AWARD/CONTRACT	1. THIS CONTRACT IS A RATED ORDER UNDER DPAS (15 CFR 700)	RATING	PAGE OF PAGES 1 56

2. CONTRACT (Proc. Inst. Ident.) NO.	3. EFFECTIVE DATE	4. REQUISITION/PURCHASE REQUEST/PROJECT NO.
31310020C0009	See Block 20C	RES-20-0043

5. ISSUED BY CODE NRCHQ	6. ADMINISTERED BY (If other than Item 5) CODE
US NRC - HQ ACQUISITION MANAGEMENT DIVISION MAIL STOP TWFN-07B20M WASHINGTON DC 20555-0001	SCD-C

7. NAME AND ADDRESS OF CONTRACTOR (No., street, country, State and ZIP Code)	8. DELIVERY
REGENTS OF THE UNIVERSITY OF MICHIGAN ATTN KATHRYN DEWITT 1058 WOLVERINE TOWER - ORSP 3003 SOUTH STATE STREET ANN ARBOR MI 481091274	☐ FOB ORIGIN ☒ OTHER (See below)
	9. DISCOUNT FOR PROMPT PAYMENT 30
CODE 073133571 FACILITY CODE	10. SUBMIT INVOICES (4 copies unless otherwise specified) TO THE ADDRESS SHOWN IN ITEM

11. SHIP TO/MARK FOR CODE NRCHQ	12. PAYMENT WILL BE MADE BY CODE NRCPAYMENTS
NUCLEAR REGULATORY COMMISSION NUCLEAR REGULATORY COMMISSION WASHINGTON DC 20555-0001	FISCAL ACCOUNTING PROGRAM ADMIN TRAINING GROUP AVERY STREET A3-G BUREAU OF THE FISCAL SERVICE PO BOX 1328 PARKERSBURG WV 26106-1328

13. AUTHORITY FOR USING OTHER THAN FULL AND OPEN COMPETITION:	14. ACCOUNTING AND APPROPRIATION DATA
☐ 10 U.S.C. 2304 (c) ( ) ☒ 41 U.S.C. 3304 (a) ( )	See Schedule

15A. ITEM NO	15B. SUPPLIES/SERVICES	15C. QUANTITY	15D. UNIT	15E. UNIT PRICE	15F. AMOUNT
	Continued				
	15G. TOTAL AMOUNT OF CONTRACT				$753,812.00

16. TABLE OF CONTENTS

CONTRACTING OFFICER WILL COMPLETE ITEM 17 (SEALED-BID OR NEGOTIATED PROCUREMENT) OR 18 (SEALED-BID PROCUREMENT) AS APPLICABLE

17. ☒ CONTRACTOR' S NEGOTIATED AGREEMENT (*Contractor is required to sign this document and return ____________ copies to issuing office.*) Contractor agrees to furnish and deliver all items or perform all the services set forth or otherwise identified above and on any continuation sheets for the consideration stated herein. The rights and obligations of the parties to this contract shall be subject to and governed by the following documents: (a) this award/contract, (b) the solicitation, if any, and (c) such provisions, representations, certifications, and specifications, as are attached or incorporated by reference herein. *(Attachments are listed herein.)*

18. ☐ SEALED-BID AWARD (*Contractor is not required to sign this document.*) Your bid on Solicitation Number 31310020R0012, including the additions or changes made by you which additions or changes are set forth in full above, is hereby accepted as to the items listed above and on any continuation sheets. This award consummates the contract which consists of the following documents: (a) the Government's solicitation and your bid, and (b) this award/contract. No further contractual document is necessary. (Block 18 should be checked only when awarding a sealed-bid contract.)

19A. NAME AND TITLE OF SIGNER (Type or print)		20A. NAME OF CONTRACTING OFFICER	
		JENNIFER A. DUDEK	
19B. NAME OF CONTRACTOR	19C. DATE SIGNED	20B. UNITED STATES OF AMERICA	20C. DATE SIGNED
REGENTS OF THE UNIVERSITY OF MICHIGAN BY (Signature of person authorized to sign)		BY [redacted] (Signature of the Contracting Officer)	06/15/2020

NAME OF OFFEROR OR CONTRACTOR
REGENTS OF THE UNIVERSITY OF MICHIGAN

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	The contractor shall provide services entitled, "Post-CHF Heat Transfer Instrumentation and Experimentation," in accordance with the enclosed Statement of Work (see Section C). This is a cost-reimbursement contract. Total Contract Ceiling: $753,812.00 Total Obligation: $275,000.00 Accounting Info: 2020-X0200-FEEBASED-60-60D003-60B301-1147-11-6-174-252A-11-6-174-1147 Period of Performance: 07/01/2020 to 06/30/2022				

B - Supplies or Services/Prices

B.1 BRIEF PROJECT TITLE AND WORK DESCRIPTION

(a) The title of this project is:

Post- Critical Heat Flux (CHF) Heat Transfer Instrumentation and Experimentation

(b) Summary work description:

The purpose and objective of this acquisition is to continue the fabrication and assembly of an advanced two-phase flow instrumentation system with the capability to be used to aid in the development of constitutive models for the U.S. Nuclear Regulatory Commission's (NRC) TRAC RELAP Advanced Computational Engine (TRACE) code and to provide the experimental database necessary for the improvement of the TRACE models for inverted annular through dispersed flow film boiling regimes, which was identified as a high priority near-term development need in the NRC's Office of Nuclear Regulatory Research Thermal-Hydraulic Code Development Plan.

Under this acquisition, the contractor shall continue to acquire the requisite components and assemble the advanced two-phase flow instrumentation system, as well as conduct validation testing. This capability will be used in experimental programs that target models for the inverted annular film boiling through Dispersed Flow Film Boiling regimes but will continue to be useful for other future experimental programs. Specifically, this advanced instrumentation will provide the first quantitative insights into the flow topology and subchannel-averaged void fractions for these post-CHF regimes.

A further objective of this acquisition is the performance of steady-state low-quality film boiling experiments in a tubular test section. A major component of this experimental program is the utilization of the X-ray radiography system that has already been nearly completed in the instrumentation portion of the effort. This advanced two-phase instrumentation system will provide not only for the accurate measurement of the void fraction during post-CHF conditions but also provide information on the flow topology such as the size and shape of the liquid slugs in the Inverted Slug Film Boiling regime.

B.2 CONSIDERATION AND OBLIGATION—COST-REIMBURSEMENT – NO FEE ALTERNATE I

(a) The total estimated cost to the Government for full performance under this contract is **$753,812.00**.

(b) The amount presently obligated by the Government with respect to this contract is **$275,000.00**.

(c) It is estimated that the amount currently obligated will cover performance through **November 30, 2020**.

(d) This is an incrementally-funded contract and FAR 52.232-22 – "Limitation of Funds" applies.

B.3 PRICE/COST SCHEDULE

CLIN NO.	DESCRIPTION OF SUPPLIES/SERVICES	TOTAL ESTIMATED COST
00001	Post-CHF Heat Transfer Instrumentation and Experimentation	$753,812.00

C - Description/Specifications

C.1 STATEMENT OF WORK

Post-CHF Heat Transfer Instrumentation and Experimentation

Contents

1. BACKGROUND

The U.S. Nuclear Regulatory Commission's (NRC) TRACE (TRAC RELAP Advanced Computational Engine) code is NRC's flagship thermal-hydraulics analysis tool. TRACE is a modernized thermal-hydraulics code designed to perform large and small break loss of coolant accident (LOCA) and system transient analyses for a wide range of nuclear plants. This code is being used as an audit tool to analyze transient and accident analyses submitted by NRC vendors and licensees. Improvement of the constitutive models in the TRACE code has been identified as a high priority. The experimental effort to be conducted under this acquisition shall provide the data and reports necessary to inform the required improvements of the constitutive models in the TRACE code.

Three post-Critical Heat Flux (CHF) flow regimes, inverted annular, inverted slug, and dispersed flow film boiling, are the focus of this effort. In particular, this contract will address these post-CHF regimes in a tubular test section with a stabilized quench front to allow for steady-state conditions and thereby facilitate model development. As explained below, this experimental program has been designed to complement that of the small rod bundle post-CHF experiments currently in the planning stages at Penn State as part of the spacer grid thermal-hydraulics program.

As described in attachment #1, the inverted annular film boiling (IAFB) regime occurs just downstream of the quench front and its precursory cooling largely governs the quench front progression by reducing the clad temperature to the point where surface rewetting can begin. In addition, its void fraction, due to its effect upon the downcomer-to-core gravity head, affects the core inlet flooding rate. Further downstream, the breakup of the inverted annular core gives rise to the inverted slug film boiling (ISFB) region that provides the initial condition for the dispersed flow regime where the peak clad temperature occurs. Therefore, for the accurate prediction of post-CHF clad temperature in transients such as large and intermediate break LOCAs, accurate models with quantified uncertainties are required for the calculation of both the wall heat transfer and the void fraction in these regimes.

High pressure IAFB can occur during an Anticipated Transient Without Scram (ATWS) event while regions of a BWR core exceed the critical heat flux during power oscillations. Both the IAFB and ISFB regimes can occur at high pressure in a PWR during the blowdown rewet phase of a large-break LOCA or during loop seal clearance with a partially uncovered core in a small-break LOCA. These scenarios involve high pressure post-CHF flow conditions for which very little data exists. Recently, some TRACE simulations have indicated that ATWS related oscillations may result in maximum cladding temperatures near the 2200 °F regulatory limit. Models in TRACE and most other thermal-hydraulic codes are largely based on low pressure data and then extrapolated. Thus, the possible bias and high uncertainty in these models is difficult to quantify and has complicated the review process. Accurate models with well-defined uncertainties for the IAFB and ISFB regimes are therefore needed to support NRC in both near-term and future licensing activities.

Two-fluid codes such as TRACE frequently use ad hoc models for wall and interfacial heat transfer as well as interfacial shear in the inverted annular and inverted slug film boiling flow regimes. Consequently, the modeling of these regimes was the subject of criticism during the TRACE peer review. Moreover, the current IAFB and ISFB models under-predict blowdown cooling in the LOFT L2-6 assessment during the time period when the in-surge of water into the bottom of the core quenches the fuel rods. Therefore, the improvement of the models for these regimes was identified as a high priority near-term development need in the Thermal-Hydraulic Code Development Plan.

The experimental effort described so far is specifically targeted to the improvement of the TRACE constitutive models for the inverted annular, and inverted slug film boiling regimes. However, the transition from the ISFB to the dispersed flow film boiling (DFFB) regime shall also be investigated.

This transition is due to droplet entrainment and the resulting constitutive models will support the addition of the droplet field into TRACE for reflood conditions. The incorporation of the droplet field in TRACE was also identified as a high priority near-term development need in the Thermal-Hydraulic Code Development Plan and this experimental effort supports that task as well.

For the inverted annular film boiling regime, the primary correlating variable is the vapor film thickness as deduced from the void fraction. The wall heat transfer correlation developed for TRACE 5.0 uses a non-dimensional form of the vapor film thickness to account for the large effect of system pressure upon the wall heat transfer coefficient. This relationship is based on laminar flow theory and there is insufficient high pressure IAFB void fraction data to verify it. Indeed, it appears that the pressure effect embodied in the TRACE formulation is overly conservative for high pressure and high flow conditions.

Similarly, recent investigations have indicated that the liquid-side interfacial heat transfer coefficient may have a pronounced mass flux effect for values of the mass flux above about 1000 (kg/m^2s). The interfacial heat transfer rate into the subcooled liquid core in IAFB governs the vapor generation rate at the interface and hence affects the vapor film thickness and wall heat transfer. The TRACE model for this interfacial heat transfer is a simple constant value of the Nusselt no. and the lack of a mass flux effect could also lead to a conservative bias in the wall heat transfer. There is little film boiling data at high flow rates such as would occur during oscillations in a BWR ATWS event and void fraction measurements are virtually non-existent.

To complete the investigation of post-CHF flow regimes, this contract includes a study of the DFFB regime. DFFB is a follow-on regime to ISFB that occurs when the vapor flow rate has become high enough to shatter the liquid slugs into smaller droplets[1] that are then entrained in the vapor flow. Post-CHF heat transfer in the DFFB regime is of prime importance to LOCA analysis as it is in this regime that the peak clad temperature occurs. Vapor-side interfacial heat transfer in DFFB will be the focus of this added task as it governs the level of vapor superheat and thereby directly impacts the clad temperature.

The calculation of vapor-side interfacial heat transfer in the dispersed flow film boiling regime depends primarily on the accurate prediction of both the entrainment rate and the drop diameter. By performing steady-state post-CHF experiments, where the bottom quench front is stabilized by means of a “hot patch”, the entrainment rate is known from a simple mass and energy balance. The remaining quantity, the droplet diameter, while it cannot be measured directly in these experiments, can be inferred from the level of vapor superheat. Consequently, it is the measurement of the superheated vapor temperature in DFFB that is the objective of one of the experimental tasks.

This contract addresses these data needs for wall heat transfer and void fraction measurements for the IAFB through DFFB post-CHF regimes for high pressure and high flow conditions. Specifically, steady-state experiments shall be conducted in a tubular test section where the quench front has been stabilized by using a directly heated hot patch (see attachment #2). This experimental program has been designed to complement that of the small rod bundle post-CHF experiments currently in the planning stages at Penn State as part of the spacer grid thermal-hydraulics program. In particular:

- Overlap tests shall be conducted to quantify the effect of the rod bundle geometry vis-à-vis that of a tubular test section,
- Experiments at high values of the pressure, mass flux and subcooling shall be conducted to provide coverage where the transient rod bundle tests may be too rapid to allow for

[1] These droplets are expected to have a Sauter mean diameter on the order of 1 mm.

accurate measurement of subchannel averaged void fractions using the gamma-ray tomography system,

- A systematic variation of pressure shall be used to modify the non-dimensional formula for the vapor film thickness so that pressure effects are correctly accounted for, and
- Tests at high mass flux conditions shall be conducted to determine the magnitude of the mass flux effect upon the liquid-side interfacial heat transfer coefficient.

To elucidate the data needs for model development and to describe the previous experimental programs, attachment #1 has sections describing:

- Post-CHF flow regimes
- Two-fluid modeling of IAFB
- Two-fluid modeling of ISFB
- Previous experimental programs

This attachment is included to enhance the shared understanding of the task at hand and was used in developing the requirements detailed below.

To execute an experimental program investigating post-CHF heat transfer, this contract includes fabrication and testing of an advanced two-phase instrumentation system to provide data necessary for this model improvement activity. The advanced two-phase instrumentation described below will provide for accurate and non-intrusive measurement of the vapor volume fraction for rod bundle geometries and provide information on the flow topology for tubular test sections. This capability will be useful for a wide range of future experimental programs; however, the immediate objective is the improvement of the constitutive models for the post-CHF regimes of ISFB and IAFB. Attachment #1 elucidates the data needs for model improvement for these two post-CHF regimes and then provides a review of the available advanced two-phase instrumentation systems.

In addition to the acquisition of the requisite components for the advanced two-phase instrumentation system, this contract provides for its assembly and validation testing. Furthermore, as this instrumentation is being developed to be used on a number of experimental programs, some of which may not be performed by the contractor who develops the instrument, the instrument assembly shall be designed with maximum portability in mind and include materials for the training of new operators.

The scope of work outlined in this contract represents an extension of work already completed under a previous contact. Between 2014 and 2019, two task orders at the University of Michigan were conducted that were focused on development of advanced instrumentation and the conduction of post-CHF heat transfer experiments. The culmination of that work was not realized under the previous contract, so the scope of the current work will encompass only the remaining tasks that need to be completed to fulfill the aims of the original work. The tasks described assume most of the instrumentation has been developed and verified, and that a high-pressure test facility has been assembled and almost fully tested.

2. OBJECTIVE

The objective of this project is to continue the acquisition of an advanced two-phase flow instrumentation system with the capability to be used to aid in the development of constitutive models for the TRACE code and to provide the experimental database necessary for the improvement of the TRACE models for IAFB, ISFB, through DFFB regimes, which was identified

as a high priority near-term development need in the Thermal-Hydraulic Code Development Plan. This effort will also support the implementation of the droplet field into TRACE by determining the conditions at the onset of DFFB for reflood conditions. The incorporation of the droplet field is planned for the next major release of TRACE.

This objective will be realized by continuing to acquire the requisite components and assemble the system, as well as conduct validation testing. Initially this capability will be used in experimental programs that target models for the IAFB through DFFB regimes but will continue to be useful for other future experimental programs. Specifically, this advanced instrumentation will provide the first quantitative insights into the flow topology and subchannel-averaged void fractions for these post-CHF (critical heat flux) regimes.

A second objective of this contract is the performance of steady-state low-quality film boiling experiments in a tubular test section. A major component of this experimental program is the utilization of the X-ray radiography system that has already been nearly completed in the instrumentation portion of the effort. This advanced two-phase instrumentation system will provide not only for the accurate measurement of the void fraction during post-CHF conditions but also provide information on the flow topology, such as the size and shape of the liquid slugs in the ISFB regime.

The test procedures and instrumentation will be designed to provide the information necessary to develop the following models for both IAFB and ISFB:

- Wall heat transfer
- Interfacial friction
- Flow regime transition criteria from IAFB to ISFB and ISFB to DFFB regimes

In addition to the IAFB through ISFB experiments, an objective of the current program is to collect the experimental data base necessary for the improvement of the TRACE constitutive models for dispersed flow. This objective will be realized by measuring the vapor superheat for a wide variety of flow conditions and over two development lengths. From the measured values of the superheat, the initial droplet diameter will be inferred and used to develop a new correlation that will be necessary for the incorporation of a droplet field model into TRACE.

3. REQUIREMENTS

<u>Requirements for Tube Test Sections:</u>

3.1. Requirements for Tubular Test Sections

3.1.1. Instrumentation Requirements

<u>X-Ray Radiography System</u>

- Should have a sampling rate in the range of 200 to 1000 Hz in order to resolve the two-phase flow topology
- Shall provide time- and cross section-averaged values of the void fraction with a measurement accuracy of 2%
- Shall provide time-averaged radial void fraction profiles
- Shall provide flow visualization graphics
- Shall provide quantitative flow topology data, such as the interfacial area and size distribution of liquid slugs

- Shall provide void fraction signal statistics to be used in flow regime discrimination between IAFB and ISFB
- Shall not be adversely affected by the high wall temperature of a directly heated tube in the post-CHF regime
- Shall be able to provide measurements of the axial void profile over a length of 1 meter via a traversing mechanism that can be remotely operated (due to safety issue with high-pressure high-temperature test section)

3.1.2. General Instrumentation Requirements

- Flow loop instrumentation shall be provided for the test section outlet pressure, inlet temperature and inlet flow rate
- Power shall be measured for the heater rods and for every separately heated hot patch
- Shall use a suitably designed automatic power control system for the bottom hot patch power based on temperature feedback from the hot patch thermocouples rather than manual adjustments
- Thermocouples shall be provided to measure the surface temperature of the test section wall for at least fifteen axial elevations
    - The axial spacing of these thermocouples should be arranged so as to provide finer resolution of the axial profile just downstream of the hot patch. For example, in the experiment of Fung (1981), the wall thermocouple elevations were located at z = 3, 6, 9, 12, 18, 24, 35, 45, 50, and 55 cm downstream of the hot patch
- A fluid thermocouple shall be provided to measure the temperature of the subcooled liquid core in IAFB as near to the end of the heated length as possible (upstream is preferable)
    - It would be preferable to have a thermocouple probe that could perform an axial traverse along the tube centerline to measure the core liquid temperature. However, due to the uncertainty of sealing constraints for high-pressure conditions, this is not a requirement.
- The pressure drop over the heated length shall be measured using a differential pressure transducer with the taps located as close to the beginning and end of the heated length as possible
- The test facility shall be constructed to allow for the use of the X-ray radiography system being developed by the University of Michigan under prior NRC contract. Specifically,
    - Consultation with the University of Michigan co-PI will be made to assure that the design of the test facility does not interfere with that of the advanced instrumentation system and allows for traversing the entire heated length
    - Test section and insulation materials shall be chosen so as to minimize their impact on the X-ray radiography system

- For the DFFB test series:
    - The fluid thermocouple shall be capable of measuring vapor temperatures at superheat values of about 400 °C and be placed just below the end of the heated length
    - The facility shall be fabricated so as to allow measurement of the void fraction from just below to just above the bottom quench front

3.1.3. Geometry Requirements

- Shall consist of a joule-heated tube with an internal diameter in the range of that for the hydraulic diameter of BWR and PWR fuel assemblies
- Shall have a heated length approximately equal to that of two grid spans in a prototypic PWR rod bundle, that is, about 1.0 m
- Shall employ a directly heated "notch type" hot patch located near the lower end of the heated length capable of stabilizing the bottom quench front. See Attachment #2 for a description of the notch-type hot patch and the results of a design study
    - Shall employ plate-type electrodes to power the hot patch with a minimum thickness to minimize distortions of the heat flux profile in this region
    - Shall minimize the axial spacing between the electrodes powering the hot patch so as to reduce the preheating of the working fluid
- Shall have thermocouples to measure the wall temperature of the "hot notch." Shall contain a hot patch located near the upper end of the heated length to prevent top-down quench front progression due to a liquid film on unheated portion of the tube
- Shall include a flow development region below the bottom hot patch elevation with a length of at least 20 tube pipe diameters
- The tubular test section shall be composed of a material that does not undergo significant oxidation at film boiling temperatures. Furthermore, the electrical resistivity of the selected material should have very low temperature dependence (e.g., similar to that of Inconel-600)
- For the DFFB test series, two different test sections shall be employed so that vapor superheats can be measured for two different development lengths. Specifically, both a "short" test section with a heated length of about 50 tube pipe diameters and a "long" test section with an L/D of about 75 should be used
- For the DFFB test series, a longer pre-heater region shall be provided so that two-phase flow conditions (qualities in the range of 30-50%) will be present at the bottom quench front

In a previously funded project by the US Nuclear Regulatory Commission (Task Order #3), a post-CHF test facility has been designed and constructed with a tubular test section at the University of Michigan (Liu et al., 2015 and 2016). All the above geometry requirements have been satisfied.

3.2. Requirements for Rod Bundle Test Section

3.2.1. Gamma Tomography System Requirements

- Shall accommodate rod bundle test sections having a size of up to 120 mm
- Shall work with acceptable accuracy (see below) for a rod bundle with a 4 x 4 matrix composed of RBHT2-style heater rods and having a flow housing capable of withstanding an internal pressure of 3.5 MPa with a superheat of up to 200 K
- Shall provide time- and subchannel-averaged values of void fractions with a measurement accuracy of 3% for the central and edge subchannels
- Shall be capable of making measurements at several axial locations over a test section length of up to 1.2 meter

Furthermore, the instrument assembly shall be designed with maximum portability in mind and include materials for the training of new operators.

3.2.2. General Geometry and Instrumentation Requirements

- Employ a mock-up of an 8 x 8 rod bundle that:
  - Has a rod diameter of 5/8 inch (15.875 mm) and a pitch of 21 mm (*P*/*D* = 1.326)
  - Has a square housing with interior dimension of about 189 mm and an acrylic wall thickness of about 19 mm (3/4 inch)
    - The distance from the rod centers to the interior of the housing should be equal to one-half the value of the bundle pitch (10.5 mm).
  - Has a length over which gamma tomography measurements can be made of at least 1.2 m
  - Has mixing vane grid spacers of the RBHT type with an axial spacing of about 89.15 cm (35 inch)
- Cover air/water two-phase flow conditions up to the onset of the annular flow regime, and specifically:
  - Includes testing at two pressure levels where the gas density varies by at least a factor of three
  - Includes liquid superficial velocities up to 1 m/s
  - Includes gas superficial velocities up to 10 m/s
  - Utilizes bubble injectors at the bottom of each rod to introduce the gas phase with the capability for non-uniform injection rates (e.g., to shut of the gas flow to the corner rods that will be unheated in the high-pressure small bundle facility)
- Include instrumentation for measuring:
  - The exit pressure,
  - Inlet flows and temperatures for both gas and liquid phases,
  - Differential pressures sufficient to determine both grid and wall frictional losses, and
  - Subchannel-averaged void fractions (e.g., a wire mesh sensor located at the bundle exit).
- Shall be capable of performing steady-state inverted annular and inverted slug film boiling experiments in upflow conditions
- Shall provide for testing over a pressure range suitable to resolving pressure scaling questions
- Shall provide for a water flow rate such that the mass flux ranges from 150 to 2,000 (kg/m^2-s)
- Shall provide for a parametric variation of inlet subcooling with values up to at least 50 °C
- Shall be capable of performing steady-state DFFB tests in upflow conditions that:
  - Have inlet mass fluxes in the range of 15 to 100 (kg/m^2-s),
  - Cover the same pressure range as the IAFB/ISFB test series, and
  - Provide two-phase flow conditions at the quench front in the slug-to-annular flow regimes.

4. SPECIFIC TASKS

4.1. Task 1: Completion of the X-ray Radiography System and Gantry

Under the prior NRC contract (Task Order #2), an X-ray radiography system meeting the work requirements stated above was developed and deployed on the high-pressure tube test section, as shown in Fig. 1. This task represents a completion and documentation of that effort.

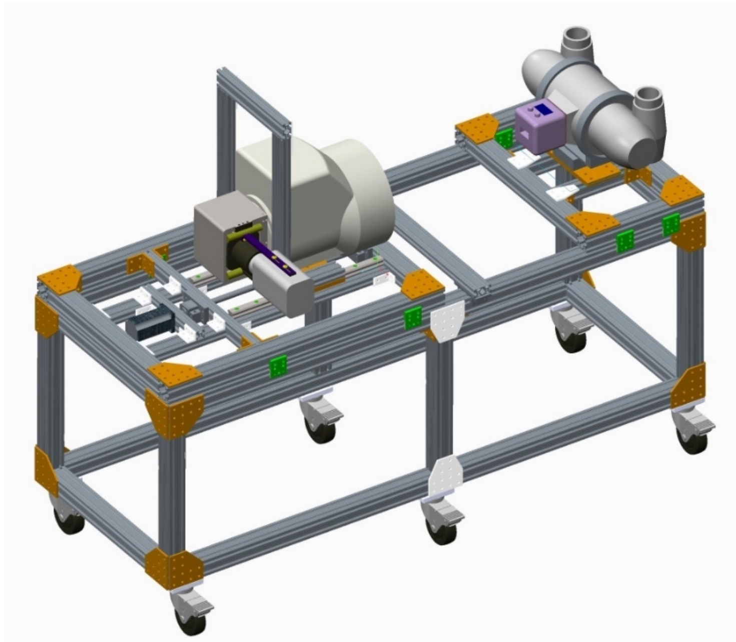

Fig. 1. X-ray radiography system

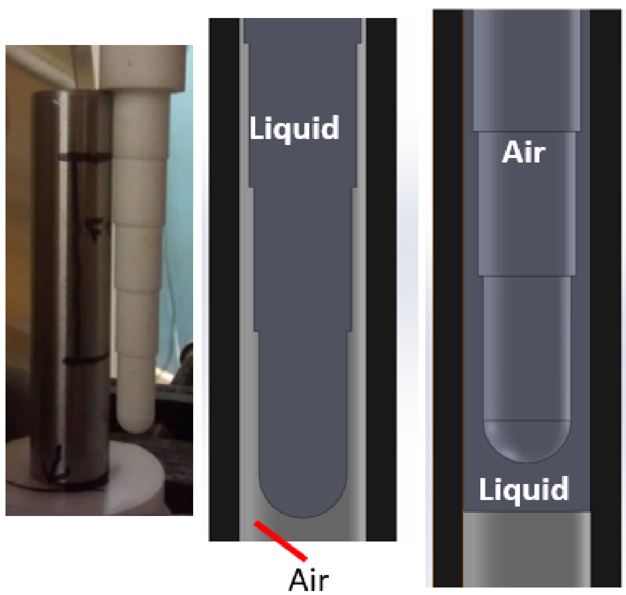

Fig. 2. Mock-up of post-CHF test section (left), with insert for inverted annular (center) and inverted slug (right) flow regimes

Initial tests were made on mock-ups of the Post-CHF test facility (see Fig. 2). The mock-ups were made of an alloy 800H/HT tube of the same size as the one employed for the Post-CHF facility test section, with plastic insert mimicking inverted annular and inverted slugs film boiling flow regimes, with different thicknesses of liquid or gas films attached to the wall.

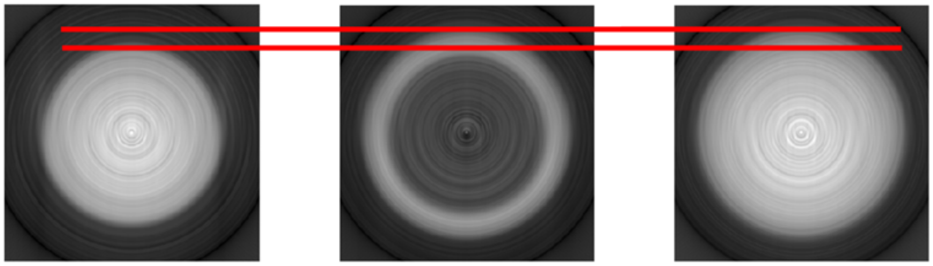

Fig. 3. X-ray measurements of mock-up of Fig. 2 with different inserts

The proposer will document the current state of the X-ray radiography and gantry system as it is currently deployed as advanced instrumentation for the high-pressure tube test section in the Post-CHF test facility. The report will additionally summarize the monetary value of large components purchased or assembled under the previous contract. Furthermore, within this task the proposer will:

- Replace the current image intensifier with a new X-ray panel, which allows for superior quantitative measurements (we have found that the response of the image intensifier to X-ray intensity is highly non-linear) and
- Complete the gantry system for the Post-CHF test facility, including installation and testing in the facility.

Deliverables:

1. Presentation or letter report detailing the current state of the x-ray radiography and gantry system and the remaining effort to complete the system

Level of effort: 24 staff hours
Completion date: 1 month after award

2. Letter report documenting the specifications of the completed x-ray radiography instrumentation package and the results of the validation testing

Level of effort: 96 staff hours
Completion date: 2 months after award

4.2. Task 2: Completion of the Gamma Tomography and Gantry Systems

Under the prior contract (Task Order #2) with the NRC, a gamma tomography system was designed and partially assembled, as shown in Fig. 4. This system was designed corresponding to the requirements specified by the previous US NRC contract and is intended to be modular in design for easiness of:

- assembly and repair/troubleshooting
- transport to other experimental facilities
- adaptability to test section of different size
- operability (the entire system can be operated remotely using a single PC)

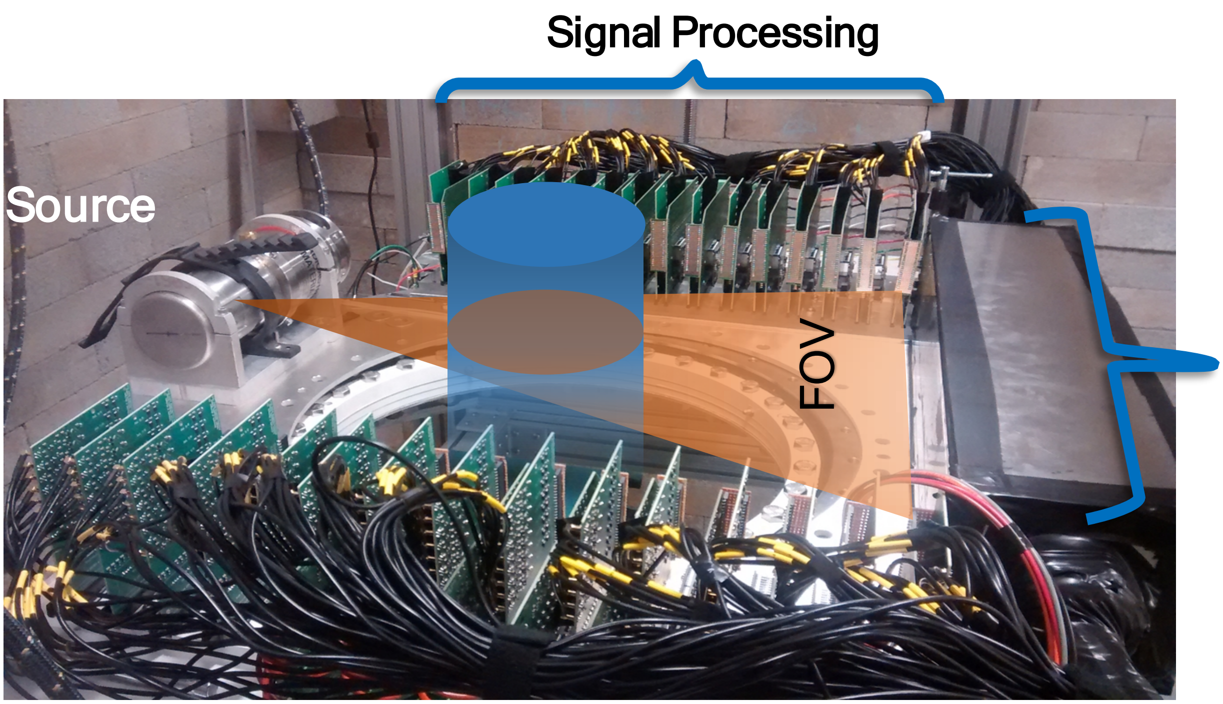

Fig. 4. Gamma tomography system

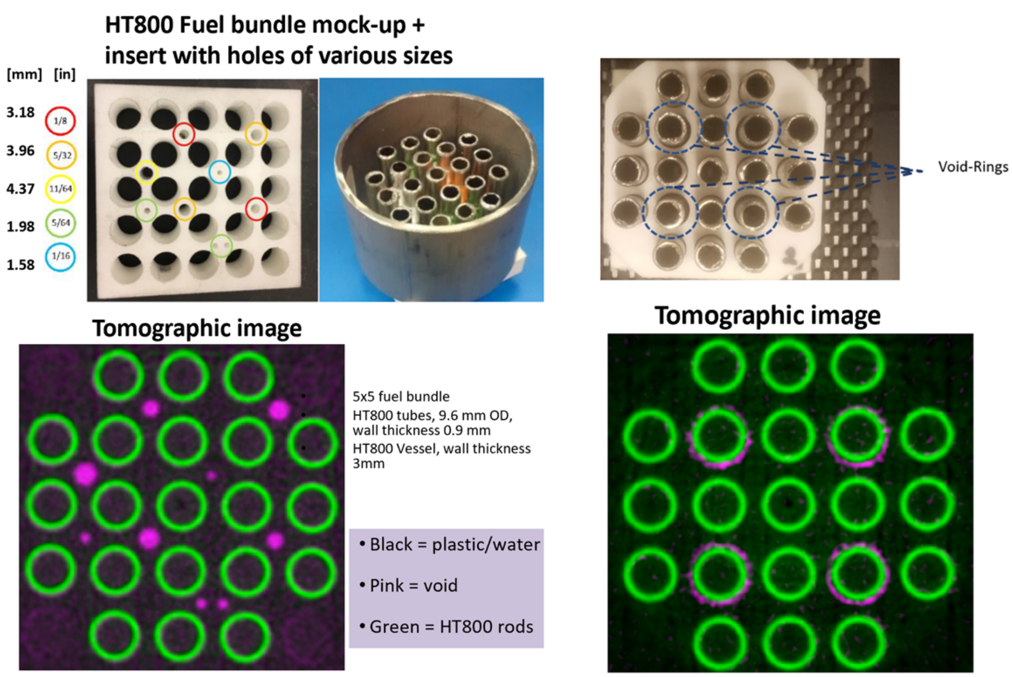

Fig. 5. Tomographic measurements of a fuel assembly mock-up

The current tomography system was successfully tested against mock-ups of 5 x 5 fuel assemblies filled with plastic insert with holes. The results of the tomography measurements are shown in Fig. 5. In Fig. 5 (left), the subchannels of the fuel assembly mock-up were completely filled with plastic (similar photon attenuation as water) and holes were made in the plastic to

simulate gas bubbles. In Fig. 5 (right), a gas film around four rods was simulated. The obtained results look very promising.

The proposer will document the current state of the gamma tomography system and accompanying gantry system. The report will additionally summarize the monetary value of large components purchased or assembled under the previous contract/task order. Once the current state is ascertained, the remaining effort to complete the system will be undertaken and a description of the instrumentation package specifications and capabilities will be produced. Ultimately, the system will be validated in the adiabatic rod bundle of Task 3 as part of the Task 4 workscope.

Deliverables:

1. Presentation or letter report detailing the current state of the gamma tomography and gantry system, the monetary value of components purchased and assembled under the previous contract, and the remaining effort needed to complete the system

   Level of effort: 24 staff hours
   Completion date: 1 month after award

2. Letter report documenting the specifications of the completed gamma tomography and gantry system

   Level of effort: 416 staff hours
   Completion date: 6 months after award

4.3. Task 3: Completion of the Adiabatic Rod Bundle

An adiabatic rod bundle, intended to be used as a validation platform for the gamma tomography system, has been partially developed under the prior NRC contract (Task Order #2). A photo of the current facility is shown in Fig. 6. This task represents the culmination of that effort.

The proposer will document the current state of the adiabatic rod bundle in terms of its purpose as a validation platform for the gamma tomography system. The report will additionally summarize the monetary value of large components purchased or assembled under the previous contract/task order. Once the current state of the test facility is determined, the remaining effort, if any, to complete the test platform will be undertaken and a report detailing the specifications of the test facility wi ll be prepared. Ultimately, this test facility will be used to validate the gamma tomography system of Task 2 as part of the Task 4 workscope.

