actuated valves are designed to actuate to their safeguards positions upon loss of power or upon receipt of a safeguards actuation signal. They are supported by multiple, reliable power sources to avoid unnecessary actuations.



pressure, and their discharge flow rate remains effectively constant for a given water level, independently of the static pressure in the RCS.

The accumulators contain borated water and a compressed nitrogen cover gas to provide rapid injection. They inject automatically through the DVI once the RCS pressure falls to the accumulator's pressure.

The IRWST provides low pressure injection of cold borated water through the two gravity injection lines, each connected to a DVI line.

Automatic Depressurization System (ADS) stages 1-3 and stage 4 in the AP600 and AP1000 plant designs are used to reduce RCS pressure to allow for the IRWST injection. The AP300 SMR design has an ADS that is similar to the AP600 design. This includes the size of the pipes, valves, spargers, and sparger placement in the IRWST. However, the ADS stages 1/2/3 are simplified to ADS stages 1 and 2. The sparger is located close to the PRHR HX in the AP300 SMR [8].

Emergency RCS boration adds negative reactivity during transients where the normal RCS boration supply is unavailable or is insufficient. This negative reactivity provides long term shutdown margin (with rods) for events that result in cooldown of the RCS. Boration is provided by CMTs and accumulators.

## 2.2 Passive Containment Cooling System

The PCS is designed to remove heat/energy from the steel containment vessel and transfer it to the atmosphere, which is the ultimate heat sink. It operates automatically and can sustain containment cooling for at least 72 hours without operator action. Figure 3 shows how the heat transfer is achieved. This system ensures that the containment design pressure and temperature are not exceeded, following any postulated design basis event.

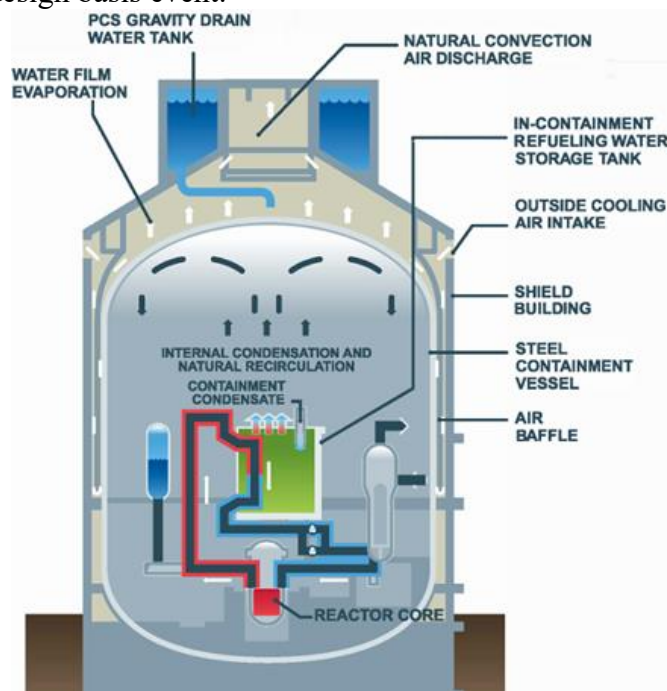


Figure 3: The Passive Containment Cooling System [7]

When water from the IRWST starts to boil, the steam is produced inside of the containment, the pressure and temperature within the containment rise, triggering the PCS to operate automatically via either Protection and Safety Monitoring System (PMS) or Diverse Actuation System (DAS). Those signals open the PCS valves and the water from the Passive Containment Cooling Water Storage Tank (PCCWST), located at the top of the shield building, flows by gravity onto the outside surface of the steel containment vessel, forming a thin film that enhances heat transfer through evaporation, convection, and conduction.

In parallel with the water film cooling mechanism, the PCS uses a natural-draft airflow path integrated into the shield building, which is always open. Air enters through an outside cooling air intake near the top of the structure, descends through an outer annulus, reverses direction at the bottom, and rises through an inner annulus in direct contact with the heated containment surface. As the air absorbs heat from the containment vessel, natural convection drives it upward toward a chimney-like exhaust at the top of the shield building, creating a continuous natural circulation pattern. This airflow provides sustained convective heat removal, ensuring that the containment cools effectively even after the water inventory in the PCCWST is depleted. The PCCWST has enough water inventory to provide cooling during the first 72 hours after the accident.

If further water inventory is needed, water makeup pumps are used to transfer water from the on-site Passive Containment Cooling Ancillary Water Storage Tank (PCCAWST) to the PCCWST to maintain water cooling of the containment. However, this requires operator action to start the pumps.

### 3 PHENOMENA IDENTIFICATION AND RANKING TABLE

The Phenomena Identification and Ranking Table (PIRT) process is a systematic way of gathering information from experts on a specific concept, and ranking the importance of the information, to meet some decision-making objectives. It has been applied to many nuclear technology issues, including nuclear analysis, to help guide research or develop regulatory requirements [9]. The PIRT process was introduced during the AP600 design development to identify sufficient and high-quality experimental database to validate safety analysis computer code for passive cooling systems.

The AP600 PIRT was developed by a cross-section of nuclear industry experts and Westinghouse thermal-hydraulic experts. It was reviewed and approved during the AP600 Design Certification by the US NRC and members of the Advisory Committee on Reactor Safeguards (ACRS). The AP600 PIRT was then re-evaluated during the AP1000 design certification process.

