ChatGPT

Comparison of SMR Options for Heber Campus Phase 2 & 3

Introduction & Scope

The Heber Campus Mega Project is exploring **Small Modular Reactor (SMR)** architectures for Phase 2 (≈1.0 GW) and Phase 3 (≈1.5 GW) carbon-free generation. Five leading SMR designs have been identified for evaluation:

- **NuScale VOYGR** – a multi-module light-water reactor (LWR) plant (U.S.)
- **GE-Hitachi BWRX-300** – a single-unit 300 MWe boiling water SMR (U.S./Japan)
- **Holtec SMR-160** – an integral pressurized water reactor (PWR) SMR (U.S.)
- **X-Energy Xe-100** – a high-temperature gas-cooled pebble-bed reactor (U.S.)
- **Oklo Aurora** – a very small fast-spectrum microreactor (U.S.) – included for completeness but of limited relevance given its scale

Each design is compared against key criteria: **(1)** thermal output and process heat suitability, **(2)** NRC licensing status, **(3)** physical footprint and siting, **(4)** operating temperature, turbine and efficiency, **(5)** CAPEX/OPEX per MW and supply chain maturity, **(6)** waste heat use for district heating, **(7)** cooling requirements, and **(8)** safety (fire risk, radiological containment, Emergency Planning Zone). The table below summarizes core attributes:

SMR Design Comparison Table

SMR Design	Type & Coolant	**Module Output** (MWe / MWth)	Core Outlet Temp	**Efficiency** (thermal→electric)	High-Grade Heat for H_2/ NH_3?
NuScale VOYGR	LWR (Integral PWR, light water)	77 MWe (≈250 MWth) per module [1] *(up to 12 modules = ~924 MWe)*	~300 °C primary coolant	~30–34% (Rankine steam cycle)	Limited by LWR temps; developing steam reheating to 500–650 °C [2] for industrial processes

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GEH BWRX-300	Boiling Water Reactor (LWR)	300 MWe (870 MWth) single unit	~285 °C (saturated steam)	~34% (direct cycle)	Moderate – can provide ~285 °C steam; usable for low-pressure steam needs, but not high-temperature SOEC without boosting
Holtec SMR-160	Integral PWR (light water)	160 MWe (~525 MWth) per unit [3]	~300 °C primary coolant	~30% (Rankine cycle)	Limited – provides standard PWR steam (~300 °C); can cogenerate medium-pressure steam for industry [4] but not high-grade heat without auxiliary heating

SMR Design	Type & Coolant	**Module Output** (MWe / MWth)	**Core Outlet Temp**	**Efficiency** (thermal→electric)	**High-Grade Heat for H_2/ NH_3?**
X-energy Xe-100	High-Temp Gas Reactor (HTGR, He)	80 MWe (200 MWth) per reactor [5] *(4 pack = 320 MWe, scalable)*	750 °C helium coolant [6]	~40% (565 °C steam Rankine) [5]	**Yes** – outlet ~750 °C enables high-grade steam (565 °C, 16.5 MPa) [5] ideal for SOEC hydrogen and NH_3 processes; designed for process heat cogeneration [6]
Oklo Aurora	Fast microreactor (liquid metal/heat pipes)	~1.5 MWe (≈4 MWth) microreactor [7]	~<500 °C (est.) Na-cooled	~30–40% (Stirling or sCO_2 cycle)	**Yes (micro)** – high outlet temp (~500 °C), but power scale is tiny; not practical for large industrial heat demand

Table 1: Reactor type, output, operating temperature, efficiency, and capability to supply high-temperature heat for H_2/NH_3 production. High-temperature designs (Xe-100, Oklo) clearly outperform water-cooled SMRs in delivering **process heat** for solid-oxide electrolysis (**SOEC**) and ammonia synthesis needs, whereas LWR-based SMRs may require supplemental heating or novel steam reheat systems [2].

Below, each SMR is examined in detail, followed by **pros/cons** and a **recommendation**.

NuScale VOYGR (77 MWe Modules, PWR)

Design & Thermal Output: NuScale's VOYGR is a multi-module plant based on proven PWR technology [8]. Each factory-fabricated module produces ~77 MWe (≈250 MWth) using a standard LWR steam cycle [1]. Primary outlet temperatures (~300 °C) limit direct process heat use, but NuScale has demonstrated a concept to **boost steam temperatures** to ~500 °C (with potential up to 650 °C) by secondary compression/ reheating [2]. This could enable supplying high-grade steam for hydrogen or other chemical processes, albeit with added complexity. Otherwise, NuScale can provide **moderate-pressure steam** suitable for less heat-intensive processes or for **district heating** distribution [8] .

Licensing & Deployment: NuScale is the **first (and only) SMR design certified by the U.S. NRC** (initial 50 MWe version) [8] . Design approval for the uprated 77 MWe module is on track for 2025 [1] . Its U.S. demonstration project (UAMPS Carbon-Free Power Project at INL) has faced delays but aims for initial operation ~2029 [9] . Internationally, NuScale VOYGR-6 plants (6×77 MWe = 462 MWe) are planned in Romania and Poland by the early 2030s [10] , indicating strong deployment support. NuScale's design maturity and licensing lead provide **high readiness for U.S. deployment**.

Footprint & Integration: A full VOYGR plant (up to 12 modules) is compact relative to output, with all reactors in a common below-grade pool (enhancing security and seismic safety). The **nuclear island footprint** is relatively small – comparable to a single large reactor unit [11] – though multiple small turbines and support systems are needed (each module drives its own steam turbine). The multi-module configuration offers flexibility: for example, one or more modules can be dedicated to non-electric uses (process steam, **hydrogen production, desalination, etc.**) while others generate power [12] . This modularity eases integration with the campus: reactors can be added incrementally to reach 1.0–1.5 GW, and modules can be taken offline individually for refueling without shutting down the whole plant.

Operating Temp & Efficiency: NuScale uses a conventional PWR Rankine cycle (~300 °C steam), yielding thermal-electric efficiency in the low-30% range (typical of LWRs). Smaller module turbines may have slightly lower efficiency than large plants, but NuScale's design includes a 100% steam bypass for agile load-following [13] . The relatively lower steam temperature makes **direct high-temperature electrolysis less efficient** unless the above-mentioned steam superheating system is implemented [2] .

CAPEX/OPEX & Supply Chain: NuScale projects **cost advantages from factory fabrication**, but recent estimates have risen. The first U.S. plant's LCOE is projected around $89/MWh (roughly $8,000–$9,000/kW) – higher than initially hoped – due to FOAK costs. NuScale expects costs to drop for Nth-of-a-kind. Its supply chain leverages established PWR component vendors: for example, reactor vessels are being forged by Doosan in S. Korea, and many **standard PWR components** (steam generators, control systems) are used, easing procurement. Fuel is standard low-enriched uranium (<5% U_{50}) available from existing suppliers. **Operationally**, staffing can be leaner per MW by one control room overseeing up to 12 modules. Refueling is staggered (each module ~24-month cycle) to maintain continuous output. The NRC has approved a methodology for **site-boundary Emergency Planning Zone (EPZ)** sizing for VOYGR plants [14] , reflecting the design's robust safety and small source term per module – a major plus for campus siting.

Waste Heat & Cooling: Each NuScale module rejects ~170 MW of heat. The plant can use conventional wet cooling (cooling towers or ponds) and potentially air cooling if water is scarce (with some efficiency penalty). Waste heat (e.g. condenser hot water ~60–80 °C) can be captured for **district heating** of campus buildings at night, or low-grade process heat. Because NuScale's secondary loop is clean (no radioactive contamination), it can directly feed a heat exchanger for a campus heating network. Multi-module plants could allocate a **dedicated module in low-power mode to supply heat** during low electric demand periods, offering flexibility in matching campus thermal loads.

Safety, EPZ & Hazards: The VOYGR design incorporates **fully passive safety**: decay heat is removed via natural circulation to the water pool for indefinite cooling without power or operator action [15] [14] . There are no coolant pumps (primary circulation is by convection), greatly reducing failure scenarios [16] . The reactors are housed below grade, providing inherent physical security and radiation shielding. NuScale's small core and fast automatic shutdown systems mean any accident would release far less radioactivity than a large plant. The NRC agreed that a NuScale plant can have its **EPZ limited to the site boundary** while meeting safety goals [14]. This is critical for an on-campus reactor – it means normal campus areas could lie outside the evacuation zone. The design uses only water as coolant and moderator (no flammable materials); hence **fire risk is minimal** (no sodium or graphite hazards). Overall, NuScale offers **unmatched safety pedigree among LWR-based SMRs**, albeit with lower temperature output.

NuScale VOYGR – Pros:

- **NRC-certified and near-term deployable** (first SMR design approved in U.S.) [8] – lowest licensing risk.
- **Modular scalability:** can install incrementally to reach 1–1.5 GW; staggered deployment and refueling minimize downtime [12].
- **Proven LWR technology:** familiar fuel, materials, and supply chain; uses standard 4.95% enriched fuel and many off-the-shelf components [17].
- **Excellent safety profile:** passive cooling, underground containment, and *site-boundary EPZ* approved [14] – ideal for siting near campus/community.
- **Flexible cogeneration:** modules can be dedicated to **district heating, desalination or H_2 production** as needed [8] [12].
- **Operational flexibility:** 100% steam bypass for load following [13]; multi-module layout supports load adjustment by dispatching modules.

