AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE

PAGE OF PAGES: 1 | 12

2. AMENDMENT/MODIFICATION NO. M0003	3. EFFECTIVE DATE See Block 16C	4. REQUISITION/PURCHASE REQ. NO. ZEROREQ-RES-16-0117	5. PROJECT NO. *(If applicable)*

6. ISSUED BY CODE NRCHQ

US NRC - HQ
ACQUISITION MANAGEMENT DIVISION
MAIL STOP TWFN-5E03
ATTN ROB ROBINSON 301-415-0728
WASHINGTON DC 20555-0001

7. ADMINISTERED BY *(If other than Item 6)* CODE NRCHQ

US NRC - HQ
ACQUISITION MANAGEMENT DIVISION
MAIL STOP TWFN-5E03
WASHINGTON DC 20555-0001

8. NAME AND ADDRESS OF CONTRACTOR *(No., street, county, State and ZIP Code)*

PURDUE UNIVERSITY
ATTN DANIELLE C EVANS
460 NORTHWESTERN AVE RM 301
WEST LAFAYETTE IN 479072024

(x) 9A. AMENDMENT OF SOLICITATION NO.

9B. DATED *(SEE ITEM 11)*

X 10A. MODIFICATION OF CONTRACT/ORDER NO.
NRC-HQ-13-C-04-0022
NRC-HQ-60-15-T-0001

10B. DATED *(SEE ITEM 13)*
05/04/2015

CODE 072051394 FACILITY CODE

11. THIS ITEM ONLY APPLIES TO AMENDMENTS OF SOLICITATIONS

☐ The above numbered solicitation is amended as set forth in Item 14. The hour and date specified for receipt of Offers ☐ is extended. ☐ is not extended.
Offers must acknowledge receipt of this amendment prior to the hour and date specified in the solicitation or as amended , by one of the following methods: (a) By completing Items 8 and 15, and returning ______ copies of the amendment; (b) By acknowledging receipt of this amendment on each copy of the offer submitted ; or (c) By separate letter or telegram which includes a reference to the solicitation and amendment numbers. FAILURE OF YOUR ACKNOWLEDGEMENT TO BE RECEIVED AT THE PLACE DESIGNATED FOR THE RECEIPT OF OFFERS PRIOR TO THE HOUR AND DATE SPECIFIED MAY RESULT IN REJECTION OF YOUR OFFER If by virtue of this amendment you desire to change an offer already submitted , such change may be made by telegram or letter, provided each telegram or letter makes reference to the solicitation and this amendment, and is received prior to the opening hour and date specified.

12. ACCOUNTING AND APPROPRIATION DATA *(If required)*
See Schedule

13. THIS ITEM ONLY APPLIES TO MODIFICATION OF CONTRACTS/ORDERS. IT MODIFIES THE CONTRACT/ORDER NO. AS DESCRIBED IN ITEM 14.

CHECK ONE	
	A. THIS CHANGE ORDER IS ISSUED PURSUANT TO: *(Specify authority)* THE CHANGES SET FORTH IN ITEM 14 ARE MADE IN THE CONTRACT ORDER NO. IN ITEM 10A.
	B. THE ABOVE NUMBERED CONTRACT/ORDER IS MODIFIED TO REFLECT THE ADMINISTRATIVE CHANGES *(such as changes in paying office, appropriation date, etc.)* SET FORTH IN ITEM 14, PURSUANT TO THE AUTHORITY OF FAR 43.103(b).
	C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF:
X	D. OTHER *(Specify type of modification and authority)* FAR 52.243-2 "Changes - Cost Reimbursement"

E. IMPORTANT: Contractor ☐ is not. ☒ is required to sign this document and return 0 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION *(Organized by UCF section headings, including solicitation/contract subject matter where feasible.)*

The purpose of this action is to A) increase the total contract ceiling in the amount of $184,310.00, from $888,680 to $1,072,990.00 to allow for additional work within scope; and B) extend the period of performance end date from 5/31/2018 - 8/25/2018.

