THERMALHYDRAULICS PROJECTS IN SUPPORT OF CONCEPTUAL DESIGN AND SAFETY ANALYSES OF CANDU SCWR

L.K.H. Leung
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

Abstract

A number of research and development (R&D) projects have been established to provide thermalhydraulics- and safety-related information in support of the development of the CANDU®[1] supercritical water-cooled reactor (SCWR). These projects are mainly funded through three separate programs: the Generation-IV national program, the NRCan-NSERC collaborative research and development (CRD) program, and the AECL CANDU-X program. Thermalhydraulics-related projects in these programs focus on the development of heat transfer prediction methods for CANDU-type bundles. These projects cover analytical and experimental studies in supercritical water and surrogate fluids in tubes and bundles. Short descriptions of these projects and the results obtained up to this point are presented.

1. Introduction

Canada is participating in the international collaborative forum on system research for two designs of the Generation-IV (Gen-IV) nuclear reactor. The forum is referred to as the Generation-IV International Forum (or GIF). Canada is participating in the supercritical water-cooled reactor (SCWR) and the Very High Temperature Reactor (VHTR) designs. The SCWR design covers both the pressure vessel and pressure-tube types. Canada focuses mainly on the pressure-tube type SCWR design, which is a natural extension of the existing CANDU reactor. Several critical research areas have been identified in the system-research plan for supporting the SCWR design. Thermalhydraulics and safety are two of the critical research areas.

GIF participants in the SCWR development have prepared a Project Plan for thermalhydraulics and safety research work. The plan lists tasks required for completing the conceptual design of the SCWR and covers key areas such as heat transfer, critical flow, instability, development of analytical toolsets for supercritical-water applications, and preliminary safety analyses. Completing these tasks demands a large coordinated effort between research organizations and the academic community.

The Canadian contribution to various key areas of the GIF SCWR Thermalhydraulics and Safety Project has been identified in the project plan. It consists of projects directly relevant to the CANDU SCWR fuel and core designs at AECL and fundamental research and development (R&D) projects related to the SCW flow and heat transfer at various Canadian universities [1]. In addition, AECL has initiated other collaborative projects with Canadian universities (with proposed support from the Ontario Research Fund) and Chinese universities

[1] CANDU – Canada Deuterium Uranium, a registered trademark of Atomic Energy of Canada Limited (AECL).

to develop the future reactor design. Information from these projects is also applicable to the Gen-IV SCWR design and will be included as part of the Canadian contribution to GIF. The objective of this paper is to present several thermalhydraulics projects in support of the CANDU SCWR design.

2. Thermalhydraulics Projects

Thermalhydraulics characteristics at supercritical water-flow conditions are required in support of the design and qualification of the fuel bundle and safety analyses for the supercritical water-cooled reactor (SCWR). Fundamental understanding of thermalhydraulics characteristics has been relying on experimental information obtained with tubes, annuli, and bundle subassemblies. One of the most critical areas for thermalhydraulics analyses is the heat-transfer characteristic at supercritical water conditions. In particular, the deterioration of heat transfer at the vicinity of the critical point has a large impact on the power output and safety of the SCWR. Figure 1 illustrates variations in the heat-transfer coefficient as a function of temperature for supercritical water flow inside a 10-mm inside diameter (ID) tube. The decrease in heat-transfer coefficient as the bulk-fluid temperature approaches the pseudo-critical temperature, T_{pc}, is referred as the deteriorated heat-transfer mode.

