Comparative Analysis of Primary Reactor Coolant Pump Architectures for a 40–120 MW PWR SMR

Introduction

Small modular pressurized water reactors (SMR) in the 40–120 MWth range demand reliable and cost-effective primary reactor coolant pumps (RCPs) to circulate high-pressure coolant, while meeting stringent ASME Section III design codes and U.S. NRC regulations. The choice of RCP architecture – whether traditional mechanical-seal pumps or modern sealless designs – significantly affects the reactor's lifecycle costs, safety case, and maintainability. This report expands on a pump analysis for such an SMR by comparing **mechanical-seal RCPs**, **canned-motor (sealless) vertical pumps**, and **horizontal wet-rotor (integrated) pumps**. Key factors addressed include initial and lifetime costs, failure modes and historical performance, primary loop integration and thermal-hydraulic behavior, as well as procurement logistics (vendor qualifications, lead times, and supply chain risks). Focus is given to commercially available pump technologies with proven nuclear service records or near-term readiness, prioritizing off-the-shelf solutions to minimize design risk and cost. Comparative summary tables are provided to highlight major differences. All pumps considered are assumed to be Nuclear Safety-related and thus designed, fabricated, and tested under nuclear quality programs (ASME N-stamp, NQA-1, 10 CFR 50 App. B/10 CFR 21 compliance).

1. Life-Cycle Cost and Performance Comparison of RCP Architectures

1.1 Mechanical-Seal Primary Coolant Pumps

Mechanical-seal RCPs have been the workhorse in most large PWRs for decades. They are typically **vertical, single-stage centrifugal pumps** with a heavy external motor and a multi-stage shaft seal cartridgemhi.co.jpmhi.co.jp. The seal assembly (often 3 seals in series) prevents high-pressure reactor coolant from leaking along the pump shaft. These pumps are usually supported by robust bearings (often hydrodynamic types) and sometimes include an external flywheel for increased rotational inertia. Table 1 summarizes key attributes of mechanical-seal RCPs versus sealless designs.

Initial Capital Cost: Mechanical seal pumps are custom-engineered, safety-critical components; their **upfront cost is high**, though historically they benefitted from an established supply chain. A large PWR RCP (~7000 HP motor) can cost on the order of $20–30 million per pump. For smaller SMRs, scaled-down mechanical RCPs would be smaller and potentially less costly, but they still require **nuclear-grade design and QA**. Notably, non-nuclear industrial pumps of similar size might cost only a fraction (e.g. $2–3 million) if not built to nuclear codes. The nuclear-specific QA, material traceability, and design pedigree drive costs up by ~10× for RCPs. Mechanical RCPs generally require additional systems (seal injection, oil lubrication skids, cooling water for seals), adding to capital cost and plant complexitymhi.co.jp.

Maintenance & Operations (60-Year Lifecycle): Mechanical seals **wear over time** and are a known maintenance focus. Typical RCP seals are designed to last at least one fuel cycle (18–24 months) between maintenanceiaea.org, but in practice they may require refurbishment or replacement during planned outages. Aging plants often budget to replace or refurbish RCP seal packages periodically to ensure leak-tight performancemhi.co.jpmhi.co.jp. Maintenance involves remote or hands-on work in high-radiation areas, incurring dose and labor costs. Any **seal failure** that causes excessive leakage can force an unplanned shutdown. In one BWR (boiling water reactor) plant's cleanup pumps (similar pressure and seal challenges), mechanical seals were failing every ~3 months, driving significant maintenance costs and radiation exposure. While primary loop RCP seals are more robust, industry operating experience has still seen **seal leakages and failures** requiring expensive troubleshooting and upgradesmhi.co.jp. Over a 60-year life, the cumulative cost of seal maintenance (parts, labor, downtime) is substantial. Mechanical RCPs also need continuous support services: seal cooling water, seal leakoff monitoring, bearing oil upkeep, etc.mhi.co.jp. These impose operational costs and complexity throughout the plant life.

Failure Modes & Reliability: The **dominant failure mode** for mechanical RCPs is seal degradation or failure. Loss of cooling to the seals (e.g. during a station blackout or loss of component cooling water) can lead to rapid seal overheating and leakage. Historically, **RCP seal failures under SBO** were identified as a potential small-break loss-of-coolant accident (LOCA) contributor, prompting industry and NRC attention. Modern mechanical seals incorporate improvements – hydrodynamic features, controlled leakage first-stage seals, and even **passive shutdown seals** – to ensure stability and leak-tightness under transientsmhi.co.jpmhi.co.jp. For example, Mitsubishi Heavy Industries (MHI) developed an improved triple-seal design with enhanced rubbing surfaces and materials to remain stable against pressure/temperature transientsmhi.co.jpmhi.co.jp. Westinghouse and others have added **passive thermal shutdown seal (SDS) devices** that activate in loss-of-cooling events to prevent seal failure and leakagemhi.co.jp. Besides seals, other mechanical pump failure modes include **bearing wear or vibration issues** and potential shaft or impeller failures. Pump bearings must handle large radial and thrust loads; phenomena like shaft whirl can occur under certain conditions, which vendors mitigate via upgraded bearing designsmhi.co.jp. Impellers and casings, traditionally cast, carry a risk of latent casting defects; the trend is toward forged components to eliminate that failure sourcemhi.co.jpmhi.co.jp. Overall, mechanical RCPs in existing plants have achieved good reliability, but the **maintenance burden is non-trivial** – seals in particular require careful monitoring. Extended operations have shown that seal upgrades and rigorous maintenance programs are needed to achieve high reliability over decadesmhi.co.jpmhi.co.jp.

Reliability & Total Ownership Cost: A well-maintained mechanical-seal RCP can operate for decades, but the **total cost of ownership** includes recurring seal maintenance, eventual motor refurbishments, and the operational overhead of supporting systems. Unplanned outages due to seal issues can be very costly (lost generation). The benefit of mechanical RCPs is that they are a **proven technology** – hundreds have been in service worldwide. Operators and regulators are familiar with their behavior and failure modes. They also historically have **high inertia flywheels** and robust motors, giving excellent coast-down performance (important for safety, as discussed in Section 2.4). In summary, mechanical seal pumps offer proven performance but tend to have **higher O&M costs** due to seal upkeep, and their **lifetime costs** are inflated by maintenance and potential retrofits (e.g. adding improved seals or SDS devices for safety.

Attribute	Mechanical-Seal RCP (vertical)	Canned-Motor RCP (vertical)	Horizontal Wet-Rotor / Hermetic RCP
Primary pressure boundary	Shaft passes through multi-stage **mechanical seals** (potential leak path).	Totally sealed (**no shaft penetration**); pressure boundary is the stator can + pump casing.	Totally sealed; **wet stator** windings inside coolant, no shaft seals.
Up-front capital cost	High — custom nuclear design **plus** seal-support skids; SMR-scale ≈ US $3-6 M per unit.	High but often similar; eliminates seal skids so some balance-of-plant savings; SMR-scale ≈ US $4-7 M.	Comparable to canned; niche supply means fewer quotes, SMR-scale ≈ US $4-7 M.
Routine O&M needs	Seal cartridge inspection / replacement every 18-24 mo; requires seal injection water, oil systems.	**Very low** (no seals, no oil). Condition-based monitoring of stator temps & vibration.	Very low (no seals/oil). Coolant purity important for wet windings; similar CBM approach.
Typical dominant failure mode	Seal degradation or failure; bearing/oil issues.	Electrical (stator insulation) or internal water-lubricated bearing wear.	Same as canned: insulation or bearing wear; wet windings add insulation-aging risk.
Historical reliability	Proven over decades, but seal events still frequent driver of forced outages.	Excellent in smaller sizes (naval & cleanup pumps). Large FOAK units (AP1000) needed QA re-work but now operating.	Limited fleet data; KSB & Hayward Tyler prototypes show promising 2 000 h endurance tests.

