Kadmos Energy Services LLC

Design Codes and Standards for SMR Primary Loop Components

1. Applicable Codes, Standards, and Regulations

ASME Boiler & Pressure Vessel Code Section III (BPVC Section III): This is the primary code for nuclear reactor components, including the **design, materials, fabrication, testing, and inspection** of pressure-retaining items like piping, valves, and vessels. Section III Division 1 is subdivided by class of component based on safety significance. In a typical Pressurized Water Reactor (PWR) primary loop (reactor coolant pressure boundary), piping and valves are classified as **ASME Class 1** (highest safety importance), so Section III **Subsection NB** applies. Less critical piping (e.g. certain auxiliary or secondary systems) may fall under Class 2 or 3 (Subsections NC or ND) if permitted by the design and regulatory classification. Section III defines stringent requirements on **allowable stress (Sm), materials, wall thickness, weld quality, and quality assurance** for each class. For example, Class 1 components use a safety factor such that allowable stress is roughly 1/3 of tensile strength (at operating temperature) to provide large design margins. Materials must be approved in Section III (SA-designated materials) and meet fracture toughness criteria. All welding procedures and welders must be qualified per ASME Section IX, and fabrication must include 100% volumetric inspection of welds for Class 1 piping. Section III also mandates a hydrostatic pressure test of the piping system at a specified multiple of design pressure after fabrication. In practice, the nuclear piping designer uses Section III rules (e.g. NB-3600 for Class 1 piping analysis) to calculate minimum wall thickness, flexibility, and stress intensities under loads (pressure, thermal expansion, seismic, etc.), and ensures stresses remain below code limits (primary membrane stress, fatigue usage factors, etc.). The code imposes constraints such as **minimum wall thickness** based on pressure and diameter, material allowable stress that decreases with temperature, weld preheat and post-weld heat treatment requirements, and mandatory nondestructive examinations (NDE). All Class 1 valves and piping must receive an **N-Stamp** (indicating Section III code certification) and be supplied with full documentation and traceability. Section III requirements are integrated early into design—piping and valve specifications must invoke Section III Class 1 rules, and procurement from vendors requires using Section III-certified materials and shops. (Note: ASME Section III itself does **not** decide which components are Class 1, 2, or 3; that classification comes from the designer/owner in accordance with regulations like NRC guides.)

ASME B31.1, "Power Piping": ASME B31.1 is a code for industrial power plant piping (fossil-fuel plants, non-nuclear portions of nuclear plants). It **applies to non-nuclear piping systems** such as balance-of-plant steam, feedwater, and heating/cooling systems that are not part of the reactor coolant pressure boundary. In a nuclear power station, B31.1 might be used for secondary systems and other piping outside the nuclear island or for systems classified as non-safety (Quality Group D) by the NRC. B31.1's scope includes design, materials, fabrication, and testing, but it is **less rigorous** than Section III for nuclear safety piping. For example, B31.1 allows higher stress limits (up to ~2/3 yield for occasional loads) and often uses a design factor of 0.72 of yield for hoop stress, whereas Section III Class 1 uses ~1/3 of tensile. B31.1 also permits use of a wider range of commercial materials (ASTM grades) without the strict Section III qualification, and typically requires spot radiography on welds rather than 100% for many systems. **If** the SMR design had any piping not required to meet nuclear Section III (for instance, some skid-mounted tertiary loop or balance-of-plant piping at similar temperatures/pressures but not safety-related), B31.1 could be applied. In general, however, the primary loop of a nuclear reactor (Quality Group A) would *not* use B31.1 for code compliance. It is important to note that when Section III class piping connects to B31.1 piping, the more stringent requirements govern at the interface (e.g. a weld between a Class 3 (Section III) pipe and a B31.1 pipe must meet Class 3 rules). Thus, B31.1 comes into play mainly for non-safety piping; it imposes constraints like minimum wall per B31.1 formula (which is similar to Barlow's formula with 0.6 weld efficiency and 0.4 yield factor by default), and requires hydrotests (typically 1.5× design pressure). Integration-wise, nuclear plants segregate piping by code class – designers clearly delineate which lines follow Section III and which follow B31.1, using appropriate specifications and QC measures for each.

ASME B31.3, "Process Piping": This code covers chemical and process industry piping. It would not normally be applied to primary reactor coolant piping in an NRC-licensed plant. However, **if applicable**, it might be used for certain auxiliary fluid systems in a research or test reactor, or perhaps portions of an SMR design that are non-safety and more akin to process systems (for example, a skid-based chemical volume control system or radwaste system could use B31.3 by design choice). B31.3 has design categories (Normal, Severe, High Pressure) with varying safety factors. Its rules are similar in concept to B31.1, but B31.3 generally allows slightly higher stress intensities and addresses a broad range of chemical process materials. In the context of an SMR primary loop operating at ~270 °C, 3–15 MPa, B31.3 would only be used if that loop were **not** part of a licensed reactor coolant boundary (e.g. perhaps in a non-NRC regulated prototype or a secondary intermediate loop in some designs). For completeness: B31.3's constraints include requiring listed materials or qualifying unlisted ones, wall thickness per formula with safety factors (often 3.5 or higher on burst), and appropriate high-temperature creep evaluation if above creep range (270 °C is below creep concern for steels). Integration of B31.3 would entail ensuring the piping spec meets its requirements (e.g. weld procedure qualifications, NDE per B31.3 standards) and that designers perform flexibility and stress analysis for thermal expansion and occasional loads as required. Again, **for an NRC-regulated SMR primary circuit, B31.3 is likely not used** – Section III would be the governing code if the piping is part of the reactor coolant system (Quality Group A).

