INVITATION TO SUBMIT A RESEARCH PROPOSAL ON AN ASHRAE RESEARCH PROJECT

1972-TRP, Data Center Direct-to-Chip Liquid Cooling Resiliency – Failure Modes and IT Throttling Impacts, Liquid Cooling Energy Use Metrics and Modeling

Attached is a Request-for-Proposal (RFP) for a project dealing with a subject in which you, or your institution have expressed interest. Should you decide not to submit a proposal, please circulate it to any colleague who might have interest in this subject.

Sponsoring Committee: TC9.9 Mission Critical Facilities, Data Centers, Technology Spaces and Electronic Equipment; Co-sponsored by: TC 4.10 Indoor Environmental Modeling & TC 7.6 Building Energy Performance

Budget Range: $350,000 may be more or less as determined by value of proposal and competing proposals.

Scheduled Project Start Date: **April 1st. 2026** or later.

All proposals must be received at ASHRAE Headquarters by 8:00 AM, EDT, December 15th, 2025. NO EXCEPTIONS, NO EXTENSIONS. Electronic copies must be sent to rpbids@ashrae.org. Electronic signatures must be scanned and added to the file before submitting. The submission title line should read: 1972-TRP, Data Center Direct-to-Chip Liquid Cooling Resiliency – Failure Modes and IT Throttling Impacts; Liquid Cooling Energy Use Metrics and Modeling and *"Bidding Institutions Name"* (electronic pdf format, ASHRAE's server will accept up to 10MB)

If you have questions concerning the Project, we suggest you contact one of the individuals listed below:

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Contractors who plan to submit a proposal must notify the Manager of Research and Technical Services (MORTS) via email by December 1st. This will ensure that they receive any late or additional information regarding the RFP before the bid due date. Monday, December 1st, 2025, is the deadline for submitting technical inquiries.

All proposals must be submitted electronically. Electronic submissions require a PDF file containing the complete proposal preceded by signed copies of the two forms listed below in the order listed below. **ALL electronic proposals are to be sent to rpbids@ashrae.org.**

All other correspondence must be sent to ddaniel@ashrae.org and shammerling@ashrae.org. In all cases, the proposal must be submitted to ASHRAE by 8:00 AM, EDT, Monday, December 15th, 2025.
NO EXCEPTIONS, NO EXTENSIONS.

The following forms (Application for Grant of Funds and the Additional Information form have been combined) must accompany the proposal:

(1) ASHRAE Application for Grant of Funds (electronic signature required) and
(2) Additional Information for Contractors (electronic signature required) ASHRAE Application for Grant of Funds (signed)

ASHRAE reserves the right to reject any or all bids.

State of the Art (Background)

Proper design of cooling systems that supports mission critical facilities requires intimate knowledge of the equipment. A marked change will be occurring as hybrid and liquid cooled servers in data centers are projected to grow significantly in the coming decade. There are many unanswered questions pertaining to high-availability operation of liquid-cooled IT equipment. For instance, there is currently no published data on acceptable rate-of-rise of liquid temperatures from various failure scenarios associated with the direct-to-chip liquid-cooling systems supporting high-density processors. In addition, the energy savings potential of liquid cooling is substantial, but there is also the potential for liquid cooling to use more energy than air cooling, and liquid cooling products have already entered the market that are not energy efficient. The industry needs information on the various approaches to liquid cooling and the associated energy consumption metrics need to be modeled and presented in a holistic manner.

1. Metrics such as average server mass/ U, average thermal capacitance, heat transfer 'effectiveness', and server time constants, have been published for air-cooled servers[14], but projections have not been made for hybrid and liquid-cooled ITE.

2. Time constants have been calculated for air-cooled servers[14] and are in the range of 5 to 10 minutes. Empirical measurements of time-to-throttle for hybrid/ liquid-cooled servers upon loss of liquid flow are on the order of 30 seconds at 100% CPU utilization[1]. A better understanding of this order-of-magnitude difference in time constants and its impact on resiliency design is needed.

3. The NSF study[1] includes servers with a thermal design power (TDP) up to 160 watts per server. Today's servers have significantly higher TDP, which needs further study.

