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Experimental and Analytical Studies of Passive Shutdown Heat Removal from Advanced LMRs*

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A facility designed and constructed to demonstrate the viability of natural convection passive heat removal systems as a key feature of innovative LMR Shutdown Heat Removal (SHR) systems is in operation at Argonne National Laboratory (ANL). This Natural Convection Shutdown Heat Removal Test Facility (NSTF) has investigated the heat transfer performance of the GE/PRISM passive design. This initial series of experiments simulates the air-side geometry of the PRISM Radiant Reactor Vessel Auxiliary Cooling System (RVACS).

The NSTF operates in either a uniform heat flux mode and a uniform temperature mode at the air/guard vessel interface. Analysis of the RVACS performance data indicates excellent agreement with pretest analytical predictions. Correlation analysis presents the heat transfer data in a form suitable for use in LMR design and verification of analytical studies.

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Summary

Using a naturally circulating air stream to remove shutdown decay heat from a nuclear reactor vessel is a key feature of advanced liquid metal reactor (LMR) concepts. General Electric and Rockwell International continue to develop innovative designs (PRISM and SAFR, respectively) aimed especially at improving safety and enhancing plant licensability. Argonne National Laboratory (ANL) provides technical support to both organizations.

Proposed shutdown heat removal systems are totally passive and reject heat from the reactor by radiation and natural convection to air. They are inherently reliable, not being subject to failure modes associated with active systems. They assure adequate cooling under abnormal operating conditions including loss of all other heat removal paths.

Although calculations indicate the viability of these systems, uncertainties remain with respect to particular designs, changing environmental conditions and material properties. Thus, needed data are being gathered in the Natural Convection Shutdown Heat Removal Test Facility (NSTF) at ANL that simulates an air-side, full-scale, segment of the corresponding reactor system; the NSTF began operations on November 21, 1986.

The reactor air cooling system consists of several concentric components with the reactor vessel being the innermost cylinder. It is surrounded by the guard/containment vessel. The space between these vessels is closed and is

filled with an inert gas. Outside the guard vessel is a cylindrical structure referred to as the duct wall. Fins or repeated ribs can be attached to the duct wall and/or the guard vessel. Ductwork provides for downward flow of environmental air to the bottom of the reactor cavity; it then flows upward in the gap between the guard vessel and the duct wall. The fundamental objective of the NSTF experiments is to provide prototypic environments for the air-side from which directly applicable thermal-hydraulic data may be extracted.

Consistent with test objectives the basic NSTF design requirements and conditions for the experiments are:

1. Geometrically simulate air-side, full-scale, segments of reactor systems.
2. Capability for operation that produces constant or variably controlled guard vessel wall temperatures up to 950 K (~ 1250°F), and either constant or variably controlled heat fluxes up to 21.5 kW/m^2 (2.0 kW/ft^2).
3. Total velocity-head losses, K's ranging from ~ 1.5 to ~ 20.
4. Reynolds Nos. ranging from $Re \approx 0.15 - 2.50 \times 10^5$.
5. Variable guard vessel-duct wall gap widths of 150 mm (6-in.) to 460 mm (18-in.).

This system constitutes the ultimate reactor heat sink for decay heat removal; it is the only safety-grade system for that purpose and its viability must be conclusively demonstrated. Thus, the data derived from these tests be unequivocally applicable to LMR designs.

The NSTF comprises a structural model, electric heaters, instrumentation, insulation, and a computerized control and data acquisition system. It simulates prototypic reactor guard vessel temperatures, air flow patterns, and heat removal conditions in a LMR during normal and/or shutdown operation.

The NSTF assembly consists of an inlet section, a heated zone and an unheated stack. All sections, except the inlet, are thermally insulated to minimize parasitic heat losses. For the initial experiments, the heated zone flow channel measured 1.3 M (52 in.) x 0.30 M (12 in.) in cross section, 6.7 M (22 ft.) tall.

Above the heated zone the flow channel expands to 1.5 M (60 in.) x 0.46 M (18 in.). The main exit flow path is through a stack nearly 18.0 M (60 ft.) tall. Within the heated zone, fins or transverse ribs may be installed on the inner walls.

Heater control and data acquisition systems are included in the facility. The heaters are assembled in groups of twenty; each such module comprises sixteen central heaters and four edge or "guard" heaters. Electrical power delivered to each of these regions is controlled separately thereby providing capability to compensate for temperature deviations at the edges. Ten such heater modules are attached to the exterior side of the guard vessel simulator that can provide uniform or variable sources of heat for the tests.

The data acquisition system (DAS) samples 300 channels, most of which are dedicated to thermocouples. The DAS stores all data on disk and selected channels may also be displayed on CRT's and hardcopy. Programs also use on-line data and algorithms to compute some system parameters that depend on multiple inputs.

NSTF instrumentation measures local surface temperatures, local and bulk air temperatures, local and bulk air velocities, and air volumetric and mass flow rates, the radiative and convective components of the total heat flux, and the local heat flux. These data are used to evaluate the heat removal performance for particular configurations and testing conditions. The primary measurement objective is to gather data needed to determine the local and bulk heat flux transport rates and associated heat transfer coefficients.

The fundamental properties of the air that must be accurately measured at various elevations are its temperature and pressure. Thus, instrumentation consists of thermocouples, Pitot-static traversing probes, Pitot-static air flow rake, differential pressure transducers, radiation and heat flux transducers, a traversing mechanism, and a wind monitor and humidity instrumentation.

Pretest calculations have provided the predicted NSTF performance which were used to select ranges of the primary parameters for Phase I operations. Following initial checkout and bakeout operations, Phase I operations were run in two main modes: (a) constant power (uniform heat flux) and (b) constant guard vessel surface temperature (because of the 10-zone incremental power control, this is actually a smoothed saw-toothed wave).

This paper presents the results obtained from the first NSTF test series which was performed to investigate the decay heat transfer performance of the GE/PRISM passive design. This initial series of experiments simulated the air-side geometry and natural convection/radiation environment of the PRISM guard vessel/collector wall (duct wall) design. This configuration is designated as the Radiant Reactor Vessel Auxiliary Cooling System (RVACS) with dimensions cited earlier.

In order to encompass all possible reactor operating conditions, the NSTF has been operated parametrically to provide heat fluxes from 1.83 kW/m^2 (0.17 kW/ft^2) to 16.1 kW/m^2 (1.5 kW/ft^2), guard vessel temperatures from 395K (250°F) to 950K (1250°F), fixed values of system loss K (number of inlet velocity heads) equal to 1.5, 5.0, 10.0 and 20.0. Resulting Reynolds Numbers range from 0.25 to 2.4×10^5.

Analysis of the RVACS performance data indicates excellent agreement with pretest analytical predictions. Correlation analysis is in progress to present the heat transfer data in a form suitable for use in LMR design and verification of analytical studies.

Facility operations have been quite satisfactory during the RVACS Phase I experiments. These experiments have been completed and preparations are in progress to install a finned configuration typical of the RI/SAFR design, designated as the Reactor Air Cooling System (RACS). RACS experiments and a series of surface enhancement tests are planned for FY88.

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