NUCLEAR ENERGY RESEARCH INITIATIVE

Development of a Supercritical Carbon Dioxide Brayton Cycle: Improving PBR Efficiency and Testing Material Compatibility

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Proposal Number: 2002-190

Generation IV reactors will need to be intrinsically safe, having a proliferation-resistant fuel cycle and several advantages relative to existing light water reactor (LWR) systems. They, however, must still overcome certain technical issues and the cost barrier before it can be built anywhere in the world. South Africa wants to build the German-type PBR, but it has no detailed calculations on postulated accidents using the German design, there are unresolved technical issues, and the cost factor is still unfavorable.

A fundamental study is proposed to determine how to make the gas-cooled reactors safer and more economical, to meet the world's power requirements for the next generation.

The proposed project establishes a nuclear power cost goal of 3.3 cents/kWh in order to compete with fossil combined-cycle, gas-turbine power generation. This goal requires approximately a 30 percent reduction in power cost for state-of-the-art nuclear plants. It has been demonstrated that this large cost differential can be overcome only by technology improvements that lead to a combination of better efficiency and more compatible reactor materials. The proposal outlines

(1) development of a supercritical carbon dioxide Brayton cycle,

(2) improvement of the plant net efficiency by using the supercritical carbon dioxide Brayton cycle, and

(3) testing of material compatibility at supercritical conditions and high temperatures.

Developing a Supercritical Carbon Dioxide Brayton Cycle and Improving Efficiency: Supercritical carbon dioxide (SC CO_2) has a moderate critical constant, T_c = 31°C and P_c = 7.29 MPa, and has a unique heat transfer capacity at the supercritical condition. For example, the density of SC CO_2 is higher than helium by a factor 2000 and higher than supercritical water (SCW) by a factor of 1.5 to 2 at a temperature of 920°C and above. SC CO_2 has advantages over even SCW and helium in terms of heat transfer and higher molecular weight. The heat capacity term (mass flow rate times heat capacity) is higher than that for helium because of higher density. SCW has a much higher pressure (22 MPa) at the critical condition and a very narrow range of high heat capacity around the critical temperature of 374°C.

INEEL calculations for the Brayton cycle indicate that SC CO_2 has a 55 percent cycle efficiency versus 41 percent for helium for the reference PBR design of INEEL and MIT. The higher efficiency is achieved at a lower turbine inlet temperature for SC CO_2, 535.4°C versus 850°C for helium. The higher molecular weight results in less work in compression, which contributes to a higher efficiency for the SC CO_2 Brayton cycle.

The use of SC CO_2 as a coolant in the secondary PBR is very attractive because the core outlet temperature can be increased, which will increase the plant net efficiency by more than 60 percent.

Testing Material Compatibility: It is proposed to characterize the creep deformation of Inconel MA 754 and 758 over a range of temperatures from 850°C to 1050°C and stresses within the power law creep regime. By varying the temperature at constant stress and the stress at constant temperature, it will be possible to determine the numerical values of the activation energy and power law exponent for creep, and whether a threshold stress formalism applies for these materials or if the ARZT type model is more appropriate. This characterization will allow the proper constitutive equation to be determined, so that the deformation behavior can be calculated for a long service time in the temperature and stresses expected for the advanced reactor concept described above.

In addition to suitable mechanical properties, the alloys must resist environmental degradation for extended periods of time for the conditions expected in this reactor concept. Preliminary analysis suggests that the nickel-based alloys with 20 to 30 percent Cr content will exhibit reasonable resistance to degradation by supercritical CO_2. An investigation is proposed of the interaction of MA 754 and 758 in supercritical CO_2 using thermogravimetric analysis combined with surface analysis to examine the possible chemical interaction mechanism(s) (e.g., breakdown of the passivating Cr oxide or carburization), at temperatures and pressures of interest.