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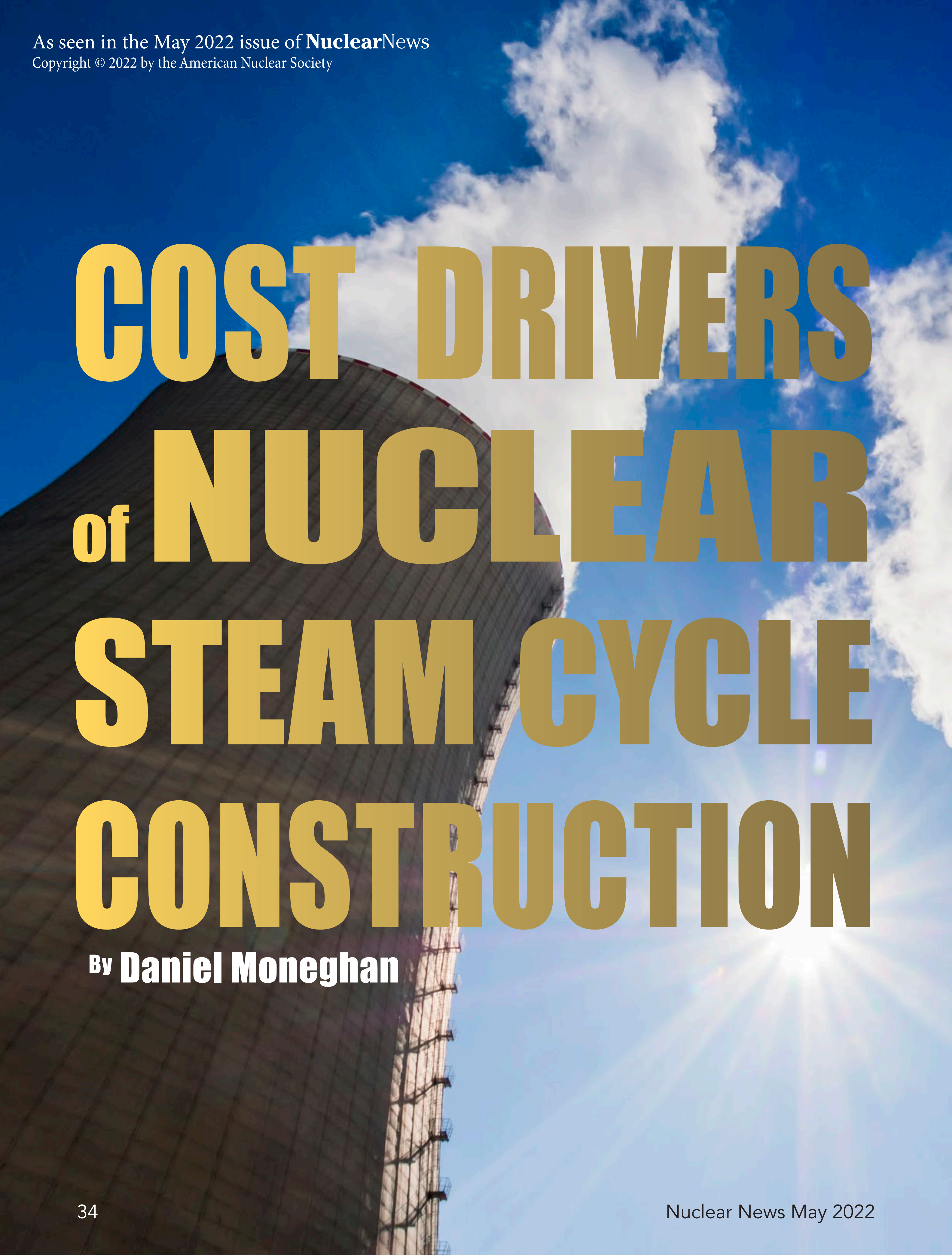

# COST DRIVERS of NUCLEAR STEAM CYCLE CONSTRUCTION

By **Daniel Moneghan**

Interest in reducing carbon emissions around the world continues to climb. As a complement to the increasing deployment of variably generating renewables, advanced nuclear is commonly shown in net-zero grid modeling for 2050 because it represents firm electricity production that can flex in output with load demands.[1] However, these projections are challenged by the high levelized cost of electricity associated with legacy nuclear construction, which is often more than double that of modern combined-cycle gas turbine (CCGT) plants.