Within this task we will:

- Complete gas injection systems, including calibration and shake down tests
- Fabricate metal grid spacers (the current grid spacers made out of plastic appear to be too flimsy)
- Extend compressed air storage to increase duration of individual tests
- Evaluate need for installation of a gas separator (after first shake down tests)
- Install and test a wire-mesh sensor
- Install pressure drop measurement sensors

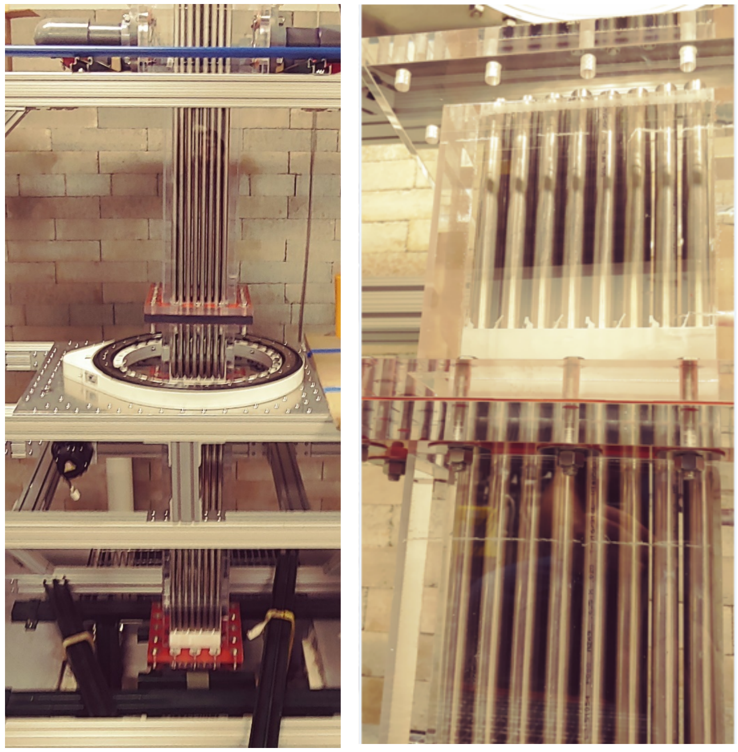

Fig. 6. Adiabatic rod bundle test facility

Deliverables:

1. Presentation or letter report detailing the current state of the adiabatic rod bundle mock-up, including components costs, and remaining effort to complete the system

Level of effort: 24 staff hours
Completion date: 1 month after award

2. Letter report documenting the specifications of the completed rod bundle mock-up facility

Level of effort: 476 staff hours
Completion date: 6 months after award

4.4. Task 4: Validation Testing of the Gamma Tomography System

Once the gamma tomography instrumentation package from Task 2 is completed and the mock-up rod bundle facility from Task 3 is finalized, the rod bundle facility will be used to validate the performance of the gamma tomography system. This effort will include the testing and completion of the visualization software developed under the previous NRC contract (Task Order #2) as well as collection of rod bundle data over the validation ranges specified in the Work Requirements.

To provide for shakedown testing of the instrument and software, demonstrate its correct operation, and to quantify the accuracy of the advanced two-phase instrumentation system before its deployment, validation testing is required. Such validation testing shall include a mix of activities such as:

- Measurement of realistic air/water two-phase flows in a mock-up of a 8 x 8 rod bundle geometry with mixing vane grid spacers as detailed above, and
- Comparisons with another measurement system of known accuracy, such as wire mesh sensors, for a variety of two-phase flow patterns.

A validation test plan, taking advantage of extant capabilities to the maximum degree possible, both in flow loops and instrumentation, will be prepared and submitted to the NRC for approval, prior to testing. Upon approval by the NRC Contracting Officer's Representative (COR), the validation testing program will be executed and documented in two letter reports that also document the design of the instrumentation systems.

Deliverables:

1. Letter report detailing proposed validation test plan including rod bundle design and instrumentation

Level of effort: 258 staff hours
Completion date: 3 months after award

2. Letter report documenting instrument design and validation test results for the gamma-ray tomography system

Level of effort: 430 staff hours
Completion date: 15 months after award

4.5. Task 5: Completion of Shakedown Testing of the Tube Test Section and Instrumentation

As part of the previous contract (Task Order #3) with the NRC, a high-pressure Post-CHF Heat Transfer test facility (PCHT) as shown in Fig. 7 was designed (Liu et al., 2015) per the requirements specified in Section 2.1.3 above and constructed with a tubular test section, which is shown in Fig. 8 (Liu et al., 2016). Figure 8 also shows the arrangement of the Type-K thermocouples on the test section. A photo of the PCHT is shown in Fig. 9. In the previous contract, two reduced-length mock-up test sections and one full-length test section, all made of Incoloy 800H/HT, were fabricated and installed in PCHT. During initial shakedown testing, the full-length test section was damaged due to overheating. A second full-length test section was then fabricated and installed in the PCHT. A photo of the current test section before installation is shown in Fig. 10. The design information of the PCHT and test section can be found in (Liu et al. (2015 and 2016). For quality control purposes, two existing turbine flow meters will need to be calibrated during the shakedown testing. This task represents the completion of the effort with shakedown testing to validate the ability of the PCHT facility and instrumentation to meet the design requirements.

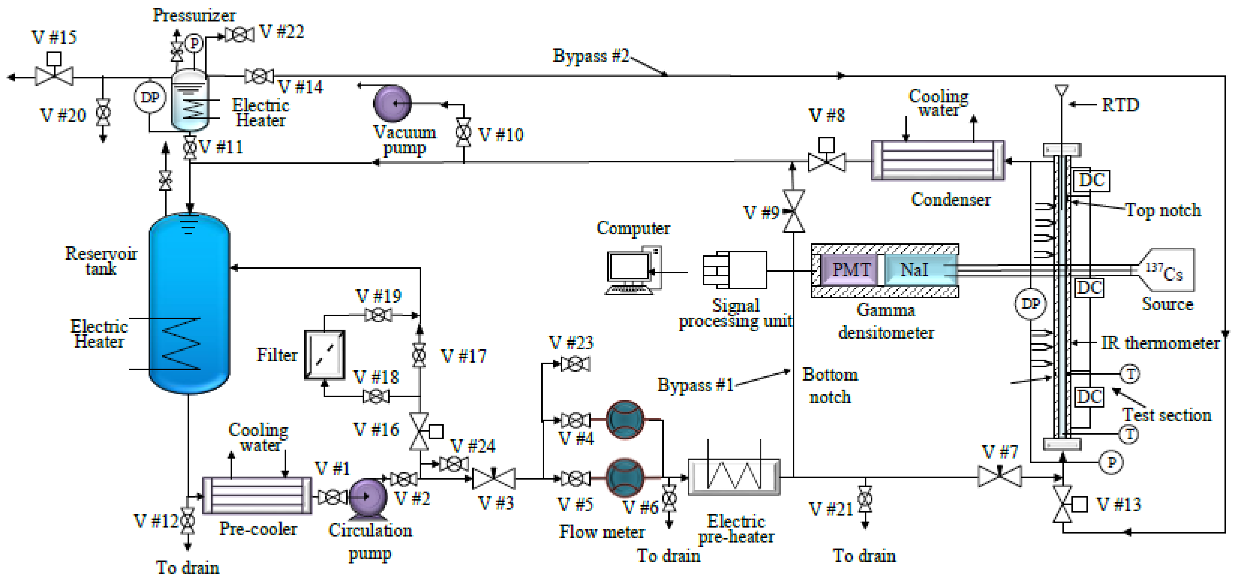

Fig. 7. Schematic of the PCHT (Liu et al., 2015)

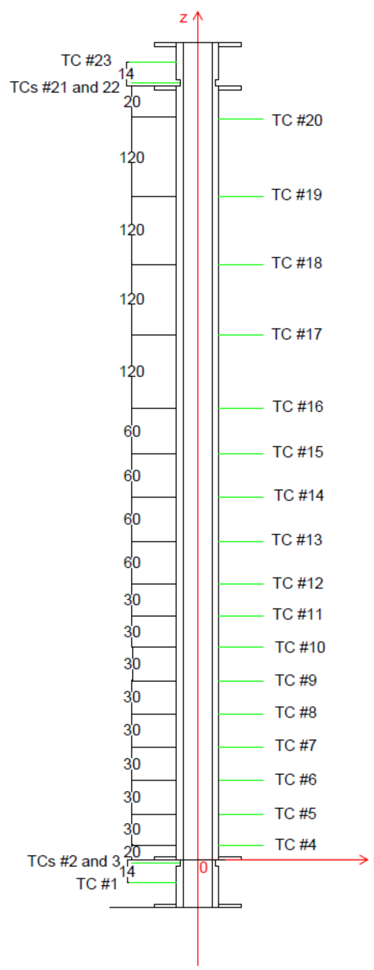

Fig. 8. Design of the tubular test section in PCHT (TC: Thermocouple; Unit: mm) (Liu et al., 2016)

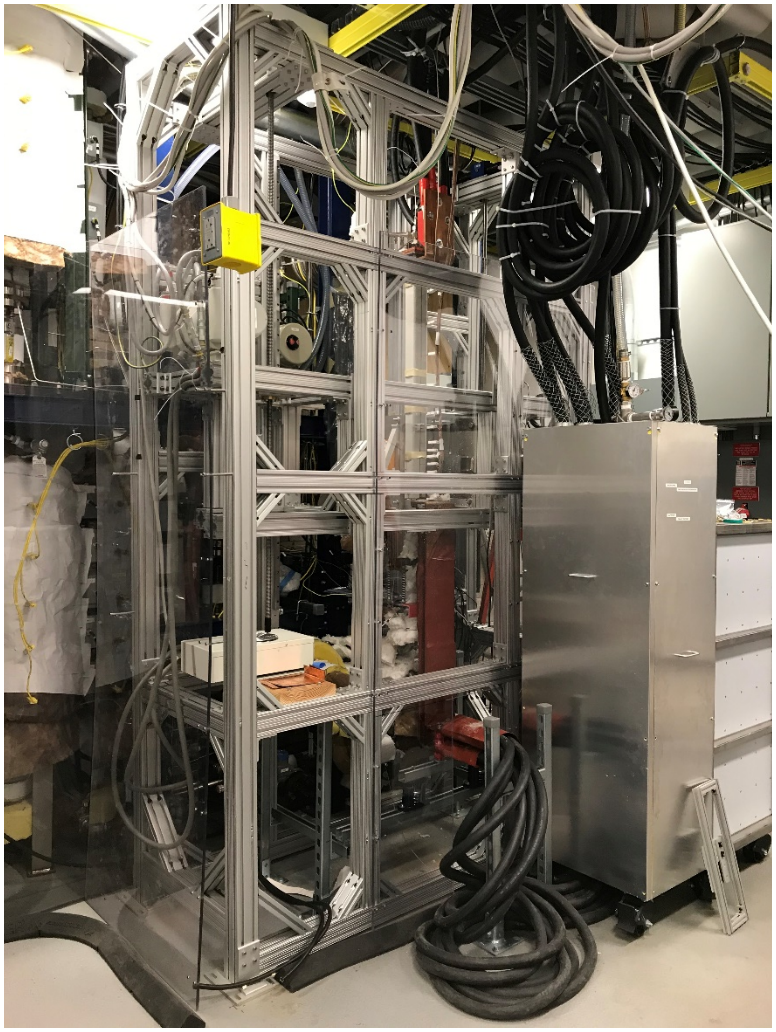

Fig. 9. Photo of the PCHT

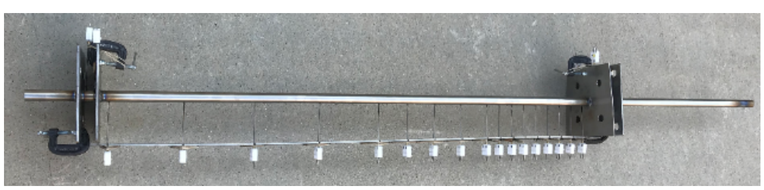

Fig. 10. Photo of the tube test section in PCHT

The current test section in the PCHT employs a directly heated hot patch of the “notch type” described in Attachment #2 (2015) to stabilize the quench front. In this task, the proposer will evaluate the performance of the joule heated tubular test section and finalize, if necessary, the design and fabrication of the test section to meet the testing, geometry and instrumentation requirements stated in Section 2.1. A letter report detailing the design of the test section and its instrumentation has been delivered to the NRC (Liu et al., 2016) and the specifications of the system will continue to conform to the designs.

The proposer will document the current state of the PCHT facility with the tubular test section and instrumentation. The report will additionally summarize the monetary value of large components purchased or assembled under the previous contract (Task Order #3).

As a second full-length test section has already been installed in the PCHT facility, in this task the proposer will perform shakedown testing. This shakedown testing program will include determining the correct control procedure for the hot patch power supply so as to stabilize the quench front. This testing program will demonstrate correct operation of the hot patch over a wide range of flow conditions. In addition, the test section heat losses as a function of the wall temperature will be characterized during these shakedown tests.

Deliverables:

1. Presentation or letter report detailing the current state of the test section and instrumentation fabrication, including major components costs

Level of effort: 24 staff hours
Completion date: 1 month after award

2. Letter report documenting the results of the hot patch shakedown testing and the performance and validation of the X-ray radiography system

Level of effort: 436 staff hours
Completion date: 6 months after award

4.6. Task 6: Inverted Annular Film Boiling Test Series

The proposer will conduct a series of steady-state film boiling tests in the PCHT facility with subcooled inlet conditions targeted at the IAFB regime. The test matrix will include at least six pressure levels and five inlet velocities. In particular, the test matrix shall include a series of tests designed to replicate the conditions of the high flooding rate reflood tests that were previously conducted in the RBHT facility. That is, pressures of 0.138 MPa [20 psia], 0.276 MPa [40 psia] and 0.414 MPa [60 psia] at a flooding rate of 15.24 cm/s [6 in/s]. In the previous contract (Task Order #3) with the NRC, a preliminary test matrix was proposed as shown in Table 1 (Liu et al., 2018). A total of 36 runs for IAFB tests was planned to be performed. The inlet subcooling values were selected as large as possible with a maximum of 50 °C. Under the flow conditions of high pressure and low mass flux, our COMSOL calculations indicate that the maximum wall temperature would exceed the temperature limit of the test section tube (Incoloy 800H/HT) if the inlet subcooling were considerably larger than 30 °C (Liu et al., 2018). Therefore, the inlet subcooling values for some proposed test runs shown in Table 1 were preliminarily selected as 30 or 40 °C. However, the UM team will make attempts to use higher inlet subcooling values, i.e., 50 °C, for those tuns during the actual IAFB tests while carefully monitoring the test section wall temperatures. Finally, if the test matrix for the planned rod bundle post-CHF experiment becomes available at this time, a suitable subset of overlap tests will be conducted.

Considering the amount of time estimated to perform one IAFB test, the duration of the period of performance, and the RFP requirement, the proposer proposed to perform a minimum of 30 tests that cover five mass flux values (with a 50% repetition, 45 tests). The proposer suggests removing 250 (or 1,500 if the NRC prefers) kg/m^2-s mass flux condition from Table 1. Therefore, the number of proposed tests for IAFB (Task 6) will be 30 plus 15 repeated tests, with a total of 45 tests. It

should be noted however that the UM team will make its best effort to also perform tests for the 250 (or 1,500) kg/m^2-s mass flux condition if time allows.

For each of these pressure and inlet flow velocity combinations, data scans at steady-state conditions for several different power levels will be performed as follows. First, steady-state film boiling conditions should be established at the maximum test section power level consonant with the facility temperature limits; the power should then be reduced progressively in steps of about 10% with data scans taken at each power level until spontaneous collapse of the vapor film occurs. The conditions at the time of vapor film collapse will then be used to evaluate the minimum film boiling point.

Table 1 Tentative test matrix for the IAFB tests (Liu et al., 2018)

<table>
<tr><td colspan="2" rowspan="2">Inlet subcooling* (ºC)</td><td colspan="6">Pressure (psia)</td></tr>
<tr><td>20</td><td>40</td><td>60</td><td>200</td><td>350</td><td>500</td></tr>
<tr><td rowspan="6">Mass flux (kg/m^2-s)</td><td>150</td><td colspan="3" rowspan="6">50</td><td rowspan="2">40</td><td rowspan="2">30</td><td rowspan="3">30</td></tr>
<tr><td>250</td></tr>
<tr><td>500</td><td rowspan="4">50</td><td>40</td></tr>
<tr><td>1,000</td><td colspan="2" rowspan="3">50</td></tr>
<tr><td>1,500</td></tr>
<tr><td>2,000</td></tr>
</table>

*: The numbers in the columns under different pressures indicate the tentatively planned water inlet subcooling values.

In addition, the test matrix will provide for a suitable number of repeat tests to demonstrate the repeatability of the results. Currently it is planned to repeat about 50% of the test runs under the IAFB regime. The test matrix will be proposed in a letter report and concurred upon by the NRC COR prior to the actual testing. Data generated from these matrix tests will be provided to the NRC in an electronic format to facilitate model development. Specifically, an MS Excel Workbook will be provided with the data from each individual test comprising one worksheet. The format of these worksheets will be agreed to in consultation with the NRC COR.

Deliverables:

1. Letter report documenting the proposed test matrix

Level of effort: 80 staff hours
Completion date: 7 months after award

2. IAFB data to be provided in electronic format (see above)

Level of effort: 720 staff hours. With six pressure levels and five inlet mass flux values, a minimum of 30 tests with a number of inlet subcooling values will need to be performed for the IAFB experiment. Due to the complexities of the test facility and X-ray radiography system as well as the relatively high-temperature and high-pressure conditions, two staff persons will be needed at any time during operation of the test facility and the X-ray radiography system. Based on our current experience with this test facility, it is estimated that a minimum of 8 hours will be needed to perform one test with a number of inlet cooling values. In each test, it is also required to performed at different power levels to measure the minimum film boiling point. It is anticipated more time may be needed for high-pressure tests due to the longer time needed to establish the intended high system

pressure conditions. Furthermore, about 15 test runs (50% of the planned tests) are planned to be repeated, as required, to demonstrate the repeatability of the results.

Completion date: 13 months after award

3. Letter report documenting the IAFB test results

Level of effort: 174 staff hours
Completion date: 14 months after award

4.7. Task 7: Inverted Slug Film Boiling Test Series

The proposer will conduct a series of steady-state film boiling tests in the PCHT facility with subcooled inlet conditions targeted at the ISFB regime. The test matrix will include at least six pressure levels and five inlet velocities. The pressure levels and mass fluxes for the ISFB tests will be the same as those identified for the IAFB tests. The test matrix and procedure will be proposed in a letter report and concurred upon by the NRC COR.

These ISFB experiments will be conducted so as to expose the highest void measurement station to the full range of conditions for the ISFB region. That is, for a given value of the mass flux, the rod power and inlet subcooling would be adjusted to cause the transition from the IAFB to ISFB to occur just upstream of the highest void measurement station. After a data scan was processed for those conditions, then the inlet subcooling would be reduced in steps causing the ISFB transition point to progress downwards into the test section thereby exposing the measurement station to progressively higher void fractions and vapor flows. This process would continue, with a data scan being recorded for each inlet subcooling step, until the operating point is reached where the flow regime at the test section exit transitions to dispersed flow.

Data generated from these matrix tests will be provided to the NRC in an electronic format to facilitate model development. Specifically, an MS Excel Workbook will be provided with the data from each individual test comprising one worksheet. The format of these worksheets will be agreed to in consultation with the NRC COR.

Deliverables:

1. Letter report documenting the proposed test matrix
Level of effort: 80 staff hours
Completion date: 7 months after award

2. ISFB data to be provided in electronic format
Level of effort: 720 staff hours. With six pressure levels and five inlet mass flux values, a minimum of 30 tests with a number of inlet subcooling values will need to be performed for the ISFB experiment. Similar to the IAFB tests, two staff persons will be needed at any time during operation of the test facility and the X-ray radiography system. Based on our current experience with this test facility, it is estimated that a minimum of 8 hours will be needed to perform one test with a number of inlet cooling values. It is anticipated that more time may be needed for high-pressure tests due to the time needed to establish high system pressure conditions. Furthermore, an appropriate number of tests are planned to be repeated to demonstrate the repeatability of the results.
Completion date: 15 months after award

3. Letter report documenting the ISFB test results
Level of effort: 174 staff hours
Completion date: 16 months after award

4.8. Task 8: Dispersed Flow Film Boiling Test Series

The proposer will conduct a series of steady-state film boiling tests in the PCHT facility with two-phase inlet conditions targeted at the DFFB regime. The test matrix will include the same six pressure levels as the IAFB/ISFB test series, as shown in Table 1. Five mass flux values will be selected from a range of 15 to 100 kg/m^2-s. The inlet subcooling will be about or less than 5 °C in order to reach the DFFB regime. The test matrix and procedure will be proposed in a letter report and concurred upon by the NRC COR. For the DFFB tests, two new flow meters will be installed to improve the water flow rate measurement accuracy for small flow rate conditions. Also due to the test section length change, the copper bus bars that connect the DC power supplies and the test section will need to be adjusted and re-connected to the new test sections.

Given the constraints of the test section maximum temperature limits and hot patch power required to stabilize the quench front, the test section inlet flow quality will be varied over as wide a range as possible. In this way, for each inlet flow and pressure combination, dispersed flow heat transfer conditions can be measured for a range of the vapor Reynolds numbers and droplet loading factors.

Data generated from these matrix tests will be provided to the NRC in an electronic format to facilitate model development. Specifically, an MS Excel Workbook shall be provided with the data from each individual test comprising one worksheet. The format of these worksheets will be agreed to in consultations with the NRC COR.

Deliverables:

3. Letter report documenting the proposed test matrix
Level of effort: 80 staff hours
Completion date: 7 months after award

4. DFFB data to be provided in electronic format
Level of effort: 960 staff hours. With six pressure levels and five inlet mass flux values, and two different lengths for the test section, a minimum of 60 tests will need to be performed for the DFFB experiment. Similar to the IAFB and ISFB tests, two staff persons will be needed at any time during operation of the test facility and the X-ray radiography system. It is estimated that a minimum of 8 hours will be needed to perform one test with a number of inlet cooling values. It is anticipated that more time may be needed for high-pressure tests due to the time needed to establish high system pressures in the test loop. No repeat tests are planned. However, if time allows, a limited number of repeat runs would be performed.

Completion date: 17 months after award

3. Letter report documenting the DFFB test results
Level of effort: 174 staff hours
Completion date: 18 months after award

4.9. Task 9: Preparation of Training Materials

As the instrumentation developed under Tasks 1 and 2 (i.e., X-ray radiography and gamma tomography systems and associated gantry systems) have been designed for use on a number of experimental programs that may not be performed at research institutions other than the University of Michigan. Therefore, we will generate materials for the training of new operators. These materials will include a fully descriptive operator's manual for both the hardware and the associated software. The training material will also include video tutorials.

Deliverables:

1. Draft training manual and video tutorials

   Level of effort: 180 staff hours
   Completion date: 16 months after award

2. Training manual and video tutorials

   Level of effort: 92 staff hours
   Completion date: 2 months after receipt of NRC comments

4.10. Task 10: Delivery of Instrumentation Package

Arrangements will be planned and made for the gamma tomography, X-ray radiography, and associated gantry system to be shipped to a location designed by the NRC, where it will be used for future experiments. We will deliver a letter report specifying the shipping requirements of the system and any special considerations or arrangements. The task concludes with the contract arranging and executing the delivery plan, as agreed upon by the NRC.

Deliverables:

1. Memo detailing the shipping requirements of the gamma tomography and X-ray radiography system

   Level of effort: 48 staff hours
   Completion date: 16 months after award

2. Memo detailing the completion of the gamma tomography system shipping

   Level of effort: 48 staff hours
   Completion date: 2 months after NRC approval and destination specification

5. MONTHLY LETTER STATUS REPORTING REQUIREMENTS

The contractor shall provide a Monthly Letter Status Report (MLSR) which consists of a technical progress report and financial status report. This report will be used by the Government to assess the adequacy of the resources proposed by the contractor to accomplish the work contained in this SOW and provide status of contractor progress in achieving tasks and producing deliverables. The report shall include contract/order summary information, work

completed during the specified period, milestone schedule information, problem resolution, travel plans, and staff hour summary.

6. LIST OF DELIVERABLES

A list of the planned deliverables is summarized in Table 2.

Table 2. List of the deliverables

Task #	Deliverable #	Description	Due Date	Format	Submit to
Task 1	1a	Letter report detailing the current state of the x-ray radiography and gantry system and the remaining effort to complete the system	1 month after award	Microsoft Word Document	COR
Task 1	1b	Letter report documenting the specifications of the completed x-ray radiography instrumentation package and the results of the validation testing	2 months after award	Microsoft Word Document	COR
Task 2	2a	Letter report detailing the current state of the gamma tomography and gantry systems and the remaining effort to complete the system	1 month after award	Microsoft Word Document	COR
Task 2	2b	Letter report documenting the specifications of the completed gamma tomography and gantry system	6 months after award	Microsoft Word Document	COR
Task 3	3a	Letter report detailing the current state of the adiabatic rod bundle mock-up and the remaining effort to complete the system	1 month after award	Microsoft Word Document	COR
Task 3	3b	Letter report documenting the specifications of the completed rod bundle mock-up facility	6 months after award	Microsoft Word Document	COR

Task 4	4a	Letter report detailing proposed validation test plan including rod bundle design and instrumentation	3 months after award	Microsoft Word Document	COR
Task 4	4b	Letter report documenting instrument design and validation test results for the gamma-ray tomography system	15 months after award	Microsoft Word Document	COR
Task 5	5a	Letter report detailing the current state of the test section and instrumentation fabrication	1 month after award	Microsoft Word Document	COR
Task 5	5b	Letter report detailing the results of the hot patch shakedown testing and the performance and validation of the x-ray radiography system	6 months after award	Microsoft Word Document	COR
Task 6	6a	Letter report documenting the proposed test matrix for the inverted annular film boiling test series	7 months after award	Microsoft Word Document	COR
Task 6	6b	IAFB data for the inverted annular film boiling test series	13 months after award	MS Excel Workbook	COR
Task 6	6c	Letter report documenting the IAFB test results for the inverted annular film boiling test series	14 months after award	Microsoft Word Document	COR
Task 7	7a	Letter report documenting the proposed test matrix for the inverted slug film boiling test series	7 months after award	Microsoft Word Document	COR
Task 7	7b	ISFB data for the inverted slug film boiling test series	15 months after award	MS Excel Workbook	COR
Task 7	7c	Letter report documenting the ISFB test results for the inverted annular film boiling test series	16 months after award	Microsoft Word Document	COR

Task 8	8a	Letter report documenting the proposed test matrix for the dispersed flow film boiling test series	7 months after award	Microsoft Word Document	COR
Task 8	8b	DFFB data for the inverted slug film boiling test series	17 months after award	MS Excel Workbook	COR
Task 8	8c	Letter report documenting the DFFB test results for the inverted annular film boiling test series	18 months after award	Microsoft Word Document	COR
Task 9	9a	Draft Training Manual and Video Tutorials	16 months after award	MS Word Document, Electronic Video File(s)	COR
Task 9	9b	Training manual and video tutorials	2 months after receipt of NRC comments on Deliverable 9a	MS Word Document, Electronic Video File(s)	COR
Task 10	10a	Memo detailing the shipping requirements of the gamma tomography and X-ray radiography systems	16 months after award	Microsoft Word Document	COR
Task 10	10b	Memo detailing the completion of the gamma tomography system shipping	2 months after NRC approval and destination specification	Microsoft Word Document	COR
MLSR	11	Monthly Report	20th of the following month	Microsoft Word Document	CO/COR

7. REQUIRED MATERIALS/FACILITIES

The successful completion of this contract will require that existing test facilities and instrumentation be finalized and implemented. Specifically, the tube test facility and adiabatic rod bundle test sections and flow loops as well as the x-ray radiography and gamma tomography systems and associated gantry systems developed under prior NRC contact and described above shall be repurposed for this contract. Significant modifications or alterations to the existing facilities or instrumentation that would change the design specifications must be approved to the NRC COR.

8. RELEASE OF PUBLICATIONS

Any documents generated by the contractor under this contract/order shall not be released for publication or dissemination without submission of an *NRC Form 390A, Release to Publish*

Unclassified NRC Contractor Speeches, Presentations, Papers, and Journal Articles to the COR.

9. PLACE OF PERFORMANCE

The work to be performed under this contract/order will be primarily performed at the contractor's facility.

10. DATA RIGHTS

The NRC shall have unlimited rights to and ownership of all deliverables provided under this contract/order, including reports, recommendations, briefings, work plans and all other deliverables. All documents and materials, to include the source codes of any software, produced under this contract/order are the property of the Government with all rights and privileges of ownership/copyright belonging exclusively to the Government. These documents and materials may not be used or sold by the contractor without written authorization from the COR. All materials supplied to the Government shall be the sole property of the Government and may not be used for any other purpose. This right does not abrogate any other Government rights. The definition of "unlimited rights" is contained in 12 Federal Acquisition Regulation (FAR) 27.401, "Definitions." FAR 52.2227-14 shall be incorporated by reference.

11. SECURITY REQUIREMENTS

None.

12. REFERENCES

1. Attachment #1: Background Information for Task Order on Post-CHF Heat Transfer at High Pressure and Flow Conditions, the U.S. Nuclear Regulatory Commission, February 2015.

2. Attachment #2: Hot Patch Design Study, the U.S. Nuclear Regulatory Commission, February 2015.

3. Fung, K. K., Subcooled and Low Quality Film Boiling of Water in Vertical Flow at Atmospheric Pressure, Ph.D. Thesis, University of Ottawa, Canada, 1981.

4. Liu, Q., Sun, X., Lv, Q., and Shi, S., Post-CHF Heat Transfer Flow Loop Design, Letter Report No. 1, Rev. 2, US NRC Task Order #3, The Ohio State University, 2015.

5. Liu, Q., Sun, X., Lv, Q., and Shi, S., Post-CHF Heat Transfer Test Section Design and Instrumentation, Letter Report No. 2, US NRC Task Order #3, The Ohio State University, 2016.

6. Liu, Q., Shi, S., and Sun, X., Post-CHF Heat Transfer Test Plan for the IAFB Tests, Letter Report No. 3, US NRC Task Order #3, University of Michigan, 2018.

D - Packaging and Marking

D.1 PACKAGING AND MARKING

(a) The Contractor shall package material for shipment to the NRC in such a manner that will ensure acceptance by common carrier and safe delivery at destination. Containers and closures shall comply with the Surface Transportation Board, Uniform Freight Classification Rules, or regulations of other carriers as applicable to the mode of transportation.

(b) On the front of the package, the Contractor shall clearly identify the contract number under which the product is being provided.

(c) Additional packaging and/or marking requirements are as follows: N/A.

D.2 BRANDING

The Contractor is required to use the statement below in any publications, presentations, articles, products, or materials funded under this contract/order, to the extent practical, in order to provide NRC with recognition for its involvement in and contribution to the project. If the work performed is funded entirely with NRC funds, then the contractor must acknowledge that information in its documentation/presentation.

Work Supported by the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, under Contract/order number 31310020C0009.

E - Inspection and Acceptance

E.1 NOTICE LISTING CONTRACT CLAUSES INCORPORATED BY REFERENCE

The following contract clauses pertinent to this section are hereby incorporated by reference (by Citation Number, Title, and Date) in accordance with the clause at FAR "52.252-2 CLAUSES INCORPORATED BY REFERENCE" in Section I of this contract.

52.246-5 INSPECTION OF SERVICES - COST-REIMBURSEMENT. (APR 1984)

E.2 INSPECTION AND ACCEPTANCE BY THE NRC (SEP 2013)

Inspection and acceptance of the deliverable items to be furnished hereunder shall be made by the NRC Contracting Officer’s Representative (COR) at the destination, accordance with FAR 52.247-34 - F.o.b. Destination.

F - Deliveries or Performance

F.1 NOTICE LISTING CONTRACT CLAUSES INCORPORATED BY REFERENCE

The following contract clauses pertinent to this section are hereby incorporated by reference (by Citation Number, Title, and Date) in accordance with the clause at FAR "52.252-2 CLAUSES INCORPORATED BY REFERENCE" in Section I of this contract.

52.242-15 STOP-WORK ORDER. (AUG 1989) - ALTERNATE I (APR 1984)

F.2 PLACE OF DELIVERY-REPORTS

The items to be furnished hereunder shall be delivered, with all charges paid by the Contractor, to:

a. Contracting Officer's Representative (COR):
Andrew Ireland
11545 Rockville Pike; M/S: T-10B58
Rockville, MD 20852

b. Contracting Officer (CO):
Jennifer A. Dudek
11545 Rockville Pike; M/S: T-7B20
Rockville, MD 20852

F.3 PERIOD OF PERFORMANCE

This contract shall commence on **July 01, 2020** and will expire on **June 30, 2022.**

F.4 2052.211-70 PREPARATION OF TECHNICAL REPORTS. (JAN 1993)

All technical reports required by Section C and all Technical Progress Reports required by Section F are to be prepared in accordance with the attached Management Directive 3.8, "Unclassified Contractor and Grantee Publications in the NUREG Series." Management Directive 3.8 is not applicable to any Contractor Spending Plan (CSP) and any Financial Status Report that may be included in this contract.

(End of Clause)

G - Contract Administration Data

G.1 REGISTRATION IN FEDCONNECT® (JULY 2014)

The Nuclear Regulatory Commission (NRC) uses Unison Software Systems' secure and auditable two-way web portal, FedConnect®, to communicate with vendors and contractors. FedConnect® provides bi-directional communication between the vendor/contractor and the NRC throughout pre-award, award, and post-award acquisition phases. Therefore, in order to do business with the NRC, vendors and contractors must register to use FedConnect® at https://www.fedconnect.net/FedConnect. The individual registering in FedConnect® must have authority to bind the vendor/contractor. There is no charge for using FedConnect®. Assistance with FedConnect® is provided by Unison Software Systems, not the NRC. FedConnect® contact and assistance information is provided on the FedConnect® web site at https://www.fedconnect.net/FedConnect.

G.2 ELECTRONIC PAYMENT (DEC 2017)

The Debt Collection Improvement Act of 1996 requires that all payments except IRS tax refunds be made by Electronic Funds Transfer. Payment shall be made in accordance with FAR 52.232-33, entitled "Payment by Electronic Funds Transfer-System for Award Management."

To receive payment, the contractor shall prepare invoices in accordance with NRC's Billing Instructions. Claims shall be submitted through the Invoice Processing Platform (IPP) (https://www.ipp.gov/). Back up documentation shall be included as required by the NRC's Billing Instructions.

G.3 2052.215-71 CONTRACTING OFFICER REPRESENTATIVE AUTHORITY. (OCT 1999)

(a) The contracting officer's authorized representative (hereinafter referred to as the COR) for this contract is:

Name:	Andrew Ireland
Address:	11545 Rockville Pike; M/S: T-10B58, Rockville, MD 20852
Telephone Number:	301-415-2146
Email:	Andrew.Ireland@nrc.gov

The Alternate COR for this contract is:

Name:	Kirk Tien
Address:	11545 Rockville Pike; M/S: T-10B58, Rockville, MD 20852
Telephone Number:	301-415-1606
Email:	Kirk.Tien@nrc.gov

(b) Performance of the work under this contract is subject to the technical direction of the NRC COR. The term "technical direction" is defined to include the following:

(1) Technical direction to the contractor which shifts work emphasis between areas of work or tasks, authorizes travel which was unanticipated in the Schedule (i.e., travel not contemplated in the Statement of Work (SOW) or changes to specific travel identified in the SOW), fills in details, or otherwise serves to accomplish the contractual SOW.

(2) Provide advice and guidance to the contractor in the preparation of drawings, specifications, or technical portions of the work description.

(3) Review and, where required by the contract, approval of technical reports, drawings, specifications, and technical information to be delivered by the contractor to the Government under the contract.

(c) Technical direction must be within the general statement of work stated in the contract. The COR does not have the authority to and may not issue any technical direction which:

(1) Constitutes an assignment of work outside the general scope of the contract.

(2) Constitutes a change as defined in the "Changes" clause of this contract.

(3) In any way causes an increase or decrease in the total estimated contract cost, the fixed fee, if any, or the time required for contract performance.

(4) Changes any of the expressed terms, conditions, or specifications of the contract.

(5) Terminates the contract, settles any claim or dispute arising under the contract, or issues any unilateral directive whatever.

(d) All technical directions must be issued in writing by the COR or must be confirmed by the COR in writing within ten (10) working days after verbal issuance. A copy of the written direction must be furnished to the contracting officer. A copy of NRC Form 445, Request for Approval of Official Foreign Travel, which has received final approval from the NRC must be furnished to the contracting officer.

(e) The contractor shall proceed promptly with the performance of technical directions duly issued by the COR in the manner prescribed by this clause and within the COR's authority under the provisions of this clause.

(f) If, in the opinion of the contractor, any instruction or direction issued by the COR is within one of the categories as defined in paragraph (c) of this section, the contractor may not proceed but shall notify the contracting officer in writing within five (5) working days after the receipt of any instruction or direction and shall request the contracting officer to modify the contract accordingly. Upon receiving the notification from the contractor, the contracting officer shall issue an appropriate contract modification or advise the contractor in writing that, in the contracting officer's opinion, the technical direction is within the scope of this article and does not constitute a change under the "Changes" clause.

(g) Any unauthorized commitment or direction issued by the COR may result in an unnecessary delay in the contractor's performance and may even result in the contractor expending funds for unallowable costs under the contract.

(h) A failure of the parties to agree upon the nature of the instruction or direction or upon the contract action to be taken with respect thereto is subject to 52.233-1 - Disputes.

(i) In addition to providing technical direction as defined in paragraph (b) of the section, the COR shall:

(1) Monitor the contractor's technical progress, including surveillance and assessment of performance, and recommend to the contracting officer changes in requirements.

(2) Assist the contractor in the resolution of technical problems encountered during performance.

(3) Review all costs requested for reimbursement by the contractor and submit to the contracting officer recommendations for approval, disapproval, or suspension of payment for supplies and services required under this contract.

(4) Assist the contractor in obtaining the badges for the contractor personnel.

(5) Immediately notify the Security Branch, Division of Facilities and Security (SB/DFS) (via e-mail) when a contractor employee no longer requires access authorization and return of any NRC issued badge to SB/DFS within three days after their termination.

(6) Ensure that all contractor employees that require access to classified Restricted Data or National Security Information or matter, access to sensitive unclassified information (Safeguards, Official Use Only, and Proprietary information) access to sensitive IT systems or data, unescorted access to NRC controlled buildings/space, or unescorted access to protected and vital areas of nuclear power plants receive approval of SB/DFS prior to access in accordance with Management Directive and Handbook 12.3.

(7) For contracts for the design, development, maintenance or operation of Privacy Act Systems of Records, obtain from the contractor as part of closeout procedures, written certification that the contractor has returned to NRC, transferred to the successor contractor, or destroyed at the end of the contract in accordance with instructions provided by the NRC Systems Manager for Privacy Act Systems of Records, all records (electronic or paper) which were created, compiled, obtained or maintained under the contract.

