KADMOS ENERGY

Steam Generator Design Options for a 40–120 MW PWR-SMR in the U.S.

Introduction

Small modular reactors (SMRs) in the 40–120 MWth range require steam generators (SGs) that are compact, efficient, and compliant with ASME Section III and U.S. NRC regulations. This report compares viable SG designs and materials for a small PWR-based SMR, and identifies available units in the target thermal output range. Key factors include configuration, cost and fabrication complexity, operational pros/cons (efficiency, maintenance, seismic considerations, licensing precedent), and suitability for a 40–120 MWth reactor module. Tables are provided to summarize technical and economic parameters. All designs discussed are assumed to use pressurized light-water primary coolant and produce steam for a secondary power cycle.

1. Viable Steam Generator Design Types for SMRs

Several SG design types are used in nuclear PWRs. Traditional large PWRs use vertical U-tube recirculating SGs, whereas many SMR designs favor once-through configurations for compactness. Below we describe four SG types and assess their merits for a 40–120 MWth SMR.

1.1 Vertical U-Tube Recirculating Steam Generator

Configuration & Operation: A vertical U-tube SG (recirculating type) is an upright cylindrical vessel containing thousands of U-shaped tubes mounted between a lower tubesheet and an upper U-bend region. Primary reactor coolant (hot, pressurized water) enters the SG's tube inlet plenum at the bottom, flows upward through the U-tubes, and returns down through the outlet plenum (red and blue flow in Figure 1). Secondary feedwater is introduced to a downcomer annulus, where it mixes with recirculated water from the SG's moisture separator section. The water flows down the annulus and up through the tube bundle, boiling into steam on the shell side. Only a fraction (typically ~25%) of the secondary water is converted to steam in one pass; the remainder is separated and recirculated within the SG. Steam separators and dryers at the top ensure that nearly dry saturated steam exits to the turbine (usually ~99.9% quality). The large water inventory in the shell side provides a buffer for load changes and acts as a heat sink.

Size, Cost & Fabrication: Traditional recirculating SGs are large and heavy components – in full-size plants they can be ~21 m tall and weigh 500–800 tons. For a small 40–120 MWth SMR, a scaled-down vertical U-tube SG would be much smaller, but still represents a substantial pressure vessel and thousands of tube welds. The complex internals (U-bends, support plates, moisture separators) add fabrication complexity and cost. Manufacturing requires precision tube bending and drilling of support plates, typically by specialized shops (e.g. BWXT, Doosan, Framatome). While economies of scale are lost at small size, the mature manufacturing base for U-tube SGs means tooling and QA processes are well-established. The cost for a new recirculating SG sized ~100 MWth is on the order of a few million USD (rough estimate), with lead times of ~24–36 months including material procurement and nuclear quality certification. The shell is usually low-alloy steel (ASME SA-508/516) with stainless cladding, which is cost-effective for thick sections, while tubing is high-grade alloy (see Section 3). Overall, vertical recirculating SGs tend to be more expensive per kWth at small scale due to fixed complexity.

Pros: Vertical U-tube SGs have decades of proven performance and licensing precedent in the U.S. (e.g. all Westinghouse and Combustion Engineering PWRs). Operators and regulators are very familiar with their behavior. Advantages include a large secondary water inventory that **improves thermal stability** and **buffering** – sudden power or load changes are dampened by the water mass. This can enhance plant **controllability** and provide grace time during transients. The moisture separators ensure high steam quality without requiring precise feedwater control. **Maintainability** is aided by a relatively accessible channel head (for plugging tubes) and a history of inspection techniques (eddy current testing of U-tubes is well-developed). Vertical orientation yields a smaller footprint (floor area) in the plant, which can aid seismic robustness when properly supported – although tall SGs have a higher center of gravity, PWR plants have successfully qualified them for seismic Category I loads by robust lateral supports. Another benefit is **licensing familiarity**: NRC has licensed numerous plants with this design, and design codes (ASME Section III Class 1 for the primary side) fully cover U-tube SG requirements. There is also a **wealth of operating experience** on degradation mechanisms (e.g. tube denting, corrosion), so mitigation strategies are well known.

Cons: The primary drawbacks for a small SMR are the **large size/weight** and **cost** of vertical U-tube SGs relative to the reactor power. The complexity of U-tube bending, heavy moisture separator internals, and substantial shell contributes to higher manufacturing and assembly effort. **Fabrication complexity** is significant – thousands of tube-to-tubesheet welds and tight tolerances on tube supports. For a modular 40–120 MWth reactor, a vertical SG might still be a few meters in diameter and height, pushing the limits of truly "modular" transport (potentially rail-shippable but heavy). From an **efficiency** standpoint, recirculating SGs produce saturated (or very slightly superheated) steam, which is thermodynamically a bit less efficient than superheated steam – although the difference is small (~0.5% cycle efficiency penalty). **Maintenance** can be challenging if tube defects occur in the U-bend region, which is hard to access; indeed, historical U-tube designs suffered stress corrosion cracking at the top U-bends and tube support plate intersections. Modern materials (Alloy 690) largely solved these issues, but the risk of tube leaks in service remains non-zero, and in an SMR design replacement of a large SG could be economically impractical. **Seismic considerations:** tall vertical SGs must be seismically qualified, typically by robust support lugs and snubbers; they concentrate mass high up, which can be a structural challenge. However, given their long use in large plants, this is a manageable issue with proper design.

Suitability for 40–120 MWth SMR: A vertical U-tube SG is technically feasible for a small PWR, but it may be **disproportionately large** relative to the reactor core, undermining some benefits of modularity. If the SMR is not an integral design (i.e. uses external primary loop components), a single vertical U-tube SG could be employed in a loop (for ~40–100 MWth, one SG might suffice per loop). For example, a single-loop PWR of ~100 MWth could use one U-tube SG akin to a scaled-down commercial unit. This approach leverages proven tech and might ease NRC licensing since it mimics existing designs, but the **economic penalty** is that the SG is still a custom, high-quality component with little scaling of complexity. Many SMR developers have steered away from this design because the volume and mass are high – diminishing the factory fabrication and transport advantages of SMRs. In summary, vertical recirculating SGs are **viable but not optimized** for the lower end of SMR power; they would likely be used only if one prioritizes proven technology over compactness and is willing to accept higher unit cost.

1.2 Horizontal U-Tube (Recirculating) Steam Generator

Configuration & Operation: Horizontal SGs are used in Russian VVER reactors and a few other designs. In this layout, the cylindrical SG vessel is **oriented horizontally**. U-tubes are arranged in a bundle that lies sideways, with primary coolant headers (inlet/outlet) at each end of the vessel. Secondary feedwater is introduced into the lower half of the shell and boils as it rises through the tube bundle, similar in principle to vertical SGs except the entire unit is rotated 90°. A steam space exists in the top half of the cylinder, often with separators to dry the steam before it exits the top. The horizontal bundle still acts as a recirculating SG: not all water evaporates in one pass, so unboiled water falls back (via gravity separation) and recirculates within the shell. VVER-440 and VVER-1000 SGs (types PGV-440 and PGV-1000) are classic examples: each horizontal SG has thousands of tubes and large steam drums integrated. The primary coolant flow is typically **once-through on the tube side** (enters one end, U-turns, exits the other end). The secondary side holds a substantial water volume across the length. One notable aspect is the **lower vertical height** of the component: horizontal SGs are short and wide (e.g. ~4 m diameter, ~10 m length for a VVER-1000 SG). This reduces the vertical space needed in containment.

Size, Cost & Fabrication: For a given thermal duty, a horizontal SG tends to have a **larger diameter but shorter height** than a vertical SG. The overall weight can be similar. Fabrication complexity is comparable – thousands of U-tubes and tube welds – but the horizontal layout requires robust internal support to hold the tube bundle against gravity. Manufacturing horizontal SGs is a specialized skill (ZiO-Podolsk in Russia is a major supplier). In the West, horizontal nuclear SGs are not common, so a U.S. SMR project would likely rely on international collaboration or novel manufacturing for this type. For a small 40–120 MWth SMR, a horizontal SG might be scaled down significantly (perhaps a few meters long). The cost drivers (materials, tube bundle construction) remain; there may be some cost saving by elimination of tall separators (some VVER designs use simple gravity separation). **Seismic** fabrication is interesting: the horizontal vessel can be mounted low to the ground with support saddles, potentially easing seismic qualification (lower center of gravity and more uniform stress distribution during horizontal earthquake accelerations). However, without a strong installed base in the U.S., cost estimates are uncertain – likely similar to vertical SGs for equivalent surface area, with added expense if a new supply chain must be established.

Pros: The main advantage of horizontal SGs is **compact vertical envelope** and potentially simpler support structure. This can be beneficial in small plants or marine reactors where height is limited. The **seismic footprint** can be favorable – the weight is spread out and close to the base, reducing overturning moments during an earthquake. Horizontal SGs also have shown **robust tube performance** in some respects: the design avoids a tight U-bend at the very top (bends are distributed along the length), potentially reducing certain stresses. Indeed, anecdotal reports suggest the horizontal SGs have been "less susceptible to degradation" than some vertical designs, though this may be influenced by different water chemistry and support designs (citation needed). Another pro is **lower pressure drop** on the secondary side – the driving head for circulation is smaller, which might mean fewer losses if properly designed. From a licensing perspective, **international precedent** exists: VVER units with horizontal SGs have been licensed in Europe and Asia (e.g. VVER-1000 in China, India), demonstrating viability, although the U.S. NRC has not yet licensed a PWR with this SG type. If partnering with an experienced vendor (e.g. Rosatom's design, if political conditions allowed), a horizontal SG for SMR could leverage proven design data.