The PIRT, developed as a part of the AP600 safety analysis licensing effort, consisted of:

- Large-break LOCA,
- Small-break LOCA,
- Long-term cooling,
- Non-LOCA transient,
- Containment.

Design changes were made to develop the AP1000 plant and AP300 SMR designs comparing to the AP600 design. Although the capacities of systems and components have been adjusted to accommodate the higher or lower core power of the AP1000 plant and AP300 SMR, respectively, the basic configuration of the passive safety systems has been maintained.

The AP300 SMR PIRT findings are similar to the AP1000 PIRT, as many of the phenomena are the same, and extensively studied during the AP1000 plant's design, development, licensing and deployment. There is no low State of Knowledge (SoK) phenomenon, but the SoK of a few phenomena are reduced to medium driven by design differences between the AP1000 plant and the AP300 SMR. Two of the most significant design differences include:

- 1) flow asymmetry due to the reduction from two loops to one loop
- 2) the inclusion of the spent fuel pool inside containment which increases heat load on the PCS.

The AP1000 NPP methods follow the Standard Review Plan (SRP) discussed in NUREG-0800 [10]. Although released later, these methods closely follow the Evaluation Model Development and Assessment Process (EMDAP) which is outlined in Regulatory Guide (RG) 1.203. EMDAP is a structured, stepwise process developed by the US NRC to guide the development, validation, and application of safety analysis codes and evaluation models (EMs) for nuclear power plants. Its main goal is to ensure that the models used for safety analysis are technically sound, appropriately validated, and suitable for their intended application. As needed, new methodology and evaluation models will follow the EMDAP process for the AP300 SMR.

The process is divided into four main elements:

1. Establish Requirements for Evaluation Model Capability,
2. Develop Assessment Base,
3. Develop Evaluation Model
4. Assess Evaluation Model Adequacy

Following the process, the AP300 SMR safety analysis PIRT was developed as Element 1. The PIRT identified important physical phenomena in design basis LOCA accidents, non-LOCA transients, and containment analyses. A group of experts ranked the safety significance and determined the SoK of each phenomenon. The AP300 SMR PIRT also defined the assessment base for the AP300 SMR (Element 2) according to the importance of phenomena and the SoK of the phenomenon. The combination of a phenomenon's relative importance and its current state of knowledge provides the basis for determining how further efforts to conduct experimental programs and develop analytical tools can be accomplished in a sufficient and cost-effective manner. Due to high similarity of the AP300 SMR and AP1000 NPP designs along with the existing assessment base from AP1000/AP600 testing programs, most of phenomena are consistent between two plants and have high SoK. This includes important phenomena without any low SoK item. For Element 3, the AP300 SMR PIRT defined all relevant phenomena and their significance. These elements lead to the functional requirements for the safety analysis evaluation model development. The PIRT established the basis for applying AP1000/AP600 testing programs as the validation basis for the AP300 SMR. The AP1000 safety analysis evaluation models used for LOCA, non-LOCA, and containment safety analyses have been validated against the tests in the validation assessment base, most of them from AP1000/AP600 testing programs. The validation effort is part of Element 4 in EMDAP. Should new methodologies be developed to support the AP300 SMR, then additional validation will be required.

### **3.1 Passive Core Cooling System PIRT**

#### **3.1.1 AP1000 Large Break LOCA**

The AP600 large-break LOCA PIRT is divided into three transient phases: blowdown, refill and reflood. The long-term cooling phases (IRWST injection and sump recirculation) are considered in a separate PIRT. Separate transient phases are considered since the system response and the corresponding phenomena are significantly different.

Compared to the AP600 design, a few of the AP1000 design changes (such as increase in the vessel, pressurizer and steam generator (SG) tube volumes, core power level, core height and the fourth stage automatic depressurization system (ADS) line size) affect the large-break LOCA (LBLOCA) transient response.

The conclusions regarding the AP600 LBLOCA PIRT were that "the new and additional passive systems, which have been added to the AP600 plant (CMTs, IRWST, ADS), do not contribute to the core cooling in the short term, nor do they influence the calculated Peak Clad Temperature (PCT) for the large-break transient. The PRHR HX can condense steam, which will enhance the AP600 reflood for some time; however, it is not essential to an acceptable calculation of the PCT. Based on the review of the AP1000 PIRT, these conclusions remain valid for the AP1000 LBLOCA PIRT [11]. As described at the beginning of Section 3 – the AP300 SMR PIRT findings are similar to the AP1000 PIRT.

#### **3.1.2 AP1000 Small-Break LOCA PIRT**

The small-break LOCA (SBLOCA) transient was divided into six major phases with a transition phase added between ADS and IRWST injection phases. The ADS to IRWST transition phase was added, as it is the critical period for maintaining core cooling during a SBLOCA.

These phases of the SBLOCA are (1) Blowdown, (2) Natural Circulation, (3) ADS, (4) ADS to IRWST Transition - CMT injection dominant - IRWST injection dominant, (5) IRWST Injection and (6) Sump Injection.

Similarly to LBLOCA, a number of the AP1000 design changes affect the SBLOCA and long-term cooling transient response. For instance, the increase in core power level produces a higher post-blowdown steaming rate, leading to greater pressure drops and potentially making more difficult the transition to IRWST injection. On the other hand, the increase in the size of the fourth stage ADS (ADS-4) line allows for a greater post blowdown steam release rate. This, in combination with injection piping of bigger sizes, helps during the IRWST injection and the sump recirculation phases.