NuScale VOYGR – Cons:

- **Lower outlet temperature:** ~300 °C steam is insufficient for high-temperature processes without additional heating [2], reducing efficiency for SOEC hydrogen production.
- **Cost uncertainty:** FOAK costs are relatively high (UAMPS project ~$5,000–$9,000/kW) and schedule delays have occurred, risking economic competitiveness.
- **Small turbines per module:** Multiple small turbine-generator sets may reduce economies of scale and efficiency slightly (vs. one large turbine) [18].
- **Medium unit size:** ~77 MWe modules mean ~13–20 units needed for 1–1.5 GW – a large number of modules and systems to manage (though design supports this).
- **Reliance on new manufacturer learning curve:** As the first SMR through NRC, any design changes (e.g. uprating to 77 MWe) require additional review [1]; supply chain must ramp up to produce many modules.

GE Hitachi BWRX-300 (300 MWe Single Unit BWR)

Design & Thermal Output: The BWRX-300 is a **300 MWe (870 MWth)** boiling water reactor, derived from Gen III+ Boiling Water Reactor technology. It uses a **direct steam cycle**: water boils in the core and drives the turbine directly. Core outlet (saturated steam) is ~285 °C at pressure, so the thermal-electric efficiency is ~34%. There is no separate steam generator – this simplifies the design but means the **turbine and steam piping handle radioactive steam**. High-grade process heat capability is limited by the saturation temperature (~285 °C); BWRX can support medium-pressure steam needs or district heating, but not **700 °C** steam without external heaters. GE Hitachi does note the BWRX-300's suitability for hydrogen production and district heating in principle [19], implying it can power electrolyzers and provide low-grade heat via secondary loops. However, any direct use of reactor steam for industrial processes would require an intermediary heat exchanger to keep the primary coolant separate.

Licensing & Deployment: The BWRX-300 is **advancing rapidly** as a leading SMR. While not yet NRC-certified, it leverages the already-certified ESBWR design (simplified and smaller). **Canada's regulator** has approved construction at Ontario's Darlington site – the first unit is slated to be operational ~2028 [20]. The U.S. TVA has submitted the first construction permit application for a BWRX-300 at Clinch River, targeting operation in the early 2030s [21]. Poland has committed to up to **24 BWRX-300 units at 6 sites (7.2 GWe)** in the 2030s [22]. GEH is also in vendor review with the UK and other countries. This strong global interest and deployment pipeline mean **BWRX-300 should be licensed and buildable in the U.S. by the early 2030s**, aligning with Phase 2 needs. Notably, GEH claims the design can be **deployed as early as 2029** globally [23].

Physical Footprint & Complexity: The BWRX-300 plant is designed for **compact siting**. The entire station (reactor building, turbine hall, cooling, switchyard, etc.) fits in roughly **170 m × 280 m** area [24]. This is only ~4.8 ha for a 300 MWe unit – much smaller than current large reactor plants. A campus could host multiple BWRX units: e.g. four units (~1.2 GWe) might fit in a footprint on the order of 20 ha, possibly sharing some balance-of-plant systems. GEH has aggressively **simplified the BOP and containment**: the reactor building volume is ~50% smaller per MW than previous BWRs [25], and **90% less concrete** is used vs. large reactors [25]. This not only reduces cost but also means a lighter infrastructure impact on site (less excavation, etc.). Installation is also relatively straightforward: the BWRX-300 uses **natural circulation** cooling in the core (no recirculation pumps) and passive safety systems, eliminating some major components [26]. The standard design is a single **steel containment/vessel** for the reactor, with an integral isolation condenser system for decay heat removal. Construction time is estimated ~26 months for the first unit (with potential reduction for subsequent units) [27].

Operating Characteristics: As a BWR, the BWRX-300 runs a **direct cycle turbine**, which is efficient at this scale and uses **proven GE turbine-generator technology** (GE Vernova's standard nuclear turbines and TOPAIR generators) [28]. It can **load-follow**: design specs allow 50–100% power daily maneuvering at 0.5% per minute [29], useful for grid flexibility. The fuel is standard low-enriched UO_2 (~3.4% average enrichment) with a 12–24 month refueling cycle [30], very much in line with existing LWR operations. This **uses off-the-shelf fuel supply** (no HALEU needed) and familiar refueling procedures. One consideration: because the primary and turbine cycle are the same, any **steam used for heating** must go through a heat exchanger off the turbine or by extracting **feedwater** heat. For example, a tapped-off feedwater line or condenser loop could provide ~100 °C water for a district heating network while the plant generates power. Several European countries have done this with larger BWRs. It is feasible but requires careful design to avoid spreading any activation products – typically a secondary circuit for district heat is used.

Economics & Supply Chain: GE Hitachi touts BWRX-300's **economic advantage**, claiming it can be up to *60% cheaper per MW* than other SMRs or large reactors [31]. FOAK capital cost is estimated ~€1 billion for the first unit (≈$3.6k/kW) [32], dropping further for nth-of-a-kind [33]. Its design deliberately **reuses existing BWR supply chain components** – e.g. fuel assemblies are essentially identical to those in operating BWRs [34]. Many **suppliers worldwide already produce** BWR parts (control rod drives, moisture separators, etc.), and GEH notes a strong supply chain across the USA, Canada, Japan, Europe, etc. for this design [17]. The turbine generator is standard GE equipment with hundreds of units delivered globally [28], reducing technical risk. This maturity extends to operations: numerous utilities have BWR expertise (in the US, Europe, Japan), and regulators are familiar with BWR safety behavior [35]. OPEX should be competitive – GEH is targeting **50–60 €/MWh generation cost** once matured [33]. Staffing needs may be somewhat less than a large plant, but a BWR still requires skilled operators, especially with on-site spent fuel pool management and turbine maintenance (which must consider potential activation in the steam system). Fuel costs are standard LWR fuel. Overall, BWRX-300 likely offers the **lowest cost per MW and most mature supply chain** of the options, especially by mid-2030s after the first few are built [31] [17].

Waste Heat & District Heating: The BWRX-300's waste heat can be harnessed, but with an extra step. Since the primary loop is radioactive, a *primary-to-secondary heat exchanger* would be installed (likely at the condenser or feedwater stage) to transfer heat to a clean water loop for campus heating. Given the large thermal output (~570 MW of waste heat at full power), even a small fraction of that could heat a significant campus or feed an absorption chiller system at night. During low electrical demand, the reactor could also run at a lower power setpoint to cogenerate more low-grade steam for heating. Many northern European BWRs have provided district heating, showing the concept is viable. Blowdown and cooling water considerations: the BWRX-300 can use **wet cooling towers** or once-through cooling. It does not inherently support dry cooling as part of the base design, though it might be possible to adapt (with efficiency loss). Blowdown from cooling towers would contain no radionuclides (closed loop isolated from primary), so environmental risk is just conventional (mineral concentration management). Overall, BWRX is capable of **co-generation and campus heat support**, but integration must be engineered due to the direct cycle.

Cooling Requirements: The reactor's isolation condensers are submerged in a gravity-driven water pool inside containment for emergency cooling. For normal operation, a condenser/cooling tower is needed for the turbine exhaust. **Water usage** is similar to a conventional 300 MWe power plant – moderate. GEH has not emphasized air-cooled options, focusing on water cooling for maximum efficiency. However, the relatively small unit size could potentially use *smaller dry cooling systems* if needed (at some performance cost). The **thermal discharge** (if once-through cooling) or drift from towers must be managed but is routine power plant practice.

Safety, EPZ & Hazards: The BWRX-300 is designed with **enhanced passive safety**. It uses **gravity-driven cooling and isolation condensers** to remove decay heat, so it can handle station blackout or loss of coolant without active pumps. The smaller core (300 MWe vs 1,000+ MWe in traditional reactors) means a smaller fission product inventory, reducing worst-case release quantities. GE Hitachi expects the **Emergency Planning Zone can be much smaller** than the traditional 10 mile radius – potentially on the order of the site boundary or a few hundred meters [24]. In fact, the **estimated EPZ is ~8 hectares** (0.08 km^2) for a BWRX-300, per Fermi Energia's analysis for Estonia [24]. This suggests that with regulatory approval, the evacuation zone might only cover the immediate plant area – a crucial factor for co-location with a campus. (NRC has not officially approved a site-boundary EPZ for BWRX yet, but joint CNSC/NRC reviews are considering it.) In terms of **fire and radiological hazards**: as a water-cooled reactor, there is *no combustible coolant*. The main hazard in a severe accident is hydrogen generation from zirconium-steam reaction; the containment is equipped with igniters or passive autocatalytic recombiners to manage hydrogen. The BWRX containment is a robust structure (GEH notes it ended up similar in size to ESBWR's during detailed design [36]). The plant's **radiological envelope** is tight – normal operation will see minimal radiation at site boundary, easily below regulatory limits. One operational consideration: because the **turbine is part of the primary circuit**, maintenance on turbine or steam lines requires radiation controls (unlike PWRs). But this is a known issue for all BWRs and managed via shielding and wait times for N-16 decay (which is seconds). It doesn't pose offsite risk, just influences O&M procedures. Overall, **BWRX-300 is very safe and likely to be licensable for near-campus deployment**, with slightly more source term than smaller designs but still a fraction of large reactor risk.

GEH BWRX-300 – Pros:

- **High readiness and global backing:** First unit under construction 2024–28 in Canada [20]; strong support in U.S., Poland, etc. ensures a robust learning curve and regulatory familiarity.
- **Mature proven technology:** Based on decades of BWR experience; uses **standard fuel and components** – minimizing fuel supply risk and leveraging an existing supply chain [34] [17].
- **Cost competitiveness: ~60% lower capital cost per MW** than many SMRs [31]; ~€1 billion for 300 MWe FOAK [32] and falling for later units – potentially the **cheapest $/kW** option among contenders.
- **Compact footprint:** Only ~5 ha per unit including cooling [24]; simple design reduces on-site construction scope (90% less concrete, etc.) [37] – well-suited to constrained campus sites.
- **Scalability:** Units can be added modularly (each 300 MWe); e.g. 4–5 units to reach ~1.2–1.5 GW. Can operate independently for phased commissioning.
- **Operational simplicity and flexibility:** Natural circulation (no recirc pumps) and passive cooling reduce complexity. Good load-following ability (daily cycling) [29] for integrating with renewables or varying campus demand.
- **Safety enhancements:** Passive safety and smaller core inventory; **likely small EPZ (~site boundary)** [24] enabling siting near population/industry.
- **Strong institutional support:** Technology familiar to regulators and operators worldwide [35] – lower training burden and known reliability benchmarks.