Cons: A critical drawback is **limited U.S. experience** – no U.S. PWR has used horizontal SGs, so domestic regulators and operators have less familiarity. This could complicate the design review (NRC would scrutinize thermal-hydraulics and safety behavior not seen in U.S. fleet). Horizontal SGs have a **large secondary water inventory** (covering the entire bundle length), which while stabilizing, can slow responsiveness. SMR designers often want strong natural circulation; a horizontal unit might achieve less driving head for natural convective flow compared to a vertical orientation (since the elevation difference between inlet water and steam outlet is small). **Maintenance** can be tricky: accessing tubes in the middle of a horizontal bundle might require removing an end cover and pulling tube bundles, which is not trivial. Additionally, **efficiency** is limited to saturated steam (like vertical recirc SGs) – no inherent superheating stage. In terms of **fabrication**, if a Western SMR project attempted this, a new qualified manufacturing route might be needed, incurring first-of-a-kind costs. The horizontal design may also occupy more floor area (footprint) which could be a drawback in a compact containment.

Suitability for 40–120 MWth SMR: Unless an SMR design specifically seeks to minimize height (for instance, a barge-mounted reactor or an existing design like KLT-40S or RITM-200 marine reactors which use horizontal SGs), this option is **uncommon for new U.S. SMRs**. The size range fits – indeed the Russian KLT-40S (~135 MWth) uses 4 horizontal SGs, each roughly ~34 MWth capacity, demonstrating feasibility. For a U.S. land-based SMR, however, adopting a horizontal SG would introduce novel engineering and licensing challenges without clear benefits over vertical designs. It might be considered if one aims to emulate certain Russian-integrated reactor designs or to achieve a very low-profile plant layout. Overall, horizontal SGs are **technically viable** but would likely increase project risk in the U.S. context.

1.3 Once-Through Steam Generator (OTSG)

Configuration & Operation: A once-through steam generator has **no recirculation** and typically **no steam drum** – all feedwater is vaporized in a single pass. OTSGs usually employ **straight tubes** (rather than U-tubes) mounted vertically in a cylindrical shell. The primary coolant flows on one side (often inside the tubes) and feedwater on the other in counterflow. In classic Babcock & Wilcox (B&W) OTSG designs, the primary coolant enters at the top and flows *downward* through tube bundles, while secondary water is pumped up inside the shell side (counter-current). By the time the secondary fluid reaches the outlet, it is completely boiled and often slightly **superheated**. **No recirculation loop or separators** are needed; instead, precise control ensures virtually all feedwater is converted to steam. Early B&W OTSGs (used in 1970s U.S. plants like Oconee and Three Mile Island) had straight Inconel tubes with upper and lower tubesheets in a tall vessel. Modern OTSG designs for SMRs can also be helical coil type (see next section) but still follow the once-through principle. Key features are **small water inventory** and **rapid response** – an OTSG has much less water in it than a recirculating SG of equal power, so it heats up and boils quickly. For example, the B&W mPower SMR uses a vertical once-through straight-tube SG inside the reactor vessel, producing superheated steam in one pass.

Size, Cost & Fabrication: OTSGs tend to be **more compact** for the same thermal duty because they don't require a large boiling volume or bulky separator equipment. The tube bundle can be densely packed and the shell just long enough to achieve the needed evaporation length. This yields a lighter component – a big driver for integral SMRs. For instance, a once-through design can achieve significantly higher power density; one analysis found a factor of 13–20 volume reduction vs. conventional U-tube SGs by using an optimized once-through design (with superheating). **Cost:** OTSGs eliminate the heavy steam drum and many internals, potentially reducing material and fabrication costs. There are fewer large forgings (no massive upper head for separators). However, the tradeoff is that **manufacturing tolerances and tube quality must be higher** – the heat transfer must be very uniform to avoid hot spots since there's no mixing of water after one pass. High-alloy tubing (Inconel) is typically used to withstand the full range from subcooled water to superheated steam in one tube. The **feedwater control and pumping** requirements are greater (pumps must handle full pressure with no recirc); thus, the overall system cost must account for high-pressure feed pumps and controls. Still, many SMR vendors find OTSGs attractive for factory fabrication. The expected cost for a small OTSG (~100 MWth) is potentially lower than an equivalent recirculating SG because of simpler construction – perhaps on the order of a couple million USD – but reliable estimates vary. **Lead time** may be shorter too, since the design is simpler (B&W reported cost and schedule benefits of OTSGs in past projects). Manufacturing OTSGs is in the capability of several suppliers (BWXT, Doosan, etc., as they have made large OTSGs and HRSGs). An OTSG's shell and tube structure is straightforward, though tight tube spacing calls for careful welding and support to avoid flow-induced vibration.

Pros: The OTSG design offers several advantages especially suited to SMRs. One major benefit is **compactness and low mass** – ideal for integral reactors where the SG sits inside the RPV (e.g. NuScale, mPower). Without a recirculation drum, the SG can fit in a smaller volume. OTSGs can also produce **drier or superheated steam**, improving turbine efficiency. This means the plant can extract a bit more energy per kilogram of steam (on the order of a few tenths of a percent increase in efficiency). Another pro is **rapid dynamic response**: with little water inventory, the OTSG can follow load changes quickly – steam production ramps up or down as feedwater flow changes, with minimal lag. This can be advantageous for load-following or cogeneration applications in SMRs. From a **maintenance perspective**, OTSGs have historically shown fewer tube degradation issues in some cases. For example, U.S. OTSGs (B&W designs) experienced substantially fewer instances of stress corrosion cracking than U-tube SGs. The absence of U-bends eliminates that failure mode entirely, and straight tubes are easier to support evenly. Also, **no blowdown system** is needed – in recirc SGs, impurities concentrate and require blowdown drains, but an OTSG continuously sweeps water through, reducing the risk of localized crud buildup (provided feedwater is high purity). This can simplify secondary chemistry control. In fact, polished condensate is typically required, and any water that remains in tubes on shutdown simply boils dry due to residual heat, preventing pooling corrosion. **Seismic** wise, the smaller mass of an OTSG can be easier to accommodate, and if housed inside the reactor vessel (integral design), seismic loads are borne by the RPV structure which is typically robust. **Licensing precedent:** The NRC has experience with once-through SGs in B&W PWRs from the 1960s–70s, which provides some pedigree. NuScale's design certification (approved in 2020) includes helical once-through SGs, marking modern regulatory acceptance of OTSGs in SMRs.

Cons: The once-through approach demands **precise control systems**. Because there is no large water reservoir to buffer transients, the feedwater flow and reactor power must be tightly coordinated to avoid overheating or quenching the tubes. **Control complexity** (especially during startup and low loads) is higher – for example, at startup, feed flow must be modulated to ensure proper outlet steam conditions since the OTSG will begin producing steam as soon as feedwater boils. Another con is **higher pressure drop**: OTSGs typically impose a larger pressure drop on the secondary side (small-diameter, long tubes) which means feedwater pumps need more power. This slightly reduces net plant output or efficiency. The minimal water inventory, while good for responsiveness, **reduces thermal inertia** – in an upset (like loss of feedwater), the steam supply can dry out rapidly, potentially challenging reactor control (though SMRs often rely on other passive safety features to handle this). **Maintenance and inspection** might be more difficult in integrated OTSGs – for instance, if tubes are within the reactor vessel, in-service inspection and potential replacement is very challenging. However, if the OTSG is external and modular, one could replace the unit at end-of-life (B&W envisioned relatively easier replacement of OTSG tube bundles if needed). Another drawback: **water chemistry tolerance is lower**. With no blowdown, any impurities in feedwater go through the steam cycle; thus feedwater must be extremely pure (on the order of <0.1% of flow as makeup). Lack of recirculation means no continuous removal of impurities, raising the stakes for proper chemistry control (use of high purity make-up, condensate polishing, etc., and possibly on-line filters). From a **licensing** view, the reactor protection system must account for the faster transients – for example, a sudden loss of load could dry out the SG quicker, affecting heat removal, so the safety analysis needs to demonstrate the reactor can stabilize without water carryover or uncovering the primary side (in practice, SMRs address this with automatic power reductions, etc.). In summary, OTSGs trade passive stability for compactness and need more active control.

Suitability for 40–120 MWth SMR: Once-through SGs are **highly suitable and widely favored** for SMRs in this power range. Many current SMR projects (NuScale, mPower, CAREM, etc.) utilize OTSG designs specifically because of their compactness and ability to be integrated. For a 40–120 MWth reactor, an OTSG can be sized to produce the required steam flow in a relatively small package. The smaller the reactor, the more important it is to minimize ancillary component size – making OTSGs very attractive. The increased control complexity is manageable with modern digital control systems and the inherently slower transients of small cores. The successful testing of NuScale's helical OTSG (see Section 1.4) demonstrates that stable operation can be achieved with proper design. Given that **licensing precedent exists** and NRC has shown openness to once-through designs, a well-engineered OTSG is arguably the **preferred choice for many SMRs**. It offers a good balance of efficiency (slightly superheated steam ~5–30 °C above saturation, e.g. CAREM-25 produces steam at 47 bar with 30 °C superheat) and simplified layout. The caveat is that developers must ensure high reliability of feedwater control and perhaps include fast-acting bypass or relief systems to handle rapid load rejection without over-pressurizing the secondary side. Overall, for cost-conscious and space-conscious SMRs, **OTSGs are often recommended**.

1.4 Helical Coil Steam Generators & Innovative Designs

Configuration & Operation: Helical coil steam generators are a specific form of once-through SG where the heat transfer tubes are coiled helically around a central axis. This design is notably used in integral SMRs like NuScale and Argentina's CAREM-25. In a typical **helical coil SG**, many small-diameter tubes are wound into helices and grouped in bundles (modules) that encircle the reactor core or are placed above it. Primary coolant flows on the shell side (outside of the tubes) while secondary feedwater flows **inside the helical tubes**, upward, picking up heat and boiling as it goes.The coil shape promotes high heat transfer area in a compact volume. The arrangement is usually vertical (coils stacked height-wise). For example, the CAREM-25 integral reactor uses **12 vertical helical coil OTSG modules** spaced around the core periphery inside the RPV. Feedwater enters the bottom of each coil tube and emerges as superheated steam at the top, while primary coolant circulates by natural convection outside the tubes. In NuScale's design, a large helical coil bundle is located in the upper reactor vessel; primary water (pressurized ~12 MPa) rises through the core and then flows downward over the outside of the steam generator tubes, causing the secondary inside the tubes to boil. Helical coils essentially implement the once-through concept but with curved tubes that can be longer (a helical path allows a long tube in a shorter vessel height by wrapping it). They also tend to induce centrifugal forces on the fluid, which can aid phase separation and heat transfer.