In conclusion, no new phenomena were identified for the AP1000 NPP. The blowdown, natural circulation, and ADS blowdown phases were unchanged from the AP600 design. A few unranked or low-ranked phenomena were re-ranked as 'low' or 'medium' importance for the IRWST Injection Cooling phase and Sump Injection phase. Hot leg entrainment was re-ranked from 'medium' to 'high' for these phases. These phenomena were considered in the AP600 design scaling and code applicability. These scaling studies show that the test facilities are adequately scaled to simulate entrainment in the hot legs that may be experienced in the AP1000 NPP [11]. As described at the beginning of Section 3 – the AP300 SMR PIRT findings are similar to the AP1000 PIRT.

### **3.1.3 AP1000 Non-LOCA Transient PIRT**

Likewise to the case of the LBLOCA, several AP1000 design changes affect the non-LOCA transients. Each non-LOCA event is considered separately during the PIRT process to show the system dynamic response to various heat up and cooldown transients. The criteria of interest for these events are the core integrity (margin to DNB), RCS integrity (pressurizer level and pressure), and offsite doses. The increase in core power level relative to the flow coastdown rate following RCP trip could have reduced the margin to DNB. To address this, the AP1000 reactor coolant pump flow coastdown characteristics have been enhanced by increasing the pump rotating inertia. The AP1000 analyses demonstrated that the flow at the time of minimum departure from nucleate boiling ratio (DNBR) is higher than in the AP600 design.

Another AP1000 design change was the decrease in the pressurizer volume-to-power ratio and an increase in SG secondary volume that could make the RCS more sensitive to shrink and swell events. During the AP1000 cooldown event associated with either a steam line or feedwater line break, if the RCS pressure were to decrease enough to cause the CMTs to begin injecting, then the gravity drain injection and the vapor condensation rate phenomena may become important [11]. As described at the beginning of Section 3 – the AP300 SMR PIRT findings are similar to the AP1000 PIRT ones.

## **3.2 Passive Containment Cooling System PIRT**

The main difference between the AP600 and AP1000 containment designs are the height and the increased thickness of the shell for the AP1000 design. The change in height affects the shell surface area and the containment free volume while the change in thickness allows for an increase in the design pressure. The main differences affecting a containment design basis accident (DBA) mass and energy release are: the RCS volume, the SG volume, the initial conditions, and the power level.

It was found that none of the geometrical or power density changes in the AP1000 design would alter the relative ranking of phenomena from the original AP600 containment PIRT. The basis for this conclusion was that none of the AP1000 design changes alter the method or phenomena by which the PCS operates. Therefore, it was concluded that the AP600 containment PIRT was applicable to the AP1000 design [11].

Only a limited number of new phenomena are identified for the AP300 SMR and are in regard to the spent fuel pool being housed within the containment. The importance ranking of containment phenomena in the AP300 SMR remains consistent with those in the AP1000/AP600 PIRT and without any new low SoK items identified. Thus, based on preliminary scaling evaluations, the

containment testing program of the AP600/AP1000 plants will remain applicable to the AP300 SMR and be scalable to the existing test database for validating the AP300 SMR containment evaluation model.

## **4 SCALING EVALUATION**

The approach taken in the AP600, AP1000 plant and AP300 SMR design scaling analyses is derived from the hierarchical two-tiered scaling (H2TS) methodology. The H2TS methodology was initially applied to the AP600 test facilities. The overall scaling approach to the integral effects test facilities involves scaling at two levels: top-down and bottom-up scaling. Top-down scaling involves scaling at a global or at a system level, where the relative influences of various components or processes can be assessed.

Top-down scaling is very efficient because it addresses multiple processes with a relatively small number of scaling groups. For an integral effects test facility, this macro-level type of scaling is well-suited to capture the integral effects of multiple processes.

Bottom-up scaling involves scaling at a local or subsystem level, where a more detailed assessment is needed for a specific component or process. This micro-level type of scaling is useful to assess separate effects and accomplish the detailed design of a scaled test facility. It is also useful where top-down scaling is not practical.

For the purpose of assessing integral effects test facilities that are already designed (i.e., SPES, APEX, or ROSA) or established, top-down scaling is primarily adopted except where impractical or where local effects are deemed to be of high importance in the PIRT (i.e., such as entrainment of liquid in the hot leg to the ADS-4 vent path). Therefore, top-down scaling is used extensively for the integral effects scaling section. Bottom-up scaling is used only where important phenomena identified in the PIRT are not readily addressed at a system level with a lower state of knowledge [11].

The H2TS methodology is a widely known scaling method across the nuclear industry and has been used for the development of previous and current reactor safety analyses such as the AP600 and AP1000 PWRs [12], Full-Spectrum LOCA for Westinghouse PWRs, Mitsubishi Heavy Industries APWR [13], Kairos molten salt reactors [14] and NuScale SMR [15].

## **5 AP TESTING**

The original AP600 test program related to the plant safety functions was selected based on the plant features that were different from the legacy PWRs (Generation II plants) and for which applicable experimental data was not readily available. The tests simulated plant features as required to demonstrate the phenomena being examined. To validate the computer models, these experiments were simulated using the same computer codes used for plant analysis [16].