(End of Clause)

G.4 2052.215-77 TRAVEL APPROVALS AND REIMBURSEMENT. (OCT 1999)

(a) All foreign travel must be approved in advance by the NRC on NRC Form 445, Request for Approval of Official Foreign Travel, and must be in compliance with FAR 52.247-63 Preference for U.S. Flag Air Carriers. The contractor shall submit NRC Form 445 to the NRC no later than 30 days before beginning travel.

(b) The contractor must receive written approval from the NRC Project Officer before taking travel that was unanticipated in the Schedule (i.e., travel not contemplated in the Statement of Work, or changes to specific travel identified in the Statement of Work).

(c) The contractor will be reimbursed only for travel costs incurred that are directly related to this contract and are allowable subject to the limitations prescribed in FAR 31.205-46.

(d) It is the responsibility of the contractor to notify the contracting officer in accordance with the Limitations of Cost clause of this contract when, at any time, the contractor learns that travel expenses will cause the contractor to exceed the estimated costs specified in the Schedule.

(e) Reasonable travel costs for research and related activities performed at State and nonprofit institutions, in accordance with Section 12 of Pub. L. 100-679, must be charged in accordance with the contractor's institutional policy to the degree that the limitations of Office of Management and Budget (OMB) guidance are not exceeded. Applicable guidance documents

include OMB Circular A-87, Cost Principles for State and Local Governments; OMB Circular A-122, Cost Principles for Nonprofit Organizations; and OMB Circular A-21, Cost Principles for Educational Institutions.

(End of Clause)

G.5 2052.216-71 INDIRECT COST RATES. (JAN 1993)

(a) Pending the establishment of final indirect rates which must be negotiated based on audit of actual costs, the contractor shall be reimbursed for allowable indirect costs as follows:

TYPE	FROM	TO	RATE	LOCATION	APPLICABLE TO
Facilities & Administrative Cost Rate - Provisional	07/01/2020	Until Amended	[redacted]	Campus	Organized Research

(b) The contracting officer may adjust these rates as appropriate during the term of the contract upon acceptance of any revisions proposed by the contractor. It is the contractor's responsibility to notify the contracting officer in accordance with FAR 52.232-20, Limitation of Cost, or FAR 52.232-22, Limitation of Funds, as applicable, if these changes affect performance of work within the established cost or funding limitations.

(End of Clause)

H - Special Contract Requirements

H.1 NOTICE LISTING CONTRACT CLAUSES INCORPORATED BY REFERENCE

The following contract clauses pertinent to this section are hereby incorporated by reference (by Citation Number, Title, and Date) in accordance with the clause at FAR "52.252-2 CLAUSES INCORPORATED BY REFERENCE" in Section I of this contract.

2052.242-70 RESOLVING DIFFERING PROFESSIONAL VIEWS. (OCT 1999)

H.2 ANNUAL AND FINAL CONTRACTOR PERFORMANCE EVALUATIONS

Annual and final evaluations of contractor performance under this contract will be prepared in accordance with FAR Subpart 42.15, "Contractor Performance Information," normally at or near the time the contractor is notified of the NRC's intent to exercise the contract option. If the multi-year contract does not have option years, then an annual evaluation will be prepared []. Final evaluations of contractor performance will be prepared at the expiration of the contract during the contract closeout process.

The Contracting Officer will transmit the NRC Contracting Officer’s Representative’s (COR) annual and final contractor performance evaluations to the contractor's Project Manager, unless otherwise instructed by the contractor. The contractor will be permitted thirty days to review the document and submit comments, rebutting statements, or additional information.

Where a contractor concurs with, or takes no exception to an annual performance evaluation, the Contracting Officer will consider such evaluation final and releasable for source selection purposes. Disagreements between the parties regarding a performance evaluation will be referred to an individual one level above the Contracting Officer, whose decision will be final.

The Contracting Officer will send a copy of the completed evaluation report, marked "Source Selection Information”, to the contractor's Project Manager for their records as soon as practicable after it has been finalized. The completed evaluation report also will be used as a tool to improve communications between the NRC and the contractor and to improve contract performance.

The completed annual performance evaluation will be used to support future award decisions in accordance with FAR 42.1502 and 42.1503. During the period the information is being used to provide source selection information, the completed annual performance evaluation will be released to only two parties - the Federal government personnel performing the source selection evaluation and the contractor under evaluation if the contractor does not have a copy of the report already.

H.3 COMPLIANCE WITH U.S. IMMIGRATION LAWS AND REGULATIONS

NRC contractors are responsible to ensure that their alien personnel are not in violation of United States immigration laws and regulations, including employment authorization documents and visa requirements. Each alien employee of the Contractor must be lawfully admitted for permanent residence as evidenced by Permanent Resident Form I-551 (Green Card), or must present other evidence from the U.S. Department of Homeland Security/U.S. Citizenship and Immigration Services that employment will not affect his/her immigration status. The U.S. Citizenship and Immigration Services provides information to contractors to help them

understand the employment eligibility verification process for non-US citizens. This information can be found on their website, http://www.uscis.gov/portal/site/uscis.

The NRC reserves the right to deny or withdraw Contractor use or access to NRC facilities or its equipment/services, and/or take any number of contract administrative actions (e.g., disallow costs, terminate for cause) should the Contractor violate the Contractor's responsibility under this clause.

H.4 WHISTLEBLOWER PROTECTION FOR NRC CONTRACTOR AND SUBCONTRACTOR EMPLOYEES

(a) The U.S. Nuclear Regulatory Commission (NRC) contractor and its subcontractor are subject to the Whistleblower Employee Protection public law provisions as codified at 42 U.S.C. 5851. NRC contractor(s) and subcontractor(s) shall comply with the requirements of this Whistleblower Employee Protection law, and the implementing regulations of the NRC and the Department of Labor (DOL). See, for example, DOL Procedures on Handling Complaints at 29 C.F.R. Part 24 concerning the employer obligations, prohibited acts, DOL procedures and the requirement for prominent posting of notice of Employee Rights at Appendix A to Part 24 entitled: “Your Rights Under the Energy Reorganization Act”.

(b) Under this Whistleblower Employee Protection law, as implemented by regulations, NRC contractor and subcontractor employees are protected from discharge, reprisal, threats, intimidation, coercion, blacklisting or other employment discrimination practices with respect to compensation, terms, conditions or privileges of their employment because the contractor or subcontractor employee(s) has provided notice to the employer, refused to engage in unlawful practices, assisted in proceedings or testified on activities concerning alleged violations of the Atomic Energy Act of 1954 (as amended) and the Energy Reorganization Act of 1974 (as amended).

(c) The contractor shall insert this or the substance of this clause in any subcontracts involving work performed under this contract.

H.5 2052.209-72 CONTRACTOR ORGANIZATIONAL CONFLICTS OF INTEREST. (JAN 1993)

(a) Purpose. The primary purpose of this clause is to aid in ensuring that the contractor:

> (1) Is not placed in a conflicting role because of current or planned interests (financial, contractual, organizational, or otherwise) which relate to the work under this contract; and
>
> (2) Does not obtain an unfair competitive advantage over other parties by virtue of its performance of this contract.

(b) Scope. The restrictions described apply to performance or participation by the contractor, as defined in 48 CFR 2009.570-2 in the activities covered by this clause.

(c) Work for others.

> (1) Notwithstanding any other provision of this contract, during the term of this contract, the contractor agrees to forego entering into consulting or other contractual arrangements with any firm or organization the result of which may give rise to a conflict

of interest with respect to the work being performed under this contract. The contractor shall ensure that all employees under this contract abide by the provision of this clause. If the contractor has reason to believe, with respect to itself or any employee, that any proposed consultant or other contractual arrangement with any firm or organization may involve a potential conflict of interest, the contractor shall obtain the written approval of the contracting officer before the execution of such contractual arrangement.

(2) The contractor may not represent, assist, or otherwise support an NRC licensee or applicant undergoing an NRC audit, inspection, or review where the activities that are the subject of the audit, inspection, or review are the same as or substantially similar to the services within the scope of this contract (or task order as appropriate) except where the NRC licensee or applicant requires the contractor's support to explain or defend the contractor's prior work for the utility or other entity which NRC questions.

(3) When the contractor performs work for the NRC under this contract at any NRC licensee or applicant site, the contractor shall neither solicit nor perform work in the same or similar technical area for that licensee or applicant organization for a period commencing with the award of the task order or beginning of work on the site (if not a task order contract) and ending one year after completion of all work under the associated task order, or last time at the site (if not a task order contract).

(4) When the contractor performs work for the NRC under this contract at any NRC licensee or applicant site,

(i) The contractor may not solicit work at that site for that licensee or applicant during the period of performance of the task order or the contract, as appropriate.

(ii) The contractor may not perform work at that site for that licensee or applicant during the period of performance of the task order or the contract, as appropriate, and for one year thereafter.

(iii) Notwithstanding the foregoing, the contracting officer may authorize the contractor to solicit or perform this type of work (except work in the same or similar technical area) if the contracting officer determines that the situation will not pose a potential for technical bias or unfair competitive advantage.

(d) Disclosure after award.

(1) The contractor warrants that to the best of its knowledge and belief, and except as otherwise set forth in this contract, that it does not have any organizational conflicts of interest as defined in 48 CFR 2009.570-2.

(2) The contractor agrees that if, after award, it discovers organizational conflicts of interest with respect to this contract, it shall make an immediate and full disclosure in writing to the contracting officer. This statement must include a description of the action which the contractor has taken or proposes to take to avoid or mitigate such conflicts. The NRC may, however, terminate the contract if termination is in the best interest of the Government.

(3) It is recognized that the scope of work of a task-order-type contract necessarily encompasses a broad spectrum of activities. Consequently, if this is a task-order-type contract, the contractor agrees that it will disclose all proposed new work involving NRC

licensees or applicants which comes within the scope of work of the underlying contract. Further, if this contract involves work at a licensee or applicant site, the contractor agrees to exercise diligence to discover and disclose any new work at that licensee or applicant site. This disclosure must be made before the submission of a bid or proposal to the utility or other regulated entity and must be received by the NRC at least 15 days before the proposed award date in any event, unless a written justification demonstrating urgency and due diligence to discover and disclose is provided by the contractor and approved by the contracting officer. The disclosure must include the statement of work, the dollar value of the proposed contract, and any other documents that are needed to fully describe the proposed work for the regulated utility or other regulated entity. NRC may deny approval of the disclosed work only when the NRC has issued a task order which includes the technical area and, if site-specific, the site, or has plans to issue a task order which includes the technical area and, if site-specific, the site, or when the work violates paragraphs (c)(2), (c)(3) or (c)(4) of this section.

(e) Access to and use of information.

(1) If, in the performance of this contract, the contractor obtains access to information, such as NRC plans, policies, reports, studies, financial plans, internal data protected by the Privacy Act of 1974 (5 U.S.C. Section 552a (1988)), or the Freedom of Information Act (5 U.S.C. Section 552 (1986)), the contractor agrees not to:

(i) Use this information for any private purpose until the information has been released to the public;

(ii) Compete for work for the Commission based on the information for a period of six months after either the completion of this contract or the release of the information to the public, whichever is first;

(iii) Submit an unsolicited proposal to the Government based on the information until one year after the release of the information to the public; or

(iv) Release the information without prior written approval by the contracting officer unless the information has previously been released to the public by the NRC.

(2) In addition, the contractor agrees that, to the extent it receives or is given access to proprietary data, data protected by the Privacy Act of 1974 (5 U.S.C. Section 552a (1988)), or the Freedom of Information Act (5 U.S.C. Section 552 (1986)), or other confidential or privileged technical, business, or financial information under this contract, the contractor shall treat the information in accordance with restrictions placed on use of the information.

(3) Subject to patent and security provisions of this contract, the contractor shall have the right to use technical data it produces under this contract for private purposes provided that all requirements of this contract have been met.

(f) Subcontracts. Except as provided in 48 CFR 2009.570-2, the contractor shall include this clause, including this paragraph, in subcontracts of any tier. The terms contract, contractor, and contracting officer, must be appropriately modified to preserve the Government's rights.

(g) Remedies. For breach of any of the above restrictions, or for intentional nondisclosure or misrepresentation of any relevant interest required to be disclosed concerning this contract or for such erroneous representations that necessarily imply bad faith, the Government may terminate the contract for default, disqualify the contractor from subsequent contractual efforts, and pursue other remedies permitted by law or this contract.

(h) Waiver. A request for waiver under this clause must be directed in writing to the contracting officer in accordance with the procedures outlined in 48 CFR 2009.570-9.

(i) Follow-on effort. The contractor shall be ineligible to participate in NRC contracts, subcontracts, or proposals therefor (solicited or unsolicited) which stem directly from the contractor's performance of work under this contract. Furthermore, unless so directed in writing by the contracting officer, the contractor may not perform any technical consulting or management support services work or evaluation activities under this contract on any of its products or services or the products or services of another firm if the contractor has been substantially involved in the development or marketing of the products or services.

(1) If the contractor under this contract, prepares a complete or essentially complete statement of work or specifications, the contractor is not eligible to perform or participate in the initial contractual effort which is based on the statement of work or specifications. The contractor may not incorporate its products or services in the statement of work or specifications unless so directed in writing by the contracting officer, in which case the restrictions in this paragraph do not apply.

(2) Nothing in this paragraph precludes the contractor from offering or selling its standard commercial items to the Government.

(End of Clause)

H.6 2052.215-70 KEY PERSONNEL. (JAN 1993)

(a) The following individuals are considered to be essential to the successful performance of the work hereunder:

Labor Category	**Personnel Name**
Faculty - Principal Investigator	[redacted]
Faculty - Investigator	[redacted]

*The contractor agrees that personnel may not be removed from the contract work or replaced without compliance with paragraphs (b) and (c) of this section.

(b) If one or more of the key personnel, for whatever reason, becomes, or is expected to become, unavailable for work under this contract for a continuous period exceeding 30 work days, or is expected to devote substantially less effort to the work than indicated in the proposal or initially anticipated, the contractor shall immediately notify the contracting officer and shall,

subject to the concurrence of the contracting officer, promptly replace the personnel with personnel of at least substantially equal ability and qualifications.

(c) Each request for approval of substitutions must be in writing and contain a detailed explanation of the circumstances necessitating the proposed substitutions. The request must also contain a complete resume for the proposed substitute and other information requested or needed by the contracting officer to evaluate the proposed substitution. The contracting officer and the project officer shall evaluate the contractor's request and the contracting officer shall promptly notify the contractor of his or her decision in writing.

(d) If the contracting officer determines that suitable and timely replacement of key personnel who have been reassigned, terminated, or have otherwise become unavailable for the contract work is not reasonably forthcoming, or that the resultant reduction of productive effort would be so substantial as to impair the successful completion of the contract or the service order, the contract may be terminated by the contracting officer for default or for the convenience of the Government, as appropriate. If the contracting officer finds the contractor at fault for the condition, the contract price or fixed fee may be equitably adjusted downward to compensate the Government for any resultant delay, loss, or damage.

(End of Clause)

H.7 2052.235-70 PUBLICATION OF RESEARCH RESULTS. (OCT 1999)

(a) The principal investigator(s)/contractor shall comply with the provisions of NRC Management Directive 3.8 (Vol. 3, Part 1) and NRC Handbook 3.8 (Parts I-IV) regarding publication in refereed scientific and engineering journals or dissemination to the public of any information, oral or written, concerning the work performed under this contract. Failure to comply with this clause shall be grounds for termination of this contract.

(b) The principal investigator(s)/contractor may publish the results of this work in refereed scientific and engineering journals or in open literature and present papers at public or association meetings at interim stages of work, in addition to submitting to NRC the final reports and other deliverables required under this contract. However, such publication and papers shall focus on advances in science and technology and minimize conclusions and/or recommendations which may have regulatory implications.

(c) The principal investigator(s) shall coordinate all such publications with, and transmit a copy of the proposed article or paper to, the NRC Contracting Officer or Project Officer, prior to publication. The NRC agrees to review and provide comments within thirty (30) days after receipt of a proposed publication. However, in those cases where the information to be published is (1) subject to Commission approval, (2) has not been ruled upon, or (3) disapproved by the Commission, the NRC reserves the right to disapprove or delay the publication. Further, if the NRC disagrees with the proposed publication for any reason, it reserves the right to require that any publication not identify the NRC's sponsorship of the work and that any associated publication costs shall be borne by the contractor.

(End of Clause)

H.8 2052.242-71 PROCEDURES FOR RESOLVING DIFFERING PROFESSIONAL VIEWS. (OCT 1999)

(a) The following procedure provides for the expression and resolution of differing professional views (DPVs) of health and safety related concerns of NRC contractors and contractor personnel on matters connected to the subject of the contract. Subcontractor DPVs must be submitted through the prime contractor. The prime contractor or subcontractor shall submit all DPV's received but need not endorse them.

(b) The NRC may authorize up to eight reimbursable hours for the contractor to document, in writing, a DPV by the contractor, the contractor's personnel, or subcontractor personnel. The contractor shall not be entitled to any compensation for effort on a DPV which exceeds the specified eight hour limit.

(c) Before incurring costs to document a DPV, the contractor shall first determine whether there are sufficient funds obligated under the contract which are available to cover the costs of writing a DPV. If there are insufficient obligated funds under the contract, the contractor shall first request the NRC contracting officer for additional funding to cover the costs of preparing the DPV and authorization to proceed.

(d) Contract funds shall not be authorized to document an allegation where the use of this NRC contractor DPV process is inappropriate. Examples of such instances are: allegations of wrongdoing which should be addressed directly to the NRC Office of the Inspector General (OIG), issues submitted anonymously, or issues raised which have already been considered, addressed, or rejected, absent significant new information. This procedure does not provide anonymity. Individuals desiring anonymity should contact the NRC OIG or submit the information under NRC's Allegation Program, as appropriate.

(e) When required, the contractor shall initiate the DPV process by submitting a written statement directly to the NRC Office Director or Regional Administrator responsible for the contract, with a copy to the Contracting Officer, Division of Contracts and Property Management, Office of Administration. Each DPV submitted will be evaluated on its own merits.

(f) The DPV, while being brief, must contain the following as it relates to the subject matter of the contract:

(1) A summary of the prevailing NRC view, existing NRC decision or stated position, or the proposed or established NRC practice.

(2) A description of the submitter's views and how they differ from any of the above items.

(3) The rationale for the submitter's views, including an assessment based on risk, safety and cost benefit considerations of the consequences should the submitter's position not be adopted by NRC.

(g) The Office Director or Regional Administrator will immediately forward the submittal to the NRC DPV Review Panel and acknowledge receipt of the DPV, ordinarily within five (5) calendar days of receipt.

(h) The panel will normally review the DPV within seven calendar days of receipt to determine whether enough information has been supplied to undertake a detailed review of the issue. Typically, within 30 calendar days of receipt of the necessary information to begin a review, the panel will provide a written report of its findings to the Office Director or Regional Administrator and to the Contracting Officer, which includes a recommended course of action.

(i) The Office Director or Regional Administrator will consider the DPV Review Panel's report, make a decision on the DPV and provide a written decision to the contractor and the Contracting Officer normally within seven calendar days after receipt of the panel's recommendation.

(j) Subsequent to the decision made regarding the DPV Review Panel's report, a summary of the issue and its disposition will be included in the NRC Weekly Information Report submitted by the Office Director. The DPV file will be retained in the Office or Region for a minimum of one year thereafter. For purposes of the contract, the DPV shall be considered a deliverable under the contract. Based upon the Office Director or Regional Administrator's report, the matter will be closed.

(End of Clause)

I - Contract Clauses

I.1 52.252-2 CLAUSES INCORPORATED BY REFERENCE. (FEB 1998)

This contract incorporates one or more clauses by reference, with the same force and effect as if they were given in full text. Upon request, the Contracting Officer will make their full text available. Also, the full text of a clause may be accessed electronically at this/these address(es): https://www.acquisition.gov/

52.202-1	**DEFINITIONS. (NOV 2013)**
52.203-3	**GRATUITIES. (APR 1984)**
52.203-5	**COVENANT AGAINST CONTINGENT FEES. (MAY 2014)**
52.203-6	**RESTRICTIONS ON SUBCONTRACTOR SALES TO THE GOVERNMENT. (SEP 2006)**
52.203-7	**ANTI-KICKBACK PROCEDURES. (MAY 2014)**
52.203-8	**CANCELLATION, RESCISSION, AND RECOVERY OF FUNDS FOR ILLEGAL OR IMPROPER ACTIVITY. (MAY 2014)**
52.203-10	**PRICE OR FEE ADJUSTMENT FOR ILLEGAL OR IMPROPER ACTIVITY. (MAY 2014)**
52.203-12	**LIMITATION ON PAYMENTS TO INFLUENCE CERTAIN FEDERAL TRANSACTIONS. (OCT 2010)**
52.203-17	**CONTRACTOR EMPLOYEE WHISTLEBLOWER RIGHTS AND REQUIREMENT TO INFORM EMPLOYEES OF WHISTLEBLOWER RIGHTS. (APR 2014)**
52.204-4	**PRINTED OR COPIED DOUBLE-SIDED ON POSTCONSUMER FIBER CONTENT PAPER. (MAY 2011)**
52.204-10	**REPORTING EXECUTIVE COMPENSATION AND FIRST-TIER SUBCONTRACT AWARDS. (OCT 2018)**
52.204-13	**SYSTEM FOR AWARD MANAGEMENT MAINTENANCE. (OCT 2018)**
52.204-14	**SERVICE CONTRACT REPORTING REQUIREMENTS. (OCT 2016)**
52.204-22	**ALTERNATIVE LINE ITEM PROPOSAL. (JAN 2017)**
52.204-23	**PROHIBITION ON CONTRACTING FOR HARDWARE, SOFTWARE, AND SERVICES DEVELOPED OR PROVIDED BY KASPERSKY LAB AND OTHER COVERED ENTITIES. (JUL 2018)**
52.209-6	**PROTECTING THE GOVERNMENT'S INTEREST WHEN SUBCONTRACTING WITH CONTRACTORS DEBARRED, SUSPENDED, OR PROPOSED FOR DEBARMENT. (OCT 2015)**
52.209-9	**UPDATES OF PUBLICLY AVAILABLE INFORMATION REGARDING RESPONSIBILITY MATTERS. (OCT 2018)**
52.209-10	**PROHIBITION ON CONTRACTING WITH INVERTED DOMESTIC CORPORATIONS. (NOV 2015)**
52.215-2	**AUDIT AND RECORDS - NEGOTIATION. (OCT 2010) - ALTERNATE II (AUG 2016)**
52.215-8	**ORDER OF PRECEDENCE - UNIFORM CONTRACT FORMAT. (OCT 1997)**
52.215-14	**INTEGRITY OF UNIT PRICES. (OCT 2010) - ALTERNATE I (OCT 1997)**
52.215-15	**PENSION ADJUSTMENTS AND ASSET REVERSIONS. (OCT 2010)**
52.215-18	**REVERSION OR ADJUSTMENT OF PLANS FOR POSTRETIREMENT BENEFITS (PRB) OTHER THAN PENSIONS. (JUL 2005)**

52.215-21	**REQUIREMENTS FOR CERTIFIED COST OR PRICING DATA AND DATA OTHER THAN CERTIFIED COST OR PRICING DATA - MODIFICATIONS. (OCT 2010) - ALTERNATE IV (OCT 2010)**
52.215-23	**LIMITATIONS ON PASS-THROUGH CHARGES. (OCT 2009)**
52.216-7	**ALLOWABLE COST AND PAYMENT. (AUG 2018) - ALTERNATE II (AUG 2012)**
52.216-11	**COST CONTRACT - NO FEE. (APR 1984)**
52.216-26	**PAYMENTS OF ALLOWABLE COSTS BEFORE DEFINITIZATION. (DEC 2002)**
52.219-8	**UTILIZATION OF SMALL BUSINESS CONCERNS. (OCT 2018)**
52.222-3	**CONVICT LABOR. (JUN 2003)**
52.222-17	**NONDISPLACEMENT OF QUALIFIED WORKERS. (MAY 2014)**
52.222-20	**CONTRACTS FOR MATERIALS, SUPPLIES, ARTICLES, AND EQUIPMENT EXCEEDING $15,000. (MAY 2014)**
52.222-21	**PROHIBITION OF SEGREGATED FACILITIES. (APR 2015)**
52.222-26	**EQUAL OPPORTUNITY. (SEP 2016)**
52.222-37	**EMPLOYMENT REPORTS ON VETERANS. (FEB 2016)**
52.222-40	**NOTIFICATION OF EMPLOYEE RIGHTS UNDER THE NATIONAL LABOR RELATIONS ACT. (DEC 2010)**
52.222-50	**COMBATING TRAFFICKING IN PERSONS. (JAN 2019)**
52.222-54	**EMPLOYMENT ELIGIBILITY VERIFICATION. (OCT 2015)**
52.223-6	**DRUG-FREE WORKPLACE. (MAY 2001)**
52.223-18	**ENCOURAGING CONTRACTOR POLICIES TO BAN TEXT MESSAGING WHILE DRIVING. (AUG 2011)**
52.225-13	**RESTRICTIONS ON CERTAIN FOREIGN PURCHASES. (JUN 2008)**
52.227-14	**RIGHTS IN DATA-GENERAL. (MAY 2014) - ALTERNATE IV (DEC 2007)**
52.228-7	**INSURANCE - LIABILITY TO THIRD PERSONS. (MAR 1996)**
52.230-5	**COST ACCOUNTING STANDARDS - EDUCATIONAL INSTITUTION. (AUG 2016)**
52.230-6	**ADMINISTRATION OF COST ACCOUNTING STANDARDS. (JUN 2010)**
52.232-17	**INTEREST. (MAY 2014)**
52.232-18	**AVAILABILITY OF FUNDS. (APR 1984)**
52.232-22	**LIMITATION OF FUNDS. (APR 1984)**
52.232-23	**ASSIGNMENT OF CLAIMS. (MAY 2014)**
52.232-25	**PROMPT PAYMENT. (JAN 2017) - ALTERNATE I (FEB 2002)**
52.232-33	**PAYMENT BY ELECTRONIC FUNDS TRANSFER - SYSTEM FOR AWARD MANAGEMENT. (OCT 2018)**
52.232-39	**UNENFORCEABILITY OF UNAUTHORIZED OBLIGATIONS. (JUN 2013)**
52.232-40	**PROVIDING ACCELERATED PAYMENTS TO SMALL BUSINESS SUBCONTRACTORS. (DEC 2013)**
52.233-1	**DISPUTES. (MAY 2014)**
52.233-3	**PROTEST AFTER AWARD. (AUG 1996) - ALTERNATE I (JUN 1985)**
52.233-4	**APPLICABLE LAW FOR BREACH OF CONTRACT CLAIM. (OCT 2004)**
52.242-1	**NOTICE OF INTENT TO DISALLOW COSTS. (APR 1984)**
52.242-4	**CERTIFICATION OF FINAL INDIRECT COSTS. (JAN 1997)**
52.242-13	**BANKRUPTCY. (JUL 1995)**
52.243-2	**CHANGES - COST-REIMBURSEMENT. (AUG 1987) - ALTERNATE I (APR 1984)**
52.244-5	**COMPETITION IN SUBCONTRACTING. (DEC 1996)**

52.244-6 SUBCONTRACTS FOR COMMERCIAL ITEMS. (AUG 2019)
52.245-1 GOVERNMENT PROPERTY. (JAN 2017) - ALTERNATE II (APR 2012)
52.245-9 USE AND CHARGES. (APR 2012)
52.246-25 LIMITATION OF LIABILITY - SERVICES. (FEB 1997)
52.247-1 COMMERCIAL BILL OF LADING NOTATIONS. (FEB 2006)
52.249-6 TERMINATION (COST-REIMBURSEMENT). (MAY 2004)

I.2 52.204-21 BASIC SAFEGUARDING OF COVERED CONTRACTOR INFORMATION SYSTEMS. (JUN 2016)

(a) *Definitions*. As used in this clause-

Covered contractor information system means an information system that is owned or operated by a contractor that processes, stores, or transmits Federal contract information.

Federal contract information means information, not intended for public release, that is provided by or generated for the Government under a contract to develop or deliver a product or service to the Government, but not including information provided by the Government to the public (such as on public Web sites) or simple transactional information, such as necessary to process payments.

Information means any communication or representation of knowledge such as facts, data, or opinions, in any medium or form, including textual, numerical, graphic, cartographic, narrative, or audiovisual (Committee on National Security Systems Instruction (CNSSI) 4009).

Information system means a discrete set of information resources organized for the collection, processing, maintenance, use, sharing, dissemination, or disposition of information (44 U.S.C. 3502).

Safeguarding means measures or controls that are prescribed to protect information systems.

(b) *Safeguarding requirements and procedures*. (1) The Contractor shall apply the following basic safeguarding requirements and procedures to protect covered contractor information systems. Requirements and procedures for basic safeguarding of covered contractor information systems shall include, at a minimum, the following security controls:

(i) Limit information system access to authorized users, processes acting on behalf of authorized users, or devices (including other information systems).

(ii) Limit information system access to the types of transactions and functions that authorized users are permitted to execute.

(iii) Verify and control/limit connections to and use of external information systems.

(iv) Control information posted or processed on publicly accessible information systems.

(v) Identify information system users, processes acting on behalf of users, or devices.

(vi) Authenticate (or verify) the identities of those users, processes, or devices, as a prerequisite to allowing access to organizational information systems.

(vii) Sanitize or destroy information system media containing Federal Contract Information before disposal or release for reuse.

(viii) Limit physical access to organizational information systems, equipment, and the respective operating environments to authorized individuals.

(ix) Escort visitors and monitor visitor activity; maintain audit logs of physical access; and control and manage physical access devices.

(x) Monitor, control, and protect organizational communications (i.e., information transmitted or received by organizational information systems) at the external boundaries and key internal boundaries of the information systems.

(xi) Implement subnetworks for publicly accessible system components that are physically or logically separated from internal networks.

(xii) Identify, report, and correct information and information system flaws in a timely manner.

(xiii) Provide protection from malicious code at appropriate locations within organizational information systems.

(xiv) Update malicious code protection mechanisms when new releases are available.

(xv) Perform periodic scans of the information system and real-time scans of files from external sources as files are downloaded, opened, or executed.

(2) *Other requirements*. This clause does not relieve the Contractor of any other specific safeguarding requirements specified by Federal agencies and departments relating to covered contractor information systems generally or other Federal safeguarding requirements for controlled unclassified information (CUI) as established by Executive Order 13556.

(c) *Subcontracts*. The Contractor shall include the substance of this clause, including this paragraph (c), in subcontracts under this contract (including subcontracts for the acquisition of commercial items, other than commercially available off-the-shelf items), in which the subcontractor may have Federal contract information residing in or transiting through its information system.

(End of clause)

I.3 52.204-25 PROHIBITION ON CONTRACTING FOR CERTAIN TELECOMMUNICATIONS AND VIDEO SURVEILLANCE SERVICES OR EQUIPMENT. (AUG 2019)

(a) *Definitions*. As used in this clause-

Covered foreign country means The People's Republic of China.

Covered telecommunications equipment or services means-

(1) Telecommunications equipment produced by Huawei Technologies Company or ZTE Corporation (or any subsidiary or affiliate of such entities);

(2) For the purpose of public safety, security of Government facilities, physical security surveillance of critical infrastructure, and other national security purposes, video surveillance and telecommunications equipment produced by Hytera Communications Corporation, Hangzhou Hikvision Digital Technology Company, or Dahua Technology Company (or any subsidiary or affiliate of such entities);

(3) Telecommunications or video surveillance services provided by such entities or using such equipment; or

(4) Telecommunications or video surveillance equipment or services produced or provided by an entity that the Secretary of Defense, in consultation with the Director of National Intelligence or the Director of the Federal Bureau of Investigation, reasonably believes to be an entity owned or controlled by, or otherwise connected to, the government of a covered foreign country.

Critical technology means-

(1) Defense articles or defense services included on the United States Munitions List set forth in the International Traffic in Arms Regulations under subchapter M of chapter I of title 22, Code of Federal Regulations;

(2) Items included on the Commerce Control List set forth in Supplement No. 1 to part 774 of the Export Administration Regulations under subchapter C of chapter VII of title 15, Code of Federal Regulations, and controlled-

(i) Pursuant to multilateral regimes, including for reasons relating to national security, chemical and biological weapons proliferation, nuclear nonproliferation, or missile technology; or

(ii) For reasons relating to regional stability or surreptitious listening;

(3) Specially designed and prepared nuclear equipment, parts and components, materials, software, and technology covered by part 810 of title 10, Code of Federal Regulations (relating to assistance to foreign atomic energy activities);

(4) Nuclear facilities, equipment, and material covered by part 110 of title 10, Code of Federal Regulations (relating to export and import of nuclear equipment and material);

(5) Select agents and toxins covered by part 331 of title 7, Code of Federal Regulations, part 121 of title 9 of such Code, or part 73 of title 42 of such Code; or

(6) Emerging and foundational technologies controlled pursuant to section 1758 of the Export Control Reform Act of 2018 (50 U.S.C. 4817).

Substantial or essential component means any component necessary for the proper function or performance of a piece of equipment, system, or service.

(b) *Prohibition*. Section 889(a)(1)(A) of the John S. McCain National Defense Authorization Act for Fiscal Year 2019 (Pub.L. 115-232) prohibits the head of an executive agency on or after August 13, 2019, from procuring or obtaining, or extending or renewing a contract to procure or obtain, any equipment, system, or service that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system. The Contractor is prohibited from providing to the Government any equipment, system, or service that uses covered telecommunications equipment or services as a substantial or essential component of any system, or as critical technology as part of any system, unless an exception at paragraph (c) of this clause applies or the covered telecommunication equipment or services are covered by a waiver described in Federal Acquisition Regulation 4.2104.

(c) *Exceptions*. This clause does not prohibit contractors from providing-

(1) A service that connects to the facilities of a third-party, such as backhaul, roaming, or interconnection arrangements; or

(2) Telecommunications equipment that cannot route or redirect user data traffic or permit visibility into any user data or packets that such equipment transmits or otherwise handles.

(d) *Reporting requirement*. (1) In the event the Contractor identifies covered telecommunications equipment or services used as a substantial or essential component of any system, or as critical technology as part of any system, during contract performance, or the Contractor is notified of such by a subcontractor at any tier or by any other source, the Contractor shall report the information in paragraph (d)(2) of this clause to the Contracting Officer, unless elsewhere in this contract are established procedures for reporting the information; in the case of the Department of Defense, the Contractor shall report to the website at https://dibnet.dod.mil. For indefinite delivery contracts, the Contractor shall report to the Contracting Officer for the indefinite delivery contract and the Contracting Officer(s) for any affected order or, in the case of the Department of Defense, identify both the indefinite delivery contract and any affected orders in the report provided at https://dibnet.dod.mil.

(2) The Contractor shall report the following information pursuant to paragraph (d)(1) of this clause:

(i) Within one business day from the date of such identification or notification: The contract number; the order number(s), if applicable; supplier name; supplier unique entity identifier (if known); supplier Commercial and Government Entity (CAGE) code (if known); brand; model number (original equipment manufacturer number, manufacturer part number, or wholesaler number); item description; and any readily available information about mitigation actions undertaken or recommended.

(ii) Within 10 business days of submitting the information in paragraph (d)(2)(i) of this clause: Any further available information about mitigation actions undertaken or recommended. In addition, the Contractor shall describe the efforts it undertook to prevent use or submission of covered telecommunications equipment or services, and any additional efforts that will be incorporated to prevent future use or submission of covered telecommunications equipment or services.

(e) *Subcontracts*. The Contractor shall insert the substance of this clause, including this paragraph (e), in all subcontracts and other contractual instruments, including subcontracts for the acquisition of commercial items.

(End of clause)

I.4 52.217-8 OPTION TO EXTEND SERVICES. (NOV 1999)

The Government may require continued performance of any services within the limits and at the rates specified in the contract. These rates may be adjusted only as a result of revisions to prevailing labor rates provided by the Secretary of Labor. The option provision may be exercised more than once, but the total extension of performance hereunder shall not exceed 6 months. The Contracting Officer may exercise the option by written notice to the Contractor within 30 days before exercising the option.

(End of clause)

I.5 52.222-35 EQUAL OPPORTUNITY FOR VETERANS. (OCT 2015)

(a) Definitions. As used in this clause-

"Active duty wartime or campaign badge veteran," "Armed Forces service medal veteran," "disabled veteran," "protected veteran," "qualified disabled veteran," and "recently separated veteran" have the meanings given at FAR 22.1301.

(b) Equal opportunity clause. The Contractor shall abide by the requirements of the equal opportunity clause at 41 CFR 60-300.5(a), as of March 24, 2014. This clause prohibits discrimination against qualified protected veterans, and requires affirmative action by the Contractor to employ and advance in employment qualified protected veterans.

(c) Subcontracts. The Contractor shall insert the terms of this clause in subcontracts of $150,000 or more unless exempted by rules, regulations, or orders of the Secretary of Labor. The Contractor shall act as specified by the Director, Office of Federal Contract Compliance Programs, to enforce the terms, including action for noncompliance. Such

necessary changes in language may be made as shall be appropriate to identify properly the parties and their undertakings.

(End of clause)

I.6 52.222-36 EQUAL OPPORTUNITY FOR WORKERS WITH DISABILITIES. (JUL 2014)

(a) Equal opportunity clause. The Contractor shall abide by the requirements of the equal opportunity clause at 41 CFR 60-741.5(a), as of March 24, 2014. This clause prohibits discrimination against qualified individuals on the basis of disability, and requires affirmative action by the Contractor to employ and advance in employment qualified individuals with disabilities.

(b) Subcontracts. The Contractor shall include the terms of this clause in every subcontract or purchase order in excess of $15,000 unless exempted by rules, regulations, or orders of the Secretary, so that such provisions will be binding upon each subcontractor or vendor. The Contractor shall act as specified by the Director, Office of Federal Contract Compliance Programs of the U.S. Department of Labor, to enforce the terms, including action for noncompliance. Such necessary changes in language may be made as shall be appropriate to identify properly the parties and their undertakings.

(End of clause)

I.7 52.244-2 SUBCONTRACTS. (OCT 2010) - ALTERNATE I (JUN 2007)

(a) *Definitions*. As used in this clause-

Approved purchasing system means a Contractor's purchasing system that has been reviewed and approved in accordance with Part 44 of the Federal Acquisition Regulation (FAR).

Consent to subcontract means the Contracting Officer's written consent for the Contractor to enter into a particular subcontract.

Subcontract means any contract, as defined in FAR Subpart 2.1, entered into by a subcontractor to furnish supplies or services for performance of the prime contract or a subcontract. It includes, but is not limited to, purchase orders, and changes and modifications to purchase orders.

