August 20, 2008

MEMORANDUM TO: Michael F. Weber, Director
Office of Nuclear Material Safety and Safeguards

FROM: Brian W. Sheron, Director //RA//
Office of Nuclear Regulatory Research

SUBJECT: COMPLETION OF NMSS USER NEED (NMSS-2007-001), PERFORM A HYDRAULIC CHARACTERIZATION FOR A PROTOTYPIC 17X17 PWR FUEL ASSEMBLY FOR LAMINAR FLOW AT LOW REYNOLDS NUMBERS

Reference: Memorandum from William E. Brach to F. Eltawila, January 31, 2007

In the above reference, the Office of Nuclear Material Safety and Safeguards (NMSS) requested the Office of Nuclear Regulatory Research (RES) assistance in experimental work. The experimental work involves the hydraulic characterization of a prototypic full-length pressurized-water reactor (PWR) 17x17 fuel assembly for low Reynolds numbers. In this region of low Reynolds numbers, laminar flow is expected. This type of flow can be found in normal storage conditions in spent fuel dry storage casks. The obtained data will be used to validate the input data used by dry cask applicants in their computational fluid dynamics (CFD) analyses. Applicants use porous media models to analyze the flow in the fuel rod region of the multipurpose cask. As part of the porous media input, frictional and inertial flow resistance are required.

Experiments performed in Sandia National Laboratory obtained flow characteristics through a prototypic full-length PWR 17x17 fuel assembly inside three different storage cells for low Reynolds number laminar flow. Two of the storage cell sizes (226.6 mm and 221.8 mm) were chosen to span the cell size commonly used in dry storage casks, and the third size (217.5 mm) was chosen as a practical minimum that forced most of the air flow through the tube bundle. Testing included pressure-drop measurements and the quantification of velocities inside every section with different flow cross-sectional area through the assembly. Accurate frictional and inertial loss factors were calculated to reduce uncertainties in CFD flow predictions through the fuel assemblies in a dry storage configuration.

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The enclosed report consists of two main parts. The first part is dedicated to pressure-loss measurement between different locations along the assembly. These measurements included the air-flow rate through the assembly, ambient air temperature, ambient air pressure, and the assembly pressure drops. Curve fits to the pressure-drop data were used to determine the frictional and the inertial loss coefficients.

The second part included velocity profile measurement across the bundle. These profiles are valuable in estimating the flow partition between the bundle and annular region within the assembly.

Pressure-drop measurements were collected at 52 different flow rates between 25 and 2,100 standard liters per minute. Three high-precision quartz crystal differential pressure gauges collected data from 36 pressure ports. The pressure ports were positioned to allow characterization of all individual spacers and bundle runs along the axis of the assembly. Overall pressure-drop data were used to calculate frictional loss coefficient (S_{LAM}) and inertial loss coefficient ($\sum k$). The technique used to determine these coefficients was successfully validated by investigation of flow in a simple annulus for which an analytic value for S_{LAM} is known (see Appendix A for details). Hydraulic loss coefficients were also determined for individual assembly components by the same technique and integrated over the length of the assembly to determine equivalent overall coefficients. The equivalent overall coefficients were in excellent agreement with the directly measured overall coefficients in all cases tested.

The overall S_{LAM} and $\sum k$ hydraulic parameters for the PWR assembly in the 217.5-mm storage cell were determined to be 132.9 and 30.6, respectively. The middle-sized PWR storage cell (221.8 mm) tested represents the smallest cell typically used in commercial dry casks. The overall S_{LAM} and $\sum k$ hydraulic parameters for the PWR assembly in the 221.8-mm storage cell were determined to be 109.9 and 27.7, respectively. The largest PWR storage cell tested (226.6 mm) represents the largest cell typically used in commercial dry casks. The overall S_{LAM} and $\sum k$ hydraulic parameters for the PWR assembly in the 226.6-mm storage cell were determined to be 98.5 and 27.4, respectively.

The viscous loss coefficient, S_{LAM}, exhibits a larger dependence on storage cell hydraulic diameter than the form loss coefficient, $\sum k$. To aid in determining the appropriate coefficients to use with storage cell sizes not tested, empirical power law correlations were determined for S_{LAM} and $\sum k$ as a function of storage cell hydraulic diameter. The resulting correlations based on the full range of flow rates tested (*Re* = 10 to 1000) are:

$$S_{LAM} = 57 + 1.891E\text{-}7 \cdot D_{H,\,Ref.}^{\;-4.348}$$

$$\sum k = 9.872E\text{-}1 \cdot D_{H,\,Ref.}^{\;-0.7527}$$

$D_{H,\,Ref.}$ is the storage cell hydraulic diameter in meters. The correlations should only be used for 17×17 PWR fuel assemblies with storage cells smaller than 230 mm.

Velocity profiles were measured across the PWR bundle using laser Doppler anemometry. These profiles are used in estimating the flow partition between the bundle and annular regions within the assembly. These measurements also indicated a redistribution of flow after spacers and intermediate flow mixers at higher flow rates, suggesting significant wake effects. The wake disturbances in the flow were not apparent in the mid-bundle measurements, which may suggest that the flow has reestablished a fully developed condition.

The partitioning of flow between the bundle and annular regions showed a strong dependence on storage cell size and a weaker dependence on Reynolds number. For *Re* = 400 at the mid-bundle location, the percentage of annular flow was 12, 34, and 52 percent in the 217.5-, 221.8-, and 226.6-mm storage cells, respectively.

In general, the percentage of annular flow decreased with Reynolds number except in the 217.5-mm cell where the percentage increased from 5 to 20 percent at *Re* = 50 to 900, respectively.

In conclusion, a commercial Westinghouse removable fuel assembly 17×17 pressurized-water reactor fuel assembly was hydraulically characterized by measuring both pressure drops and velocities inside three different storage cells in the laminar regime. Two of the storage cell sizes (226.6 mm and 221.8 mm) were chosen to span the cell size commonly used in dry storage casks, and the third size (217.5 mm) was chosen as a practical minimum that forced most the air flow through the tube bundle. These tests spanned Reynolds numbers from 10 to 1,000 based on the hydraulic diameter and average assembly velocity. The pressure drop results were used to calculate viscous and form loss coefficients, namely S_{LAM} and $\sum k$, respectively. The velocity profiles were used to estimate the partitioning of flow in the tube bundle and the annular region between the tube bundle and the storage cell wall. The velocity profile data also suggest that transition away from laminar flow behavior may begin at Reynolds numbers as low as 200.

The enclosed report documents the results of the study. Based on the completion of this study, RES considers the subject of the user need closed. The enclosed report contains proprietary information and is marked for Official Use Only.

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