4. A compact cooling system model developed for heat exchangers and CRAH units[6] can potentially be modified to model both CDUs and direct-to-chip cold plates under both steady-state and transient (failure) conditions.

5. A recent ASME study[8] estimated that migration from a 100% air-cooled to a 25% air/ 75% liquid-cooled data center could reduce facility energy consumption by 27%, with a 15.5% reduction in the whole data center site annualized energy use.

6. Some work has been performed on the modeling of air-cooled CDUs, including "Guidelines and Experimental Hydraulic Performance Evaluation for Single-Phase CDUs Under Steady and Transient Events"[9] , and "Advances in IBM Z Water Cooling z13, z14, z15"[10].

7. Efficiency metrics for data centers have typically been applied to air-cooled data centers. Some metrics, such as TUE, may be better suited to liquid-cooled data centers[7,8].

Advancement to the State-of-the-Art:

Advancement to the state-of-the art in liquid cooling, both with regard to redundancy and resiliency, and to energy consumption, is expected in the following ways:

Redundancy and Resiliency:

At its core, those involved with the design and operation of data centers supporting liquid cooling need to provide systems that will keep the critical liquid-cooled IT infrastructure operational in the instance of "common failure scenarios". Some research has been carried out in this regard, but it needs to be expanded to include the latest processors and servers on the market.

A major concern that can be remedied by this research is that while redundant and resilient systems have been designed into data centers that are air-cooled, and the value of these redundant systems probably runs into the hundreds of billions of dollars on a national scale, it is likely that this existing infrastructure will fail to prevent the failure of liquid-cooled systems. A more detailed understanding of the failure modes and time constants of liquid-cooling failures will aid in the design of more resilient infrastructure, and hopefully provide the same level of resilient design for hybrid- and liquid-cooled ITE as exists for air-cooled ITE.

Metrics that are expected to be modeled, measured, and published as part of this research include:

The impact of partial and full loss of liquid coolant flow in the Technology Cooling System, or TCS loop, with high IT chip heat rejection levels (up to 1000 watts per chip, exact values to be chosen after Phase 1 research is complete).

The ability of 'standard thermal ride-through backup systems' to provide short-term backup in failure scenarios such as TCS or FWS pump failure.

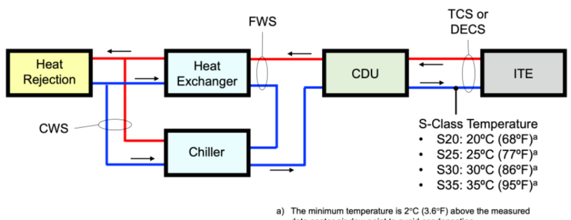
Suggestions on improvements to 'state-of-the-art' thermal resiliency to allow back-up systems to respond quickly to liquid cooling system component failures and avoid server performance throttling or failure.

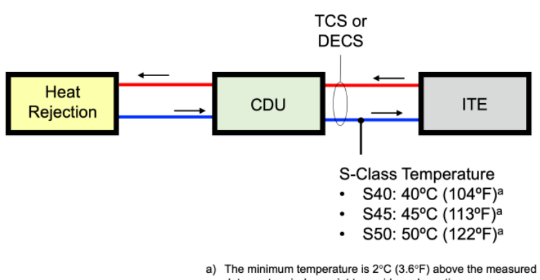
Most direct-to-chip liquid-cooled servers also have air-cooling requirements. The modeling will be able to determine how the failure time constants vary as a function of the percentages of heat rejection to the liquid loop (such as 50%, 75%, 90%).

Liquid-to-air CDU's typically reject the TCS loop heat to the data center environment, such as to the hot aisle. While Phase 3 testing of air-cooled CDUs is not expected as part of this contract, Phase 2 thermal modeling to determine the thermal time constants associated with CDU fan failure is included. In lieu of Phase 3 testing, the bidder shall calibrate the model to detailed thermal data obtained from manufacturers.

Energy Consumption:

There are several liquid temperature classes defining the liquid supply temperature to the chip. These classes (as defined in ASHRAE's Liquid Cooling Book 4[18]), are: S20, S25, S30, S35, S40, S45, and S50. The following diagrams (also from reference 18) show typical cooling/ heat rejection routes for these cooling classes.





