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ПЕРЕМЕННАЯ ЭЛЕКТРОЭНЕРГИЯ С РАБОТОЙ РЕАКТОРА БАЗОВОЙ НАГРУЗКИ

VARIABLE ELECTRICITY WITH BASE-LOAD REACTOR OPERATION

Аннотация: Другой способ хранения энергии для обеспечения переменного электроснабжения при работе реактора в режиме базовой нагрузки предложен Чарльзом Форсбергом из Массачусетского технологического института, основанный на последних технологиях и исследованиях, предложенных Форсбергом и др. в рамках проекта по комбинированному циклу с использованием воздуха и Брайтона на основе ядерного топлива, который является результатом непрерывного сотрудничества [1].

Цель их сотрудничества — не только работа в условиях низкого уровня выбросов углерода и использование таких источников энергии, как ядерная, но и рассмотрение других возобновляемых источников энергии, таких как ветер, солнечная энергия и водород, получаемый с помощью сверхвысокотемпературного реактора (VHTR) атомной электростанции нового поколения в сочетании с установкой по производству водорода (HPP) в условиях сосуществования.
Ключевые слова: Электростанция, воздушный поток, турбинная система, пар, природный газ, реактор, прототип, газотурбинная система.

Abstract: Another way of storing energy to meet a variable electricity with base-load reactor operation is suggested by Charles Forsberg of MIT based on recent technology and research suggested by Forsberg et al. On Nuclear Air-Brayton Combined Cycle which is a continuous collaboration [1].

The goal of their collaboration is not only to deal with a low-carbon world and use the energy sources such as nuclear but also to look at other means of renewable energy source such as wind, solar, and hydrogen produced by means of very-hightemperature reactor (VHTR) of next-generation nuclear plant coupled with hydrogen production plant (HPP) in a coexisting circumstance.
Key words: Power plant, airflow, turbine system**,** steam**,** natural gas, reactor, prototype, gas turbine system.

Introduction. The defining characteristics of these technologies are:

1. High capital and low operating costs requiring full capacity operation for economic energy production.
2. Output does not match the variable energy needs by men.

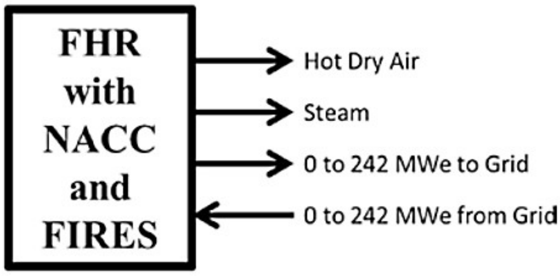

FIGURE 1. Hybrid Renewable Energy Systems. Capability of modular FHR with NACC and FIRES with base-load FHR operation (See references by Forsberg et al).

This challenge suggests a need to develop new nuclear technologies to meet the variable energy needs for low-carbon world while improving economics. Hence, to the above challenge, we have been developing a fluoride-salt-cooled high-temperature reactor (FHR) with a Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES) [2]. The goals are to:

1. Improve nuclear power plant economics by 50–100% relative to a base-load nuclear power plant.

2. Develop the enabling technology for a zero-carbon nuclear renewables electricity grid by providing dispatchable power.

3. Eliminate major fuel failures and hence eliminate the potential for major offsite radionuclide releases in a beyond design basis accident.

Figure 1 shows the capabilities of a modular FHR when coupled to the electricity grid. FHR produces base-load electricity with peak electricity produced by a topping cycle using auxiliary natural gas or stored heat or further into the future using hydrogen. The FIRES heat storage capability enables the FHR to replace energy storage technologies such as batteries and pumped storage—a storage requirement for a grid with significant non-dispatchable solar or wind generating systems.

The FHR is a new class of reactors (Figure 2) with characteristics different from light-water reactor (LWR). The fuel is the graphite-matrix coated-particle fuel used by high-temperature gas-cooled reactor (HTGR) resulting in similar reactor core and fuel cycle designs—except the power density is greater because liquids are better coolants than gases. The coolant is a clean fluoride-salt mixture. The coolant salts were originally developed for the molten salt reactor (MSR) where the fuel is dissolved in the coolant. Current coolant-boundary material limitations imply maximum coolant temperatures of about 700 °C. New materials are being developed that may allow exit coolant temperatures of 800 °C or more. The power cycle is like that used in natural gas-fired plants.

