SUSTAINABILITY PROFILE: Nuclear Power Plants

The United States has approximately 100 nuclear power reactors. Globally, there are around 450. In 2019 22.9% of US electricity came from nuclear power. 61.7% of non-carbon emitting electricity came from nuclear power. Yet, because of questions of nuclear waste storage, proliferation of nuclear weapons, the expense of new power plants, and especially, nuclear accidents at Three Mile Island in 1979, Chernobyl in 1986, and Fukushima Dai-ichi in 2011 the development of nuclear power in the United States came to a standstill until very recently. A gap of nearly 20 years (between 1996 and 2014) exists where no new power plants were licensed or built. The Watts Bar 2 reactor in Tennessee (a 1.2 GW reactor) became operational in 2016, and the Vogtle 3 and 4 reactors in Georgia (both 1.2 GW reactors) are expected to become operational in 2021 and 2022. Two reactors were to be added to the V.C. Summer Nuclear Generating Station in South Carolina, but this project was cancelled in 2017 due to delays and cost overruns.

While future of nuclear power in the United States is somewhat uncertain, many think that there will be a renaissance of nuclear power as fossil fuel based electricity production are phased out due to concerns about the damage CO_2 emissions are doing to earth's atmosphere, climate, and oceans. While no new nuclear power plants were being built in the US during the past few decades, there were power plants being built in other countries and nuclear scientists and engineers were developing a next generation of power plants that were less expensive to build and were safer to operate.

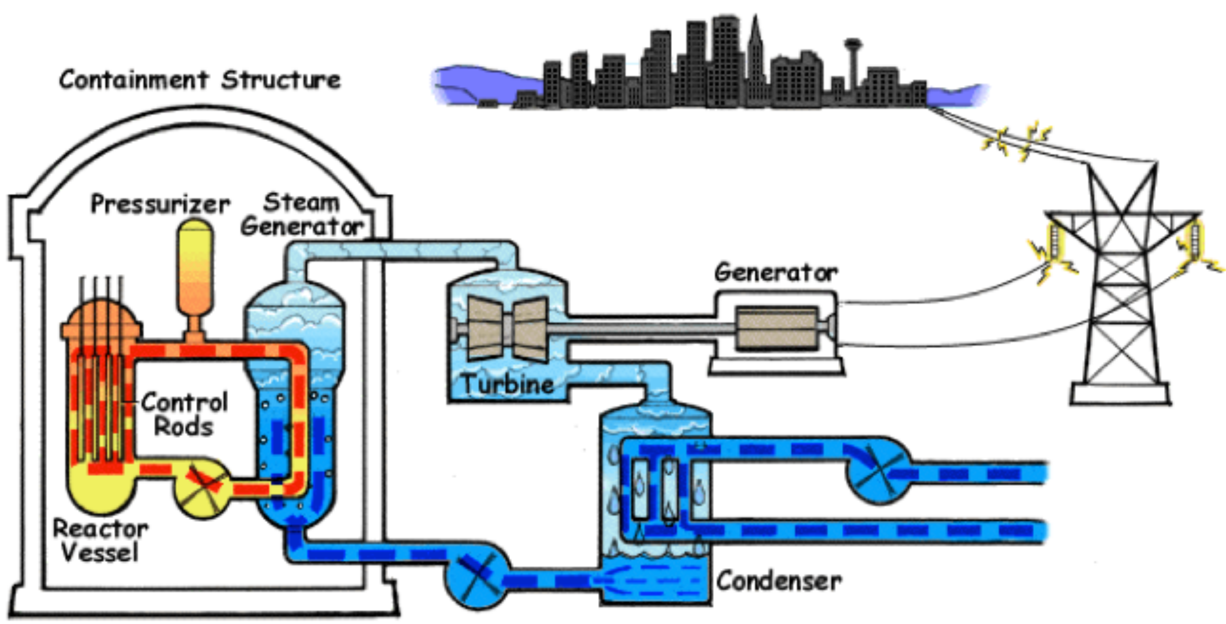

Figure 1. A schematic of a nuclear power plant.