While many factors contribute to levelized cost of electricity calculations, around 80 percent of the value for nuclear is derived from the high capital cost.[2] Much of this cost can be related to the construction of the nuclear island (reactor, pipes, pumps, and structures up to and including the steam generator) and the associated quality requirements. For the steam cycle (turbines, pipes, pumps, condenser, and related equipment excluding the steam generator), there are many similarities between fossil and nuclear, yet nuclear steam cycle costs exceed those for CCGT plants. For this article, the Electric Power Research Institute's (EPRI's) Advanced Nuclear Technology (ANT) program[3] compared cost data for typical steam cycles for nuclear, CCGT, and concentrated solar power (CSP) plants.

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## TECHNOLOGY OVERVIEW

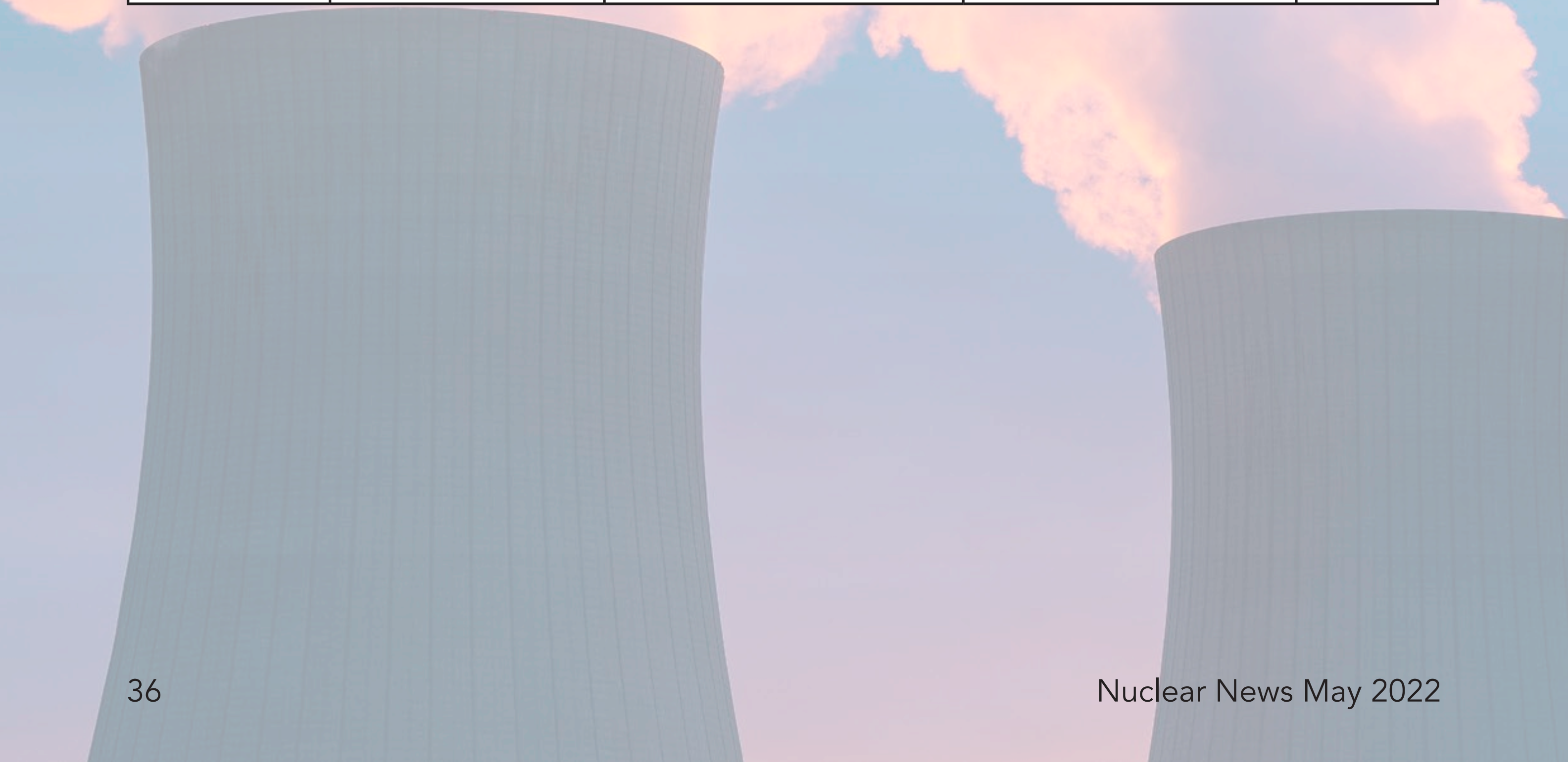
The nuclear plants considered in this study include the pressurized water reactor, drawing on data from Oak Ridge National Laboratory,[4] alongside three advanced reactor technologies: the high-temperature gas reactor (HTGR), sodium-cooled fast reactor (SFR), and solid-fueled molten salt reactor (MSR). A CCGT plant is the second technology category considered—specifically, a 2 × 1 multishaft, meaning the plant contains two gas turbines, two heat recovery steam generators, and one steam turbine. The final technology considered is the CSP plant. Although several configurations of CSP plant exist, they all focus mirrors onto a single line or point, concentrating the energy reflected from the sun. Attributes of these technologies are shown in the table below, a reproduction of Table 4-1 from the 2021 EPRI ANT program report.[3]