Currently, there are five primary product types/ systems for removing liquid-cooled processor heat from a data center. They are:

Liquid (from chip)-to-air heat exchanger (with heat rejected to the data center space)
Liquid (from chip)-to-cold liquid heat exchanger (through CDU, with rejection to chilled water loop)
Liquid (from chip)-to-warm liquid heat exchanger (through CDU, with rejection to cooling tower)
Liquid (from chip)-to-warm liquid heat exchanger (through CDU, with rejection to dry cooler)
Liquid (from chip)-to-air heat exchanger (with reclaimed heat used for office building heating, etc.)

The energy consumption of each type of liquid heat rejection will be modeled for all ASHRAE climate zones[23].

The modeling research will show the energy efficiency associated with the matrix of (a) S-classes[18], (b) heat rejection system types, and (c) ASHRAE climate zones. The preferred energy efficiency metrics will be MLC and ELC, as defined in the most recent ASHRAE 90.4 Standard[20]. The successful bidder will align modeling with existing 90.4 calculations to the extent possible so that the engineers, end users, and the 90.4 SPCC gain insight into the energy impact of liquid vs. air-cooled systems. PUE and TUE metrics will also be modeled, along the lines discussed in (Heydari, 2022)[8].

Justification and Value to ASHRAE

There is currently a lack of detailed engineering information and guidance to aid designers in the design of hybrid- and liquid-cooled infrastructure for data centers. Research is limited on the impact of hybrid- and liquidcooling system failures under specific conditions, and the subsequent rate-of-temperature rise, based on the ability of servers to safely throttle operations and migrate the processing to another facility as needed. Without more comprehensive guidance, engineers will typically overdesign their systems, resulting in stranded capacity, more expensive infrastructure, and higher energy consumption / USEPA Scope 2 greenhouse gas emissions. Scope 3 emissions will also increase since more cooling hardware will be installed. In addition, due to the 'explosive' growth rate anticipated for liquid cooling, manufacturers are marketing cooling solutions that do not take full advantage of the energy efficiency gains that are inherent to liquid cooling. Without a single-source analysis, endusers may end up deploying inefficient liquid-cooling solutions without realizing the energy implications.

This research would be used to provide additional guidance to hybrid- and liquid-cooled infrastructure engineers to allow for:

(a) extension of research already completed on air-cooled servers and associated transient failures to both hybrid- and liquid-cooled equipment, especially to processors with high thermal design power (TDP).

(b) the extension of thermal models of air-cooled servers to hybrid- and liquid-cooled servers

(c) the extension of empirical research already completed on hybrid air/liquid cooled server failures to higher TDP equipment.

(d) aligning the above information with existing ASHRAE publications, such as to the liquid cooling inlet temperature classes in ASHRAE's Liquid Cooling[18] publication.

(e) providing designers with the technical information needed to design hybrid- and liquid-cooled system resiliency without overdesign

(f) reducing energy and carbon-reduction impacts of data center cooling infrastructure by providing detailed data on the energy use of various hybrid and liquid-cooled configurations, relative to an air-cooled IT Equipment baseline.

Liquid-cooled IT equipment is new for most design engineers and data center professionals. Additional research is required to ensure predictable, serviceable and compliant solutions.

This research aligns with ASHRAE's Strategic Plan in several ways (please refer to section titled "Applicability to the ASHRAE Strategic Plan").

In addition, the research would allow for updates to several state-of-the-art ASHRAE special publications, as listed below:

ASHRAE Datacom Book 1 Thermal Guidelines for Data Processing Environments[15]: Additional guidance, such as maximum rate-of-rise for liquid cooling, would rely on data from this research.

ASHRAE Datacom Book 2 IT Equipment Power Trends[16]: The transition from air- to hybrid- to liquid-cooled servers is expected in future additions of Book 2. It would be aided by this research project.

ASHRAE Datacom Book 3 Design Considerations for Datacom Equipment Centers[17]: The results of this research would provide basic technical data to aid in addressing the transition to liquid cooling.