10 CFR 50.55a (Code of Federal Regulations Title 10 Part 50.55a, “Codes and standards”): This U.S. Nuclear Regulatory Commission (NRC) regulation **incorporates ASME codes by reference into law** for nuclear power plants. It requires that the reactor coolant pressure boundary and other safety class components of a commercial power reactor be designed, fabricated, and inspected to NRC-approved editions of ASME Section III. Essentially, 10 CFR 50.55a makes compliance with Section III (and Section XI for in-service inspection, and OM Code for in-service testing) mandatory. It specifies which edition and addenda of Section III are accepted, and it is periodically updated by the NRC as code editions evolve. For a new SMR, the applicant must use Section III edition approved in 10 CFR 50.55a (or later editions via request) for the primary loop piping, valves, etc. The regulation also addresses code cases: only NRC-approved code cases (listed in Regulatory Guides) can be used without special permission. In practice, 10 CFR 50.55a ensures that ASME Class 1, 2, 3 components meet the minimum standards of Section III and that any deviations or alternatives get NRC review. It also imposes additional NRC conditions on the code in some areas (for example, certain Code Cases may be mandated or prohibited, and use of later code editions requires NRC approval). Additionally, 10 CFR 50.55a references **OM (Operations & Maintenance) Code** requirements for periodic valve testing and Section XI for inspection of welds over the plant’s life. For the **design and procurement stage**, 10 CFR 50.55a means the SMR vendor must build the design to the correct code edition and have an NQA-1 quality program in place, and procurement specs for piping, insulation, and valves must invoke compliance with these ASME code requirements. The NRC will review conformance during the design certification and construction permit process.

NRC Regulatory Guides (RG) for Piping, Insulation, and Valves: Several RGs provide guidance on acceptable methods to meet NRC regulations for these components:

- **RG 1.26, “Quality Group Classifications”** – This guide classifies fluid system components by safety significance and radioactive content. It ties each **Quality Group** to specific codes. For example, RG 1.26 designates the reactor coolant pressure boundary as Quality Group A, which corresponds to ASME Section III Class 1 construction. Auxiliary systems that are important to safety (e.g. emergency core cooling) might be Group B (Class 2) or Group C (Class 3), whereas non-safety water systems are Group D (which can use B31.1). Thus RG 1.26 ensures that primary loop piping and valves (Group A) are built to the highest standards (Section III Class 1) for material, design, and inspection. It imposes **constraints such as code class, seismic category, and quality assurance requirements** for each group, effectively integrating with 10 CFR 50.55a by guiding what code class to apply.
- **RG 1.36, “Nonmetallic Thermal Insulation for Austenitic Stainless Steel”** – This guide addresses the prevention of chloride stress-corrosion cracking in stainless steel piping due to insulation materials. It recommends using insulation with **very low leachable chloride, fluoride, and sulfur** content on austenitic stainless steel piping. Insulation must be **halogen-free or meet strict impurity limits**, verified by standardized

tests (ASTM C692/C871 and ASTM C795 are often cited for certifying insulation is safe for stainless steel). For example, fiberglass, calcium silicate, or mineral wool insulation must be manufactured with low chloride content (often <10 ppm leachable chloride) and sometimes treated to immobilize chlorides. The RG effectively constrains material selection for thermal insulation on primary loop pipes – **only insulation certified to have low corrosive ions and to cause no stress corrosion is acceptable**. In practice, procurement specs for insulation will require compliance with RG 1.36 (by meeting ASTM C795 or NRC-approved test criteria), and installers must ensure no chlorides (including from mastics or vapor barriers) contact stainless steel surfaces. This RG is integrated into design by specifying appropriate insulation products and into procurement by requiring vendor test reports and lot traceability for insulation materials.

- **RG 1.44, "Control of the Use of Sensitized Stainless Steel"** – This guide (related to General Design Criterion 14) ensures that austenitic stainless steels in wetted service are not susceptible to intergranular stress corrosion cracking. It recommends avoiding fabrication practices that sensitize stainless steel (e.g. keeping carbon content low, using solution annealed materials, or avoiding slow cooling in the 500–800 °C range). For primary loop piping (which is typically Type 304L or 316L stainless), RG 1.44 means **using low-carbon grades (L grades)** or stabilizing elements, and carefully controlling weld procedures and post-weld heat treatment so as not to sensitize the material. The constraints include limiting carbon to 0.03% and in some cases performing hardness or corrosion tests to ensure no sensitization. This is implemented in design/procurement by specifying material grades like SA-312 TP316L and by qualifying welding procedures (e.g. minimal heat input, proper filler metal) to meet the guide's criteria.
- **RG 1.84, "Design, Fabrication, and Materials Code Case Acceptability – ASME Section III"** – This guide provides NRC-approved lists of Section III Code Cases (alternative methods or new materials in the ASME Code). It is updated periodically (Rev. 40 was issued March 2024). For piping and valves, RG 1.84 would list acceptable Code Cases that, for example, allow the use of new high-strength alloys or alternative welding techniques. The constraint is that only code cases in RG 1.84 (or specifically approved by NRC) may be used; others require NRC review. Integration: during design, if a vendor wants to use a code case (say, for using Grade 91 steel or a special valve design method), they must check RG 1.84 to see if it's approved and follow any conditions stated.
- **RG 1.147, "Inservice Inspection Code Case Acceptability – Section XI"** and **RG 1.192, "Operations & Maintenance Code Case Acceptability"** – While these pertain to inspection and testing rather than initial design, they indirectly affect design by indicating what inspection regimes and valve testing practices are expected. For example, certain valves might need design features to accommodate in-service testing (IST) per the ASME OM Code (e.g. position indication for power-operated valves). 10 CFR 50.55a and RG 1.192 now require new reactors to comply with ASME OM Code for valve IST. Thus, a **control valve or isolation valve in the primary loop must be designed to allow**

periodic stroke testing and leakage testing as required by the OM Code (this might influence selection of valves with actuators capable of partial-stroke tests, etc.).

