X-Energy: XE-100 REACTOR THE KEY TO AN INTEGRATED ENERGY SYSTEM, RELIABLE BASELOAD, AGILE LOAD FOLLOWING, INDUSTRIAL APPLICATIONS

Prepared by Yvotte Brits and Jordan Crowell, of X-Energy, LLC, founded in 2009 by Dr. Kam Gaffarian to pursue energy solutions to alleviate energy poverty and climate impact, is developing Gen-IV High-Temperature Gas-cooled Reactors (HTGR) and the TRISO fuel that powers them.

1.1 Introduction

X-energy is an advanced reactor & fuel design engineering company developing Generation IV high-temperature gas-cooled (HTGR) nuclear reactors and the TRISO-X fuel to power them. The two reactor designs – the Xe-100 and the Xe-mobile – meet a wide range of energy needs across a variety of geographic conditions.

With designs that build on generations of innovation and some key principles – safety, simplicity, affordability and versatility – the X-energy advanced reactor and fuel solutions meet the world's growing demand for low-carbon energy to power a sustainable future. In 2019, X-energy brought this world-class advanced nuclear technology to Canada to meet the country's clean energy goals. Canada's X-energy will also serve as a catalyst for development of a Canadian SMR industry that will work with partners globally to do the same for people around the world.

The Xe-100 in particular, the focus of this article, is a 200 MWth pebble bed gas-cooled reactor: an 80 MWe reactor that can be scaled into a 'four-pack' 320 MWe power plant. With its modular design, the scale can grow even larger as needed.

Its unique reactor and fuel design combination provide unprecedented opportunities for flexible electricity generation, process heat application and co-generation possibilities in the following ways:

- As part of a low-carbon electricity grid, the reactor provides reliable baseload power with highly agile load following, making it an ideal partner technology with variable renewables as a foundation to building a clean-infrastructure economy; and
- Producing high quality steam at 565°C that can readily provide co-generation opportunities and support an optimized integrated energy system through various applications such as mining, petroleum applications, hydrogen production, desalination, agriculture, and district heating.

1.2 A Powerful Combination: The XE-100 and TRISO-X Fuel

The Xe-100 has been designed from the outset with fundamental requirements to be simple, affordable, safe, and secure, in addition to being highly flexible. Xe-100 was designed to adjust power output based on demand without compromising plant integrity throughout its 60-year lifespan, which helps provide a good return on investment.

The Xe-100 is powered with tri-structural isotropic (TRISO) fuel. X-energy has designed and is fabricating TRISO-X, a proprietary TRISO fuel with demonstrated superior consistency.

It is composed of uranium oxycarbide fuel kernels, which are surrounded by four barrier layers. These four barriers include a porous carbon buffer, inner pyrolytic carbon, silicon carbide, and an outer pyrolytic carbon layer. Figure 1 shows the fuel that will be used in the Xe-100 reactor, and the reactor itself. Current analysis and testing are proving that this fuel is capable of very high (>99.99%) fission product retention under all postulated conditions.

Because of the incredibly robust fuel design, the Xe-100 addresses safety intrinsically, guarantees that fuel melting is not possible, and is 100% walk-away safe.