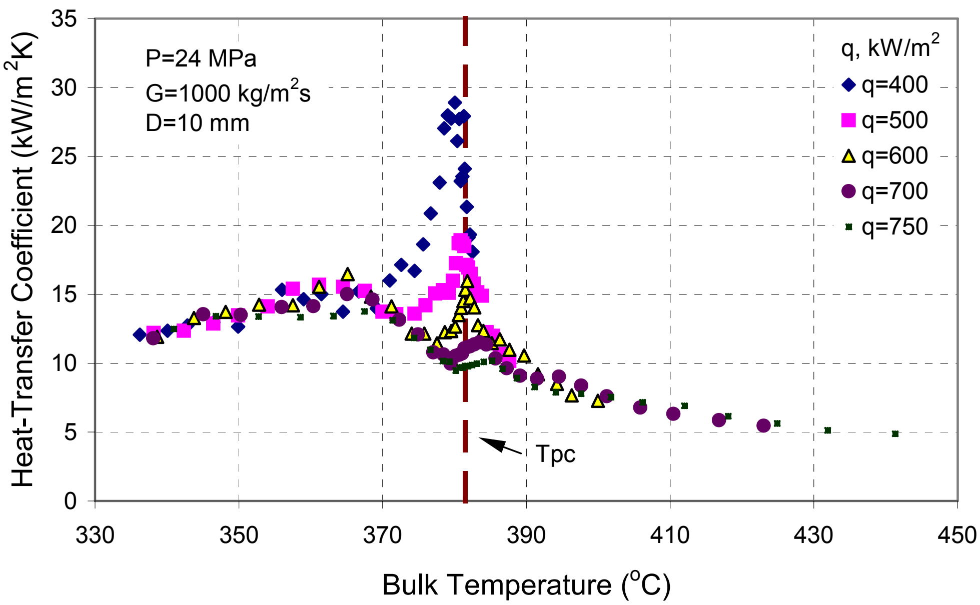


Figure 1 Heat-Transfer Coefficient in Supercritical Water Flow.

2.1 Heat-Transfer Studies with Supercritical Water Flow

Heat-transfer studies with water flow at supercritical conditions were performed mainly in support of the fossil-power plants. Circular tubes of various diameters were used as test sections in most of these studies. Annuli and small bundle assemblies were also used but generally in very limited number of experiments. Bundle geometries employed in these studies differ from those proposed for use as fuel bundle in SCWRs, which will be considerably more compact in size. Experimental data, and correlations derived using these data, are primarily applicable to these test geometries.

2.1.1 Supercritical Water Heat-Transfer Analyses

Prediction methods for supercritical heat transfer are required for preliminary design and safety analyses of the CANDU SCWR. Many prediction methods were developed with tube data, but none of them has been able to capture the experimental trends and provide reasonable prediction accuracy at conditions beyond their database. The deficiency is attributed to the limited database used in the development of these prediction methods.

A database of supercritical heat transfer in water and non-aqueous fluids was established [2]. It contained primarily experimental data obtained from studies listed in [3]. Recently, the database has been expanded to include additional experimental data that have not been identified previously [4]. Figure 2 illustrates the range of reduced pressure and reduced temperature covered in the supercritical water heat-transfer database[2]. These data are being applied in the development of an improved prediction method for supercritical heat transfer coefficients.