ASHRAE Datacom Book 4 Liquid Cooling Guidelines for Datacom Equipment Centers[18]: Technical information relating to resilient design of liquid-cooled servers is expected to be added to Book 4 because of this research.

ASHRAE Datacom Book 6 Best Practices for Datacom Facility Energy Efficiency[19]: Chapter 9 of this publication is devoted specifically to liquid cooling. This book and Chapter 9 specifically would benefit from the results of this study.

ASHRAE 90.4 Energy Standard for Data Centers[20]: The ability of ASHRAE Standard 90.4, to make modifications to the mechanical and electrical load components (MLC/ELC) over time based on the transition from air-cooled to liquid-cooled servers would benefit from the data obtained from this research.

ASHRAE Standard 127[21]. As of this writing, the ASHRAE Standard 127 SSPC has the addition of Cooling Distribution Units (CDUs) to Standard 127, Method of Testing for Rating Air-Conditioning Units Serving Data Center (DC) and Other Information Technology Equipment (ITE) Spaces, under public review. Data and researcher experience gained from the testing of CDUs as part of this research may be of assistance to Standard 127 in establishing and updating the test standard for CDUs.

Objectives

Project Objectives include the following:

Objective 1: Research failure system design for air/liquid hybrid and liquid-cooled IT equipment using models and empirical data.

A major concern in proposing this research is that current practices for cooling system standby power typically do not include UPS back-up for chillers, pumps, and other cooling components. The thermal ride-through of aircooled data centers typically allowed for at least 1 minute, and often several minutes, of cooling system outage before servers would have to reduce their computational performance to protect the devices from damage. The time cushion is likely to be significantly less with liquid cooling, and as such designers need to know what time constants to design for.

Objective 2: Examine ITE power and thermal capacitance impact on IT throttling time, normalized by curb weight and processor/server types.

The time-to-throttle to mitigate component failure is likely associated with the heat rejection requirements of the ITE relative to the thermal capacitance of the product. Some data is available for air-cooled products, but it is expected to be different for hybrid- and liquid-cooled products due to higher heat transfer rates facilitated by liquid cooling.

Objective 3: Assess the impact of TCS loop liquid inlet temperatures (S-classes from the ASHRAE Liquid Cooling Book) on IT throttling time

There is quite a range of liquid inlet temperatures listed in ASHRAE's Liquid Cooling Book[18], ranging from S20 (20^{o} C, 68^{o} F) to S50 (50^{o} C, 122^{o} F). It is not currently known how operation at the different S-classes will impact the IT throttling time in the event of a cooling system failure.

Objective 4: Assess the impact of TCS loop liquid delta t on IT throttling time

There are not any ASHRAE standards relating to the range of TCS loop delta t, but it is expected that this will also impact IT throttling time in the event of a cooling system failure. The successful bidder is expected to determine the range of the Technology Cooling System (TCS) loop delta t for liquid cooling from the literature search (Phase 1), and to model (Phase 2) and test (Phase 3) the impact of a range of flow rates and resultant delta t's on the IT throttling time.

Objective 5: Assess the impact of a hybrid server's liquid-cooling percentage on rate-of-rise and IT throttling time

For direct-to-chip cooling, the liquid cooling system is typically only designed to reject the heat of the main processors. The servers still have fans for air cooling, and the ancillary component heat is still rejected via an air pathway. It is not known how the percentage of heat rejection via liquid vs. air impacts rate-of-rise and IT throttling time. This study is intended to look at the impact of liquid-cooling percentage on rate-of-rise and IT throttling time.

Objective 6: Assess the impact of TCS loop liquid flow rate failure percentage on IT throttling time

Most TCS loops have multiple pumps (or fans) in the CDU. Previous studies have shown that the impact of a full pumping failure has a much greater impact on time-to-throttle than a partial pumping failure. This study aims to examine this impact on high-power chips to determine if the same relationship holds. If so, it would likely impact CDU design.

Objective 7: Conduct a comprehensive analysis (modeling, and where possible testing) of 30+ factor combinations (of the above parameters), as approved in advance by the Project Monitoring Subcommittee.