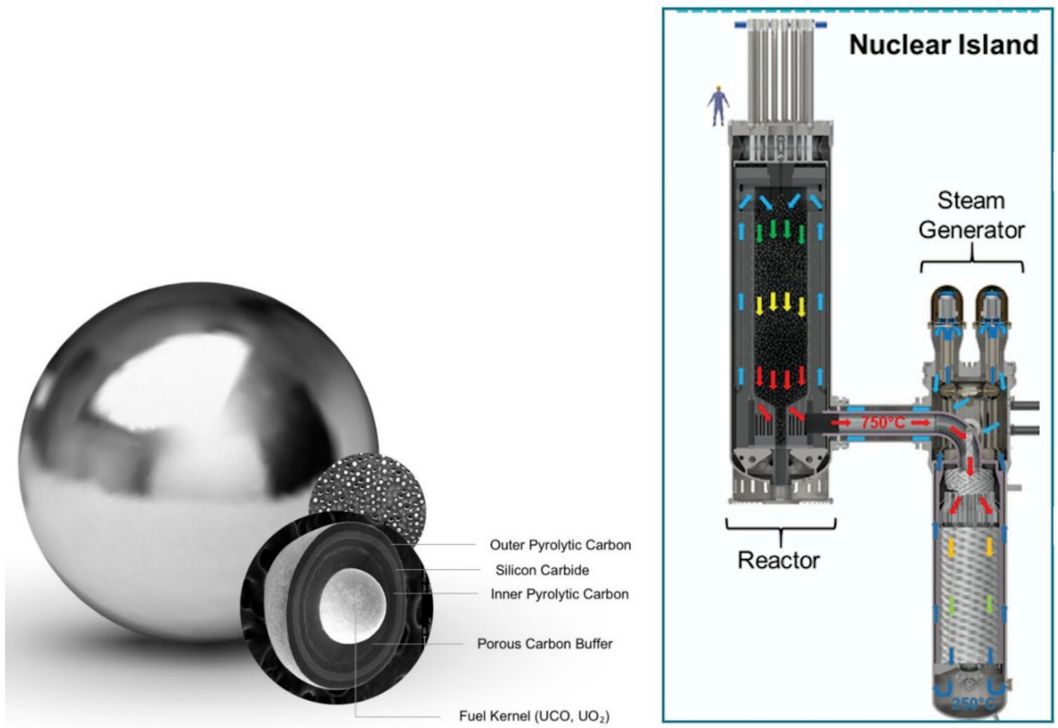

Figure 1: TRISO-X Fuel to be used in Xe-100, along with Xe-100 reactor.

1.3 Load Following

The Xe-100's control logic and approach contribute to its automated load-following capabilities. The helium circulators, for example effectively adjusts the helium mass flow for purposes of on-line load demand changes within a given band width of load follow operations. It can power down from 100% to 40% of full power (FP), and then back up to 100% FP, at a ramp rate of 5% per minute (X-energy, 2017a). One of the high-value attributes of the Xe-100 is a 60-year design life. Since load following does not require significant temperature or pressure cycles in the reactor, the required 60-year design life is not impacted (X-energy, 2017b).

The control approach for load following is based on controlling three things:

1. Power output of the turbine generator;
2. The speed of helium and feed water pumps; and
3. The control rod positions (see Figure 2).

As one of these three variables in the system changes, the rest of the system responds by adjusting each controlled variable back to its set-point. If the power output of the turbine generator is required to increase (i.e., increased load demand), then the speed of the helium and feed water pumps, along with the control rod positions will adjust to ensure that the reactor can operate safely while allowing the turbine generator to increase its power output. Ramping speed (i.e., how quickly the turbine generator can increase its power output) is achieved by opening and closing the main steam valve on the turbine, as demonstrated from load-following transient analyses (X-energy, 2017a).

The main steam valve is the single contact point for turbine control. This valve will open or close to accommodate the demand from the grid following that change through the rest of the system adjusting reactor power to follow suit.

As an example, if the load were to drop from 100% FP to 60% FP, recognizing the reduced load demand, the main steam valve will respond by slightly closing to reduce the quantity of steam entering the turbine. This reduction in steam will reduce the force on the turbine blades and result in a decrease of power output. With the main steam valve closing, the result is a slight rise in the main steam pressure as it leaves the steam generator.

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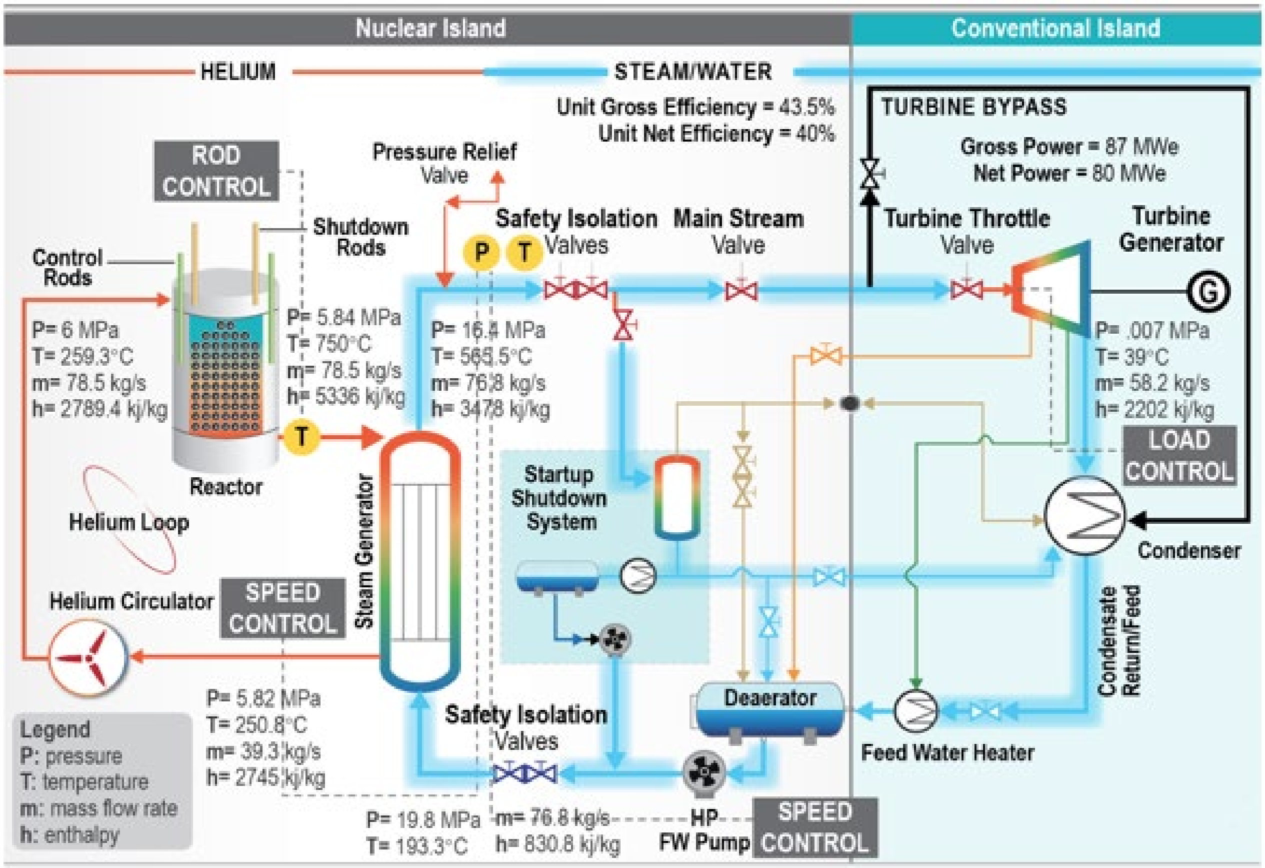