Coast-down behaviour	Large external flywheel; meets ≥ 30 % flow @ 1 s. Seal heating is a concern in SBO.	Internal high-inertia rotor/flywheel; no seal-LOCA concern during SBO.	Internal inertia; same SBO advantage as canned.
Maintenance philosophy	Frequent hands-on seal work; pump stays installed, workers in high-rad area.	**Swap-out / refurbish off-site** every few decades; minimal in-containment work.	Similar swap-out concept; horizontal orientation can allow rail-mounted removal.
Total cost of ownership (≈ 60 yr)	Highest — recurring seal parts, labor, outage risk.	Lowest — no seals, simplified ancillaries, longer mean time to intervention.	Potentially lowest, but long-term operating data still sparse.
Containment footprint	Tall vertical unit + seal-cooler skids; needs crane clearance.	More compact vertical form; only small motor-cooler lines & cables.	Horizontal cylinder; frees vertical space but needs lateral clearance.
Safety case impact	Seal failure = potential small-break LOCA; mitigated by shutdown seals and cooling.	Removes seal-LOCA accident class entirely; simplifies SBO analysis.	Same LOCA benefit; wet windings must be qualified for radiation & T.

1.2 Canned-Motor (Sealless) RCPs – Vertical Configuration

Canned-motor pumps integrate the pump impeller and drive motor in a **hermetic assembly**, eliminating all shaft seals. The motor's stator is enclosed behind a thin "can" pressure boundary, while the rotor runs wet in the reactor coolant. This design has **no dynamic seals** to leak – a major safety and maintenance advantage. Modern canned RCPs (such as those in AP1000 reactors) are vertical, single-stage centrifugal pumps with a *wet rotor, dry stator* configuration, often with an internal flywheel for inertia. The entire unit is typically mounted directly to the reactor vessel or primary loop piping via a flange.

Initial Capital Cost: Canned RCPs are highly engineered and, in large sizes, can be expensive. The AP1000 canned pumps – the largest ever built – cost roughly $28 million each. However, for a **small SMR (40–120 MWth)**, the RCP duty is an order of magnitude smaller, enabling use of **off-the-shelf hermetic pumps** based on prior designs (e.g. naval reactor pumps or smaller PWR pumps). Off-the-shelf availability can defray development cost. Vendors like Curtiss-Wright, KSB, Hayward Tyler, and Optimex offer canned-motor pumps in various sizes for nuclear service. The upfront cost of a canned pump includes the integrated motor and any auxiliary cooling (many designs include a small **motor cooling heat exchanger**). Despite high unit cost, sealless pumps can simplify the plant by removing the need for seal injection systems and leak-off handling, potentially reducing **balance-of-plant costs**. In SMR applications, multiple smaller canned pumps may be used in parallel (e.g. one design used eight small canned pumps around the vessel), each of which could be manufactured in a factory setting to reduce cost by economy of series production.

Maintenance & Operations: By design, canned-motor pumps require **minimal routine maintenance**. There are **no seals to replace**, no oil lubricant (coolant acts as lubricant for internal bearings), and no external coupling alignment needed. This greatly reduces the day-to-day monitoring compared to mechanical pumps. The main upkeep is ensuring the motor windings and bearings remain within limits: typically, canned pumps are equipped with temperature and vibration sensors and possibly coil insulation monitors. Experience from retrofitting sealless pumps in a nuclear cleanup system showed over 6 years of continuous operation **without any maintenance or failure**. The primary operational consideration is the **motor cooling** – heat generated by the motor is removed by a coolant recirculation through an integral heat exchanger. This requires a small secondary cooling water supply, but it is a static system with no moving parts, often relying on natural circulation (thermosyphon) to circulate coolant through the motor region. Over a 60-year life, a canned RCP might only need **periodic overhaul** (e.g. replacing motor windings or bearings perhaps once if at all). Some manufacturers advertise "maintenance free" designs intended to last the full design life without overhaul. Even if an overhaul is needed (say after 20–30 years), it would likely involve removing the pump and refurbishing in a shop environment. Because sealless pumps incur far fewer **planned interventions**, their lifetime O&M costs (parts, labor, dose) are expected to be significantly lower than for mechanical pumps.

Failure Modes & Historical Performance: Canned-motor RCPs eliminate the single most problematic failure mode (seal leaks), but they introduce **electrical failure modes**. The stator windings operate in a high-temperature, high-radiation coolant environment behind a thin pressure barrier. If the motor cooling is insufficient or if insulation degrades, a **motor winding short or burnout** could occur. However, the designs mitigate this with radiation-resistant insulation and by maintaining coolant flow through the motor can. Another potential issue is **internal bearing wear** – canned pumps use either graphite or metal matrix bearings lubricated by the coolant; these must endure years of operation. Loss of bearing tolerance could cause rotor drag or contact with the stator can. Historically, smaller canned pumps (such as those in naval reactors and early PWRs) have shown excellent reliability – **Rod Adams notes 25+ years of service with no mechanical failures in similar canned pumps**. Only the very large first-of-a-kind (FOAK) units for AP1000 encountered issues: during testing, one pump's impeller had a manufacturing defect leading to a piece breaking off, and some pumps failed initial qualification tests due to tight tolerances that needed refinement. These issues were **design/QA related**, not fundamental flaws – they were eventually resolved by rework and design tweaks, albeit causing schedule delays. In operation, AP1000 canned RCPs have to run continuously with no onsite spares, and the expectation is for full 60-year life. The Chinese SMR ACP100 has also adopted fully sealed canned pumps, citing *"stringent requirements such as high safety, full sealing, and* *long life"*. Overall, **historical performance of canned RCPs is very robust at small scales**, and with proper engineering they can meet reliability needs for SMRs. The key benefit is the **removal of leakage risk**, which greatly simplifies safety analysis and reduces unplanned outage drivers.

Reliability & Ownership Cost: With no routine seal replacements and a simplified support system, canned-motor pumps promise a **lower total cost of ownership**. The reliability advantage directly translates to cost savings: fewer outages and less maintenance labor. For example, a plant that retrofitted to canned pumps avoided frequent seal failures, preventing reactor shutdowns that would have occurred due to water chemistry degradation. Over decades, avoiding even a handful of forced outages or major repairs can save millions. Reliability is high provided design margins are kept – one must ensure adequate cooling of the motor under all conditions (including coast-down and natural circulation scenarios). Vendors incorporate safety margins like **passive cooling loops** in the motor housing and **dual pressure boundaries** (the stator can plus motor casing give double containment of coolant). The result is that canned RCPs can run with very low likelihood of causing a plant trip or LOCA. Plant operators thus can focus maintenance efforts elsewhere. In summary, for SMR applications, a well-designed canned-motor RCP offers **leak-free operation, reduced O&M burden, and robust long-term performance**, making it a cost-effective choice despite a potentially higher initial price tag.