Since this research aims to study the impact of several variables on rate-of-rise and IT throttling time, it is premature at the RFP stage to fully design a modeling and testing plan. Rather, we expect that the successful bidder will work with the PMS to determine this limited modeling and testing plan, consisting of 30 tests, after single-variable modeling has been carried out.

Objective 8: The energy impact of all the variables listed above will be modeled to aid liquid cooling infrastructure designers on the energy impact of a specific design, and ASHRAE Standard 90.4 on the impact of liquid cooling on MLC and ELC.

Since direct-to-chip liquid cooling products are fairly new, systems to cool them are also fairly new. A number of cooling products are entering the market, and not all of them are optimized for energy efficiency based on the local climate and the applicable ASHRAE liquid cooling classes (W-classes for Facility Water System (FWS) loop, S-classes for the TCS or direct-to-chip loop). The energy modeling performed by the successful bidder will collect data on cooling products/ approaches and determine the design approach that will result in the lowest energy consumption for the facility. The analysis will concentrate on alignment with Standard 90.4's MLC and ELC calculations. It will also examine PUE (Power Usage Effectiveness) and TUE (Total Usage Effectiveness) to pull in the impact of reduced server and cooling system fan energy on energy consumption of the facility as a whole. The analysis will be performed for all ASHRAE climate zones, as listed in ASHRAE Standard 169- 2021[23].

Objective 9: Share information obtained from CDU testing with ASHRAE Standard 127 SSPC.

As of this writing, the ASHRAE Standard 127 SSPC is working on adding Cooling Distribution Units (CDUs) to Standard 127, Method of Testing for Rating Air-Conditioning Units Serving Data Center (DC) and Other Information Technology Equipment (ITE) Spaces[21]. Data from the testing of CDUs as part of this research may be of assistance to Standard 127 in establishing the test standard for CDUs. The successful contractor for this research shall reach out to the Standard 127 SSPC to determine how CDU data collection can best be tailored for use by the committee, and all CDU performance data shall be shared.

Scope:

The research project shall be comprised of 4 phases: a literature search, computer modeling, laboratory testing, and real-world failure report/ energy efficiency reporting.

Phase 1, Literature search to further identify state-of-the-art as it relates to the impact of infrastructure failures on the performance of liquid-cooled IT equipment. Hybrid liquid/air-cooled and liquid-cooled ITE product specifications, as well as CDUs, will be reviewed and summarized so that design ranges for common parameters, such as those investigated in this study, are obtained to bracket the work of subsequent phases. Papers depicting the energy attributes of liquid cooling will also be researched.

Phase 2, Computer modeling (CFD for air-side, hydraulic models for liquid side, energy models for both sides) will be developed to model various failure scenarios. Previous papers will be leveraged to build on air-side ITE thermal cooling models. The energy models will leverage existing 90.4 calculations where possible to establish an air-cooled baseline for comparison to the liquid-cooled systems modelled and analyzed.

Phase 3, Laboratory testing will be used to determine the impact of various failure scenarios. Modeling won't be able to fully characterize failure impacts (thus the need for testing). Testing will align with Phase 2 modeling.

Phase 4, Assembling empirical data from existing installations of project partners, including failure and energy data, to normalize data to be manufacturer independent and publishable. More detailed information on each phase is provided below.

Phase 1 Literature and Product Specification Search

Literature search to further identify state-of-the-art as it relates to the impact of infrastructure failures on the performance of liquid-cooled IT equipment. Hybrid liquid/air-cooled and liquid-cooled ITE product specifications will be reviewed and summarized so that design ranges for common parameters, such as those investigated in this study, are obtained to bracket the work of subsequent phases.

A specific item of interest for the failure modeling is the decrease in liquid flow in a pump over time once power is lost to the pump. It is likely that this is not a single value, but rather a value that is at least somewhat correlated with pump size.

A possible model for a liquid server would be to incorporate a liquid-cooled component in parallel with an air-cooled component. For the air-cooled component of the server model, review of (Pardey, 2015(14) is recommended. For the liquid-cooled component of the server model, review of the CRAC model in (VanGilder, 2018[6]) is recommended.

Papers depicting the energy attributes of liquid cooling, such as (Heydari, 2022[8]) will also be researched and summarized.