Figure 2: Xe-100 Control Approach, showing the five main control loops.

The main steam pressure is brought back to its set-point of 16.5 MPA by manipulating the speed of the helium circulator. The main steam temperature is maintained at 565℃ by controlling the high-pressure feed pump speed, and the feed water temperature is maintained at around 208℃ by controlling the turbine extraction steam valve, which controls the pressure.

Finally, the control rods are adjusted up or down to maintain the reactor outlet temperature at 750℃. In this scenario, the control rods would lower further into the core to reduce reactivity. With the drop in thermal power of the reactor core, the helium circulator speed would need to decrease to maintain the reactor outlet temperature at 750°C. (This is based on the equation $\dot{Q} = \dot{m} c_p \Delta T$, where $\dot{Q}$ is the reactor thermal power, $\dot{m}$ is the mass flow rate, c_p is the heat capacity, and ΔT is the change in temperature. The five different controls loops can be seen in Figure 2.

The only external input is the command to the turbine throttle valve (i.e., the main steam valve) to perform a ramp rate at 5%/min from 100% - 40% FP and back to 100% FP. It is evident that the turbine power follows the turbine throttle valve closely and that the main steam temperature and pressure are well controlled (X-energy, 2017a).

With this agile load following capability, the Xe-100 can provide baseload power to complement intermittent renewables such as wind and solar. Figure 3 shows a simulation demonstrating the flexibility of the Xe-100 to serve as backup power to renewable sources complementing their availability.

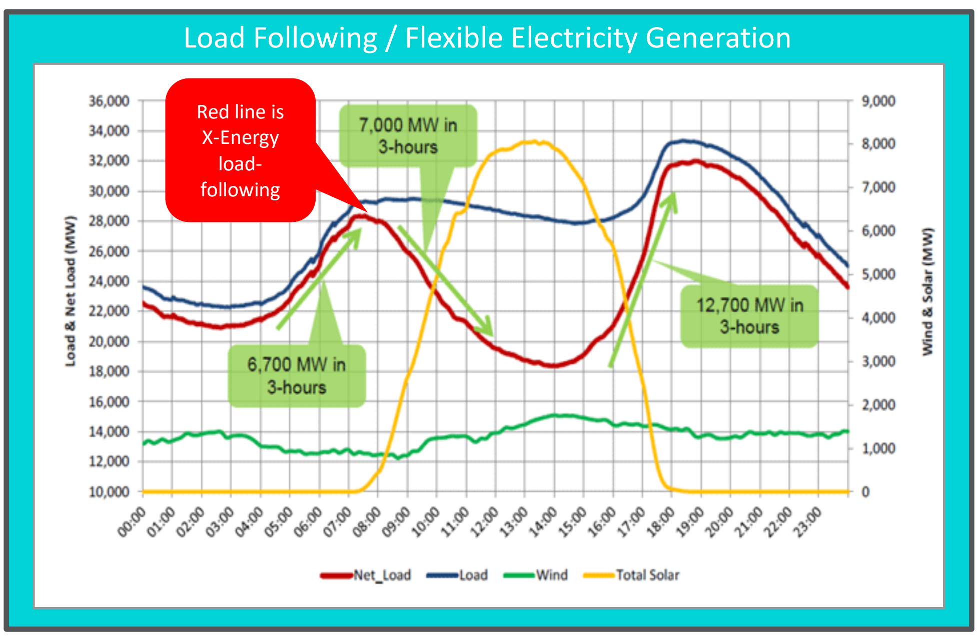

Figure 3: The graph is an actual simulation of typical loads and the ability of the Xe-100 to follow.