Size, Cost & Fabrication: Helical coil SGs are extremely **compact for their surface area**. Coiling tubes allows a large heat transfer area (hundreds of square meters) to fit in an annular volume. This is why designs like NuScale (160 MWth) could incorporate the SG inside the reactor vessel. The downside is that fabrication of helical coils can be challenging – tubes must be bent to precise radii and pitch without thinning or kinking. Advanced tube bending machines and full-scale prototyping (as done by NuScale and SIET in Italy) have been used to qualify these manufacturing techniques. Cost-wise, the material for helical SGs is similar (Inconel or stainless tubes, steel shell), but the labor is in bending and welding many coil loops. A **helical SG likely has more but smaller tubes** compared to a straight-tube OTSG. For instance, CAREM's 12 SGs have relatively small diameter tubes ~30 m long each in helical form. The fabrication is modular: coils can be made as sub-assemblies and inserted. This suits factory production, albeit with careful QA. Overall, cost can be competitive – mass production of identical coil modules could drive costs down if SMRs are built in numbers. The **lead time** is dominated by material procurement (Alloy 690 or equivalent tubing) and setup for coiling; once processes are established, multiple coil units can be produced in parallel. A potential extra cost is testing: flow instability and thermal performance tests are highly recommended (NuScale did extensive tests to ensure the HCSG is stable against flow oscillations). Another innovative category is **compact heat exchangers (plate or printed-circuit)** – these use diffusion-bonded plates with micro-channels. Such designs promise even greater compactness (an MIT study showed a plate-type once-through SG could reduce volume by 13–20× and improve efficiency slightly). However, two-phase flow in micro-channels is unproven for nuclear steam generation, so these remain experimental. For near-term SMRs, helical coils are the more practical innovative choice.

Pros: Helical coil SGs combine many of the OTSG advantages with additional benefits for integral layouts. Their **high surface area-to-volume ratio** makes them ideal for space-limited reactors. By curving tubes, one can achieve the needed heat transfer in a shorter height, which helps keep the entire reactor module compact. Helical coils also have **excellent heat transfer characteristics** – the curvature induces secondary flow patterns that enhance mixing and boiling heat transfer. This can allow slightly shorter tube length for the same duty (one analysis indicated tube length could be ~11.5% shorter for a given thermal condition in a coil vs straight tube). Another advantage is potentially **lower tube stresses**: the gentle bend of a helix spreads out thermal expansion, avoiding a single U-bend apex with high stress. The tube support in a helical bundle can be continuous (the shell itself supports the coil along its length), which can reduce vibration issues. Helical SGs inherently produce **dry steam** – e.g., CAREM's helical SGs output steam at 47 bar with 30 °C superheat – providing efficiency gains and preventing moisture carryover. They are conducive to **natural circulation** on the primary side: placing them above the core (like in integral designs) means the core-to-SG height difference drives flow without pumps. From a safety perspective, the low secondary inventory and placement inside the RPV (in many cases) mean that in a LOCA, the SG doesn't introduce a large secondary break source, and cooldown can be managed within the vessel. **Seismic** pros: if inside the RPV, the SG experiences the same motion as the reactor (no large external component to mount/seismically qualify separately). The overall plant design can be simpler (no loop piping at all in integral designs). For licensing, while novel, helical coil SGs have now been reviewed by NRC (NuScale's DCA included a first-of-a-kind HCSG, which passed review for stability and performance). Internationally, designs like CAREM-25 have been approved by Argentinian regulators, adding confidence. The **innovative factor** also future-proofs the reactor – the SG modules could potentially be swapped or improved in future upgrades if designed for accessibility at refueling outages (though this is non-trivial inside a vessel).

Cons: The major concerns with helical SGs revolve around **uncertainties in two-phase flow behavior** and **maintenance difficulty**. Helical coil SGs can be prone to **flow instability** (density-wave oscillations) if not properly designed, because of the long, coiled flow path. Extensive R&D was needed to ensure stable operation over all power ranges. If an instability occurs, it could cause oscillatory thermal stresses. NuScale addressed this by testing and likely by adding flow restrictors or optimized elevation differences. **Inspection and repair** of helical coil SGs are challenging: the tubes are densely packed and curved, making traditional straight-probe eddy current testing difficult. Special curved probes or visual inspection might be needed, which are not yet standard. If a tube leaks in an integral reactor's helical SG, repair or plugging might be very hard without removing the module. Thus, ensuring high-quality tubing and corrosion resistance is absolutely essential (to avoid ever having to repair it during the reactor's life). Another con is that helical SGs, being inside the reactor vessel for many designs, **experience primary-side neutron irradiation** (albeit at the vessel periphery). Over decades, this could cause some embrittlement or radiological activation of the tubing, factors that must be accounted for in material choice and analysis. **Fabrication tolerances** are tight – any misalignment in coils could lead to uneven flow distribution. In terms of cost, initial units may be pricey due to complexity and testing requirements. Also, **licensing risk** historically was higher – until recently, no NRC-licensed plant had such SGs, but NuScale's certification in 2020 has largely mitigated this risk by setting a precedent. One must also consider **scalability limits**: very high-power reactors might not favor helical coils because the number of coils would become large; but in the 40–120 MWth range, this is not an issue.

Suitability for 40–120 MWth SMR: Helical coil steam generators are **highly recommended** for the lower end of this range, especially for integral PWR configurations. For a 40 MWth micro-reactor, a few helical coils could easily handle the heat load in a small package, enabling the entire primary system to reside in one vessel (improving safety and simplifying containment). At ~100 MWth, as proven by CAREM (100 MWth) and NuScale (~160 MWth), helical SGs are quite feasible and allow the SMR to remain compact and modular. They align with the SMR philosophy of **factory fabrication and high inherent safety** – by eliminating large external piping and components. The slight increase in design complexity (thermal-hydraulic analysis) is outweighed by the benefits in many designs. It's worth noting that not all SMRs use integral layouts; if an SMR is a loop-type, it might still opt for a straight-tube OTSG to avoid complexities. But for any SMR seeking maximum modularity, the **helical coil OTSG is a leading contender**. We anticipate that U.S. vendors (NuScale, Westinghouse for their future designs, etc.) will continue to refine this approach, and international collaborators from countries like South Korea or Argentina could provide additional operational feedback.

Other Innovative Designs: Beyond helical coils, there are emerging concepts like **printed-circuit steam generators (PCSGs)** and **plate-and-shell heat exchangers** for nuclear applications. These use mini-channel technology and diffusion bonding (adopted from aerospace and process industries). A PCSG could drastically reduce volume and potentially eliminate tube failure concerns by using solid metal plates with etched channels. Westinghouse, for instance, in one integral PWR concept (the IRIS successor) considered replacing U-tube SGs with a plate heat exchanger to shrink size. The promise is high, with studies indicating up to 0.5% efficiency gain and much smaller size if two-phase issues can be managed. However, to date, no nuclear plant has implemented a phase-change PCHE/plate SG due to uncertainty in how to handle fouling and flow distribution in such small channels. So, while **innovative heat exchangers** are on the horizon, they are not yet commercially available for near-term SMRs. For the scope of our SMR (licensed in the U.S. in the next few years), the practical choices remain the four types above, with the helical coil being the most novel that is actually being deployed.

Table 1 summarizes the characteristics of the four SG types discussed, highlighting their pros, cons, and suitability for a small SMR:

SG Type	Configuration	Pros	Cons	SMR Suitability (40–120 MWth)
Vertical U-tube (Recirc.)	Vertical shell, U-tube bundle; recirculating water & steam drum (separators).	– Proven design (licensed in many PWRs) – Large water inventory (stability) – High steam quality (moisture separators) – Easier to inspect U-tubes	– Bulky and heavy for small output – Higher cost per MWth – Saturated steam (lower cycle efficiency) – Historical tube corrosion issues (solved by materials)	**Feasible** but not optimal. Used if prioritizing familiarity over compactness. Might be used in loop-type SMR, but large relative size.
Horizontal U-tube (Recirc.)	Horizontal drum, U-tubes horizontal; recirculating.	– Low height, can reduce containment height – Strong secondary inventory (thermal inertia) – Possibly less U-bend stress issues – Good seismic stability (low CG)	– Limited U.S. experience (licensing risk) – Larger footprint (floor space) – Harder tube access for maintenance – Saturated steam only	**Uncommon for SMRs in U.S.**. Technically viable; seen in Russian designs ~100 MWth per SG. Would need new supply chain; chosen only for special cases (e.g. marine or height-restricted designs).
Once-Through (OTSG)	Vertical (usually) shell, **straight tubes** (or slight U); no	– Compact, no steam drum – Can produce superheated	– Minimal thermal buffer (needs fast controls) – Higher feed	**High**. Preferred in many SMRs (mPower, Holtec SMR-160, etc.) for external or integral use. Good match

	recirculation, single-pass evaporation.	steam – Fast response to load changes – Simpler internal structure (no separators) – Proven in B&W plants and modern SMRs	pump power (greater ΔP) – Demands very pure feedwater (no blowdown) – Potential for dryout instabilities if not designed well	for ~50–120 MWth modules due to size and performance.
Helical Coil (OTSG)	Vertical helical coil tubes, often modular bundles; once-through flow.	– Ultra-compact, high area/volume – Integral layout enabled (in-vessel SG) – Steam can be slightly superheated (improves efficiency) – Natural circulation friendly (when above core) – No U-bends; potentially fewer tube failures	– Newer technology (limited operating history) – Complex fabrication (tube coiling) – Inspection/repair is difficult – Requires thorough stability testing – Tubes in-core (if integral) see radiation	**Very High**. Favored by leading SMRs (NuScale, CAREM). Ideal for 40–120 MWth range to maximize modularity. Need to ensure robust design against flow oscillations and have strong QA on tubing.