- **Other relevant NRC guides and standards:** NRC's Standard Review Plan (NUREG-0800) Section 3.9.3 and 3.12 provide review criteria for ASME Code Class 1, 2, 3 piping system design and supports. These ensure that Section III stress analysis and support design are properly done. **Regulatory Guide 1.29** classifies structures, systems, and components for seismic design – it requires that Class 1 piping and valves (Quality Group A) be **Seismic Category I**, meaning they must withstand safe-shutdown earthquake loads without loss of function. So seismic analysis per Section III NB-3200 and IEEE/ANS standards is mandatory for primary loop piping. **RG 1.100** addresses seismic and dynamic qualification of active mechanical equipment: safety-related valves with active functions (e.g. powered control or isolation valves) must be tested to demonstrate they can operate under seismic loading and vibrations. This often means large motor-operated valves in the primary loop are shake-table tested or experience-based qualified. Finally, **General Design Criteria (GDC) 1, 14, 30, 31** in 10 CFR Part 50 Appendix A set broad requirements: e.g. GDC 14 requires an extremely high quality for the reactor coolant pressure boundary to prevent leakage – compliance is achieved by using Section III code and rigorous QA as described above.

Summary: In the design of an SMR's primary loop piping, insulation, and valves, ASME Section III (with Class 1 for reactor coolant boundary) is the governing code, enforced by 10 CFR 50.55a. This ensures robust design margins, high-quality materials (typically stainless steel for corrosion resistance), and thorough inspection/testing. Other piping codes like B31.1/B31.3 are generally limited to non-safety support systems. NRC Regulatory Guides impose additional constraints, particularly on material choices (low-chloride insulation per RG 1.36, avoidance of sensitized stainless steel per RG 1.44, etc.) and on classification/seismic requirements (RG 1.26, RG 1.29). These codes and guides are integrated into the SMR project via specifications and procurement documents: for example, a valve procurement spec would state that the valve must be ASME Section III Class 1, Code Stamp N, meeting all NB requirements, and the insulation specification would require certification to ASTM C795 and NRC RG 1.36 for use on stainless steel. Throughout design reviews and regulatory audits, compliance with these standards must be demonstrated through analysis reports, material certifications, and quality program adherence.

---

2. Off-the-Shelf Components for ~270 °C, 3–15 MPa Service

For the primary loop of an SMR (PWR type) operating at approximately 270 °C and pressures ranging from 3 MPa up to 15 MPa, there are commercially available components from the high-pressure industrial and nuclear markets. Below is a curated list of suitable **piping**, **thermal insulation**, and **control valves**, including typical specifications, vendors, and cost estimates. (All cost figures are rough order-of-magnitude for budgetary purposes.)

2.1 High-Pressure Piping (20–30 inch NPS)

Large-diameter pipe in the 20–30 inch Nominal Pipe Size (NPS) range for 15 MPa pressure service is a specialized product, but standard options exist in both stainless steel and low-alloy steel. Table 1 summarizes some typical pipe choices:

Table 1 – Example Piping Specifications for 24–30″ Diameter, ~270 °C, up to ~15 MPa

Pipe Size & Schedule (est.)	Material (ASME /ASTM Spec)	Design Pressure (@270 °C)	Wall Thickness (mm)	Typical Vendor /Source	Est. Cost (USD per ft)
24″ NPS Sch 160 (heavy wall)en.wikipedia.org	SA-312 TP316L Stainless Steel (seamless) *(Austenitic SS, nuclear grade)*	~2200 psi (15.2 MPa)engineeringtoolbox.comen.wikipedia.org (meets Class 1500 flange rating)	59.5 mm (2.343″)en.wikipedia.org	Vallourec, PCC Energy, or Nippon Steel (large OD seamless)	~$400–600 per ft (bulk)
24″ NPS Sch 120 (medium wall)en.wikipedia.org	SA-335 P22 Low-Alloy Steel (2¼Cr-1Mo) *(for insulated carbon*	~2200 psi (15 MPa) (if design stress ~20 ksi at 270 °C)	46.0 mm (1.812″)en.wikipedia.org	Benteler Steel/Tube or US Steel (power plant piping)	~$300–500 per ft

Kadmos Energy Services LLC

	steel option)				
30″ NPS Sch 140 (est.*heavy*)	SA-312 TP304/ 304L Stainless Steel (welded) *(Stainless, Section III Class 1)*	~2000 psi (13.8 MPa) (with code stress ~18 ksi at 270 °C)	~50–55 mm (≈2″) *(approx. required)*	Special order via Japan Steel Works or Europipe (welded from plate)	~$800+ per ft (limited suppliers)
30″ NPS Sch 80 (standard wall)	SA-106 Grade C Carbon Steel *(for non-nuclear applications)*	**Note:** Not suitable for RCPB without cladding. Design P ≈ 5 MPa at 270 °C (limited by lower strength)	9.53 mm (0.375″)en.wikipedia.orgen.wikipedia.org	(Commodity pipe – e.g. Welspun, JSW for pipelines)	~$150–250 per ft

Notes: All designs assume code-compliant allowable stresses (Section III Class 1 for stainless, B31.1 values for ferritic steels). Wall thickness shown is nominal per ASME B36.10/B36.19 schedules. Costs vary widely with material and quantity; stainless steel and nuclear-grade certifications significantly increase cost.

Material Selection: Primary loop piping in modern reactors is almost always **austenitic stainless steel** for corrosion resistance and cleanliness (to avoid activation/corrosion of coolant). Indeed, advanced PWR designs use Type 304L, 304LN, 316L, or 316LN stainless for virtually all reactor coolant piping. These materials have excellent corrosion resistance in high-temperature borated water and good toughness. For example, **SA-312 TP316L** seamless or welded pipe is a common choice. Such stainless pipe in 24–30″ size often must be **welded or formed** from plate (since seamless production at that diameter and wall thickness is limited). Vendors for large-diameter stainless pipe include companies like **Nippon Steel & Sumitomo** (Japan), **Tenaris/PCC Energy**, or **Tubacex**; some heavy-section components may even be supplied as forgings by **Japan Steel Works (JSW)** or **BWX Technologies**. The cost of large stainless nuclear-grade pipe is high – on the order of $5,000–$8,000 per 20-ft length (hundreds of dollars per foot), given the material and NQA-1 quality program requirements.