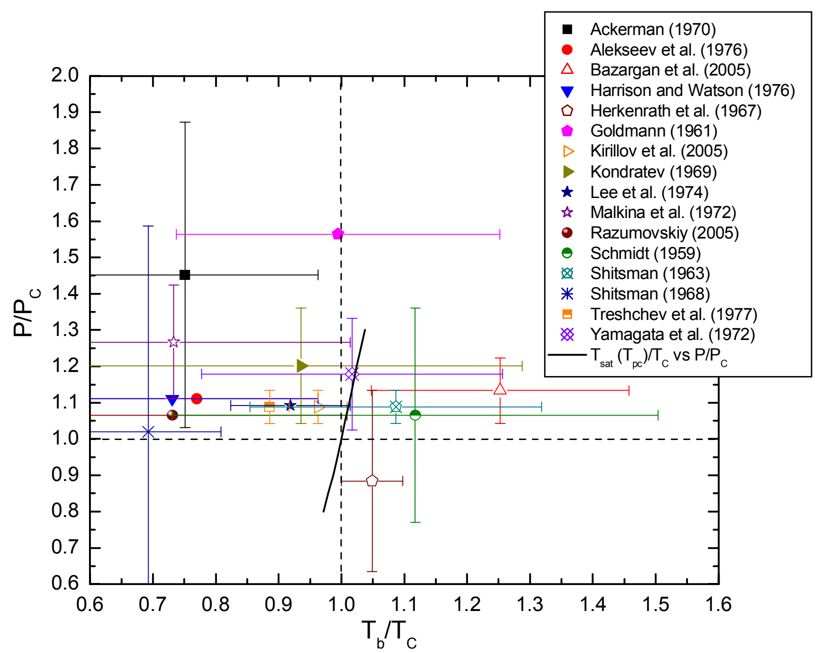


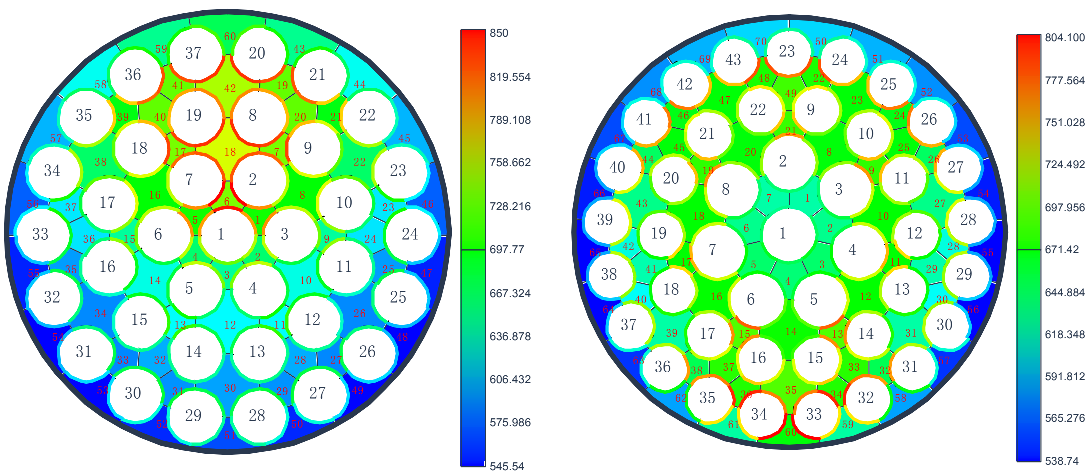
Figure 2 Range of Selected Supercritical Heat-Transfer Data for Water Flow [4].

Tube-data-based prediction methods are applicable for subchannel analyses. These methods can be extended to safety analyses, but must be validated against experimental full-scale bundle data. Full-scale bundle (or bundle subassemblies) data are often classified as proprietary information and details of the experiments are generally unavailable. Based on the

[2] Details of these water data sets are provided in [4].

published information on small bundles, there are differences in SC heat-transfer characteristics between tubes and bundles. The subchannel effect in bundles appears to have improved the SC heat transfer.

Through a collaborative project between AECL and Xi'an Jiaotong University in China, a subchannel analysis has been performed to understand the flow and temperature distributions in subchannels of CANDU bundles at supercritical water conditions [5]. Figure 3 illustrates the surface-temperature predictions in subchannels of the CANDU 37-element and CANFLEX[3] bundles. The high-temperature region corresponds to the inner subchannel at the top portion of the 37-element bundle, but the outer subchannels at the bottom portion of the CANFLEX bundle. At the same flow conditions, the maximum bulk-fluid temperature and surface temperature in the 37-element bundle are higher than those in the CANFLEX bundle.



Max. Tw: 850°C

Max. Tb: 762°C

Parameters	Values
Coolant inlet pressure	25 MPa
Coolant inlet temperature	350°C
Coolant exit temperature	625°C
Average coolant mass flux	$890.3\ kg \cdot m^{-2} \cdot s^{-1}$
Average heat flux	$0.978\ MW \cdot m^{-2}$
Limit of cladding surface temperature	850°C

Max. Tw: 804°C

Max. Tb: 693°C

Figure 3 Subchannel Predictions of Surface Temperature Distributions in 37-Element and CANFLEX Bundles.

2.1.2 Supercritical Water Tests

Currently, there is no supercritical water test facility in Canada for exploratory investigation of geometry and spacing-device effects on supercritical heat transfer. A joint project between Carleton University and AECL has been proposed for the Ontario Research Fund in the design and construction of a supercritical water facility for small-scale tests using tubes, annuli, and bundle subassemblies (three to four rods). This facility will be unique in Canada and will allow the investigation of various separate effects at relevant range of water-flow conditions.

[3] CANFLEX – CANDU Flexible, a registered trademark of AECL and Korea Atomic Energy Research Institutes (KAERI).