*Figure 1: Cross-section of a horizontal canned-motor pump retrofit (Hayward Tyler). The motor and pump share a common shaft in a sealed pressure housing. Key features: resin-encapsulated stator windings behind a thin stator can (primary pressure boundary), a wet rotor with internal thrust and radial bearings lubricated by coolant, and an integral heat exchanger to remove motor heat*haywardtyler.comhaywardtyler.com*. No mechanical seals are used, eliminating leakage.*haywardtyler.comhaywardtyler.com

1.3 Horizontal Wet-Rotor (Hermetic) Pump Designs

Horizontal wet-rotor pumps are a variant of sealless pump where both the motor's rotor **and stator are in contact with the coolant** – the stator windings are typically sealed in waterproof insulation (a "wet winding" motor). These pumps often feature a **canned or fully immersed motor** integrated with the pump hydraulics, but oriented horizontally. Some SMR designers prefer horizontal pumps for an integral layout (mounting pumps on the vessel side or skid). A historical example is the internal recirculation pumps of certain BWRs (e.g. ABWR), which use wet stator motors mounted within the reactor vessel. In PWR SMRs, a horizontal hermetic pump might be mounted external to the vessel but within the containment, connected via short piping.

Initial Capital Cost: Horizontal wet-rotor pumps would be procured from specialized manufacturers – currently a smaller niche. Companies like KSB have developed **wet winding**

motor RCPs (model "RUV") for advanced PWRs, positioning them as an alternative to canned pumps. These are large vertical units, but the same technology can be applied in a horizontal configuration for smaller reactors. The cost profile is similar to canned pumps: a high-end custom motor-pump unit. If a vendor has an existing design that can be scaled or adapted, development costs are moderate. **Optimex and Hayward Tyler** also market wet stator motor pumps for SMRs. Given the overlapping technology with canned pumps, capital cost is high but competitive with other nuclear RCPs. Additional engineering might be needed to ensure horizontal orientation does not impair bearing performance (gravity acts sideways on the rotor) and to facilitate removal/replacement in tight spaces.

Maintenance & Operations: A horizontal hermetic pump should have similar maintenance advantages as a canned pump: **no seals, no oil**, and potentially maintenance-free for long periods. One possible operational consideration is that a horizontal unit might be more accessible for replacement – it could be slid out on rails rather than lifted, which is advantageous in a compact SMR containment. The **bearings** in a horizontal pump support both radial and axial loads; some designs use hydrostatic bearings or self-aligning features to handle this. As with vertical hermetic pumps, internal monitoring of temperature and vibration is critical. If the pump uses a wet stator (windings in coolant), maintaining coolant chemistry purity is important to prevent any conductive deposits or corrosion on windings. The **operations cost** is expected to be low: aside from periodic checks of instrumentation, the pump runs continuously with little human intervention. Over 60 years, one might plan a small number of motor replacements or rewindings, but those intervals could be decades apart. Manufacturers aim for these pumps to run the life of the plant without major maintenance (e.g., KSB's wet motor RCP is described as "maintenance free" under normal operation).

Failure Modes & Performance: Wet-rotor pumps share failure modes with canned pumps: electrical insulation failure, bearing wear, or coolant flow blockage in the motor region. Because the stator is "wet" (in contact with primary water), the insulation system must be extremely robust (typically epoxy or ceramic encapsulation). A failure of insulation could lead to a short and pump trip. However, this is mitigated by design and proven in applications like **submersible motors** and prior nuclear uses. Another consideration: **vibration and hydraulic forces**. Horizontal pumps may experience uneven flow at the inlet (depending on piping geometry), which can induce vibration. Research suggests careful design of pump inlet geometry is needed to avoid non-uniform flow effects in horizontal RCPs. Vendors claim *"perfect rotor dynamic behavior"* for integrated wet motor pumps, achieved via balance and stiff shaft design. In terms of historical data, horizontal RCPs have been used in some experimental or naval reactors; Westinghouse's 2011 SMR concept had **eight small horizontal canned pumps** and was deemed feasible based on existing technology. The Chinese ACP100 SMR's main pumps are actually vertical, but one can infer that a horizontal orientation would have comparable reliability if engineered properly.

Reliability & Cost of Ownership: Wet-rotor pumps, if successfully implemented, offer the **same reliability benefits as canned pumps** – elimination of seal failures and reduction of maintenance interventions. Their total ownership cost could be even lower if the design is simpler (e.g., no need for a thick stator can, which can improve efficiency and reduce parts count). KSB's RUV pump highlights efficiency gains from wet winding technology and a high overall efficiency due to fewer barriers to magnetic flux. For an SMR operator, using hermetic pumps can simplify the **safety case** (no seal LOCA risk) and reduce **outage scope**, both valuable for economic performance. The risk in adopting this newer architecture lies in the **limited operational pedigree** – thus, selecting a vendor with a fully qualified design and doing extensive prototype testing is crucial. Assuming that is done, horizontal wet-rotor pumps should provide **robust, long-life service** with minimal unexpected costs, aligning with SMR goals of simplified, autonomous operation.

2. Primary Loop Integration and Design Considerations

2.1 Thermal-Hydraulic Performance and Pressure Loss

All pump options must meet the SMR's required coolant flow and head (pressure rise) to remove ~40–120 MWth from the core and drive it through the steam generators (or heat exchangers). At this scale, required flows are on the order of a few thousands of m^3/h, which is within reach of either small number of large pumps or multiple smaller pumps in parallel. The **thermal-hydraulic performance** (head-flow characteristics, efficiency) depends more on the pump's hydraulic design (impeller type, stage design) than the seal vs sealless aspect. Thus, a **properly designed canned or mechanical pump can both achieve high efficiency (~70–80%)** at the duty point. There are subtle differences, however, that impact overall loop performance:

- **Pump Efficiency:** A canned-motor pump may incur a slight efficiency penalty due to the **stator can** – a thin metal can separates the stator from coolant, introducing a small gap that magnetic flux must cross and adding windage losses as the rotor spins in fluid. This can cause a few percent lower efficiency compared to a dry motor. Wet-rotor designs (wet winding) avoid a thick can, potentially improving motor efficiency; KSB's wet stator RCP is advertised with "very high hydraulic efficiency" and optimized motor efficiency. In either case, modern designs use advanced computational fluid dynamics (CFD) and electromagnetic analysis to optimize performance. For a small SMR, the impact on core thermal-hydraulics is negligible as long as pumps can maintain required flow.
- **Pressure Loss and Loop Configuration:** The arrangement of RCPs in the primary circuit influences pressure drops. A classic loop PWR (with external pumps and steam generators) has large loop piping where pressure losses occur. If an SMR uses external **mechanical-seal pumps**, the coolant flows through several large bends and valves (e.g.,

through an RCP suction nozzle, out the pump discharge into the loop). If an SMR instead uses **integral pumps** (canned or wet rotor) mounted directly on the vessel or integrated with the steam generator module, it can **eliminate long piping runs**, reducing pressure drop and improving natural circulation paths. Indeed, one SMR design goal was to "simplify the structure" by using an **integrated horizontal pump** attached directly, which inherently reduces piping complexity and associated losses. Canned pumps can be placed at low elevations to minimize NPSH issues and can even be submerged in the coolant (if inside the vessel) to ensure adequate suction head – this mitigates cavitation risk. Optimex notes that in SMRs, canned pumps' partial immersion helps *"minimize risk of cavitation"* and reduces vibration by fluid damping. Mechanical pumps typically require a suction leg design that ensures NPSH (Net Positive Suction Head) margin, which may dictate loop geometry (often pumps at a low point in the loop). In contrast, sealless pumps could be more flexibly positioned.