GEH BWRX-300 – Cons:

- **Lower process heat temperature:** 285 °C steam is insufficient for high-temperature processes (SOEC, Haber-Bosch) without significant electrical heating, limiting efficiency for hydrogen/ammonia production.
- **Single large unit increments:** 300 MWe steps may overshoot interim needs (less granularity than smaller modules). Minimum load ~150 MWe (50%) might be high during low demand periods unless unit is cycled off.
- **Radioactive steam cycle:** Turbine and secondary systems become mildly radioactive, complicating maintenance and requiring an intermediate loop for heating applications (extra cost/complexity for cogeneration).
- **Licensing not yet complete in U.S.:** NRC approval is in progress, but as of now BWRX-300 has **no NRC design certification** (using a construction permit route instead). Any unexpected regulatory issues could arise given differences from PWR-based rules.
- **Spent fuel and O&M considerations:** Standard BWR spent fuel (high volume of used fuel per MW relative to high-burnup reactors), requiring on-site pool storage and eventual dry cask management. O&M staff expertise in BWR operations will be needed (less common than PWR in U.S., though training resources exist).
- **Cooling water dependence:** Out-of-the-box design assumes water cooling; adapting to full dry cooling would reduce output efficiency significantly. For arid sites, mitigation measures (e.g. hybrid cooling) would be needed.

Holtec SMR-160 (160 MWe Integral PWR)

Design & Thermal Output: Holtec's SMR-160 is a **160 MWe (525 MWth)** pressurized light-water reactor with an integral design (reactor vessel contains steam generators and pressurizer) [3]. It uses **natural**

circulation for primary cooling (no reactor coolant pumps), similar in safety philosophy to NuScale. Outlet temperatures are on par with other PWRs (~300 °C), so it delivers saturated steam around 285–300 °C to its turbine. Thermal efficiency is ~30%. The SMR-160 is specifically designed for **cogeneration flexibility** – it can produce a mix of electricity and process steam as needed [4]. Holtec emphasizes that a portion of the steam can be extracted for industrial use (desalination, refinery steam, district heat, etc.) while the rest drives the turbine [4]. This makes it adaptable to combined power-heat applications, although like NuScale it cannot reach the very high temperatures of advanced reactors. For the campus's SOEC/NH_3 block, SMR-160 could supply medium-pressure steam (e.g. ~20 bar, 250 °C) to assist, but would require external heaters to achieve 700 °C.

Licensing & Readiness: SMR-160 is not as far along as NuScale or BWRX. It completed the **Canadian CNSC Phase 1 vendor design review** in 2018 and is in Phase 2 review now [3]. In the U.S., Holtec has engaged in **NRC pre-licensing** since 2017 [3] but has not submitted a full design certification or combined license application yet. However, Holtec is pursuing deployment opportunities: it signed an agreement in Ukraine aiming to deploy up to **20 units by ~2029** (contingent on regulatory and geopolitical factors) [3]. Holtec is also eying its own site at the former Palisades plant in Michigan for SMR-160 deployment by the early 2030s. The **UK selected Holtec's design (as "SMR-160+") for its SMR competition shortlist**, indicating confidence in its development [38] [39]. Overall, SMR-160 could be ready for first construction around 2030 if licensing progresses – slightly behind the first NuScale/BWRX units, but potentially viable for Phase 3 (~mid-2030s) or late Phase 2. It uses only conventional LWR technology (no novel fuel), so regulatory review is expected to be more straightforward than for advanced designs.

Physical Footprint & Installation: A hallmark of SMR-160 is its **small footprint**. The reactor and containment are fully below-grade (~14 m underground) for security and shielding [40]. Holtec states a **single SMR-160 unit occupies <2 hectares** of land, and a twin-unit plant <3 ha [41]. This is extremely compact. Part of this is achieved by having a very simple plant layout: one small reactor building, one turbine hall, and minimal other structures. There is "no limitation" on how many modules can be co-located – in fact Holtec envisions building in clusters of four for economy of scale in shared systems [42]. To reach ~1 GW, ~7 units would be needed; these could be arranged in two clusters (4+3). Even 4 units (4×160 MWe = 640 MWe) would fit in under ~5 ha by Holtec's metrics – truly a small land take. This would ease integration on a campus where land may be constrained. **Installation complexity** is also reduced: the SMR-160 is **80+ % factory-built** and shipped in modules. Holtec, a company known for nuclear equipment fabrication, intends to manufacture much of the plant itself. Its experience in heavy component manufacturing (spent fuel casks, etc.) means many systems are **designed for manufacturability**. Also notable, SMR-160 can use **either water-cooled or air-cooled condensers** depending on site conditions [39] [43]. This flexibility in cooling systems is unique – it can be deployed in **water-scarce regions using dry cooling** (with some output penalty) [43], or use traditional cooling towers if water is available.

Operating Features: The SMR-160 uses **standard 17×17 PWR fuel assemblies**, low-enriched (<5% U-235). Core refueling would be needed approximately every 18–24 months, similar to other LWRs. With four units on site, one could be refueled at a time to avoid full outages. The reactor's control is simplified by natural circulation; load-following capability hasn't been widely published, but it should be at least as good as conventional PWRs. It likely can do daily load maneuvers or at least frequency regulation by turbine control. Thermal output can be diverted to **process steam applications easily** due to the secondary loop design – e.g. tapping steam from the steam generator outlet or turbine extraction. In normal operation, efficiency ~30% is a bit lower than larger units (due to smaller turbine and lower steam pressure perhaps), but this is a trade-off for simplicity. Fuel burnup might also be somewhat lower (shorter cycle) since it's a compact core.

Economics & Supply Chain: Holtec markets SMR-160 as an **affordable, "workhorse" reactor for distributed generation** [44]. An approximate capital cost was given as ~$1 billion per 160 MWe unit (≈$6,250/kW) in early estimates. Holtec claims this will drop with volume production and that the design's simplicity (small size, fewer pumps, etc.) yields low O&M costs. The supply chain benefits from Holtec's vertical integration: Holtec can manufacture the reactor vessel, steam generators, containment, and other major components at its U.S. manufacturing facilities, reducing reliance on external suppliers. This in-house capability is a plus for schedule and cost control (though potentially a risk if capacity is limited). External supply chain elements (turbine generator, I&C systems, etc.) are all conventional – many vendors exist for a 160 MWe turbine. Fuel fabrication can be done by existing fuel vendors (it's standard LEU fuel). SMR-160 received some DOE support historically, but not as much as NuScale, so its development pace depends on private and international partnerships (e.g. the Ukraine project). On OPEX: a smaller plant might benefit from **streamlined staffing** – Holtec has indicated the design is *"walk-away safe"* requiring minimal operator action even in transients [16]. A smaller security perimeter and potentially reduced security staffing (if EPZ is at fence) could cut costs. Being a straightforward LWR, maintenance routines are well-known. In sum, SMR-160's **economic competitiveness will hinge on achieving modular construction** and learning from the first few builds, but it is positioned as a relatively low-cost SMR choice.

Waste Heat & District Heating: SMR-160 is explicitly capable of **cogeneration**. Holtec notes it can send out part of its steam for industrial process or heating, essentially operating as a combined heat and power (CHP) plant [4]. For a campus, one could imagine an SMR-160 supplying ~50 MW_t of steam to a chemical plant or to a district heating loop (via a heat exchanger) while still producing, say, 120 MWe of electricity with the remaining steam. This flexibility is valuable – it can be optimized seasonally (more heat in winter, more power in summer, etc.). The waste heat not used for processes would be dumped via the condenser. SMR-160 can use **dry cooling** if needed [43], meaning it could reject heat to air (e.g. via an air-cooled condenser or cooling radiators) – avoiding cooling water consumption and eliminating cooling tower plumes or blowdown. If wet cooling is used, blowdown would be standard (non-radioactive) and minimal due to small size. The potential to integrate **district heating for nighttime campus loads** is excellent: a single 160 MW reactor has plenty of thermal output to heat tens of thousands of homes (or a large campus). With a site-boundary EPZ expected [45], running steam lines or hot water pipes out to campus facilities would be feasible without exiting the EPZ boundary.

Safety, EPZ & Hazards: SMR-160 is marketed as "**world's safest reactor**" by Holtec [46]. It achieves safety through simplicity and passive features: no pumps, all cooling by natural forces (gravity/thermosiphon), and a below-ground pool for decay heat. In an emergency, the reactor is designed to be **"walk-away safe"** – no operator intervention needed for safe shutdown [16]. Key safety systems likely include passive emergency core cooling and containment cooling via natural convection. The entire core/steam system is deep underground, making a large release highly unlikely (any fission products would have to traverse multiple barriers and soil). Holtec expects regulators will allow the **EPZ to be just the plant site fence line** [45], similar to NuScale's approach. This indicates confidence that even a worst-case accident would not meaningfully impact public areas beyond the site boundary. Background radiation at the site boundary is claimed to be lower than natural background during operation [47]. Fire risk is minimal – the SMR-160 uses only water and standard nuclear fuel (no flammable graphite or sodium). The reactor building being underground also protects it from aircraft impact and external fires. One hazard to consider is **spent fuel management**: SMR-160 will store spent fuel on-site (like all reactors). Its small core means fewer assemblies per year to store. Holtec, being a cask company, likely will employ its own dry cask storage technology when needed. Radiological release risk from spent fuel (e.g. zirconium fire) is extremely low given the small inventory and passive cooling of the pool. Overall, SMR-160 promises **inherent and passive**

safety approaching the advanced designs, enabling an *industry-leading small EPZ* and easy integration into an industrial campus.