The AP600 PXS has undergone several Separate Effects Tests (SETs), Integral Effects Tests (IETs) and equipment verification tests. This section focuses on the purpose, description, and results of IETs and SETs.

### **5.1 PXS Separate Effects Tests**

SETs provide local details of phenomena to support evaluation model or correlation development. SETs are primarily used to obtain component level data for important advanced technology features, including basic research and experiments, that provide insight and guidance for phenomena that may also be studied in larger-scale or integral effects experiments. Table 1 presents the SETs that were completed for the AP600 PXS and the corresponding scaling conclusions for the AP1000 plant and AP300 SMR.

Table 1: PXS SETs Purpose and Scaling Conclusions.

Test	AP600 Testing Purpose	AP1000 NPP	AP300 SMR
Departure from Nucleate Boiling Test	To determine the critical heat flux (CHF) performance at low-flow conditions.	Data obtained for the AP600 plant is applicable to the AP1000 plant	Additional low-flow testing may be required to confirm DNB correlation with AP600 and worldwide Westinghouse fuel current data set.
Passive Residual Heat Removal Heat Exchanger Test	To characterize the thermal performance of the PRHR HX and the mixing behaviour of the IRWST.	Heat transfer correlations developed from the AP600 test data valid for the AP1000 PRHR HX.	Heat transfer correlations developed from the AP600 test data valid for the AP300 SMR PRHR HX.
Automatic Depressurization System Test Phase A and Phase B	To confirm the design of the ADS sparger and to determine the dynamic effects on the IRWST structure.	Data obtained for the AP600 plant is applicable to the AP1000 plant.	Data obtained for the AP600 plant is applicable to the AP300 SMR.
Core Makeup Tank Test	To simulate the operation of the CMT and its level instrumentation and to obtain data to support the development and verification of computer models.	Data obtained for the AP600 plant is applicable to the AP1000 plant.	Data obtained for the AP600 plant is applicable to the AP300 SMR.

### 5.1.1 Departure from Nucleate Boiling (DNB) Test

The AP600 DNB testing was performed to measure critical heat flux behavior at low-flow conditions typical of earlier, higher-power-density cores. This test used data accumulated over years of testing on the Westinghouse fuel designs.

For the AP1000 NPP, no additional low-flow DNB testing was needed because its higher normal core flow and greater pump inertia keep operation outside the low-flow range of the AP600 tests [11].

For the AP300 SMR, core-size differences relative to AP600 result in lower flow per fuel assembly, which extends beyond the current range of the existing database for Westinghouse fuel. To ensure that the DNB correlations used in the core design and analyses are fully supported for the AP300 SMR specific conditions, the design development program is defining a target low-flow DNB test plan to supplement existing Westinghouse fuel experience database.

### 5.1.2 Passive Residual Heat Removal Heat Exchanger Test

The AP600 PRHR HX tests were conducted to measure heat removal performance and the IRWST mixing behaviour using full height, full size tubes in a scaled volume IRWST. Preserving tube geometry and vertical height allowed realistic buoyancy driven flow patterns to develop, and the test matrix covered the full AP600 operating range.

The AP1000 plant PRHR HX is similar to the one in the AP600 plant with minor geometric differences (bigger sizes). Scaling evaluations showed that the AP600 correlations remain valid for the AP1000 design and that the heat fluxes in the case of the AP1000 remain well below critical heat flux limits [11]. Consequently, the AP300 SMR PRHR HX is also similar to the one in the AP600 plant with slightly fewer tubes and smaller connection piping. Preliminary scaling indicates that the AP600 heat transfer- correlations will remain applicable to the AP300 SMR [8].

### 5.1.3 Automatic Depressurization System Test Phase A and Phase B

The AP600 ADS Phase A and B tests were full-scale, full-pressure simulations used to validate the ADS sparger design, measure the IRWST dynamic loads, and characterize thermal-hydraulic behavior across the full ADS flow range. The ADS spargers are used for ADS Stages 1, 2, and 3

(ADS-1/2/3). Phase A focused on sparger performance and structural effects during steam blowdown into the IRWST, while Phase B added prototypical ADS valves and two-phase conditions to support analytical model development and valve specification.

In the AP1000 plant, ADS-1/2/3 use the same pipe sizes, valves, and spargers as in the AP600 design, therefore the AP600 test data are directly applicable [11]. In the case of the AP300 SMR, ADS-1/2 retain the same key geometric and functional features as in the AP600 design, with a simplified two-stage sparger arrangement [8]. The sparger design, placement, and piping are similar and scaling evaluations concluded that the AP600 ADS data remain applicable to the AP300 SMR.

#### 5.1.4 Core Makeup Tank Test

The AP600 CMT tests were full-pressure, full-temperature simulations of the CMT flow path and level instrumentation, covering hot-water natural circulation, steam-driven drain-down, and steam condensation in the upper CMT region. The data supported both model development and verification for the AP600 safety analyses.

For the AP1000 plant, the CMTs retain the same arrangement, pipe sizes, valve sizes, and elevations as in the AP600 plant, with a volume increase and a reduced orifice resistance. Scaling evaluations concluded that the AP600 CMT test data remain applicable for the AP1000 design [11].

For the AP300 SMR, the CMTs follow the same overall arrangement with reduced volume, adjusted orifice resistance, and a balance-line inlet moved to the vessel downcomer at matching elevation opposed to the cold leg connection [8]. Preliminary scaling evaluations likewise have found the AP600 CMT test data applicable to the AP300 SMR.