(b) When this clause is included in a fixed-price type contract, consent to subcontract is required only on unpriced contract actions (including unpriced modifications or unpriced delivery orders), and only if required in accordance with paragraph (c) or (d) of this clause.

(c) If the Contractor does not have an approved purchasing system, consent to subcontract is required for any subcontract that-

(1) Is of the cost-reimbursement, time-and-materials, or labor-hour type; or

(2) Is fixed-price and exceeds-

(i) For a contract awarded by the Department of Defense, the Coast Guard, or the National Aeronautics and Space Administration, the greater of the simplified acquisition threshold or 5 percent of the total estimated cost of the contract; or

(ii) For a contract awarded by a civilian agency other than the Coast Guard and the National Aeronautics and Space Administration, either the simplified acquisition threshold or 5 percent of the total estimated cost of the contract.

(d) If the Contractor has an approved purchasing system, the Contractor nevertheless shall obtain the Contracting Officer's written consent before placing the following subcontracts: [ ]

(e)(1) The Contractor shall notify the Contracting Officer reasonably in advance of placing any subcontract or modification thereof for which consent is required under paragraph (b), (c), or (d) of this clause, including the following information:

(i) A description of the supplies or services to be subcontracted.

(ii) Identification of the type of subcontract to be used.

(iii) Identification of the proposed subcontractor.

(iv) The proposed subcontract price.

(v) The subcontractor's current, complete, and accurate certified cost or pricing data and Certificate of Current Cost or Pricing Data, if required by other contract provisions.

(vi) The subcontractor's Disclosure Statement or Certificate relating to Cost Accounting Standards when such data are required by other provisions of this contract.

(vii) A negotiation memorandum reflecting-

(A) The principal elements of the subcontract price negotiations;

(B) The most significant considerations controlling establishment of initial or revised prices;

(C) The reason certified cost or pricing data were or were not required;

(D) The extent, if any, to which the Contractor did not rely on the subcontractor's certified cost or pricing data in determining the price objective and in negotiating the final price;

(E) The extent to which it was recognized in the negotiation that the subcontractor's certified cost or pricing data were not accurate, complete, or current; the action taken by the Contractor and the

subcontractor; and the effect of any such defective data on the total price negotiated;

(F) The reasons for any significant difference between the Contractor's price objective and the price negotiated; and

(G) A complete explanation of the incentive fee or profit plan when incentives are used. The explanation shall identify each critical performance element, management decisions used to quantify each incentive element, reasons for the incentives, and a summary of all trade-off possibilities considered.

(2) If the Contractor has an approved purchasing system and consent is not required under paragraph (c) or (d) of this clause, the Contractor nevertheless shall notify the Contracting Officer reasonably in advance of entering into any (i) cost-plus-fixed-fee subcontract, or (ii) fixed-price subcontract that exceeds either the simplified acquisition threshold or 5 percent of the total estimated cost of this contract. The notification shall include the information required by paragraphs (e)(1)(i) through (e)(1)(iv) of this clause.

(f) Unless the consent or approval specifically provides otherwise, neither consent by the Contracting Officer to any subcontract nor approval of the Contractor's purchasing system shall constitute a determination-

(1) Of the acceptability of any subcontract terms or conditions;

(2) Of the allowability of any cost under this contract; or

(3) To relieve the Contractor of any responsibility for performing this contract.

(g) No subcontract or modification thereof placed under this contract shall provide for payment on a cost-plus-a-percentage-of-cost basis, and any fee payable under cost-reimbursement type subcontracts shall not exceed the fee limitations in FAR 15.404-4(c)(4)(i).

(h) The Contractor shall give the Contracting Officer immediate written notice of any action or suit filed and prompt notice of any claim made against the Contractor by any subcontractor or vendor that, in the opinion of the Contractor, may result in litigation related in any way to this contract, with respect to which the Contractor may be entitled to reimbursement from the Government.

(i) The Government reserves the right to review the Contractor's purchasing system as set forth in FAR Subpart 44.3.

(j) Paragraphs (c) and (e) of this clause do not apply to the following subcontracts, which were evaluated during negotiations: [ ]

(End of clause)

J - List of Documents, Exhibits and Other Attachments

Attachment Number	Title	# of Pages
1	Background Information on Post-CHF Heat Transfer at High Pressure and Flow Conditions	36
2	Hot Patch Design Study	29
3	Monthly Letter Status Report Instructions/Template	10
4	Billing Instructions for Cost Reimbursement Contracts	8

Attachment #1: Background Information on Post-CHF Heat Transfer at High Pressure and Flow Conditions

I. Introduction

The USNRC's system thermal-hydraulic analysis code TRACE (TRAC RELAP Advanced Computational Engine) is being developed by the NRC to perform large and small break loss of coolant accident and system transient analyses for a wide range of nuclear plants. This code will be used as an audit tool to analyze transient and accident analyses submitted by the vendors and licensees. As described below, the inverted annular film boiling (IAFB) regime occurs just downstream of the quench front and its precursory cooling largely governs the quench front progression by reducing the clad temperature to the point where surface rewetting can begin. In addition, its void fraction, due to its effect upon the downcomer-to-core gravity head, affects the core inlet flooding rate. Further downstream, the breakup of the inverted annular core gives rise to the inverted slug film boiling (ISFB) region that provides the initial condition for the dispersed flow regime where the peak clad temperature occurs. Therefore, for the accurate prediction of post-CHF clad temperatures in transients such as large and intermediate break loss of coolant accidents, accurate models with quantified uncertainties are required for the calculation of both the wall heat transfer and the void fraction in these regimes.

Two-fluid codes such as TRACE frequently use ad hoc models for wall and interfacial heat transfer as well as interfacial shear in the inverted annular and inverted slug film boiling flow regimes. Consequently, the modeling of these regimes was the subject of criticism during the TRACE peer review. Moreover, the current IAFB model under-predicts blowdown cooling in the LOFT L2-6 assessment during the time period when the insurge of water into the bottom of the core quenches the fuel rods. Therefore the improvement of the models for these regimes was identified as a high priority near-term development need in the Thermal-Hydraulic Code Development Plan. The experimental effort called for in this statement of work is specifically targeted to the improvement of the TRACE constitutive models for the inverted annular and inverted slug film boiling regimes.

Although much experimental work has been performed on inverted annular film boiling in the past, deficiencies exist in the presently available database that render it unsuitable for model development (though it can and will be used for the quantification of model uncertainties). Specifically, a consistent set of steady-state film boiling data is needed for prototypical rod bundle geometries with measurements of:

- Wall temperatures
- Void fractions
- Liquid-core temperatures

While almost all film boiling experiments report wall temperatures, the only data available for the inverted annular and inverted slug film boiling regimes in a rod bundle is that collected during reflood experiments which by their nature are transient. Although such transient data can be used in model development, significant uncertainties are introduced due to the quench front heat release rendering them more suitable for validation studies of the entire reflood model.

Since the introduction of the “hot patch” technique (Groeneveld 1974), a large database for film boiling in tubes has been developed. However, very little of this database includes the measurement of the void fraction and liquid-core temperature measurements are virtually non-existent. To elucidate the data needs alluded to above, brief descriptions of the post-CHF flow regimes, and the two-fluid modeling of the IAFB and the inverted slug film boiling (ISFB) regime are given below. These descriptions are then followed by a summary of the post-CHF experimental programs that were conducted in the previous THI contract.

II. Description of Post-CHF Flow Regimes

Before discussing the modeling needs, it helps to better characterize the regime itself, as there are several distinct flow regimes that may occur in film boiling. Based on the heat transfer characteristics observed in forced convection film boiling inside vertical tubes, Hammouda et al (1996) and El Nakla et al (2011) identified four distinct regimes as shown in Figure 1 for a case with a high value of the mass flux and for the refrigerant R-134a.

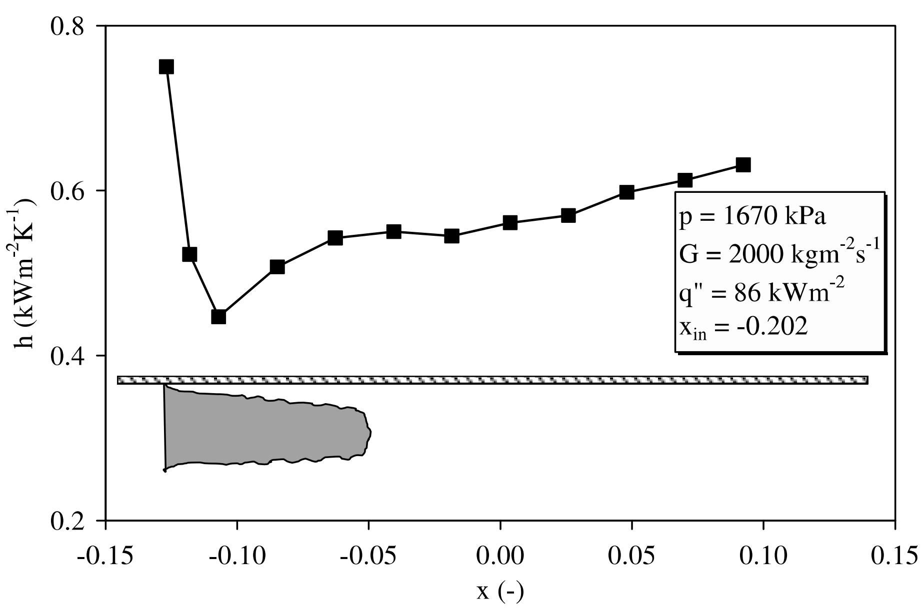

Figure 1: Heat transfer regimes during inverted annular film boiling (Nakla et al 2011).

Hammouda et al (1996) described these four regimes as:

- Region I: this region is usually referred to as the “subcooled IAFB” regime and is characterized by a strong decrease in the wall heat transfer coefficient in the direction of the flow as the subcooling of the liquid core is reduced and the vapor film begins to thicken. The vapor is confined to a thin layer at the superheated wall, the interface is smooth and stable, and significant non-equilibrium exists between the phases.

- Region II: further downstream, as the subcooling of the liquid core has been reduced due to interfacial heat transfer, the vapor velocity increases due to the increased vapor generation rate. In this region, the vapor layer thickness increases; the vapor-liquid interface becomes wavy and unstable; and convective heat transfer becomes important. This regime is generally accompanied by an increase in the wall heat transfer coefficient in the flow direction as the vapor flow increases and is referred to as the "wavy IAFB" regime.
- Region III: downstream of the wavy IAFB region, the flow regime might be that of "inverted slug flow" (ISF) or "agitated inverted annular flow" (AIAF). At low flow velocities, inverted slug flow is expected to be present: i.e. most of the liquid is in the form of liquid slugs in the center of the flow channel. At higher flow velocities, AIAF may be present; the liquid core may have a helical appearance or consist of sheet-like segments as a result of large amplitude roll waves. The flow is usually highly agitated and the vapor phase is distributed across the channel. Both ISF and AIAF represent transitions to the dispersed flow film-boiling region of region IV. In what follows, ISF will be used to denote both of these regimes.
- Region IV: the dispersed flow film-boiling (DFFB) regime occurs as the increasing vapor velocity induces breakup of the large liquid fragments of region III into droplets of various sizes. The wall heat transfer coefficient (referenced to the saturation temperature) may either increase or decrease in the flow direction as described below:
    - For high mass velocities, the vapor superheat is minimal, and an increase in quality results in an increase in vapor velocity and hence an increase in heat transfer coefficient.
    - For low mass velocities, convection also becomes more important as quality increases. However, reduced interfacial heat transfer to the droplets allows the vapor superheat to increase, so that the net effect is a decrease in the value of the effective wall heat transfer coefficient.

The focus of this task order is the subcooled and wavy inverted annular flow regimes (regions I and II) and the inverted slug flow regime (region III). In addition, the conditions at the onset of dispersed flow film boiling (region IV) will be determined.

III. Two-Fluid Modeling of IAFB

For a two-fluid model of IAFB, four types of constitutive models are needed:

- Wall heat transfer
- Interfacial friction
- Interfacial heat transfer
- Flow regime transition criteria (region II to III)

Each of these constitutive models is described in turn below together with the data needed for model development.

The heat transfer pathways present during IAFB are illustrated schematically in Figure 2 where:

- Qwv : wall-to-vapor heat transfer

- Qvi : vapor-to-interface heat transfer
- Qli : liquid-to-interface heat transfer
- Qrad : radiation heat transfer from wall-to-interface

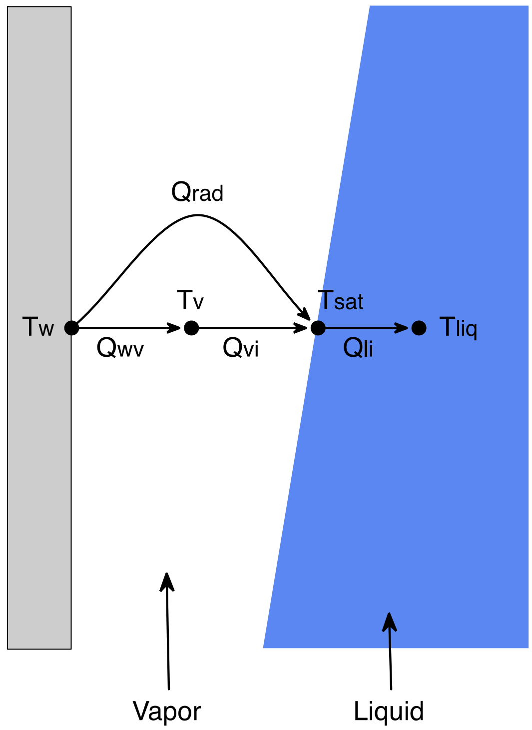

Figure 2: Heat transfer pathways for two-fluid model of IAFB.

The primary component of the wall heat transfer is convection from the wall to the vapor phase. Radiation heat transfer, from the wall to the liquid interface, occurs in parallel with the convective component but generally is of secondary importance and is not discussed here. It is customary to express the film boiling wall heat transfer convective component in terms of a heat transfer coefficient that is referenced to the saturation temperature as

$$h_w = \frac{\left(q''_w - q''_{rad}\right)}{\left(T_w - T_{sat}\right)} \qquad (1)$$

where

- q''_w : total wall heat flux
- q''_{rad} : wall heat flux due to radiation (estimated)
- T_w : wall surface temperature
- T_{sat} : saturation temperature

h_w : wall convective heat transfer coefficient

The wall-to-vapor heat transfer would then be given by

$$q''_{wv} = h_{wv}\left(T_w - T_v\right) = h_w\left(T_w - T_{sat}\right) \tag{2}$$

and the vapor-to-interface heat transfer by

$$q'_{vi} = h_{vi} \cdot P_i \cdot \left(T_v - T_{sat}\right) \leq h_w \cdot P_w \cdot \left(T_w - T_{sat}\right) \tag{3}$$

where P_i and P_w are the interfacial and wall perimeters respectively. The inequality in equation (3) results from the sensible heat that is absorbed by the vapor phase. Unfortunately, with respect to the needs for developing a two-fluid model of IAFB, all known empirical IAFB heat transfer correlations are of the type given by equation (1).

The reason for this simplified approach is the near impossibility of measuring the vapor temperature due to the thinness of the vapor film and the presence of interfacial waves on the liquid core. Consequently, some type of ad hoc formulation must be used to relate h_{wv} and h_{vi} to the overall wall heat transfer coefficient h_w. This is not a serious modeling deficiency and will not be addressed in this task order.

However, it is still necessary to develop a database sufficient for the development of a wall heat transfer model that is applicable to IAFB in rod bundles over a wide range of flow conditions. Initially, just downstream of the quench front, the vapor film is quite thin, the flow is laminar, the liquid is highly subcooled, and the vapor-liquid interface smooth. Under these conditions, almost all of the heat transferred from the wall to the interface is subsequently transferred into the liquid core as sensible heat resulting in little vapor generation. It is then appropriate to simply express the wall heat transfer coefficient as conduction across a vapor gap, that is,

$$h_w = \frac{k_v}{\delta} \tag{4}$$

where δ is the thickness of the vapor gap separating the wall from the liquid core and k_v is the vapor thermal conductivity. For such a laminar model, it is sufficient to measure the wall temperature (to get h_w) and the void fraction (to get δ). If possible, the direct measurement of the time-averaged vapor film thickness would be superior to that of the void fraction for this purpose.

Fung (1981) performed just such an experiment for steady state film boiling of water at atmospheric pressure in a tube using the hot patch technique. Figure 3 compares the film boiling heat transfer data of Fung to the laminar value given by equation (4) above. For void fractions less than about 10%, the laminar model represents the data quite well, however, as the void fraction increases a significant under-prediction becomes evident.

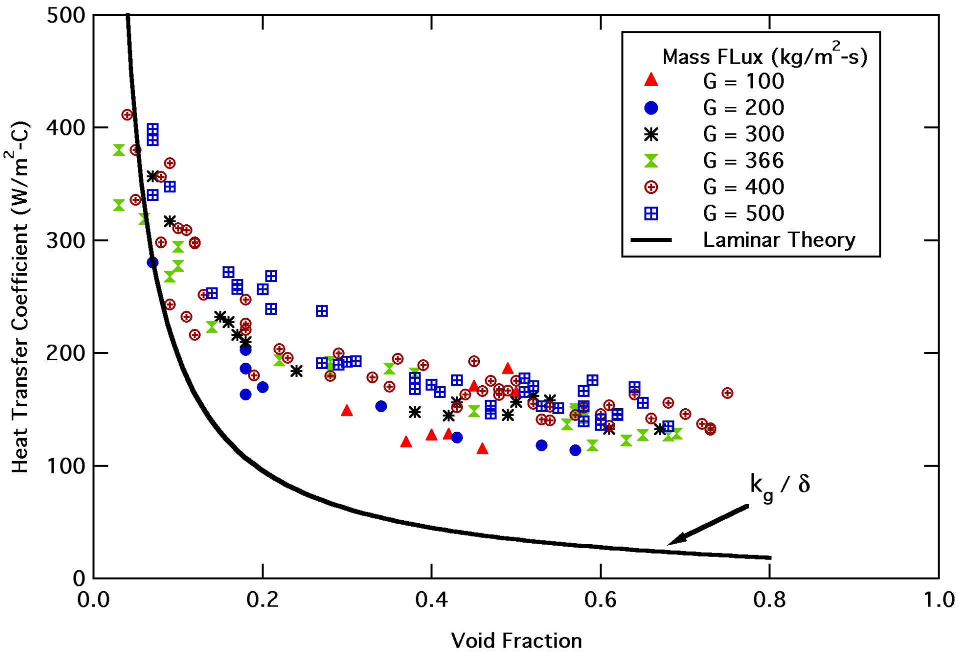

Figure 3: Comparison of Fung's low pressure IAFB data to laminar theory.

Further downstream, as the liquid-core subcooling decreases due to liquid-side interfacial heat transfer, the vapor generation rate increases and convective effects become more important. Two phenomena contribute to the enhanced wall heat transfer for this "wavy IAFB" regime:

- The effect of surface waves and/or oscillations of the liquid core upon the vapor heat transfer, and
- The possible transition of the vapor flow from the laminar to the turbulent regime.

De Cachard (1996) demonstrated that most of the enhancement due to the waviness of the vapor-liquid interface could be reasonably well correlated using a simple function of a non-dimensional vapor film thickness given by

$$\delta^{*} = \delta \cdot \left(\frac{\rho_v \cdot g \cdot \Delta\rho}{\mu_v^2} \right)^{1/3} \qquad (5)$$

This approach was used in the TRACE 5.0 model development and was successful in correlating IAFB data for both tubes (over a wide range of pressures) and rod bundles (for low pressure reflood conditions) though the heat transfer coefficient for rod bundles was enhanced about 30% above those for tubes. In subsequent code validation studies, this model was found to significantly under-predict the blowdown cooling in the LOFT L2-6 test during the time period when the insurge of water into the bottom of the core quenches the fuel rods. This under-prediction was attributed to the lack of modeling the turbulent flow effects on the vapor film heat transfer. For this reason, and to provide for a smoother transition to the inverted slug regime, the TRACE IAFB wall heat transfer model is proposed to be recast as both a function of the non-dimensional film thickness and the vapor Reynolds number. To accomplish this, a film boiling database is needed

that includes information on the vapor mass flux in addition to both the wall temperatures and void fractions. As discussed below, the estimation of the vapor mass flux from the equilibrium quality is not possible due to the substantial subcooling of the liquid core.

The void fraction, and hence the vapor-wall gap thickness, is governed primarily by the phasic flow rates and the interfacial friction. The pressure gradient term can be eliminated from the steady-state 1-D two-fluid momentum equations for IAFB to yield:

$$\tau_i = \frac{\alpha(1-\alpha)A}{P_i}\left\{\rho_l U_l \frac{dU_l}{dz} - \rho_v U_v \frac{dU_v}{dz} + g\cdot\Delta\rho + \frac{\tau_{wv}P_w}{\alpha A}\right\} \tag{6}$$

where

τ_i	:	interfacial shear stress (N/m^2)
τ_{wv}	:	wall-vapor phase shear stress (N/m^2)

For most IAFB conditions, the momentum flux terms are negligible in comparison to the buoyancy term; this allows equation (6) to be recast as

$$\alpha(1-\alpha)\cdot g\cdot\Delta\rho\cdot A \approx \tau_i\cdot P_i - (1-\alpha)\cdot\tau_{wv}\cdot P_w \tag{7}$$

Further, neglecting the wall-vapor shear stress[1] and substituting for the interfacial shear stress term gives

$$\alpha(1-\alpha)\cdot g\cdot\Delta\rho\cdot A \approx \tfrac{1}{2}\cdot\rho_v\cdot f_i\cdot P_i\cdot\left(U_v - U_l\right)^2 \tag{8}$$

and finally, in terms of the vapor mass flux, we have

$$\alpha(1-\alpha)\cdot g\cdot\Delta\rho\cdot A \approx \tfrac{1}{2}\cdot\rho_v\cdot f_i\cdot P_i\cdot\left(\frac{G_v}{\alpha\rho_v} - \frac{(G-G_v)}{(1-\alpha)\rho_l}\right)^2 \tag{9}$$

So, for an IAFB experiment where the void fraction is measured, the interfacial friction factor can be determined as long as the vapor mass flux is known.

Once again, to establish the values for the constitutive models needed for a two-fluid model of IAFB, we see that the crux of the matter is the determination of the vapor mass flux. As stated above, this determination is not a straightforward calculation employing the equilibrium quality, as would be done in a saturated two-phase experiment, due to the substantial subcooling of the liquid core in IAFB. Instead, the local value of the vapor mass flux has to be calculated by integration of the vapor mass equation

$$\frac{dG_v}{dz} = \Gamma_v \tag{10}$$

in the axial direction where Γ_v is the vapor generation rate per unit volume. Γ_v is given by an energy balance at the vapor-liquid interface, that is

[1] Note: in evaluating the interfacial friction factor from void fraction data, the wall shear stress term (and possibly the momentum flux terms) should not be neglected. These assumptions are made here solely for the purpose of clarifying the relationship between the void fraction, the interfacial friction and the phasic mass fluxes.

$$\Gamma_v \quad = \quad \frac{q''_{rad} \cdot P_w \; + \; q''_{vi} \cdot P_i \; + \; q''_{li} \cdot P_i}{A\left(h_{v,sat} - h_l\right)} \tag{11}$$

In equation (11), the usage of the subcooled liquid enthalpy, h_l, in the denominator accounts for the sensible heat required to raise the liquid from the subcooled liquid-core to the temperature of the interface.

Examining equation (11), we see that there are three heat fluxes that must be resolved so that the vapor mass flux can be determined. However, the first two of these can be related to the wall heat flux by performing an energy balance on the vapor film so that

$$\frac{q''_{wv} \cdot P_w - q''_{vi} \cdot P_i}{A} \quad = \quad G_v c_{P,v} \frac{dT_v}{dz} - \Gamma_v \left(h_v - h_{v,sat}\right) \tag{12}$$

yielding

$$\Gamma_v \cdot \left(h_v - h_l\right) \quad = \quad \frac{q''_w \cdot P_w + q''_{li} \cdot P_i}{A} - G_v \cdot c_{P,v} \cdot \frac{dT_v}{dz} \tag{13}$$

In equation (13), the two unknown heat fluxes, q''_{rad} and q''_{vi}, were eliminated but at the cost of adding two other unknowns: the superheated vapor enthalpy, h_v, and the axial gradient of the vapor temperature. Fortunately, suitable assumptions can be made to estimate these values without introducing a significant error. Specifically, the superheated vapor enthalpy can be evaluated by assuming that the vapor temperature is equal to the film temperature

$$T_v \quad \approx \quad \tfrac{1}{2}\left(T_w + T_{sat}\right) \tag{14}$$

and the vapor temperature gradient by

$$\frac{dT_v}{dz} \quad \approx \quad \frac{dT_w}{dz} \tag{15}$$

Therefore, in equation (13), there remains one significant unknown to be determined, namely the liquid-side interfacial heat transfer, q''_{li}. This interfacial heat flux is calculated from the liquid subcooling as

$$q''_{li} \quad = \quad h_{li} \cdot \left(T_l - T_{sat}\right) \tag{16}$$

where h_{li} is the liquid-side interfacial heat transfer coefficient.

There is almost no IAFB data available, either in tube or rod bundle geometries, from which even the magnitude of the liquid-side interfacial heat transfer coefficient can be estimated. As a result, all of the models proposed for this coefficient are ad hoc and subject to considerable uncertainty.

Consequently, the primary objective of this task order is to produce a database from which a reasonably accurate formulation for the liquid-side interfacial heat transfer coefficient can be deduced. With this formulation in hand, the vapor mass flux can be calculated so that a consistent set of constitutive models for both the wall heat transfer coefficient and the interfacial friction factor can be developed. Furthermore, it should be realized that for subcooled film boiling, it is this liquid-side interfacial heat transfer that governs the wall heat transfer. Basically, the effect is that the interfacial heat transfer

determines the amount of vapor generation and hence controls the vapor film thickness, which in turn controls the wall heat transfer rate.

One way that the liquid-side interfacial heat transfer can be deduced is by measuring the axial gradient of the liquid temperature for the liquid core and then performing an energy balance over the liquid phase. Thence,

$$q''_{li} = G_l \cdot c_{P,l} \cdot \frac{dT_l}{dz} \tag{17}$$

In practice, one would not attempt to measure the actual liquid temperature gradient but rather approximate it from the difference between two measurement points, that is

$$\frac{dT_l}{dz} \approx \frac{\Delta T_l}{\Delta z} \tag{18}$$

Such an approach, where a centerline temperature measurement is used to approximate the bulk liquid temperature, should provide a reasonable estimate for the value of the liquid-side interfacial heat transfer while avoiding the attendant difficulties of measuring a heat flux at a vapor-liquid interface that is subject to surface waves and oscillatory motion.

The final constitutive model required to complete the two-fluid model for IAFB is the flow regime transition criteria from inverted annular (regions I and II) to inverted slug (region III). The general consensus is that this flow regime transition is associated with the breakup of the liquid core due to Kelvin-Helmholtz instability. It has also been observed that the point at which the breakup occurs is often close to the point at which the liquid core becomes saturated. This observation complements the Kelvin-Helmholtz theory in that the vapor flow rate rapidly increases as the liquid subcooling is lost and liquid-side interfacial heat transfer goes to zero.

Consequently, many authors have proposed that the breakup of the inverted annular core is governed by a critical Weber number,

$$We_{crit} = \frac{\rho_v \cdot (U_v - U_l)^2 \cdot D_c}{\sigma} = const \tag{19}$$

where D_c is the diameter of the liquid core and σ is the surface tension. Values suggested for this critical Weber number have ranged from 8 to 20 with no general consensus being reached. One of the problems in estimating the critical value of the Weber number, and indeed of applying this criterion, is that the interfacial drag model for IAFB must yield a calculated value for the Weber number that increases monotonically in the axial direction until breakup is predicted. For example, it is well known that as the vapor flow and film thickness increase that the magnitude of the interfacial friction factor increases markedly. If the proposed model for interfacial drag increases too rapidly as the vapor film thickens, then the product of the relative velocity and the liquid-core diameter may begin to decrease before the critical value of the Weber number is reached so that breakup is never predicted.

Consequently, the interfacial drag model and the flow regime transition criteria should be developed together in order to insure consistency. To provide a database from which a model for liquid core breakup can be developed, in addition to the measurements discussed above (α, T_w, T_l), the length of the inverted annular core also must be

measured. The point at which core breakup occurs may be observed visually, for a test section with transparent walls or view ports, or possibly inferred from inflections in the axial profiles of the other measured quantities. However, the transition from IAF to ISF appears to be very smooth so that it is difficult to identify inflection points in quantities such as the void fraction or wall heat transfer coefficient. Therefore, for this task order, it is preferable that some other means, such as visual observation or frequency analysis of fluid thermocouple or optical probe signals be used.

In summary, there are four constitutive models for which a database will be generated suitable for development of a consistent two-fluid model for IAFB:

- Wall heat transfer coefficient
- Interfacial friction factor
- Liquid-side interfacial heat transfer coefficient
- Flow regime transition criterion

To accomplish this task, the database shall include measurements for the axial profiles of the wall temperature, the void fraction, and the liquid core temperature. In addition, the breakup location of the inverted annular core will be required to be measured. If a suitable alternative method for determining the liquid-side interfacial heat transfer is proposed, then the measurement of the liquid core temperature can be omitted.

IV. Two-Fluid Modeling of ISFB

Typically, when subcooled liquid flows past the quench front, the flow regime is inverted annular and, just downstream of the quench front, a thin vapor film separates this subcooled liquid core from the superheated wall. The vapor velocity is low so that the flow is laminar and the vapor-liquid interface is smooth. Further downstream of the quench front, as the subcooling of the liquid core is reduced, the vapor flow increases causing the interface to first become wavy and then oscillate violently until breakup occurs at about the point where the liquid becomes saturated. Experimental data indicate that the inverted annular regime persists up to void fractions of 60-70% and that a smooth transition is made to the dispersed flow regime. This transitional regime will be denoted as inverted slug flow (ISF).

The ISF regime is considered to be composed of a mixture of large liquid chunks (i.e., liquid slugs resulting from the disintegration of the IAFB liquid core) and entrained droplets as depicted schematically in Figure 4. As the vapor flow increases, the liquid slugs are progressively broken up into smaller fragments and the fraction of the flow consisting of entrained droplets increases. Finally, the vapor velocity increases to the point where all of the liquid flow can be construed as entrained droplets and the regime is denoted as dispersed flow film boiling (DFFB). The key feature of the ISFB regime is that, with respect to the wall heat transfer, a smooth transition is provided from IAFB to DFFB.

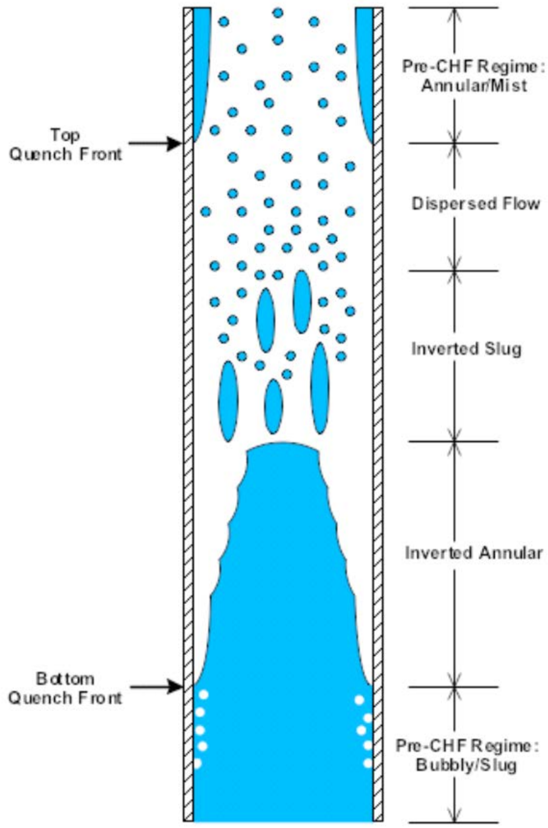

Figure 4: Schematic of the inverted flow regimes that occur for post-CHF conditions.

As no suitable models for the ISFB regime were available, TRACE 5.0 models this regime by using an ad hoc interpolation between IAFB and DFFB. Although the primary focus of this task order is the IAFB regime, a task to develop a database suitable for model development (or at least validation) of a model for ISFB is included. Consequently, the design of the flow loop, test section, and instrumentation must consider the data needs for ISFB.

To form a consistent set of models for the ISFB regime, the following constitutive models will need to be developed:

- Wall-to-vapor heat transfer
- Vapor-to-interface heat transfer
- Interfacial friction
- Wall-to-vapor shear
- Entrainment rate (or fraction)

A brief description of the data needs for each of these models follows.

The wall heat transfer mode is primarily that of turbulent forced convection to the vapor. The form of the model would probably be something similar to

$$q''_{wv} \quad = \quad \Psi_{2\Phi} \cdot h_{spv} \cdot \left(T_w - T_v\right) \tag{20}$$

where h_{spv} is the single-phase vapor heat transfer coefficient and $\Psi_{2\Phi}$ a “two-phase multiplier” to account for the enhancement effects due to the presence of the liquid chunks and droplets within the superheated vapor. The single-phase vapor heat transfer coefficient would be expected to be a function of the vapor Reynolds number and hence of the vapor mass flow rate. While the determination of the vapor flow rate was a critical factor for the IAFB models described above, it is not so much of a problem here. The reason is that the liquid phase can be considered to be saturated and hence, for a steady-state experiment, a good estimate of the vapor flow can be made from a simple energy balance. The two-phase enhancement factor is expected to be a function of the liquid loading and would require the measurement of the void fraction in addition to that of the wall temperature.

The wall heat transfer model given in equation (20) also relies upon the knowledge of the superheated vapor temperature. To a first approximation, the vapor temperature can be viewed as the result of two competing processes: wall heat transfer adding heat to the vapor, and interfacial heat transfer serving to cool the vapor by transferring heat to the liquid phase. For the sake of simplifying the discussion, we’ll omit the other terms that would appear in an energy balance for the vapor phase and write

$$\frac{4}{D} \cdot \Psi_{2\Phi} \cdot h_{spv} \cdot \left(T_w - T_v\right) \quad \approx \quad h_{vi} \cdot A_i \cdot \left(T_v - T_{sat}\right) \tag{21}$$

Equation (21) then highlights the importance of the vapor-side interfacial heat transfer in determining the superheated vapor temperature. Unfortunately, due to the high liquid loadings in this regime, it is not practical to directly measure the vapor temperature due to thermocouple wetting and hence the interfacial heat transfer rate cannot be determined. Instead, models for the wall convective heat transfer and the vapor-side interfacial heat transfer will have to be developed together to provide a consistent modeling approach. Of course, any information that could be provided on the interfacial area or particle sizes for the ISF regime would significantly aid the model development effort and decrease the reliance on ad hoc assumptions.

To be consistent with the three-field model that will be part of the next major release of TRACE, the vapor-side interfacial heat transfer would be expressed as the sum of the contributions from the inverted slugs and the dispersed droplets. Then,

$$h_{vi} \cdot A_i \quad = \quad \left(h_{vi} \cdot A_i\right)_{IS} + \left(h_{vi} \cdot A_i\right)_{DF} \tag{22}$$

where the subscripts “*IS*” and “*DF*” refer to inverted slug and dispersed flow respectively. This type of formulation would provide a natural transition from the ISFB regime to DFFB as the fraction of the liquid phase treated as slugs would go to zero as the entrainment fraction approached unity. Of course, this places yet another data need on the modeling effort, namely the need to know the entrainment rate (or fraction).

The interfacial friction factor for ISFB[2] can be determined from equation (6) above more

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[2] In a three-field model, the interfacial friction for the droplet field would be handled separately. As the volume fraction of entrained droplets would be miniscule (on the order of 0.005) it is not necessary to consider it in evaluating the interfacial shear for the inverted slugs.

simply than was the case for IAFB because good estimates for the phasic flow rates can be determined from a mass and energy balance. Thus, the sole data requirements are the measurements of the void fraction and pressure drop. For IAFB, it is customary to estimate the void fraction from a delta-P measurement by ignoring the momentum flux and wall shear, that is

$$\left[\alpha\rho_v + (1-\alpha)\rho_l\right]\cdot g\cdot\Delta z \quad \approx \quad \Delta P_{meas} \tag{23}$$

This approach is not acceptable for the ISF regime because the wall shear term is non-negligible. Therefore, an alternative measurement technique for the void fraction must be provided as discussed below.

The wall friction in the ISF regime would be correlated similar to that of the wall-to-vapor heat transfer using a suitable two-phase multiplier. That is, the pressure gradient due to wall-to-vapor drag would be expressed as

$$\left[\frac{dP}{dz}\right]_{frict} \quad = \quad \Phi_v^2\cdot\frac{2}{D_h}\cdot f_v\cdot\frac{G_v^2}{\rho_v} \tag{24}$$

Once again, the sole data requirements are the measurements of the void fraction and pressure drop as a good estimate of the vapor mass flux can be obtained from a mass and energy balance. Note that the temperature of the superheated vapor is needed in order to evaluate both the vapor density that appears explicitly in equation (24), and the viscosity that is implicit in the evaluation of the friction factor due to its Reynolds number dependence. As it is likely impractical to measure the vapor temperature, the value used here must be consistent with that resulting from the wall and interfacial heat transfer relations discussed above.

For the inverted annular flow regime, it is necessary to measure the axial evolution of the void fraction profile due to the wall heat transfer's strong dependence upon the vapor film thickness. These void fraction measurements must be either bundle average values or subchannel average values as point values would give no information on the vapor film thickness nor be suitable for model validation studies. As the frictional pressure drop in IAFB is relatively small compared to the buoyancy force, it is acceptable to infer the void fraction from differential pressure measurements. However, as noted above, the use of delta-Ps to infer void fraction is not acceptable for the inverted slug regime and hence an alternative measurement technique is required.

Traditionally, one would use a gamma densitometer to measure bundle average void fractions. In addition to the high costs associated with such a device, for a rod bundle employing heater rods composed of metal, the gamma source has to be quite strong. This may impose restrictions on the working environment, e.g. shielding, that would render this approach impractical.