For **low-alloy steel** alternatives, materials like **SA-335 P22 (2¼Cr-1Mo)** or **P91 (9Cr-1Mo-V)** are used in fossil power plants for high-pressure steam lines (because they offer higher strength at elevated temperature, thus thinner walls). At 270 °C, these alloys have allowable stresses in the 20–30 ksi range (higher than stainless steel's ~18–20 ksi), so a P22 or P91 pipe could handle 15 MPa with somewhat thinner wall. However, in a PWR primary loop, **ferritic steels would require an internal stainless cladding or heavy water chemistry control** to prevent corrosion and oxide release. Historically, some older plants used low-alloy steel reactor coolant piping with stainless cladding, but modern practice favors solid stainless. If an SMR designer chose low-alloy steel for cost or strength, they would need to follow ASME Section III rules for fracture toughness (nil-ductility transition temperature must be low) and ensure a qualified cladding process on the inside surface. Low-alloy steel pipe (e.g. 24″ P22) is commercially available (commonly for steam lines) from suppliers like **Vallourec** or **Baosteel**. It is cheaper per ton than stainless (perhaps half the material cost), but the need for cladding and stricter quality control may offset savings.

Pressure Ratings: A design pressure of 15 MPa at ~270 °C corresponds roughly to an ASME **Class 1500** piping system (since Class 1500 flanges are rated around 2175 psi at 500 °F for typical steel). In many cases, **Class 1500 or 2500 flanged joints** would be used for valves and fittings to match this pressure. For example, a 24″ Class 1500 flange (A105 carbon steel) can handle ~2200 psi at 500 °F. Stainless steel flanges of the same class have similar or slightly lower ratings (due to material strength differences at temperature). Thus, **20–30″ piping for 15 MPa service will use high-pressure flanges (Class 1500 or above)** or more likely will be welded with integral reinforcement and only terminate at specialized flanges or vessel nozzles.

Wall Thickness and Schedule: Table 1 shows that a 24″ Sch 160 pipe has ~59 mm wall, which by formula (Barlow's equation) can sustain on the order of 15 MPa with typical Section III safety margins. Indeed, one calculation indicates ~1.4–1.7″ (~35–43 mm) of wall would be needed for 24″ diameter at 2200 psi using stainless steel (allowable ~17–20 ksi) – Sch 140 (52 mm) or Sch 160 (60 mm) covers that with margin. For 30″ diameter, even thicker walls (~50–60 mm) are needed at 15 MPa, which often means **custom-fabricated pipe**. It is common in large reactor designs that the "pipe" is actually a **machined forging** or a built-up weldment, since standard pipe schedules do not exist beyond 24″ for very heavy walls. For instance, a 30″ RCP loop might be manufactured by forging a ring or joining steel segments and then boring out the inner diameter. These bespoke solutions come from heavy forge shops (JSW, **Creusot Forge**, etc.). They are expensive (on the order of $10k+ per meter), but sometimes necessary for the largest sizes.

Vendors and Costs: In the U.S., suppliers for nuclear-grade piping include **Energy Steel & Supply** (which sources Section III materials), **Penn Stainless** (for commercial stainless pipe), and international mills. Because SMRs might leverage off-the-shelf industrial pipe, one could also procure ASME B31.1 pipe from companies like **US Steel** or **Webco** and then up-rate it via analysis if it meets Section III requirements. Cost estimates: as noted, 24″×2″ wall stainless pipe might be about $500 per foot in raw material cost, whereas an equivalent carbon steel pipe might be $200–$300 per foot (not accounting for cladding or extra QA). The nuclear N-stamp paperwork and testing (e.g. full radiography, material certification to Section III) typically add 20–30% premium.

2.2 Thermal Insulation for 270 °C Piping

Thermal insulation on primary loop piping serves to **minimize heat loss, protect personnel, and manage containment heat loads**, but in a nuclear application it must also meet unique requirements: **radiation tolerance, fire safety, low chloride content, and resistance to becoming debris** (to avoid clogging emergency core cooling strainers in event of a LOCA). Below we compare common insulation options:

Table 2 – Insulation Materials for Nuclear Piping (~270 °C)

Insulation Type & Product	Form & Material	Suitable Temp. Range	Key Features (Nuclear Suitability)	Approx. Cost	Suppliers (examples)
Reflective Metal Insulation (RMI) (*e.g. Transco Products "MRI" Panels*)transcoproducts.comtranscoproducts.com	Rigid, pre-fabricated stainless steel modular panels enclosing layers of thin dimpled SS foils (air gaps)mattress-	Up to 600 °C + (metals)	**Zero fiber/particulate debris** (all-metal, solves GSI-191 LOCA debris issue)transcoproducts.com. Very durable and **radiation-proof** (no organic binders). Panels are custom-made to fit piping/elbows and are **removable** for inspectiontranscoproducts.com. Provides good insulation (high thermal resistance via reflective foil layers) while being thin profile. **High initial cost** and engineering	High – ~$400–$800 per m² (several hundred $ per foot of large pipe) due to stainless steel fabrication and custom design.	**Transco Products** (USA)transcoproducts.com; **Kaefer**/PCI; others (e.g. Adiabatix in EU). Widely used inside reactor containments.

Kadmos Energy Services LLC

	insulation.com.		required, but essentially no maintenance over decadestranscoproducts.comtranscoproducts.com.		
Calcium Silicate Pipe Insulation (*e.g. Johns Manville "Thermo-12 Gold"*)	Rigid pre-formed sections (calcium silicate hydrate with fibers) typically 2″ thick segments wired in place, with aluminum or SS jacketing.	Up to ~650 °C (1200 °F).	Traditional high-temperature pipe insulation. **Non-combustible, inorganic**. Can be made low-chloride: modern nuclear-grade cal-sil is tested to meet **ASTM C795** for use on stainless (low leachable chloride)owenscorning.com. Moderate thermal efficiency (k ≈ 0.06 W/m·K at ambient). It is **water absorbent**, so needs waterproof jacketing outdoors or in spray zones. In radiation areas, no significant degradation (it has no organic binder, though it is brittle). Pieces are removable but not as easily as modular panels. Produces **dust/debris** if broken, so inside containment its use is limited to areas where it can be encapsulated or where RMI is not feasible.	Low/Moderate – ~$30–$50 per 3-foot section for 24″ pipe (about $10–$15/ft²). Installation labor additional. Still, one of the **cheapest** per unit length.	**Johns Manville, Owens Corning (Fab Thermo-12)**; **IIG (Industrial Insulation Group)**. Often installed by mechanical insulation contractors on-site.
Mineral Wool Blankets/Boards (*Mineral Fiber, e.g. Isover "Tech Telisol 5.0"*)mattress-insulation.com	Flexible blankets or rigid boards of rock wool (basalt) or glass fiber, often supplied as	Up to ~600 °C (depending on binder; fiber itself is good	**Good thermal performance** (k ~0.045 W/m·K at 200 °C). Mineral wool is **non-combustible** and can be made with **virtually no organic binder** (special nuclear grades use stainless steel mesh stitching and binder-free fiber)mattress-insulation.com. Key for	Moderate – raw mineral wool batts ~$5–$15/ft²; custom-fabricated removable blankets range from ~$50 up to a few hundred dollars each	**Isover (Saint-Gobain)** supplies nuclear-grade woolmattress-insulation.com; **Rockwool, Thermafiber** (for industrial); fabrication into blankets