Period of Performance: 6/1/2015 - 8/25/2018 (Changed)
Total Task Order Ceiling: $1,072,990.00 (Changed)
Total Obligated Amount: $500,209.44 (Unchanged)

See additional pages for specific changes regarding this modification.
All other terms and conditions remain unchanged.
Continued ...

Except as provided herein, all terms and conditions of the document referenced in Item 9 A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE OF SIGNER *(Type or print)*		16A. NAME AND TITLE OF CONTRACTING OFFICER *(Type or print)* SHARLENE M. MCCUBBIN	
15B. CONTRACTOR/OFFEROR _(Signature of person authorized to sign)_	15C. DATE SIGNED	16B. UNITED STATES OF AMERICA [signature]	16C. DATE SIGNED 07/14/2016

NSN 7540-01-152-8070
Previous edition unusable

STANDARD FORM 30 (REV. 10-83)
Prescribed by GSA
FAR (48 CFR) 53.243

SUNSI REVIEW COMPLETE

TEMPLATE - ADM001

AUG 16 2016

ADM002

CONTINUATION SHEET	REFERENCE NO. OF DOCUMENT BEING CONTINUED NRC-HQ-13-C-04-0022/NRC-HQ-60-15-T-0001/M0003	PAGE 2 OF 12

NAME OF OFFEROR OR CONTRACTOR
PURDUE UNIVERSITY

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	Delivery Location Code: NRCHQ US NUCLEAR REGULATORY COMMISSION- MAIL PROCESSING CENTER 4930 BOILING BROOK PARKWAY ROCKVILLE MD 20852 USA Period of Performance: 06/01/2015 to 08/25/2018				

AMENDMENT OF SOLICITATION/MODIFICATION OF CONTRACT

1. CONTRACT ID CODE	
PAGE OF PAGES	1 of 12
2. AMENDMENT/MODIFICATION NO.	M0003
3. EFFECTIVE DATE	See Block 16C
4. REQUISITION/PURCHASE REQ. NO.	ZEROREQ-RES-16-0117
5. PROJECT NO. *(If applicable)*	
6. ISSUED BY — CODE NRCHQ	US NRC - HQ ACQUISITION MANAGEMENT DIVISION MAIL STOP TWFN-5E03 ATTN ROB ROBINSON 301-415-0728 WASHINGTON DC 20555-0001
7. ADMINISTERED BY *(If other than Item 6)* — CODE NRCHQ	US NRC - HQ ACQUISITION MANAGEMENT DIVISION MAIL STOP TWFN-5E03 WASHINGTON DC 20555-0001
8. NAME AND ADDRESS OF CONTRACTOR *(No., street, county, State and ZIP Code)*	PURDUE UNIVERSITY ATTN DANIELLE C EVANS 460 NORTHWESTERN AVE RM 301 WEST LAFAYETTE IN 479072024
CODE	072051394
FACILITY CODE	
(x) 9A. AMENDMENT OF SOLICITATION NO.	
9B. DATED *(SEE ITEM 11)*	
X 10A. MODIFICATION OF CONTRACT/ORDER NO.	NRC-HQ-13-C-04-0022 NRC-HQ-60-15-T-0001
10B. DATED *(SEE ITEM 13)*	05/04/2015

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12. ACCOUNTING AND APPROPRIATION DATA *(If required)*
See Schedule

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	C. THIS SUPPLEMENTAL AGREEMENT IS ENTERED INTO PURSUANT TO AUTHORITY OF:
X	D. OTHER *(Specify type of modification and authority)* FAR 52.243-2 "Changes - Cost Reimbursement"

E. IMPORTANT: Contractor ☐ is not, ☒ is required to sign this document and return 0 copies to the issuing office.

14. DESCRIPTION OF AMENDMENT/MODIFICATION *(Organized by UCF section headings, including solicitation/contract subject matter where feasible.)*

The purpose of this action is to A) increase the total contract ceiling in the amount of $184,310.00, from $888,680 to $1,072,990.00 to allow for additional work within scope; and B) extend the period of performance end date from 5/31/2018 - 8/25/2018.

