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Viability of HTR-10 as a Primary Driver of an Energy Complex for Remote Settlement

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Abstract - *HTR-10, a proven 10 MWt prototype pebble bed reactor, is capable of generating 4 MWe to the power grid. However, with evolutional power upgrades, its output performance can be substantially enhanced to drive an energy complex to co-generate electricity, hydrogen, desalinated water and process heat for a remote island or settlement of several thousand people. Unlike the much publicized SMR power concepts in the literature, HTR-10 is the only full-blown stand-alone power system that has been demonstrated to be inherently safe and capable of high temperature output. Furthermore, this particular HTR family of reactors is proliferation-resistant and possesses many desirable market-competitive advantages such as high thermal efficiency, low thermal pollution, zero carbon footprints and minimal exclusion zones. An innovative classroom project course is structured to stimulate science and engineering students to explore novel use of HTR-10 as a high temperature heat source to be the core of an intelligent zero emission energy (Smart-ZEE) module capable of providing all energy needs of a remote community or island.*

I. INTRODUCTION

Since the successful demonstration of safety characteristics of the helium-cooled pebble bed reactor (HTR-10) in 2004 at INET (Institute of Nuclear and New Energy Technology) in Tsinghua University, a scaled-up 105 MWe commercial module of HTR-10 designated as HTR-PM, has been designed and is being deployed by Chinergy in Rongcheng, China. The first pair of HTR-PM is being built as a commercial demonstration module in the Shidaowan Nuclear Power Industrial Park. Infrastructure facilities for production of fuel pebbles, core vessels, helium blowers, generators, etc. necessary for both the nuclear and conventional islands are basically in place for the anticipated deployment of 38 HTR-PM in Rongcheng as well as in other locations. The specific cost of construction for HTR-PM modules has been projected to be around 2000 $/kWe. Thus, the cost of replicating the 4 MWe HTR-10 should be substantially less than the original development cost in 1995 of 275 million RMB which includes the one-time R&D costs of the nuclear island, and all 34 sub-systems involved. Furthermore the online refueling of HTR-10 is expected to yield a very high capacity factor and to make such power plant suitable for base-load operation providing power needs in a small community of a few thousand people. A rough estimate for the replication cost of the prototype HTR-10 puts it at around 100 million RMB or 4,032 $/kWe. Using this specific capital cost as a reference along with a set of conservative assumptions of 9% discount rate, 5-year construction time, 3-year fuel cycle time, 40-year design life, $50 per pebble and 0.85 life-time capacity factor, the resulting levelized electricity cost is calculated to be about $79/MW-h. All things considered, this is not an outrageous cost in comparison with the alternative diesel power cost in a similar situation. However, using a more optimistic assumptions of N-th reactor capital cost of $3000/kWe and the following assumptions of 6% discount rate, 3-year construction time, 5-year fuel cycle time, 60-year design life, $25 per pebble and 0.9 life-time capacity factor, the calculated electricity generation cost is decreased to $34/MW-h. This generation cost is not only affordable and but also cost-competitive. So it appears that HTR-10 "as is" already can be commercially utilized as a stand-alone power generating unit. However, electric power by itself cannot sustain an isolated community especially in a remote island because a thriving community also needs transportation fuel, drinking water, process heat, etc.

II. AGRO-NUCLEAR COMPLEX

In the late 1960's, Dr. Alvin Weinberg of Oakridge National Lab (ORNL) launched a feasibility project to study the potential of maximizing the usage of nuclear energy, more specifically molten salt reactor (MSR) in an Agro-Nuclear Complex [1]. High-temperature reactors such as MSR were envisioned as the enabling power source to drive a complex of energy consuming devices such as steam/gas turbines, hydrogen generators and seawater desalinators for light industry applications in a commune-like settlement. In 1967, as the Director of ORNL, Dr. Alvin Weinberg recruited Prof. E.A. Mason from MIT to lead this visionary project. It was an intensive multidisciplinary study to explore novel use of inexpensive nuclear energy with a particular focus on the applications in developing countries or regions. The study has shown that the use of low cost nuclear energy in a rural or under-developed region can have a profound impact on the livelihood of the region. The combination of electric power and potable water provides the basis for industrial, agricultural and general economic advancement. This novel energy system concept can increase standards of living in under-developed regions quickly and hopefully promote world peace in the long run. Widespread acceptance and deployment could relieve the world food, potable water, fossil fuel and greenhouse gas emission concerns [2]. Unlike fossil energy, the energy source to drive this novel complex is carbon-emission-free and inexhaustible thorium nuclear fuel.

III. HIGH TEMPERATURE SMR

The half-century old Nuclear-Agro Complex concept of ORNL is still very sound and valid today. In principle, it should be also applicable to remote settlements or lightly inhabited islands such as the Sansha City in Paracel Islands or Xisha and Taiping in Spratly Islands or Nansha in Hainan Province shown in Figure 1. Most offshore islands with human settlements generally use polluting and expensive diesel fuel to provide electricity needed for daily activities. Because of the limited fossil fuel storage, the size of the settlement and the scope of industrial activities are severely restricted. High temperature nuclear power not only can help remove such restrictions but also can enable co-generation of other important necessities such as potable water, process heat and transportation fuel to support light industry economic activities. Small Modular Reactors (SMR) such as HTR-10 is a proven high temperature reactor. The core performance still has a lot of room to grow. Even "as is" without major development, its performance capability can be substantially augmented by integration with wind turbines and solar photovoltaic systems to drive a mix of energy devices such as gas turbines, steam turbines, hydrogen generator, seawater desalinator, etc. as depicted in Figure 2. Being a nuclear system, this SMR must meet the following basic requirements:

1. Inherent safety
2. Reliability
3. Proliferation resistance
4. Affordability
5. Scalability
6. High temperature output

The last is not the least because it is of utmost importance for the SMR to possess high temperature capability. Success of the zero emission energy complex concept is dependent on the high temperature output because it is needed for efficient energy conversion, thermal-chemical hydrogen production, and industrial process heat applications. Additionally, the resulting waste heat can still be of value for desalination or district heating to minimize unnecessary thermal pollution.