	removable blankets sewn in silicone /teflon-coated fiberglass cloth for valves & complex shapes mattress-insulation.com.	to 700 ° C).	nuclear use is low impurities: products like Tech Telisol have almost no corrosive ions (no boron or halogens added)mattress-insulation.com. Often used in **removable insulation blankets**, where the wool is completely enclosed in a tough fabric cover – this prevents any loose fibers from escaping even under accident jetsmattress-insulation.com. Such blankets are custom-fitted and secured with hooks/Velcro, allowing quick removal for maintenance (common on valves, flanges). Mineral wool blankets can tolerate radiation reasonably if binder-free (radiation may embrittle organic cloth covers over long term, so materials like silicone-coated fiberglass are chosen for covers). **Moderate cost** solution and very widely used outside primary containment or on secondary systems; inside containment, they must be carefully enclosed to prevent debris.	depending on size/complexitymattress-insulation.com. Still cheaper than all-metal RMI.	by specialists (e.g. **Madrass**, **Thermaxx**, **Shannon** Insulation). Many U.S. plants get blankets made to spec by contractors.
Aerogel Blanket Insulation (*e.g. Aspen Aerogels "Pyrogel HPS"*)	Flexible blanket composed of silica aerogel embedded in	Up to ~650 °C continuous (silica aerogel	**Ultra-high thermal performance** – extremely low thermal conductivity (k ~0.02–0.03 W/m·K) meaning thinner insulation can achieve the same heat retention. Hydrophobic (sheds	Moderate/High – approx. \$20–\$40 per ft² of blanket (material cost). For a 24″ pipe, ~\$100+ per	**Aspen Aerogels** (USA) makes Pyrogel and Cryogel. Distributors (e.g. **Thermal Cer**

Kadmos Energy Services LLC

	fiberglass mat. Thickness 5–10 mm layers, often layered to achieve needed performance.	stable; fiber char at higher temps).	water) and **compact**, saving space (beneficial in tight modular SMR configurations). It is available in rolls that wrap pipes, then typically covered with metal lagging. For nuclear use, an advantage is that it's **non-fibrous dust** (the aerogel particles are encapsulated, though some dust can release during install). Chloride content is low (silica-based). Drawbacks: it is relatively new in nuclear service – needs testing for radiation stability (organics are minimal, but hydrophobic treatment might degrade). Also, it is **expensive per area**, and the thin blanket requires careful installation to avoid gaps. If used, likely in secondary or outside-containment piping, or potentially inside containment if enclosed. It has been evaluated in some plants as part of ALARA (thin insulation to reduce surface area).	linear foot for a typical thickness (since multiple layers may be needed).	**amics, McAllister**) can provide kit forms. Not yet a "standard" nuclear product but gaining interest for compact insulation needs.
Cellular Glass (*FOAMGLAS® by Owens Corning*)	Rigid foam blocks or curved segments made of sealed glass cells. Installe	–268 °C to 482 °C (usable up to ~250 °C continuous	**Fully inorganic, contains zero chlorides**, and is waterproof/impervious. Commonly used in LNG and some hot piping. For nuclear, foam glass offers **no risk of chloride SCC** and does not absorb water, so it could be used on stainless lines especially where moisture is a concern. It also	Moderate – material ~$20/ft², but installed cost can double due to sealing work.	**Owens Corning FOAMGLAS®** is the main product. Used in industry for pipe racks and underground piping. Nuclear use has been niche (sometimes on

	d with joints sealed by adhesive, often with jacketing.	; above that, binders may fail).	provides some **radiation shielding** due to density (contains boron in glass, marginal benefit). However, it’s quite **heavy and brittle**; in high-vibration or seismic environments like a primary loop, it could crack unless well-supported. It also insulates less effectively than fiber (k ~0.05 W/m·K at ambient). Usually outside containment or for special applications (e.g. around penetrations or where water exposure is likely). Cost is moderate, but installation is labor-intensive (pieces must be sealed with bitumen or resin).		reactor vessel supports, etc.).

In a modern SMR containment, the **preferred insulation for primary loop piping is often RMI (Reflective Metal Insulation)** due to its safety advantages. RMI was widely adopted in operating plants to replace fibrous insulations that could become **LOCA debris**. For example, Transco Products’ metal reflective insulation features all-stainless construction with reflective foil layers, eliminating any latent fibers. It has been proven as a **“zero-debris” solution to GSI-191**, the NRC Generic Safety Issue regarding sump clogging. The panels are built to fit components like steam generator outlets, reactor vessel nozzles, and large diameter piping. They attach via banding or studs and can often be removed and reinstalled easily, facilitating inspection of welds or supports. SMR designs, which emphasize modular construction and maintainability, would likely use RMI on primary loop piping and equipment within containment. The **downside is cost** – RMI can cost several times more upfront than conventional insulation, and it requires precise measurements and engineering. However, considering life-cycle cost, plants find it worthwhile because it **does not need periodic replacement**, cannot soak up water, and will not contaminate containment even if subjected to a high-energy line break.