## 5.2 PXS Integral Effects Tests

IETs provide the integrated system response for important parameters of interest such as in the PXS integral effects tests, long term core integral systems tests, and large scale integral passive containment cooling tests. Table 2 presents the IETs that were completed for the AP600 PXS and the corresponding scaling conclusions for the AP1000 plant and AP300 SMR.

Table 2: PXS IETs Purpose and Scaling Conclusions.

Test	AP600 Testing Purpose	AP1000 NPP	AP300 SMR
Low-pressure APEX Test	Capture the thermal-hydraulic phenomena during SBLOCAs.	APEX scaling remains valid for the AP1000 plant.	Evaluations indicate that scaling remains valid.
High – pressure SPES-2 Test	Provide a simulation of the PXS system integrated performance and obtain detailed experimental results for verification of safety analysis computer codes.	SPES-2 is adequately scaled to the AP1000 plant.	Not used for the AP300 SMR scaling. The ROSA facility shows less scaling distortion than APEX facility for the AP300 SMR.
High-pressure ROSA Test	Provide a simulation of the PXS system integrated performance. Conducted for NRC confirmatory purposes.	Scaling not done, however it is expected that applicability will be demonstrated.	Scaling evaluations has concluded that it is adequately scaled.

### 5.2.1 Low-pressure, integral systems test, OSU (APEX)

The AP600 Low-Pressure Integral Systems APEX Test (OSU) was performed at low-pressure, with 1/4-height scaled integral systems test to capture the thermal-hydraulic phenomena during SBLOCAs. The facility reproduced the AP600 primary system geometry, passive safety systems, and long-term cooling behavior, allowing simulation of a wide range of SBLOCA sizes, locations, and orientations. An additional APEX1000 confirmatory test was conducted by the NRC to extend the database in support of the AP1000 NPP licensing, although Westinghouse did not use NRC data for design or licensing activities.

For the AP1000 plant, the passive safety configuration remains essentially the same as in the AP600 plant, with increased capacities. Evaluations show that APEX scaling remains valid for the AP1000 plant during the low-pressure phase of SBLOCA transients [11].

For the AP300 SMR, the passive system layout is similar, with differences such as a single RCS loop and relocated balance line. Due to its smaller size, the AP300 SMR benefits from more favourable volume scaling relative to the APEX1000, and preliminary evaluations indicate adequate scaling for the AP300 SMR in low pressure SBLOCA conditions.

### **5.2.2 High-pressure, integral systems test, SPES-2**

The AP600 Full-Pressure, Full-Height Integral Systems Test (SPES-2) was performed to provide a simulation of the PXS system integrated performance and to obtain detailed experimental results for verification of safety analysis computer codes. The test facility was designed to be capable of performing tests representative of SBLOCA, steam generator tube rupture (SGTR), and steam line break (SLB) transients. The test facility included two loops with one hot leg and two cold legs per loop, CMTs, accumulators, a PRHR HX, an IRWST, and an ADS. Active non-safety systems providing makeup to the reactor and SGs were also simulated. The test showed that the core remained covered following all simulated events, including a double-ended guillotine (DEG) DVI line break with only passive safety systems operating.

The AP1000 design has the same configuration of the passive safety features and the active non-safety features as the AP600 design. The scaling evaluation concluded that SPES-2 is adequately scaled to the AP1000 plant during the high pressure- phases of small LOCAs up to ADS-4 actuation, though its oversized ADS-4 limits the applicability at low pressure [11]. The AP300 SMR has the same configuration of the passive safety features and the active non-safety features as the AP600 design. However, the SPES-2 will not be used for the validation of computer code in the AP300 SMR project because ROSA-AP600 is a better scaled IET facility.

### **5.2.3 High-pressure, integral systems test, ROSA**

The AP600 Full-Pressure, Full-Height Integral Systems Test (ROSA-AP600) was performed to provide a simulation of the PXS system integrated performance. The test facility included two loops with one hot leg and one cold leg per loop, CMTs, accumulators, a PRHR HX, an IRWST, and all stages of the ADS. Non-safety systems providing makeup to the reactor and SGs were simulated. The test facility was designed to be capable of performing tests representative of a SBLOCA, SGTR, SLB, and station blackout transients. These tests were conducted for NRC confirmatory purposes; Westinghouse did not use the data for the AP600 or AP1000 design or licensing.

Although Westinghouse has not done a formal scaling evaluation of the ROSA test facility to the AP1000 design, based on similar scaling studies and design features to the AP600 design, it is expected that scaling would demonstrate the applicability of the ROSA test facility to the AP1000 plant [11]. The AP300 SMR has the same configuration of the passive safety features and the active non-safety features as the AP600 design. Due to the reduced reactor size from the AP600 design to the AP300 SMR, the volume scale of ROSA-AP600 to AP300 SMR is also smaller. The preliminary scaling evaluation has concluded that ROSA AP600 is adequately scaled to AP300 SMR during most of the phases of small LOCAs (except sump recirculation). The ROSA facility shows less scaling distortion than APEX facility for the AP300 SMR. This includes the accident phases of blowdown through ADS-4 actuation and IRWST injection. However, a refined scaling analysis of the IET will be developed in a later phase of the AP300 SMR design development.