Nuclear power plants are very similar to coal fired power plants. Water is heated to produce high pressure steam which turns a turbine which then turns a generator to produce electricity. The hot water/steam is condensed. The water-steam-water cycle is a closed loop. Cooling water comes from some outside lake, river, or the ocean. Burning coal provides the heat to boil water in a conventional coal-fired power plant, whereas the heat from a nuclear fission reaction provides the heat to boil water in a nuclear power plant. Figure 20.10 in the Burdge and

Overby, *Chemistry: Atoms First* is a schematic of a conventional light water power plant. Figure 1 above shows a similar diagram. The fissionable material ^{235}U must be enriched from 0.7% to 3-4% in the naturally occurring uranium ore which is mostly ^{238}U and not fissionable. In a thermal (or slow) reactor the neutrons are slowed down by a moderator (usually water) in order to more efficiently be captured by the ^{235}U nucleus and then fissioned. Control rods made of cadmium, boron, or carbon capture some of neutrons emitted by fission reaction and allow the reaction to be controlled. The water in the reaction vessel is high pressure liquid water that is pumped through the reactor vessel. This water carries heat from the reactor vessel to the steam generator. Notice that the water that comes in contact with the nuclear fuel and subsequent nuclear waste never comes in direct contact with the water that is converted to steam which drives the turbine. Only heat is exchanged between the two water lines.

NuScale Power has developed small modular reactors (SMR). These reactors are light water reactors but are smaller and produce under 100 MW in power (compared to 1 GW). They can be mass produced in a factory and shipped by truck or rail to the power plant. Several can be co-located to provide more power typical of municipal power plants.

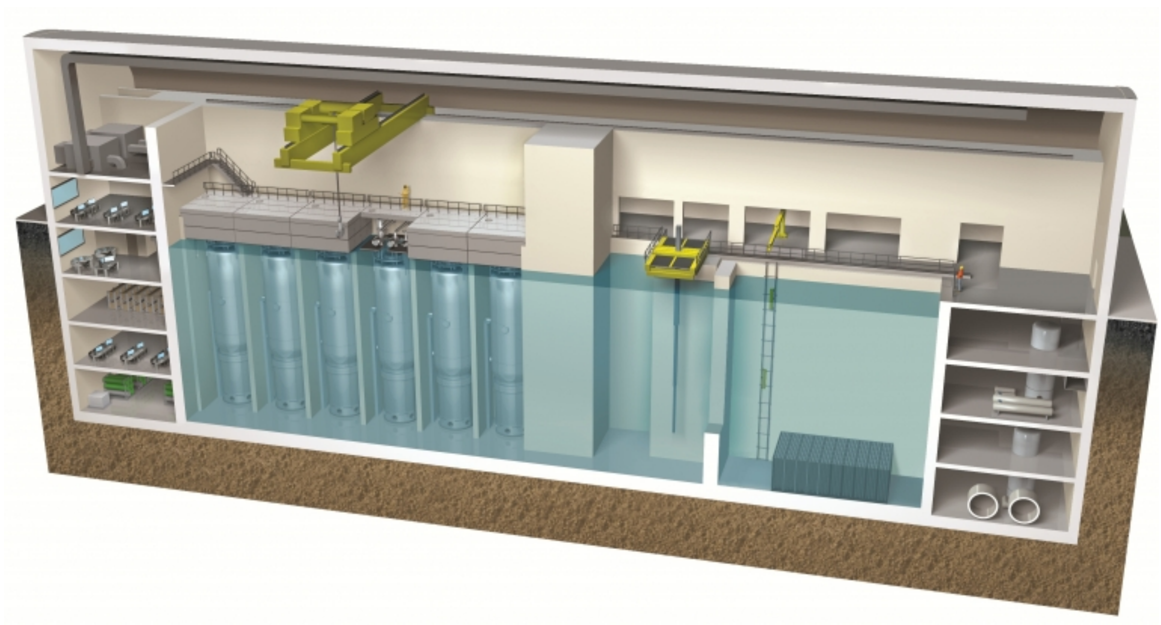

Figure 2. A NuScale Small Modular Reactor. Each cylinder in the left underwater compartment is a small nuclear reactor that can be robotically loaded (and unloaded/reloaded) with nuclear fuel. See the video to see the SMR in operation.

See http://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors and https://www.nuscalepower.com for more information. The Nuclear Regulator Commission (NRC) is currently reviewing NuScale’s license application. The first power plant is expected to be operational in the mid-2020s.

Newer designs, called 4th generation reactors, have slightly different features in the reactor part of the power plant. The very-high-temperature reactor (VHTR) is shown in Figure 3. The reactor is cooled by helium gas or by molten salt. Nuclear reactor accidents have been primarily due to the liquid water being overheated and decomposing into hydrogen gas and oxygen gas. The hydrogen gas explodes and destroys the containment building and spreads