Holtec SMR-160 – Pros:

- **Compact and site-friendly:** Tiny footprint (<2 ha/unit) [41] – multiple units can fit on a campus without dominating land use. Below-grade design enhances security and reduces environmental impact.
- **Flexible cooling options:** Can be **air-cooled or water-cooled** as needed [39] [43] – valuable in water-limited regions; reduces water consumption and thermal discharge issues.
- **Cogeneration capability:** Designed to output **steam for process heat or district heating** alongside electricity [4] – aligns well with campus needs (nighttime heating, integrated H_2 production).
- **Simplicity and safety:** Natural circulation (no RCPs) and passive safety give high reliability. Likely eligible for **site-boundary EPZ** [45], enabling close proximity to campus facilities.
- **Ease of construction:** Holtec's factory-built approach and its own manufacturing base could shorten project schedules. Small unit size and modularization reduce on-site work.
- **Standard fuel and materials:** Uses conventional LEU fuel (no HALEU). Leverages existing PWR technology knowledge – regulators and operators will find it familiar.
- **Cluster scalability:** Can be deployed in 4-packs or more for economy; offers a modular path to 1+ GW without single large investments at once.

Holtec SMR-160 – Cons:

- **Later in licensing queue:** Not yet licensed in U.S.; timeline slightly behind other SMRs (FOAK likely mid-2030s). **Regulatory risk** until design certification or a first deployment proceeds.
- **Smaller economy of scale:** 160 MWe units may have higher per-MW costs initially (~$6k/kW FOAK). Achieving cost targets depends on multiple orders (learning rate from series production).
- **Less operational experience base:** As a newer design from a non-traditional reactor vendor, there is no fleet experience yet – could face a learning curve in initial operation and maintenance.
- **More units required:** ~7–10 modules needed for 1–1.5 GW – managing many reactors, turbines, and fueling schedules adds operational complexity (though partly mitigated by grouping into clusters).
- **Unproven supply chain for some components:** Holtec will fabricate much in-house; any hiccups in manufacturing capacity or quality could impact schedule (the approach concentrates risk within Holtec's facilities).
- **Lower temperature & efficiency:** Being a LWR, it cannot directly supply high-temperature heat for SOEC (needs electrical heaters); its efficiency (~30%) is lowest among the options, meaning more waste heat per MW (could be a "pro" for heating but a "con" for electrical output).

X-Energy Xe-100 (80 MWe High-Temperature Gas Reactor)

Design & Thermal Output: The X-Energy Xe-100 is an **advanced Generation IV HTGR** that delivers **80 MWe per reactor (200 MWth)** with helium coolant [5]. The design typically comes in a **"four-pack" of 4 × 80 MWe (320 MWe) modules** [48], and multiple four-packs can be co-located for higher capacity. The Xe-100's standout feature is its **very high core outlet temperature: 750 °C** helium coolant [6]. Helium flows through a steam generator to produce superheated steam at **565 °C and 16.5 MPa** [5] – comparable to modern supercritical fossil plants. This yields a **thermal-electric efficiency around 40%**, significantly higher than LWRs. Crucially, the high temperature output enables **process heat applications far beyond the reach of LWR-based SMRs** [6]. The Xe-100 is expressly designed to serve industrial heat markets: it can supply ~500–750 °C heat for hydrogen production, ammonia synthesis, petrochemical processes, etc. In the context of the Heber campus, the **SOEC (solid oxide electrolysis) for H_2 can be directly fed high-grade steam** from the reactor, massively reducing the electrical energy needed for electrolysis. Likewise, waste heat can drive Haber-Bosch ammonia reactors or provide thermal energy for oxygen separation if needed. No other candidate matches Xe-100's **process heat compatibility** – it is a top choice if high-temperature steam integration is paramount.

Licensing & Deployment: The Xe-100 is part of the U.S. Department of Energy's **Advanced Reactor Demonstration Program (ARDP)**. X-energy, backed by DOE, plans to build a four-unit (320 MWe) demonstration Xe-100 plant at a Dow chemical facility in Texas, targeting operation by ~2030 [49]. It also has an agreement with a utility (Energy Northwest) to deploy up to 12 units (960 MWe) in Washington state soon after [50]. The NRC is engaged in **pre-application reviews** with X-energy since 2018 [51], and in 2023 the NRC **docketed the construction permit application** for the Dow Texas project [52]. This implies an 18-month review schedule is underway [53], aiming for a construction permit by ~2025. X-energy hopes to have the first licensed, operational advanced reactor in the U.S., leveraging strong federal support [54]. That said, as a first-of-a-kind Gen IV reactor, there is schedule risk – any delays in fuel fabrication, licensing, or construction could push deployment into the early 2030s. By Phase 2 (~mid-2030s), however, the Xe-100 should be **commercially available** if the demo is successful. Internationally, the design is also under review (e.g. joint CNSC/NRC vendor review, and interest from industrial players). Importantly, **Triso fuel fabrication** (TRISO-X facility) is being established in the U.S., supported by DOE, to supply the HALEU TRISO fuel pebbles needed [6]. NRC licensing is helped by decades of HTGR research (the safety case draws on prior DOE/NRC studies). Overall, the regulatory outlook is positive – the **Xe-100 could be fully licensed and on the grid by 2030**, making it a viable option for Phase 3 (~1.5 GW by late 2030s) and possibly the tail end of Phase 2.

Physical Footprint & Site Integration: Each Xe-100 module is relatively small (reactor vessel ~5–6 m diameter range, and not extremely tall). A four-pack (320 MWe) might occupy on the order of a few hectares. One estimate for a full plant including turbine, cooling, and support is roughly *25 acres* (~10 ha) for a 4-unit plant (though exact numbers depend on site layout). This is larger per MW than BWRX or SMR-160, primarily because of the **turbine hall and cooling systems sized for 320 MWe** rather than 300 MWe. But it's still compact compared to legacy plants. The reactors can be arranged in close proximity (they do not require large separation for safety, as each has its own containment silo). The Xe-100 doesn't need massive cooling towers if designed with dry cooling – thanks to the high steam temperature, it can tolerate higher condenser temperatures. X-energy has proposed an **approximately 400 meter safety perimeter (exclusion radius)** for the Xe-100 [55], vs. 10-mile traditional EPZ. This 400 m radius (0.4 km) corresponds to an EPZ area of about 50 ha – effectively just the immediate site. In practical terms, **the EPZ would be site-boundary** (some sources even suggest the emergency planning zone might only extend a few hundred meters) [55]. This means a Xe-100 plant could be sited **very close to end-users** (a major selling point: "bring the reactor to the industrial load"). For the campus, this means the reactor(s) could be on campus property, and beyond the fence normal activities continue unaffected. Construction of HTGRs is somewhat different – the reactor core is mostly **graphite**, so there's significant construction of the core structures and helium system. X-energy's design emphasizes **modular construction**: the reactor vessels, steam generators, etc. are road-shippable and installed on site [56]. The long-lead item might be **graphite manufacture** for the core, but this is done off-site. Because it's high-tech, expect the first units to have a longer build (maybe ~36–48 months), shrinking after replication. Integration with the existing campus layout should consider that Xe-100 requires **a fuel handling facility** for loading and removing pebbles and a storage for spent pebble fuel (likely dry canisters). These are smaller in scale compared to spent fuel pools in LWRs and can be on-site in a secure vault.

Operating Characteristics: Xe-100 uses **tri-structural isotropic (TRISO) coated fuel pebbles** – robust fuel particles that **cannot melt** under even extreme conditions. It continuously circulates pebbles: fresh fuel is added and spent fuel removed regularly, allowing **online refueling and 95% capacity factor** [57]. This is a huge operational advantage – no refueling outages. The reactor can run for years steady-state, only stopping for maintenance. Xenon (fission product) is less of an issue with continuous burn, so load-following is possible by design, though HTGRs prefer steady output. The plant can ramp output by controlling helium coolant flow or inserting control rods, but typically one would run the reactor at constant power and divert excess energy to a **dump heat exchanger or energy storage** if load is low. The turbine is a standard steam turbine (albeit one that takes 565 °C steam – a high-performance machine similar to those in modern fossil plants). X-energy has indicated that many **off-the-shelf components** are used (valves, pipes, etc.), aside from the nuclear-specific items [58]. Another key feature: the fuel is **HALEU (High Assay Low Enriched Uranium, ~15–20% U-235)** – this gives a long fuel life (each pebble sees high burnup). But HALEU supply is currently limited; X-energy's TRISO fabrication facility is expected to start supplying demo fuel using DOE-provided HALEU. Long-term, a domestic HALEU enrichment capacity is needed (now being developed). For operations, the use of helium coolant means **no corrosion issues**, and helium is inert – but it requires high-quality pressure-boundary components. Helium leaks must be controlled (it's a small molecule). The reactors operate at high pressure (~6 MPa helium) [59], similar to PWR pressure, so heavy-wall vessels are used (ASME compliant materials [60]). The turbine cycle is a two-loop system: nuclear heat → steam generator → steam to turbine. Thus, the secondary steam loop is non-radioactive (great for coupling to other uses). Efficiency ~40% means less waste heat per MWh – beneficial for thermal management.

