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ENGINEERING SMALL MODULAR NUCLEAR REACTORS FOR MICRO AND NANO GRID APPLICATION: THE CASE STUDY BASED ON NASA'S 10 KILOWATT UNIT

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SUMMARY

The British Institute of Engineering Technology has reported that NASA has developed a 10 kW small modular nuclear reactor, coupled with a stirling engine, to meet the power demand requirements for the MARS spacecraft. This design has opportunity to promote the commercial market development of small-distributed power generators for use by individual customers, micro and nano grids. The constant energy source is available 24/7 for a period of a decade or two. When the source is depleted, the unit is exchanged for another whilst maintenance and spent fuel recovery is conducted in specialist workshops and environments.

This paper reviews the technical merits of the opportunity and proposes a functional design for a small modular nuclear reactor working in association with a stirling engine for electricity generation. Being a heat source, the waste heat is available for other applications such as steam generation, water purification and sanitation disposal. The customised plant can supply individual needs and requirements as in residential, commercial, and agricultural customers. The opportunity is available for specialist applications such as power supply for the generally remotely located mobile cellular base stations and water pump stations.

KEYWORDS

Industrial Revolution 4.0, Small Modular Reactor, Stirling Engine, Nuclear Energy, Solar Energy

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1 INTRODUCTION

Society is presently in the age of industrial revolution 4.0 that refers to autonomous decision making in the manufacturing of goods and provision of services. The 4.0 age commenced around 2011 and builds upon earlier ages of 3.0 (around 1969 – we had the introduction of large scale automated manufacturing driven by electronics, programmable logic controllers and robotics), 2.0 (around 1870 – we had the introduction of mass manufacturing as driven by electrical power) and 1.0 (around 1784 – we had the introduction of mechanized manufacturing as driven by steam and water power). Industrial revolution 4.0 is based on a confluence of many technologies. The human – machine symbiosis is at the core. The earlier technologies had just served society whilst industrial revolution goes one step further, it empowers society. Industrial revolution 4.0 technical areas of coverage includes artificial intelligence, machine learning, blockchain and distributed ledgers, digital trade, internet of things, 3 D printing, cloud computing; all embedded in real time outcomes. Industrial revolution 4.0 is totally dependent on the reliability and stability of all the enabling systems inclusive of power supply, data collection and processing, information security and integrity. In summary, the 4.0 age has three parts; electrified, automated and connected. It is independent of human intervention and interaction. It is driven by digital systems totally dependent on guaranteed security and quality of the electric power supply.

The space environment consists of the earth, moon, mars and the associated planetary system. On Mars, the sun's power varies widely. Periodic dust storms can last for months. On the Moon, the cold lunar nights are long. It can last up to 14 days. The use of solar energy and external fuels such as hydrogen has limitations. NASA, in its pursuit for guaranteed security and quality of the electric power supply for human and robotic exploration into space, called for a design of power supply that was independent, safe, efficient and reliable. The design was to produce an abundance of electrical energy. An abundance of electrical energy was essential for the day-to-day space activities of lighting, providing water and oxygen and for mission objectives of experiments and making fuel for the travel back to earth. The choice of nuclear as fuel was an ideal energy resource for the environment and for the application; nuclear is lightweight, reliable and efficient. With disciplined engineering and design of a suitable reactor, the required electrical power supply can be delivered safely; the quality and security of supply is guaranteed by design.

A parallel exists between society's electrical energy requirements for the 4th industrial revolution and that of NASA's space programme for Mars [1]. With the passage of time, society will be absorbed deeper into the technologies of industrial revolution 4.0 and quality and security of the electricity power supply must be guaranteed by design. Society, just like NASA, will come to the same conclusion; the use of solar renewable energy and external fuels such as hydrogen has boundary conditions with limitations.

For noting, each of the successive industrial revolutions occured almost a century apart, except for the fourth revolution which occured some four decades after the third. One can expect the fifth industrial revolution to occur in a shorter space of time. A prediction is that age 5.0 will occur around 2030. The urgency for the next industrial revolution will most likely come from global warming and climate change;

the ice is melting. Society will have to move speedily away from carbon based energy resources of coal, oil and gas. The unfolding scenario clearly positions nuclear fuel as a choice on the menu of energy resources amongst non carbon based resources such as solar, wind, hydro, bio resources and hydrogen. The NASA development of their Kilowatt Reactor is worthy of review as an option to power the economy of the 4th and successive industrial revolutions.

2 DESCRIPTION OF THE NASA KILOPOWER NUCLEAR POWER SUPPLY

NASA and the US Department of Energy's National Nuclear Security Administration (NNSA) have successfully demonstrated a new nuclear reactor for safe, secure and reliable power supply. The project was driven to power long duration crewed missions to the Moon, Mars and destinations beyond. The project started in October 2015. In March 2018, NASA announced the design and performance results of their new development, called the Kilopower Reactor Using Stirling Technology (KRUSTY) [2].