A separate collaborative project has been initiated between AECL and Xi'an Jiaotong University in China to obtain experimental supercritical heat-transfer data with annuli and a 4-rod bundle in water flow. The annuli tests are designed to gain experience in heater design and construction, and to provide supplemental heat-transfer data for examining the geometry effect (as compared to tubes and bundles). Figure 4 illustrates the annulus test section designed for the supercritical heat-transfer test with water flow. The test section consists of a heated inner tube of 8-mm outer diameter (OD) and an unheated shroud of 16-mm ID. Electric power is applied to heat the inner tube over a length of 2 metres. Movable thermocouples are installed inside the inner tube to measure the surface-temperature distribution. A test section was constructed and installed into the test facility, but failed during commissioning. The failure was attributed to arcing between the inner and outer tube at the downstream end of the test section. The design to isolate the inner tube from the outer tube is being improved. A separate test section will be constructed once the design is complete.

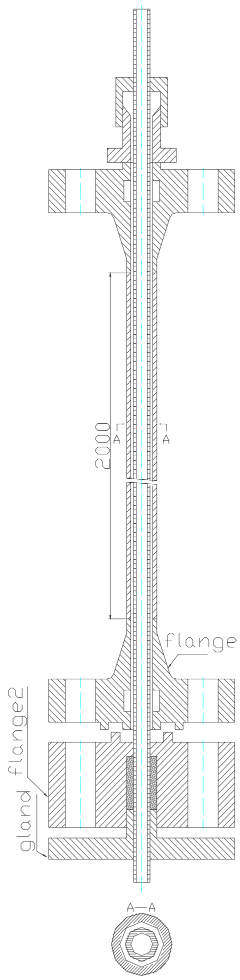


Figure 4 Annulus Test Section for the Supercritical Water Heat Transfer Test.

2.2 Heat-Transfer Studies with Surrogate Fluids

Performing heat-transfer experiments with supercritical water flow is complex and expensive due primarily to the harsh operating environment and the high level of required heating power. Surrogate fluids (such as carbon dioxide and refrigerants) have been suggested for replacing water in heat transfer studies. These fluids were previously utilized in studies of critical heat flux and film-boiling heat transfer at subcritical conditions. Using these fluids reduces experimental cost and schedule, reduces test-section design and operation risk, and increases testing flexibility. This arises from the fact that supercritical conditions for surrogate fluids are less severe than those for water. Table 1 summarizes critical properties of water, carbon dioxide and refrigerant R-134a.

Table 1 Critical Parameters for Water, Carbon Dioxide and Refrigerant R-134a.

Parameter	Unit	Water	CO_2	R-134a
Critical pressure, P_c	MPa	22.1	7.38	4.06
Critical temperature, T_c	K (ºC)	647.3 (374.1)	304.2 (31.0)	374.2 (101.0)
Critical density, ρ_c	kg m^{-3}	315	468	512

Experimental heat-transfer data with surrogate fluids have considerably expanded the relevant database to conditions at which possible damage to test sections could result during water tests. Figure 5 illustrates the range of reduced pressure and reduced temperature covered in the supercritical heat-transfer database for carbon dioxide flow[4] [4]. Information obtained with surrogate fluids is not directly applicable to water flow. Transformation of flow conditions and thermalhydraulics parameters for the surrogate fluid is required to establish water-equivalent values for water applications. Fluid-to-fluid modeling parameters have been established for critical heat flux and film-boiling heat transfer at subcritical conditions, and shown to be appropriate. This approach has been extended to supercritical water conditions. The appropriate set of modeling parameters for flow conditions and heat transfer had yet to be established. A study has been initiated to examine various modeling parameters using the assembled supercritical heat-transfer databases for water and surrogate fluids.