## COST DRIVERS FOR NUCLEAR STEAM CYCLES

For this study, representative data were used and scaled to 2019 U.S. dollars. The data supporting analysis for the representative PWR comes from the 1987 Phase IX update report for the Energy Economic Database (EEDB).[5] In previous analyses of this dataset, EPRI's ANT program evaluated potential areas where significant cost savings could be realized for nuclear construction. The most significant reduction in cost to nuclear construction comes from changes to reduce construction duration, as over half of the overnight construction cost is due to labor, two-thirds of which is associated with indirect costs.[6]

**Primary loop temperatures to steam generators for considered generating technologies.[3]**

| Technology | Primary Fluid | Steam Generator Outlet Temperature (°C) | Steam Generator Inlet Temperature (°C) | Power (MWt) |
|---|---|---|---|---|
| **Currently Deployed Nuclear Power Technology** | | | | |
| PWR | Water | 290 | 330 | 3417 |
| **Reference Power Cycles** | | | | |
| CCGT | Gas turbine exhaust | 90 | 590 | ~900 |
| CSP | Molten nitrate salt | 290 | 550–650 | ~310 |
| **Non-LWR Nuclear Technologies** | | | | |
| HTGR | Helium gas | 325 | 750 | 625 |
| MSR | F-Li-Be molten salt | 550 | 650 | 320 |
| SFR | Liquid sodium | 266 | 480 | 1475 |



In this analysis, only systems, structures, and components (SSCs) that are comparable between the three generating technologies' steam cycles were considered. The EEDB cost data were compared to data for CCGT plants and data for CSP plants taken from a National Renewable Energy Laboratory study.[7]

When considering direct costs, all generation sources appear comparable. The CSP cost may be due to the inclusion of more costly air-cooled condenser and emergency diesel backup power systems factored into the direct cost, whereas the CCGT and PWR include water-cooling systems. Despite this, major differences between the PWR and CCGT plants are not apparent until the indirect costs are considered. The primary cost drivers for the PWR disparity will be addressed individually.

**Construction duration** is one of the key differences between these three technologies. CCGT plants are constructed over two and four years and CSP plants are estimated to take three years, whereas historical PWR construction averages over seven years. It has been shown that a 10 percent increase in construction duration leads to estimated overnight cost increases of 18 to 22 percent.[8] Unlike direct costs, which tend not to increase with delays, indirect costs such as office engineering or quality control will scale proportionally with delays, impacting cost disproportionally with schedule overruns.

**Quality requirements** are different for each of these technologies. While the entirety of the steam cycle in a nuclear power plant is not safety related, the quality requirements imposed by nuclear regulators often lead to owners electing to use more costly components for systems that don't strictly require them. This can drive up costs in a variety of ways. One of the more anecdotally understood is that of "quality creep," wherein safety-related components, such as high-strength rebar, are procured for use in both safety- and non-safety-related parts of the plant to avoid accidental use of lower-quality components in safety-related areas.

**Construction experience** was identified as the final primary cost driver for steam cycles. After the completion of Shearon Harris in the 1980s, no new nuclear construction was initiated until 25 years later, with V. C. Summer Units 2 and 3 and Vogtle Units 3 and 4. The experienced workforce that stood up the near entirety of the operating fleet had retired, and with them went much undocumented knowledge.

## COST REDUCTION OPPORTUNITIES

Several convenient strategies exist to reduce cost for the nuclear steam cycle based on the intersection of identified cost drivers. Reducing construction duration and right-sizing quality requirements can be addressed together with techniques like standardization and simplification.

**Standardization**, or heavy reuse of design, is what allows many industries to rapidly deploy facilities. The CCGT market at several points has applied large design reuse to design and deploy plants within short timescales; reuse has played a clear part in their success at bringing construction times down to around three years. The successful nuclear deployment in various parts of the world between 1966 and 2002 saw that those regions where standardization practices were adopted had a reduction in construction lead times and overnight capital costs.[9]

**Simplification** is one contributor to the reduced cost of CSP and CCGT plants compared to nuclear. While water-cooled reactors cannot take advantage of the simplification that superheated steam cycles permit, a reduced complexity in feedwater heating is potentially viable for future designs. Non-water-cooled reactors that operate at higher temperatures may also be able to use a similar steam cycle design to a CCGT plant, with the removal of moisture-separating equipment in favor of a simple reheat mechanism.

