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SMALL ADVANCED REACTORS FOR REMOTE ELECTRICITY GENERATION

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ABSTRACT – Small advanced reactors provide unique technology advantages for remote electricity generation. Advanced reactor attributes that provide these advantages include:

- Fast spectrum physics
- High temperature coolants
- Accident resistant fuels

The result can be simpler design and operation, longer core life (without refueling), and improved safety.

Gen4 Energy (formerly Hyperion Power Generation) is developing a small next generation nuclear power reactor. Sealed at the factory, including fuel for its 10 year operational lifetime, the Gen4 Reactor Module (G4M) will require no refueling and no on-site access to nuclear fuel (vastly reducing safety and proliferation concerns).

1. Introduction

The G4M has been designed for one specific purpose, to provide a small reliable power source to locations that currently rely on diesel power for electrical generation. These applications tend to be in remote locations that do not have access to other fuels and are not connected to major electrical grids. Key design requirements include:

- Transportable – a compact reactor vessel that can fit in a spent fuel cask
- No Onsite Refueling – long-lived core (10 years) to avoid onsite refueling
- Nuclear Simplicity – fast spectrum reactor simplifies the physics and operation
- High Outlet Temperature – about 500 ^{o}C to maximize thermal efficiency

The key to achieving these design requirements was the use of advanced reactor technology.

2. Why Fast Spectrum?

A fast-spectrum system is preferred to achieve a long core lifetime without refueling because the absorption cross section of fission products for fast neutrons is small, thus the impact of fission products on reactivity is small, and there is relatively little isotopic transmutation that could reduce reactivity (because of low cross sections and high fission-to-capture ratios). As a result, the loss of reactivity during burnup is almost entirely attributable to the change in actinide inventory (primarily fission of ^{235}U). Breeding of new fissile material can also contribute a long core lifetime.

The risk for this system has been reduced by basing it on established physics and technologies, and designing in simplicity. Analysis has shown that a fast-spectrum core is simpler than a moderated core with respect to reactivity feedback mechanisms, burnup reactivity mechanisms, nuclear data uncertainties, dynamic performance, localized/heterogeneous effects, system modeling and predictability, and changes in system characteristics with lifetime. The neutronic simplicity of a small fast-spectrum reactor simplifies operation and safety for several reasons:

- In a fast reactor temperature feedback is mostly caused by physical material and core expansion, which generally provides simple, monotonic, negative feedback.
- There is less chance for spatial or localized reactivity feedback because of the longer neutron mean free path; i.e. the neutronics are well-coupled and stable.
- Small reactivity feedback translates to a small temperature defect (defined as the difference in reactivity between the startup temperature and the operating temperature) which simplifies reactor startup/shutdown and requires less excess reactivity; this can make some safety requirements easier to meet.
- A fast spectrum system generally has a larger delayed neutron fraction because more fission occurs in U-238. Delayed neutron fraction is a first-order safety significant parameter.
- The relatively constant neutron energy spectrum of a fast reactor over lifetime greatly simplifies the prediction and verification of reactor dynamics.

3. Why Lead Bismuth Eutectic?

Liquid metal was selected for the reactor coolant because it allows for a compact core design that can produce a high coolant temperature (~500^{o}C). Three liquid metal coolants were considered: sodium (Na), lead (Pb) and lead-bismuth eutectic (LBE or PbBi).

Looking first at Pb vs. LBE, both are neutronically good, have very high boiling temperatures, are non-reactive with air or water and have similar densities and thermal-hydraulic properties (heat transfer coefficient, heat capacity, pumping power). Reactor designs proposing Pb or LBE have been developed in Japan, the US and in Russia, but the only reactors built and operated are the LBE-cooled Soviet Alfa-class submarine reactors. LBE was selected over Pb because of its much lower melting temperature and because it undergoes virtually no expansion at melting. These were determined to be important to system reliability and operation.

The selection between Na and LBE involved issues that are summarized below.

LBE and Sodium Comparison

Chemical reactivity	Na is somewhat reactive with air and highly reactive with water. This is a known safety issue for Na cooled designs. For a transportable reactor, this issue extends to the transportation to and from the site.
Expansion upon melting	At melting, Na expands about 3%, whereas LBE experiences virtually no expansion. The concern with this thermal expansion is the stress and strain in the system components and piping.
Boiling temperature	Na boils at 883^{o}C and LBE at 1670^{o}C. The concern with the low boiling temperature is during a core heat up event.
Corrosion	Both Na and LBE have potential corrosion issues, which require control of the oxygen in the coolant and impose limits on operating coolant/clad temperatures.
Erosion	With LBE, there is an erosion concern with the protective coating which is needed to control corrosion, requiring the coolant velocity to be limited.

Na-24/Polonium	Capture in Na produces Na-24, an intense radiation source that can create operational issues. The polonium (Po-210) produced in the LBE coolant is a potential biological hazard in the event of a leak.

For the Gen4 reactor, LBE was selected for the coolant. A major reason was a desire to avoid the risk of a potential Na leak and subsequent chemical reaction with water or air, either during transport or during operation at a remote site. Also important to design and operations is that LBE undergoes no net expansion at melting. Finally, the significantly higher boiling temperature provides greater operating margins.

4. Why Uranium Nitride?

Three fuel types were considered for the Gen4 reactor: Uranium Nitride (UN), Uranium-metal (U-metal), and Uranium Oxide (UO_2).

U-metal has a fairly good data base, is much denser than UO_2 and has a higher thermal conductivity. However, it has a low temperature limit, and large swelling and fission gas release (requiring a large fission gas plenum). UN fuel was selected over U-metal fuel because, based on a compilation of UN data, it appears to be a better performing fuel, in particular for the high-temperature long-life requirements of the Gen4 reactor.

UN has similarities to UO_2 in that they are both ceramic fuels and have similar melting temperatures (2888^{o}C for UN vs. 2749^{o}C for UO_2). Key advantages of UN over UO_2 include:

Key Advantages of UN over UO_2

Thermal conductivity	• UN has ten times higher thermal conductivity than UO_2 (26 vs. 2 W/m-K) • UN fuel centerline temp can be 1000^{o}C lower than UO_2, resulting in improved margin to fuel damage
Uranium Density	• 13.52 g/cc for UN vs. 10.5 g/cc for UO_2, means a smaller reactor size with UN
Core Life	• Low fission gas release and low fuel swelling • Greater resistance to irradiation damage over extended periods of time

UN fuel was selected because it has better performance than UO_2 fuel over the relevant operating range. However, UO_2 has been included as a backup option in the final studies for the Gen4 design, because of its much greater experience and qualification base.

5. Summary

Small advanced reactors can provide unique technology advantages for remote deployment, resulting in small, simple, and safe designs. Gen4 Energy has optimized these advantages with a fast reactor that uses LBE coolant and UN fuel.