Period of Performance: 6/1/2015 - 8/25/2018 (Changed)
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Total Obligated Amount: $500,209.44 (Unchanged)

See additional pages for specific changes regarding this modification.
All other terms and conditions remain unchanged.
Continued ...

Except as provided herein, all terms and conditions of the document referenced in Item 9 A or 10A, as heretofore changed, remains unchanged and in full force and effect.

15A. NAME AND TITLE OF SIGNER *(Type or print)*	16A. NAME AND TITLE OF CONTRACTING OFFICER *(Type or print)* SHARLENE M. MCCUBBIN
15B. CONTRACTOR/OFFEROR Digitally signed by Kenneth W. Suter DN: cn=Kenneth W. Suter, o=Purdue University, ou=Sponsored Program Services, Contracting, email=kwsuter@purdue.edu, c=US Date: 2016.07.14 15:37:06 -04'00' Kenneth W. Suter I Contract Analyst PURDUE UNIVERSITY SPONSORED PROGRAM SERVICES CONTRACTING *(Signature of person authorized to sign)* 15C. DATE SIGNED	16B. UNITED STATES OF AMERICA *(Signature of Contracting Officer)*
	16C. DATE SIGNED

NSN 7540-01-152-8070
Previous edition unusable

STANDARD FORM 30 (REV. 10-83)
Prescribed by GSA
FAR (48 CFR) 53.243

CONTINUATION SHEET	REFERENCE NO. OF DOCUMENT BEING CONTINUED NRC-HQ-13-C-04-0022/NRC-HQ-60-15-T-0001/M0003	PAGE 2 OF 12

NAME OF OFFEROR OR CONTRACTOR
PURDUE UNIVERSITY

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	Delivery Location Code: NRCHQ US NUCLEAR REGULATORY COMMISSION- MAIL PROCESSING CENTER 4930 BOILING BROOK PARKWAY ROCKVILLE MD 20852 USA Period of Performance: 06/01/2015 to 08/25/2018				

Specific Changes are as Follows:

1. Section A.2 "NRCB030A CONSIDERATION AND OBLIGATION – COST REIMBURSEMENT – NO FEE ALTERNATE I" is deleted in its entirety and replaced with the following:

"A.2 NRCB030A CONSIDERATION AND OBLIGATION—COST-REIMBURSEMENT – NO FEE ALTERNATE I

(a) The total estimated cost to the Government for full performance under this Task Order is **$1,072,990.00**.

(b) The amount presently obligated by the Government with respect to this Task Order is **$500,209.44**.

(c) It is estimated that the amount currently obligated will cover performance through February 2017.

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

2. Section A.3 "COST SCHEDULE" is deleted in its entirety and replaced with the following:

"A.3 COST SCHEDULE

Period of Performance – 6/1/2015 – 8/25/2018

Description	Total
Cost to Perform Requirements of the Task Order (Purdue)	$95,495
Cost to Perform Requirements of the Task Order (Subcontractor – Ohio State University)	$977,495
Grand Total	**$1,072,990.00"**

3. Section A.6 "NRCF032 TASK/DELIVERY ORDER PERIOD OF PERFORMANCE (SEP 2013)" is deleted in its entirety and replaced with the following:

"A.6 NRCF032 TASK/DELIVERY ORDER PERIOD OF PERFORMANCE (SEP 2013)

This order shall commence on 6/1/2015 and expire on 8/25/2018."

4. Delete Statement of Work in its entirety and replace with the following:

"STATEMENT OF WORK

Post-CHF Heat Transfer at High Pressure and Flow Conditions: Experimental Support for TRACE Model Development

I. BACKGROUND

II.

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 is being used as an audit tool to analyze transient and accident analyses submitted by the vendors and licensees. Two post-CHF flow regimes, inverted annular and inverted slug film boiling, are the focus of the task order. In particular, this task order 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 loss of coolant accidents (LOCA), 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 NRR and NRO 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 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. Also, the transition from the ISFB to the dispersed flow film boiling (DFFB) regime will 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.