Outside of primary containment or in less critical areas, **removable blanket insulation** (mineral wool or fiberglass in encapsulated covers) is common. These provide flexibility for covering valve bodies, flanges, pump casings, etc., where custom-shaped metal insulation would be extremely complex. The example from Madrass (a supplier of nuclear insulation blankets) shows use of **Isover's Tech Telisol 5.0 mineral wool mats sewn with stainless steel wire**, which are almost free of organics and corrosive ions. They note that enclosing the fiber completely mitigates the risk of debris, as evidenced by past incidents where loose insulation caused blockage issues. The cost of such blankets can vary widely – a small valve blanket might be a few hundred dollars, whereas a large pump blanket can be a few thousand. Typically, nuclear plants budget tens of thousands of dollars for insulating one large component with removable blankets (still usually cheaper than RMI for that same component).

Installation and Maintenance: Regardless of type, insulation for 270 °C service must be installed with an appropriate **metal jacket or enclosure** to meet fire and physical protection requirements. Stainless steel or aluminum jacketing is used for conventional insulations to provide a cleanable, protective surface (and in some cases acts as a vapor barrier). For SMRs, the modular construction may allow insulation to be pre-installed on equipment skids. RMI panels, for example, might be pre-fabricated and shipped along with the piping modules to minimize field work. Maintenance-wise, RMI and cellular glass are essentially maintenance-free (no degradation over time). Calcium silicate and mineral wool can **settle or compress** slightly and may need periodic inspection; they can also **absorb moisture or borated water** if leaks occur, necessitating replacement to avoid corrosion under insulation. Removable blankets typically have to be removed for every maintenance access and then reinstalled, so their Velcro/buckle fasteners should be inspected for wear; over many cycles, the fabric can tear or fasteners corrode (requiring refurbishment of the blanket).

In summary, **recommended insulation for the SMR primary loop**: **RMI panels for the main piping runs and vessel nozzles**, to guarantee no latent debris and excellent longevity; complemented by **encapsulated mineral wool blankets on valves and irregular components** for ease of maintenance. All insulation in contact with stainless steel must be **certified per ASTM C795 and RG 1.36** to have low chloride (to preclude stress corrosion cracking). The combination of these approaches addresses both the thermal performance and the strict nuclear safety criteria for insulation materials.

2.3 Control Valves and Isolation Valves (High Pressure, 20–30″ Size)

The primary loop of an SMR may include several types of large valves – for example, **reactor coolant isolation valves**, pressurizer spray or surge line valves, and perhaps **flow control valves** in auxiliary lines or an intermediate heat exchanger loop (depending on design). We focus on valves that can handle the full primary loop conditions (~270 °C, up to 15 MPa) and match the ~20–30″ main pipe size. Such valves are available as standard designs from industrial and nuclear valve manufacturers. Table 3 provides examples of suitable valve types and models:

Table 3 – Example Valves for 24–30″, 15 MPa, 270 °C Service

Valve Type & Example Model	Size & Pressure Class	Materials (Body/Trim)	Actuation Method	Standards & Ratings	Supplier / Notes	Est. Unit Cost (USD)
Gate Valve, Wedge Type *e.g. Velan Bypass Gate Valve*velan.comvelan.com	30″ NPS, ASME Class 1500 (or 2500)	Body: ASTM A216 WCB (Carbon Steel) or A351 CF8M (Stainless) Trim: 13Cr or Stellite hard-faced	Motor-operated (electric actuator) or Gear/Hand wheel (for slow operation)	ASME B16.34 (valve design standard) Section III Class 1 qualified (N-stamp)	**Velan Inc.** – offers forged or cast gate valves up to NPS 96 for nuclear servicevelan.com. Typically used for isolation (full-port). Pressure-seal bonnet common for high class. In SMR, a pair of such valves could isolate the reactor loop.	~$80k – $150k (with motor actuator)
Globe Valve, Y-Pattern (Control) *e.g. CCI DRAG® Valve or Fisher HP Series*	12″ NPS (typical max size for throttling control at high ΔP) Class 1500	Body: ASTM A182 F22 or F91 (forged alloy steel) or A351 CF8/CF8M Trim: Multi-stage plug/seat (Stellite, Inconel overlays)	Pneumatic diaphragm actuator or Electro-hydraulic actuator (for throttling)	ASME B16.34; API 623 (globe valves) Section III Class 1 (if safety-related)	**IMI CCI** – DRAG® high-pressure letdown valves (multi-stage cage) for precise flow control at high pressure drop. **Emerson/Fisher** – HP and EH series control valves for feedwater, etc., up to ~12–16″. Larger sizes often custom-engineered in	~$50k – $100k (with actuator and positioner)

					parallel arrangements. These valves handle ~15 MPa inlet and throttling duty with anti-cavitation trim.	
Ball Valve, Trunnion Mounted *e.g. ValvTechnologies HP Ball or KTM*	24″ NPS, Class 1500 (full bore ~21″ ID)	Body: ASTM A105/ A350 (Carbon Steel) or A182 F316/F51 (Stainless/Duplex) Ball: Inconel or 17-4PH with Tungsten Carbide coating (for hardness)	Hydraulic piston actuator or Electric motor with gearbox (for fast isolation)	API 6D (pipeline ball valves) ASME B16.34 design & B16.5 flange dims	**Relia** (China) – example 24″ Class 1500 ball valve ~$30k. **ValvTechnologies** – specialized metal-seated ball valves for severe service (class 1500–2500, zero-leak). **Mogas** – known for high-pressure severe-service balls (to 24″). Ball valves provide quick quarter-turn isolation and can double as emergency shut-off valves. Metal seats handle temperature and radiation.	~$30k – $60k (large bore, metal-seated, actuator extra)
Butterfly Valve, Triple-Offset	30″ NPS, Class 1500	Body: AISI 410 stainless or	Electric actuator or	API 609 Category B (triple	**Velan** – offers TORQSEAL	~$20k – $50k (significa

e.g. Adams or Velan TOV	(wafer or flanged)	ASTM A995 Gr CD4 (duplex stainless) Disc: Triple-offset laminated seal (Inconel graphite)	Hydraulic (fast close)	offset) ASME Section I II Class 2/3 use (commonly)	® triple-offset valves up to large sizes. These are torque-seated, suitable for tight shutoff at high DP, and much lighter than gate valves. Often used in feedwater and main steam isolation (class 2 or 3) but could be adapted for primary isolation if design allows. Advantages: compact, relatively lower cost; Disadvantage: not typically used for reactor coolant boundary in current designs due to less historical data.	ntly lower weight and cost, actuator cost adds)

