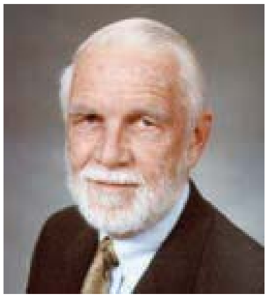

Featured Column: ***As the Turbine Turns...***

PBMR–A Future Failsafe Gas Turbine Nuclear Power Plant?

By Dr. Lee S. Langston, Professor Emeritus of Engineering, University of Connecticut

Langston is a former editor of the ASME Journal of Engineering for Gas Turbines and Power and has served on the IGTI Board of Directors as both Chair and Treasurer.

Earlier this year on Friday, March 11, a severe earthquake of magnitude 9.0 commenced at 2:46 pm (Japan time) in the Pacific Ocean sea-bed, 80 miles east of the coastal city of Sendai on the central island of Honshu. Operating nuclear power plants in this northeast part of Japan underwent automatic shutdown, with control rods inserted into reactor cores, triggered by earthquake ground acceleration sensors.

The large 4700 MWe Fukushima Daiichi nuclear power plant complex, on the coast some 150 miles north of Tokyo, was one of these. The complex, one of the 25 largest nuclear power stations in the world, is made up of six separate boiling water reactor (BWR) units. These BWR units, powering steam turbine driven generators, were designed to withstand a 8.2 Richter scale earthquake (comparable to the 1906 San Francisco event). On the logarithmic Richter scale the March 11 9.0 earthquake was 7 to 8 times more powerful than that for which the reactors were designed.

Of the Fukushima Daiichi six reactors, Units 5 and 6 were offline for planned inspection and Unit 4 had been completely defueled. Units 1, 2 and 3, with nominal outputs of 498 MWe, 796 MWe and 796 MWe respectively, were in operation before their earthquake induced automatic shutdown. Even with control rods fully inserted, these three units still needed electric powered circulating water pump cooling, due to the residual heat (as much as 3% of the normal operating heat load) generated by intermediate radioactive elements, created by the uranium fission process.

At 3:44 pm, a 14 meter high tsunami reached the Fukushima Daiichi complex, overtopping facilities designed to withstand a 5.7 meter tsunami. All alternating current sources - both off-site and on-site emergency diesel generators - were knocked out by the high tsunami, depriving the reactor cores (and associated spent fuel pools) of internal cooling water and their ultimate heat sink, pumped-in sea water.

In addition, plant workers reported seeing the diesel generator fuel tanks being washed out to sea in the receding tsunami. There were backup batteries to supply emergency power for a matter of hours, but eventually, reactor coolant water overheated, increasing pressures and temperatures in the reactor pressure vessel. Pressure was automatically relieved to the containment suppression pool, but this reduced the water inventory in the reactor. As the water level lowered in the reactor, the fuel rods continued to heat up and an exothermic reaction between the zirconium fuel rod cladding and the remaining coolant generated hydrogen. When the hydrogen was subsequently released from the reactor pressure vessel and mixed with air, the resulting explosions caused further damage to the units.[1]

The inability to provide reactor coolant, despite multiple-layered backup systems that all depended on AC power, led to extensive damage to at least three separate nuclear reactors. In Pennsylvania in 1978 similar damage occurred at Three Mile Island (TMI) due to operator error when the emergency cooling system was turned off. In the New York Times,[2] Lake Barrett, the senior US Nuclear Regulatory Commission engineer for TMI, noted that TMI – which took 14 years and the removal of about 150 tons of radioactive rubble to clean up – "...was a walk in the park compared to what they've got..." in Japan. With Fukushima Daiichi, at least three water cooled reactors of the six are damaged and stabilizing each one is complicated by the presence of its leaking neighbors. It is almost certain that four reactors grouped together are lost investments, never to operate again.

Under development, there is a gas turbine nuclear power plant that completely eliminates the possibility of a devastating loss-of-coolant accident. Called the Pebble Bed Modular Reactor (PBMR) it was to be built in South Africa, until funding problems recently ended this promising program. Both Past Chair of the IGTI Electric Power Committee, Sep van der Linden,[3] and I[4] have written about the PBMR power plant.