Table 1: Comparison of SG design types for a small PWR SMR (40–120 MWth). Recirculating types use a steam-separating drum and recirculate unevaporated water; once-through types convert all feedwater to steam in one pass.

2. Commercially Available Steam Generators (40–120 MWth)

In this section we identify steam generators that are (or could be) **procured commercially** for a SMR in the 40–120 MWth range. This includes purpose-built new SGs and potential refurbished or adaptable units from existing designs. Key parameters listed are the vendor/supplier, type/configuration, heat transfer surface area, tube material, pressure/temperature ratings, estimated cost & lead time, and code compliance. Table 2 provides a summary of candidates, followed by additional notes.

Existing and Prospective SGs in Target Range: Because large PWR SGs are much bigger (handling thousands of MWth), we focus on smaller scale units. Notably, **integral SMR SGs** (like NuScale's and CAREM's) are part of the reactor supply, but their designs illustrate available tech. There are also **research reactor** or naval reactor SGs that fall in this thermal range, although not openly marketed. Additionally, several companies offer **modular boiler units** that, with adaptation and proper code qualification, could serve as nuclear SGs.

Vendors/Suppliers: In the U.S., **BWX Technologies (BWXT)** is a leading SG fabricator (they built B&W OTSGs historically and many replacement SGs). BWXT could supply a custom SG for a small reactor, leveraging their ASME Section III "N-Stamp" capabilities. Internationally, **Doosan Enerbility (South Korea)** has emerged as a manufacturer for SMR steam generators – Doosan is producing the helical coil SGs for NuScale's modules. **Framatome** (France) and **Mitsubishi Heavy Industries (MHI)** (Japan) both have designed and built SGs in the past (including for large PWRs and replacements) and could adapt to smaller designs; MHI, for example, built the San Onofre replacement SGs and has designs down to around 300 MWth. **Rosatom's ZiO-Podolsk** (Russia) makes horizontal SGs down to ~70 MWth per unit (for VVER-440), though Russian supply is likely off the table for U.S. projects due to regulatory constraints. **CNEA/INVAP** (Argentina) is building the CAREM-25 SGs, possibly through a local fabricator (CONUAR or Tecna); while not a traditional exporter, this shows technical availability. **China** (SNPTC or Dongfang) has developed SGs for the ACP100 (a 385 MWth SMR with two external SGs ~190 MWth each), but Chinese components would need U.S. certification. Lastly, **Holtec** in the U.S. (with its SMR-160 design) and **Westinghouse** (for its notional SMR) would likely partner with one of the above manufacturers for SG supply.

Table 2 lists a sample of available or adaptable steam generators for the SMR range:

SG & Vendor	Type & Configuration	Thermal Capacity	Heat Transfer Area	Tube Material	P/T Ratings (Primary / Secondary)	Estimated Cost	Lead Time	Code Compliance

NuScale SMR Helical Coil SG (Doosan Enerbility for NuScale)	Once-through **helical coil** bundle, vertical, internal to RPV. Primary outside tubes, secondary inside.	~160 MWth per SG (per module) – produces 77 MWe/module.	**Approx. 940 m²** (est.) per SG – very high power density (full-scale tube length ~200 km across bundle).	**Alloy 690TT** (Ni-Cr alloy) tubing. Shell (RPV) SA-508 steel.	Primary: ~12.5 MPa, ~300 °C inlet/~280 °C outlet (PWR conditions). Secondary: ~5–6 MPa, feeds ~200 °C, steam ~~ 300 °C (slightly superheated).	Part of reactor module; SG cost embedded in module cost. Est. **$5–10 million** per SG in mass production (rough).	**24–30 months** (first-of-kind longer). Long-lead tubing orders already placed (Alleima, 200 km tubes). Fabrication concurrent with RPV.	ASME Sec. III Class 1 (tubes within RPV primary). NRC DC approved.
CAREM-25 Mini Helical SG (CNEA, Argentina)	Once-through **helical coil**, vertical modules (12 units inside RPV). Natural circ. primary.	~8.3 MWth per SG (100 MWth core / 12 SGs). Each SG generates ~2.25 kg/s steam.	**~120 m² per module** (approx., coil ~30 m long tube each). Total ~1440 m² for all SGs.	**Incoloy 800HT or Alloy 690** (not publicly confirmed; likely a high Ni alloy for good SCC resistance). Shell is RPV steel.	Primary: ~12 MPa, 326 °C core outlet. Secondary: 4.7 MPa, feed ~190 °C, **steam 4.7 MPa @ 281 °C** (30 °C superheat).	Not sold separately; est. cost ~$1–2 M per module (projected). CAREM prototype SGs are first-of-kind.	Fabrication underway in Argentina (first unit). **Lead ~18–24 mo** for a set of 12 (small size eases fabrication).	Designed to ASME-like standards (PIE Code), likely meets Sec. III equivalence. Would require **N-stamp and NRC validation** for U.S. use.
B&W mPower OTSG (BWXT mPower Inc.)	Once-through **straight-tube** SG, vertical internal in RPV. Counterflow shell-and-tube (superheater section).	~500 MWth (designed for 180 MWe module). **Too large for 120 MWth,** but can be scaled down (concept only).	~? (Not published; presumably several thousand m²). mPower's SG ~size of a large PWR SG but shorter.	**Alloy 690TT** (as per modern spec).	Primary: ~15 MPa, ~315 °C; Secondary: ~6–7 MPa, steam ~~ 290 °C superheated.	Development halted; not commercially available. Would have been ~$10–15M per SG.	— (mPower project on hold).	ASME Sec. III planned. NRC pre-application done. Not an active offering now.
SMART External SG (KAERI/Doosan, Korea)	Vertical **U-tube recirculating** SGs (4 units external to RPV). Each SG ~25% of 330 MWth reactor. Economizer + separators integrated.	~82.5 MWth per SG (SMART 365 MWth, 4 loops). Suitable for upper end of range.	**~700 m² per SG** (estimated from 330 MWth design).	**Alloy 690TT** tubes, **405 SS** supports (as in APR1400 SG).	Primary: 15 MPa, 310 °C; Secondary: 6 MPa, feed ~180 °C, sat. steam ~275 °C.	Not sold standalone yet. Est. cost $15M each in prototype, could drop if serial-built.	Prototype stage. ~30 months fabrication. Doosan is experienced from large PWR SGs.	ASME Sec. III Class 1 (Korean code compliant, planning for NRC in future).

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Holtec SMR-160 SG (Holtec Intl. & External Partner)	Once-through **straight tube** SG, external vertical unit. Single-loop plant (1 SG). Possibly uses **bayonet tubes** (Holtec hasn't publicized details).	~525 MWth (core), single SG. **Above 120 MWth,** but concept could be adapted to smaller (~100 MWth) with fewer tubes.	Likely **1000–1500 m²** (for full size). For 120 MWth, ~300 m² needed.	Expected **Alloy 690** or **800**. (Holtec may use Inconel per standard practice).	Primary: ~15 MPa, ~310 °C; Secondary: likely ~5–6 MPa, some superheat (SMR-160 aims at simplicity, maybe saturated).	Not yet built; projected cost per SG ~$8–12 M. Holtec's business model includes in-house manufacturing (via Holtec Manufacturing Division).	Long-lead ~24 mo (Holtec would source tubing globally).	ASME Sec. III planned. (SMR-160 under NRC review).
VVER-440 SG (PGV-440) (Zio-Podolsk, Russia)	Horizontal **U-tube recirc.** SG, drum-style. Each SG ~70–75 MWth (6 per 440 MWth reactor).	~**1300 m²** per SG (approx.). Very large volume.	**Alloy 08Kh18N10T** (Russian austenitic SS similar to 304 SS) in older units; newer replacements use Alloy 690.	Primary: 12.3 MPa, 269 °C; Secondary: 4.7 MPa, 260 °C sat. steam.	Available via Russia only; not practical for U.S. SMR (export/sanctions issues). Cost est. $5M each historically.	24+ months (Russian supply chain).	GOST and Russian codes (not ASME). Would need substantial requalification for NRC.	
Naval/Submarine PWR SG (several designs)	Various (some use helical coils or straight tube OTSGs). E.g., latest US Navy reactors reportedly use compact OTSGs.	~50–150 MWth per SG (data not public).	N/A – classified designs.	Likely **Alloy 690** tubes.	P~15 MPa primary, sec ~5 MPa.	Not commercially available due to defense restrictions.	N/A	Military spec, not civilian licensed.
Industrial Once-Through Boilers (e.g. **Innovative Steam Tech. OTSG** for oil/gas)	Vertical once-through coil/straight tube boilers used in power/process industries (non-nuclear). Could be **retrofitted** as SG if materials upgraded and code stamped.	10–100 MWth (various sizes). For example, IST OTSGs used on ~40 MWth gas turbines.	Varies – typically smaller area due to higher allowable heat flux in fossil use.	Typically **Alloy 800** or carbon steel in non-nuclear; would need upgrade to Inconel and QA for nuclear.	10–20 MPa, high temps (designed for steam ~500 °C in some cases).	**Lower cost**: e.g. a 100 MWth HRSG may cost <$2 M. But need add'l cost for nuclear QA mods.	12–18 months (faster if off-the-shelf design).	Could be built to Section I (boiler code) – would require **Section III NB** certification for nuclear primary interface.

Table 2: Commercially available (or near-commercial) steam generators applicable to 40–120 MWth SMRs. (Note: "est." = estimated; blank cells indicate data not publicly available. Cost figures are rough order-of-magnitude for comparison only.)