This task order addresses these data needs for wall heat transfer and void fraction measurements for the IAFB and ISFB post-CHF regimes for high pressure and high flow conditions. Specifically, steady-state experiments will 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 will 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 will be conducted to provide coverage where the transient rod bundle tests may be too rapid to allow for accurate measurement of subchannel averaged void fractions using the gamma-ray tomography system,

- A systematic variation of pressure will 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 will 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 was included to enhance the shared understanding of the task at hand and was used in developing the requirements detailed below.

On April 28, 2015, task order #3 of NRC-HQ-13-C-04-0022 was awarded to Purdue University with the Ohio State University as a subcontractor. This revised statement of work adds task #6 to the subject task order.

Specifically, this added task completes the investigation of post-CHF flow regimes through the inclusion of the dispersed flow film boiling (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 this additional task.

III. OBJECTIVE

The objective of this task order is to provide the experimental database necessary for the improvement of the TRACE models for inverted annular and inverted slug film boiling. 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. This effort will also support the implementation of the droplet field into TRACE by determining the conditions at the onset of dispersed flow film boiling for reflood conditions. The incorporation of the droplet field is planned for the next major release of TRACE.

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

This objective will be realized by performing 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 being developed at the University of Michigan under Task Order #2 of the THI contract. 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

The objective of task #6 is to provide 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.

IV. WORK REQUIREMENTS

Before detailing the individual tasks, deliverables and milestones that will be required under this task order, a listing of specific requirements that the proposed experimental approach must satisfy are given below. These specific requirements are given in the form of a bulleted list and are organized into the following categories: testing, geometry, and instrumentation requirements.

Testing Requirements:

- 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 from 0.138 MPa [20 psia] to 3.5 MPa [500 psia] to provide suitable data to resolve pressure scaling questions. A higher pressure level, up to 7 MPa [1000 psia], would be preferable if attainable within the task order budget.
- Shall provide for a water flow rate such that the mass flux ranges from 150 to 2,000 (kg/m^2s).
- Shall provide for a parametric variation of inlet subcooling with values up to at least 50 °C.
- Shall be capable of performing steady-state dispersed flow film boiling tests in upflow conditions that:
  - Have inlet mass fluxes in the range of 15 to 100 (kg/m^2s),
  - 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.

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 L/D's.
- 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 L/Ds 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.

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).

  - o 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 cell 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 task order #2 of the THI contract. Specifically,
  - o Consultation with the University of Michigan will be required 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.
  - o 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:
  - o 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.
  - o The facility shall be fabricated so as to allow measurement of the void fraction from just below to just above the bottom quench front.

Should any of the above requirements not be able to be met, the requirement may be waived if it can be demonstrated that the objectives of the experiment can still be met. The individual tasks, deliverables and milestones that will be required under this task order are given below.

Task 1: Flow Loop Design and Construction

The first element of this task is the design of the flow loop and the determination of its operating procedure for the film boiling experiments. A letter report describing the proposed flow loop, its operating procedure, and how the testing requirements given above will be met shall be provided. Upon approval by the NRC project manager, procurement activities and construction of the flow loop may proceed.

Deliverables	**Level of Effort**	**Completion Date**
Letter report describing the design and operating ranges of flow loop.	3 Staff Months	4 months after award
Construction of the flow loop.	8 Staff Months	8 months after NRC approval

It is expected that all capital equipment costs, including those of the test section, will be less than $300K.

Task 2: Test Section Fabrication and Hot Patch Testing

The contractor shall design and fabricate a joule heated tubular test section to meet the testing, geometry and instrumentation requirements stated above. This test section shall employ a directly heated hot patch of the "notch type" described in Attachment #2 to stabilize the quench front. A letter report detailing the design of the test section and its instrumentation shall be delivered to the NRC. Upon approval by the NRC project manager, procurement activities and fabrication of the test section may proceed.

Upon completion of the test section it shall be installed in the flow loop and shakedown testing performed. 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 shall demonstrate correct operation of the hot patch over a wide range of flow conditions. In addition the test section heat loss as a function of wall temperature shall be characterized during these shakedown tests.

A technical review meeting shall be held to discuss the design of the test section, its instrumentation (including the operation of the X-ray radiography system), and the shakedown testing program.