Uranium dioxide nuclear fuel, coated with mass diffusion and radioactive fission product containment layers of pyrolytic carbon and silicon carbide, is formed into nuclear poppy seed-sized fuel particles. Some 15,000 of these are embedded in a tennis ball-size graphite sphere, which is encased in a thin carbon shell, sintered, annealed and machined to a uniformed diameter of 6 cm. These are the "pebbles" – the name given by Farrington Daniels in the early days of nuclear power in 1944-1945.

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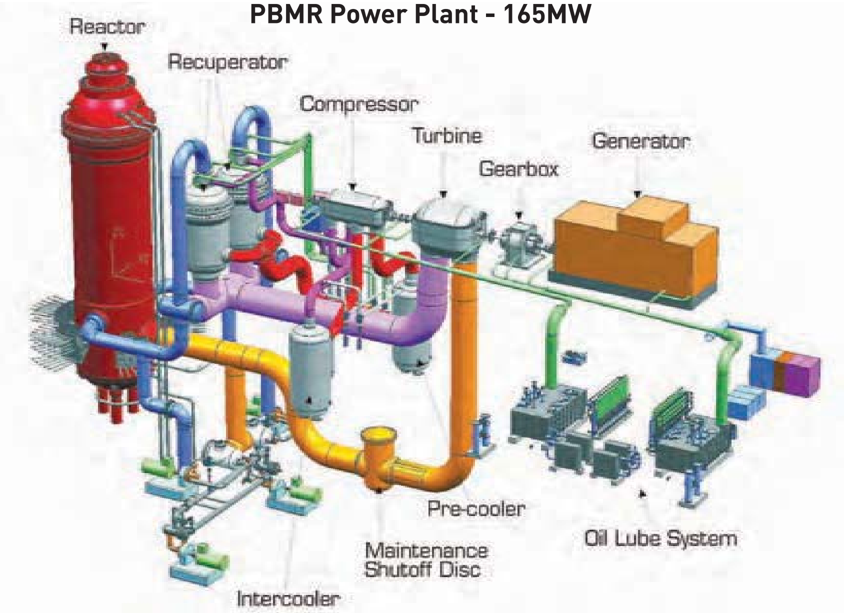
PBMR Power Plant - 165MW



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We are pleased to announce the new technical committee officers for July 2011 through June 2013.

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The PBMR reactor vessel, 90 ft high and 20 ft wide, is packed with about 450,000 heat-producing nuclear pebbles. Helium gas coolant then flows around and between the pebbles stacked in the reactor vessel, emerging at about 900 deg F. The reactor, acting in place of a combustor, provides heated gas (helium) to drive a gas turbine, connected to a 165 MWe electric generator. The non reacting helium flow continues through the rest of the regenerative, intercooled Brayton cycle, and re-enters the pebble bed reactor to be heated again, completing a closed cycle, of 41% thermal efficiency.

In the event of a complete shutdown of helium flow in a pebble bed reactor, the temperature would rise at most to 2,900 deg F, a level well below the thermal limit of graphite pebbles. At the higher temperature, the more plentiful uranium-238 nuclei absorb more neutrons (due to an effect called Doppler broadening) and the reactor output decreases, lowering the reactor temperature until an equilibrium is reached. The reactor heat is transferred passively by radiation, conduction, and natural convection to the steel reactor vessel, which is designed to reject the heat without human intervention.

The first pebble bed reactor began operation near Aachen, Germany in 1966 and ran successfully for 21 years, providing heat for a small steam power plant. Tests run during it's life demonstrated safe operation in the event of a total shutdown of the helium coolant.

Although the South African PBMR project has ended, the Chinese are currently building two pebble reactors, but these are used to generate steam for a conventional Rankine cycle. The Rankine (steam turbine) cycle is being used because it is less challenging from both design and material standpoints. This makes no sense to me, since it adds another working fluid (water) which lowers the thermal efficiency and retains the danger of water ingress into the reactor, with it's attendant reactions with high temperature graphite. Also, gas turbine power plants have long since been shown to have lower operating and capital costs than those of steam.

What we need is a government-private industry sponsored effort to develop a gas turbine nuclear power plant using a pebble bed reactor, which holds so much promise as a failsafe, high reliability carbon-free source of electricity. ✲

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