Discussion of Entries: The NuScale helical coil SG is a prime example – while it is not sold separately (it's integral to the NuScale Power Module), its specifications show what is achievable: roughly 160 MWth throughput in a very compact design using Alloy 690TT tubing. Notably, Alleima (formerly Sandvik) is supplying ~200 km of Alloy 690 tubing for the first modules, confirming material choices. The CAREM-25 SG modules are smaller and could theoretically be exported or reproduced under license; they use once-through helical coils with slightly lower pressures (47 bar steam). A U.S. project might partner with CNEA/INVAP for design details, but would need to manufacture under ASME code.

The SMART SG (from Korea) is an example of a **modular loop PWR SG** at the upper end (~82 MWth each). Doosan, having built OPR1000 and APR1400 SGs, could fabricate these; if a U.S. SMR developer wanted a traditional recirculating SG around 100 MWth, Doosan or BWXT could adapt the SMART or APR1400 SG design (scaling down as needed). Those SGs use Alloy 690TT and 405 SS supports, consistent with best practices.

Holtec's SMR-160 uses a once-through SG but at a larger scale (single 525 MWth SG). They have not publicly detailed it, but it might use a variant of a feedwater-heater style U-tube or bayonet tube design. In principle, that design could be scaled to a smaller reactor or one could use multiple small OTSGs instead of one large. Holtec has heavy manufacturing capability in-house and could produce an SG with ASME N-stamp.

For refurbished units, there are not many options in this size. One theoretical source is the **NS Savannah** (the decommissioned nuclear ship) which had a ~74 MWth reactor and two steam generators. Those SGs were vertical recirculating units built by Babcock & Wilcox in the 1960s. However, they are far beyond design life and not practical for reuse. Similarly, **MH-1A** (Army floating reactor, 10 MWe) and **OTH** early reactors had SGs, but all are long retired and not stored for reuse. Thus, "refurbished" likely refers to surplus equipment from a decommissioned plant. No U.S. PWR of that era falls in 40–120 MWth range (the smallest PWRs were around 150–250 MWth electric, thus >500 MWth thermal). So realistically, a new SMR project would procure new SGs rather than try to reuse an old one.

One interesting prospect is leveraging **industrial OTSGs/HRSGs**. Companies like Innovative Steam Technologies (Canada) or Babcock & Wilcox (through their boiler division) supply once-through boilers for power plants (like combined cycle heat recovery steam generators). These are built to high standards and sometimes use materials like Alloy 800 or even 625 in high-temperature sections. If one were to adapt a design to nuclear, the primary difference is the secondary side of a nuclear SG must be ultra-reliable and prevent any cross-contamination (plus meet seismic and nuclear QA). A conventional OTSG could be upgraded with nuclear-grade materials (Alloy 690 tubes, etc.) and then code-stamped Section III. This approach might reduce cost if the vendor has proven designs that only need material tweaks. The **cost** of such units is relatively low compared to custom nuclear SGs – possibly only a couple million USD – but the certification and modifications would add to that. Still, this is a potential avenue for a cost-focused SMR: e.g., use a robust industrial OTSG design (which inherently produces superheated steam for turbines) and qualify it for nuclear service. The caution is ensuring all materials (welds, supports) can handle PWR water chemistry and radiation if applicable.

Compliance: All SGs interfacing with the primary coolant must meet ASME Section III, Division 1, Subsection NB (Class 1) for the primary pressure boundary. For the secondary side, typically Section III Class 2 or Class 3 is applied to parts of the SG (and sometimes Section VIII for portions not affecting nuclear safety). In practice, most modern nuclear SGs design the entire unit to Class 1 for simplicity. The tube material must be Section III approved (Alloy 690 is approved, many stainless steels are as well). Welding procedures, NDE, and quality control are stringent. For international designs like CAREM or VVER SGs, a thorough gap analysis is needed to ensure their design meets ASME stress criteria, etc.

In summary, **commercial options exist and are expanding**. NuScale's choice of Doosan and Alleima means those companies now have production lines and experience for small SGs, which could potentially be tapped by other SMR developers. BWXT in North America remains a strong candidate especially if a design similar to older B&W OTSGs is desired. The main materials across all available units are nickel alloys (preferred for tubing). We next discuss the material considerations in more detail.

3. Cost-Effective Material Choices for SG Tubes and Shells

Material selection for steam generators must balance **corrosion resistance, mechanical performance, availability, and cost**. The primary candidates for tubing in PWR steam generators are **nickel-base alloys (Inconel series)**, **austenitic stainless steels (300-series)**, and possibly **ferritic alloys** (including ferritic stainless or low-alloy steels) in certain components. The shell (pressure vessel) of a SG is typically a ferritic low-alloy steel (for strength and cost) with a corrosion-resistant cladding. Below we examine the trade-offs:

3.1 Nickel-Base Alloys (Inconel/Incoloy)

Description: "Inconel" is a trade name often referring to Alloy 600 (Nickel ~75%, Chromium ~15%, Iron ~10%) and its successors. Alloy 600MA was widely used in early SG tubing but suffered stress corrosion issues. The modern choice is **Alloy 690**, which has ~60% Ni, ~30% Cr, ~10% Fe and is usually thermally treated (Alloy 690TT) for optimal corrosion resistance. Another alloy used is Incoloy 800 (Fe ~32%, Ni ~46%, Cr ~21%) – technically an Fe-Ni alloy, but similar application. Alloy 800 was used in some CANDU SGs and has good resistance to steam-side corrosion. Nickel alloys are favored because they **resist corrosion and stress-corrosion cracking** in high-purity water under heat and radiation. They form a stable oxide layer and handle the PWR chemistry (borated primary water with LiOH, and secondary water with hydrazine/amine) very well.

Pros: Inconel alloys have demonstrated **long life and reliability** in SG service when properly heat-treated. Alloy 690TT, in particular, essentially solved the intergranular stress corrosion cracking problems that plagued Alloy 600MA tubes in the 1970s. With high chromium, Alloy 690 forms a protective Cr oxide that greatly resists cracking and general corrosion. Nickel alloys can also withstand **acidic and caustic excursions** better than stainless steel – e.g., they are less prone to chloride pitting or caustic stress cracking, which can occur if chemistry upsets happen. They have decent high-temperature strength and can endure the thermal stresses of startup/shutdown without creep or fatigue issues (Alloy 690's creep rupture performance up to 350 °C is excellent, well above normal SG temps). Importantly for SMRs, Ni alloys have a lot of operating **service experience**: All U.S. SG replacements since the 1980s use Alloy 690TT tubing, and they have had virtually no SCC indications in over two decades. This track record is valuable for licensing confidence. They are also **compatible with borated water** – experiments show that in simulated PWR primary (with boric acid and lithium hydroxide), Ni alloys corrode at very low rates, whereas plain carbon steels would corrode rapidly if exposed. Another plus is that Ni alloys handle radiation well: they do not become as brittle as ferritic steels under neutron flux, and their corrosion doesn't significantly worsen under irradiation in PWR conditions.

Cons: The primary disadvantage is **cost**. Nickel is an expensive base metal and Alloy 690 tubing is costly to produce (approx on the order of $40+ per kg for raw material). For thousands of feet of tubing, this adds up. Also, fabrication (bending, welding) of Ni alloys requires expertise – they are tougher to machine than carbon or stainless steels. There have been issues with **manufacturing flaws** like micro-cracks or dents in Ni tubes which need strict QA (for example, a few replacement SGs had to plug some tubes pre-service due to manufacturing indications). Another consideration is **thermal conductivity**: Ni alloys have slightly lower thermal conductivity than carbon steel, meaning for the same heat transfer one might need a bit more surface area (the difference is modest, but as TECDOC noted, SGs with Alloy 690 had to be slightly larger than those with Alloy 600 to compensate for slightly lower heat transfer coefficient). **Availability** can be an issue; only a handful of suppliers (Alleima/Sandvik, Special Metals, etc.) produce nuclear-grade Alloy 690TT tubing, so lead times can be long (hence NuScale ordering tubing years in advance). If SMRs demand increases, supply might tighten and prices may rise. From a welding standpoint, Ni alloys require high-quality welding procedures for tubesheet joints, but this is well understood (e.g., explosive expansion + seal weld or hydraulic expansion – all have ASME-qualified procedures).

Conclusion: Nickel alloys (especially Alloy 690TT) are the **material of choice for SG tubing** in virtually all modern PWRs. For an SMR aiming at low maintenance and long life, it is prudent to use these despite their higher cost. The cost trade-off is justified by the avoidance of forced outages or early replacements due to corrosion. In small SMRs where SG replacement is nearly impossible (integral designs), using the highest grade tubing (Alloy 690TT or potentially Alloy 800/800H) is essential to meet a 60-year life.

3.2 Austenitic Stainless Steels (300-series)

Description: These are iron-based alloys with ~18% chromium and 8–12% nickel (the classic 18-8 stainless type 304, or stabilized versions like 321 or 347 with Ti/Nb, or molybdenum-bearing 316). Stainless steel tubing was used in some early nuclear SGs (e.g., some first-generation SGs tried 304 SS and found stress corrosion issues in certain areas). Stainless steels have good general corrosion resistance (due to chromium oxide film) but are susceptible to **chloride stress corrosion cracking (SCC)** in the presence of tensile stress and impurities (like even trace chlorides can crack them at 300 °C). They are also susceptible to **lead-induced SCC** and **accelerated corrosion** if secondary chemistry is not tightly controlled.