EPRI proposes the concept of *separation of the nuclear island* to address several of these cost drivers. By developing the technical basis for decoupling of the nuclear island, the balance of plant can be shown to be non–safety related. This approach could allow for separate construction and operation practices to be in place on each "side" of the plant. Construction staff experienced with CCGT balance of plant can be brought on to build that portion of the plant, with all the experience developed over decades and dozens of projects, allowing the nuclear safety culture to be applied to specifically the safety-related nuclear island. This could reduce costs from quality creep in addition to reducing construction duration.

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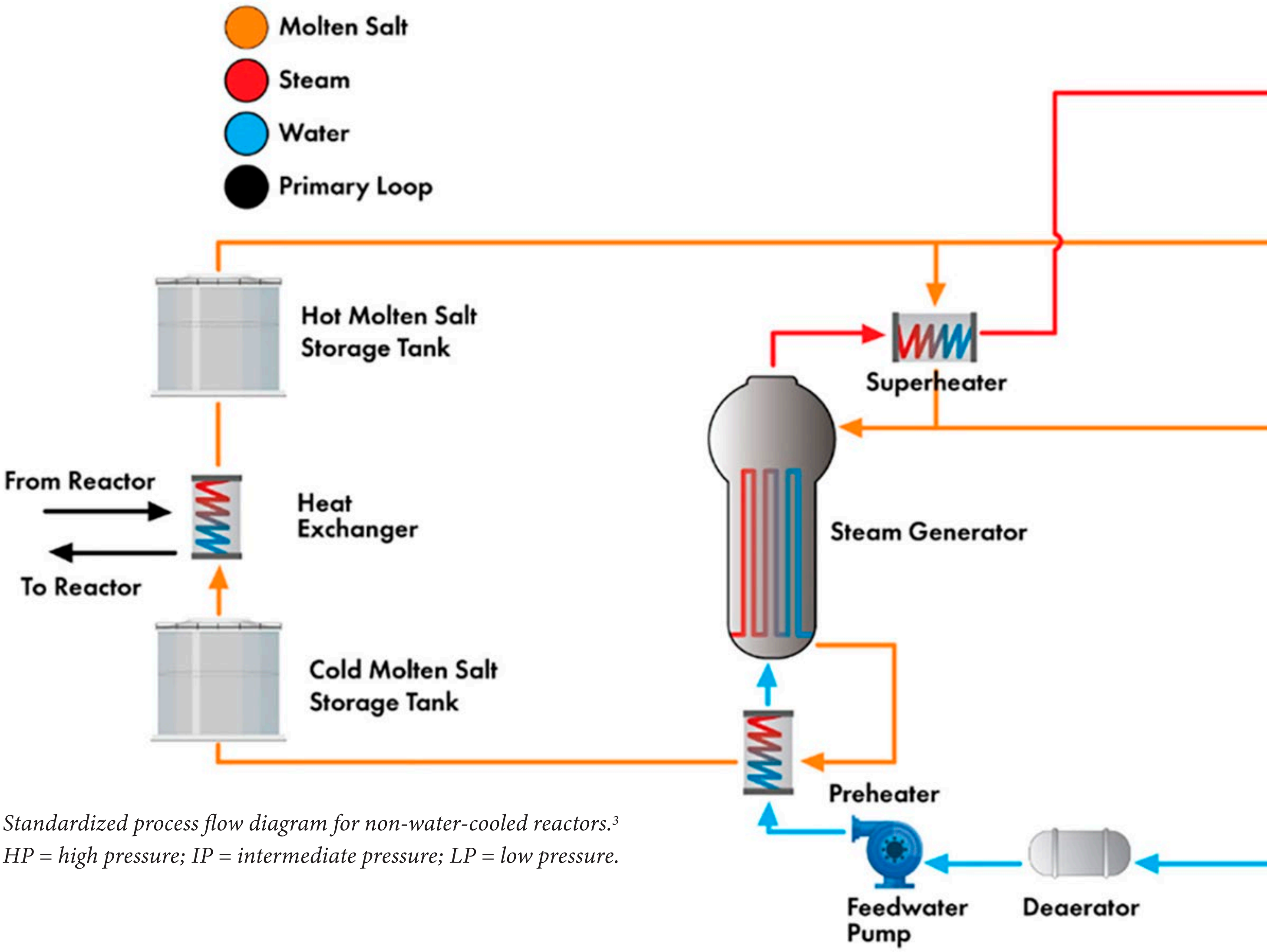