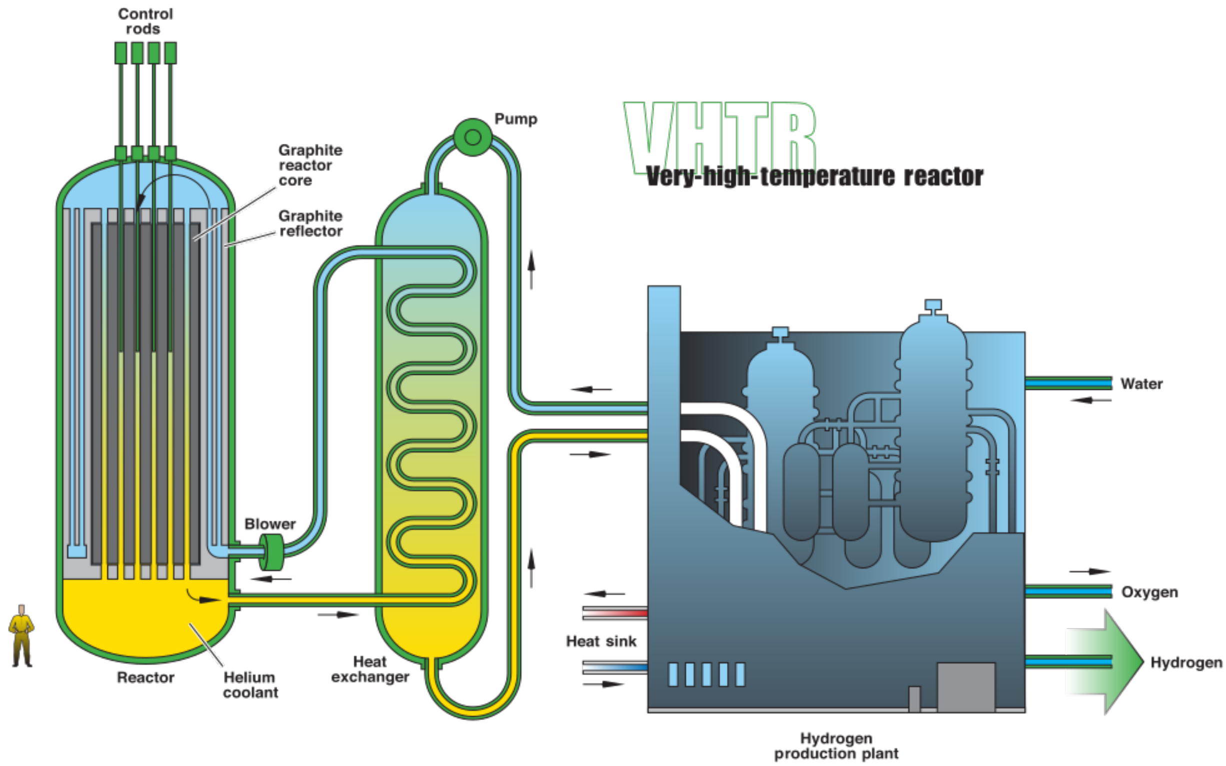

Figure 3. A schematic of the very-high temperature reactor. Schematic from US Department of Energy Nuclear Energy Research Advisory Committee/Public Domain.

radioactive material from the fuel rods or the core. These newer designs can achieve high temperatures at much lower pressures and vastly reduce the danger of these hydrogen explosions. In addition to producing electricity, because these reactors operate at higher temperatures the VHTR is able to produce hydrogen gas via the thermal decomposition of water in a facility removed from the reactor itself or provide high temperature heat for other applications. This reactor uses a once-through uranium fuel cycle similar to what is found in light water reactors. A once-through fuel cycle means that fuel rods (or fuel containing pebbles) are used once and then replaced in a refueling step. Typically, once used these fuel rods or pebbles are further encased and simply stored as nuclear waste.

The molten salt reaction (MSR) utilizes molten salt as the coolant and in some designs the fuel itself is mixed with the molten salt. In molten salt reactors molten salt coolants allow for high temperatures at low pressures thus increasing the safety of the reactors. If the uranium or thorium fuel is dissolved in the molten salt then a temperature increase that may result from a loss of active cooling would dissipate in the molten salt coolant and expand the fuel/molten salt mixture to achieve a non-critical mass in which the nuclear reaction would stop. As shown in Figure 4 some designs include a freeze plug which would melt if the reactor core overheated and the fuel/salt mixture would drain into emergency dump tanks and passively cool, also achieving non-criticality and stopping the reaction. A closed fuel cycle is possible where the fuel/salt mixture can be pumped to a chemical processing unit to add new fuel and remove fission waste products without ever shutting down the reactor. These reactors can also use thorium and transuranium products normally associated with breeder reactors as fuels.