Pros: Stainless steels are **cheaper** than Ni alloys – significantly so. They also are easier to procure in various forms and sizes. Their fabrication (bending, welding) is straightforward as many shops are experienced in stainless. They have **higher thermal conductivity** than Ni alloys by a small margin and a lower thermal expansion coefficient than pure Ni (though still higher than ferritic steels). Some grades like 316L can handle PWR primary water with minimal general corrosion (the film is stable in reducing conditions). If the water chemistry is kept very pure and free of chlorides, stainless can actually perform well. For example, some research reactors and test SGs have used stainless steel without incident because of tightly controlled conditions. Austenitic SS is also non-magnetic, which can be beneficial to avoid flow-induced vibration issues from magnetic support plates (carbon steel supports caused denting of alloy 600 tubes partly due to magnetite buildup – using stainless supports solved that). As noted in the **Wikipedia excerpt**, manufacturers moved to stainless steel for support plates to prevent galvanic corrosion and denting. So stainless in non-tubing components (supports, wrappers) is common and beneficial. Another factor is **availability** – 300-series tubes can be sourced from many suppliers in nuclear grade (though not commonly for SGs nowadays, but in principle). They are also generally **softer** and less likely to cause tube fretting wear on supports (though the support material matters more for fretting).

Cons: The biggest concern is **stress corrosion cracking (SCC)**. Stainless steels under PWR conditions can crack in the presence of aggressive ions like Cl, even at very low concentrations (on the order of ppm) if oxygen is present. PWR secondary sides historically had issues with 304 SS components cracking due to chloride ingress. In SG tubing, one feared mechanism is if hideout of impurities occurs in crevices, stainless could crack faster than Inconel. Additionally, stainless steels are prone to **pitting** if oxidizing conditions occur (e.g., during shutdown air ingress). Pits can be crack initiation sites. Another issue: under long-term neutron irradiation (if used inside an integral reactor vessel), austenitic stainless can undergo some irradiation-assisted stress corrosion cracking (IASCC) – though at SG temperatures (~300 °C) and low flux, this might not be severe. **Thermal expansion** of stainless is quite high (17 µm/m-K for 304 at room temp, slightly less at 300 °C), which is even higher than Alloy 690 (around 13 µm/m-K). This means stainless tubes will expand/contract more with temperature swings, potentially putting more strain on tube joints or supports relative to ferritic supports. Historically, the combination of carbon steel support plates and stainless tubes could cause crevice corrosion (due to galvanic differences and differential thermal expansion). If stainless tubes were used, supports should also be stainless or otherwise inert. **Corrosion resistance**: in the primary side, stainless does fine in borated water if oxygen is absent (it will just form a thin oxide). However, if any oxygen gets in (e.g., during outages), stainless can experience a phenomenon called **boric acid corrosion** at concentrated sites. Studies (like NRC's boric acid corrosion tests) showed carbon and low-alloy steels corrode extremely fast in concentrated boric acid, but stainless and Inconel are much more resistant. Type 304/316 stainless generally resist uniform boric acid attack, but can pit in concentrated hot boric acid if not cleaned. So one must ensure no boric acid accumulations on stainless surfaces.

Cost & Availability: Stainless steel is much less expensive – maybe $5–$10 per kg for raw 304/316 vs $40 for Alloy 690. So tubing costs could be 4–5× cheaper. For a small SMR SG, this might save a few hundred thousand dollars in materials – not huge in the context of a nuclear island cost, but not negligible either. More significantly, if stainless steel could be used, perhaps a broader range of suppliers (even those without Ni alloy capabilities) could fabricate the SG, possibly reducing cost via competition. However, given the risk profile, most SMR developers are sticking with proven Ni alloys.

Use Cases: Is there any modern SG that uses stainless tubes? Some CANDU reactors built in the 1990s use Monel 400 or Alloy 800, not stainless. One notable case: **Wolsong-1** (a CANDU in Korea) originally had type 405 ferritic stainless tubes and experienced rapid corrosion, leading to a replacement with Alloy 800. That highlights that stainless (even ferritic stainless) was problematic. One exception was some early experimental SGs in test reactors. For SMRs, unless there is a compelling cost imperative, **austenitic stainless is generally avoided for tubing** due to SCC risk. However, for secondary-side components like feedwater distributors, separator internals, etc., stainless is fine and commonly used. For SMR applications where perhaps the design life is shorter or one is willing to accept more frequent inspection, stainless could be a backup option if Ni supply fails. Another potential is if one uses **duplex stainless steel** (which has higher resistance to chloride SCC than 304/316). Duplex or super austenitic grades (like Alloy 690's cousin Alloy 693 is Ni-based, scrap that idea, but say 316NG or 347NG which were nuclear-grade stainless used in piping) – these are tweaks but still not proven in SG service.

Conclusion: Austenitic stainless steels offer a **cost advantage and good general corrosion resistance**, but their vulnerability to stress corrosion under certain conditions makes them a **higher-risk choice for SG tubing**. For a cost-sensitive SMR, one might consider stainless if operating conditions are mild (lower temps or very assured chemistry control), but for a PWR with conventional conditions, the safer bet is Ni alloy. Stainless **is recommended for ancillary components** (shell cladding, support plates (as 405 or 410 ferritic SS), etc.) and potentially for the secondary-side pressure boundary (some recent SGs have stainless feedwater rings, etc.). If used in tubing, extensive testing and perhaps a shorter life expectancy should be assumed.

3.3 Ferritic Steels (Low-Alloy & Ferritic Stainless)

Description: Ferritic materials include the low-alloy steels like SA-508, SA-533 (used for pressure vessel shells) and ferritic stainless like type 405 or 430 (straight chromium steels with little or no Ni). These have the benefit of low thermal expansion and high thermal conductivity, plus generally good strength. In SG context, ferritic steel has been used in support structures and historically even as tubing in one case. **Carbon steel** (mild steel) was never used for SG tubing due to rapid corrosion in hot water, but SG shells are made of carbon/low-alloy steel with an internal cladding.

Pros (Ferritic Steels): They are **very inexpensive** and readily available. Low-alloy pressure vessel steels are the workhorses of nuclear components – strong, tough (especially with proper heat treatment), and exhibit **low thermal expansion (~12 µm/m-K)**, which is beneficial for minimizing differential expansion between tubes and supports. Using ferritic support plates (like 405 SS which is a stabilized ferritic stainless) eliminated tube denting issues because 405 SS doesn't form hard rust like carbon steel did. Ferritic stainless (like 409 or 410S) has much better corrosion resistance than plain carbon steel but still has low expansion similar to carbon steel – an ideal combination for internals. On the secondary side, ferritic steels are more tolerant of feedwater chemistry excursions in terms of SCC (they don't undergo SCC like austenitics; however, they can suffer flow-accelerated corrosion if oxygen/ammonia control is poor). Ferritic steels also handle radiation well (they don't show the irradiation-assisted SCC that austenitics do). For the shell, using a ferritic steel with cladding is far cheaper than an all-stainless shell – a carbon steel forging or rolled plate for the shell can be maybe one-tenth the cost of a similar size stainless forging.

Cons: Poor corrosion resistance in pure water without protective measures. Carbon and low-alloy steels will rust quickly in aerated water and even in deaerated high-temperature water they can corrode, producing magnetite. In PWR secondary circuits, carbon steel is used but requires careful oxygen scavenging and pH control to form a protective magnetite film and avoid flow-accelerated corrosion (FAC). In an SG, if carbon steel were exposed to the primary (borated) water, it would corrode aggressively if any oxygen was present and also suffer general thinning over time. For example, the phenomenon of **boric acid corrosion**: leaks of primary water have eaten away reactor vessel heads (made of low-alloy steel) at rates of inches per year when boric acid crystallized on them. Thus, any ferritic surface in contact with borated water must be clad or chemically controlled. In the secondary side, carbon steel surfaces (like feedwater pipes) often suffer FAC – indeed many plants have had to replace carbon steel components due to wall thinning from high-velocity water with certain chemistries (low oxygen, low pH can ironically accelerate carbon steel dissolution). So using ferritic steel for tubing in contact with high-purity water is generally a **no-go**, as it would continuously lose metal or foul the system with corrosion products. Ferritic stainless steels, like 405, have better corrosion resistance than plain carbon steel but still not on par with austenitic or Ni alloys; they can rust in hot water if oxygen intrudes. Type 405 was used for some early SG tubing (in Wolsong-1's CANDU SG) and had unexpected rapid thinning due to grooving corrosion, leading to failure within a decade. That indicates that even with ~12% Cr, it wasn't enough to withstand long-term operation in the SG secondary environment.

Another con is **embrittlement**: ferritic materials can undergo a shift in ductile-brittle transition temperature if subjected to certain environments. Low-alloy steel is tough at SG temps, but if it were to see any hydrogen uptake or neutron irradiation, it could embrittle. This is more a vessel issue than a tube issue though.

Applications: In steam generators, ferritic steels are used in the shell (with stainless cladding inside). The inside cladding (often stainless steel layer of ~3–5 mm) protects the base steel from water. Support plates historically were carbon steel but that caused tube denting (the carbon steel rust swelled in crevices). Modern SGs use **405 ferritic stainless support plates** because 405 forms a protective film and doesn't undergo the same rust swelling; it also closely matches the thermal expansion of the carbon steel shell and the Alloy 690 tubes, reducing differential expansion issues. Another use: some SG designs have **integral economizer** tubes or preheaters made of ferritic steel to take advantage of its high thermal conductivity for the lower-temperature region (some old Westinghouse SG models had a lower bundle of carbon steel tubes to act as a preheater, but these had to be isolated from oxygen). This is not done in modern ones due to corrosion concerns.

Cost & Availability: Ferritic steels are **widely available** and inexpensive. Any heavy engineering shop can work with SA-516/SA-508 steel for shells. Ferritic stainless (405, 430) is also cheaper than austenitic because it has no nickel (which is a major cost driver). So from a pure cost perspective, if one could use ferritic tubes, it'd save a lot. But the operational risk is far too high to justify that in most cases.