Valve Design Considerations:

- **Pressure Class and Ratings:** As mentioned, Class 1500 valves are generally required to cover 15 MPa at operating temperature. All the examples above are available in Class 1500, and many in Class 2500 as well (for additional margin). For instance, Velan's catalog includes gate, globe, check, and ball valves up to Class 2500 and sizes

60″ or larger for specialized needs.The valve bodies must be forged or cast to withstand the hoop and bending stresses at these pressures – typically they are **thick-walled** and use pressure-seal bonnets or robust bolted bonnets.

- **Materials:** For reactor coolant service, **stainless steels or high-grade alloys are preferred** to avoid corrosion. Many nuclear valves use **ASTM A351 Grade CF8M** (cast 316 stainless) or **A182 Grade F316/F304** (forged stainless) for bodies, especially for any part in contact with primary water. However, large valves can also be supplied in **low-alloy steel (e.g. A216 WCB or A217 WC9)** with internal stainless cladding, similar to piping practice. In the table, we listed WCB (carbon steel) as an example for a gate valve body – this would be common for a balance-of-plant valve, but for a primary loop isolation, one might use CF8M or a forged equivalent for better corrosion resistance. Trim materials (seats, discs, stems) need to handle high temperatures and water chemistry: hardfacing with Stellite (cobalt alloy) is often used on seats for wear resistance, though in reactor coolant some designs avoid cobalt to reduce radiation hot spots (cobalt-59 can activate to Co-60). Alternatives like nickel-free hardfacings or cobalt-free valves have been developed for modern reactors.
- **Actuation:** Large valves 20″ and above are typically **motor-operated or hydraulic**. Traditional motor-operated valves (MOVs) use an electric actuator (e.g. Limitorque, Auma) with a gearbox to open/close the valve in tens of seconds. This is acceptable for normal isolation or throttling. However, if **fast closure** is required (for example, a reactor coolant isolation valve that needs to shut within <1 second to limit leak size), a hydraulic or pneumatic actuator is used. For instance, main steam isolation valves in BWRs (around 30″) use hydraulic actuators to slam shut quickly. An SMR primary loop might or might not include quick isolation – if it does, a **hydraulically actuated ball or butterfly valve** could meet the need (quarter-turn valves lend themselves to fast operation). Control valves (as opposed to on-off isolation) often use **pneumatic diaphragm or piston actuators** because of their fine throttling control and fail-safe characteristics (air fail can stroke valve to a safe position). For example, a Fisher HP globe valve at 12″ size would use a large spring-diaphragm actuator or a piston with positioner to modulate flow. It is important that any active valve in the primary loop be **qualified for its environment**: the actuator and internals must handle radiation, high ambient temperature, and seismic loads. NRC requires environmental qualification (EQ) for safety-related valve actuators – electric actuators inside containment must be tested for high temperature and radiation exposure over time.
- **Type Selection: Gate valves** are common for isolation – they provide full bore flow and low pressure drop when open, and they are proven in reactor service (used on primary loops, pressurizer isolation, etc., in many PWRs). A wedge gate or parallel slide gate can provide tight shutoff under high differential pressure. They do tend to be large and heavy (especially Class 1500+ gate valves have massive bodies and yokes). **Globe valves** are used for throttling control, but a 24″ globe valve is extremely large to use as a control valve – usually, for that size and pressure, multiple smaller control valves in parallel are

used, or an alternate type (like a control butterfly with characterization or a multi-stage valve) is chosen. Some SMR designs might not require any continuously throttling valve of that size in the primary circuit (reactor power is often controlled by reactor internals or coolant pumps rather than a throttling valve in the loop). However, smaller globes (4–12″) might be used on pressure control lines (e.g. spray valves, makeup lines) – those can be off-the-shelf from Fisher, CCI, etc. **Ball valves** in trunnion-mounted configuration are increasingly popular for high-pressure isolation because they combine tight shutoff with quick operation. Metal-seated ball valves can handle high temperature and even slurries. Companies like **ValvTechnologies** (USA) market nuclear-grade ball valves (with hard coatings, zero leakage guarantee) for applications like feedwater isolation, extraction steam, etc., and could adapt them to primary coolant service. A 24″ Class 1500 ball valve will have a thick body and a supported ball to handle the force; the example from Relia (a general industrial supplier) shows a price range \$6.9k–\$32k for 24″ ball valves depending on classreliavalves.com – likely the higher end (near \$30k) is for Class 1500 with special materials. **Triple-offset butterfly valves** are another high-performance type: they are much lighter and can handle high pressure when designed properly. Velan's Torqseal triple-offset valves, for instance, are offered in large sizes and high classes for steam and feedwater systemsvelan.com. These have an offset disc that cams into the seat, achieving tight shutoff (often meeting zero-leakage criteria per API 598 for high performance butterfly). In a nuclear primary loop, a triple-offset butterfly could theoretically serve as an isolation valve on large diameter piping with some benefits: lower weight (important for seismic), lower cost, and simpler actuation (quarter-turn). The AP1000 design actually uses squib-actuated double disc gate valves for main loop isolation – future SMRs might explore triple-offset as an alternative given their success in other industries.