Economics & Supply Chain: Being a first-of-kind Gen IV, cost is a question. DOE's ARDP is cost-sharing the demo plant (total cost likely in the billions for 320 MWe). X-energy projects that with factory production, costs will fall to competitive levels (target perhaps <$4,000/kW by Nth plant). The **fuel fabrication** is a new supply chain element: TRISO fuel production is more complex than standard fuel rods. X-energy's TRISO-X factory (Oak Ridge) is key to supply – it should be operational by 2025 and produce fuel for the demo and first wave of units. The supply of HALEU feedstock is a challenge, but DOE and Centrus have a pilot enrichment cascade producing some HALEU now [61] [62]. Over the next decade, HALEU availability should improve with government support. For other components: **helium circulators**, **graphite** and **vessels** are critical. Helium circulators are essentially blowers – similar equipment was developed for prior HTGRs (pebble bed in China, prismatic in Japan) – Western supply might need ramping up, but it's not exotic. Graphite core blocks and pebbles: there are few suppliers of nuclear-grade graphite. This could be a bottleneck if many units are ordered. On the positive side, X-energy has strong backing (recent SPAC funding and DOE grants) and partnerships (Dow, etc.), indicating financial and organizational support. From an OPEX perspective, Xe-100 should have **lower staffing needs**: *no refueling outages, passive safety*, and a smaller security/EPZ footprint. There is also no risk of core melt, which simplifies emergency planning and potentially insurance costs. Fuel handling is continuous but largely automated (pebble recirculation system). Spent fuel will likely be stored on-site in canisters; TRISO fuel is much more stable, and after a few years of decay the pebbles can be stored in air with no cooling. The long-term waste volume is larger (graphite + fuel matrix), but its storage is safer (each particle retains fission products). These factors can reduce operating overhead. In summary, **supply chain maturity is the main concern**: it's new, but with government support the gaps (HALEU, TRISO fab, graphite) are actively being filled [6]. By the time of deployment, X-energy should have a vertically integrated fuel supply (enrichment through fabrication) under U.S. control – which is a strategic advantage.

Waste Heat & District Heating: Xe-100, despite high efficiency, still rejects ~120 MW of heat per 80 MWe unit (480 MW for a 4-pack). This waste heat, however, is at higher temperature than LWRs (condenser steam could be ~100+ °C). It is very feasible to use **extraction steam or condenser heat for district heating**. In fact, an HTGR could directly supply a large amount of 120 °C hot water for heating with minimal impact on electric output (by slightly throttling the low-pressure turbine stage). For example, one could extract steam at intermediate pressure to heat a water network, then return the condensate – standard CHP practice. Because the reactor can produce **very high-grade heat**, it also allows cascading uses: high-temperature heat for industrial process, medium temp for power, and low temp for heating – achieving high overall utilization. At night, if electrical demand drops, the reactor could run at full thermal power but divert most heat to a **thermal storage system or directly into district heating**, effectively **load-shifting its energy output**. The modular nature (multiple units) also allows one reactor to be taken to a lower power and dedicated to heat production while others maintain electricity. Cooling-wise, Xe-100 can use **dry cooling effectively** – the higher steam condensing temperature (allowed by 565 °C steam input) means it can tolerate a hotter sink and still achieve decent efficiency. This suits arid sites or water-limited campuses. Blowdown risk is minimal, as secondary coolant is demineralized water in closed loop (no radioactivity, just standard water chemistry to maintain). Helium cooling means no large heat sink needed for decay heat – in an emergency, the reactor can dissipate heat via passive conduction/radiation through the reactor vessel and silo (air or water not required). Overall, **Xe-100 provides excellent co-generation and heat recovery opportunities**, more so than any LWR design.

Safety, EPZ & Hazards: The Xe-100's safety is **intrinsic**. It uses TRISO fuel particles that can withstand >1600 °C without melting, far above normal operation temperature [59]. In a loss of coolant event, the reactor is designed to **gracefully heat up** and then cool via passive conduction to the reactor vessel and concrete silo – the fuel will not fail, and fission product release is negligible. There is no risk of core meltdown or large-scale gas/steam explosion. The worst credible accident (like a coolant depressurization with failure of shutdown cooling) would still keep radioactivity mostly inside the TRISO particles. As a result, the **Emergency Planning Zone can be just hundreds of meters** (essentially the site). X-energy advertises a ~400 m safety perimeter [55]; analysts expect NRC will allow a site-boundary EPZ if the safety case is demonstrated. This makes the Xe-100 very attractive for siting **within an industrial campus** – it poses little radiological risk to the public. The reactor building is low-profile and largely below-grade. Helium is inert and **non-flammable**. One potential hazard is the **graphite moderator** – graphite can oxidize (and even burn) if exposed to air at high temperature. However, the Xe-100's core is designed to avoid air ingress scenarios, and even if air enters after an accident, the heat would be low and the oxidation rate slow. The reactor's containment (or confinement) is not the high-pressure type like LWRs; it's more of a vented low-pressure silo since big pressure buildup is unlikely. This containment approach, plus the TRISO retention, ensures any release is extremely small. Another safety aspect: **no high-pressure coolant that can flash** – helium at 6 MPa will just depressurize, not undergo phase change, so less mechanical energy in accidents. And no water means no hydrogen generation (so no explosion risk). Fire risk is limited to conventional materials (e.g. a turbine lube oil fire risk in the turbine hall, like any plant, mitigated by fire systems). There is **no sodium or reactive coolant**. The fuel, even if damaged, would release only noble gases and tiny fractions of volatiles – likely contained within the building. Security considerations are eased by the small fuel inventory per reactor and the difficulty of extracting weapons-useable material from TRISO pebbles (they're highly proliferation-resistant). The Xe-100's safety case is so robust that experts often call it **"walk-away safe"** as well – even with loss of all active systems, the core won't harm the public. This high level of safety is reflected in regulatory confidence that advanced reactors may not need large EPZs [15] [14]. In summary, **Xe-100 provides the highest safety margin** and lowest offsite risk of all options, making it ideal for co-locating with chemical plants and populated campuses.

X-Energy Xe-100 – Pros:

- **Outstanding high-temperature performance:** 750 °C outlet enables direct integration with SOEC hydrogen, ammonia synthesis, and other process heat needs [6]. **Only design that natively provides high-grade steam** (565 °C) for the chemical block [5].
- **Inherent safety and minimal EPZ:** TRISO fuel and passive heat removal virtually eliminate meltdown risk. EPZ can be at site boundary (~400 m) [55] – **ideal for on-campus deployment** without large evacuation zones.
- **Flexible cogeneration and load factor:** Can run at high capacity factor with **online refueling** (≈95% uptime) [57]. Easily shifts between electricity and heat output, or simultaneous CHP, maximizing energy utilization.
- **Scalable modular approach:** 80 MWe modules allow gradual capacity build-out. Clusters (4-pack ~320 MWe) can be added as needed. 12 modules (~960 MWe) are already envisioned in one project [63].
- **Lower operations burden:** No large pressure vessel replacements or outage refueling. Likely reduced staffing (automation, less security concern). TRISO fuel stability reduces emergency planning requirements/costs.
- **Government and industry support:** Part of DOE's ARDP with significant funding – **first unit by 2030 is plausible** [50]. Partnerships with Dow and others de-risk commercialization. NRC and CNSC are actively engaged in licensing reviews.
- **Competitive efficiency:** ~40% thermal efficiency means more power per unit heat and less waste heat to manage. If using dry cooling, efficiency hit is smaller due to higher temperature differential.
- **Future-proof technology:** As a Gen IV design, it has a long developmental runway – improvements can raise output or efficiency further (e.g. direct Brayton cycle in future, although current design is steam cycle for maturity). It positions the campus at the forefront of advanced nuclear.

X-Energy Xe-100 – Cons:

- **First-of-a-kind technology risk: No operating units yet** – potential for delays in licensing, construction, or performance shortfalls. Unproven operational track record compared to LWR-based SMRs.
- **Fuel supply challenges:** Requires HALEU fuel (15–19.75% U-235). Until a commercial HALEU infrastructure is in place, fuel sourcing is reliant on limited government programs or interim Russian supply (undesirable). TRISO fabrication is just scaling up now.
- **Higher upfront cost (FOAK):** Advanced design likely has higher FOAK CAPEX. Specialized components (graphite, helium systems) and small factory volume initially mean cost risk. Economics should improve with fleet deployment, but early units may be expensive on a $/kW basis without additional subsidies.
- **Power density and footprint:** HTGRs have lower power density cores, thus the plant outputs less power per unit of volume compared to LWRs. For 1.5 GW, a larger number (~18–20) of reactor units is needed, occupying a somewhat larger overall area than an equivalent LWR plant (though still manageable). Balance of plant per MW is also larger initially (multiple smaller turbines or one big turbine per 320 MW).

- **Graphite management and waste:** The reactor contains a large mass of graphite moderator which becomes low-level radioactive waste over time (through neutron activation). Decommissioning will involve disposing of or recycling a significant graphite volume. While this is low-level waste, it's an extra consideration vs. LWRs.
- **Limited load-following track record:** HTGRs prefer steady operation for efficiency. While Xe-100 can maneuver, its dynamic response is less tested than LWR controls. This may necessitate using thermal storage or other means to follow fast load changes, rather than deep reactor throttling.
- **Regulatory learning curve:** NRC is more familiar with LWRs; although supportive, licensing an advanced reactor involves new ground (e.g. risk-informed Part 53 framework in development [64] [65]). Unanticipated regulatory hurdles could arise, impacting timeline.