The reactor is a small, lightweight fission power system capable of providing up to 10 kilowatts of electrical power. The prototype power system has a solid, cast uranium-235 reactor core. Passive sodium heat pipes transfer reactor heat to high-efficiency stirling engines. The stirling engines converts the heat energy to rotary energy that drives a conventional generator to produce electricity. By design, the electricity output is continuous for 12 - 15 years.

The core of the reactor consists of a solid cast uranium 235 alloy with a beryllium oxide reflector. The reflector refocuses the neutron emissions and returns their energy back into the core to minimize the nuclear gamma radiation. The prototype unit of one kW rating weighs 134 kg and contains 28 kg of uranium 235. The 10 kW unit weighs 226 kg and contains 43.7 kg of uranium 235.

A single rod of boron carbide controls the nuclear reaction. The control rod serves as a neutron absorber. The neutron absorbing control rod, on withdrawal, allows the start of the nuclear reaction. The depth of insertion provides a mechanism to adjust the heat output from the reactor core to the load demand. Once the reaction commences, the chain of events continues into time.

The passive heat pipes, filled with liquid sodium, transfers the reactor core heat to the Stirling engines. The Stirling engines converts heat into rotary motion to drive a conventional electric generator. The melting point of sodium is 98 °C (208 °F) which means that liquid sodium can flow freely at high temperatures between about 400 and 700 °C (750 and 1,300 °F). The nuclear fission cores will typically operate at about 600 °C (1,100 °F). By design, the reactor is intrinsically safe and employs passive cooling with no mechanical mechanisms to circulate the coolant.

The Kilopower experimental demonstration was conducted in four phases. The first two phases was performed without power so as to establish that each component of the system behaved as expected. In the third phase, power was introduced to heat the core incrementally. The final phase included reactor startup, ramp up to full power, steady operation and shutdown. Throughout the experiment, the team simulated power reduction, failed engines and failed heat pipes. The test showed that the system was safe and stable to operate. It successfully handled multiple failures. On March 20, 2018, a 28-hour test using a 28 kg uranium-235 reactor core, the unit delivered a temperature of 850 °C (1,560 °F) which produced 5.5 kW of fission power. The experiments included failure scenarios including shutting down the Stirling engines, adjusting the control rod, thermal cycling, and disabling the heat-removal system. The experiment concluded with a scram test. Table1 summarises the NASA design specification for the Kilopower reactor. Figure 1 presents a photograph of the prototype unit.

Table 1 : Summary of the Design Specification of NASA's Kilopower Reactor

Title	Description
Reactor Type	Stirling Engine
Fuel	Uranium 235
Fuel State	Solid – Cast Cylinder
Primary Control Method	Boron Carbide Control Rod
Neutron Reflector	Beryllium Oxideradial Reflector
Primary Coolant	Sodium Heat Pipes
Power (Thermal)	4.3- 43.3 kW
Power (Electric)	1.0 – 10.0 kW