Compatibility with SMR coolant: SMR primary coolant is typically borated light water, same issues as PWR. Any ferritic surface there should be clad or it will corrode (and release corrosion products that can foul core or SG tubes). Secondary coolant in SMRs is similar to large plants, maybe even using the same amine chemistry. Ferritic steel on the secondary side will see FAC if flow is high and pH is not sufficiently elevated. Many newer plants raise secondary pH (with ETA or other amines) to ~9.8–10 to protect carbon steel feedwater systems. This could also help protect a carbon steel SG tube, but again, a single failed chemistry incident (like oxygen ingress during an outage) could pit the tubes and start crack propagation.

Conclusion: Use ferritic steels for **SG shell material and secondary structural internals**, but **not for tubing that directly contains primary or secondary water** in steady operation (except in strictly low-temperature portions with protection). The best practice is to rely on ferritic strength for structure (with clad) and use corrosion-resistant alloys for the heat transfer surfaces. This yields a cost-effective mix: e.g., SA-508 shell with SS cladding (the cladding is often 308/309 stainless weld overlay) – this gives carbon steel strength and cheap bulk, and stainless surface. For tube supports: type 405 stainless is common – it's cheap and has done well to prevent denting and support plate corrosion. For tubes: stick to Alloy 690 or possibly Alloy 800, and avoid ferritic tubes.

3.4 Summary of Material Trade-offs

Let's summarize the trade-offs in a table for clarity:

Material	Examples & Role	Corrosion Resistance	Mechanical/ Thermal	Cost & Availability	Nuclear Use Notes
Nickel-base alloys (Inconel/Incoloy)	Alloy 690TT (tubes), Alloy 800 (alt. tubes), Alloy 600 (old, avoid)	Excellent against primary water SCC, very good in secondary (resists chloride SCC). Low general corrosion. Fouling resistant (less magnetite deposition).	High strength, good creep/fatigue. Thermal expansion moderate (13 µm/m-K). Thermal conductivity modest. Easy to form oxide layer for passivation.	High cost (Ni ~$40/kg). Limited suppliers (long lead). Nuclear grade 690TT tubing is available (Alleima, etc.).	Preferred for SG **tubing**. 690TT used in all modern PWR SGs due to SCC resistance. Ensures long life – critical for SMRs where SG not easily replaced.
Austenitic Stainless (300-series)	304/316 SS (shell cladding, misc piping); 321/347 SS	Good general corrosion resistance (Cr oxide). Susceptible	Adequate strength (lower than Ni alloys at temperature). High	Moderate cost (stainless ~$5–$10/kg). Many	Used for **cladding and internals** often. Tubing use is **rare now** due to SCC risk.

	(stabilized); 316NG (nuclear grade); **Not commonly used for tubing now**.	to chloride SCC and pitting if impurities present. Tolerates boric acid fairly well generally but can corrode in concentrated hot acid.	thermal expansion (~17 µm/m-K) – can cause differential stress. Good thermal conductivity.	suppliers; easy to fabricate.	If used, must rigorously control water chemistry and limit stress. Historical SG tube failures with SS discourage its use.
Ferritic Steels (low-alloy & ferritic SS)	SA-508/533 (SG shell/base material); 405 SS (tube support plates); 410 SS, 2.25Cr-1Mo, etc.	Poor in untreated water – needs cladding or protective chemistry. Ferritic SS (12% Cr) is better than plain carbon but still can corrode and was problematic in past SG usage. Not prone to SCC, but prone to FAC and general wastage.	High strength and toughness (low-alloy steels). Low thermal expansion (~11–12 µm/m-K) – favorable. High thermal conductivity. Can embrittle if not protected (e.g., if hydrogen diffuses into steel).	Low cost (carbon steel <\$1/kg, ferritic SS <\$3/kg). Widely available, easy to weld.	Standard for **shells** (with cladding) – cost-effective for thick sections. **Not recommended for tubing** or wetted surfaces without cladding. Use for supports (405 SS) to avoid denting and match expansion. Requires chemistry control to avoid FAC.

Table 3: Material trade-off summary for SG construction.

Compatibility with SMR coolant chemistry: In a PWR SMR, primary coolant will be borated (typically 1000–2000 ppm B as boric acid) and lithiated to pH 7–7.4. Nickel alloys and stainless steels can maintain passivity in this environment; carbon steel cannot without being clad. Secondary coolant will be high-purity water with volatile amines for pH (~9–10) and oxygen <5 ppb (hydrazine used). Nickel alloys thrive in this environment too – indeed Alloy 690 shows **very low corrosion rates and excellent SCC resistance in various high-temperature waters**. Stainless steels can do well in secondary water if oxygen is low and no chlorides ingress; however, if a condenser leak introduces salt, stainless could pit or crack whereas Alloy 690 would be more forgiving (though still not immune to all impurities, e.g., lead or phosphate can attack even Alloy 690 in some cases). Ferritic steel in secondary water tends to suffer FAC if pH and oxygen are not carefully controlled (many plants saw wall thinning of carbon steel feedwater lines). So if any ferritic steel surfaces exist (like a shell or economizer), one must ensure proper water chemistry regime (oxygen scavenging and pH >9). Borated primary water is also very corrosive to ferritic steel if oxygen is present; but since primary is kept reducing (hydrogen added) and at pH ~7, a protective magnetite layer forms on carbon steel components like core support structures. Still, any small leak that dries and concentrates boric acid can eat through carbon steel quickly – which is why reactor vessel heads made of carbon steel needed high-quality coatings or Alloy 600 CRDM nozzles; when those leaked, the carbon steel head suffered severe wastage.

Material recommendation: For a cost-conscious SMR, one might be tempted to use less exotic materials. However, given that reliability and longevity are paramount (and NRC licensing would heavily scrutinize any deviation from proven materials), the recommended approach is:

- **Tubing:** Use **Alloy 690TT** (or a proven equivalent like Thermally Treated Alloy 800 if justified, but Alloy 690TT is more common in PWRs). This ensures minimal risk of corrosion or cracking over decades. The cost is higher, but tubing volume in a small SG is not enormous (e.g., a 100 MWth SG might have a few thousand kg of tubing – the premium might be a few hundred thousand dollars, which is worth the reliability). Alloy 800 is an alternative that has been used in some SGs (French N4 reactors, CANDUs) with good results, and it's somewhat cheaper (more iron content) – but it's still a high-alloy material and not dramatically cheaper than 690. The slight downside (a bit lower strength, slightly more corrosion in some conditions) likely outweighs the minor cost benefit, so Alloy 690TT remains the gold standard. **No compromise on tubing** is advisable because a SG tube leak in an SMR could cause costly downtime and complicated repairs. Even NRC would likely expect an applicant to use materials with extensive operating experience (which Alloy 690 has, whereas using stainless tubes would be a big deviation).
- **Shell & Heads:** Use **SA-508/SA-516 steel with Type 304/308 stainless cladding** on all internal surfaces exposed to water. This is standard practice and minimizes cost (ferritic steel provides strength at ~1/3 the material cost of an austenitic vessel). The stainless cladding (3–10 mm) prevents general corrosion and provides a corrosion-resistant layer in case of any water ingress to shell. This way, the shell sees little to no corrosion and the cladding handles the water.
- **Supports & Internals:** Use **405 ferritic stainless steel** for tube support plates or grids. This material has low carbon (to avoid sensitization) and a small addition of aluminum to stabilize carbon/nitrogen, preventing hardening. It resists corrosion better than carbon steel (forms a thin Cr-oxide) and doesn't undergo the tube-denting corrosion mechanism. Many replacement SGs in the U.S. used 405 SS tube support plates and reported no further denting issueswww-pub.iaea.org. For anti-vibration bars or flow baffles, 405 or 410S (unhardened 12% Cr steel) is good. These ferritic SS are relatively cheap and easy to fabricate. They also match the expansion of Alloy 690 tubes reasonably well (Alloy 690's expansion is ~13, and 405 SS is ~11, much closer than 304 SS which is ~17, so differential expansion is limited).
- **Secondary-side attachments:** any steam separators, dryers (if present in recirc SG) should be stainless steel (304 or 316) as they are exposed to steam and some water – stainless will resist corrosion and is standard for these components. Feedwater rings and nozzles can be stainless as well for longevity.
- **Welds and clad materials:** Typically, the cladding is applied with a stainless weld alloy (308L or similar) onto the ferritic steel. Dissimilar metal welds (like tube to tubesheet

joints if tubesheet is low-alloy steel) should use a compatible nickel-base filler (Alloy 82/182 or improved Alloy 52/152 which has higher Cr). Indeed, replacement SGs often use Alloy 52 for welds to avoid earlier Alloy 182 issues (182 was prone to primary water stress corrosion cracking over long term; 52 is much more resistant).

Thermal Stresses & Compatibility: One reason to consider materials like ferritic vs austenitic is differential expansion. Using Alloy 690 tubes and a ferritic support plate (405 SS) is a good combination – it minimizes stress at tube supports across temperature swings, reducing the wear and potential fretting. If one were to use stainless supports with Alloy 690 tubes, the expansion mismatch could be larger (though tubes expand more than supports in that case, which could actually reduce crevice stress, but cause other fit issues). Historically, **Alloy 690 tubes + 405 supports + carbon steel shell** is a validated combination that works well. So SMRs should stick to that triad for any external SG. For helical coil SGs inside RPV, the shell is the RPV itself (low-alloy steel) and the tubes are Alloy 690 – this is effectively what NuScale does, and presumably they ensure the coil structure has flexibility to accommodate differential expansion (the primary water heating/cooling will make the coil structure move a bit relative to vessel, but acceptable).

Material Cost vs Performance: To put in perspective, tubing might constitute maybe <10% of the SG cost, whereas the bulk forging or vessel might be 30–40%. So cutting tubing cost by using stainless might save a small fraction but potentially jeopardize the whole SG. It's typically not worth it. A study in the 1980s did consider some **cost trade-off** of Alloy 600 vs stainless: at that time Alloy 600 was more expensive, but utilities still chose it due to expected life. Today, Alloy 690 is essentially mandated by industry practice for SG tubes because the long-term economics (avoiding a $100M replacement outage) dwarf the upfront material savings of a cheaper alloy.