Methods. The fluoride-salt coolants were originally developed for the US Aircraft Nuclear Propulsion in the late 1950s. The goal was to develop a nuclear-powered jet bomber. These fluoride salts have low nuclear cross sections with melting points of 350– 500 °C and boiling points more than 1200 °C—properties for efficient transfer of heat from a reactor to a jet engine. Since then there have been two developments. The first development was high-temperature graphite-matrix coated-particle fuels

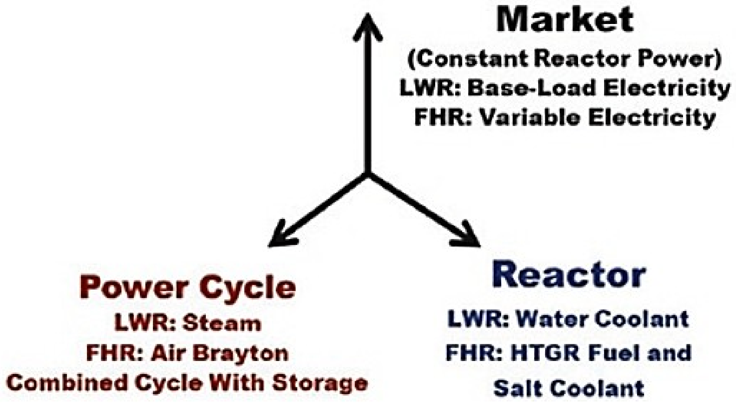

FIGURE 2. Comparison of the LWR and FHR

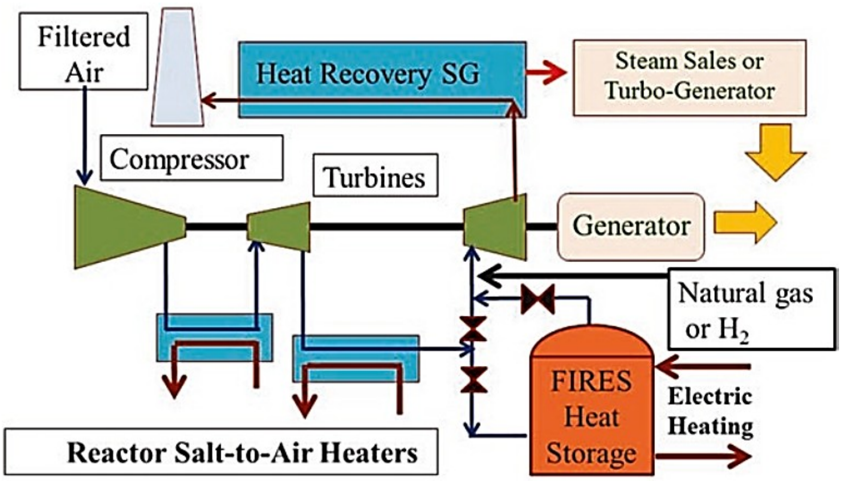

FIGURE 2. Nuclear air-Brayton combined cycle (NACC) with firebrick resistance-heated energy
storage (FIRES)

for HTGRs that are compatible with liquid salt coolants. The second has been a half-century of improvements in utility gas turbines that now make it feasible to couple a nuclear reactor (the FHR) to NACC.

The FHR is coupled to a NACC with FIRES (Figure 3). In the power cycle, external air is filtered, compressed, heated by hot salt from the FHR while going through a coiled tube air heat exchanger (CTAH), sent through a turbine producing electricity, reheated in a second CTAH to the same gas temperature, and sent through a second turbine producing added electricity. Warm low-pressure airflow from the gas turbine system exhaust drives a heat recovery steam generator (HRSG), which provides steam to either an industrial steam distribution system for process heat sales or a Rankine cycle for additional electricity production. The air from the HRSG is exhausted up the stack to the atmosphere. Added electricity can be produced by injecting fuel (natural gas, hydrogen, etc.) or adding stored heat after nuclear heating by the second CTAH. These boost temperatures in the compressed gas stream going to the second turbine and to the HRSG [3].

Since a NACC system looks quite good for a salt cooled reactor, it is worth considering what it might do for a sodium-cooled reactor. With some modifications, it appears that it could be competitive with systems that have been built. A computer model was built based on standard techniques for analyzing Brayton and Rankine systems. System performance was optimized by varying the turbine outlet temperatures for a fixed turbine inlet temperature. A second parameter that can usually be varied to obtain optimum performance is the peak pressure in the steam cycle. For most of the cases considered here, this was held constant at 12.4 MPa (1800 psi) [4].

The stored heat option involves heating firebrick inside a press-tress concrete pressure vessel with electricity to high temperatures at times of low electricity prices; that is, below the price of natural gas. When peak power is needed, compressed air after nuclear heating and before entering the second turbine would be routed through the firebrick, heated to higher temperatures, and sent to the second turbine. The efficiency of converting electricity to heat is 100%. The efficiency of converting auxiliary heat (natural gas or stored heat) to electricity in our current design is 66%. This implies a round-trip efficiency of electricity to heat to electricity of ~66%. Improvements in gas turbines in the next decade are expected to raise that efficiency to 70%. FIRES would only be added to NACC in electricity grids where there are significant quantities of electricity at prices less than the price of natural gas. As discussed later, these conditions are expected in any power grid with significant installed wind or solar capacity.