- **Flow Coast-Down and Natural Circulation:** Thermal-hydraulically, an important factor is how the system behaves when pumps trip (loss of power). Pump coast-down provides short-term flow to remove decay heat until natural circulation or backup systems engage. Larger pumps with high inertia (flywheels) provide a gradual decay of flow. Mechanical RCPs traditionally have large flywheels mounted on the shaft or motor for this purpose. Canned and wet-rotor pumps also incorporate flywheels (internal or external to the rotor) to meet the **required coast-down curve**. The AP1000 canned pump design, for instance, included an internal high-inertia rotor assembly to ensure adequate flow for several seconds post-trip. In small SMRs, natural circulation might take over relatively quickly due to the small size, but pumps still need to avoid an abrupt stop which could cause thermal stratification or boiling hotspots. All considered pump types can be designed to meet coast-down criteria (see Section 2.4 for safety implications). The difference is mechanical pumps often rely on a heavy external flywheel, whereas canned pumps must integrate it (making the rotor longer/heavier). Wet-rotor designs similarly incorporate a heavy rotor and use the motor coolant loop (thermosyphon) to remove heat during coast-down with no active cooling. From a thermal-hydraulic modeling perspective, a sealless pump simply appears as a head source like any pump; its presence does not significantly alter core thermal margins except by eliminating the possibility of seal leakage flow (which in a LOCA scenario could be a flow path).

In summary, **all pump types can be engineered to deliver the required flow and head**, but integrated designs (canned/wet) allow more compact loop layouts with potentially lower overall pressure drops. This can slightly improve steady-state efficiency of the primary circuit and enhance natural circulation capability (fewer flow restrictions). SMR designers often favor integral or close-coupled pumps to reduce loop volume and surface area, which improves heat retention and passive cooling characteristics. Thermal-hydraulic performance is ultimately a function of pump design quality, not whether it has seals or not – except that eliminating seals removes one abnormal flow path (seal leak-off) which simplifies accident flow analyses.

2.2 Footprint and Spatial Layout (Containment Integration)

Spatial constraints are a major concern in SMR designs, which aim for a compact **containment or module**. The choice of pump architecture impacts the **footprint, orientation, and support structure** needed:

- **Vertical Mechanical Pumps:** These are typically **large and tall**. In a loop-type SMR (external steam generators), a vertical RCP would be mounted at a low point on the loop piping. It requires significant headroom for installation/removal – usually a crane must lift the motor (which can weigh tens of tons in large designs). The motor sits atop the pump casing, contributing to height. The footprint on the containment floor can be small (just the pump casing penetrations), but one must allocate overhead clearance equal to the pump's height for maintenance lifts. Additionally, mechanical pumps often need a robust support structure or **pump stand** to carry their weight and react to hydraulic forces. In a small containment, fitting a ~5–6 m tall pump plus crane clearance could be challenging. Thus, mechanical RCPs might push an SMR containment to be taller or larger in diameter.
- **Vertical Canned-Motor Pumps:** These can be somewhat more compact vertically because the motor and pump are integrated, eliminating the large motor pedestal/coupling seen in mechanical pumps. For example, the AP1000 canned RCP is about 6.9 m tall, which is still huge due to its ~125 MWth per pump capacity. A smaller SMR canned pump would scale down significantly. These pumps can be mounted directly on the reactor vessel or steam generator, even in an **inverted orientation** if needed (some integral PWR concepts considered mounting pumps on the vessel head/downcomer area). The canned pump doesn't require an oil system skid or large seal service piping, which reduces floor space usage – only an electrical connection and a small cooling water line are needed. **Maintenance space** is still needed around the pump for instrumentation and eventual removal. One SMR approach is to use multiple smaller canned pumps distributed around the vessel; Westinghouse's 225 MWe SMR design had 8 horizontal sealless pumps mounted externally around the vessel mid-height. This allowed a **very compact containment**: the pumps protruded only modestly and were accessible via radial hatches. The distribution of multiple small pumps also spreads out the footprint, avoiding one large concentration of mass.
- **Horizontal Pumps (Canned or Wet-Rotor):** A horizontal orientation can be advantageous for layout. These pumps can be **skid-mounted on the vessel side or on a support frame** at roughly mid-vessel elevation. They will extend laterally. The benefit is that they do not add to height, and servicing them might be done by sliding out rather than lifting. A horizontal pump likely has the motor and pump impeller on the same axis, so the length of the assembly could be a few meters. An SMR containment would need a clear space around the vessel to accommodate their length and allow extraction. Some

designs provide dedicated bays or penetrations in the biological shielding so a pump can be removed straight out through a hatch. For example, ABWR internal pumps (though vertical) are removed downward through vessel nozzles. Similarly, a horizontal external pump could potentially be withdrawn through an opening in the containment wall if designed for replacement. **Footprint-wise**, horizontal pumps require more lateral space but can be arranged in a ring or in symmetrical positions to balance the layout. They likely need robust lateral support and anchoring, since the motor's center of gravity is offset. Vibration isolation mounts might be used to avoid transmitting loads to the vessel.

- **Inside vs Outside Vessel:** Another integration consideration is whether pumps are located inside the reactor pressure vessel (RPV) or external. Some integral SMRs (like NuScale) eliminate primary pumps entirely by natural circulation, but others (like ACP100, certain research SMRs) have pumps within the RPV. An **internal pump** would obviously be a canned or wet motor type. This frees up containment space (pumps don't occupy external volume) and eliminates large nozzles (the pump intake/discharge are internal). However, internal pumps are harder to access; you must open the vessel to repair or replace them. In contrast, **external pumps** (whether mechanical or canned) reside in containment but outside the RPV, meaning they can potentially be serviced or swapped without opening the reactor – an advantage for maintenance turnaround. External pumps, if they are safety-grade, will necessitate primary loop isolation or check valves if one needs to be removed while reactor coolant is present. Most PWRs cannot isolate RCPs easily, so pump replacement waits for shutdown and drain-down. SMRs might design modular pumps that can be disconnected and replaced with the module shut down but not fully defueled (this is speculative).

*Figure 2: Installation of a fully-sealed primary coolant pump in an SMR (China's ACP100 reactor). The pump is a **vertical canned-motor design** with integrated motor in a cylindrical housing. Four such pumps are mounted to the vessel nozzles. This configuration has a compact footprint within the containment and meets "high safety, full sealing, and long life" requirements*

- **Space for Support Systems:** Mechanical pumps require additional space for support equipment: seal injection pumps, coolers, oil reservoirs, and maybe a backup cooling water accumulator for SBO scenarios. These subsystems need to be accommodated on platforms or in cubicles near the pump. Sealless pumps avoid most of that – typically just a control panel with a VFD (variable frequency drive) or starter and a small heat exchanger skid for motor cooling. Those can be located remotely or in less crowded areas.

In summary, **canned and wet-rotor pumps enable more compact and flexible layouts** in an SMR. They can be positioned to minimize containment height and overall volume. Mechanical pumps, being bulkier and vertically oriented, could force a larger containment design or more challenging maintenance logistics in the small modular context. The SMR designer must trade off the easier maintainability of external pumps against the space savings of internal/integral designs. Many SMRs opt for sealless pumps to achieve a **modular, space-efficient** primary system that can be factory-fabricated as a compact unit.