Deliverables	**Level of Effort**	**Completion Date**
Letter report documenting test section design and instrumentation.	2 Staff Months	8 months after award
Technical review meeting.		8 months after award
Test section fabrication.	3 Staff Months	4 months after NRC approval
Hot patch shakedown testing.	3 Staff Months	8 months after NRC approval

Task 3: Advanced Instrumentation System

The objective of this task is the installation, and shakedown testing of the advanced instrumentation measurement system. This task would also account for the packing and shipping costs associated with moving the X-ray radiography system from the University of Michigan (should this task order be placed with a different THI member institution). Similarly, though the University of Michigan has been separately tasked to provide training materials for the instrument, any consulting costs necessary to insure its proper operation in the film boiling test facility shall be borne by the subcontractor for this task order.

Deliverables	**Level of Effort**	**Completion Date**
Installation and shakedown testing of X-ray radiography system in film boiling test facility.	2 Staff Months	2 months after completion of the hot patch shakedown testing

Task 4: Inverted Annular Film Boiling Test Series

The contractor shall conduct a series of steady-state film boiling tests in the film boiling test facility with subcooled inlet conditions targeted at the IAFB regime. The test matrix shall 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]. Finally, if the test matrix for the planned small bundle post-CHF experiment is available at this time, a suitable subset of overlap tests will be conducted.

For each of these pressure, and inlet velocity combination, data scans at steady-state conditions for several different power levels should be performed as follows. First, steady 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.

In addition, the test matrix shall provide for a suitable number of repeat tests to demonstrate the repeatability of the results. The test matrix shall be proposed in a letter report and concurred upon by the NRC project manager. Data generated from these matrix tests shall be provided to the NRC in electronic format to facilitate model development. Specifically, a 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 project manager.

Deliverables	**Level of Effort**	**Completion Date**
Letter report documenting the proposed test matrix.	1/2 Staff Month	18 months after award
IAFB data to be provided in electronic format (see above).	6 Staff Months	27 months after award
Letter report documenting the IAFB test results.	1 Staff Month	28 months after award

Task 5: Inverted Slug Film Boiling Test Series

The contractor shall conduct a series of steady-state film boiling tests in the post-CHF test facility with subcooled inlet conditions targeted at the ISFB regime. The test matrix shall include at least six pressure levels and five inlet velocities. The test matrix and procedure shall be proposed in a letter report and concurred upon by the NRC project manager.

These ISFB experiments shall 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 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 transitioned to dispersed flow.

Data generated from these matrix tests shall be provided to the NRC in electronic format to facilitate model development as described above in Task #4.

Deliverables	Level of Effort	Completion Date
Letter report documenting the proposed test matrix.	1/2 Staff Month	27 months after award
ISFB data to be provided in electronic format.	6 Staff Months	36 months after award
Letter report documenting the IAFB test results.	1 Staff Month	36 months after award

Task 6: Dispersed Flow Film Boiling Test Series

The contractor shall conduct a series of steady-state film boiling tests in the post-CHF heat transfer test facility with two-phase inlet conditions targeted at the dispersed flow film boiling (DFFB) regime. The test matrix shall include the same six pressure levels as the IAFB/ISFB test series and five inlet velocities. The test matrix and procedure shall be proposed in a letter report and concurred upon by the NRC project manager.

Given the constraints of test section maximum temperature limits and hot patch power required to stabilize the quench front, the test section inlet flow quality shall 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 vapor Reynolds numbers and droplet loading factors.

Data generated from these matrix tests shall be provided to the NRC in electronic format to facilitate model development as described above in Task #4.

Deliverables	Level of Effort	Completion Date
Design of DFFB test section.	1 Staff Month	August 31, 2017
Letter report documenting the test section design and the proposed test matrix.	1/2 Staff Month	August 31, 2017
DFFB data to be provided in electronic format.	5.25 Staff Months	August 25, 2018
Letter report documenting the DFFB test results.	1 Staff Month	August 25, 2018

ALL OTHER TERMS AND CONDITIONS REMAIN UNCHANGED

[END of M0003]