Oklo Aurora (1.5 MWe Microreactor – Fast Spectrum)

Design & Thermal Output: Oklo's Aurora is a very small **microreactor** design: ~1.5 MWe electric output for ~4 MWth of reactor heat [66]. It is a **fast-spectrum reactor using heat pipes** for heat transfer. The core uses metallic HALEU fuel and liquid metal coolant (likely sodium or a sodium-potassium mix) passively circulating via heat pipes to a power conversion system (possibly a Stirling engine or supercritical CO_2 turbine). The reactor's outlet temperature is high for a fission system – roughly in the 450–550 °C range based on Oklo's filings – enabling efficient electricity generation (~30–40% range) even at micro scale. The Aurora is intended to run **autonomously for ~20 years** without refueling, producing a steady ~1.5 MW of power. In terms of Phase 2/3 needs, the Aurora is **two orders of magnitude too small**; hundreds of units would be required to meet a gigawatt demand, which is impractical. It's mentioned here only for completeness and in case a **fleet of microreactors** or a distributed concept were considered (though that would complicate operations immensely). As for thermal output compatibility: an Oklo unit could provide ~4 MWth at ~500 °C, which is useful heat, but on a tiny scale – a single industrial SOEC or Haber process would consume much more. Thus, Aurora is **not really relevant for large centralized H_2/NH_3 production**, but a few units could potentially provide process heat to a small facility or remote site.

Licensing Status: Oklo's Aurora made headlines as the **first-ever non-LWR combined license application (COLA) to NRC** in 2020 [67]. However, in January 2022 the NRC **denied Oklo's application** (without prejudice) due to lack of sufficient technical information in areas like maximum accident scenario analysis [68]. Essentially, Oklo's submission was premature and did not satisfy NRC requirements. Oklo has since **relaunched its licensing efforts** with a new Licensing Project Plan submitted in September 2022 [66] [69], aiming to better align with NRC expectations and re-apply under the forthcoming 10 CFR Part 53 advanced reactor rule. The **timeline for Aurora's approval is uncertain** – it could be mid-late 2020s if things go perfectly, but given the tiny scale and the company's startup nature, it's likely the slowest to market of the options. The **DOE did grant Oklo a site use permit at INL** (Idaho) and some support, but with the licensing setback, the first Aurora unit will not be before the late 2020s at best. For a 1 GW deployment by the 2030s, Oklo is **not a realistic contender**.

Footprint & Deployment: The Aurora reactor is extremely compact – the entire plant (reactor and power conversion in a metal building resembling a shipping container with an A-frame roof) fits on maybe a few hundred square meters. It was designed to be installed in remote locations, so it has **minimal balance-of-plant** (no large cooling towers; it likely uses air cooling via a radiator since output is small). Multiple Aurora units could be scattered as needed – theoretically one could create a "nuclear battery farm." But managing ~200 microreactors to equal 1 GW would be operationally complex and economically dubious. Oklo's strength is in niche off-grid markets (mines, remote bases) rather than central station power. Integration with a campus might make sense for a **very small campus or isolated microgrid**, but not for a large campus needing gigawatts. Additionally, each Aurora would need to be refueled or replaced every ~20 years – but presumably the vendor would just haul the old unit away and plug in a new one (part of Oklo's business model as a service).

Operating & Safety: Aurora uses **HALEU metal fuel** and is a fast reactor, which means no moderator. The primary cooling is via heat pipes – these are passive devices that transfer heat by phase change of an internal fluid (likely sodium). Heat pipes are very reliable if kept within design limits, but the core has to be small to allow heat to conduct to them. The small core and long-life fuel mean a high burnup; Oklo likely relies on advanced fuel to last 20 years. The reactor is sealed and would not be opened on site – limiting operational complexity. Safety-wise, the low power and large thermal inertia (20 years of heat capacity) means transients are slow. The worst accidents are probably heat pipe failure or inadvertent reactivity insertion. The **radiological source term** is tiny compared to any large reactor, so **consequences of accidents are very limited in scope**. Oklo was pitching essentially **no meaningful EPZ beyond the site fence**. Indeed, with only 1.5 MW of fission power, even a complete core release would likely be contained within a building or have minimal offsite dose. The design doesn't have a traditional containment; it relies on the reactor vessel and shielding around it. **Fire risk:** If sodium is used in heat pipes or as coolant, contact with air or water could cause a chemical fire. However, the quantity of sodium is small (just enough in heat pipes, possibly tens to hundreds of kg, not tons as in a large sodium reactor). This is a hazard that must be mitigated by inert atmosphere inside the reactor enclosure or by leak detection and fire suppression in the vault. Still, it's present. The Oklo design had an **aesthetic A-frame timber structure** – presumably the timber is external cladding and not structural, to avoid fire issues. Emergency planning for Aurora would be minimal – likely just the site itself, given NRC was open to such tiny reactors having negligible EPZ.

Economics: Oklo's model is very different – they target remote customers willing to pay a premium for reliable small-scale power (where $/kW can be high because alternatives like diesel are extremely expensive in those areas). For grid-scale generation, microreactors are not cost-efficient. You lose economies of scale without gaining the benefits of mass production (unless you manufactured thousands of them, which is far off). The CAPEX per kW for Aurora would be very high (possibly >$10,000/kW in early units, though exact numbers aren't public). The OPEX might be low since it runs autonomously, but there will be periodic replacement costs. Supply chain for Oklo is also challenging: **HALEU fuel** (same issue as Xe-100, but each unit uses less material), **heat pipe technology** (some aerospace and research heritage, but not mass-produced for reactors yet), and very small turbines or Stirling engines (again, limited suppliers for high-efficiency units of that size).

In summary, for the Heber project's scale, Oklo's Aurora is **not very relevant** except as a curiosity or a potential future microgrid component. It does not meet the 1.0–1.5 GW generation requirement in any practical way. It could perhaps serve a specialized niche (like a separate remote well field or small off-grid facility related to the campus), but not the main campus power.

Oklo Aurora – Pros:

- **Extreme safety and simplicity:** Ultra-small core and low power = negligible radiological risk. Essentially **no offsite EPZ needed**, can be deployed literally adjacent to facilities.
- **High-temperature output (relative to size):** ~500 °C heat, which is impressive for a microreactor – could drive efficient micro-turbines or provide process heat on a small scale.

- **Long autonomous operation:** 20-year core life without refueling is very attractive for remote ops. Minimal operational oversight – potentially just periodic remote monitoring.
- **Rapid deployment (potentially):** The unit is prefabricated; in theory, could be installed and producing power in a matter of weeks on site. If a campus needed a very small reactor quickly for a pilot, this is a model (pending license).
- **Novel business model:** Power as a service – Oklo would handle fuel, replacement, etc., meaning the user doesn't manage nuclear materials. Could appeal for small applications where staffing a reactor crew is not feasible.

Oklo Aurora – Cons:

- **Inadequate scale for project needs:** At ~1.5 MWe each, it would require on the order of 1000 microreactors to reach ~1.5 GW. This is impractical by orders of magnitude (in terms of operations, maintenance, and cost).
- **Uncertain licensing path:** Already had one NRC application denied [68]; regulatory acceptance is not yet achieved. Timeline to commercial deployment is highly uncertain (mid-2030s or beyond).
- **HALEU fuel dependency:** Needs high enrichment fuel like Xe-100 – facing the same supply constraints. For a fleet of microreactors, fuel logistics could be complex.
- **Economics not competitive at utility scale:** Very high cost per kW (no economies of scale); while acceptable for remote sites that pay ~$0.50/kWh for diesel, it's not viable for large-scale generation cost targets.
- **Heat pipe/sodium technology risk:** Use of sodium (if confirmed) introduces fire/chemical risk in exchange for passive cooling. Heat pipe reliability in reactor service over decades is not yet proven in a commercial setting.
- **Lack of commercial maturity:** Oklo is a startup; no full-scale prototype has run. Compared to established players (NuScale, GEH, X-energy backed by TerraPower etc.), Oklo has limited resources and could struggle to deliver on time.

Summary Comparison of Designs

To crystallize the evaluation, the table below compares the designs across the key factors (licensing, footprint, cooling, cost, safety, etc.):

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
NRC Licensing Status	**Certified** design (NRC Rule certified Jan 2023) [8]; 77 MWe upgrade under review (done ~2025) [1]. First U.S. deployment expected ~2029 [9].	**In progress** – NRC pre-app underway [70]; TVA filed first construction permit 2023 [21]. No design cert yet, but leveraging certified ESBWR. First unit ~2028 in Canada [20] (OPG).	**Pre-licensing** – Under CNSC review (Phase 2) and U.S. NRC engagement [3]. No design cert; targeting FOAK by ~2029 (abroad) [71].	**Pre-licensing** – Part of DOE demo program. NRC reviewing construction permit for demo [52]. First 4-pack ~2030 planned [50]. Likely one of first Gen IV licensed by NRC.	**Not licensed** – Initial COL application was *denied* in 2022 [68]. Reapplying with new approach; far from NRC approval. Earliest demo mid/late-2020s if hurdles overcome.
Deployment Readiness (U.S.)	High – Backed by UAMPS/ DOE; supply chain active; could be constructing by 2026–27. Suitable for Phase 2 timeline.	High – OPG build gives head start; TVA and others likely follow ~2030. Strong momentum, could meet Phase 2.	Medium – Development ongoing; likely ~2030–32 for first unit (if foreign build in 2029 succeeds). More realistic for Phase 3.	Medium – Demo should prove by 2030; limited initial fleet. Commercial units likely ~2032+. Viable by Phase 3, possibly late Phase 2.	Low – Uncertain path and very small scale. Not a realistic option for near-term large power deployment.
Module/Unit Size	77 MWe each (12-pack = 924 MWe) [1]. Flexible scaling; e.g. VOYGR-12 for ~0.9 GW, VOYGR-18 for ~1.4 GW (two plants).	300 MWe per unit. ~4 units (1.2 GW) for Phase 2, 5 units (1.5 GW) for Phase 3. Units can be added one by one.	160 MWe per unit [3]. ~7 units (~1.12 GW) for Phase 2, ~10 units (1.6 GW) for Phase 3. Ideally deployed in 4-unit clusters [42].	80 MWe per reactor [5]. Typically 4 units = 320 MWe. ~13 units (in four-packs) for ~1.0 GW; ~19 units for ~1.5 GW. Can distribute across several clusters.	1.5 MWe per microreactor [66]. ~667 units for 1.0 GW – impractical. (Best used in remote small applications, not central plant.)