2.3 Accessibility for Maintenance and Overhaul

Ease of maintenance is a crucial design consideration, especially for SMRs aiming for short outage durations and possibly remote/unmanned operation. The pump type and placement influence how maintainable the system is:

- **Mechanical-Seal Pump Maintenance:** These pumps are complex to service. Seal maintenance often requires decoupling the motor, extracting the seal cartridge, and meticulous installation of new seal faces and O-rings. This is typically done during refueling outages. If a seal fails during operation, the plant may have to reduce power or shut down, since running for long with a damaged seal risks leakage. Replacing an entire RCP in a large plant is a major operation (the pump assembly can weigh ~90 tons). For a smaller SMR pump, weights are less but still likely in many tons range. Maintenance of mechanical RCPs in a small containment requires providing crane or hoist access. The SMR design would need a hatch or removable roof to lift the pump motor out. Additionally, workers performing maintenance will be near contaminated components – **ALARA (radiation dose)** principles demand features like quick-disconnect fittings, leak collection, and perhaps **equipment to allow seal replacement in-situ** without completely removing the pump. Some newer plants have moved to cartridge seal designs that allow faster swap-out. Overall, mechanical pumps score poorer on maintainability due to number of steps and highly precise work needed on the seals.
- **Canned-Motor Pump Maintenance:** Routine maintenance is minimal, but when it comes time to service or replace a canned pump, the process is more of an all-or-nothing swap. The entire canned pump unit would be unbolted and removed for refurbishment off-site, and a replacement unit installed. The pump's design can facilitate this – for instance, *quick disconnect electrical connectors*, flanged coolant lines, and alignment features. Because no seal setting is required and the motor-pump alignment is fixed at manufacture, reinstallation is simpler (no on-site alignment or calibration aside from checking instrumentation). If the SMR uses multiple small canned pumps, it could have a strategy of rotating spares: a failed pump could be swapped with a spare within one outage, and the removed one sent to a factory for repair. This approach can **minimize downtime**, albeit at the cost of purchasing a spare or two. Importantly, since canned pumps have **no process leaks**, the maintenance is cleaner – there isn't a cavity of trapped coolant that spills when you open a seal housing. However, the pump internals will be radioactive from coolant exposure, so remote handling tools or shielding might be needed. Some designs include a **"canister" or housing** that allows removing the pump

without draining the entire loop (e.g. a double isolation at pump interface), but typically the primary system must be drained to open it. In short, canned pumps are replaced as units and can be designed for relatively quick change-out, which suits the modular philosophy.

- **Horizontal Pump Maintenance:** A horizontal orientation could improve maintainability in certain layouts. For example, a pump could slide out on rails into a shielded cask or transfer corridor, rather than requiring a vertical lift through the containment top. This could be advantageous if the containment doesn't have a large crane or if multiple modules share a single crane. The Hayward Tyler retrofit pumps were horizontal and were designed such that they kept the existing casing, meaning the motor could be swapped without disturbing piping. In an SMR context, a horizontal canned pump mounted on a nozzle could similarly allow the motor section to be removed while leaving the pump casing attached to the vessel – if valves or other means isolate the vessel. Another aspect is **accessibility for inspection**: horizontal pumps at mid-level might be easier to reach via platforms than a tall vertical pump that sits under a steam generator.
- **Maintainability of Internals:** Internal (in-vessel) pumps pose the greatest challenge. If a pump fails internally, the reactor module must be shut down and opened. In some designs like SMART (a Korean integral reactor), several small canned pumps are installed inside the vessel to circulate coolant. Replacing these likely involves pulling the reactor module or vessel internals – a complex, lengthy process. Therefore, internal pumps are typically designed with *significant redundancy and conservatism*, expecting never to need replacement within life. If an SMR chooses internal pumps, it trades off maintainability for compactness, and must accept the potential of a long outage should a pump need replacement. The trend in SMRs (ACP100, Westinghouse SMR, etc.) is to keep pumps **external to the RPV but within containment** for easier access.
- **Vendor Services and Spare Parts:** Maintenance also depends on vendor support. For mechanical RCPs, utilities often rely on the OEM (or specialized service contractors) for seal refurbishment, balancing rotors, etc. For canned pumps, the utility might perform basic electrical testing on site, but major rework (like rewinding a stator) would go back to the manufacturer. In that sense, the plant's maintenance crew may handle canned pumps more as "black boxes" – replace the unit and send the old one out – rather than overhauling in place. This can simplify site work but requires that the vendor maintain capabilities to turn around a pump rebuild efficiently.

In summary, **canned and wet-rotor pumps generally improve maintainability** for the operator by eliminating frequent service tasks (like seal adjustments) and enabling a swap-out maintenance philosophy. Mechanical pumps have more on-site maintenance demands and complexity. SMR developers prioritize designs that **minimize outage critical path** – leaning toward pumps that can either run without attention for long periods or be replaced quickly as modular components. The maintenance strategy thus aligns with the pump choice: a key reason many SMRs favor sealless pumps is to achieve a **"plug-and-play" maintenance approach** that supports fleet deployment and shorter outages.

2.4 Safety Considerations and Coast-Down Performance

The reactor coolant pumps play a role in several safety-related scenarios. Key considerations include their behavior in **loss-of-power events (station blackout), loss-of-coolant accidents, and transients**. The pump architecture influences these in the following ways:

- **Loss of Offsite Power / Station Blackout (SBO):** In an SBO, all RCPs lose power and begin to coast down. For core cooling, most SMRs rely on natural circulation or passive decay heat removal once pumps are off. However, the **coast-down period** is important to avoid an abrupt loss of coolant flow that could cause local fuel overheating before natural circulation establishes. Pumps with **high rotational inertia** keep pushing coolant for longer. Mechanical RCPs typically include heavy flywheels to extend flow decay (for example, large PWR pumps might provide tens of seconds of useful flow). Canned and wet-rotor pumps also incorporate inertia – KSB's hermetic RUV pump includes a *"high inertia flywheel to address coastdown requirements"*. Thus, all architectures can be designed to meet required coast-down times (usually specified in the safety analysis for that reactor). One difference is how the **pump assembly handles heating during coast-down**: mechanical pumps have seals that can overheat without cooling. This was a major safety concern historically – during an SBO, if seal injection is lost, seal faces can heat up from friction and cause seal failure (creating a LOCA path). Vendors responded by developing **passive shutdown seals** that lock up and hold pressure when temperatures rise, preventing leakage. Canned and wet pumps inherently don't have this issue – with no seals, there's no special action needed to maintain pressure boundary integrity. The motor in a canned pump will heat up as it coasts down (due to eddy currents and friction), but designs like the RUV use thermosiphon cooling to continue removing heat from the motor even with no power. In short, **sealless pumps eliminate the SBO seal failure risk**, a significant safety advantage. The NRC recognized RCP seal failure as a potential core damage risk in SBO events – using canned pumps essentially closes out that risk.
- **LOCA and ECCS:** In a loss-of-coolant accident, the RCPs may trip on low pressure or may continue running if on intact loops. Mechanical RCPs, if they continue running during a small break, could **exacerbate coolant loss through a failed seal or break** – one reason they are usually tripped to prevent pumping inventory out of a break. Canned pumps, having no external leak paths, can be run longer if needed without concern of aggravating a LOCA (though generally pumps are also tripped to avoid spraying water in containment in any scenario). From an ECCS (Emergency Core Cooling System) standpoint, having sealless pumps means one less potential LOCA source (seal failure

was classified as a small LOCA contributor). This can simplify ECCS design or sizing since the maximum leak rate to plan for is lower.