The other constraints on the void measurement system are that it be non-intrusive and have a reasonable sampling time. The non-intrusive constraint arises from the desire not to perturb the flow regime for all the downstream locations, e.g. causing additional breakup of the liquid slugs. However, as was the case for traversing fluid thermocouples, an intrusive type probe may be used as long as it can be withdrawn from the test section flow area during a test or, as discussed below, only be used near the end of the heated length. The sampling rate constraint arises from the amount of time that would be required to hold the steady-state film boiling conditions constant to gather the data for one test. For example, if one were using an instrument such as an optical

probe to measure the time-averaged void fraction at one point in a subchannel, and then had to measure a sufficiently large enough number of points to be able to calculate a subchannel average value, it may not be possible to hold constant film boiling conditions long enough for such a measurement.

A possible alternative would be to use an intrusive void measurement system, such as a wire grid [see Manera et al (2009) and Arai et al (2012)], and locate it near the end of the heated length. The ISF experiments would then be conducted so as to expose this measurement station to the full range of conditions for the ISFB region. For example, for a given value of the mass flux, the rod power and inlet subcooling would be adjusted to cause the transition from IAFB to ISFB to occur just upstream of the void measurement station. After a data scan was processed for those conditions, then the inlet subcooling would be reduced in steps causing the ISFB transition point to progress downwards into the test section and exposing the measurement station to progressively higher void fractions and vapor flows. Eventually, the operating point would be reached where the flow regime at the bundle exit transitioned to dispersed flow. The entire range of conditions for ISFB could thus be covered using only one void measurement station. Additionally, the use of such advanced instrumentation might provide data on the interfacial area and geometry of the liquid slugs that would greatly aid model development.

With measurements of the wall temperature, the void fraction, and the pressure drop, a consistent set of model for the wall and interfacial heat transfer, the interfacial friction, and the wall drag could be developed. A limitation would be that the temperature of the superheated vapor calculated using this set of models could not be directly validated due to the impracticality of measuring the vapor temperature in the ISF regime. However, the overall performance of the model, and in particular its accuracy in predicting the rod surface temperature, could be quantified.

To predict the transition from ISF to dispersed flow, the entrainment rate or entrained fraction needs to be known. As was the case with the vapor temperature, it would be practically impossible to measure this in the inverted slug regime as it would require the ability to discriminate between flowing droplets and liquid chunks over a void fraction range of 60-90%. However, using a procedure such as described above to allow measurement of the void fraction at the bundle exit, one should be able to identify the point at which the flow has fully transitioned to dispersed flow. For these conditions then, one would know that the entrained fraction was unity. This would at least allow the development of a model that correctly predicted the point at which full entrainment occurred. Furthermore, for dispersed flow conditions, it would also be possible to measure the vapor superheat and possibly the droplet diameter. Knowing these parameters at the onset of the DFFB regime would then allow for more accurate modeling of that regime which is where the peak clad temperature occurs in a reflood transient.

In summary, the measurement of the wall temperature and pressure drop along the test section, and the void fraction and vapor temperature at the bundle exit, together with an experimental approach such as described above would enable the development of a consistent set of models for the inverted slug regime. These models would then replace the ad hoc interpolation scheme used in TRACE 5.0 and be consistent with the three-field model that will be used in its next major release. Further enhancements to the phenomenological bases of these models would accrue if measurement techniques were available to quantify the interfacial area for inverted slug flow and the droplet diameter at the onset of the dispersed flow regime.

V. Previous Experimental Programs

In the previous Thermal Hydraulic Institute program, there was a task order entitled "Post-CHF Heat Transfer and Hydrodynamics." A brief description of the experiments conducted under the auspices of this task order is given below. This statement of work is designed to build on the progress made during these previous efforts.

V.1. UCLA Vertical Plate Experiment

This experiment was conducted to investigate both the effects of mass flux and liquid subcooling upon the wall heat transfer coefficient in inverted annular film boiling. In addition, a unique feature of this experimental program was an effort to measure the liquid-side interfacial heat transfer rate. It is the effort that will be the focus of the discussion below. This experimental program is documented in Meduri's Ph.D. thesis (Meduri, 2007) and two papers (Meduri et al, 2006 and 2009).

Meduri's subcooled flow film boiling experiments were conducted using water at atmospheric pressure in a vertical flow channel with the heated surface being a vertical flat plate. The flow channel is depicted in Figure 5 and has a rectangular cross-section with one wall (labeled copper block) being heated. The heated surface was a temperature-controlled flat plate, 30.5 cm in height, and 3.175 cm wide. Data were obtained for mass fluxes ranging from 0 to 700 (kg/m^{2}s), inlet subcoolings ranging from 0 to 25 °C and wall superheats ranging from 200 to 400 °C.

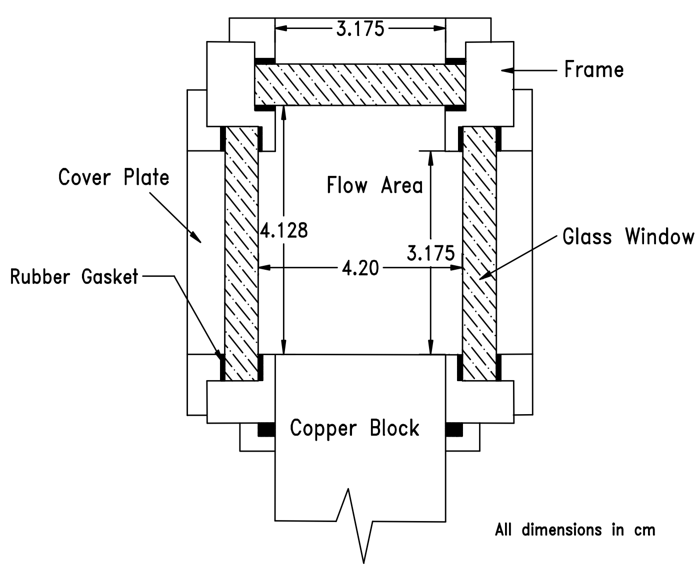


Figure 5: Cross-section of vertical flow channel used in UCLA flat plate experiments.

The unique feature of this experiment was the effort made to measure the liquid-side interfacial heat transfer coefficient. This was accomplished by using traversing micro-

thermocouples (see Figure 6) to measure the liquid temperature profile in the direction normal to the vapor-liquid interface. Some typical results are given in Figure 7 for three different subcoolings with a mass flux of 350 (kg/m^{2}s) and a wall superheat of 270 °C. In this figure, the horizontal line at 100 °C denotes the saturation temperature and hence the approximate location of the vapor-liquid interface.

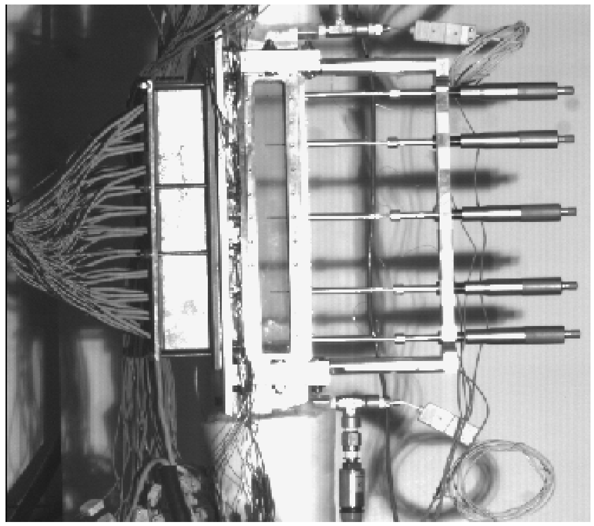


Figure 6: Side view of test section showing traversing micro-thermocouples.

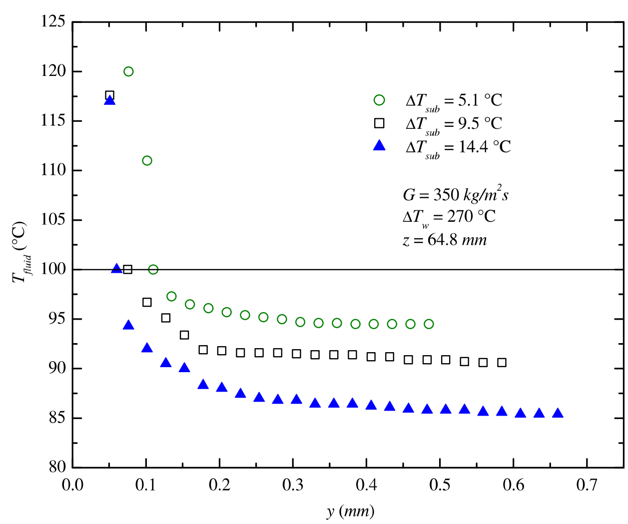


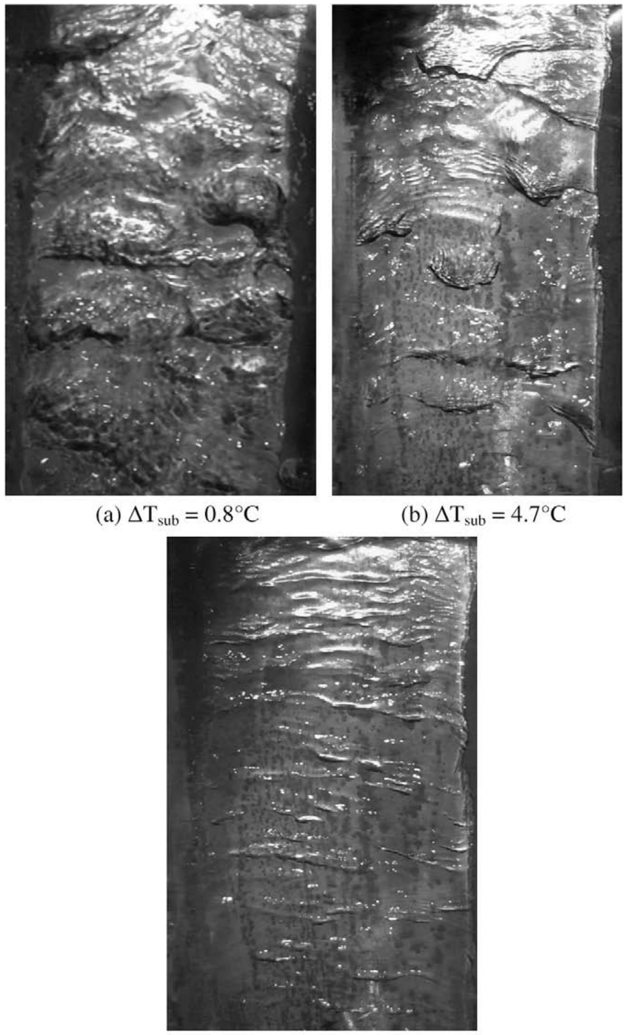
Figure 7: Close-up view of typical time-averaged measurements of the liquid temperature profile near the vapor-liquid interface.

The liquid-side temperature gradient was estimated by calculating the gradient at the

vapor–liquid interface of a smooth profile (cubic polynomial) drawn through the measured liquid temperatures. Liquid-side interfacial heat fluxes were then estimated as

$$q''_{li} \approx k_l \left. \frac{dT_l}{dy} \right|_i \tag{25}$$

There are two questionable aspects of this experimental procedure. The first has to do with the nature of the interface itself as depicted in the photographs of Figure 8. Large interfacial waves would periodically wash over and then uncover the thermocouples obscuring not only the location of the interface but also affecting the time-averaged value of the temperature measurement in a somewhat unpredictable way. Secondly, equation (25) is only valid if the temperature gradient is indeed at the interface and within the laminar sublayer. For example, if the measured temperature gradient extended into the turbulent region, then the molecular thermal conductivity in equation (25) would need to be replaced by the turbulent thermal conductivity. Despite these reservations, the reported values for the liquid-side interfacial heat flux appear very reasonable. Their magnitude ranges from 60-100% of the wall heat flux and has the correct trends (e.g., increasing with liquid subcooling).



(a) $\Delta T_{sub} = 0.8°C$ (b) $\Delta T_{sub} = 4.7°C$

(c) $\Delta T_{sub} = 9.5°C$

Figure 8: Visual observations showing interfacial waves for G = 350 (kg/m^{2}s), ΔTw = 250 °C, and (a) ΔTsub = 0.8 °C, (b) ΔTsub = 4.7 °C, and (c) ΔTsub = 9.5 °C.

Figure 9 gives a sampling of the results for the liquid-side interfacial heat transfer coefficient for a fixed wall superheat and subcooling[3] with mass flux as a parameter. Two surprising observations can be made from this figure. First, although there is a dependence upon the mass flux, it is relatively feeble. Comparing the results for a mass flux of 175 versus those for 750 (kg/m^{2}s), we see that the interfacial heat transfer coefficient only increases by about 30% while the mass flux has increased by a factor of four. This would imply a dependence upon the liquid Reynolds number to only about the 0.2 power instead of about 0.8 as would be expected for turbulent flow. Secondly, there is little apparent entrance length effect upon the interfacial heat transfer coefficient as

[3] Because of the large flow area used in these experiments, the liquid subcooling remained at essentially the inlet value over the entire length of the test section.

well. It should also be noted that the observations for this sampling of the results are also true for the entire set of data.

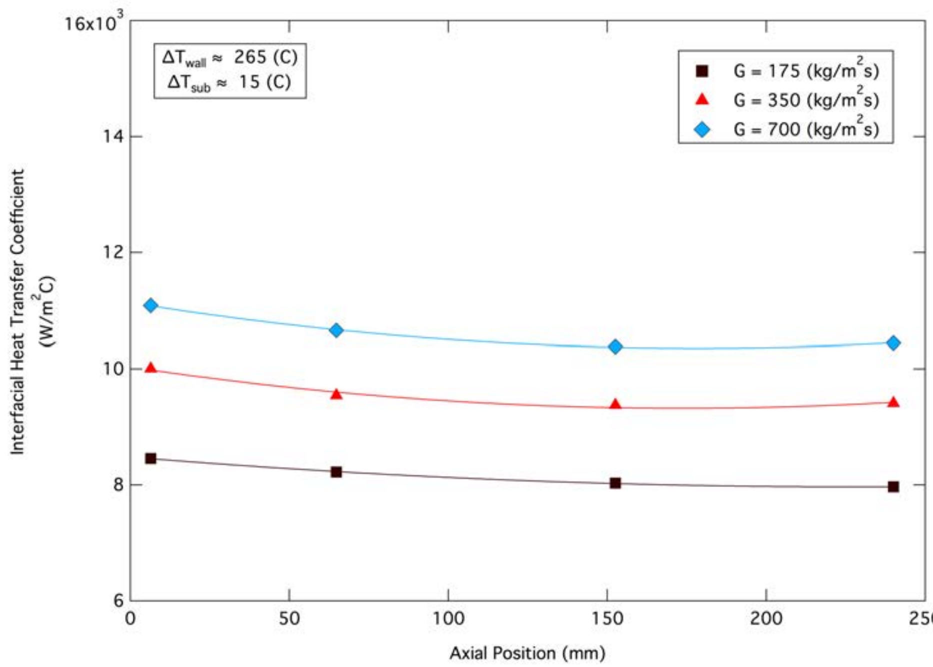


Figure 9: Effect of mass flux on the liquid-side interfacial heat transfer coefficient.

Figure 10 gives a sampling of the results for the liquid-side interfacial heat transfer coefficient for a fixed wall superheat and mass flux with subcooling as a parameter. Once again, a very surprising feature is noted. Namely the large increase in the magnitude of the interfacial heat transfer coefficient as the subcooling is reduced. This behavior would appear to be related to the changes in the structure of the vapor-liquid interface as depicted in Figure 8. Basically, when the liquid is significantly subcooled (see Figure 8c), the vapor film is thin, the vapor flow rate is low, and the surface is relatively smooth. As the subcooling decreases, see Figure 8b & c) the vapor flow increases, the vapor film thickens and large waves develop on the interface. I is supposed that the resultant surface oscillations promote mixing in the liquid core thereby enhancing the interfacial heat transfer.

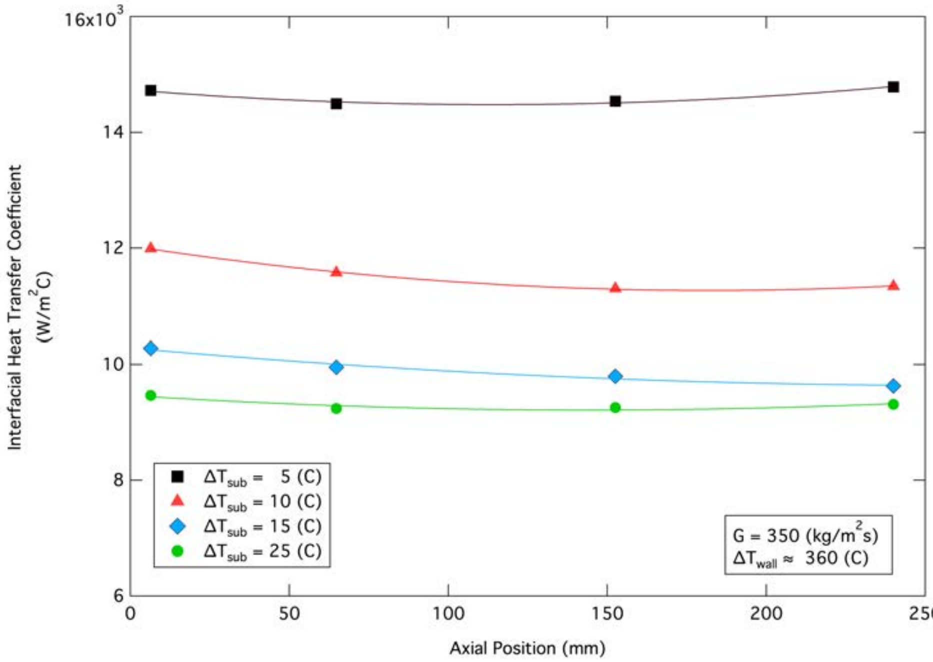


Figure 10: Effect of subcooling on the liquid-side interfacial heat transfer coefficient.

Figure 11 plots all of the liquid-side interfacial heat transfer coefficients that were inferred from the UCLA vertical plate experiment versus liquid subcooling with mass flux as a parameter. As noted above, there is a dependence upon mass flux, however, it is overshadowed by the subcooling effect. One other feature of the subcooling effect evident in Figure 11, see the data for a mass flux of 350 (kg/m^{2}s), is that it dies out for subcoolings greater than about 15 °C. Determining the dependence of the liquid-side interfacial heat transfer coefficient upon mass flux and its apparent dependence upon subcooling for IAFB in a rod bundle geometry will be a focus of this new task order.

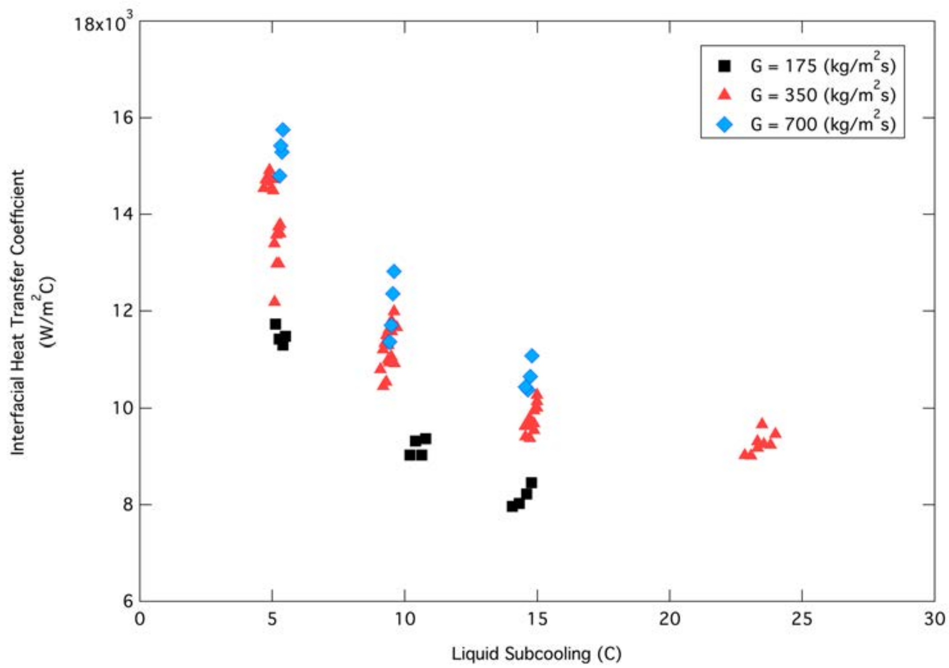


Figure 11: Inferred values of the liquid-side interfacial heat transfer coefficient versus subcooling with mass flux as a parameter.

Despite the interesting results presented above, there are several non-prototypical features of their experiment, as compared to the reflooding of a rod bundle, that prevent its direct use in the development of a model for TRACE. Specifically:

1. In this experiment, due to the large flow area (relative to the heated perimeter), the liquid temperature was essentially isothermal rather than increasing in the direction of the flow. Consequently, the liquid-side heat transfer and hence the vapor generation rate would stay approximately constant along the heated surface. Whereas in the real situation, the liquid subcooling decreases in the axial direction leading to a rapid rise in the evaporation rate and breakup of the liquid column.
2. The heater surface was a small rectangular plate located on the side of a pool. Consequently the liquid column was confined on three sides by walls rather than being surrounded by a vapor film. Thus, the liquid configuration would be relatively stable compared to the real case where a freestanding column of liquid would be subject to large-scale oscillations in addition to the surface perturbations observed here.
3. In this flat plate experiment, there is no vapor generation upstream of the leading edge, whereas during reflood there is violent boiling at the quench front thereby providing an initial source of vapor to the film and also perturbing the film. In contrast, for this experiment, the film is initially smooth and only develops ripples and large waves some distance downstream as the vapor flow rate increases. This contrasting behavior was recently noted by UCLA while performing steady state film boiling tests using a "hot patch" to freeze the quench front (see section V.2 below).

4. Due to the configuration of the vertical channel used in this experiment, it is not obvious what characteristic length should be used when converting the measured interfacial heat transfer coefficient into a Nusselt number for correlation purposes. For example:
   a. Hydraulic diameter: if the entire wetted perimeter is used to calculate this characteristic dimension, is value is 3.93 cm.
   b. Heated diameter: if only the heated perimeter is used, the resulting characteristic dimension has a value of 20.61 cm.
   c. Thickness: if the thickness of the liquid core is considered to correspond to the radius of the liquid core, then the characteristic dimension is 8.26 cm.

To address the above deficiencies caused by the non-prototypical geometry, this task order was modified to include a task on post-CHF heat transfer in a rod bundle geometry as discussed below.

V.2. UCLA Single-Rod Tests

The UCLA single-rod tests were not an experimental program unto themselves. Rather this was a subtask of the rod bundle experiment described in the next section. The purpose of these tests was to determine the requirements for effective operation of a "hot patch" integrated into a heater rod so that it could be used in the rod bundle tests.

The hot patch technique is to supply enough separate power to a short section just ahead of the test section to reach CHF, thereby preventing the rewetting front from advancing. This technique allows steady-state subcooled flow film boiling experiments to be run without running the entire test section at high power. It was first used in freon experiments by Groeneveld (1974). Later, to increase the power of the hot patch so that water could be used as the coolant, Groeneveld & Gardiner (1978) used a thick copper cylinder equipped with a number of cartridge heaters as depicted in Figure 12a for an indirectly heated hot patch applied to a tubular test section.

To allow operation at higher hot patch powers but avoid some of the problems other experimenters had experienced with contact losses between the copper blocks and the test section, Chen & Li (1984) developed a directly heated hot patch technique. As shown schematically in Figure 12b, the tubular test section included relatively short grooves where the wall thickness was reduced locally, so that a heat flux peak could be created due to the higher electric resistance. For the groove at the entrance of the test section, a separate power supply was provided so that the advancement of the quench front could be arrested at that location. A second groove at the top of the test section prevented the top-down progression of a quench front from the unheated region above the test section. In addition to avoiding contact problems between the hot patch and the test section, this directly heated method also controlled the location of the quench front more precisely due to its shorter length.

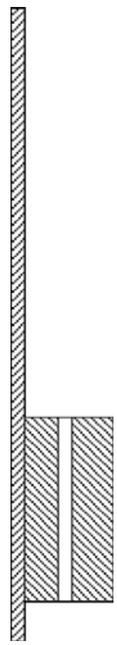


Figure 12: Schematic diagram of test sections equipped with (a) indirectly, and (b) directly heated hot patches.

Figure 13 (Chen 2011) illustrates the efficacy of the hot patch technique in providing steady-state subcooled film boiling conditions. Comparing Figure 13 (a) and (b), we see a similar effect of subcooling upon the vapor-liquid interface as that depicted above in Figure 8. The third image in Figure 13 shows the advancement of the quench front into the test section when the hot patch is turned off. As stated above, although such transient data could be used for model development, it is difficult to quantify the heat release at the quench front and hence the inlet conditions for the film boiling region.

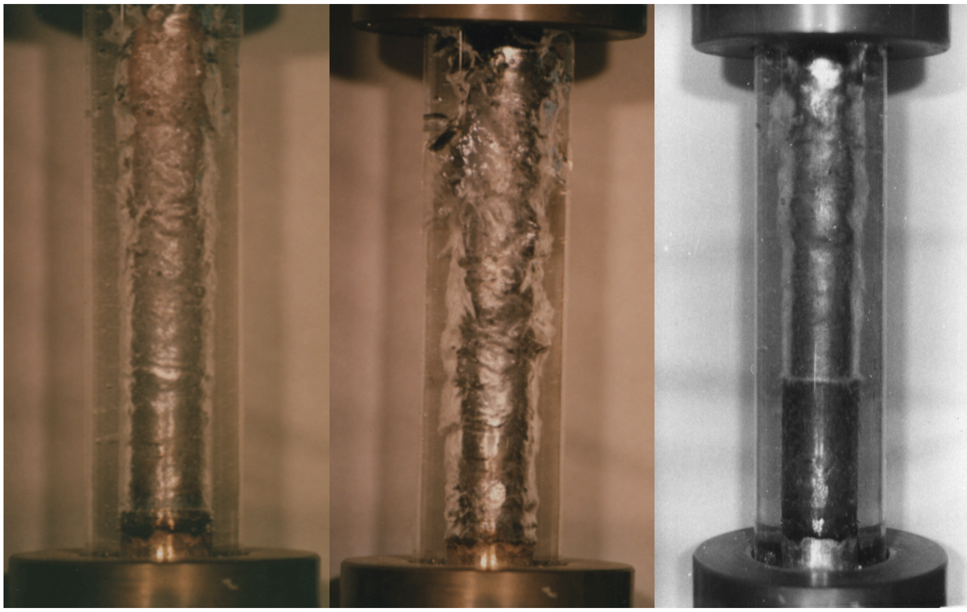
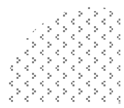

(a) (b) (c)

Figure 13: Inverted annular film boiling in an annulus with water flowing upwards: (a) and (b) Stable regime with the hot patch on, $T_{l,a} < T_{l,b}$, and (c) Reflood transient with the hot patch off.

Although the hot patch technique has been used very successfully for tubular test sections, the challenge for this task order was the design of a hot patch that could effectively stabilize the quench front at the test section inlet for a rod bundle. UCLA solved this problem with the rod design depicted in Figure 14 and Figure 15 below. The heat source for the film boiling region was a directly heated tube (either stainless steel or zircaloy) while the hot patch power was supplied by a cartridge heater embedded within the rod. In the film boiling region, the interior of the rod was filled by an aluminum silicate (lava) rod to add thermal inertia to help stabilize temperatures and to provide for positioning the wall thermocouples against the inner surface of the tube wall. At the location of the hot patch, the cartridge heater was enclosed in a cylinder of boron nitride both to electrically insulate the heater from the tube wall and to provide a high conductivity material to transfer the heat to the tube wall. Also, note the provision of two thermocouples at the location of the hot patch to provide temperature control for the cartridge heater power and to determine the axial position of the frozen quench front.



(a) (b)

Figure 14: Cross-section of heater rod assembly: (a) with hot patch, and (b) without hot patch.

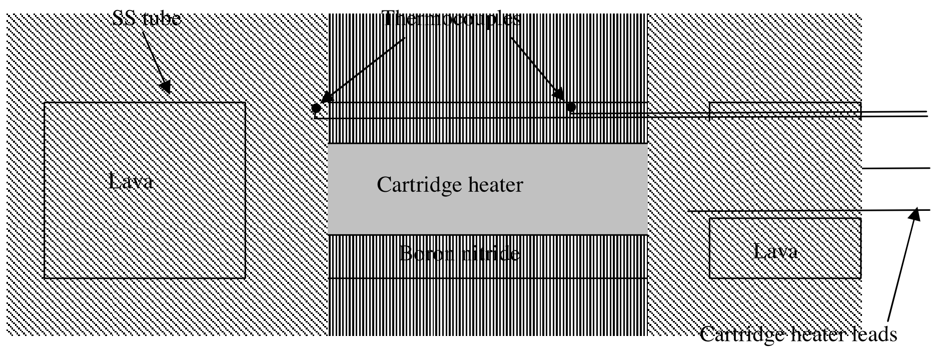


Figure 15: Cross-sectional view of hot patch showing location of cartridge heater.

To stabilize the quench front in a test section cooled by water requires a very high hot patch power. For example, a typical tubular test section (with an ID = 12 mm, and heated length of 80 cm) required the use of 8 cartridge heaters each with a power rating of 250 W to freeze the quench front for a test at atmospheric pressure, a mass flux of 500 (kg/m^{2}s), and an inlet subcooling of only 20 °C. The required hot patch temperature was over 500 °C and the hot patch power was about 30% of the entire power applied to the test section. These power requirements, together with the objective of keeping the length of the hot patch as short as possible to better locate the quench front, ruled out the use of water as the coolant for the proposed rod bundle film boiling tests.

For these reasons and others discussed in the next section, it was decided to use a simulant fluid, specifically Fluorinert FC-72 (also referred to as PF-5060) due to its low latent heat and low boiling point. As a result, the hot patch power was only a few percent of the test section power while the wall superheat required to stabilize the quench front was only about 150 °C. For example, typical values for the wall heat flux in the film boiling region were about 6-7 (W/cm^2) with an additional 2-4 (W/cm^2) applied at the hot patch that was only 2.54 cm in length. In contrast, for a water-cooled experiment at the same flow conditions, the film boiling heat flux would be about 20-30 (W/cm^2) with an additional 60-70 (W/cm^2) required for the hot patch.

Figure 16 gives a schematic of the single-rod test section while Figure 17 is a photograph of it fully instrumented and installed in the flow loop. The heater rod described above had an outside diameter of 1.11 cm and a heated length of 71 cm. The rod was inserted concentrically within a glass tube having an ID of 1.59 cm, creating an annular flow channel with a gap width of 2.4 mm. This geometry provides a hydraulic diameter, based on the heated perimeter, of 1.168 cm that is equal to that of the RBHT rod bundle used in the reflood experiments conducted for the NRC by Penn State.

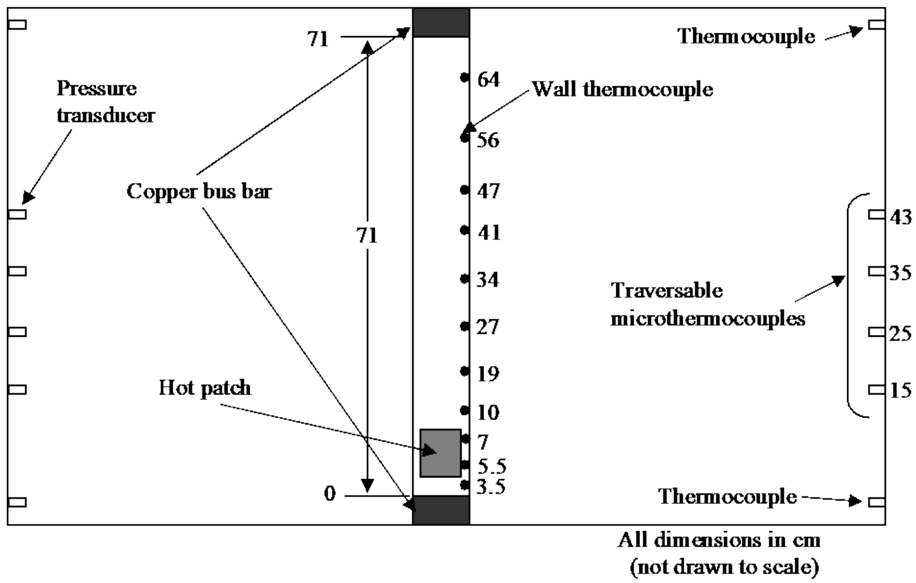


Figure 16: Schematic of the UCLA single-rod test section.

Despite the purpose of the single-rod tests being the shakedown of the heater rod and hot patch design, the test section was instrumented in a manner similar to that planned for the follow-up rod bundle tests. A total of 11 wall thermocouples were installed along the heated length together with 6 fluid thermocouples (for liquid-core subcooling) and 6 pressure taps (to measure differential pressure from which the void fraction can be inferred). The data from these single-rod tests would then form a useful baseline for the data from the rod bundle tests helping to quantify differences due to the geometry.

The traversing micro-thermocouples were intended to serve a dual purpose. First, to measure the bulk temperature of the liquid core so that the liquid-side interfacial heat transfer coefficient could be inferred using the procedure described in Section III and given by equation (17). Secondly, to attempt to measure the radial liquid temperature profiles as was done in the UCLA vertical plate film boiling tests described in Section V.1 above. These attempts were not very successful due primarily to the fact that while traversing, most of the micro-thermocouples made contact with the heater rod and were consequently destroyed. Hence, no liquid temperature profiles were reported.

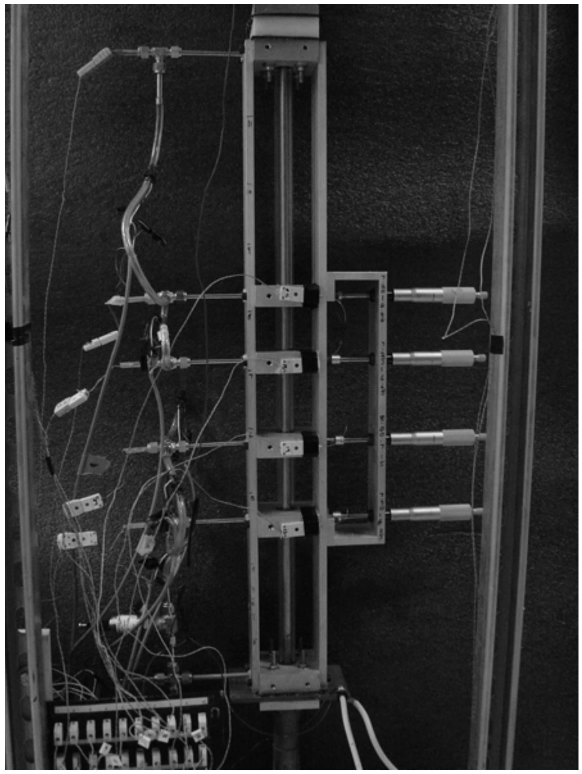


Figure 17: Photograph of the UCLA single-rod test section.

A series of 20 subcooled film boiling experiments were successfully conducted in the single-rod test facility to confirm the operation of the hot patch design and determine its operating requirements for the planned rod bundle tests. The test matrix is given in Table 1 below. The hot patch performed well in all of these tests and the design was approved for use in the follow-on rod bundle tests. The results of these tests, with respect to wall heat transfer, were reported in Yi et al (2009). An example of the test results for wall heat transfer is given below in Figure 18.

Table 1: Experimental conditions for UCLA single-rod tests.

Run	G	V	Superheat	Inlet subcooling	Pressure	q - rod	q - cartridge
	(kg/m^2 s)	(m/s)	(°C)	(°C)	(bar)	(W/cm^2)	(W/cm^2)
1	235	0.14	269	24.8	1.18	6.5	2.3
2	318	0.19	256	18.9	1.11	6.1	2.7
3	492	0.3	254	15.3	1.04	6.1	2.4
4	410	0.25	219	23.6	1.08	5.5	3.9
5	470	0.29	261	23.5	1.07	6.5	2.8
6	513	0.31	308	23.6	1.05	7.7	2.0
7	768	0.47	212	14	1.03	5.4	3.3
8	811	0.5	260	13.6	1.03	6.8	2.3
9	812	0.5	286	13.5	1.03	7.7	1.8
10	632	0.39	283	22	1.16	7.4	2.6
11	578	0.36	230	21	1.15	6.1	3.5
12	567	0.34	273	26.8	1.16	7.1	2.7
13	604	0.37	296	26.8	1.16	7.8	2.1
14	296	0.18	224	20.2	1.15	5.4	3.3
15	260	0.16	298	19.9	1.11	7.3	1.2
16	493	0.3	228	18.5	1.12	5.6	2.7
17	519	0.32	303	18.7	1.10	7.7	1.0
18	574	0.35	280	22	1.06	6.9	2.2
19	516	0.31	212	20.8	1.04	5.2	4.2
20	227	0.14	211	21.4	1.04	4.7	2.9

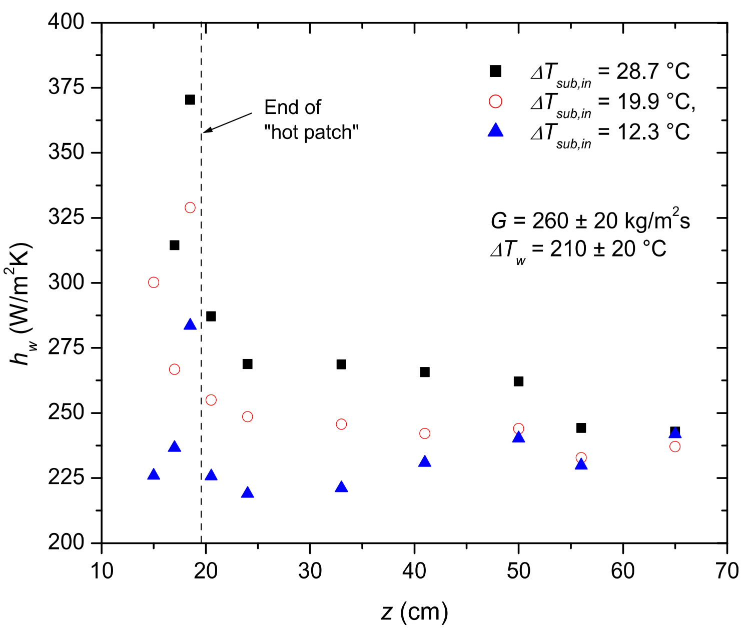


Figure 18: Effect of inlet subcooling on wall heat transfer coefficient.

