Summary submitted to the ANS 2001 Winter Meeting, Track 2j, Generation IV Nuclear Technologies and Road Map, Special Session on The Encapsulated Nuclear Heat Source, Reno, NV, November 11-15, 2001.

Feasibility of Natural Circulation Heat Transport in the ENHS*

by

J. J. Sienicki
Argonne National Laboratory
Reactor Analysis and Engineering Division
9700 South Cass Avenue
Argonne, Illinois 60439

*This work was performed under the auspices of the U.S. Department of Energy under Contract W-31-109-ENG-38.

Feasibility of Natural Circulation Heat Transport in the ENHS

by

J. J. Sienicki
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

The Encapsulated Nuclear Heat Source (ENHS) is a small (125 MWt) modular reactor concept incorporating a fast neutron spectrum core with a 20 year core life utilizing lead-bismuth eutectic (LBE) or lead primary and intermediate circuit coolants.[1-2] The fuel is "encapsulated" inside a cylindrical primary coolant vessel throughout the core lifetime restricting access to fuel and neutrons. Primary-to-intermediate coolant heat exchange takes place inside an annular heat exchanger (HX) region inside which the intermediate coolant flows upward through long aspect ratio thick-walled rectangular plate channels while the primary coolant flows downward over the plate exterior surfaces. The ENHS does not incorporate any mechanical main circulation pumps in the primary or intermediate circuits. Heat is removed from the core to the HX by natural circulation of the primary coolant. The removable ENHS module containing the HX is placed inside an annular intermediate coolant pool. Heat is removed from the HX to modular steam generators near the top of the pool by natural circulation of the intermediate coolant. If needed, the ENHS optionally incorporates the injection of noncondensable gas into the primary coolant above the core or into the intermediate coolant above the HX plate channels to enhance the coolant flowrate above that from single-phase natural circulation alone.

The objective of the present work is to establish the feasibility of natural circulation heat transport of both the primary and intermediate coolants for alternative ENHS designs that either rely upon purely single-phase natural circulation or natural circulation augmented by gas injection. The approach is based upon a fundamental first principles analysis.

The primary coolant temperature rise across the core, or intermediate coolant temperature rise through the HX, is given by

$$\Delta T = T_{out} - T_{in} = \frac{Q_{tot}}{\rho u_c A_c c} .$$

Using this equation to eliminate the temperature rise from a one-dimensional momentum equation incorporating the Boussinesq approximation provides an equation for the primary coolant velocity through the core (or analogously, the intermediate coolant velocity through the HX) in terms of the total core power,[3]

$$u_c = \left[\frac{Q_{tot} g \beta \left(L_{diff} - \frac{\alpha_{2\varphi} L_{2\varphi}}{2} \right)}{2 \bar{\rho} c A_c} + \frac{g \alpha_{2\varphi} L_{2\varphi} u_c}{2} \right]^{1/3} \left\{ \frac{1}{\left[\frac{L_c}{D_{h,c}} \left(f_c + \frac{\sum_i K_{i,c} D_{h,c}}{4 L_c} \right) + \left(\frac{A_c}{A_{HX}} \right)^2 \left(f_{HX} + \frac{\sum_i K_{i,HX} D_{h,HX}}{4 L_{HX}} \right) \right]} \right\}^{1/3} ,$$

where L_{diff} = HX-core thermal centers separation
height, $\alpha_{2\phi}$ = void fraction from gas injection, $L_{2\phi}$ = two-phase region height.

Four ENHS design variants (Table 1) were analyzed. Case NLP4 (No Lift Pump Case No. 4) incorporates the greatest riser heights above the core and HX to enhance single-phase natural circulation from coolant temperature differences alone. Case LP6 (Lift Pump Case No. 6) includes enhanced circulation from gas injection with somewhat reduced riser heights. Case LP7 features a compact design with gas injection and significantly reduced riser heights above both the core and HX. A fourth variant of LP7 extends the bottom of the HX that was located completely above the core down to the active core lower elevation.

Table 2 shows the results calculated for each case with the alternative choices of LBE and lead coolants. The single constraint upon the temperatures in the calculations is that the primary coolant inlet temperature at the bottom of the core equals 400°C. The major figures of merit are the primary and intermediate coolant temperature rises across the respective heated zones. It is desired that the temperature rises remain less than about 160°C. This limits the coolant outlet temperatures to values of 560°C or less for which it is expected that ferritic steels such as HT9 could be used as a structural material together with the formation and maintenance of a corrosion-inhibiting oxide layer on the structural wall surface.

The calculated heated zone temperature rises all meet the figures of merit such that reliance upon pure or gas-injection augmented natural circulation of the primary and intermediate coolants is effective in transporting the nominal core power from the fuel rods to the HX as well as from the HX to the steam generators. As observed from Table 2, very small differences in the results are calculated between LBE and lead coolants.

The calculations were carried out with temperature dependent heavy liquid metal coolant thermophysical properties evaluated at the mean of the primary and intermediate coolant inlet and outlet temperatures. These properties are being used consistently by all members of the ENHS Project Team. Effects of uncertainties in the thermophysical properties were examined. The most significant uncertainties involve the volume expansion coefficient, β. Uncertainties in β could raise the heated zone temperature rises by 6°C above the values in Table 2. Additional property uncertainties could further increase the heated zone temperature rises to a total of 9°C.