- **Pump Seizure or Trip:** A seized rotor is a postulated accident (if a pump impeller were to suddenly lock, causing asymmetric cooling). Large PWR analyses show it's usually less limiting than other transients, but the pump design can mitigate it by having a **shearable shaft or clutch** if torque spikes. Both mechanical and canned pumps could incorporate such features (though it's uncommon – more often the breaker trips on overcurrent to avoid seizure). Another consideration: if power is restored after a grid disturbance, mechanical pumps have to be slowly re-accelerated to avoid thermal shocks; canned pumps can potentially also restart, but sometimes designers prefer to wait for natural circulation cooling rather than restarting pumps into a hot stagnant loop (depends on scenario).
- **Natural Circulation and Residual Heat Removal:** For passive safety, it's beneficial if the core can be cooled by natural convection with the pumps off. Some pump designs might impose resistance to natural circulation. Mechanical RCPs, when stationary, have to let flow pass through their impeller and diffuser; typically they do, but the large pump internals can add some friction. Canned pumps might have tighter internal clearances that slightly impede free convection flow. However, this is usually minor compared to overall loop resistance (steam generators are the main resistance). In any event, pump selection should ensure the **flow-through when pumps are off** is sufficient. Many canned pumps are designed with vanes or flow paths to allow natural circulation through the pump body when it's stationary (some might even free-spin like a turbine in reverse flow, reducing drag). The SMR safety analysis will include a **coast-down to natural circulation transition** which must be satisfied by whichever pump is used.
- **Active vs Passive Safety Classification:** One advantage of natural circulation designs (like NuScale) is claiming the elimination of RCPs improves safety. However, if pumps are present but not needed for decay heat removal (only for power operation), they can be classified as non-safety (not credited in accident mitigation). Many SMRs, including Holtec's SMR-160/300, state that *"no electrically powered pumps are needed to keep the reactor safe and cool"* – implying that the RCPs are not needed in accidents; they will coast down and passive systems take over. In that case, the pumps do not need safety-grade power, etc., but they should be **highly reliable to avoid initiating events** (e.g. pump failure shouldn't cause an accident). Sealless pumps help here by virtually eliminating one initiator (loss of coolant via pump). A mechanical pump seal failure could itself be an initiating event for a leak; a canned pump would not have that failure mode.
- **Coast-Down Performance:** To illustrate, suppose the SMR requires a minimum flow for 5 seconds after trip to ensure heat flux drops. A mechanical pump with a large flywheel can easily provide this. A canned pump must achieve similar inertia by design – perhaps a slightly longer rotor or higher speed. In AP1000's case, the canned pumps achieved the needed inertia, though at first there were concerns due to smaller size; ultimately they

met requirements (with some reports indicating ~20 seconds of significant flow). Vendors publicly emphasize that their designs meet coast-down: *"High inertia flywheel to address coastdown requirements"*. So, practically, **no disadvantage in coast-down for sealless pumps** with proper design.

- **Post-Accident Cooling of Pump Motor:** After a pump trips in an accident, the heat from the motor (decay heat in windings, eddy currents) must be removed. Mechanical pump motors are outside the primary circuit, so they are usually not a concern (they'll coast and eventually cool by convection to containment air or via any cooling still on bearings). Canned pump motors, being inside the primary boundary, will dump their heat into the reactor coolant. However, compared to decay heat in the core, the motor's residual heat is negligible. For example, a 5 MW motor that trips might have a few tens of MJ of thermal energy to dissipate – the reactor core decay heat at that moment is orders of magnitude higher. As long as the motor doesn't overheat itself (which could damage insulation), it's not a safety issue. Designs handle it as noted with passive cooling loops.

In conclusion, from a safety standpoint **sealless pumps offer clear advantages**: they remove the risk of seal LOCAs and reduce required safety systems (no need for AC power or backup cooling for seals). They simplify compliance with NRC General Design Criteria related to RCS pressure boundary integrity. Mechanical seal pumps can be made safe (as proven in existing plants) but require additional features (SBO backup seal cooling or shutdown seals)mhi.co.jp. Both pump types can satisfy coast-down and flow requirements for an SMR; the differences lie in reliability under duress. Thus, many SMRs lean towards hermetic pumps to *"provide higher safety, more reliable and stable operation, extended service life, and minimal maintenance"*, aligning with the overall SMR philosophy of inherent safety and simplicity.

3. Procurement and Vendor Logistics

3.1 Vendor Availability, Lead Times, and Manufacturing Capacity

Selecting a primary pump for an SMR is not only an engineering choice but also a supply chain decision. **Manufacturing nuclear RCPs is a specialized capability** – relatively few companies worldwide have the expertise, facilities, and certifications to produce these pumps. The current vendor landscape includes: **Curtiss-Wright/EMD (USA)**, **KSB/SEC (Germany/China)**, **Mitsubishi Heavy Industries (Japan)**, **Framatome/Jeumont (France)**, **ClydeUnion/SPX or Hayward Tyler (UK/USA)** for smaller pumps, and a few others. An SMR developer must ensure the chosen vendor can meet **ASME Section III, Class 1 requirements** and has a **10 CFR 50 Appendix B / NQA-1 quality program** in place. Many industrial pump makers lack these nuclear qualifications, so using an "off-the-shelf" design often still requires going to an established nuclear supplier or doing a **commercial-grade dedication** (CGD) process which can be time-consuming.

Lead times for RCPs are traditionally long. For large plants, pump lead time can be **3–5 years** from order to delivery, including design, fabrication, and full-scale testing. For example, Curtiss-Wright's contracts to supply AP1000 pumps spanned multiple years and involved extensive testing programs. For an SMR pump, one can expect shorter lead times if it's a smaller pump with existing design pedigree. Some SMR developers may opt for **pre-qualification** of pumps before the plant construction schedule, to de-risk this critical path item. It is also prudent to have spare pumps or at least spare motors available; hence, manufacturing capacity for multiple units is important if a fleet of SMRs is planned.

Manufacturing capacity concerns arise if there is high demand or limited suppliers. During the AP1000 build-out, only Curtiss-Wright's EMD division could make the pumps, which became a bottleneck (delays in pump delivery impacted the overall project). For SMRs aiming at rapid deployment, relying on a single-source could pose schedule risk. Mitigation strategies include: qualifying an alternate supplier (e.g., KSB in addition to EMD), or designing the SMR pump to be within capabilities of a more common pump supplier (for instance, some SMR pumps might be similar in size to naval propulsion pumps, which in the US are made regularly for the Navy by EMD and others, indicating available capacity). The **fabrication and testing** of RCPs require specialized test loops (to run the pump at full pressure/temperature), high-precision machining, and often custom motor manufacturing – not every factory can do this. Vendors like **Hayward Tyler** have positioned themselves to produce smaller canned pumps with ASME N-stamp certification, which could be beneficial for SMRs.

In terms of schedule integration, **the RCP is usually on the critical path** of nuclear plant construction. The pump needs to be delivered and tested before reactor commissioning. Any delay in the pump can idle the completion of the reactor (since you cannot finish integrated system testing without pumps). Therefore, when planning procurement, SMR developers often engage pump suppliers early – possibly during detailed design or even late in conceptual design – to ensure the pump design is frozen and long-lead materials (forgings, motor laminations, etc.) are ordered. To illustrate, in 2007 Westinghouse ordered the first AP1000 pumps to support 2013 plant startups, but unexpected redesigns pushed actual first-of-a-kind pump installation to ~2015. This lesson underlines the need for **proven designs**: if an SMR can use an RCP design that's already tested (even if in a different project), it greatly reduces risk of late redesigns and their knock-on delays.