In addition to the literature search, product specifications related to high-density liquid cooling must also be researched and included in the report to help with the selection of server hardware (or simulated server design) for Phase 2 modeling and Phase 3 testing. Information on servers should include, but not be limited to:

Server Manufacturer and Model Number
Total power draw at maximum utilization (watts)
Maximum heat rejection to liquid (watts)
Number of processors, and maximum processor power
Internal liquid cooling circuitry (parallel, series, combination)
Liquid, and recommended liquid flow rate
Expected liquid delta t through server at maximum utilization
Expected liquid delta p through server at maximum utilization
Information available through DCIM, such as processor temperatures, processor power draw, processor status (100% utilization, idle, throttling)

Product specifications for Cooling Distribution Units (CDUs), both water-cooled and air-cooled, shall also be listed as part of the Phase 1 research. Information on CDUs should include, but not be limited to:

CDU Manufacturer and Model Number
Heat transfer at maximum utilization (watts)
Number of Pumps (number of fans for air-cooled CDUs), and level of flow redundancy (N+?)
List of compatible liquids
Maximum rated liquid flow (FWS & TCS loops)
Fluids and Temperatures for heat transfer rating (FWS supply and return, TCS supply and return)
Fluids and Pressures for heat transfer rating (FWS supply and return, TCS supply and return)
Fluids and Flows for heat transfer rating (FWS, TCS)
Maximum individual pump flow (airflow for air-cooled CDUs)
Maximum individual pump head (air pressure for air-cooled CDUs)
Pump curves for individual pumps (fan curves for air-cooled CDUs)
Pump curve for CDU system at rated flow (aggregate fan curves for air-cooled CDUs)
Thermal storage capacity options, if any

A deliverable of Phase 1 is a report that summarizes all of the researched papers, and all of the product specifications. As part of this effort, recommendations for changes and/or refinements to the scope of subsequent phases shall be made for consideration by the PMS. (However, no changes can be made without written approval from the PMS).

Phase 2 Modeling

Failure Modeling

This phase of the research will provide server and cooling system modeling to allow for a detailed understanding of the impact of cooling system failure modes for hybrid liquid/air cooled and liquid-cooled IT equipment.

1. Model the impact of ITE processor power and effective processor thermal capacitance on time to IT throttling (up to 4 values to be tested, including newer high-power processors, such as up to 1000 watts). Thermal models should match 'off-the-shelf' servers, as researched and reported in Phase 1 of this study, and which can subsequently be tested in Phase 3 of the study. Thermal capacitance to be normalized to simple factors like curb weight and composition of processor/ server types to the extent possible, incorporating hybrid- and liquid-cooled ITE. Model should provide as baseline operation 100% of the manufacturer's recommended flow, and the maximum liquid inlet temperature, as provided in the manufacturer's environmental specifications. The failure mode will consist of loss of 100% of liquid flow for a specified period (such as 120 seconds). Server is assumed to be on UPS with 100% of airflow through the server at the maximum recommended air inlet temperature. Possible concurrent failure of the FWS or air-side cooling to be coordinated with the PMS.

2. Model the impact of the variation in design TCS loop liquid inlet temperatures on time to IT throttling (inlet temperatures of 20ºC [68ºF], 25ºC [77ºF], 30°C [86º F], 35°C [95º F], 40°C [104º F], 45°C [113º F] and 50°C [122º F]), corresponding to Liquid Cooling S-Classes as defined in ASHRAE's Liquid Cooling Guidelines for Datacom Equipment Centers, 3rd Edition[18] (2024).

3. Model the impact of design TCS loop liquid delta t on time to IT throttling (10°C [18º F], 15°C [27º F], 20°C [36º F], and 25°C [45º F], or similar 4 values to be tested, dependent on vendor research carried out during first phase of project). Deviation from the recommended flow for a specific server will likely be required to obtain this information.

4. Model the impact of the percentage of server power absorbed by liquid cooling (50%, 75%, 90% or similar 3 values) on time to IT throttling under conditions of (a) complete liquid cooling failure without air-cooling failure, (b) complete air cooling failure without liquid cooling failure, and (c) concurrent loss of both liquid and air cooling. Operating the server at less than full processor power will likely be required to obtain this data.