Local friction factors are calculated using the equation of Colebrook and White.[4] A roughness grain size of 10 μm is nominally assumed as representative of an oxide film. The calculated primary and intermediate temperature rises for NLP4 with LBE are about 5 amd 2°C greater, respectively, than would be obtained for a hydraulically smooth channel that corresponds to roughness sizes less than 1 μm. An increase in effective roughness grain size to 50 μm would increase the temperature rises for NLP4 by another 11 and 7°C, respectively, relative to the values at 10 μm.

In summary, the analysis has established that the ENHS can be designed so that natural circulation of the primary and intermediate coolants, or natural circulation enhanced by gas injection into the primary coolant above the core or the intermediate coolant above the heat exchange zone, is effective in transporting the nominal core power to the steam generators.

References

1. E. Greenspan, H. Shimada, D. C. Wade, M. D. Carelli, L. Conway, N. W. Brown, and Q. Hossain, "The Encapsulated Nuclear Heat Source Reactor Concept," ICONE-8750, Proceedings of ICONE-8, 8th International Conference on Nuclear Engineering, Baltimore, April 2-6, 2000.
2. L. Conway, Q. Hossain, D. C. Wade, N. W. Brown, M. D. Carelli, M. Dzodzo, E. Greenspan, D. Saphier, and J. J. Sienicki, "Promising Design Options for the Encapsulated Nuclear Heat Source Reactor," ICONE-9417, Proceedings of ICONE-9, 9th International Conference on Nuclear Engineering, Nice, France, April 8-12, 2001.
3. J. J. Sienicki and D. C. Wade, "Thermal Hydraulic Analysis of the Encapsulated Nuclear Heat Source, "ICONE-9771, Proceedings of ICONE-9, 9th International Conference on Nuclear Engineering, Nice, April 8-12, 2001.
4. H. Schlichting, Boundary Layer Theory, Fourth Edition, McGraw-Hill Book Company, Inc. New York (1960).

Table 1. Comparison of ENHS Design Variants

Design	**NLP4**	**LP6**	**LP7**	**LP7 with HX Extending to Bottom of Active Core**
Gas Injection Above Core	No	Yes	Yes	Yes
Heated Core/Fission Gas Plenum Height, m	1.25/0.625	1.25/0.625	0.933	0.933
Core Radius, m	0.989	0.788	0.933	0.933
Fuel Rod Diameter, cm	1.20	1.20	1.20	1.20
Rod Pitch-to-Diameter Ratio	1.208	1.108	1.247	1.247
Riser/HX Channel Heights, m	13/11	10/8	3.0/1.75	3.0/3.25
HX Channel Thickness/Width, cm	2.5/40	1.7/40	0.5/50	0.5/50
HX Channel Wall Thickness, cm	0.4	0.4	0.4	0.4
SG Heat Exchange Height, m	4.6	4.6	4.6	4.6
Number of SG Modules/Tubes per Module	8/613	8/613	8/163	8/163
Primary/Intermediate Two-Phase Region Height	0/0	8/2	1.75/2	1.75/2
Primary Coolant Core/HX Hydraulic Diameter, cm	0.732/4.41	0.425/3.14	0.856/1.00	0.856/1.00
Intermediate Coolant HX/SG Hydraulic Diameter, cm	4.71/2.51	3.26/2.51	0.990/2.51	0.990/2.51

Table 2. Comparison of Thermal Hydraulic Conditions for Lead-Bismuth Eutectic (LBE) and Lead Coolants Calculated with ANL Natural Circulation Model

Case Designation	**NLP4**	**LP6**	**LP7**	**LP7 with HX Extending to Bottom of Active Core**
Coolant	LBE/Lead	LBE/Lead	LBE/Lead	LBE/Lead
Gas Injection Above Core/Lift Pump	No	Yes	Yes	Yes
Primary Coolant Velocity in Core, m/s	0.515/0.492	1.08/1.06	0.600/0.582	0.479/0.466
Primary Coolant Velocity in HX, m/s	0.384/0.366	0.446/0.436	0.552/0.536	0.441/0.429
Intermediate Coolant Velocity in HX, m/s	0.447/0.426	0.795/0.776	0.725/0.710	0.604/0.589
Intermediate Coolant Velocity in SG m/s	0.294/0.281	0.414/0.404	0.384/0.376	0.320/0.312
Primary Coolant Temperature Rise, C	145/147	158/157	127/127	160/160
Intermediate Coolant Temperature Rise, C	139/141	99.0/98.2	107/105	129/128
Primary Coolant Outlet Temperature, C	545/547	558/557	527/527	560/560
Intermediate Coolant Temperature at Top of HX, C	497/502	479/480	477/478	519/519
Intermediate Coolant Temperature at Bottom of HX	358/360	380/382	370/372	390/391
Primary-to-Intermediate Coolant Temperature Difference at Top of HX, C	47.8/45.6	78.8/76.9	50.5/49.8	41.1/41.0
Primary-to-Intermediate Coolant Temperature Difference at Bottom of HX, C	42.4/39.6	19.7/17.8	29.9/27.6	9.62/8.87