1.4 Applications of the XE-100 Plant

The Xe-100 high quality steam at 565°C can readily support and optimize an integrated energy system through co-generation and various applications such as mining, petrochemical applications (such as oil sands), hydrogen production, desalination, agriculture, and district heating (see Figure 4).

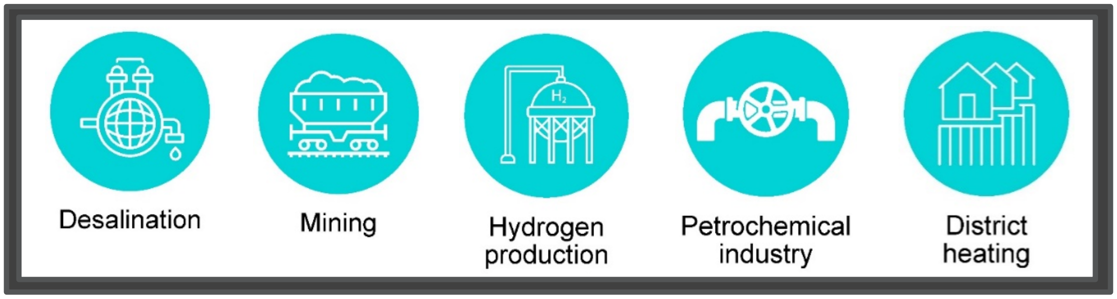

Figure 4: Process heat applications for the Xe-100.

A potential major application of the Xe-100 in Canada is to use its process heat to support the recovery of oil from the oilsands. This is a clean alternative to using large volumes of natural gas to create steam to extract oil, which is carbon intensive (Duffey & Millera, 2016). The Xe-100 presents a great opportunity, due to its higher steam temperature and the flexibility to site closer to the demand.

The electricity from the Xe-100 and/or the steam produced can be used to produce clean hydrogen for various applications. An immediate application would be for fuel cells in transportation, such as trains, buses, and automobiles. There are three main processes of stimulating electrolysis of water and producing hydrogen (O'Brien, et al., 2010), which include using: 100% electricity, varying amounts of electricity and heat, or 100% heat. Using process heat alone to split water into its constituent components (H_2 and O_2), the efficiency increases as the temperature of the added heat increases (O'Brien, et al., 2010). Based on research performed by Idaho National Laboratory (INL), the Xe-100 plant could have hydrogen production efficiencies in the range of 30 – 40% (O'Brien, et al., 2010).

Using the process heat from the Xe-100 plant for thermal desalination would be a highly-effective application. According to the IAEA, the heating requirements for thermal desalination range between 100°C and 130°C (International Atomic Energy Agency, 2017). The Xe-100 Plant can be configured in a co-generation configuration where steam is tapped from the lower turbine stages to provide the 100°C to 130°C process steam, resulting in both electricity and process steam for desalination to be produced.

The Xe-100 can support various aspects of the agricultural industry such as greenhouses. Heat from the Xe-100 plant could be siphoned off to provide sustainable heat to greenhouses allowing food production year-round in colder climates. Using process heat to support various uses is not a foreign concept in Canada. Though dismantled later on, Ontario Hydro (the predecessor to Ontario Power Generation) demonstrated through the Bruce Bulk Steam System and the Bruce Energy Centre that process heat can be used in various applications such as heavy water production and local district heating, including greenhouses and other potential industrial applications (International Atomic Energy Agency, 2017).

1.5 Summary

The Xe-100 has noteworthy characteristics providing flexibility of operation and application. In addition to Xe-100's agile load-following capabilities, it can be integrated in a broad variety of geographies, energy uses and industries. The Xe-100 is ideal for an integrated energy system where it can flexibly optimize power and process heat production to integrate with other energy sources. It can meet diverse on-grid and off-grid energy needs, including load-following for greater grid stability, multiple process heat applications, and co-generation opportunities. As a result, the Xe-100 supports the energy goals of providing clean and affordable energy while at the same time supporting other industries. Finally, and consistent with the goals of X-energy's founder, the Xe-100 is an energy source that can provide clean electricity, home heating, food production, and clean drinking water to contribute to the quality of life for people globally, wherever they may live.

For more information on X-energy and the Xe-100, please go to https://x-energy.com/.

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