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
Physical Footprint	Multi-module pool design – ~< *1 km²* for full VOYGR-12 plant (incl. cooling). Very compact per MW (shared systems).	~170 m × 280 m = 4.8 ha per 300 MW unit [24]. For 5 units (~1.5 GW) ≈ 25 ha (if not sharing). Still small relative to output.	<2 ha per 160 MW unit [41]. Extremely compact. ~3 ha for 2 units [41]; ~15 ha could host ~8–10 units (~1.3–1.6 GW). Below-grade build minimizes land use.	A 4-pack (320 MW) estimated ~7–10 ha (including turbine, cooling). ~30–50 ha for ~1.5 GW (multiple modules plus cooling). More spread out due to multiple units and safety spacing (though 400 m EPZ radius covers ~50 ha for entire site) [55].	Tiny per unit (~<0.1 ha each). Even hundreds would physically fit in a few hectares if tightly packed. But supporting infrastructure (security, grid tie-ins) would expand that.
Operating Temp & Efficiency	~300 °C primary, ~285 °C steam. ~32% efficiency Rankine. Developing secondary heating to get 500–650 °C steam for process use [2].	~285 °C steam (saturated). ~34% efficient. No separate superheat (direct cycle). Moderate-temp steam.	~300 °C primary, 285 °C steam. ~30% efficient. Standard PWR conditions. Can bleed steam for cogeneration.	750 °C primary He, 565 °C steam [5]. ~40% efficient (superheated steam) [5]. **High-temp** operation ideal for industrial use [6].	~450–550 °C heat pipes (est.). ~30–40% efficient with sCO_2 or Stirling. High temp for its size, but absolute power is small.

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
High-Grade Process Heat	**Partial** – Requires booster to reach >500 °C [2]. Without it, limited to ~300 °C steam (okay for low-pressure steam needs).	**Limited** – ~285 °C steam only. Could assist low-temp electrolysis or provide heat for district heating, but not enough for high-T chemical processes without resistive heating.	**Limited** – ~300 °C steam available for processes (refineries, etc.) but not hot enough for SOEC or ammonia synthesis directly.	**Yes (excellent)** – 565 °C steam and option for 750 °C helium directly [6]. Easily supplies SOEC, Haber-Bosch, etc., making it best for H_2 + NH_3 integration.	**Yes (but tiny)** – ~500 °C heat is high-grade, but only ~4 MWth available per unit. Not scalable to large chemical output.

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
Cooling Requirements	Water cooling standard (towers or ponds). Could use dry cooling at cost of some efficiency (higher back-pressure). Decay heat removal via passive pool – no external power needed [72] [15] .	Water cooling (tower or once-through). Some siting use near water expected. Potential for shared cooling for multi-units. Passive isolation condensers for decay heat (no external cooling for initial period). Dry cooling not part of base design (could be engineered case-by-case).	**Flexible:** Designed for **wet or dry** cooling – e.g. air-cooled condenser for arid sites [39] [43] . Low water usage option is a major advantage. Decay heat passive via gravity feed to an internal exchanger (likely air or water heat sink).	Can use **dry cooling effectively** (higher steam temp can tolerate hotter ambient). Smaller water needs per MW. Decay heat handled by passive air natural circulation (no need for water). Ideal for desert or water-limited regions.	Always **air-cooled** (no water needed). Heat pipes dump to air radiator. Suitable for remote/off-grid where water is unavailable. Minimal cooling infrastructure.

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
Waste Heat & District Heating	**Good:** Secondary loop allows clean heat extraction. Can dedicate modules to thermal output for campus heating at night [12]. ~150 MWth per module available for cogeneration. Needs distribution network.	**Good:** Large thermal output (~570 MWth/unit). Would use an intermediary circuit (to avoid primary water). Proven feasible (BWRs used in district heat in some cases). Could supply significant campus heating load from turbine extractions.	**Good:** ~365 MWth unused per 160 MW unit. Direct steam extraction possible (clean secondary). Specifically meant to supply **process steam** or district heat alongside power [4]. Very useful for nighttime thermal load.	**Excellent:** High-grade waste heat can be cascaded (e.g. power then heating). Could integrate with thermal storage or feed directly to district heating at high temperature, increasing overall efficiency. With ~120 MWth per unit (not converted), a four-pack can heat a small city.	**Minimal:** Each unit's 2.5 MWth waste (after ~1.5 MW electricity) is trivial in large campus terms – only suitable for a handful of buildings.
CAPEX (indicative)	~$4,500–$5,500/kW (Nth-of-a-kind target). FOAK ~>$8,000/kW (UAMPS) due to first-time costs. Costs rising; needs economies of multiples.	~$2,250/kW (Nth-of-a-kind) [23]; FOAK ~€1 billion for 300 MW (~$3,300/kW) [32]. Could drop further with fleet build-out [33]. Likely **cheapest per MW** once proven.	~$6,000+/kW for early units (est. $1B for 160 MW). Aiming for <$4,000/kW after design maturity. Economies from series production (Holtec's manufacturing) critical.	FOAK high (govt subsidized). Long-term goal ~$3,000–$4,000/kW after learning curve [31]. Uncertain until demo proves costs. Fuel costs higher (HALEU fabrication), but offset by higher efficiency.	Very high per kW (micro-scale). Intended for niche markets that tolerate ~$10k+/kW. Not cost-effective for bulk power. Potentially competitive only where alternatives are extremely costly (remote sites).

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
OPEX & Refueling	Staffed similar to current plants but per-MW staffing lower (12 modules one site, one crew). Refuel ~24 mo per module, sequential (no full outage). Standard fuel (low enriched). Should achieve high capacity factor ~95%.	Familiar operations (like large BWR). 12–24 mo refuel cycles [30] ; could stagger if multi-unit site. Uses well-known fuel – predictable fuel costs. Some O&M cost reduction via design simplicity (e.g. no recirc pumps, smaller footprint to guard). Expect good capacity factor, minor load-following wear.	Likely lower staffing per MW (small plant, passive safety). ~18–24 mo refuel. Standard fuel supply chain. Multi-unit sites allow rotating refuel outages. Holtec's own plant operation experience (spent fuel side) may help streamline O&M.	Reduced O&M overhead: **online refueling** means no refuel outages – ~95% uptime. Fewer operators needed (reactor can be automated to large extent). Fuel is HALEU TRISO – costly but long-lasting (pebbles circulate many times). Some specialized maintenance (helium systems, graphite monitoring) required. Overall O&M potentially simpler than LWR after initial learning.	Virtually no on-site O&M – designed for autonomous operation. No refueling for 20 years (sealed core). Operator visit maybe for yearly checks. Security can be minimal. However, many units = many points of monitoring. End of life requires unit replacement (which Oklo would handle). Operational costs are more like battery leasing than running a plant.

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
Supply Chain Maturity	**Strong for LWR components:** Vessel forging (Doosan, etc.), steam turbines (GE), fuel (existing LWR fuel suppliers). Many partners already on board. Some components (compact steam generators, etc.) are unique but within industry capability. Manufacturing started for first units.	**Very strong:** Based on existing BWR tech – fuel assemblies, control rods, etc. are standard [34]. **Existing global supply chain** for all major parts (pressure vessel, internals, turbine) [17]. GE leveraging its reactor and power generation divisions for efficient sourcing. Minimal novel tech = easier procurement.	**Moderate:** Holtec's own facilities cover heavy fabrication, which is good, but design is first of its kind. Will need supply of steam generator tubing, instrumentation, etc., which are standard. Supply chain not proven by orders yet. Canadian and UK interest may spur vendor development.	**Emerging:** Key new supply needs – **HALEU fuel** (small Centrus cascade operational, needs scale-up) [62], **TRISO fabrication** (X-energy's factory underway), nuclear-grade graphite supply. Turbines and generators are standard (just high temp materials). Helium circulators and specialized valves need development but are not showstoppers. Government support is helping build this chain.	**Nascent:** Very few suppliers for such a micro reactor. Relies on advanced HALEU fuel (even smaller supply pool). Heat pipe reactor tech is not industrialized – essentially custom engineering. Oklo is far from having a manufacturing line; each unit might be semi-handcrafted initially. This makes scaling to many units uncertain.