As we said, much of the FIRES heat storage technology is being developed by General Electric® and its partners for adiabatic compressed air energy storage (CAES) system called ADELE (German abbreviation). The first prototype storage system is expected to be operational by 2018 with 90 MWe peak power and storing 360 MWh. When the price of electricity is low, the air is (1) adiabatically compressed to 70 bars with an exit temperature of 600 °C, (2) cooled to 40 °C by flowing the hot compressed air through firebrick in a prestress concrete pressure vessel, and (3) stored as cool compressed air in underground salt caverns. At times of high electricity prices, the compressed air from the underground cavern goes through the firebrick, is reheated, and sent through a turbine to produce electricity with the air exhausted to the atmosphere.

The expected round-trip storage efficiency is 70%. The ADELE project is integrating firebrick heat storage into a gas turbine system. For NACC using FIRES, the differences are (1) the peak pressure would be about a third of the ADELE project, (2) the firebrick is heated to higher temperatures, and (3) electricity is used to heat the firebrick at times of low electricity prices to higher temperatures. The technology for heat storage integration into NACC is partly under development.

NACC systems can be applied to most of the proposed next-generation systems. Their strongest competitor in terms of cycle efficiency is the supercritical CO2 system. NACC systems will match or better the efficiency of these systems at or above 700 °C. But NACC systems have the competitive advantage of a large customer base for system hardware, significantly reduced circulating water requirement for rejecting waste heat, and much greater efforts to improve the technology relative to other power cycles [5].

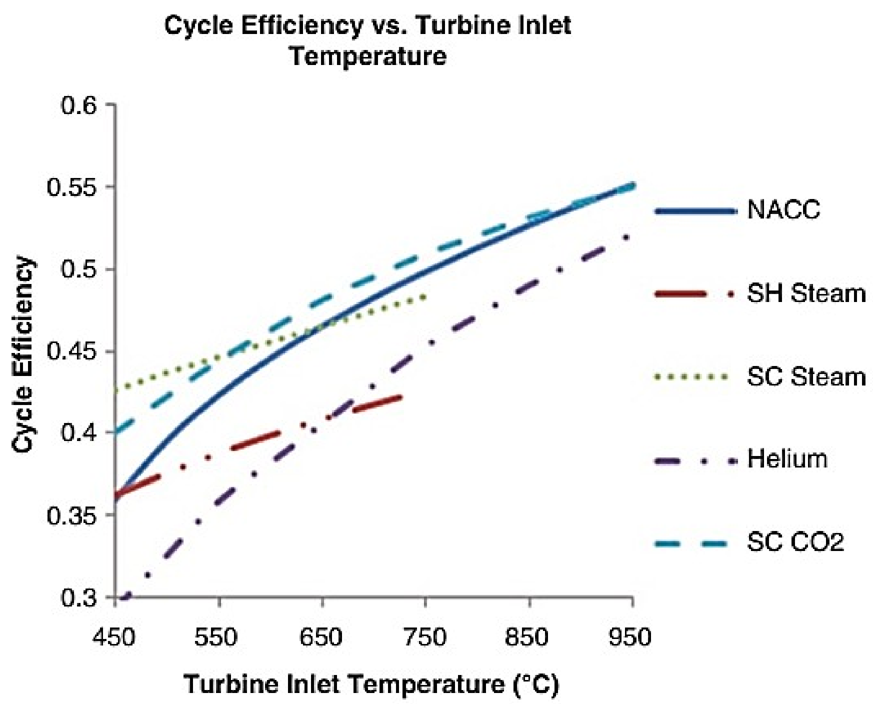

FIGURE 3. Cycle efficiencies for various advanced cycles.

However, construction of a prototype brings new obstacles and other challenges. The engineering of heat storage sites capable of holding the energy over longer periods without significant losses, compressors that can handle both high pressures and high temperatures, and turbines with the ability to maintain on a constant output under changing conditions (changing temperatures, decreasing air pressure) are some of the challenges. However, with the current state of the art, it is very doable.

Conclusion

The article highlights the development of advanced nuclear technologies aimed at supporting a flexible, low-carbon energy system. The combination of the Fluoride-Salt-Cooled High-Temperature Reactor (FHR), the Nuclear Air-Brayton Combined Cycle (NACC), and Firebrick Resistance-Heated Energy Storage (FIRES) is presented as an integrated solution capable of meeting variable electricity demand while maintaining base-load reactor efficiency.

FHR technology offers significant advantages over conventional light-water reactors due to its high-temperature capability, improved passive safety, and higher power density. When coupled with NACC, the system can efficiently utilize modern gas-turbine technology. The addition of FIRES provides low-cost, high-temperature thermal storage, enabling the plant to store cheap off-peak electricity and generate additional power during peak demand. This makes the system competitive with, and in some cases superior to, existing energy storage technologies such as batteries or pumped hydro.

The integrated FHR–NACC–FIRES configuration supports grid stability in systems with high penetration of intermittent renewable sources such as wind and solar. It enables dispatchable, zero-carbon electricity while enhancing nuclear plant economics by 50–100%. Furthermore, the design reduces the risk of major fuel failures, improving overall safety.

Although several engineering challenges remain—such as high-temperature materials, long-duration thermal storage integrity, and turbine operation under variable conditions—the article concludes that these obstacles are solvable with current and near-term technology.

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