3.2 Quality Assurance, Certification, and Regulatory Compliance

Any primary RCP for a U.S. SMR must meet **NRC regulatory requirements** for safety-related components. That means the manufacturer must hold appropriate **ASME Section III N-Certificates (N, NPT, NS)** for the scope of work, or work under an N-certificate holder's program. The pump itself needs design verification per ASME BPVC Section III, Division 1, Subsection NB (Class 1 components). This entails stress analysis, fatigue evaluation, seismic qualification, etc., which the vendor typically provides with their design reports. For example, the AP1000 RCP went through extensive structural and dynamic analyses as part of design cert. An **Authorized Nuclear Inspector (ANI)** must witness and sign off critical fabrication steps and final stamping.

Vendors must also comply with **10 CFR 21 (Report of Defects)** – essentially having a program to evaluate and report any potential defects in delivered safety equipment. Established nuclear suppliers have procedures for this. New or smaller companies entering the nuclear market have to develop a full **NQA-1 compliant QA program** and pass audits by the reactor vendor or utility. This can be a high hurdle – for instance, a pump company might have a great product from the oil & gas industry, but unless they implement nuclear QA controls (material traceability, calibration, document control, etc.), they cannot supply directly to a nuclear project.

SMR developers often perform **supplier audits** early on. They will audit potential pump suppliers for NQA-1 compliance and for **commercial-grade dedication** capability if any off-the-shelf components are to be used. For instance, maybe the pump's electric motor core could be a commercial design that is dedicated via special inspections. The developer must ensure things like material certifications (e.g. fracture toughness of the pressure boundary) meet ASME Code. Many pump vendors advertise their nuclear credentials: e.g., **Hayward Tyler** highlights holding ASME N and NPT certificates and NQA-1 compliance; Curtiss-Wright EMD similarly is an N-stamp holder with decades of nuclear production.

Another regulatory consideration: the **NRC's dedication to safety** of RCP seals in large reactors was historically a point of review (Generic Issue 23 on RCP seals). For an SMR using sealless pumps, the design certification or licensing application must demonstrate that the pumps will not become a new reliability problem (for instance, demonstrating that a canned motor pump meets its design life and won't cause common-cause failures). Probabilistic risk assessments (PRA) will include RCP failures; typically, canned pumps have lower failure probability for loss-of-coolant type failures (virtually zero for seal LOCA), but perhaps a slightly higher probability of **loss of flow** if a motor fails. However, redundancy (multiple pumps) can mitigate that. The NRC will scrutinize the **testing and qualification program** for any new pump design. This usually means a full-scale prototype test running for hundreds of hours, including transient testing (startup/shutdown, simulated SBO coast-down, etc.). The vendor and SMR designer must plan those tests and include them in the project schedule.

Finally, **traceability and documentation** from procurement is huge. Every piece of material in the pump (forged casings, shaft, impeller, can, bolts) must have certified material test reports. Welding on the pump (if any) must be done by qualified nuclear welders with procedures reviewed by the ANI. Non-destructive examinations (NDE like radiography, ultrasonic of the impeller, etc.) are required to ensure no defectsmhi.co.jp. These stringent processes contribute to the cost and lead time but are mandatory for compliance.

3.3 Domestic vs. International Sourcing Trade-offs

The SMR developer has a choice to source pumps domestically (within the U.S.) or from qualified international suppliers. Each approach has pros and cons:

- **Domestic Sourcing:** The prime U.S. source is Curtiss-Wright's EMD in Pennsylvania, which has a long track record (they supplied pumps for Shippingport, the U.S. Navy, and many Western PWRs). Domestic sourcing benefits include easier **oversight and communication**, no import/export hurdles, and alignment with U.S. industrial base goals. The NRC and DOE often encourage using domestic suppliers for critical components to avoid reliance on foreign entities. Domestic supply can simplify **regulatory audits** (NRC inspectors can visit the factory easily). However, domestic options might be limited in technology: EMD is known for large canned pumps (AP1000) and mechanical pumps; if an SMR wanted a different style (like wet stator horizontal pumps), they might not have that off-the-shelf. U.S. companies like Flowserve have produced mechanical RCPs in the past (e.g., legacy Westinghouse pumps), but their current nuclear product lines are not as prominent for primary pumps. There is also **limited competition** domestically, which could affect pricing.
- **International Sourcing:** Several international vendors have strong offerings – **KSB (Germany)** has both mechanical and sealless RCP designs (they partnered with Shanghai Electric to form SEC-KSB, supplying pumps to Chinese reactors). **Mitsubishi** provides mechanical RCPs for Japanese plants and perhaps could for an SMR. **Toshiba or Hitachi** engineered the ABWR internal pumps. **Rosatom OKBM** in Russia makes canned pumps for their reactors, but that's likely not an option due to geopolitical reasons. **Chinese firms** like Harbin Electric now build pumps under license (e.g., for ACP100), but using Chinese-sourced pumps in a U.S. SMR might raise concerns about intellectual property, export controls, and political acceptance. International sourcing can bring in **proven designs** (for example, KSB's RUV wet-motor pump was planned for the 1400 MW CAP1400 reactor, which is a larger reactor but demonstrates technology). It can also potentially offer cost advantages due to lower manufacturing costs in some countries. However, it introduces challenges: **currency fluctuations, trade tariffs**, and the need to translate and verify all documentation to U.S. code requirements. NRC will expect the same quality documentation, which means the foreign supplier must essentially operate as if under NRC scrutiny. Another risk is schedule: cross-border logistics (shipping a massive pump, dealing with customs) can add time. Also, differences in standards (e.g., European standards vs ASME) need reconciliation – though most big vendors are familiar with ASME and have dual certifications.

- **Partnership and Localization:** A hybrid approach is possible – e.g., **license a design from an international vendor and build it domestically**. Curtiss-Wright's AP1000 pump was essentially that: based on international experience (naval pumps, etc.) and made in the U.S., then later some were co-produced in China. If an SMR vendor likes KSB's design, they might work with KSB to produce it in the U.S. under license, leveraging an American facility (maybe a joint venture). This can satisfy both the technical needs and domestic content preferences. It does require strong collaboration and tech transfer.
- **Cost and Schedule Impact:** International competition could help drive down price, but the flip side is **potential delays due to unfamiliar QA expectations**. A notable example: the AP1000 RCP initial contract was with an international supplier (KSB), but difficulties led to a switch to a domestic supplier (EMD) – the exact details aren't public, but it highlights the complexity of global procurement. If a foreign vendor's QA isn't up to par, it can cause rework and schedule slips. On the other hand, some foreign vendors (like those under European or Japanese nuclear oversight) are extremely high quality. It essentially comes down to specific cases rather than a blanket rule.

For SMRs hoping to deploy internationally themselves, having a diverse qualified supply chain is beneficial. They might certify two pump designs – one domestic, one foreign – to hedge against any one source issues. **Lead times** internationally could be longer if the supplier is busy with its own domestic reactor programs (e.g., Chinese suppliers might prioritize Chinese projects, affecting deliveries elsewhere). The **geopolitical risk** must also be considered – relying on a supplier from a country that could face export restrictions or sanctions is a risk (again, Russian or Chinese components might see such issues).

In summary, **domestic vs international sourcing is a trade-off between control and possibly cost/availability**. A prudent approach is to engage multiple suppliers early (at least at RFI/RFQ stage) to see who can meet requirements and then choose a path that ensures timely delivery and compliance. Many SMR developers will likely lean domestic for pumps, given the importance of the component, but they will keep international options as a backup or leverage them to improve design and cost.