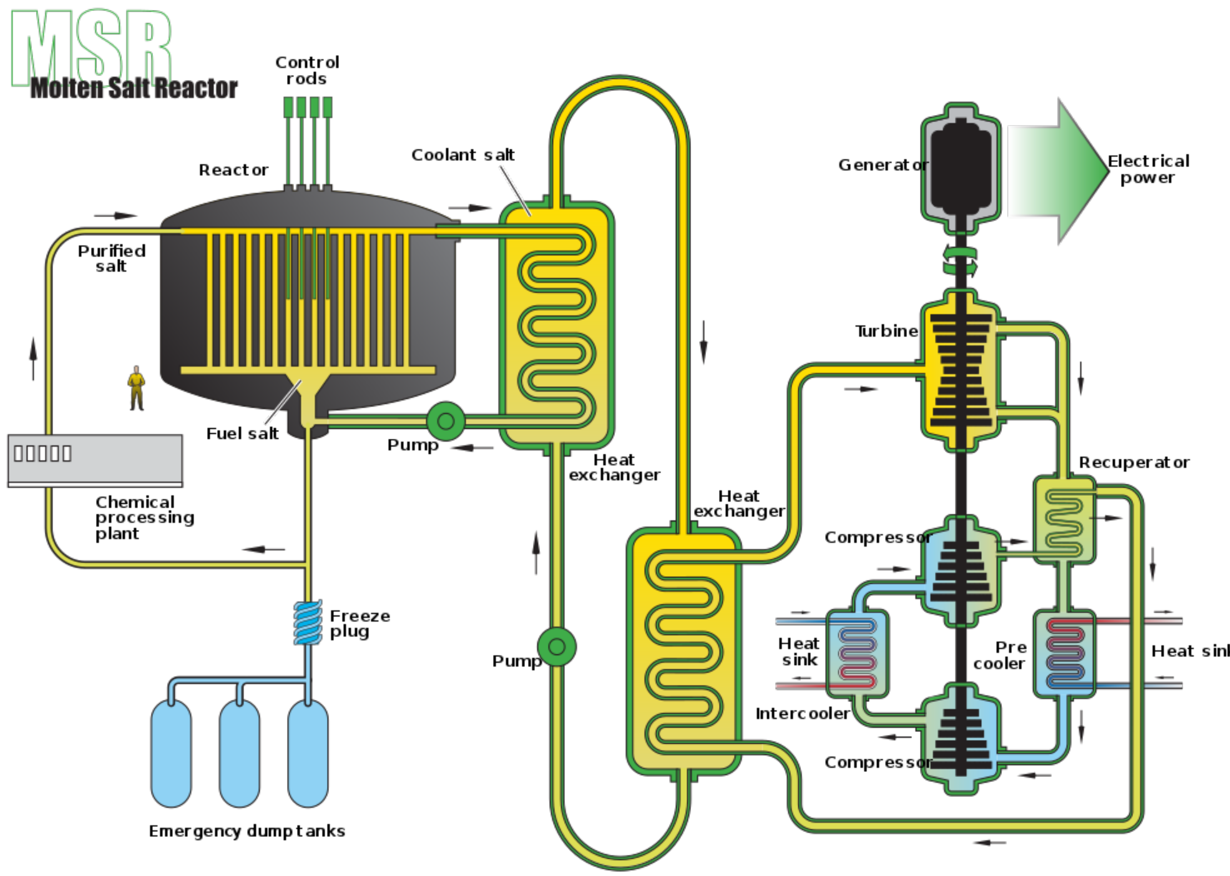

Figure 4. A schematic of a molten salt reactor. Schematic from US Department of Energy Nuclear Energy Research Advisory Committee/Public Domain.

Sodium-cooled fast reactors (SFR) are breeder reactors that produce more fissionable material than they consume (see Figure 5). Breeder reactors use high energy (fast) neutrons to convert non-fissionable ^{238}U into ^{239}U which transmutes into ^{239}Pu which is fissionable. They can also convert non-fissionable ^{232}Th into ^{233}Th which transmutes into ^{233}U which is fissionable. The higher energy neutrons also produce other transuranium elements that can be fissioned or transmuted into fissionable material. These sorts of reactor can also use spent nuclear fuel (SNF) from light water reactors (our repository of nuclear waste) and use it as fuel thus providing a partial solution to the nuclear waste problem. SFRs operate at high temperature but at low pressure making them safer in that regard than the high pressure water used in light water reactors or super-critical water cooled reactors. The fuel (labeled “core” in Figure 5) expands as the temperature increases and this slows the reaction down so the nuclear reaction passively stops in the absence of a cooling system. A 7:40 video clip of this style of reactor was featured in the documentary *Pandora’s Promise*. The traveling wave reactor funded and discussed by Bill Gates in this 6:21 2010 TED talk. Gates envisions a 60 year underground reactor that produces very little waste and requires no refueling.