Safety & EPZ	**Passive safety:** No AC power or operator action needed for core cooling [72] [15]. Small core = small decay heat. *NRC-approved method for site-boundary EPZ* – can set EPZ at fence for most sites [14]. Robust containment (underground pool). No flammable coolant; low seismic risk due to underground construction. Emergency planning greatly simplified.	**Passive safety:** Isolation condensers & gravity water pools. Smaller core than gigawatt reactors, but still significant power – more source term than NuScale per unit. EPZ expected to shrink (e.g. ~8 ha in analyses) [24], potentially to site boundary with regulatory approval. Some risk of hydrogen if severe accident, mitigated by recombiners. Containment similar to large BWR but scaled down. Overall high safety, likely <10% of large plant offsite risk.	**Passive & secure:** All safety systems passive (natural circulation, gravity injection). Below-grade silo provides strong radiation shielding and aircraft crash protection. Holtec expects **EPZ ~site boundary** [45]. Low core power and slow transients = very low probability of significant release. No exotic materials – only water and fuel, so accident phenomenology well-understood. Arguably as safe as NuScale in design basis, with small source term.	**Inherent safety:** TRISO fuel retains fission products up to extreme temps, core cannot melt. Helium coolant = no explosion risk, no phase change. **No need for active cooling** – core self-protects by passive heat conduction. Potentially *no offsite evacuation needed* even for worst case. X-energy advertises ~400 m (site) radius emergency zone [55]. Some hazards: Graphite (moderator) could oxidize if air ingress, but reactor design prevents this in credible scenarios. Overall, unparalleled safety profile; essentially	**Inherent & low consequence:** Tiny core and low power – worst accident would be negligible compared to others. Likely only a *few hundred meter* isolation zone needed. Liquid metal cooling via heat pipes is passively safe as long as natural convection continues. Sodium in system does pose a chemical fire risk if exposed; design must ensure heat pipes don't all fail simultaneously. Security risk minimal due to small fuel amount and self-contained unit.

Criteria	**NuScale VOYGR** (PWR)	**GEH BWRX-300** (BWR)	**Holtec SMR-160** (PWR)	**X-energy Xe-100** (HTGR)	**Oklo Aurora** (Microreactor)
				meltdown-proof.	

Table 2: Deployment, scale, and safety comparison. NuScale and BWRX-300 are **most deployment-ready** (late 2020s) with proven tech and solid supply chains, whereas X-energy and Holtec are **slightly further out** but offer unique advantages (high temp and flexibility for Xe-100; compactness and cooling options for SMR-160). Oklo Aurora, while intrinsically safe due to its tiny size, is **not suited for large-scale deployment** and is far behind in licensing.

Recommendation for Phase 2 & 3

Considering the above comparisons, the top SMR architecture(s) for the Heber Campus Mega Project are identified based on **compatibility with the campus's integrated energy needs, deployment timeline, and overall risk**. Key drivers include the need for **high-grade steam for SOEC hydrogen and ammonia production (thermal integration)**, the desire for **minimal EPZ to allow on-campus siting**, and achieving the **1.0–1.5 GW capacity** within the project timeframe.

After weighing all factors, **two leading candidates** emerge, with a preference depending on prioritization of near-term readiness versus optimal thermal integration:

- **1. X-energy Xe-100 – *Recommended as the top architecture for Phase 3 (1.5 GW) and possibly Phase 2***: The Xe-100 HTGR is the **best fit for integrated electricity + chemical production**. Its 750 °C outlet and 565 °C steam can directly drive high-efficiency hydrogen generation and other thermal processes [6], which aligns perfectly with the campus's Phase 2/3 plan for SOEC, NH_3, and O_2 production. It offers **excellent cogeneration capability** (supplying both power and district heat) and has the **strongest safety case** (site-boundary EPZ, no meltdown mode) of all options [55] – ideal for placement within or adjacent to an occupied campus. By Phase 2 (~early-mid 2030s), the Xe-100 should be commercially available (with its DOE-backed demo operating by 2030) [50]. For Phase 2's 1.0 GW, ~12–13 modules (3–4 four-packs) can be deployed, and scaled up to ~19 modules by Phase 3 for ~1.5 GW. This modular scaling allows a **phased build-out** matching campus load growth. **Pros:** optimal thermal output for H_2/NH_3, inherent safety, modular scalability, high efficiency, flexible siting. **Cons/Risks:** First-of-kind deployment risk (ensure schedule aligns), HALEU fuel logistics to be secured, cost unknown but expected to decrease with federal support. On balance, if the project can accommodate a slightly later start (to wait for licensing completion) and is willing to be a frontrunner adopter of Gen IV technology, the Xe-100 is recommended as the **primary choice** – it best meets the integrated energy and safety needs of Heber's advanced campus concept. It future-proofs the campus with a state-of-the-art reactor that can supply **both** electricity and process heat efficiently.

- **2. GE Hitachi BWRX-300 – *Recommended as a strong alternative (or complement) for Phase 2***: If the project prioritizes **proven technology and lower execution risk for the initial 1.0 GW deployment**, the BWRX-300 is an excellent choice. By leveraging well-known light-water reactor tech and an aggressive cost-reduction design, the BWRX-300 offers a more **certain near-term deployment** (first unit 2028, multiple units in production by 2030) [21] [20]. It has the **lowest**

projected cost per MW of the options [31] and a very mature supply chain [17], which would make Phase 2 financially and logistically more achievable. While it cannot provide high-grade heat above ~285 °C, it can still contribute to hydrogen production by powering electrolyzers and providing moderate steam for pre-heating. Its **passive safety and expected small EPZ** (likely site-boundary with regulatory approval) [24] make it viable to site on the campus periphery, though slightly more stand-off may be needed compared to Xe-100. For Phase 2, **four BWRX-300 units** (≈1.2 GW) could be deployed to meet the 1 GW target with some margin, and an additional unit added in Phase 3 to reach 1.5 GW. Alternatively, if a hybrid approach is acceptable, BWRX units could supply the bulk of electric power in Phase 2 while a smaller number of Xe-100 reactors are introduced in Phase 3 to supply high-temperature heat for the chemical processes (this combination would mitigate technology risk while still enabling advanced heat usage in later phases). **Pros:** near-term availability, cost-effective, simple & compact plant, known operational profile, strong chance of on-budget/on-schedule delivery. **Cons:** lower temperature output (less efficient hydrogen production), requires multiple units (but manageable at 4–5 units), direct-cycle BWR means slightly more complexity in coupling to heat uses (requires heat exchangers for district heating). Overall, if schedule certainty and budget discipline are paramount for Phase 2, BWRX-300 is a **highly attractive option**; it could be pursued either as the sole solution (with engineering workarounds for heat integration) or in tandem with a pilot HTGR system for specialized high-temperature needs.

NuScale VOYGR and Holtec SMR-160 are also viable but rank just below the above for this specific project. **NuScale** offers proven safety and multi-use flexibility [8], but its lower steam temperature and recent cost escalations make it a slightly less ideal fit for a project centered on high-grade heat utilization (though NuScale's steam reheat concept is promising) [2]. If the campus primarily wanted reliable power and moderate cogeneration with an NRC-certified design, NuScale would be a top contender – however, given the emphasis on SOEC/NH_3 integration, it falls behind Xe-100 in thermal compatibility. **Holtec SMR-160** impresses with its ultra-compact footprint and air-cooling option [73] [43], which could be valuable if water resources or site space are constrained. Its inherent safety and cogeneration ability are strong, and it might become a lower-cost competitor in the 2030s. The main hesitation is its later deployment timeline and lack of full licensing – it's slightly less proven than the others at this point. For Phase 3, if Holtec accelerates (especially with international projects in 2029), SMR-160 could be considered as an alternative to augment capacity (e.g. adding multiple 160 MW units to fine-tune the Phase 3 output beyond what initial reactors provide).

Oklo Aurora is **not recommended** for the main campus generation needs – it simply does not scale to 1–1.5 GW in any practical manner, and its licensing is too uncertain. It could perhaps be revisited in the future for small auxiliary power needs or remote satellite facilities if microreactor tech matures, but it should not be a focus for Phase 2/3 goals.

In conclusion, the **preferred strategy** is to adopt a solution that balances **technological ambition with proven reliability**:

- For an **all-in-one solution**, **deploy X-energy Xe-100 reactors** in a phased approach: e.g. start Phase 2 with a cluster of ~8–12 units (approximately 0.64–0.96 GW) and expand with additional units in Phase 3 to reach 1.5 GW. This yields a state-of-the-art nuclear plant fully synergized with the chemical production block, at the cost of being an early adopter (with federal backing mitigating a lot of risk). The campus would become a showcase for integrated clean energy (electricity +

hydrogen + chemicals), with the Xe-100's high-temperature output maximizing overall efficiency and minimal EPZ simplifying integration with campus operations.

- If a more conservative initial step is desired, **use GEH BWRX-300 for Phase 2** to quickly establish ~1 GW of capacity with a well-understood LWR platform, then **introduce Xe-100 modules in Phase 3** to provide the additional 0.5 GW plus high-grade heat for the chemical plant. This hybrid approach leverages BWRX-300's cost and schedule strengths to meet near-term power needs, while adding the advanced reactor capability in the later phase when it's commercially ready. The BWRX units would supply base-load power and some low-temperature steam (e.g. for district heating or pre-heating electrolyzers), and the Xe-100s would supply high-temperature steam and flexible cogeneration for the hydrogen/ammonia systems. Both designs have small EPZs and could coexist on the campus site (with appropriate siting considerations for independence of safety systems).

Final Recommendation: *Pursue the X-energy Xe-100 high-temperature gas reactor as the primary SMR architecture for the Heber Campus Phase 2/3, given its unparalleled thermal output for chemical processes, inherent safety (tiny EPZ), and modular scalability to 1.5 GW. As a risk-mitigating alternative, consider an initial deployment of GE Hitachi BWRX-300 units to achieve Phase 2 power targets on schedule and budget [23], then integrate Xe-100 reactors in Phase 3 for high-grade heat and additional capacity. Both options far outperform the others in aligning with the project's technical and strategic objectives.* Each offers **decision-grade benefits**: Xe-100 for maximum synergy and future-proofing, and BWRX-300 for execution certainty and economic efficiency. The ultimate choice may hinge on the project's tolerance for first-of-a-kind innovation versus need for proven solutions. On balance, **adopting the Xe-100 HTGR (with potential BWRX-300 support)** positions the Heber Campus to meet its power goals while fully leveraging nuclear energy's capabilities for round-the-clock clean power **and** industrial heat – an integration that will make the campus a flagship of advanced nuclear-enabled sustainability.

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