Although these tests were successful for the most part in looking at the wall heat transfer, they were not particularly successful in quantifying the liquid-side interfacial

heat transfer. First, as noted above, the technique of measuring the radial liquid temperature profile did not work for these tests. Also, there was a problem with the bulk liquid temperature measurements recorded for two of the six fluid thermocouples as illustrated in Figure 19 where there appears to be an almost linear axial profile for the bulk liquid temperature from the inlet to the exit. However, the readings for the two thermocouples at 35 and 43 cm display a non-monotonic behavior that would be unphysical. The results depicted in this figure are typical of those for all 20 of the tests, consequently, it was concluded that these two thermocouples systematically read low temperatures. As the single-rod tests were only a proof-of-principle for the hot patch design, the reasons for these low readings were never uncovered nor corrected.

Figure 19: Axial profile of the bulk liquid temperature for Trial #4 of the UCLA single-rod tests.

In an undergoing model development effort, due to the aforementioned problems with the fluid thermocouples, it was necessary to disqualify data from these two points. Recalling that the hot patch is located between 5 and 7.5 cm, and that the exit thermocouple (located at 71 cm) may not be in IAFB, the only data span for the liquid temperature differential that may be considered valid for the evaluation of the liquid-side interfacial heat transfer is that between 15 and 25 cm.

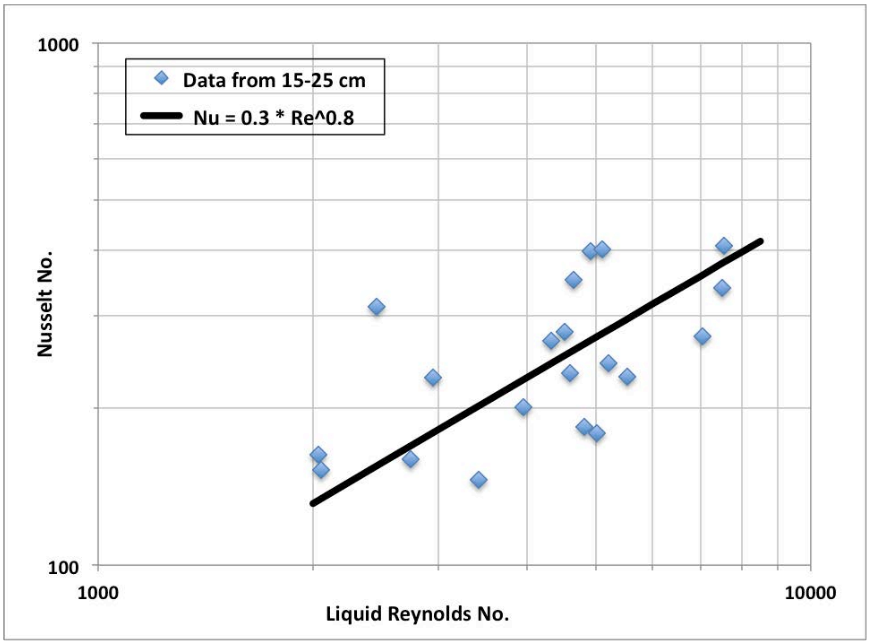


Figure 20: Values for the liquid-side interfacial heat transfer coefficient inferred from the data from the fluid thermocouples at 15 and 25 cm in the UCLA single-rod tests.

Figure 20 plots the Nusselt number for liquid-side interfacial heat transfer against the Reynolds number for the liquid core for all 20 of these tests using only the data from the fluid thermocouples at 15 and 25 cm. There is substantial scatter for these inferred values, which is not unusual for tests concerned with interfacial heat transfer. Some of this scatter is probably due to the effect of subcooling that was noted above for the UCLA vertical flat plate tests. The solid line plotted in this figure seems to indicate that the Nusselt number for liquid-side interfacial heat transfer has a dependence upon the liquid Reynolds number to approximately the 0.8 power corresponding to that expected for turbulent flow. This is in stark contrast to the results reported above for the vertical plate tests that indicated a dependence only to about the 0.2 power. Therefore, resolving the magnitude of the liquid-side interfacial heat transfer, its dependence upon liquid mass flux, and perhaps on subcooling, remains a critical data need for the improvement of the TRACE model for IAFB.

V.3. UCLA Rod Bundle Experiment

Upon the successful demonstration of the hot patch design in the single-rod experiments, the go-ahead was given for the rod bundle experiment described below. Unfortunately, the rod bundle film boiling experiment was not concluded successfully before the end of the Thermal Hydraulic Institute contract. Most of the problems encountered have to do with the home-built nature of the heater rods. In particular, the rod bundle facility experienced:

- In the initial attempt to establish film boiling conditions in the test section, one heater rod burned out. As a result, all testing was halted and the rod bundle was removed from the test loop and disassembled. Upon inspection of the damaged rod, it was found that the outer Zr-4 tube was intact and that only the cartridge

heater had burned out. However, the rod design[4] does not allow for the replacement of the cartridge heater and a new rod had to be fabricated.

- During the second attempt to run steady-state film boiling tests, film boiling conditions were successfully established on all 9 rods. However, after a few minutes of running two more of the cartridge heaters used in the bottom hot patch burned out despite being operated at only about 25% of their rated power of 250 W. This again necessitated replacement of the rods and, as no spares were available, new rods had to be fabricated.
- During preliminary testing of the reassembled rod bundle, it was found that almost all of the thermocouples in the bundle gave erratic readings once the DC power to the heater rod sheaths was turned on. The thermocouples used to measure wall temperature in the heater rods lie in a groove machined in the lava rock insert and are held in place using high temperature epoxy. Some of these thermocouples were apparently not adequately electrically insulated from the rod sheath, which is a thin-walled tube with DC Joule direct heating. Consequently, these “bad” thermocouples picked up some voltage and affected the readings of the other thermocouples. Identifying which thermocouples were bad and disassembling and repairing the heater rods caused another delay.

Despite the above problems, based on the successful operation of the single-rod tests, UCLA expressed confidence that the approach would work for a rod bundle. However, it was suggested that a better power control system for the hot patches be used. Specifically, an automated power control system using the readings from the thermocouples at the hot patch location should be used rather than the manual adjustments used for the current test rig.

As briefly discussed above, a simulant working fluid with low latent heat and boiling temperature was selected for these experiments. The particular working fluid chosen was Fluorinert FC-72, which was the only fluid with the desired heat transfer properties that also met the environmental restrictions in California. The reasons for choosing the use of a simulant working fluid for the rod bundle tests were partially discussed above; a more complete listing is given below:

- The wall temperatures in the film boiling region for FC-72 are on the order of 250-350 °C versus 700-1000 °C for water.
    - This allows the use of a small rod bundle (such as a 4x4) without significant distortions due to radiation heat transfer.
    - Heat losses from the bundle are small due to the reduced operating temperatures, again very important in allowing the use of a small rod bundle.
    - Lower operating temperatures allow for the use of transparent test section walls enabling visual observation and possibly optical instrumentation.
    - Problems caused by thermal expansion of the rods and sealing of the rod penetrations are minimized.
- The hot patch power required to stabilize the quench front is a factor of 10-20 times smaller than that for water.

[4] The copper bus bars are shrink fit onto the ends of the Zr-4 heater tubes and so cannot be opened up for replacement of the cartridge heater.

- This greatly simplifies the design of the hot patch allowing for its use in a rod bundle where the heat source must be embedded within the rods.
- It allowed a relatively short hot patch (2.54 cm) to be used providing for better localization of the quench front. Even shorter hot patches could be realized if smaller cartridge heaters were available or a different rod design used[5].
- For FC-72, the hot patch power required was only a few percent of that for the film boiling region whereas for water it can be as high as 40%. This greatly reduces the uncertainty associated with the fluid state at the beginning of the film boiling region and allows testing with larger subcoolings in the IAFB region.
- The reduced hot patch power requirements provide a greater flexibility in extending the mass flux and inlet subcooling range.

- The different fluid properties of a simulant working fluid allow for high-pressure conditions to be simulated in a bundle operating at low pressure. Thus the data would serve to complement that of the RBHT facility (max operating pressure of about 4 bar) and better simulate the blowdown rewet conditions of the LOFT experiments.

For the above reasons, a simulant working fluid was chosen for the UCLA rod bundle film boiling experiment and is recommended for the proposed future experimental program. The remainder of this section describes the UCLA rod bundle.

The heater rod design for each of the nine rods in the bundle was similar to that of the single-rod heater used in the hot patch tests. A schematic is given in Figure 21 and the main characteristics were:

(a) Total length = 74.6 cm.

(b) The material of the outer DC Joule heated tube is Zircalloy-4.

(c) The wall thickness of the Zr-4 tubes is 0.2 mm.

(d) Two “hot patches” were incorporated into the heater. One close to the bottom and the other at the top to prevent top down quenching.

(e) Number of wall thermocouples in each rod is 11. The axial location of the thermocouples is given in Table 2.

[5] In the Rod Bundle Heat Transfer (RBHT) test facility operated for the NRC by Penn State, the heater rods were manufactured by Stearn Laboratories and have proved to be very robust. These rods are indirectly heated employing a thin-walled tube within the rod as the resistance element; an axially varying heat flux profile was provided by varying the thickness of this tube. As a heat flux spike of only about 50% is needed to freeze the quench front for a fluid such as FC-72, a notched type of hot patch could be employed. However, the probable need to provide power control for the hot patch would complicate this design.

Table 2: Axial location of wall thermocouples.

Thermocouple	Location (cm)
1	3.8
2	5.7
3	7.6
4	12.7
5	20.3
6	27.9
7	35.6
8	43.2
9	50.8
10	62.2
11	71.1

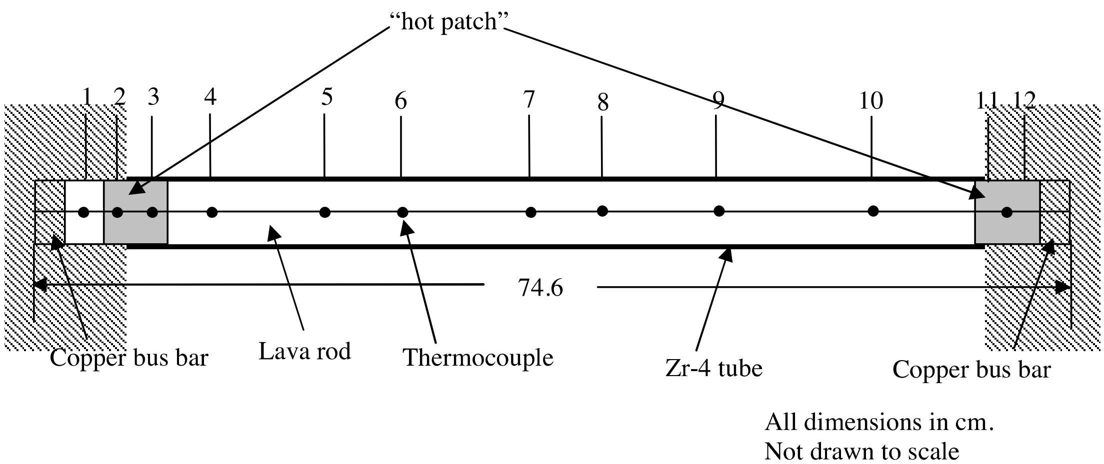


Figure 21: Details of heater rod design.

The nine rods were arranged in a 3x3 square array as shown below in Figure 22. The 3x3 array has a pitch of 1.5 cm and is installed in a square housing with an inner dimension of 4.5 cm. The resulting hydraulic diameter, based on heated perimeter, is therefore 1.471 cm for all three subchannel types (normal, edge, and corner) present in the bundle. Constraining the ratio of the flow area to heated perimeter to be the same for all subchannels results in the bundle average void fraction and the void fraction in the individual channels being approximately the same for inverted annular flow.

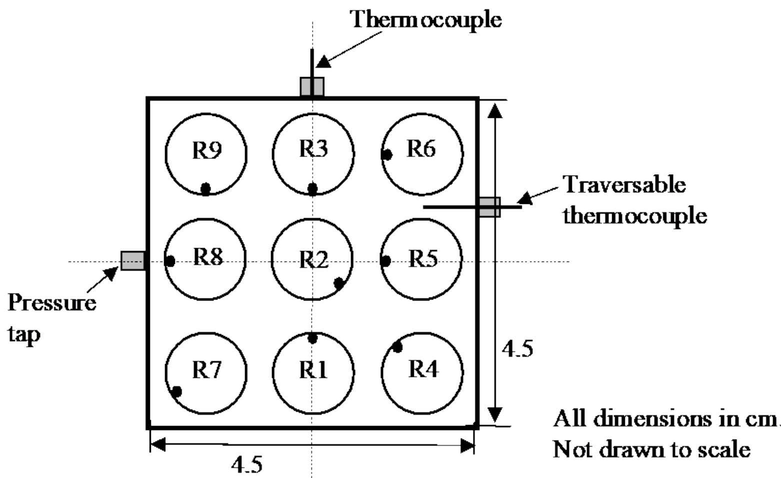


Figure 22: Cross-section of 9-rod bundle.

The schematic of the complete test section is shown in Figure 23. The test section is made from aluminum (0.64 cm thick) and is provided with glass windows (0.64 cm thick) on all four sides for visual observation. The glass windows are present along the entire length of the test section. Pressure and liquid temperatures were measured at six axial locations along the test section (inlet, z = 14.0 cm, z = 30.5 cm, z = 47.0 cm, z = 63.5 cm, and outlet). In addition, traversable micro-thermocouples, to measure the fluid temperature at the centroids of interior subchannels, are also provided at four axial locations as shown in Figure 23: (z = 14.0 cm, z = 30.5 cm, z = 47.0 cm, z = 63.5 cm). One key feature of the traversable micro-thermocouples is that they can be completely withdrawn from the test section. This allows for liquid temperatures to be measured at a lower elevation and then the thermocouple withdrawn so that temperatures further downstream can be measured without flow perturbations.

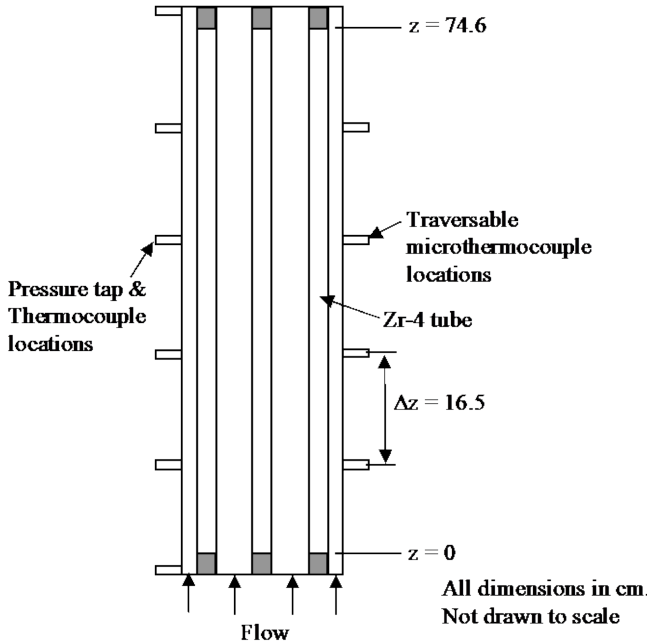


Figure 23: Schematic of the 9-rod bundle test section.

As stated above, despite the failure of this experimental program to be completed before the end of the previous Thermal Hydraulic Institute contract, significant enough progress was made to warrant a follow-up experimental program. To improve the chances of success, any follow-up program should:

- Use professionally manufactured heater rods (if possible) to avoid the difficulties that were encountered in the UCLA program using “home-built” rods.
- Use a suitably designed automatic power control system for the hot patch power based on feedback from the hot patch thermocouples rather than manual adjustments.
- Make adequate provisions for spare heater rods so that long delays do not ensue if a rod fails and needs replacement.

This completes the description of the UCLA rod bundle post-CHF heat transfer experiment.

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Attachment #2: Hot Patch Design Study

Objective

The objective of this study is to determine the feasibility of performing low-quality steady-state film boiling experiments for a directly heated tube using water as the coolant. In addition, this study aims to provide guidance as to a possible design for the “hot patch” that will be used to stabilize the quench front for steady-state film boiling tests at high pressure and flow conditions.

Background

The constitutive models for two post-CHF flow regimes have been identified as high priority items for improvement involving near-term experimental programs: inverted annular film boiling (IAFB) and inverted slug film boiling (ISFB). For both of these regimes, there is a critical need for accurate void fraction measurements over a wide range of flow conditions. To facilitate both the needed void fraction measurements and the subsequent model development activity, it would be preferable to conduct steady-state experiments. To do so requires a means of “freezing” the quench front and that is the subject of this study.

The operating principle of the hot patch technique is to supply enough separate power to a short section just ahead of the test section to reach CHF, thereby preventing the rewetting front from advancing. This technique allows steady-state subcooled flow film boiling experiments to be run without running the entire test section at high power and was first used in Freon experiments by Groeneveld (1974). Later, to increase the power of the hot patch so that water could be used as the coolant, Groeneveld & Gardiner (1978) used a thick copper cylinder equipped with a number of cartridge heaters as depicted in Figure 1a for an indirectly heated hot patch applied to a tubular test section.

To allow operation at higher hot patch powers but avoid some of the problems other experimenters had experienced with contact losses due to cracking of the braze between the copper blocks and the test section, Chen & Li (1984) developed a directly heated hot patch technique for experiments conducted by the Chinese Institute for Atomic Energy (CIAE). As shown schematically in Figure 1b, the tubular test section included relatively short grooves where the wall thickness was reduced locally so that a heat flux peak could be created due to the higher electric resistance. For the groove at the entrance of the test section, a separate power supply was provided so that the advancement of the quench front could be arrested at that location. A second groove at the top of the test section prevented the top-down progression of a quench front from the unheated region above the test section[1]. In addition to avoiding contact problems between the hot patch and the test section, this directly heated method also controlled the location of the quench front more precisely due to its shorter length and resulted in fewer distortions of the film boiling region just downstream of the quench front.

[1] In one paper (Chen et al, 1988), it was found necessary to also independently power the top hot patch to prevent top-down quenching at high flow conditions.

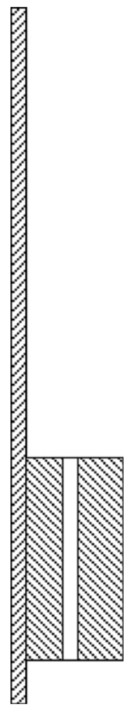


Figure 1: Schematic diagram of test sections equipped with (a) indirectly, and (b) directly heated hot patches.

Figure 2 (Chen 2011) illustrates the efficacy of the hot patch technique in providing steady-state subcooled film boiling conditions for inlet conditions with both high subcooling (Figure 2a) and low subcooling (Figure 2b). The third image in Figure 2 shows the advancement of the quench front into the test section when the hot patch is turned off. Although such transient data could be used for model development, it is difficult to quantify the heat release at the quench front and hence the inlet conditions for the film boiling region.

Through a series of experimental programs, this directly heated hot patch technique was steadily improved until Chen et al (1989) were able to conduct steady-state film boiling experiments at pressures up to 60 bar. Specifically, the range of test conditions covered was:

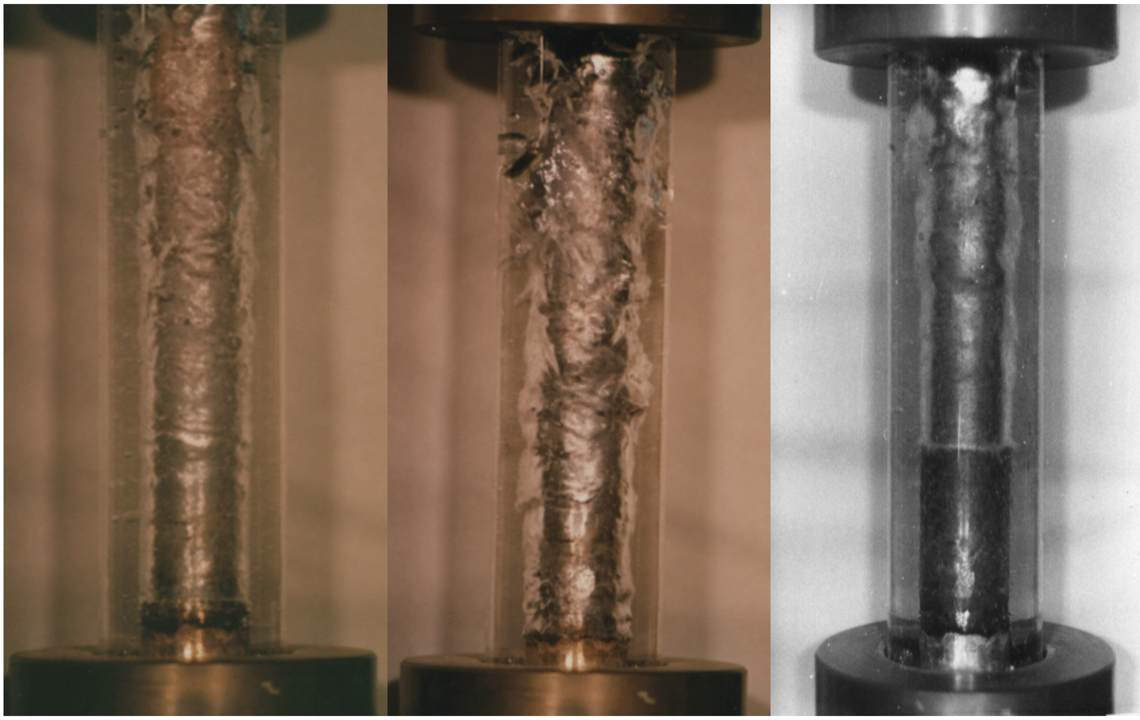
Pressure: 4.1 – 60 (bar)

Mass Flux: 48 – 1462 (kg/m^2s)

Inlet Quality[2]: -0.05 – 0.24

[2] Refers to the equilibrium quality at the dryout point, assumed to be located at the top of the bottom "hot notch".

Heat Flux: 28 – 260 (kW/m^2)



(a) (b) (c)

Figure 2: Inverted annular film boiling in an annulus with water flowing upwards: (a) and (b) Stable regime with the hot patch on, $T_{l,a} < T_{l,b}$, and (c) Reflood transient with the hot patch off.

For these high-pressure tests, the test section was made of Inconel-600 tubing with a 12 mm ID and 15 mm OD as shown in Figure 3 below. The film boiling length (section BC) was 2.2 m, and the length of the bottom hot patch (section AB) varied from 25 mm to 50 mm in order to study the effect of the upstream heating condition. Both sections were direct heated using AC power supplies with the terminals located at points A, B, and C as shown in the figure. These power terminals were made from stainless steel sheets that were argon welded onto the tube and had a thickness of 1.5 mm.

The small notches, machined just upstream of the power terminals at points B and C, are 0.7 mm in depth, 1 to 2 mm in length, and cause higher electrical resistances creating heat flux peaks to stabilize the quench front. After establishment of the film boiling regime, the quench front was maintained just 1 to 2 mm upstream of point B and the flow was very stable. In this experimental campaign, Chen et al (1989) conducted a total of 151 successful test runs and noted that “no trouble was encountered at the highest pressure.” This successful operation was observed despite the reduced tube wall thickness at the notch being only 0.8 mm thick.

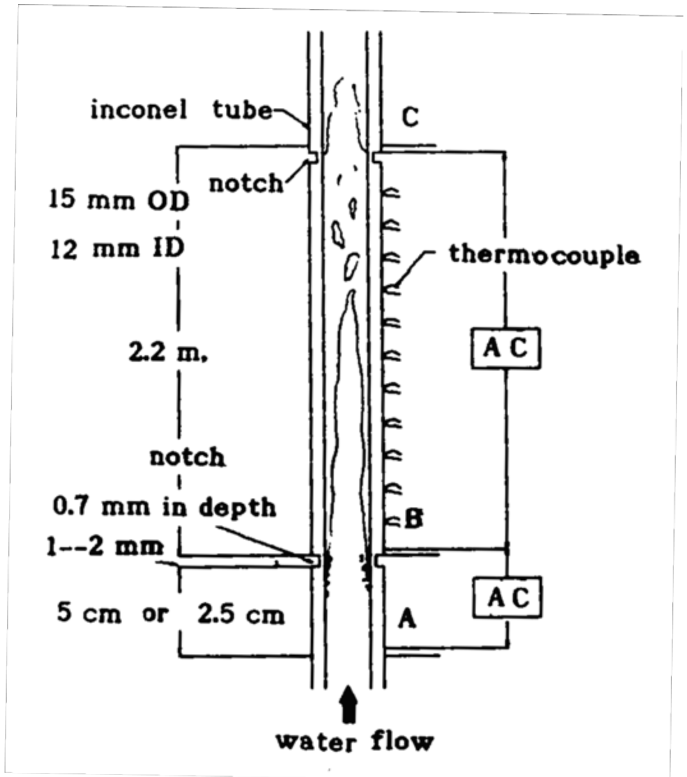


Figure 3: Schematic of test section with directly heated hot patch (Chen et al, 1989).

Steady-state low-quality film boiling experiments were also conducted at Winfrith in the UK. For their first three series of tests an indirectly heated hot patch of the type pioneered by Groeneveld was used. This technique appeared to work reasonably well at low-pressure conditions, however, as detailed by Swinnerton et al (1988) the braze connecting the copper hot patch to the test section developed circumferential cracks at high-pressure conditions. The contact resistance attributed to these cracks resulted in ever-increasing hot patch power requirements in order to stabilize the quench front thereby greatly limited the effective operating range and preventing reproducibility of their data.

Consequently, for the last two series of film boiling tests, Winfrith switched to a directly heated "hot notch" type of hot patch as developed by Chen et al for the CIAE and described above. In their Series 4 tests (Savage et al, 1992) the film boiling length was 0.92 m, while the addition of sapphire viewing ports at 0.79 m above the hot patch reduced the effective film boiling length to 0.71 m for the Series 5 tests (Savage et al, 1993). For both series the test section was comprised of Inconel-600 tubing with a 9.42 mm ID and a 12.68 mm OD. Three stainless steel discs were welded onto the tube at the positions shown in Figure 4. Independent AC power supplies were connected between the lower and middle disc, and between the upper and middle disc, which enabled the heat flux to the two regions of the tube to be separately controlled. Both the middle and upper discs were 1.6 mm thick, while the lower disc was 3.2 mm thick. The distance between the top of the lower disc and the bottom of the middle disc was 25 mm.

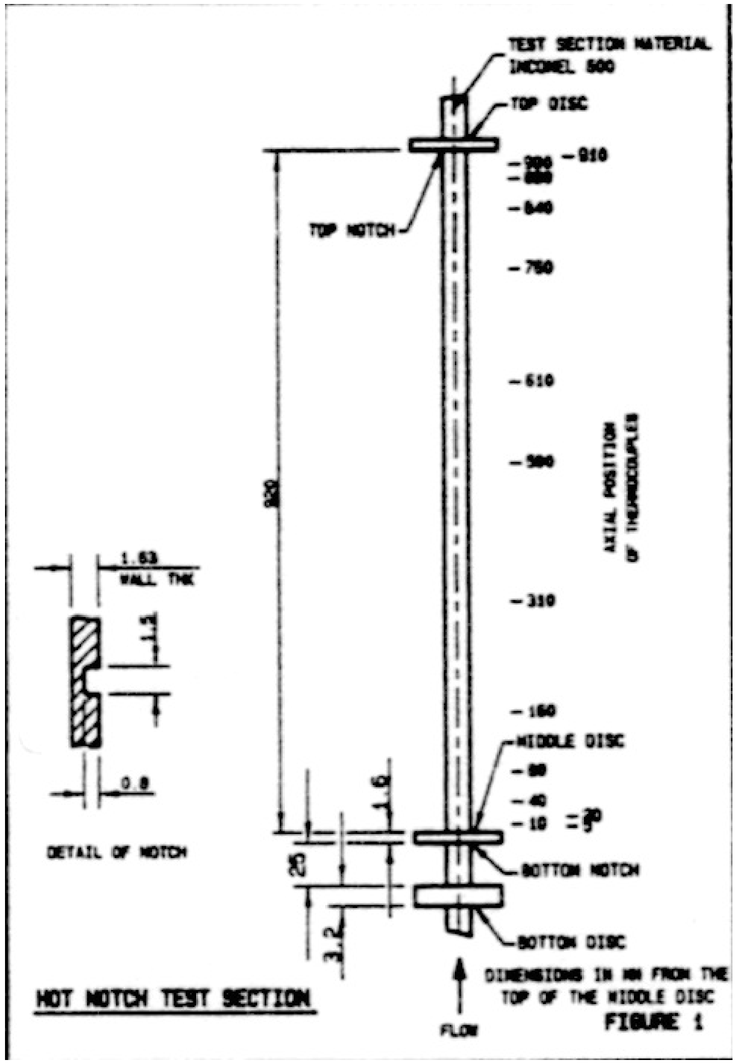


Figure 4: Schematic of the Winfrith Series 4 Test Section (Savage et al, 1992).

Small circumferential notches were machined in the outer wall of the tube immediately below the middle and upper discs. These notches provided the high resistance, high heat flux regions needed to stabilize the quench front and were denoted as "hot notches." These notches were similar in design to those used in the CIAE tests, having a depth of 0.8 mm and a length of 1.5 mm. The surface temperature of the notches was measured using bare wire precision welded thermocouples and was used to control the lower hot patch power.

Using this directly heated hot notch design, Winfrith was able to successfully conduct steady-state film boiling tests for:

Pressure:	5 – 70 (bar)
Mass Flux:	100 – 1000 (kg/m^{2}s)
Inlet Subcooling:	18 – 50 (^{o}C)

Savage et al (1993) commented that “the hot notch test section operated well over a range of conditions, but has a short working life of less than 40 hours.” Unfortunately, no details were given as to what limited the working life of the test section and so it is not known if the limiting factor was related to the reduced tube wall thickness of only 0.83 mm or to the sapphire windows. Nevertheless, while both CIAE and Winfrith were able to safely conduct high-pressure film boiling tests, at 60 and 70 bar respectively, the development of a more robust test section design is one of the goals of this design study.

Test Section Design

For this study, the directly heated hot patch technique was adopted. The reasons for this deign choice were:

- The problems that Winfrith experienced with cracking of the braze between the copper hot patch and the Inconel test section when using the indirectly heated technique (Swinnerton et al, 1988).
- Better localization of the quench front with the notch-type hot patch that has a length of a few millimeters as opposed to the large copper block type that has a length of 25 to 100 mm.
- Less distortion at the entry to the film boiling region and allowance of measurements closer to the dryout point.

In both the CIAE and Winfrith experiments Inconel-600 tubing was used for the test section due both to its mechanical strength at high temperature and its relatively temperature independent electrical resistivity. For both of these reasons, and its ready commercial availability in a number of standard sizes, Inconel-600 was selected as the test section material here as well.

A number of other design criteria need to be considered as well. Specifically:

- The test section inside diameter should be in the range of the hydraulic diameter for modern BWR and PWR fuel assemblies,
- The tubing OD and wall thickness should correspond to that of commercially available Inconel-600 tubing,
- The wall thickness should be maximized to provide strength for high-temperature high-pressure conditions,
- The notch length should be as short as possible to better localize the quench front and minimize the distortion at the entry to the film boiling region,
- The notch depth should be as deep as possible to provide the necessary heat flux spike to stabilize the quench front but should not compromise the mechanical strength of the test section,
- The notch temperature should be as low as possible,
- The operating range for the hot patch power should be as large as possible to facilitate power control, and
- The pre-heater section, that is the separately powered region that contains the hot notch (see section AB of Figure 3), should be as short as possible so that the subcooling at the quench front is not too different from that of the inlet.

Through a consideration of these criteria and by performing a number of sensitivity studies, a workable directly heated hot patch design was obtained that should also be

more robust than that used in the CIAE and Winfrith experiments. This design will be described here and used as the base case for the sensitivity studies presented below.

A number of candidate off-the-shelf Inconel-600 tube sizes were considered based on a tubing selection guide from the Eagle Stainless Tube & Fabrication of Franklin, MA. The selected tube OD was 0.75" (19.05 mm) and the wall thickness was 0.12" (3.048 mm). This gives an inside diameter of 12.95 mm that satisfies the criterion of being in the range of hydraulic diameter for modern fuel assemblies as shown in the table below.

Reactor Type	Vendor	Assembly Type	Pitch (mm)	Rod OD (mm)	D_h (mm)
BWR	GE	8x8 Barrier	16.26	12.27	15.17
BWR	GE	8x8 GE-4a	16.26	12.52	14.37
BWR	Areva	9x9 JP 3-5	14.52	10.76	14.19
BWR	Areva	9x9 1X, 9X	14.45	10.95	13.33
PWR	Westinghouse	17x17 Vantage 5	12.6	9.14	12.98
PWR	RBHT	17x17	12.6	9.50	11.78

The wall thickness of the selected tubing is 3.048 mm that is nearly double that used in the CIAE (1.5 mm) and Winfrith (1.63 mm) experiments. The selection of a thicker walled tube was made to increase the robustness of the test section, especially for operation at high-pressure conditions. However, the thicker tube wall allows for more axial conduction at the quench front where the axial temperature profile is the steepest. To counteract the effect of this increase in axial conduction required changes to the notch geometry as described below.

First, let's introduce two design parameters that will affect the operability and robustness of the test section: 1) the ratio of the tube cross-sectional area to that of the notch, and 2) the hoop stress geometry factor. To stabilize the quench front, a local spike in the linear heat generation rate is introduced by machining a notch in the tube wall thereby decreasing the wall thickness and increasing the electrical resistivity and hence the heat generation rate. It is important to realize that this applied linear heat rate does not exceed the CHF value, were it to do so the test section would experience "burn out", perhaps literally. Rather this local heat generation spike needs to be just large enough to counteract the axial conduction from the notch to the wetted region below it.

For a directly heated tube, the linear heat generation rate is given by

$$q' = I^2 \cdot \frac{\rho}{A}$$

where

I : current (A)

ρ : electrical resistivity (Ω·m)

A : cross-sectional area (m^2)

The electrical resistivity is a property of the material and is temperature dependent. However, Inconel-600 was selected in part due to its relatively low temperature dependence and so in the ensuing discussion the resistivity will be treated as a constant. Also, as the current is constant for the hot patch region, that includes both the notch and a pre-heater section (see section AB of Figure 3), the ratio of the linear heat generation rate for the notch relative to that of the pre-heater is simply

$$\frac{q'_N}{q'_{PH}} = \frac{A}{A_N} = \frac{\left(D_O{}^2 - D_I^2\right)}{\left(\left(D_O - 2\cdot\delta_N\right)^2 - D_I^2\right)}$$

where

A_N : cross-sectional area for the notch region

D_O : tube outside diameter

D_I : tube inside diameter

δ_N : notch depth

For the hot patch geometries used by CIAE and Winfrith, this parameter has the values: 1.98 and 2.12 respectively. So, it seems like a successful design might need to have a value of about 2 for this area ratio. With the tubing geometry selected above (i.e., OD = 19.05 & ID = 12.95 mm), this would imply that a notch depth of about 1.4 mm would be needed.

The other design parameter concerns the hoop stress than would occur at the notched part of the tube. Assuming that the thin-walled tube assumption can be used, the hoop stress would be given by

$$\sigma \approx \Delta P\cdot\left(\frac{D_I}{2\delta}\right)$$

where δ is the tube wall thickness at the notch. Thus, to compare the ratio of the hoop stress at the same pressure conditions, one can compare the geometry factor given by the tube ID divided by twice the wall thickness. For the test sections used by CIAE and Winfrith, this hoop stress geometry parameter has the values: 7.5 and 5.67 respectively. So, to produce a more robust design, this geometry factor should have a value less than about 5. As discussed below, a notch depth of 1.5 mm was selected as the base case for this design study resulting in a hoop stress geometry factor of 4.18 and so satisfies this criterion. In addition, the much greater wall thickness at the notch, 1.55 mm for our base design versus 0.8 and 0.83 mm for the CIAE and Winfrith designs respectively, will provide more resistance to other mechanical stresses that may arise during fabrication, installation and operation.

Along with the above two design parameters, both the hot patch operating range and notch maximum temperature were used as criteria to select the notch length and depth. The hot patch operating range was defined as the difference between the minimum and maximum values of the hot patch power for which the quench front can be stabilized. At hot patch powers lower than the operating range, the test section will quench no matter that the applied heat flux is greater than the minimum film boiling point. Conversely, for hot patch powers higher than the operating range, the tube will dryout as the quench front recedes into the pre-heater section. The maximum notch temperature is simply that, the maximum value for the material temperature in the notch region and is important due to its effect on the mechanical strength of the region where the highest stresses will occur.

From the sensitivity studies described below, it was determined that the most significant factor affecting the hot patch operating range is the notch length. Indeed, for our base design conditions, the operating range increased from a value of only 14 (W) for a notch length of 2 mm to a value of 172 (W) for a notch length of 4 mm. Likewise, the notch power necessary to stabilize the quench front decreased from 1221 (W) to 860 (W) as the notch length increased from 2 to 4 mm. However, as the notch length increased more of the notch region was exposed to film boiling and so a small increase in its maximum temperature was observed. This together with the desire to keep the notch as short as possible to better localize the quench front led to the selection of 3 mm for the notch length corresponding to an operating range of 115 (W).

The notch depth exhibited the same trends on operating range, hot patch power and maximum notch temperature, as did the notch length. Specifically, the operating range increased from a value of 67 (W) for a notch depth of 1.4 mm to a value of 153 (W) for a depth of 1.6 mm. Also, though the hot patch power requirements decrease with notch depth, the resulting increases in the notch heat generation rate result in somewhat higher temperatures. Most importantly, to keep the hoop stress geometry factor as low as possible yet maximize the operating range, an intermediate value of 1.5 mm was selected for the notch depth.