In summary, **preferred materials** for minimizing cost *and* meeting performance/regulatory needs are: **Alloy 690TT for tubing**, **low-alloy steel + stainless cladding for shells**, and **409/405 ferritic stainless for support structures**. These combinations have proven to virtually eliminate the corrosion problems experienced in earlier generationsen.wikipedia.org. They strike a good balance – using expensive alloy only where needed (the heat transfer tubing) and cheaper strong steel for load-bearing parts.

4. Recommendations: Preferred SG Configurations & Materials for a Cost-Effective SMR

Considering the analysis above, we now recommend the optimal steam generator design and material configuration for a small modular PWR (40–120 MWth) that meets U.S. regulatory requirements while minimizing cost:

- **Choose a Once-Through SG Design (Helical Coil if Integral, Straight-Tube if External):** For SMRs in this size, a once-through steam generator provides the best combination of **compact size, efficiency, and proven performance**. If the SMR uses an **integral reactor vessel** (housing the SG inside), we recommend a **helical coil OTSG** arrangement, as implemented by NuScale and CAREM, to achieve high power density and eliminate large external piping. NuScale's success with helical HCSG testing and NRC certification gives confidence that such a design can meet licensing standards in the U.S. The helical coil design minimizes the reactor system footprint and can be entirely factory-fabricated, aligning with SMR cost goals of modular construction. On the other hand, if the SMR is a **loop-type design** (separate vessel for SG), we advise using a **vertical once-through straight-tube SG** (or a slight U if needed for thermal expansion) similar to B&W's designs but with modern enhancements. This will still be much smaller than a recirculating SG and avoids the complexity of moisture separators and recirc pumps. A single OTSG can be designed to handle the full 40–120 MWth (for instance, a ~100 MWth SG with ~10,000 ft² area, which is feasible as demonstrated by the small once-through boilers in industry). The **OTSG's ability to produce superheated steam** is a bonus for efficiency – for a small plant, every percentage point counts to improve the economic viability. Additionally, OTSGs inherently have **fewer thick sections** (no heavy steam drum), making the component easier and cheaper to manufacture and to transport.
- **Leverage Established Designs & Vendors:** To reduce licensing risk, it is wise to **reference proven steam generator models or work with suppliers who have them**. For example, NuScale's SG (Doosan) or SMART's SG (Doosan) or even Holtec's planned SG could form the basis. A potential approach is to engage Doosan or BWXT early, using their SG design expertise to ensure the new SG meets ASME III and NRC expectations. Using an existing heat transfer design (with validated performance codes) will simplify the safety analysis. The NRC will expect to see either operational data or high-fidelity test data for the SG performance and stability – by sticking close to a known design, one can utilize existing data (e.g., from NuScale tests or historic once-through SG behavior studies). This reduces regulatory uncertainty.
- **Incorporate Features to Enhance Maintainability:** One critique of once-through SGs is control complexity, but modern digital control mitigates that. More pressing for cost is ensuring you don't have to **replace or repair** the SG during the plant's life – which is an expensive prospect. Thus, the design should include features like **access for inspection** (for example, design the tube bundle in modules that could be inspected by remote tooling). If helical, consider "laydown" provisions or inspection ports on the vessel. **Modular replacement** concept: In an integral SMR, possibly design the SG coils to be

removable in a major outage (even if it's very infrequent, having the option is valuable). For an external SG, plan for a reasonable exchange method (flanged connections, etc.). These design choices upfront can save enormous costs later if an issue arises. NRC will also likely query how one would detect and manage a tube leak; having a robust monitoring system (moisture detectors, chemistry monitors) and a contingency plan to plug or replace the SG module will strengthen the licensing case, as required by General Design Criteria (leak-before-break demonstration, etc.).

- **Seismic and Footprint Considerations:** To comply with seismic Category I, we suggest **choosing the SG orientation that best fits the overall plant seismic design**. For an underground or small footprint SMR, vertical components might be limited by enclosure height. However, given the small size, a vertical SG is still likely fine (e.g., NuScale's entire module is 23 m tall). Horizontal SGs, while seismically stable, are not recommended due to lack of U.S. precedent and manufacturing support – the cost and schedule risk of going horizontal outweigh potential savings. Instead, a vertical OTSG can be seismically qualified by design – for instance, incorporate **integral support lugs and snubbers** tying it to the reactor or containment structure to handle seismic loads. The smaller mass of an SMR SG (compared to an 800-ton commercial SG) makes seismic issues more manageable. Bottom line: stick with vertical orientation unless a specific design reason compels horizontal (which in U.S. context is unlikely).
- **Material Recommendations:** Use **Alloy 690TT for all heat-transfer tubing**, despite its cost. This will virtually ensure that **tube corrosion is a non-issue** over the plant life, which is critical for cost containment (avoiding forced outages and replacements). The rest of the SG can use cheaper materials: the shell (if separate) can be SA-516 Gr70 or SA-508 Class 3 steel, clad with Type 304/308 stainless – this meets ASME Code and minimizes material cost by using carbon steel for thickness and only a thin stainless layer for protection. All internal structures in contact with water should be corrosion-resistant: supports in 405 SS as discussed, feedwater distribution maybe 316 SS. Don't use plain carbon steel in wet areas; even though it's cheapest, it will cause long-term headaches with corrosion products (which could deposit on tubes and insulate them or cause under-deposit corrosion). The Alloy 690 vs Stainless tubing decision is likely to come up: one might ask "could we use 316NG stainless tubes to save money?" Our recommendation is **no** – the cost saved isn't worth the potential for SCC or pitting, which could cause leaks and force expensive repairs. The NRC would also likely question using stainless tubes in a PWR SG given that industry moved away from that for reliability. Sticking with Alloy 690TT aligns with industry best practice and would expedite regulatory approval (they will recognize it as the standard). If cost must be shaved, a possible compromise is **Alloy 800NG** (nuclear-grade Incoloy 800) which was used in some SGs and has fairly good SCC resistance (not as good as 690, but much better than 600 and perhaps on par with stainless in some respects). It's somewhat cheaper due to iron content. However, Alloy 800 did experience some corrosion in certain CANDU plants (fretting and pitting

issues), so it's still a riskier choice than 690. Given SMR vendors like NuScale and GEH (for BWRX-300, though BWRs have different steam cycle) all choose 690, it's clear the modern consensus is to use the premium alloy.

- **Secondary-side Chemistry and Materials:** To reduce cost and complexity, design the SG to operate with **all-volatile treatment (AVT) chemistry** (no secondary side chemical additives that could foul). This means a simpler system (no phosphate or complicating factors). Use materials that can tolerate AVT – which the recommended ones do. In doing so, you can avoid issues that early plants had (like denting from phosphate hideout or cracking from impurities). This "clean" approach will support the goal of a maintenance-light SMR. Also consider using **filtration and high-purity makeup water** – a slightly higher operating cost but prevents material problems, saving cost in the long run.
- **Cost Considerations:** While advanced SG designs might seem costly, their smaller size in SMRs actually can drastically cut absolute cost. For example, a NuScale SG is presumably a small fraction of the cost of a traditional PWR SG (which is \$10–\$20M each) – maybe only a few million dollars per module. The focus should be on reliability to ensure no replacement is needed (because even a \$5M SG is dwarfed by the \$100M+ cost of a replacement outage and new module). So spending on Alloy 690, proper QA, testing, etc., is **money well spent to de-risk future costs**. In contracting, the SMR developer should engage the SG fabricator early to lock in material prices (Ni alloy prices can be volatile) and ensure timely delivery (as lead times for Alloy 690 tubing can be 12+ months). Economies could be gained by ordering in bulk if multiple modules are built – e.g., NuScale ordering 200 km of tubing covers several SGs and likely got volume discount.
- **International Sourcing vs U.S.:** To minimize cost, one might consider international vendors like Doosan (Korea) or others who might offer lower labor costs. This is acceptable as long as they have ASME N-stamp and a track record. Doosan, for instance, is ASME certified and has supplied large SGs and now SMR SGs. Partnering with them could yield cost savings compared to sole sourcing from a U.S. shop with potentially higher labor costs. However, keep an eye on tariffs or regulatory approvals for importing nuclear components. Another potential is **China** – Chinese companies have built many steam generators (for AP1000, etc.), often at lower cost, but currently the U.S. climate makes direct Chinese supply difficult. Still, one could leverage Chinese expertise indirectly (e.g., through joint ventures or design licensing). For example, China's ACP100 is building an integral PWR with internal SGs, likely helical – their experience could be valuable. But any Chinese components would need thorough quality documentation to satisfy NRC, which could offset cost benefits.
- **Licensing Precedent & Documentation:** Use references to already licensed SG designs in your Safety Analysis Report. For instance, note that the chosen tubing material Alloy 690TT has decades of satisfactory use with "no reported instances of in-service stress corrosion cracking in U.S. plants since its adoption" – this will reassure the NRC

about materials. Show that your SG design is similar to those in design certs or standard review plans. If using a novel feature (like plate heat exchanger concept), be prepared to do extensive R&D and that may not be worth it for first units.

In conclusion, the **preferred configuration** for a cost-effective yet safe SMR steam generator is a **compact once-through unit** (favoring helical coil if inside vessel, or vertical straight-tube if outside) constructed with **proven corrosion-resistant materials** (Alloy 690TT tubes, low-alloy steel shell with stainless cladding, ferritic stainless supports). This setup leverages the benefits of modern SG technology (compactness and reliability) while minimizing the likelihood of costly failures. It aligns with both U.S. regulatory expectations (by using known solutions) and the economic imperative of SMRs (factory fabrication, minimal downtime).

By implementing these recommendations, a small modular PWR can achieve a **robust steam generator system** that will operate efficiently over decades, with reduced maintenance and strong safety margins, all at a reasonable cost. The approach marries the hard lessons learned from past large PWRs with the innovative design needed for SMRs, resulting in a balanced solution ready for NRC licensing and commercial deployment.