Standards: All valves listed conform to **ASME B16.34**, the primary valve design standard which dictates wall thickness, pressure-temperature ratings, materials, and testing for industrial valves. A Class 1500 valve per B16.34 will inherently meet the pressure requirements (if made from appropriate material). Additionally, there are API standards specific to valve types (e.g. API 600 for gate valves, API 6D for ball valves, API 609 for butterfly) which manufacturers follow for general design and dimensions. Nuclear-specific valves (safety-related) would also need to meet **ASME Section III NB or NC** requirements – in practice, that means they must be designed, fabricated, and inspected to Section III, and an "N" certificate of authorization is required. Many valve manufacturers have an **N-Stamp** program (Velan has held N-stamps since 1970, Flowserve/Edward, Crane, etc., as well). This includes extra requirements like 100% volumetric exam of castings or forgings, additional certified material reports, and typically a tougher seismic qualification regime.

Vendors: Key vendors serving the nuclear valve market include **Velan** (Canada/USA), **Flowserve (Edward Valves)**, **Crane Nuclear (incl. Aloyco, Pacific brands)**, **IMI CCI** (for control valves), **Emerson/Fisher** (control valves, mostly non-safety but some can be

Section III), **Mogas** and **ValvTechnologies** (specialty ball valves), **KSB** (Germany, makes isolation and ERV valves), and **CWNuClear/Target Rock** (for some special valves like pressurizer spray). For SMRs, manufacturers may leverage standard product lines: e.g. a 14″ pressurizer spray valve could be a Fisher EH series globe (with Section III pedigree), or a 24″ reactor loop isolation could be a modified Velan gate or a commercial ball valve adapted to nuclear QA. The **Velan nuclear valve catalog** highlights they can do custom large valves (e.g. a 30″ Class 1500 stainless gate valve with bypass lines, as pictured in their literature). This indicates that while off-the-shelf designs exist, they are often tailored case-by-case for nuclear projects, especially at the upper end of size and pressure.

Estimated Costs: Large high-pressure valves are expensive. A **24″ Class 1500 motor-operated gate valve** for nuclear use can cost on the order of $100,000 (including actuator). The cost drivers are the massive forging or casting required, precise machining, NDE (ultrasonic, radiography of body), actuator and gear, and documentation. The table's estimates reflect that magnitude. For example, a **24″ Class 150 ball valve** (much lower pressure) might be $10k, but at Class 1500 with special seats and Section III QA, $50k+ is more realistic. The **actuator** itself for a 30″ MOV (electric motor operator) can cost $20k or more, and a hydraulic control skid similarly adds cost. In contrast, a simpler 30″ butterfly valve might be half or two-thirds the cost of an equivalent gate, owing to less material and simpler construction, but still tens of thousands of dollars. The Relia Valve listing suggests a **24″ ball valve ranges $6,900–$32,000** across Class 150 to 1500, aligning with our range.

Integration into the SMR design: When specifying these valves, engineers will define requirements for **leakage performance** (typically zero allowable leakage for isolation valves, per ANSI/FCI 70-2 or MSS SP-61 test standards – metal-seated valves often achieve Class V or VI shutoff by testing). They also include **operability criteria**: e.g. the valve must shut against full ΔP of 15 MPa within X seconds; the actuator must be capable of multiple operations under loss-of-power (for safety valves, perhaps stored energy actuators or manual override). **Inservice testing (IST)** needs are considered: valves will have to be stroked and leak-tested periodically per ASME OM Code, so the design should permit that (stroke times, position indication, accessible test connections for seat leakage). Vendors in the nuclear sector supply valves with **documentation for design qualification**, including seismic analysis reports or shake test results (per RG 1.100), environmental qualification reports (for actuators per IEEE-323 and IEEE-344), and code compliance certificates.

In conclusion, the **primary loop valves** can largely be selected from proven designs in the high-pressure industrial market, with adaptations for nuclear service. A likely scenario for an SMR primary loop (PWR) might be: **no large continuously throttling valve in the main circuit** (control is via reactor internals or pump speed), but **one or two large isolation valves at the vessel outlet/inlet** for maintenance or accident isolation. Those could be 24″ Class 2500 gate valves by Velan or Crane, motor-operated. Additionally, smaller high-pressure control valves (4–

8″) would handle pressurizer spray, makeup letdown, etc., drawn from standard lines (Fisher™, CCI). For any intermediate heat exchanger loops (in designs like NuScale, which has an integral vessel so no large external loops, this is moot; but other SMRs with primary loop piping could have an isolation between reactor and steam generator), similar large valves would apply. The components listed, from piping to insulation to valves, demonstrate that **off-the-shelf solutions exist** to meet ~270 °C and ~15 MPa – leveraging the knowledge from both nuclear power (ASME Section III) and high-pressure industries (petrochemical, thermal power). By selecting standard sizes and classes (24″, Class 1500, etc.), the SMR can utilize an existing supply chain, while applying the necessary nuclear quality and regulatory requirements to those components.

Sources:

1. Piping classification and ASME Section III scopepipingguide.netpipingguide.net; NRC Quality Group classificationspipingguide.net.
2. NRC 10 CFR 50.55a and use of ASME Section IIIpipingguide.net; NRC Regulatory Guides on code casespipingguide.net.
3. Primary loop materials (300-series stainless steels) in advanced PWRspnnl.gov.
4. ASME B36.10 pipe schedules for large sizes (e.g. 24″ Sch 160 = 59.5 mm wall)en.wikipedia.org.
5. NRC Regulatory Guide 1.36 requirements – insulation must be low in chlorides, fluorides, etc.mattress-insulation.com.
6. Madrass insulation blog – use of mineral wool with no organic content, enclosed to prevent debrismattress-insulation.commattress-insulation.com, and past incidents of fibrous debris prompting fully enclosed designsmattress-insulation.com.
7. Description of Reflective Metal Insulation (Transco) – all stainless, zero fiber, long-term solution for GSI-191transcoproducts.com and features (removable panels, custom fit)transcoproducts.com.
8. Relia Valve spec – 24″ ball valve, Class 150–1500, priced $6.9k–$32kreliavalves.com.
9. Velan nuclear valves brochure – sizes up to NPS 96 and Class 4500, with example of 30″ stainless gate valve assemblyvelan.comvelan.com.
10. Engineering discussion of flange ratings – Class 1500 corresponds to ~1500 psi at 600 °F for steelreliavalves.com (supports selection of Class 1500 for ~15 MPa at 270 °C).