The last design parameter to be determined is the length of the hot patch region itself, that is, the distance between the top of the bottom electrode and bottom of the middle electrode. For both the CIAE and Winfrith test sections this length had a minimum value of 25 mm. It is supposed that this value may be constrained by either the necessary mechanical connections for the power cables to the electrodes, or by fabrication limitations (e.g., clearance space needed to weld the electrodes to the tubing). Regardless of the controlling factor, a spacing of 25 mm should be achievable, as it has already been done. To maintain the subcooling at the inlet to the film boiling region as close to the inlet subcooling as possible, the length of this pre-heater section should be minimized. Consequently, a value of 25 mm has been selected for this length. This completes the description of the geometry selected for this design study; the following section describes the methodology used to calculate the hot patch performance.

Methodology

A thermal analysis was performed to determine the hot patch power and temperature requirements necessary to stabilize the quench front using the COMSOL Multiphysics finite element analysis code. No attempt was made to solve the two-phase flow equations; rather a steady-state equilibrium quality calculation was combined with the

wall temperature to specify an appropriate boiling curve as described below. In addition, a PID controller (Proportional-Integral-Derivative) was used to determine the hot patch power necessary to keep the notch temperature at a specified set point.

Boiling Curve

A complete boiling curve from single-phase liquid forced convection through film boiling was specified as a function of:

- Pressure
- Mass flux
- Wall superheat
- Local equilibrium quality

In doing so, an effort has been made to keep the wall heat transfer models as consistent as possible with those of the TRACE code. The notable exception to this is the film boiling heat transfer coefficient that would require a full two-fluid flow solution to implement the TRACE post-CHF constitutive model package.

Liquid single-phase forced convection is calculated using the Gnielinski (1976) correlation as given by

$$Nu_{FC} = \frac{(f/2)(\mathrm{Re}-1000)\cdot \mathrm{Pr}}{1+12.7\cdot (f/2)^{\frac{1}{2}}\left(\mathrm{Pr}^{\frac{2}{3}}-1\right)}$$

where the friction factor is evaluated using the smooth tube formula of Filonenko (1954),

$$f = \left[1.58\cdot \ln(\mathrm{Re})-3.28\right]^{-2}$$

and the local value of the liquid subcooling is determined from the equilibrium quality.

For nucleate boiling, the pool boiling correlation of Gorenflo (1993) was used. The pool boiling model of Gorenflo uses a reference point formulation and is given by

$$h_{PB} = h_0\cdot F_P\cdot \left(q''/q''_0\right)^n\cdot \left(R_P/R_{P0}\right)^{0.133}$$

where, for water,

$$h_0 = 5600 \quad (\mathrm{W/m^2-C})$$

$$q''_0 = 20{,}000 \quad (\mathrm{W/m^2})$$

$$F_P = 1.73\cdot P_r^{0.27} + \left(6.1+\frac{0.68}{1-P_r}\right)\cdot P_r^2$$

$$n = 0.9-0.3\cdot P_r^{0.15}$$

with P_r being the reduced pressure,

$$P_r = \frac{P}{P_{crit}}$$

and the surface roughness having the reference value

$$R_{P0} = 0.4 \quad (\mu\mathrm{m})$$

For boiling surfaces that have not been characterized, it is recommended that the roughness be taken to be 0.4 μm, so that the surface roughness term is unity and this is the approach used in TRACE and in this design study.

For the pre-CHF regime, the wall heat transfer coefficient is then taken to be the maximum of the values for forced convection and nucleate boiling as

$$h = \max\left[h_{FC},\ h_{PB}\cdot\left(\Delta T_{sat}/\Delta T_{liq}\right)\right]$$

In the above formula, it was necessary to convert the pool boiling heat transfer coefficient from a wall superheat reference, namely

$$\Delta T_{sat} = T_{wall} - T_{sat}$$

to one relative to the wall-to-liquid temperature difference

$$\Delta T_{liq} = T_{wall} - T_{liq}$$

The wall-to-liquid temperature difference will be used as the driving potential for all of the wall heat transfer coefficients in this model. This pre-CHF heat transfer coefficient will be used for all points where the wall temperature is less than the CHF point.

The point where the maximum heat flux occurs will be denoted as the CHF point, $\left(q''_{CHF}, T_{CHF}\right)$, and is characterized by both the critical heat flux and the wall temperature at which it occurs. This is the point where the heat transfer regime transitions from that where the liquid phase wets the wall (i.e., nucleate boiling), to the post-CHF regimes where liquid-wall contact is either transient (transition boiling) or non-existent (film boiling).

In TRACE, the role of the CHF model is two-fold:

1) Determine the transition point for the heat transfer regime, and
2) Serve as the anchor point for the transition boiling wall heat flux.

To accomplish this dual objective, the 1995 AECL-IPPE CHF look-up table (Groeneveld et al, 1996) was selected for TRACE and is used in this model. The AECL-IPPE CHF table is based upon an extensive database of CHF values obtained in tubes for a vertical upward flow of a steam–water mixture. While the database covers a wide range of flow conditions, the look-up table was designed to provide CHF values for tubes at discrete values of pressure, mass flux, and dryout quality. Three-dimensional linear interpolation is used to determine the CHF for conditions between tabulated values.

The wall temperature, T_{CHF}, at which CHF occurs is found by solving the equation

$$q''_{PB}\left(\Delta T_{CHF}\right) = q''_{CHF}\left(P, G, x_{eq}\right)$$

using the pool boiling model of Gorenflo. The other anchor point for the boiling curve is the minimum film boiling point that corresponds to the minimum heat flux condition and defines the switch from the transition boiling to the film boiling regime. The Groeneveld-Stewart model (Stewart & Groeneveld, 1981) for the minimum film boiling temperature, T_{min}, is used in TRACE and in this model.

The Groeneveld-Stewart correlation for saturated water (or positive quality conditions) is given by

$$T_{min,sat} = 557.85 + 44.1 \cdot P - 3.72 \cdot P^2$$

for pressures less than 9 MPa where $T_{min,sat}$ is in °K and P is in MPa. In their database, both the effects of mass flux and quality (for positive values) were deemed negligible.
A significant effect of subcooling was observed and was correlated by

$$T_{min} = T_{min,sat} - \frac{x_{eq} \cdot 10^4}{(2.82 + 1.22 \cdot P)}$$

where x_{eq} is the subcooled quality. The resulting values for T_{min} are shown below in Figure 5 as a function of pressure and subcooling.

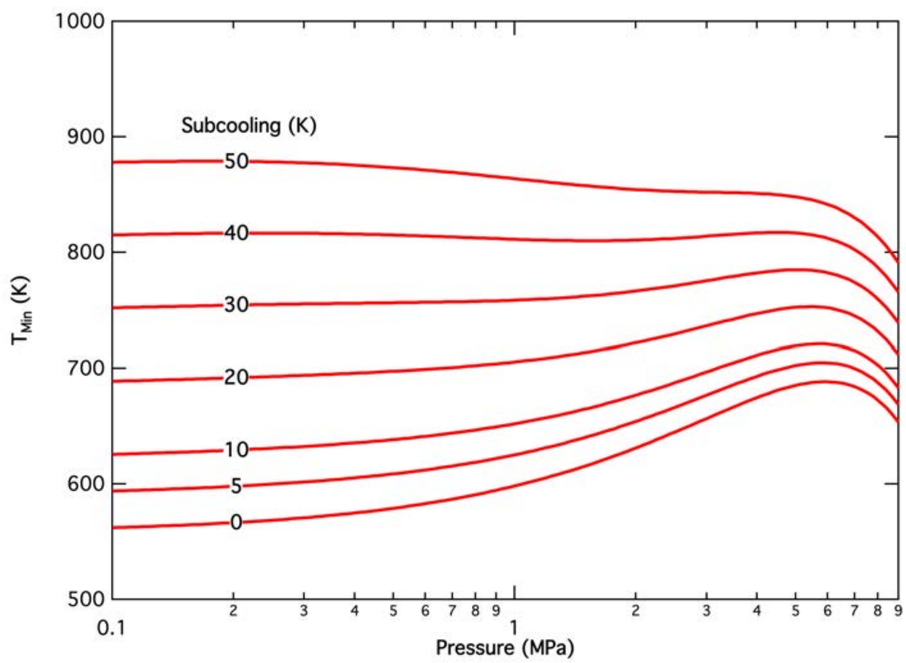


Figure 5: Values for the minimum film boiling temperature of Groeneveld & Stewart as a function of pressure and subcooling.

To complete the specification of the minimum film boiling (MFB) point, the heat flux is calculated from

$$q''_{min} = h_{FB}\left(P, G, x_{eq}, \Delta T_{min}\right) \cdot \left(T_{min} - T_{sat}\right)$$

where the film boiling heat transfer coefficient is a function of pressure, mass flux, quality, and wall superheat. As noted above, to use the post-CHF heat transfer models of TRACE would require the solution of a full two-fluid model and so is impractical for this application. Instead, the film boiling look-up table of Groeneveld et al (2003) was used in this design study.

In this look-up-table, the film boiling heat transfer coefficient is given as a four-dimensional table, however COMSOL-MP only has the capability of performing interpolation for three-dimensional tables. To resolve this, separate 3D tables were generated for each pressure level and imported into the corresponding COMSOL model. An example of the minimum film boiling heat flux calculated using this approach is given below in Figure 6. This value for the minimum film boiling heat flux provides a lower limit for the test section wall heat flux if steady-state film boiling conditions are to be maintained. The film boiling LUT will be used to evaluate the heat transfer coefficient whenever the wall temperature exceeds T_{min}.

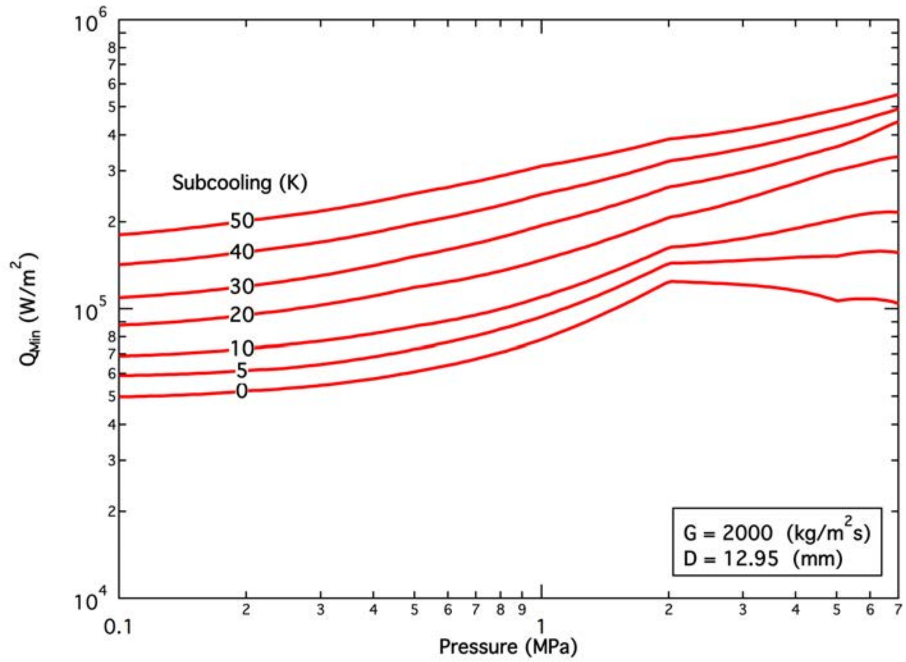


Figure 6: Minimum film boiling heat flux as a function of pressure and subcooling for a mass flux of 2000 (kg/m^{2}s) calculated using the film boiling look-up-table.

Between the CHF and the MFB points, the transition boiling regime provides the transition between the "wet wall" heat transfer of the nucleate boiling regime and the "dry wall" heat transfer of the film boiling regime. The wall heat flux in the transition boiling regime is calculated using the TRACE interpolation scheme as

$$q''_{TB} = f_{wet} \cdot q''_{CHF} + \left(1 - f_{wet}\right) \cdot q''_{min}$$

where

$$f_{wet} = \left(\frac{T_w - T_{CHF}}{T_{min} - T_{CHF}} \right)^2$$

An example of boiling curves calculated during COMSOL simulations using the above models is given in Figure 7. Note that these boiling curves are functions of the local equilibrium quality that varies along the test section during the calculation and so the local subcooling is not fixed. This dependency is responsible for the small bump that

occurs in the film boiling region for the 150 (kg/m^{2}s) curve due to the quality change at the "hot notch".

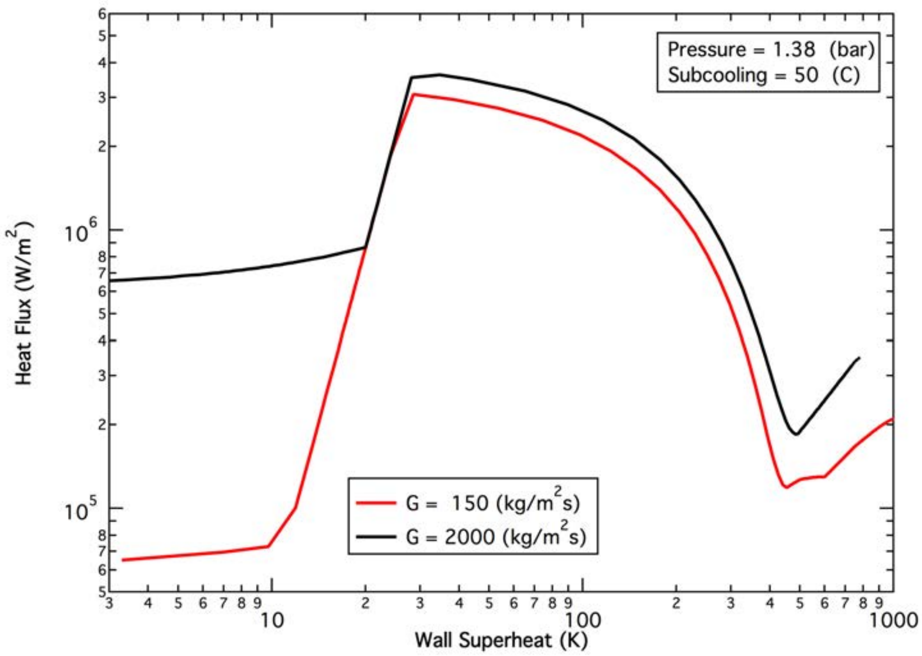


Figure 7: Example of boiling curves calculated during hot patch simulation calculations at a pressure of 1.38 bar (20 psia).

This completes the description of the models used to calculate the boiling curve for this hot patch design study. The next section describes the PID controller that was used to control the hot patch power in order to match the notch temperature to a specified set point value.

Temperature Controller

Because of the non-linearity intrinsic to the boiling curve, it is impossible to do a direct steady-state calculation, so a transient simulation is required for this hot patch simulation study. Also, it is impossible to know a priori the correct power level for the bottom hot patch necessary to stabilize the quench front for the selected flow conditions (pressure, mass flux and subcooling). Consequently, to automatically find the correct hot patch power level during these transient simulations, a proportional-integral-derivative (PID) controller was implemented.

For these simulation studies, the hot patch power refers to the power applied across the bottom set of power terminals, which is section AB of Figure 3. The objective is to control the hot patch power so that the quench front is stabilized but without inducing unnecessarily high temperatures in the high-powered notch region. As noted above, the average wall heat flux for the notch region is about double that of the hot patch region as a whole and so proper power control is necessary to prevent overheating and possible failure. The PID control algorithm used to calculate the hot patch power, P_{HP}, is

$$P_{HP} \;=\; k_P \cdot \left(T_{set} - T_N\right) + k_I \cdot \int_0^t \left(T_{set} - T_N\right) \cdot dt + k_D \cdot \frac{\partial}{\partial t}\left(T_{set} - T_N\right)$$

where

k_P, k_I, k_D	:	control parameters for proportional, integral and derivative
t	:	time (s)
T_N	:	notch temperature (°K), measured on outside surface at midpoint
T_{set}	:	set point for notch temperature (°K)

In practice, the derivative constant, k_D, was set to zero as the appropriate value for this parameter can be difficult to determine and the derivative term may increase the fluctuations in the system because it tends to amplify noise in the error $T_{set} - T_N$.

Reasonable values for the proportional and integral control parameters were determined through trial and error to be:

$$k_P \;=\; 5 \quad \left(W/K\right)$$
$$k_I \;=\; 10 \quad \left(W/K \cdot s\right)$$

with a notch set point temperature of 800 °K.

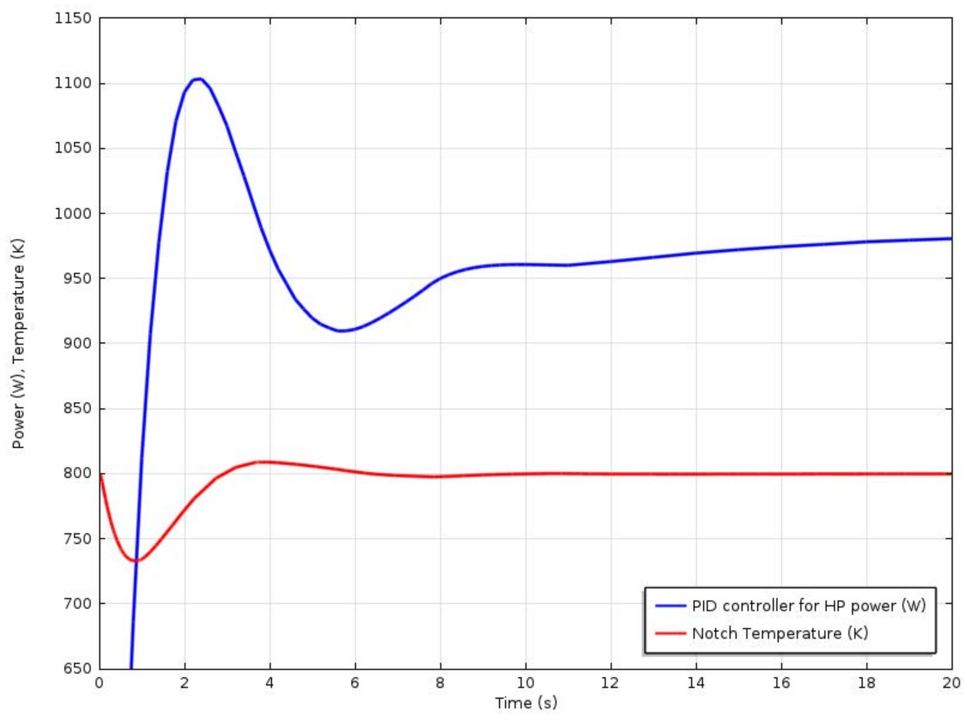


Figure 8: Close-up of PID controller results for base case simulation.

An example of the efficacy of this temperature-power controller is given in Figure 8 that shows a close-up of both the controlled hot patch power and the resulting notch temperature versus time for the first 20 seconds of the transient. Initially the hot patch power was set to zero and rose almost linearly to a value of 1100 W in 2.4 seconds before converging to its final value of 999.1 W. The notch temperature was initialized at its set point value of 800 °K and fell to a minimum of 734 °K. The maximum notch mid-point temperature encountered during this simulation was only 808.5 °K.

Initial & Boundary Conditions

For the transient hot patch simulation studies described below both initial and boundary conditions must be specified. The initial conditions are simply an axial temperature profile for the following three regions:

Test Section	:	1000 (°K)
Hot Notch	:	800 (°K)
Pre-Heater	:	inlet temperature

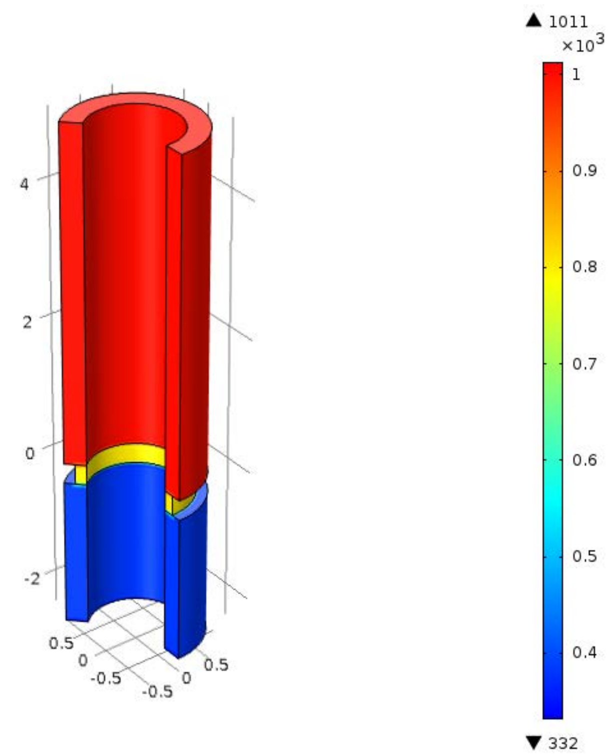


Figure 9: Initial temperature distribution for hot patch simulation studies.

The bottom hot patch is composed of two regions: the “hot notch” itself, and a pre-heater section. The entire notch region is initialized to the notch set point temperature while the pre-heater region is set to the fluid inlet temperature. This allows for the quench front to initially form at the bottom of the notch and greatly facilitates the transient. Otherwise, if the temperature of the pre-heater region was in the film boiling regime, the quench front would form at the inlet and a reflood transient would ensue as it progresses upwards to

its final position just below the notch. In practice, this reflood transient is what would be expected to occur during an actual experiment.

The test section is the powered region between the bottom notch and the top notch. For purposes of these simulations, only the first five centimeters of the test section was modeled to reduce computational times. For steady-state film boiling tests with water as a coolant it is necessary to initialize the test section temperature significantly above the minimum film boiling temperature to prevent its quenching at the onset of the transient. This is true both for the numerical simulations described here and for the actual experiments as the power required to initiate dryout would be excessive and might lead to material damage due to over-heating of the notch. Here the initial test section temperature is simply set to a constant value of 1000 K.

Boundary conditions include both those for the fluid and the heat transfer solutions. For the fluid, the mass flux, subcooling and pressure are specified in order to determine the axial profile of the equilibrium quality and the wall heat transfer coefficient including both the CHF and MFB points. For the tube wall, the outer surface is considered to be perfectly insulated, as is the upper boundary. In practice both the insulating material and the heat losses would need to be modeled. At the bottom boundary of the tube wall, the temperature is held at the value of the fluid inlet. Again, for a true pre-test calculation, it would be necessary to model some portion of the unheated section below the pre-heater region.

The power applied to the test section is set to a value corresponding to the desired heat flux operating condition and held constant. As noted above, this value needs to be at least somewhat above the minimum film boiling heat flux in order to prevent spontaneous quenching of the test section. The maximum heat flux value is primarily limited by test section temperature considerations though it can also adversely affect the ability of the PID controller to stabilize the quench front. The hot patch power, that includes both the notch and pre-heater regions, is controlled as described above to keep the notch mid-point temperature at its set point value.

Sensitivity Studies

To help finalize a reasonable hot patch design, a series of sensitivity studies were conducted looking at the effect of hot patch power, the notch length and depth, the test section heat flux, and the system pressure. Before describing these sensitivity studies, the results of the "base case" for the final design will be detailed.

Base Case

The flow conditions selected for the base case were as follow:

Pressure	:	1.379 (bar) [20 psia]
Mass Flux	:	2000 (kg/m^{2}s)
Subcooling	:	50 (°K)
Heat Flux	:	250 (kW/m^2)

The pressure was set to the minimum value used in the RBHT experiments as low pressure correlates with low heat transfer coefficients and hence high notch temperatures. Conversely, the mass flux was set to the maximum value expected to be

run in the experimental program as that corresponds to higher values of the critical heat flux and hence higher hot patch power requirements. Inlet subcooling was specified as 50 °K as that is about the maximum practical value. Although higher values of the subcooling would be desirable for the experimental program, its effect upon the minimum film boiling temperature, see Figure 5, may render this impractical as for these conditions T_{min} increases about 6.3 °K for every degree of subcooling. Finally, the test section wall heat flux was taken as 250 (kW/m^2) so that it would be about 1/3rd greater than that of the MFB point.

As discussed above the hot patch power was controlled so that the outside wall temperature at the notch mid-point would match its set point value of 800 °K. This required a hot patch power of 999.1 W and yielded a maximum notch temperature of 882.9 °K. Figure 10 shows the calculated temperature profile for the base case conditions where it can be seen that most of the axial temperature gradient occurs across the notch.

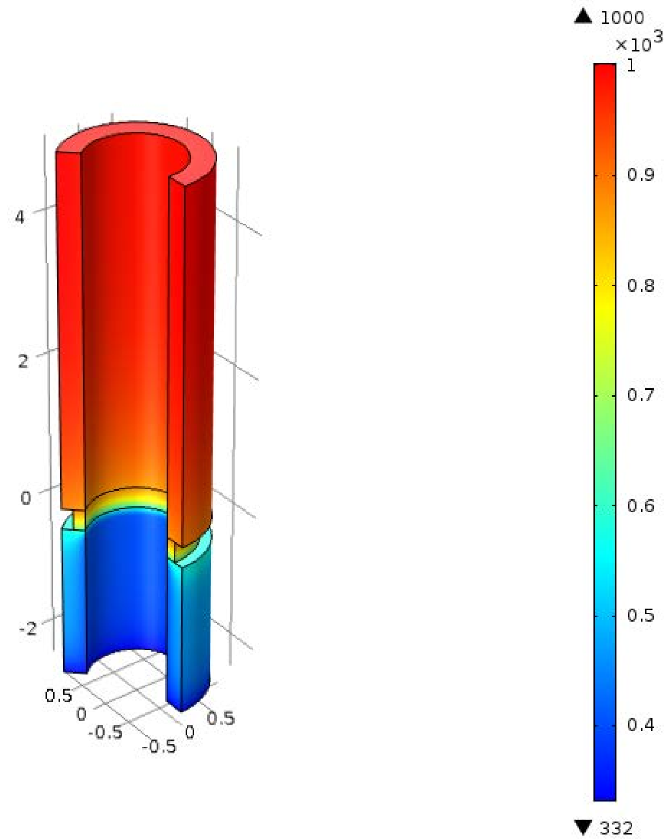


Figure 10: Calculated 3-D temperature profile for base case conditions.

The stabilization of the quench front at the notch region is further delineated by the axial prolife plots of Figure 11 and Figure 12 where the notch is located between the 0 and the -0.3 cm elevations. For these conditions T_{min} is about 879 °K which is just slightly greater than the tube inside wall temperature of 867.5 °K at the top of the notch. Also, as shown in Figure 12, the minimum wall heat flux point also coincides with the top of the notch.

The maximum heat flux point, that is the CHF point, is located at about the -0.42 cm position and so is in the pre-heater region just slightly more than 1 mm below the notch.

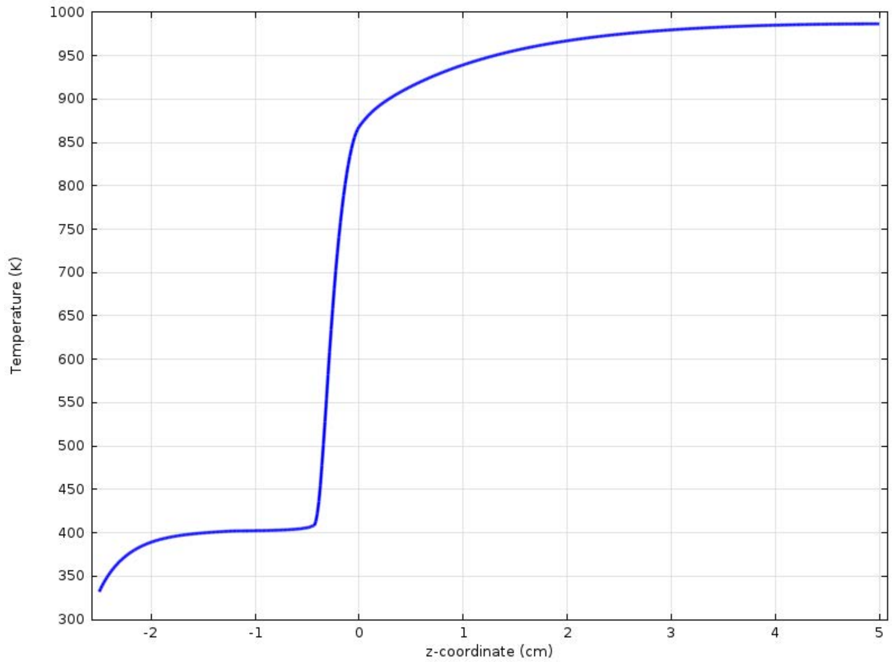


Figure 11: Axial profile of the tube inside wall temperature for the base case showing location of the stabilized quench front in the notch region (from 0 to -0.3 cm).

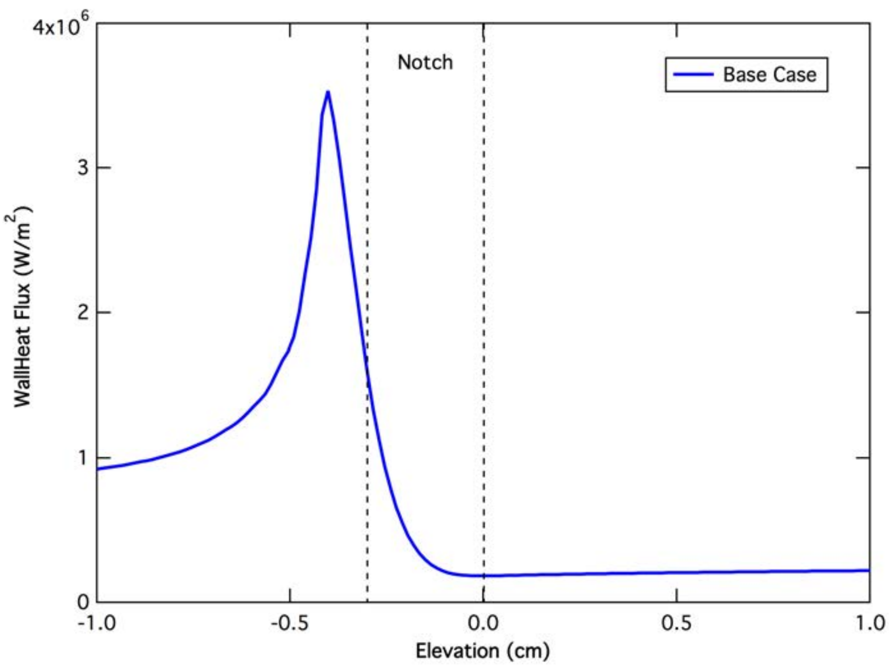


Figure 12: Close-up of the axial heat flux profile for the base case showing the location of the stabilized quench front relative to the "hot notch".

This completes the description of the simulation results for the base case; the remainder of this section presents the results of the various sensitivity studies that helped select the hot patch design parameters.

Hot Patch Power

The hot patch power necessary to stabilize the quench front is a result of the notch geometry, the flow conditions and the test section heat flux. Using the PID power controller to force the notch mid-point temperature to its set point value effectively removes the hot patch power as a sensitivity parameter. However, one of the most important features of the design is the size of the possible operating range for the hot patch power. Consequently, with the PID controller turned off, a sensitivity study was performed to determine the minimum and maximum hot patch powers that would result in a stabilized quench front for the flow and test section heat flux conditions of the base case.

For the purposes of these sensitivity studies, the allowable operating range was determined to the nearest watt and steady-state film boiling conditions were considered to be achieved when time derivative of the notch temperature was less than 0.1 (°K/s). The minimum power condition is that just sufficient to keep the test section from quenching (advancing quench front), while conversely the maximum power condition is that just below a value that would cause dryout of the pre-heater section (receding quench front).

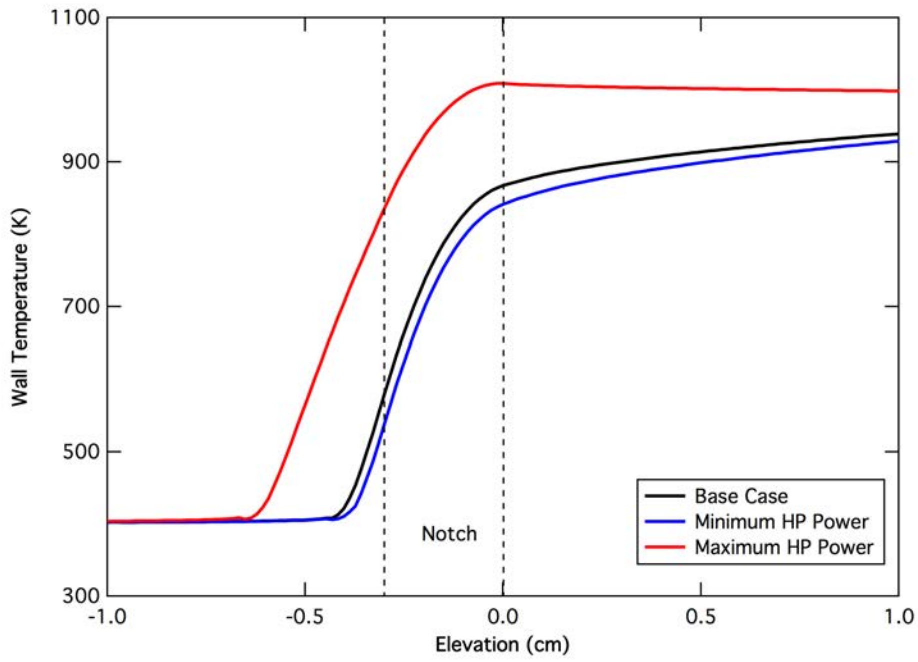


Figure 13: Comparison of tube inside wall temperature profiles in the notch region for the possible hot patch operating power range at the base case conditions.

A comparison of the tube axial temperature profiles for the notch region is given in Figure 13 for the entire possible hot patch power operating range. The operating power levels

and resulting temperatures of interest are given quantitatively in the table below. Here we see that the PID controlled case is only slightly above the minimum power condition and so provides a well-stabilized quench front but without undue high-temperature conditions for the thin-walled notch region. As the hot patch power is increased to its maximum operating point, the quench front recedes further into the pre-heater section and the peak temperature location can move from the test section into the notch region with possible negative consequences relative to structural integrity.

Sensitivity Case	Hot Patch Power (W)	Notch Temperatures[3] (°K)	
		Mid-Point	Maximum
Base (PID Controlled)	999.1	800	882.9
Minimum HP Power	987	770.7	858.2
Maximum HP Power	1102	974.9	1017.7

The crucial result from this sensitivity study is the size of the possible operating envelope for the hot patch power. This is crucial due to its effect upon the controllability of the hot patch power itself. A narrow operating envelope would require precision control and be susceptible to small fluctuations in the flow conditions, whereas a large operating envelope would be easier to control and more forgiving. The envelope for this base case design has a relatively large operating envelope where the power can vary by as much as 115 (W).

One other result of this sensitivity study is the necessity of powering the bottom hot patch separately from the film boiling test section. For example, for the base case discussed above, the heat flux in the film boiling region is 250 (kW/m^2) whereas in the pre-heater region below the notch, the applied wall heat flux due to the hot patch power would be 860.9 (kW/m^2). This is a factor of 3.44 times greater and would require a current 1.86 times as large as that of the test section.

Notch Length

The most critical design parameter was determined to be the notch length. For this study, the notch length was varied ±1 mm from its base design value of 3 mm and comparisons made based on the hot patch operating range and notch maximum temperature. The hot patch operating range was defined as the difference between the minimum and maximum values of the hot patch power for which the quench front can be stabilized. At hot patch powers lower than the operating range, the test section will quench no matter that the applied heat flux is greater than the MFB point. Conversely, for hot patch powers higher than the operating range, the tube will dryout as the quench front recedes into the pre-heater section. The maximum notch temperature is simply that, the maximum value for the material temperature in the notch region and is

[3] In this and subsequent tables, the notch temperatures correspond to those of the outside surface.

important due to its effect on the mechanical strength of this thin-walled region where the highest stresses will occur.

The results of the notch length sensitivity studies are given in the following table:

Sensitivity Case		**Hot Patch Power (W)**	**Notch Temperatures (°K)**	
			Mid-Point	**Maximum**
Base Case (ΔZ_N = 3 mm)	Min. HP Power	987	770.7	858.2
	PID Controlled	999.1	800	882.9
	Max. HP Power	1102	974.9	1017.7
Short Notch (ΔZ_N = 2 mm)	Min. HP Power	1221	808.9	865.8
	PID Controlled	-	-	-
	Max. HP Power	1235	885.6	928.8
Long Notch (ΔZ_N = 4 mm)	Min. HP Power	853	776.2	886.2
	PID Controlled	859.8	800	903.6
	Max. HP Power	1025	1038.3	1081.3

For each sensitivity case, results from three separate calculations are presented in the above table: the PID controlled power case, and the minimum and maximum hot patch power calculations. This both defines the possible hot patch operating range but also gives some perspective on the performance the PID controller. The base case has a notch length of 3 mm and provides for flexible hot patch power control due to a relatively wide operating range of 115 (W). Note also that the PID controlled case is only slightly above the minimum power case and so, at least for these flow conditions, the selection of 800 °K as the set point provides for stable operation without unnecessarily high notch temperatures.

Decreasing the notch length to 2 mm, which is still longer than that used by Winfrith, increases the hot patch power by more than 20% and drastically reduces the operating range. With this shorter hot patch, operation with a stabilized quench front was only found to be possible within a power range of 14 (W). Such a narrow operating range would make the hot patch power control very difficult and sensitive to very small fluctuations in the flow conditions. Indeed, it was not possible to use the PID controller with a set point of 800 °K for the notch mid-point temperature as this temperature was already exceeded for the minimum power condition. For the Winfrith Series 5 tests, the temperature of the bottom hot patch was reported and ranged from 1000-1100 °K which was about 200 °K hotter than the film boiling region of the test section itself. It is possible that the need to run at such high notch temperatures, likely due to the short 1.5 mm length of the notch, resulted in the relatively short working life reported for their test section.

Increasing the notch length to 4 mm further increased the hot patch power operating range to 172 (W) while also further decreasing the hot patch power. However, as the notch length increased, more of the notch region was exposed to film boiling and so a small increase in its maximum temperature was observed for the PID controlled case. For the maximum power case, the entire notch region was in the film boiling heat transfer regime and this, coupled with the high hot patch power, caused the peak temperature to occur in the notch region, as shown in Figure 14. Consequently, even though the possible operating range is larger than that of the base case, much of this extended range would be at the expense of higher notch temperatures and so would be best avoided.