III.A. HIGH TEMPERATURE PEBBLE-BED REACTORS

General speaking high temperature reactors with the coolant exit temperatures in excess of 800 degrees centigrade is only beginning to be usable for efficient co-generation of electrical power as well as hydrogen production. Generation IV reactors such as HTR (High Temperature Pebble-bed Reactor) are inherently safe and proliferation resistant. Banks or cluster of these HTR modules can provide enhanced reliability, availability, growth as well as the load-following capability to efficiently co-generate electricity, hydrogen fuel and desalinated water to support basic energy needs of a community without any carbon emission. Any excess energy can be stored in the form of hydrogen fuel for power peaking or emergency uses. The concept embodied in Figure 2 is actually a rudimentary "Hydrogen Economy". At present time HTR-10 is ready to demonstrate a prototype carbon-emission-free Hydrogen Economy operation.

III.B. ZERO EMISSION ENERGY COMPLEX

There are many SMR concepts in the open literature but most of them are not qualified for consideration as a primary driver of the envisioned zero emission energy (ZEE) complex for lack of high temperature capabilities. The sole exception is probably the HTR technology, such as HTR-PM in construction and its prototype HTR-10 [3, 4]. This reactor technology has been demonstrated to be inherently safe or walk-away safe [5]. The HTR-10 replication cost is estimated to be about $16 million including the steam generator. However with co-generation such as those in ORNL's Agro-Nuclear Complex, its economic viability can be greatly enhanced. Theoretically HTR-10 could be a good candidate as the primary energy source of the proposed ZEE complex because it satisfies all aforementioned requirements. Most important of all, it is available now. However this emission-free energy complex still needs an intelligent system optimization controller to ensure efficient integration of various energy devices to make it into a functioning Smart-ZEE.

IV. SMART-ZEE DEMO PLAN

To further mature the Smart-ZEE concept, we have a strategy. An innovative multi-discipline course in a seminar workshop format for college senior or graduate school level is offered to let students explore innovative uses of HTR-10 for off-shore islands or remote settlements. During the semester, students in groups are to evaluate applicability of various energy devices, conduct in-depth system optimization study, design a smart system controller and compete amongst themselves to come up with an economic and practical conceptual system design. The winner team will be presented a Weinberg Scholarship Award to motivate further entrepreneurial pursuits. The course instruction includes lectures and invited speakers and is foremost an education process for students to learn Generation IV technology. However, the by-products from the workshop design activity may include intellectual property in the form of patents and engineering reports. The knowledge gained is useful for assessing the viability of HTR-10 as a primary base-load energy source for a zero-emission energy (Smart-ZEE) complex. The long-term goal of this exercise is to train future nuclear engineers to focus on the unique high temperature characteristics of the HTR technology for applications in large energy complex involving wind and solar farms to hasten the arrival of environment-friendly hydrogen economy. The near-term goal is to build a prototype Smart-ZEE complex to showcase its capability to provide power, process heat, hydrogen fuel and potable water to support and sustain a remote community.

This Weinberg Seminar course mentioned above is to be offered at both the College of Engineering at Peking University (PKU) in Beijing and the Chinese-French Institute of Nuclear Engineering and Technology (ICFEN) at the Sun Yat-Sen University in Zhuhai, Guangdong. It is hoped that a series of this seminar course will produce supporting data to confirm the viability of HTR-10 as an enabler of the Smart-ZEE complex. Seed funds will be provided to seek regulatory approval to find a suitable site to launch a demonstration Smart-ZEE project.

Fig. 1 Yongxin island in Paracel Islands and Taiping island in Spratly Islands in South China Sea

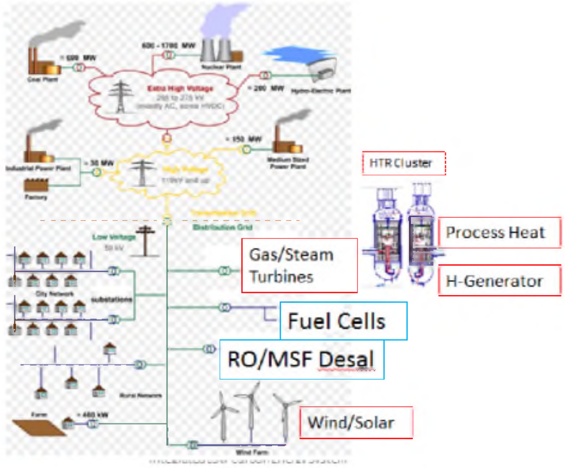

Fig. 2 Zero Emission Energy Complex Schematic. ZEE complex on lower right providing energy needs to local community on the left and send surplus output to outside world via power grid on top.

V. REFERENCES

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