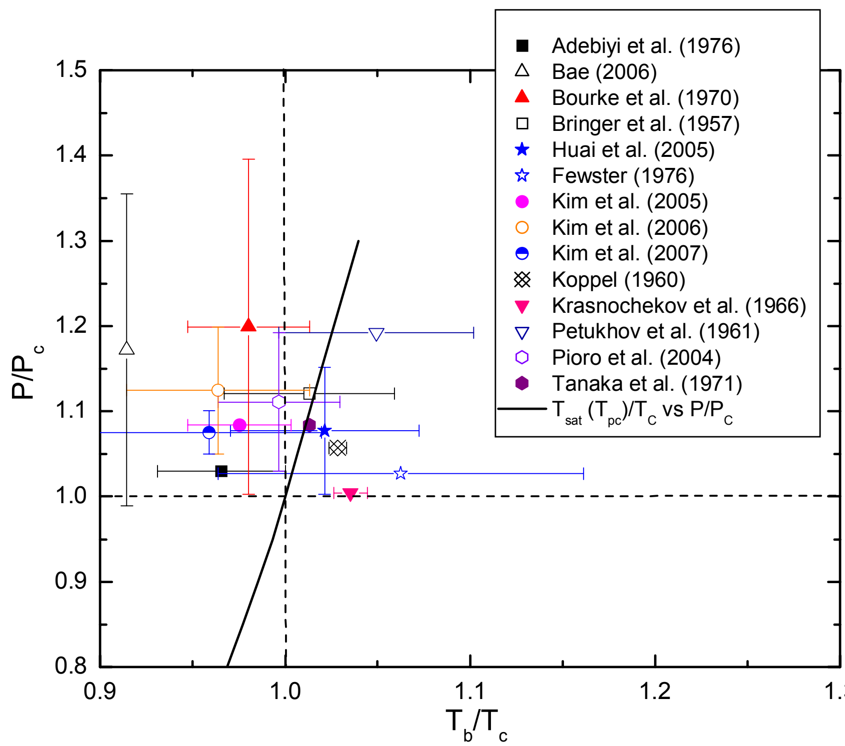


Figure 5 Range of Selected Supercritical Heat-Transfer Data for Carbon Dioxide Flow [4]

A heat-transfer test facility has been designed for construction at the University of Ottawa (UO) [2]. It employs carbon dioxide as working fluid and is capable to test small bundle subassemblies. Figure 6 presents the schematic diagram of the UO heat-transfer test facility.

[4] Details of these carbon-dioxide data sets are provided in [4].

Keys components of this test facility have been procured and loop construction has commenced. Once completed, the test facility will be commissioned with an 8-mm ID vertical tube of 2-m heated length. Experimental data obtained from the commissioning test will be compared against those in the database.

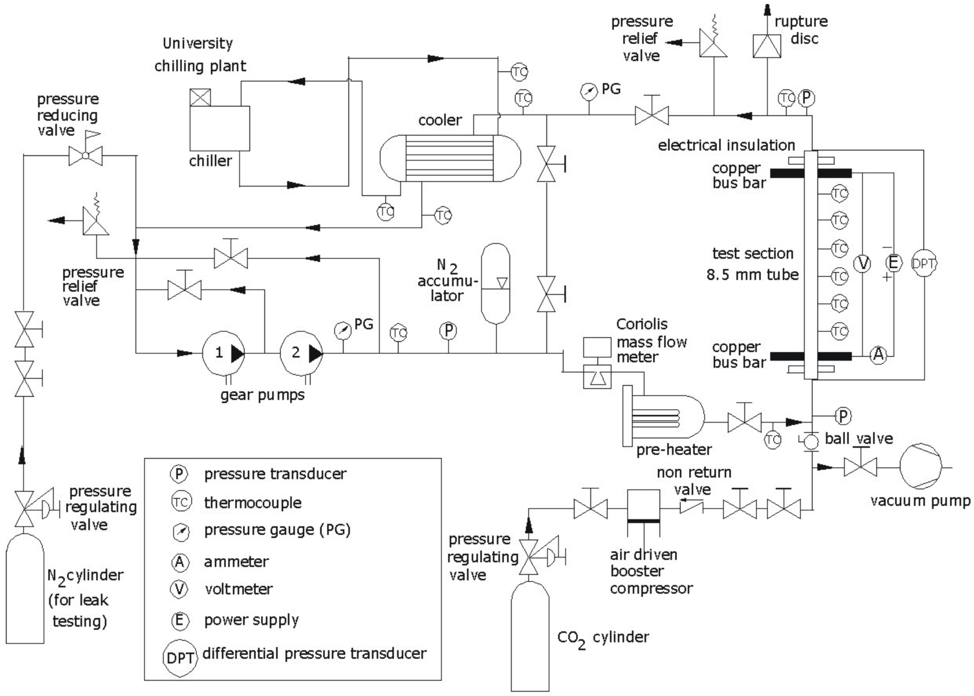


Figure 6 Sketch of the proposed CO_2 flow loop [2].