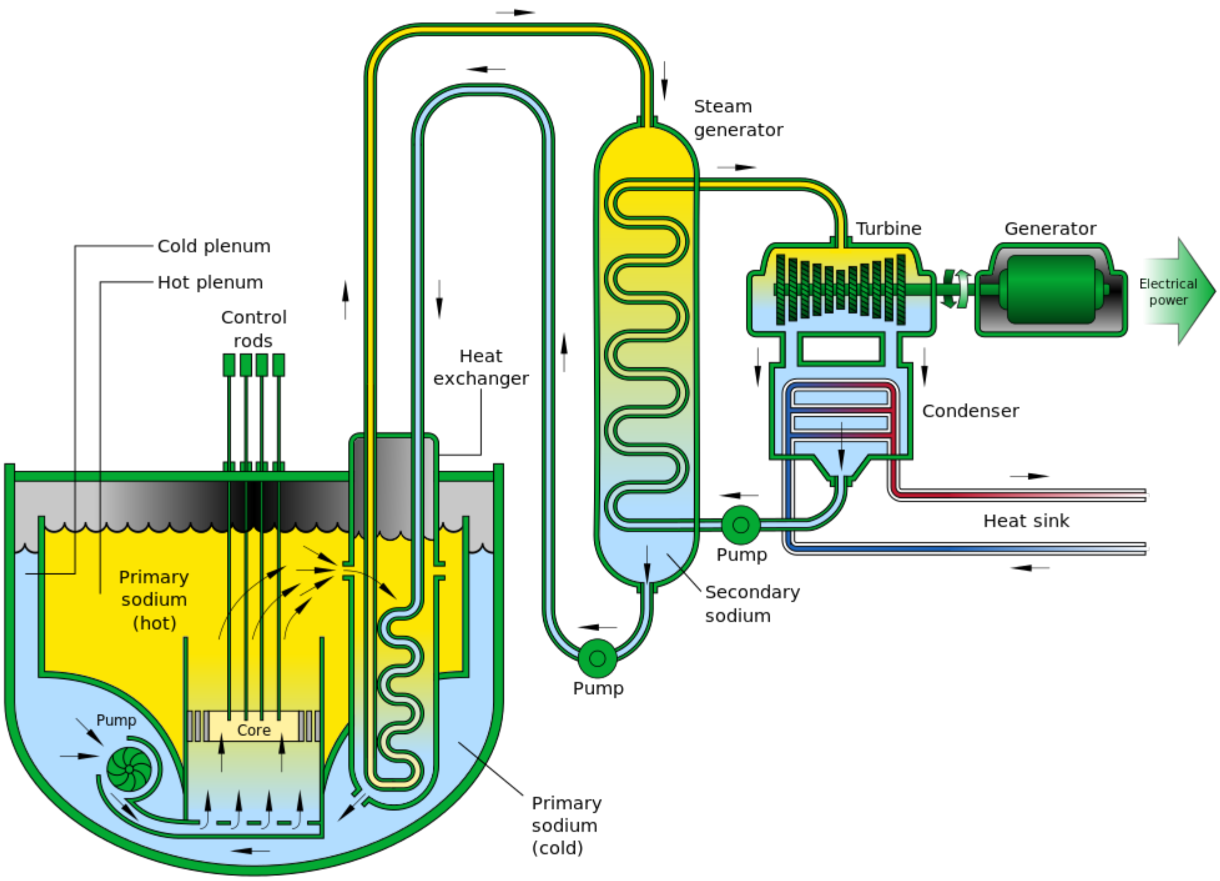

Figure 5. A schematic of a sodium cooled fast reactor. Schematic from US Department of Energy Nuclear Energy Research Advisory Committee/Public Domain.

Learning Goal

Identify the components and function of different parts of a conventional nuclear power plant (Figure 20.10) and the so-called next generation reactors. (20.5 + this handout)

Study Questions

1. What is the role of the nuclear reaction in a nuclear power plant?
2. What do each of the following components do in a nuclear reactor: fuel rods, core, control rods, reactor, steam turbine, generator, condenser?
3. What is the main advantage of a small modular reactor?
4. What are the advantages of a molten salt or liquid metal reactor compared to one that uses water as the primary coolant?
5. How can a fast reactor like a liquid metal reactor reduce the amount of nuclear waste produced? Or use up previously produced nuclear waste?
6. What is the difference between active and passive safety features in a nuclear power plant?
7. What is meant by the term “breeder reactor”?
8. What is the difference between a “once through” fuel cycle and a “closed” fuel cycle?