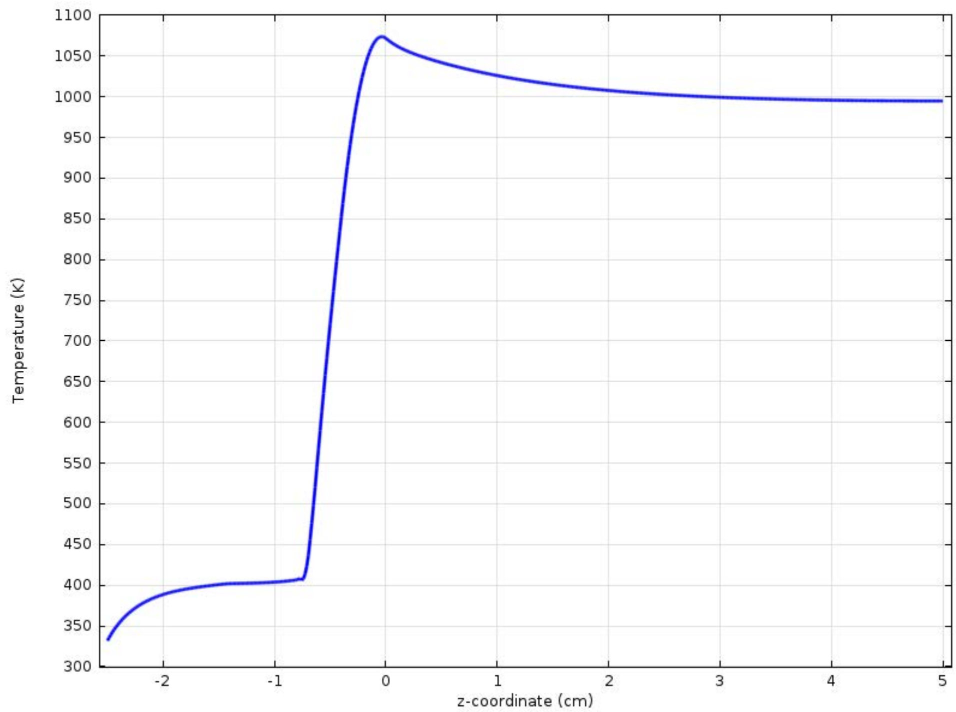


Figure 14: Axial profile of the tube inside wall temperature for the maximum hot patch power case with a notch length of 4 mm.

The above together with the desire to keep the notch length as small as possible to better localize the quench front led to the selection of 3 mm for the notch length corresponding to an operating range of 115 (W).

Notch Depth

The notch depth controls the level of the heat generation spike at the notch region and hence the deeper the notch, the lower the required hot patch power. However, increasing the notch depth, obviously, reduces the wall thickness and so adversely affects the structural integrity of the test section. For this sensitivity study, the notch depth was varied ±0.1 mm from its base design value of 1.5 mm resulting in the following values for the linear heat rate ratio and the hoop stress geometry factor:

Sensitivity Case	$\left(q'_N / q'_{PH} \right)$	$\left(D_I / 2 \cdot \delta \right)$
Shallow Notch (δ_N = 1.4 mm)	2.03	3.93
Base Case (δ_N = 1.5 mm)	2.17	4.18
Deep Notch (δ_N = 1.6 mm)	2.38	4.47

In this sensitivity study, the notch depth exhibited the same trends on operating range, hot patch power and maximum notch temperature, as did the notch length. Specifically, the operating range increased from a value of 67 (W) for a notch depth of 1.4 mm to a value of 153 (W) for a depth of 1.6 mm. Also, though the hot patch power requirements decrease with notch depth, the resulting increases in the notch heat generation rate result in somewhat higher temperatures as shown in the following table:

Sensitivity Case		**Hot Patch Power (W)**	**Notch Temperatures (°K)**	
			Mid-Point	**Maximum**
Base Case (depth = 1.5 mm)	Min. HP Power	987	770.7	858.2
	PID Controlled	999.1	800	882.9
	Max. HP Power	1102	974.9	1017.7
Shallow Notch (depth = 1.4 mm)	Min. HP Power	1053	796.4	875.1
	PID Controlled	1054.3	800	877.9
	Max. HP Power	1120	940.8	987.8
Deep Notch (depth = 1.6 mm)	Min. HP Power	926	775.8	867.0
	PID Controlled	941.4	800	886.4
	Max. HP Power	1076	989.0	1031.6

Based on these results, to keep the hoop stress geometry factor as low as possible yet maximize the operating range, an intermediate value of 1.5 mm was selected for the notch depth.

Test Section Heat Flux

To operate stably in the film boiling region, in addition to a correctly working hot patch, the applied heat flux for the test section must be greater than that of the minimum film boiling point. If the test section power were reduced so that the wall heat flux falls below q''_{min}, spontaneous vapor film collapse would occur leading to rapid quenching of the test section. Indeed, this is exactly the experimental procedure used by Stewart & Groeneveld (1981) to determine the minimum film boiling temperature. Consequently, the test section heat flux becomes an important parameter when trying to conduct steady-state film boiling tests.

For the flow conditions chosen for the base case, the value of the minimum film boiling heat flux is about 188.8 (kW/m^2) as shown in Figure 6 above. A test section heat flux value of 250 (kW/m^2) was selected for the base case, so that it would exceed the minimum value by about 1/3rd as described above. In this sensitivity study, the heat flux was varied from 200 to 300 (kW/m^2), or roughly from 6% to 60% above the q''_{min} value. The results are given in the following table:

Test Section Heat Flux (kW/m^2)	Hot Patch Power (W)	Temperature (°K)	
		Notch Maximum	Test Section Maximum
200	1083.4	863.5	903.8
225	1039.6	873.0	949.0
250 (Base Case)	998.9	882.0	992.4
275	958.5	890.9	1034.6
300	919.0	899.6	1075.2

As expected, as the test section heat flux increases it becomes easier to stabilize the quench front and the required hot patch power decreases. Also, as expected, the maximum wall temperature[4] in the film boiling region increases as the heat flux is increased. It was also observed that, despite the reduced hot patch power, the maximum notch temperature increases with the test section heat flux. The reason for this increase becomes apparent in Figure 15 where it can be seen that the higher test section wall temperatures affect the temperature at the top of the notch. Note that almost no difference is observed in the axial temperature profiles for the nucleate and transition boiling regimes due to the high heat transfer coefficients there.

[4] The length of the test section used in these sensitivity calculations was only 10 cm. Maximum wall temperatures in the film boiling region would be different in an actual experiment as the quality increases with axial distance.

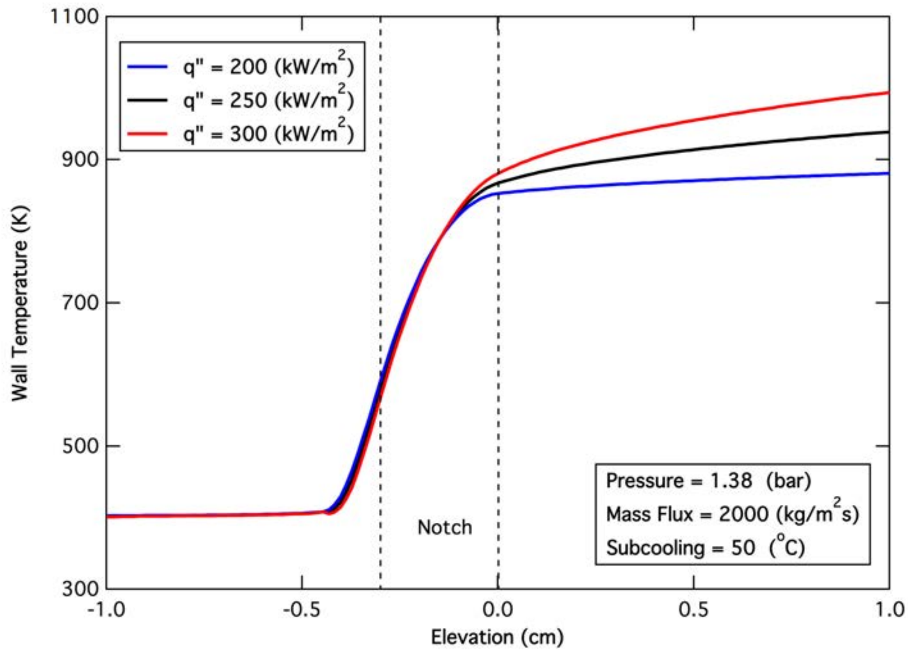


Figure 15: Axial temperature profiles in notch region for base flow conditions with test section heat flux as a parameter.

System Pressure

The last sensitivity study to be conducted was that for the effect of system pressure. The purpose of this study was simply to confirm the operability of the hot patch design for the full range of conditions considered for possible future experimental programs. Here the pressure was varied from 1.379 bar (20 psia), that matches the lowest value used in the RBHT reflood experiments, to a maximum value of 70 bar that is relevant to BWR stability studies and for PWR blowdown rewet.

It was not possible to solely vary the system pressure in this sensitivity study due to its impact on the minimum film boiling heat flux. As shown in the table below, the calculated MFB heat flux increases by a factor of almost 3 as the pressure increases from 1.38 to 70 bar. Therefore, in order to prevent spontaneous quenching of the test section, the applied wall heat flux in the film boiling region has to similarly increase. For these studies, the applied wall heat flux was set to a value about 1/3rd greater than the MFB point and so was increased from 250 to 730 (kW/m^2).

Using the PID controller with a set point of 800 °K for the notch mid-point temperature, the quench front was predicted to be stabilized at the notch over the entire pressure range. Consequently, given the caveat that the validity of these calculations is only as good as the accuracy of the boiling curve that was used, it appears that low-quality high-pressure steady-state film boiling experiments can be successfully conducted even for high mass flux conditions.

The trends with pressure calculated in this study were pretty much as expected with one notable exception. Namely that as the pressure increased from 10 to 70 bar, the

required hot patch power decreased. Looking more closely at the details of the boiling curve for these two pressures, one sees that as the pressure increased from 10 to 70 bar, the value of the critical heat flux decreased by about 12%, and that the minimum film boiling temperature decreased from 863.8 °K to 829.8 °K. These decreases serve to explain the lower hot patch power requirement for the 70 bar case.

The results for the system pressure sensitivity study are given in the following table:

Pressure (bar)	Test Section Heat Flux (kW/m^2)	Minimum Film Boiling (kW/m^2)	Hot Patch Power (W)	Temperature (°K)	
				Notch Maximum	Test Section Maximum
1.379 (20 psia)	250	188.8	998.9	882.0	992.4
4.138 (60 psia)	315	235.7	1048.9	885.8	989.6
10 (145 psia)	415	312.4	1251.8	890.5	972.0
70 (1015 psia)	730	551.9	1118.8	883.8	957.3

Conclusions

A hot patch design has been developed to perform low-quality high-pressure steady-state film boiling experiments with water as a coolant. This design is for a joule-heated tubular test section and employs the so-called directly heated hot patch technique to stabilize the quench front at a small notch machined into the tube exterior. The tube OD is 19.05 mm and its ID is 12.95 mm. Sensitivity studies were conducted to select a notch length of 3 mm and a depth of 1.5 mm. This design has a minimum wall thickness of 1.55 mm that is nearly twice as thick as that of the test sections used by the CIAE and Winfrith and so is expected to be more robust.

This design study showed the feasibility of conducting high-pressure steady-state film boiling experiments even for high mass flux conditions. However, the validity of these calculations is only as good as the accuracy of the boiling curve that was used. Consequently, any future experimental program should not rely entirely on computational results such as those of this study but rather include a task for small prototype testing to optimize the hot patch design for the expected flow conditions. The results of such a prototype test program would then be used to both inform the final test section design and to improve the computational tool so that more accurate pre-test calculations could be made.

The directly heated hot patch technique was shown to work well for a joule heated tubular test section. However, to stabilize the quench front, an independent power

supply had to be provided for the bottom hot patch. For some high flow conditions, it may also be necessary to independently power the hot patch at the top of the test section to prevent top-down quenching. The requirement to independently power the hot patch makes this design very difficult to implement in a heater rod such as would be used for rod bundle experiments.

The calculations presented in this study, and upon which these conclusions are based, only considered a thermal analysis for the hot patch design. Before employing this or a similar design in an actual experimental program, the multi-physics aspect of the design problem should be considered. In particular, a solution for the electrical field should be added to this model to assess the impact on the heat flux profile due to the presence of the electrodes (stainless steel plates of about 1.5 mm thickness welded to the test section). Subsequent calculations could also be performed to examine the stress levels at the notches.

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MONTHLY LETTER STATUS REPORT INSTRUCTIONS FOR CONTRACTS AND ORDERS

The contractor shall submit an electronic Monthly Letter Status Report (MLSR) by the 20th day of each month to the Contracting Officer's Representative (COR) and the Contracting Officer (CO). If orders are issued under the contract, a separate MLSR must be provided for each order. MLSRs are not required once the NRC determines that work under the contract/order is complete, and the final costs are acceptable. A SAMPLE TEMPLATE, WHICH MAY BE USED TO COMPLETE THE MLSR, IS ENCLOSED.

Provide the information requested in each of the following sections if applicable.

I. CONTRACT/ORDER IDENTIFICATION & CONTACT INFORMATION

- Reporting period:
- Contract number:
- Order number:
- Contract title and period of performance:
- Order title and period of performance:
- COR's name, telephone number, and e-mail address:
- Full name and address of the contractor:
- Name, telephone numbers and email addresses of the Contractor Project: Manager(s)/Contractor Lead Reviewer:

II. FINANCIAL STATUS

A. Overall Funding Information

- Total Ceiling Amount: $
- Total Amount of Funds Obligated to Date: $
- Total Invoiced for this Reporting Period: $
- Total Amount Invoiced - Cumulative Amount to Date: $
- Total Amount of Funds Expended to Date (Based on Obligated Funds): $
- Percentage of Funds Expended to Date (Based on Obligated Funds): %
- Balance of Obligated Funds Remaining (Based on Invoiced Amount): $
- Total Amount Invoiced & Costs Incurred (Invoiced amounts & amounts not yet invoiced—e.g. pending /outstanding to subcontractor): $
- Balance of Obligated Funds Remaining After Deducting Total Amount Invoiced & Amounts Not Yet Invoiced (Costs Incurred): $
- Balance of Funds Required for Completion: $

B. Contractor Acquired Property

Report all property with an acquisition cost of $5,000 or more (including Information Technology (IT) hardware and software), acquired for the project during the month. Report all sensitive property regardless of cost. The following information is required for each reported item:

- Item/property description;
- Manufacturer, model number, and serial number, if applicable;
- Acquisition cost or development cost; and
- Date received.

If property was not acquired during the reporting month, include a negative statement to that effect in the MLSR.

The final MLSR for the contract shall include a closeout property report certifying that property with an acquisition cost of greater than $5,000 (including IT hardware and software) and sensitive property regardless of cost is included in the final property report and that the list is complete. For each item listed, the report shall contain:

- Item/property description;
- Manufacturer; the model number, & the serial number, if applicable;
- Acquisition or development cost; and
- Date received.

The closeout property report shall identify any ongoing or contemplated NRC projects on which the property could be utilized. If no property was acquired under the contract, include a negative report. Note any property requiring special handling based on security, health, safety, or other reasons as part of the report.

C. NRC-Funded Software

Report NRC funded software with a useful life of 2 years or more and a development cost of greater than $5,000. Provide the following information for each item of NRC funded software:

- Software name and function:
- Development cost:
- Computer language used:
- Operating system:
- Physical location of the software and/or the hardware system:
- Date the software development was completed:
- Scheduled replacement date or projected useful life. If the useful life is not readily apparent, the useful life is considered to be 5 years from the day the software was considered operational:

III. TECHNICAL STATUS

A. Deliverables/Milestones Schedule

Provide the following information for each deliverable/milestone identified in the SOW:

- Task/subtask:
- Description:
- Planned completion date:
- Revised completion date if applicable:
- Actual completion date:

The deliverables/milestones schedule shall be revised as necessary. **Any variance in schedule shall be identified and discussed in detail. Discussion shall include the cause for the variance, together with any proposed solution to bring the dates within the original planned dates.**

B. Progress During Reporting Period

Provide a clear and concise discussion of the work performed during the reporting period. Include sufficient detail to support the costs reported for the reporting period. A summary of significant meetings and conference calls must be included. In addition, the current status of each deliverable, task, or service shall be identified. **Progress reported as "worked on all tasks" is not acceptable.**

C. Travel

Travel taken during the reporting period shall be fully described and shall include, at a minimum, the purpose of the travel, whether prior NRC authorization was required and obtained, the names of all travelers, the beginning and ending dates of the travel, and the destination point.

D. Anticipated and Encountered Problem Areas

Problems encountered during the reporting period and anticipated in subsequent period(s) *(to include, for example, problems or circumstances that require a change in the level of effort or estimated cost, scope of work, or travel requirements)* shall be identified. Discussion of problems encountered during the reporting period shall include the actual solution. If the solution was not implemented during the reporting period, a detailed discussion of the proposed solution shall be included. The status of the problem shall be updated in subsequent MLSRs until problem resolution is achieved and reported**. Clearly identify the person(s) and/or organization(s) with responsibility to address the problem.** If NRC is required to take action to resolve a problem or concern, the COR should be notified separately.

A discussion of the impact on the projected cost and schedule of the project or task order shall be included. If the projected actual cost is expected to be greater than or less than the planned cost and/or if the schedule is projected to be longer than or less than the planned schedule, an in depth rationale for the difference(s) shall be provided. Actions to mitigate schedule delays and/or cost/price increases shall be thoroughly described.

Problems or circumstances requiring a modification to the level of effort, estimated cost, scope of work, or travel requirements shall also be discussed in the MLSR. The COR should be notified separately if a modification is needed. **Such notification shall not be delayed until issuance of the MLSR.**

E. Plans for the Next Reporting Period

Provide a concise discussion of work to be performed and a description of anticipated travel during the next reporting period. Describe milestones anticipated to be completed in the next reporting period.

F. Staff Hours Summary

The staff hours summary must identify the task/subtask, the staff assigned to the task/subtask, hours budgeted, hours expended for this reporting period, total cumulative hours expended and the task/subtask status.

IV. CONTRACTOR REQUIRED TRAINING

In accordance with the following clauses, NRC INFORMATION TECHNOLOGY SECURITY TRAINING and FAR 52.224-3 Alt. 1 Privacy Training, contractors shall ensure that their employees, consultants, and subcontractors with access to the agency's information technology (IT) equipment and/or IT services complete NRC's online initial and refresher IT security training requirements to ensure that their knowledge of IT threats, vulnerabilities, and associated countermeasures remains current. Both the initial and refresher IT security training courses generally last an hour or less and can be taken during the employee's regularly scheduled work day. The contractor shall also ensure that any other required training as stipulated by the contract terms and conditions, shall be taken in a timely manner. Failure to do so, shall be reflected in the contractors CPARS report.

Where the contract/order includes the clauses, **NRC INFORMATION TECHNOLOGY SECURITY TRAINING and FAR 52.224-3 Alt. 1,** the MLSR must include the following information for all completed training:

(1) Name of the individual completing the course:
(2) Course title:
(3) Course completion date:

The MLSR must also include the following information for those individuals who have not completed their required training:

(1) Name of the individual who has not yet completed the training:
(2) Title of the course(s) which must still be completed:
(3) Anticipated course completion date(s):

V. LICENSE FEE RECOVERY COST STATUS

This section is <u>required</u> if any portion of the work described in the Statement of Work is fee recoverable.

Pursuant to the provisions on fees of Title 10 of the *Code of Federal Regulations* Parts 170 and 171, provide the total amount of fee recoverable costs incurred during the reporting period, the fiscal year to date costs, and the cumulative total costs to date for each task/project. The License Fee Recovery Cost Status (LFRCS) shall be recorded on a separate page as part of the MLSR, and shall be in the format provided in the MLSR template under the LFRCS Section.

Each report will contain a docket number, cost activity code (CAC) or other unique identifier. Facilities must be sorted by docket number/identifier. Unit numbers must be identified for each facility included in the LFRCS table. For work that involves more than one facility at the same site, each facility should be listed separately, and the costs should be split appropriately between the facilities. Common costs, as defined below, must be identified separately in the LFRCS.

Common costs are those costs that are not licensee unique and associated with the performance of an overall program that benefit all similar licensees covered under that program or that are required to satisfactorily carry out the program. Common costs include costs associated with the following: preparatory or start-up efforts to interpret and reach agreement on methodology, approach, acceptance criteria, regulatory position, or technical reporting requirements; efforts associated with the "lead plant" concept that might be involved during the first one or two plant reviews; meetings and discussions involving the above efforts to provide orientation, background knowledge or guidance during the course of a program; any technical effort applied to a docket or other unique identifier; and project management. Common costs must be reported monthly for each docket or unique identifier. Common costs must be computed based on the proportion of direct costs incurred against each docket or unique identifier for the reporting period.

Any/all non-fee recoverable costs must be accounted for in the cost breakdown table of the MLSR template with the corresponding non-fee recoverable CAC as directed by the COR.

VI. SPENDING PLAN UPDATE—Required for Cost Reimbursement, Labor-Hour and Time-and-Materials Contracts/Orders (Complete as Applicable for Other Contract Types)

The initial Spending Plan must be included in the initial MLSR. Thereafter, the spending plan shall be updated on the MLSR Spending Plan Update Template in Excel (enclosed), and submitted with the MLSR. Spending plan updates shall encompass two fiscal years (current fiscal year and following fiscal year). Discussion shall include significant spending plan variances, the cause for the variance, and proposed solutions to bring the cost within planned amounts. Definitions of spending plan terms are provided below:

Planned – Spending plan agreed to by the parties at time of award.

Revised – Updated spending plan revised by the contractor. Spending plan shall be updated as necessary.

Actual – Total amount/costs expended by the contractor as reported in the MLSR.

Variance – Percentage difference between planned, or revised if applicable, and actual

MONTHLY LETTER STATUS REPORT-TEMPLATE

<table>
<tr><td colspan="2">Reporting Period Start Date</td><td colspan="2">Reporting Period End Date</td></tr>
<tr><td colspan="2">NRC Contract Number</td><td colspan="2">Order Number (if applicable)</td></tr>
<tr><td colspan="4">Contract/Order Title</td></tr>
<tr><td colspan="2">Period of Performance Start Date:</td><td colspan="2">Period of Performance End Date:</td></tr>
<tr><td>Contracting Officer’s Representative (COR)</td><td colspan="2">COR Telephone</td><td>COR E-mail</td></tr>
<tr><td colspan="4">Contractor Name</td></tr>
<tr><td colspan="4">Contractor Complete Address (Street, City , State, and Zip Code)</td></tr>
<tr><td colspan="2">Contract Project Manager(s)/Contractor Lead Reviewer</td><td>Telephone</td><td>E-mail</td></tr>
</table>

Provide the information requested in each of the following sections if applicable. (Please insert N/A beside items that are not applicable)

FINANCIAL STATUS

A. Overall Funding:

1.	Total Ceiling Amount	$
2.	Total Amount of Funds Obligated to Date	$
3.	Total Amount Invoiced - This Period	$
4.	Total Amount Invoiced - Cumulative Amount to Date	$
5.	Total Amount of Funds Expended to Date (Based on Obligated Funds)	$
6.	*Percentage* of Funds Expended to Date (Based on Obligated Funds)	____%
7.	Balance of Obligated Funds Remaining (Based on Invoiced Amounts)	$
8.	Total Amount/Costs Incurred (Invoiced amounts & amounts not yet invoiced—e.g. pending; outstanding to subcontractor)	$
9.	Balance of Obligated Funds Remaining after Deducting Total Incurred Amounts/Costs	$
10.	Balance of Funds Required for Completion	$

B. Contractor Acquired Property:

Item*	Description	Manufacturer	Model Number	Serial Number	Acquisition Cost ($)	Receipt Date	Property Identification Number

*****Asterisk represents sensitive item

C. NRC-Funded Software:

Name*	Function	Development Cost ($)	Computer Language Used	Operating System	Location of System	Date Software Completed	Date of Scheduled Replacement/ Useful Life

*****Asterisk represents sensitive software

TECHNICAL STATUS

A. Deliverables/Milestones Schedule:

(Any variance in schedule shall be identified and discussed in detail. Discussion shall include the cause for the variance, together with any proposed solution to bring the dates within the original planned dates.)

Task/Subtask	Description	Planned Completion Date	Revised Completion Date (if applicable)	Actual Completion Date

B. Progress during Reporting Period: ____

C. Travel for this Period:

Staff	Purpose of Travel	NRC Authorization Required/ Obtained*	Start Date	End Date	Destination/Activity

*Include name of NRC authorizing official and date authorization was obtained.

D. Anticipated and Encountered Problem Areas: ____________________________________

E. Plans for the Next Reporting Period: ____

F. Staff Hours Summary:

Task/Subtask/Phase	Staff Assigned	Hours Budgeted	Hours Expended This Reporting Period	Total Cumulative Hours Expended	Notes

TRAINING
(Complete if contract/order includes the clause, NRC INFORMATION TECHNOLOGY SECURITY TRAINING)

Completed Training:

Name of Individual Completing the Course During This Period	Course Title	Course Completion Date

Training To Be Completed:

Name of Individual Who has NOT, To Date, Completed the Required Training	Course Title	Anticipated Course Completion Date

LICENSE FEE RECOVERY COST STATUS

Reporting Period Start Date	**Reporting Period End Date**
Contract Number	**Order Number**
Project Title	

Licensee	**Task Order No.**	**Facility Name/Unit Number**	**Docket Number**	**CAC Number**	**Period Costs**	**Fiscal Year Costs to Date**	**Cumulative Costs to Date**

Important Note - Individual administrative costs (e.g. costs associated with overall project management/coordination, administrative setup/monitoring of the task order/agreement, preparation of the MLSR, etc.) must be included in the current period costs (i.e. these costs should not be noted as separate costs/items). Administrative costs must be proportionately allocated to each line item listed in the summary table above. Any/all non-fee-recoverable costs must be accounted for in the above table with the appropriate non-billable Cost Activity Code (CAC) as provided by the COR. <u>The total Period Costs in the above table shall equal the total amount charged to NRC for this period.</u>

SPENDING PLAN - Fiscal Year (FY) _______

Required for Cost Reimbursement, Labor-Hour and Time-and-Materials Contracts/Orders
(Complete as applicable for other contract types)

FY_____	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	TOTAL
Planned ($)													
Revised ($)													
Actual ($)													
Variance (%)													

FY_____	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	TOTAL
Planned ($)													
Revised ($)													
Actual ($)													
Variance (%)													

Spending Plan.xlsx

Version Control Date: September 20, 2018

BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)

General: During performance and through final payment of this contract, the contractor is responsible for the accuracy and completeness of data within the System for Award Management (SAM) database and the Invoice Processing Platform (IPP) system and for any liability resulting from the Government's reliance on inaccurate or incomplete SAM and/or IPP data.

The contractor shall prepare invoices/vouchers for payment of deliverables identified in the contract, in the manner described herein. FAILURE TO SUBMIT INVOICES/VOUCHERS IN ACCORDANCE WITH THESE INSTRUCTIONS MAY RESULT IN REJECTION OF THE INVOICE/VOUCHER AS IMPROPER.

Electronic Invoice/Voucher Submissions: Invoices/vouchers shall be submitted electronically to the U.S. Nuclear Regulatory Commission (NRC) is through the Invoice Processing Platform (IPP) at www.ipp.gov.

Purchase of Capital Property: *($50,000 or more with life of one year or longer)*

Contractors must report to the Contracting Officer, electronically, any capital property acquired with contract funds having an initial cost of $50,000 or more, in accordance with procedures set forth in NRC Management Directive (MD) 11.1, NRC Acquisition of Supplies and Services.

Agency Payment Office: Payment will continue to be made by the office designated in the contract in Block 12 of the Standard Form 26, or Block 25 of the Standard Form 33, whichever is applicable.

Frequency: The contractor shall submit requests for reimbursement once each month, unless otherwise authorized by the Contracting Officer.

Supporting Documentation: Any supporting documentation required to substantiate the amount billed shall be included as an attachment to the invoice created in IPP. If the necessary supporting documentation is not included, the invoice will be rejected.

Task Order Contracts: The contractor must submit a separate invoice/voucher for each individual task order with detailed cost information included as Supporting Documentation. This includes all applicable cost elements and other items discussed in paragraphs (a) through (k) of the attached instructions.

Billing of Costs after Expiration of Contract: If costs are incurred during the contract period and invoiced after the contract has expired, you must cite the period during which these costs were incurred. To be considered a proper expiration invoice/voucher, the contractor shall clearly mark it "EXPIRATION INVOICE" or "EXPIRATION VOUCHER".

Final invoices/vouchers shall be marked "FINAL INVOICE" or "FINAL VOUCHER".
Currency: Invoices/Vouchers must be expressed in U.S. Dollars.

Version Control Date: September 20, 2018

BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)

Supersession: These instructions supersede previous Billing Instructions for Cost-Reimbursement Type Contracts (SEPT 2017).

Does my company need to register in IPP?

If your company is currently registered in IPP and doing business with other Federal Agencies in IPP, you will not be required to re-register.

If your company is not currently registered in IPP, please note the following:

- You will be receiving an invitation to register for IPP from IPP Customer Support, STLS.IPPHELPDESK@stls.frb.org.
- IPP Customer Support will send you two emails: the first email will contain the initial administrative IPP User ID and the second email, sent within 24 hours of receipt of the first email, will contain a temporary password.
- Please add the Customer Support email address (STLS.IPPHELPDESK@stls.frb.org) to your address book so you do not disregard these emails or mistake them for spam.
- During registration, one initial administrative user account will be created for your company and this user will be responsible for setting up all other user accounts including other administrators.
- Registration is complete when the initial administrative user logs into the IPP web site with the User ID and password provided by Treasury and accepts the rules of behavior.

What type of training is provided?

Vendor training materials, including a first time login tutorial, user guides, a quick reference guide, and frequently asked questions are available on Treasury's IPP website. **Individuals within your company responsible for submitting invoices should review these materials before work begins on the contract.**

How do I receive assistance with IPP?

Treasury's IPP Customer Support team provides vendor assistance related to the IPP application, and is also available to assist IPP users and to answer any questions related to accessing IPP or completing the registration process. IPP application support is also available via phone at (866) 973-3131, Monday through Friday from 8:00 am to 6:00 pm ET, and via email at IPPCustomerSupport@fiscal.treasury.gov.

Specific questions regarding your contract or task order should be directed to the appropriate NRC Contracting Officer.

BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)

INVOICE/VOUCHER FOR PURCHASES AND SERVICES OTHER THAN PERSONAL (SAMPLE FORMAT – INVOICE ATTACHMENT)

a. Billing Period. Insert the beginning and ending dates (day, month, year) of the period during which costs were incurred and for which reimbursement is requested.

b. Description of Deliverables. Provide a brief description of supplies or services, quantity, unit cost, and total cost.

c. Work Completed. Provide a general summary description of the services performed or products submitted for the invoice period and specify the section or Contract Line Item Number (CLIN) or SubCLIN in the contract pertaining to the required deliverable(s).

d. Shipping. Insert weight and zone of shipment, if shipped by parcel post.

e. Charges for freight or express shipments. Attach prepaid bill if shipped by freight or express.

f. Instructions. Include instructions to consignee to notify the Contracting Officer of receipt of shipment.

g. Direct Costs. Insert the amount billed for the following cost elements, adjustments, suspensions, and total amounts, for both the current billing period and for the cumulative period (from contract inception to end date of this billing period). The contractor shall not bill at rates that have not been incorporated into the contract by formal modification.

   1. Direct Labor. This consists of salaries and wages paid (or accrued) for direct performance of the contract itemized as follows:

Labor Category	Staff Assigned	Hours Billed	Rate	Total	Cumulative Hours Billed

   2. Fringe Benefits. This represents fringe benefits applicable to direct labor and billed as a direct cost. Where a rate is used indicate the rate. Fringe benefits included in direct labor or in other indirect cost pools should not be identified here.

   3. Contractor-acquired property ($50,000 or more). List each item costing $50,000 or more and having a life expectancy of more than one year. List only those items of equipment for which reimbursement is requested. For each such item, list the following (as applicable): (a) an item description, (b) manufacturer, (c) model number, (d) serial number, (e) acquisition cost, (f) date of purchase, and (g) a copy of the purchasing document.

**BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)**

4. Contractor-acquired property (under $50,000), Materials, and Supplies. These are equipment other than that described in (3) above, plus consumable materials and supplies. List by category. List items valued at $1,000 or more separately. Provide the item number for each piece of equipment valued at $1,000 or more.

5. Premium Pay. This enumeration in excess of the basic hourly rate. (Requires written approval of the Contracting Officer.)

6. Consultant Fee. The supporting information must include the name, hourly or daily rate of the consultant, and reference the NRC approval (if not specifically approved in the original contract).

7. Travel. Total costs associated with each trip must be shown in the following format:

Start Date		Destination		Costs
From	To	From	To	$

(Must include separate detailed costs for airfare, per diem, and other transportation expenses. All costs must be adequately supported by copies of receipts or other documentation.) To include a copy of the airfare receipt to include airline itinerary (boarding pass), lodging receipt(s), and car rental receipt(s), regardless of the dollar amount. Receipts are also required for any other items over $75. All foreign travel must be approved in advance by the NRC on NRC Form 445, Request for Approval of Official Foreign Travel, and must be in compliance with FAR 52.247-63, Preference for U.S. Flag Air Carriers.

Per Diem allowances covers lodging, meals, and incidental expenses. The rates for U.S. lodging must be in accordance with the rates on GSA website: https://www.gsa.gov/travel/plan-book/per-diem-rates. International travel rates must be in accordance the rates found on the Department of State's website: https://aoprals.state.gov/web920/per_diem.asp.

8. Subcontracts. Include separate detailed breakdown of all costs paid to approved subcontractors during the billing period.

9. Other Costs. List all other direct costs by cost element and dollar amount separately.

h. Indirect Costs (Overhead and General and Administrative Expense). Cite the formula (rate and base) in effect in accordance with the terms of the contract, during the time the costs were incurred and for which reimbursement is requested. The contractor shall not bill at rates that have not been incorporated into the contract by formal modification.

i. Total Amount Billed. Insert columns for total amounts for the current and cumulative periods.

**BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)**

j. Adjustments. Insert columns for any adjustments, including outstanding suspensions for deficient or defective products or nonconforming services, for the current and cumulative periods.

k. Grand Totals.

Version Control Date: September 20, 2018

BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)

Sample Invoice/Voucher Information (to be included as an attachment)

Sample Invoice/Voucher Information (Supporting Documentation must be attached)

This invoice/voucher represents reimbursable costs for the billing period from_____through___.

			Amount Billed	
			Current Period	Cumulative
(a)		**Direct Costs**		
	(1)	Direct labor	$_________	$_________
	(2)	Fringe benefits (% of direct labor)	$_________	$_________
	(3)	Government property ($50,000 or more)	$_________	$_________
	(4)	Government property, Materials, and Supplies (under $50,000 per item)	$_________	$_________
	(5)	Premium pay (NRC approved overtime)	$_________	$_________
	(6)	Consultants Fee	$_________	$_________
	(7)	Travel	$_________	$_________
	(8)	Subcontracts	$_________	$_________
	(9)	Other costs	$_________	$_________
		Total Direct Costs:	**$**_________	**$**_________
(b)	**Indirect Costs** *(provide the rate information applicable to your firm)*			
	(10)	Overhead ___ % of _________(Indicate Base)	$_________	$_________
	(11)	General and Administrative (G&A) ___ % of _________(Indicate Base)	$_________	$_________
		Total Indirect Costs:	**$**_________	**$**_________
(c)	**Total Amount Billed**		**$**_________	**$**_________
(d)	**Adjustments** (+/-)		**$**_________	**$**_________
(e)	**Grand Total**		**$**_________	**$**_________

(The invoice/voucher format provided above must include information similar to that included below in the following to ensure accuracy and completeness.)

SAMPLE SUPPORTING INFORMATION

**BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)**

The budget information provided below is for format purposes only and is illustrative.

Cost Elements:

1) Direct Labor - $2,400

Labor Category	Staff Assigned	Hours Billed	Rate	Total	Cumulative Hours Billed
Senior Engineer I	Pete Smith	100	$14.00	$1,400	975
Engineer	Rob Johnson	50	$10.00	$ 500	465
Computer Analyst	John Roberts	100	$ 5.00	$ 500	320
				$2,400	1,760 hrs

2) Fringe Benefits - $480

Fringe @ 20% of Direct Salaries

Labor Category	Salaries	Fringe Amount
Senior Engineer I	$1,400	$280
Engineer	$ 500	$100
Computer Analyst	$ 500	$100
	$2,400	$480

3) Government-furnished and contractor-acquired property ($50,000 or more) - $60,000

Prototype Spectrometer - item number 1000-01 = $60,000

4) Government-furnished and contractor-acquired property (under $50,000), Materials, and Supplies - $2,000

10 Radon tubes @ $110.00	= $1,100
6 Pairs Electrostatic gloves @ $150.00	= $ 900
	$2,000

5) Premium Pay - $150

Walter Murphy - 10 hours @ $10.00 Per Hour (Reg. Pay) = $100 x 1.5 OT rate = $150 (EX: Premium pay for this individual was approved and authorized under this contract by the NRC Contracting Officer by letter dated 6/1/2011.)

6) Consultants' Fee - $100

**BILLING INSTRUCTIONS FOR
COST-REIMBURSEMENT TYPE CONTRACTS (SEPTEMBER 2018)**

Dr. Carney - 1 hour fully-burdened @ $100 = $100

7) Travel - $2,640

(i) Airfare: (2 Roundtrip trips for 1 person @ $300 per r/t ticket)

Start Date	End Date	Days	From	To	Cost
4/1/2011	4/7/2011	7	Philadelphia, PA	Wash, D.C.	$300
7/1/2011	7/8/2011	8	Philadelphia, PA	Wash, D.C.	$300

(ii) Per Diem: $136/day x 15 days = $2,040

8) Subcontracting - $30,000

Company A	= $10,000
Company B	= $20,000
	$30,000

(EX: Subcontracts for Companies A & B were consented to by the Contracting Officer by letter dated 6/15/2011.)

9) Other Costs - $5,100

Honorarium for speaker at American Nuclear Society conference = $5,000
Nuclear Planet Journal subscription fee = $100

10) Overhead Expense - $41,148

Overhead @ 40% of Total Direct Costs

11) General and Administrative (G&A) Expense - $22,784

G&A @ 20% of Total Costs, excluding subcontracts and consultants

12)

Total Amount Billed	$175,020
Adjustments (+/-)	- $ 0
Grand Total	$175,020