3.4 Schedule Risks and Impact on SMR Deployment

The reactor coolant pumps are among the **most critical long-lead components**, and any delay or issue with them can ripple through the entire SMR deployment schedule. There are several risk factors and their potential impacts:

- **First-of-a-Kind (FOAK) Engineering Risk:** If the SMR chooses an unproven pump design or requires modifications to an existing design (scale changes, material changes), there is a risk of discovery of issues late in the project. The AP1000 pump saga is instructive – scaling the canned pump to an unprecedented size led to unforeseen problems in testing, causing redesign and multi-year delays. For an SMR, avoiding FOAK risk is a priority: that means selecting a pump either identical or very close to one with operating experience. For example, an SMR of ~100 MWth could possibly use pumps derived from naval reactor pumps which have decades of service. Using **proven technology can greatly de-risk the schedule**. Conversely, if an SMR developer tries an exotic new pump concept to push efficiency or novel integration, they must budget time for iterative testing. Any needed redesign (for instance, if a pump fails a factory acceptance test) can push back the deployment timeline since a fix might involve manufacturing new parts or even re-casting large components. A slip in pump readiness might mean the reactor can't be started, thus affecting customer delivery dates and project economics.

- **Manufacturing/QA Issues:** Pumps are subject to rigorous quality checks. If any subcomponent fails to meet specs (e.g. an impeller with a flaw, as happened in AP1000 testing), the project faces a delay for investigation and remanufacture. Under NRC rules (10 CFR 21), such defects must be reported and evaluated for safety significance. The **corrective actions** can range from minor rework to complete redesign of a part, either of which may halt production or even require already-delivered pumps to be returned or retrofitted (as occurred when AP1000 pumps had to be shipped back from China to the U.S. for fixes). This scenario can also erode stakeholder confidence. Mitigation is to ensure the supplier has robust QA processes and perhaps to **oversee critical fabrication steps** (some SMR teams might station their own inspectors at the pump factory).
- **Impact on Licensing:** If a new pump design is part of the SMR, the NRC will review its technical qualifications. Any **open issue with pump reliability or performance could delay the design certification or operating license**. For example, if during review an NRC question arises like "demonstrate that the RCP will operate for 60 years without seal leakage" or "provide test data for coast-down performance," the inability to answer with evidence might delay licensing. Thus, any schedule slip in testing can also affect licensing submissions. However, once a pump type is licensed in one SMR, subsequent units benefit from that precedent.
- **Project Integration:** RCPs typically must be installed relatively early in plant assembly if they are internal, or before primary system testing if external. A delay in pump delivery can thus idle other work. Additionally, the **commissioning schedule** often has a dedicated RCP test (pump startup tests) that must succeed before moving to nuclear heat tests. If a problem is found at that stage (late in commissioning), it could significantly delay fuel loading or power ascension. This is what happened in some new builds where last-minute pump issues forced rework and re-testing, holding up operations.
- **Mitigating Deployment Delays:** SMR vendors can employ strategies such as **parallel development** – while the FOAK pump is being fabricated and tested, work on other modules continues, to absorb some delays. They can also maintain close communication

with the pump vendor's schedule. In contract terms, they might include incentives for on-time delivery or penalties for delays (Curtiss-Wright's contracts often include incentive fees for meeting schedules). Another tactic is to **order multiple sets of pumps** if multiple units are planned – ensuring the production line stays warm and any lessons from the first set are applied to the next, thus improving reliability and reducing delays for follow-ons.

- **Scaling Up Production for Fleet Deployment:** If an SMR is successful, dozens of units might be built. Can the chosen pump supplier scale up production? This is both a logistics and risk issue. A sole-source supplier might become overwhelmed if suddenly asked to produce, say, 50 pump sets in a decade. It's important that the vendor has or can expand manufacturing capacity (e.g., add shifts, build new facilities). If not, it could bottleneck the entire SMR rollout. Some SMR developers may qualify a second source over time or encourage their supplier to license manufacturing to partners to meet volume.
- **Regulatory and Political Risks:** If international, changes in trade policy could impose delays (e.g. export license delays, tariffs requiring renegotiation). Domestically, any significant quality issue could trigger NRC inspection or even a stop-work order until resolved. Pump issues have in past drawn regulatory scrutiny – e.g., the NRC closely followed AP1000 RCP development and even international regulators (like in China) insisted on resolution before fuel load.

Given the above, the RCP is often labeled a **"project critical" component.** The success of SMR deployment is tightly linked to pump success. The industry has learned this the hard way in recent large reactor projects, so SMR teams are taking a cautious approach: using established technologies, conducting thorough **prototype testing well ahead of needing the pumps on site**, and engaging with regulators transparently about pump design margins and testing outcomes. By doing so, the likelihood of late-stage surprises is minimized, and even if issues arise, they can be corrected with less impact on the overall deployment timeline.

Conclusion

In evaluating primary coolant pump options for a 40–120 MWth PWR SMR, it is evident that **sealless pump architectures (canned-motor and wet-rotor designs) offer compelling life-cycle benefits** over traditional mechanical-seal pumps for this application. Canned and wet-rotor pumps virtually eliminate coolant leakage and significantly reduce maintenance burdens, improving reliability and total ownership cost across a 60-year plant life. They enable a more compact and modular primary system layout – a critical advantage for SMRs – and remove the need for ancillary seal support systems, thereby simplifying operations and safety analysis. Mechanical-seal pumps, while proven and available, carry higher maintenance costs (due to seal replacements and the need for safety enhancements like shutdown seals) and present a potential LOCA risk under severe scenarios, which sealless designs inherently avoid.

From a **safety and regulatory** standpoint, adopting hermetic pumps aligns with SMR goals of passive safety: without shaft seals, the reactor coolant pressure boundary is more robust and failure modes are reduced. Coast-down performance and pump trip transients can be met by both types, but sealless pumps achieve this without introducing new vulnerabilities, as demonstrated by their successful use in modern reactors (AP1000, ABWR, ACP100).

The choice of pump must also consider **practical deployment factors**. Proven commercial availability and a qualified supply chain are essential. Fortunately, multiple vendors offer nuclear-grade canned motor pumps (or are developing SMR-specific models), and established nuclear pump suppliers have the necessary QA programs to support SMR projects. Engaging these suppliers early to lock in design and schedule will mitigate risks. The historical lessons from large reactor projects underscore the importance of using **off-the-shelf technology and thoroughly testing it** under prototypical conditions to avoid downstream delays.

In conclusion, for a U.S.-based 40–120 MWth SMR, a **canned-motor RCP (vertical or horizontal as fits the design)** appears to be the optimal solution when evaluating cost, reliability, integration, and safety. It provides a leak-tight, low-maintenance operation that aligns with SMR economics (maximize capacity factor, minimize O&M cost) and meets regulatory expectations for long-term safe performance. A mechanical-seal pump could be used if necessary, but it would likely incur higher lifecycle costs and require additional safety provisions to achieve comparable reliability. If a horizontal wet-rotor design is feasible from available vendors, it could further enhance efficiency and maintenance simplicity, though it carries more uncertainty due to less widespread use.

The final decision may be informed by a detailed cost-benefit analysis including vendor quotes and risk evaluations. Yet, the analysis herein supports that **investing in sealless primary pumps is a prudent strategy** for an SMR, yielding long-term payoffs in safety assurance and cost of ownership. With proper vendor selection and early qualification efforts, the chosen RCP architecture will become a reliable “heart” of the SMR’s primary circuit, ensuring effective heat removal and contributing to the overall success of the SMR deployment.