## **5.3 PCS Separate Effects Tests**

Table 3 presents the SETs that were completed for the AP600 PCS and the corresponding scaling conclusions for the AP1000 plant and AP300 SMR.

Table 3: PCS SETs Purpose and Scaling Conclusions.

Test	AP600 Testing Purpose	AP1000 NPP	AP300 SMR
Air flow path pressure drop Test	To quantify the air-flow path resistance, determine if aerodynamic improvements were needed, and demonstrate the system effectiveness.	Test results were adequately scaled to the AP1000 plant.	Test results were adequately scaled to the AP300 SMR
Water film formation Test	To demonstrate the wettability of the containment surface to characterize general requirements for forming a water film over a large surface area.	Similar water spreading/coverage was similar to the AP600 plant.	Similar water spreading/coverage was similar to the AP1000 plant.
Wind tunnel bench experiment	To establish the proper location of the air inlets and to confirm that wind will always aid containment cooling air flow.	Cooling air flow is better due to inlets location on a taller shield building.	Range of test data that was used to validate the AP1000 PCS heat and mass transfer correlations is expected to remain acceptable and the conclusions from the test will remain valid.
Condensation Test	To examine, in detail, condensation of air/steam mixtures flowing over cold surfaces.	The AP1000 NPP is bounded by the composite heat-transfer data, and therefore this test was applicable and sufficient for the AP1000 plant.	The AP1000 NPP is bounded by the composite heat-transfer data, and therefore this test was applicable and sufficient for the AP300 SMR.
PCS water distribution Test	To provide a full-scale demonstration of the capability to distribute water on a sector of the steel containment dome outer surface and top of the containment sidewall.	Similar water spreading/coverage to the AP600 plant.	Similar water spreading/coverage to the AP1000 plant.
PCS wind tunnel Test	To demonstrate that wind does not adversely affect natural circulation air cooling through the shield building and around the containment shell and to determine the loads on the air baffle.	The shield building is taller which is expected to reduce the effects of surrounding buildings on the air flow over the containment shell from the air inlet vents.	The shape of the shield building of the AP300 SMR differs from the AP1000 design but maintains the key features to maintain a wind-neutral design.
Heated plate Test	To obtain data for the heat and mass transfer processes, and to observe film hydrodynamics including possible formation of dry patches due to surface tension instabilities.	The AP1000 plant is bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for the AP1000 NPP.	The AP300 SMR is bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for the AP300 SMR.

### 5.3.1 PCS Air Flow Path Pressure Drop Test

The Robust Air Flow Characterization Test (RAFT) facility is a one-sixth scale replica of a 14-degree section of the entire PCS air-flow path that was constructed to quantify the air-flow path resistance, determine if aerodynamic improvements were needed, and demonstrate the system effectiveness. Modifications were made to the air flow path to reduce pressure losses. The resulting design was adopted for the AP600 plant and used in subsequent analysis of the PCS performance. This test for the AP600 plant demonstrated that the pressure coefficients in the air flow path could be estimated, verified, and improved with simple design changes.

The AP1000 air flow path is very similar to that of the AP600 plant, the main difference being that the increased length due to the increase in containment height and the air intake update for the

enhanced shield building design. The increase in the straight downcomer and riser portions of the air flow path have a very small impact on the overall flow resistance and can be easily calculated. The highest resistances occur at the inlets, turning region, and chimney exhaust. The RAFT was updated with the new inlet design, and results were scaled and applied to the AP1000 safety analysis [11]. In turn, the AP300 SMR air flow path length is shorter than the one of the AP1000 plant due to the decrease in containment height, but the inlet and outlet design remained very similar. The decrease in the straight downcomer and riser portions of the air flow path will have a very small but favorable impact on the overall flow resistance and the test results can be extrapolated to the AP300 SMR [8].

### **5.3.2 Water film formation Test**

A simple qualitative test was performed for the AP600 design to demonstrate the wettability of the containment surface, to characterize general requirements for the formation of a water film over a large surface area. The test apparatus consisted of a flat steel plate coated with the prototypic paint selected for the containment outer surface. The plate was pivoted so that it could simulate nearly horizontal sections of the dome as well as the vertical containment sidewalls.

The containment dome of the AP1000 plant is the same size/shape as in the AP600 design and uses the same coating and water spreading devices. The maximum water flow rate is only slightly larger, while the minimum flow rate is significantly larger. As a result, water spreading/coverage was similar to the AP600 plant [11]. The containment dome of the AP300 SMR design is a similar shape as the AP600/AP1000 designs with a smaller diameter. It will also utilize the same surface coatings and water spreading devices will be used on the containment vessel surface. The PCS flow rate per unit surface area is very similar between the AP1000 NPP and AP300 SMR designs. As a result, water spreading/coverage for the AP300 SMR is expected to be comparable to the AP1000 design.

### **5.3.3 Wind tunnel bench experiment**

Wind tunnel bench tests of the AP600 PCS were conducted at the Westinghouse Science and Technology Center using 1/100-scale models of the AP600 shield building, air inlets and outlets, annulus baffle, and containment. These tests were performed to establish the proper location of the air inlets and to confirm that wind will always aid containment cooling air flow. Two models were used: one consisted of only the shield building and diffuser discharge without inlets and internal flow; the second included the air inlets, air baffle, containment, tank support structure, and a fan to simulate convective air flow. The results from this test were used to select the current AP600 air inlet location at the top of the shield building sidewalls. With this inlet location, wind either provided no impact or an increase in PCS air cooling flow.