As stated previously, there is a lack of supercritical heat transfer data for bundle geometries. The main purpose for constructing the UO test facility is to generate bundle data in carbon dioxide flow to quantify the impact of flow and enthalpy distributions in subchannels on supercritical heat transfer. A 3-rod bundle string previously constructed for high-pressure (10 MPa nominal) water test at Chalk River Laboratories has been transferred to UO for supercritical carbon dioxide flow test (critical pressure at 7.38 MPa, see Table 1). Figure 7 illustrates schematically the 3-rod bundle-string configuration. The bundle string consists of six 0.5-m long segments, each equipped with endplate, spacers (only at the mid plane), and wear pads (at two ends and mid plane). Two of the three elements contain two fixed thermocouples attached to downstream ends of the last two bundle segments. The other element has been equipped with a movable-thermocouples assembly that can be rotated and moved axially to obtain detailed surface-temperature distributions in each of the last two bundle segments. The bundle string is installed inside a 32.5-mm unheated shroud. Unheated fillers are installed at subchannels between elements and the shroud to minimize flow diversion from the center subchannel between the three elements. The scheduled experiment would provide detailed surface temperature and pressure drop measurements to improve the understanding of supercritical heat transfer behaviors in bundle geometry. In addition, these measurements are ideal for validation of subchannel codes and computational fluid dynamic tools.

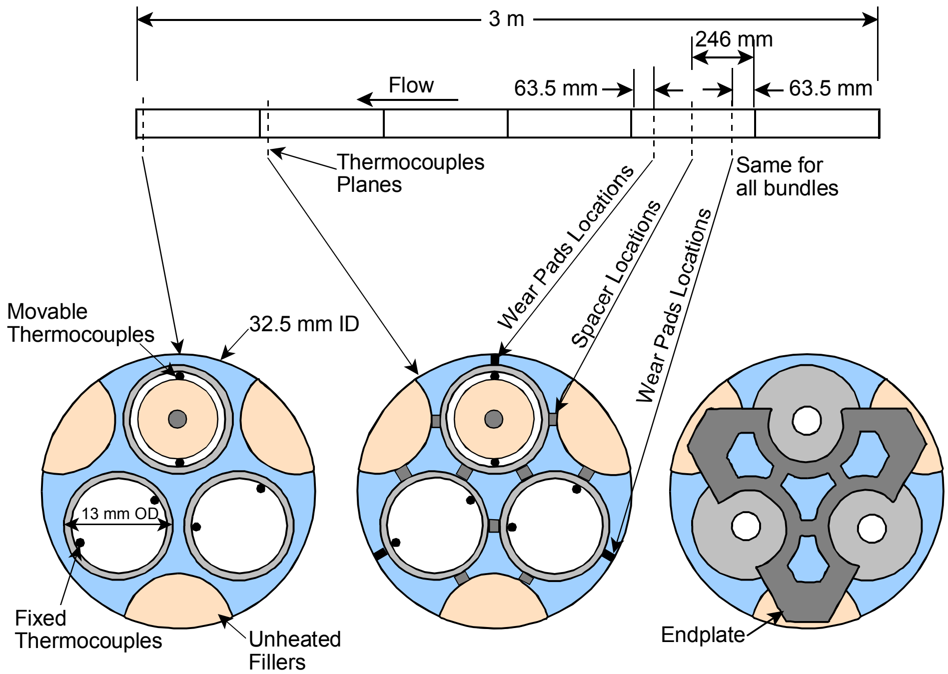


Figure 7 Sketch of the three-rod bundle subassembly

3. Conclusion

Canada is participating in GIF on SCWR, focusing on the pressure-tube type design. Our contribution to the Thermalhydraulics and Safety Projects has been included in the Project Plan, and is led by NRCan with support from NSERC and AECL.

The Canadian projects cover key technical areas and are being carried out at AECL and several Canadian universities. Other collaborative efforts between AECL and international universities have also been included as the Canadian contribution.

Thermalhydraulics projects focus on the development of supercritical heat-transfer prediction methods for subchannel and safety analyses. The objectives, experimental facilities, and test sections have been described for several thermalhydraulics projects. Some preliminary results are presented.

Overall, a large amount of supercritical heat transfer data has been assembled for water and surrogate fluids in tubes. However, there is a lack of bundle data to quantify the impact of subchannel flow and temperature distributions on heat transfer. Several projects have been initiated to establish test facilities for providing supercritical heat transfer data for bundle subassemblies. Preliminary subchannel analyses have shown a large variation in surface temperature distribution in bundles. Maximum fluid temperature and surface temperature are generally lower for the CANFLEX bundle than the 37-element bundle.

4. References

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