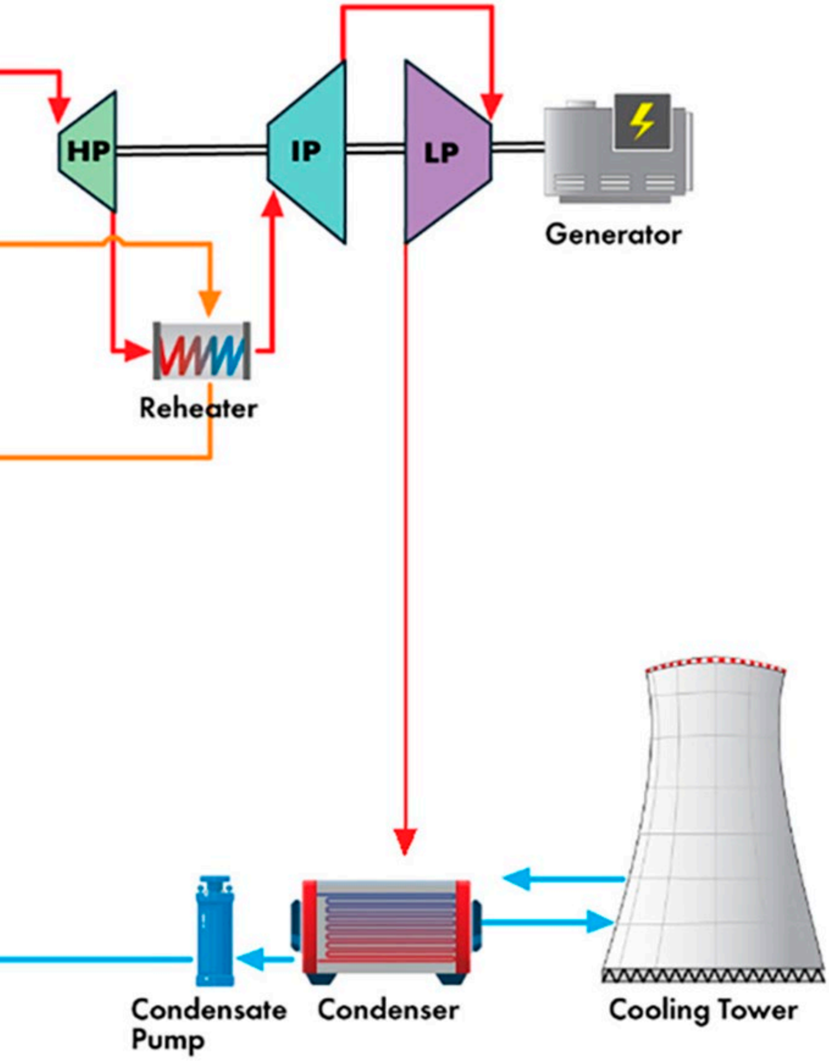
*Standardized process flow diagram for non-water-cooled reactors.*[3] *HP = high pressure; IP = intermediate pressure; LP = low pressure.*

## CONCLUSIONS

Taking all of the discussed cost reduction strategies into consideration, it is possible that applying a degree of standardization that enables flexibility in mission is a convenient solution to explore. To that end, EPRI is researching a proposed concept of a typical balance of plant for non-water-cooled reactors that simplifies the SSCs required for operation and could allow for detailed design and construction to be performed by a team experienced with CCGT deployment. The figure above is a high-level process flow diagram showing a proposed typical system, adapted from the 2021 EPRI report.[3]

Despite the differences in outlet temperatures for the higher-temperature advanced reactors, they all satisfy the minimum needed for a molten salt intermediate loop, which can both provide thermal storage and contribute to the decoupling of the nuclear island. The higher temperatures support simplified equipment through the elimination of costly moisture separation systems similar to in a CCGT or CSP plant. The optimization of a more typical set of SSCs could allow for more streamlined development on the part of constructors. Linking this concept to that of a decoupled nuclear island could provide a blueprint to reduce construction duration and cost without creating safety impacts for the nuclear island.

These are some of many possible ways to address the primary cost drivers for the higher overnight cost of nuclear power plant steam cycles. Any solution that can sufficiently reduce construction durations, right-size quality requirements without incident, and develop expertise for the designers and constructors could make a difference in increasing the deployment of nuclear energy around the world.



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