The AP1000 air inlets are located in the same place as in the AP600 design. The diameter of the containment shield building is the same. The height of the containment/shield building in the case of the AP1000 plant is greater, which, if anything, has a beneficial effect by moving the inlets further above the surrounding buildings [11]. The top of the AP300 SMR shield building has been selected to minimize the pressure at the chimney exhaust and a higher integrated pressure along the air inlets. The AP300 SMR air inlets are also located in the same place as in the AP600 design. The height of the containment shield building is smaller, which decreases the overall pressure drop through the annulus, but it also decreases the distance between the inlets and the surrounding buildings. Therefore, the range of test data that was used to validate the AP1000 PCS heat and mass transfer correlations is expected to remain acceptable and the conclusions from the test will remain valid. Additional evaluation will be performed to confirm the initial conclusions.

### **5.3.4 Condensation Test**

A series of condensation experiments were conducted for the AP600 PCS to examine, in detail, condensation of air/steam mixtures flowing over cold surfaces. These experiments were used to

develop improved models for the PCS containment interior heat transfer. These small-scale, well-instrumented tests provided the basis for computer code model improvements and biases, so that the AP600 containment interior heat transfer performance could be conservatively predicted.

Results of this test contributed to the composite heat transfer data used to develop the condensation, conduction and convection heat transfer correlations used in containment integrity evaluation model. Scaling calculations have shown that both the AP1000 design and AP300 SMR are bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for these AP designs [11] [8].

### **5.3.5 PCS water distribution Test**

The AP600 PCS Water Distribution Tests were conducted to provide a full-scale demonstration of the capability to distribute water on a sector of the steel containment dome outer surface and top of the containment sidewall. The overall objectives of the PCS water distribution test were to quantify the effectiveness of the water distribution over the containment dome and top of the containment sidewall, and to provide data to finalize the design of the AP600 containment water distribution and wetted coverage assumptions. The test was conducted in several phases. Phase 1 utilized a full-scale simulation of the center of the containment dome out to the 10-ft radius. The test was used to evaluate water delivery to the dome. Phase 2 was conducted on a full-scale 1/8 sector of the containment dome and water distribution devices at the Westinghouse Waltz Mill facility. Phase 3 was used to confirm the final design of the water distribution system and to verify its performance, to be used in subsequent safety analysis over the applicable PCS delivered flow rates.

The containment dome of the AP1000 plant is the same size/shape as the AP600 design and uses the same coating and water spreading devices. The maximum water flow rate is only slightly larger and the minimum flow rate is significantly larger. As a result, water spreading/coverage is expected to be as good, or better, than for the AP600 plant [11]. Water coverage on the outer surface of the containment vessel has been confirmed equal to or better than the test results during preoperational testing at all operating AP1000 units. The containment dome of the AP300 SMR has a similar shape to the AP600/AP1000 containments, reduced in diameter, and will use the same coating and water spreading devices. The maximum water flow rate per unit area of dome is similar between the AP300 SMR and the AP1000 plant. As a result, water spreading/coverage is expected to be similar to the AP1000 plant [8].

### **5.3.6 PCS wind tunnel Test**

The AP600 wind tunnel tests were conducted primarily in a boundary layer wind tunnel at the University of Western Ontario. The overall objectives of the PCS wind tunnel test were to demonstrate that wind does not adversely affect natural circulation air cooling through the shield building and around the containment shell, as well as to determine the loads on the air baffle. The test was conducted in four phases at two different scales (1/100-scale and 1/30-scale models of the AP600 shield building and surrounding site structures, including the cooling tower). Phases of the tests had different focuses: including the effects of the flow path on the developed pressure coefficients, determining wind loads on the air baffle, and the effects of surrounding structures and topography. The tests confirmed that the AP600 design could be located on sites with extreme topographies with no adverse PCS impact.

The containment shield building of the AP1000 plant is the same diameter/shape as the AP600 design although the PCS water storage tank is somewhat larger in diameter. The shield building is taller comparing to the AP600 plant which reduces the effects of surrounding buildings on the air flow over the containment shell from the air inlet vents [11]. The containment shield building of the AP300 SMR has a smaller diameter compared to the AP600 design. The distance between the inlets and the top of the chimney has been proportionally scaled to the overall height of the containment to maintain buoyancy drive flows. The shield building is shorter, which is expected to have minimal

impact on the effects of surrounding buildings on the air flow over the containment shell from the air inlet vents, assuming that the surrounding buildings do not impact the wake regions at the air inlets or chimney exit. The shape of the shield building of the AP300 SMR differs from the AP1000 design but maintains the key features to maintain a wind-neutral design.

### 5.3.7 Heated Plate Test

The AP600 PCS heated plate test was performed in order to obtain data for the heat and mass transfer processes on the containment vessel surface, and to observe film hydrodynamics including possible formation of dry patches due to surface tension instabilities. The test was performed on a thick steel plate heated on one side and with an evaporating water film and ducted air flow on the other side. The plate could be placed in a vertical position to simulate the containment side wall or inclined somewhat from horizontal, to simulate the different slopes on the elliptic containment dome. Experiments were performed at a range of water film flow rates as well as a dry plate simulating the high-water flow on the upper part of containment down to the lower part of containment where the water was nearly completely evaporated at the high heat flux.