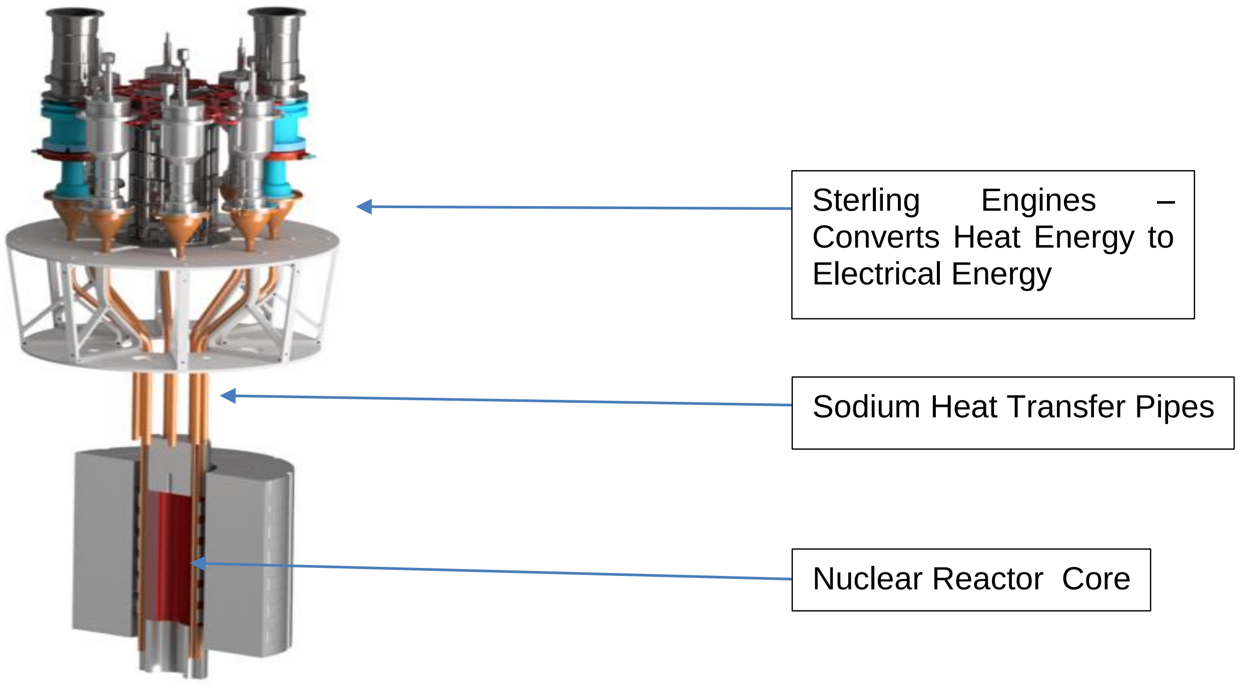

Figure 1 : NASA 1 kW Prototype Nuclear Reactor of Height 1,9m

The heart of the NASA unit is the Stirling engine. The Stirling engine absorbs and manages passively the thermal energy and produces electrical energy. The Stirling engine operates on a closed thermodynamic cycle. The engine converts heat energy to rotational energy. The rotational drive powers a conventional synchronous generator to produce electricity.

3 TOWARDS A FUNCTIONAL DESIGN OF A GENERALISED POWER SOURCE

For a generalised power source, irrespective of source of heat and rated capacity of power supply, we have in general a conventional and commercial synchronous generator driven by a conventional and commercial Stirling engine. Alibaba online sales has a menu of offers for the conventional and commercial products [3].

3.1 The Synchronous Generator

The design is mature and synchronous generators are commercially available.

3.2 The Sterling Engine

Extracting from the menu of Stirling engines on offer by Alibaba [3], figure 2 provides an exhibit of a laboratory demonstration model, showing the heat source and the rotary drive for the synchronous generator.

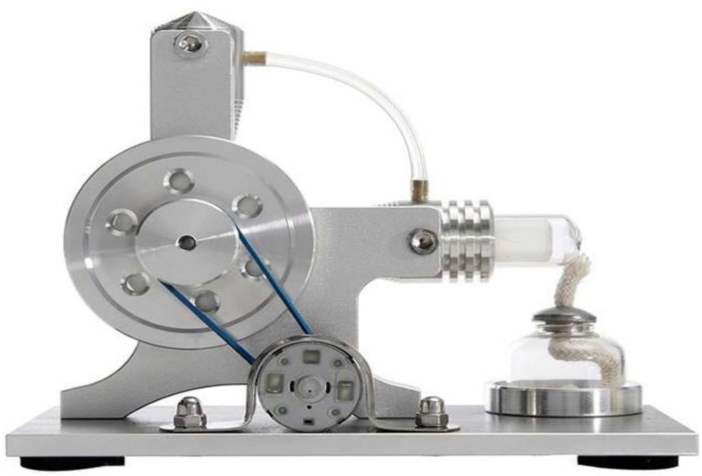

Figure 2 : Laboratory Demonstration Model of a Stirling Engine

In 1816, Robert Stirling invented the Stirling engine [4]. The invention was to solve the challenge of explosions in steam powered engines caused by high pressure acting on the poor strength of the materials of the day. This was an industrial revolution 1.0 technology. The Stirling engine is designed to operate at low pressures. The working gas (usually air, or helium or hydrogen) is alternately heated and cooled by shifting the gas to different temperature locations within a closed system that is bounded by friction free moving pistons. The process starts with the heating of the gas. The gas expands and moves the pistons outwards. The pistons rotate a crankshaft. The heated gas displaces to a cold chamber. The gas cools, contracts and pulls the pistons inwards; again rotating the crankshaft. A drive of one full cycle results. The process repeats as long as the heat source is maintained. The process passively stops if the heat source is removed or fails.

Stirling engines are extremely efficient, quiet and are completely embedded in a closed loop system. Their environmental impact is zero. Their one disadvantage is that of slow response to varied power requirements. The internal combustion engine had this advantage and displaced the Stirling engine for duty in the automotive industry.

4 CONCLUSION

Passive heat transfer using pipes filled with liquid sodium holds the key to making small amounts of electricity for use in stand-alone applications or for nano and micro grid distribution. The stand-alone applications could be a simple domestic installation or a mission critical installation.

Nuclear energy can deliver continuous electricity supply for a decade and a half. Post a decade and a half; the nuclear heat source will require refueling, possibly in a specialized workshop. The nuclear powered solution is available in laboratory. The migration of the technology to the commercial markets will occur in the next decade; possibly accelerated by global warming and climate change. Economics and criticality of application will determine the pace of commercialization.

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