The evaporation rate of water from the heated plate was shown to agree with, or exceed those expected, and confirmed the overall heat transfer capability of the PCS concept. The following conclusions were drawn from the test results: heat transfer from the containment, including water film evaporation and radiation to the air baffle, agreed with, or exceeded, predicted values. A water film was easily formed and remained adhered to the coated steel surface, even in the vertical orientation. Once formed, the film showed no instability or tendency to form rivulets or dry patches. The results of this test contributed to the composite heat transfer data used to develop the evaporation, conduction and convection heat transfer correlations used in the containment integrity evaluation model. Both the AP300 SMR and the AP1000 NPP are bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for these plant designs [8][11].

## 5.4 PCS Integral Effects Tests

Table 4 presents the IETs that were completed for the AP600 PCS and the corresponding scaling conclusions for the AP1000 plant and AP300 SMR.

Table 4: PCS IETs Purpose and Scaling Conclusions.

Test	AP600 Testing Purpose	AP1000 NPP	AP300 SMR
Small Integral PCS Test	To simulate PCS heat transfer processes occurring on both the inside and outside containment surfaces.	Plant design is bounded by the composite heat-transfer data, and therefore this test is applicable to AP1000 design.	Plant design is bounded by the composite heat-transfer data, and therefore this test is applicable to AP300 SMR.
Large-scale Integral PCS Test	To examine, on a large scale, the natural convection and steam condensation on the interior of the AP600 containment combined with exterior water film evaporation, air cooling heat removal, and water film behaviour.	Plant design is bounded by the composite heat-transfer data, and therefore this test is applicable to the AP1000 design.	Plant design is bounded by the composite heat-transfer data, and therefore this test is applicable to the AP300 SMR.

### 5.4.1 Small Integral PCS Test

The small-scale integral AP600 PCS test simulated PCS heat transfer processes occurring on both the inside and outside containment surfaces. The test apparatus included a 3-ft. diameter and a 24-ft. high steel pressure vessel internally heated by steam supplied at various pressures. A transparent wall around the pressure vessel was used to create an annulus for fan-driven or natural

circulation air flow. The test simulated the full range of internal pressures/temperatures and external water/air flow rates, pressures/temperatures/humidities. The following conclusions and observations were drawn from this test: the heat removal capability from the external surface of the test vessel for both wetted and dry conditions agreed well with previous heated plate experiments and analytic predictions, and supported the AP600 containment analysis.

The AP1000 containment diameter and dome size/shape are the same as in the AP600 design and uses the same coating and water spreading devices. The results of this test contributed to the composite heat transfer data used to develop the evaporation, conduction, and convection heat transfer correlations used in WGOthic. Both the AP300 SMR and AP1000 plant design is bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for the AP1000 plant and AP300 SMR designs [8][11].

#### **5.4.2 Large-Scale Integral PCS Test**

The large-scale AP600 integral PCS test consisted of a 1/8-scale model of the AP600 containment in which both internal steam/air non-condensable gas conditions and external PCS operation were simulated in order to demonstrate the AP600 PCS heat transfer capability. The purpose of this test was to examine, on a large scale, the natural convection and steam condensation on the interior of the AP600 containment combined with exterior water film evaporation, air cooling heat removal, and water film behavior. The PCS heat transfer test results provided data for the verification of the computer model used to predict the containment response.

The AP1000 containment diameter and dome size/shape are the same as in the AP600 containment, while the AP300 SMR containment dome has similar shape as the AP600 plant but with a smaller diameter. All these designs use the same coating and water spreading devices. The internal structures are the same, except for the larger SG and pressurizer and the taller containment shell. The results of this test contributed to the composite heat transfer data used to develop the evaporation, conduction, and convection heat transfer correlations used in the containment integrity model. Both the AP300 SMR and AP1000 NPP are bounded by the composite heat-transfer data, and therefore this test is applicable and sufficient for the AP300 SMR and the AP1000 plant.

Heat and mass transfer constitutive relations from the AP600 tests cover the AP1000 NPP and AP300 SMR operating ranges, with dimensionless parameters such as density differences, Reynolds, and Grashof numbers within tested data bounds [11].

## **6 CONCLUSIONS**

The design of the AP600 plant was founded on key principles of design simplification, plant modularization, and a fully passive safety systems philosophy. Extensive AP600 and AP1000 SETs and IETs established a strong experimental foundation for Westinghouse advanced passive technology and supported AP1000 licensing and successful deployment of plants worldwide. The AP1000 plant design leveraged the AP600 test database through established scaling methods, with additional confirmatory testing and verification through pre-operational and routine testing at current operating plants.

Since the AP300 SMR is targeted as a fast follower of the AP1000 plant, it has the advantage of leveraging a proven design and a well-established experimental basis described in this paper. The established scaling approach, together with the extensive AP600/AP1000 SET/IET database and AP1000 plant operating experience, supports AP300 SMR design development and enables an expedited path to deployment without the need for dedicated new major scaled test programs.

Initial PIRT studies confirm that the AP300 SMR accident scenarios are comparable to those of the AP1000 plant, but with improved safety margins due to enhanced passive safety features and lower core power density. The extensive validation matrix of experiments from the AP600 and AP1000 testing programs provides strong confidence in the AP300 SMR safety analysis models and licensing approach [8].

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