5. Model the impact of TCS loop liquid flow rate failures (0%, 25%, 50%, 75% or similar 4 values) on time from failure to IT throttling.

6. Model the impact of a select matrix of the above (at least 30 combinations, with the exact combination to be recommended by the PI based on initial results of individual impacts and approved in advance by the Project Monitoring Subcommittee). Combinations should be capable of being tested in Phase 3 of the research.

7. Model the impact of FWS loop cooling heat rejection failure (such as complete pump or chiller shutdown) on time to IT throttling, assuming that the TCS loop continues operation (TCS loop to have 3 levels of thermal storage). Since FWS loops are likely already in place at test facilities, the Project Monitoring Subcommittee will work with the successful bidder to approve the model of the FWS and TCS loops and associated components.

8. Model the loss of air-cooled CDU fans ((0%, 25%, 50%, 75% or similar 4 values) on time from fan failure to IT throttling.

9. Where CFD is used for modeling air-side components, the successful bidder shall carefully review ASHRAE's Research Report RP-1675[22] for guidance with modeling in a data center environment. The simultaneous modeling of

transient heat loss from a server through air and liquid heat rejection is reasonably novel, and the PMS will provide guidance as needed.

Energy Modeling

The energy modeling baseline for each climate zone (an air-cooled model) shall be obtained from ASHRAE Standards Committee SSPC 90.4. The most efficient air-cooled option for a large data center that includes a chiller and circulating chilled water system shall be the baseline for comparison to the direct-to-chip liquidcooled options.

Each of the following liquid-cooled options shall be examined:
Liquid (from chip)-to-air heat exchanger (with heat rejected to the data center space)
Liquid (from chip)-to-cold liquid heat exchanger (through CDU, with rejection to chilled water loop)
Liquid (from chip)-to-warm liquid heat exchanger (through CDU, with rejection to cooling tower)
Liquid (from chip)-to-warm liquid heat exchanger (through CDU, with rejection to dry cooler)
Liquid (from chip)-to-air heat exchanger (with reclaimed heat used for office building heating, etc.)

The energy modeling will be performed for all ASHRAE Climate Zones[23].

The metrics examined for energy modeling shall include MLC (ASHRAE,2022[20]), ELC (ASHRAE,2022[20]), PUE (Heydari, 2022[8]), and TUE (Heydari, 2022[8]).

For the purposes of data center energy models, the researcher should assume 10 MW of IT cooling is required (as the combination of air-cooled and liquid-cooled heat rejection from the servers) or align with Standard 90.4 model sizes for a large data center.

A deliverable of Phase 2 is a report that summarizes all the modeling performed and results and conclusions of the effort. As part of this effort, recommendations for changes and/or refinements to the scope of subsequent phases shall be made for consideration by the PMS. (However, no changes can be made without written approval from the PMS).

Phase 3 Laboratory Testing

This phase of the research will provide empirical data to allow for the testing of failure modes for hybrid liquid/air cooled and liquid-cooled IT equipment.

Lab Setup
It is expected that the testing lab will require the following equipment:

Air Cooling System

Capacity: sufficient capacity to cool the air-cooled component of hybrid-cooled servers
Flow rate: sufficient flow rate to provide the desired uniform supply air temperature to the servers being tested
Supply Temperature: The system shall be capable of providing desired and uniform supply air temperatures within the recommended temperature ranges of the ASHRAE Thermal Guidelines15 for Classes A1 to A4 (i.e. 18-27º C, or 64.4 to 80.6º F)
Airflow Directivity: A cold-aisle/ hot-aisle arrangement is recommended to allow for uniform supply air temperatures, with a preference for fully-contained cold/hot aisles.
Measurements: ability to measure inlet temperature, discharge temperature, and flow rate to determine air-cooled cooling component of heat rejection
Air cooling source: The air cooling source should be capable of being "failed" for a short period of time, so that the impact of an air-cooling failure in parallel with a liquid-cooling failure can be tested. An example of such a cooling air source would be a CRAH unit with an on-off switch for fan operation. A CRAC unit without the potential to modulate supply temperatures to within +/-1º F will not qualify.

Liquid Cooling System
Capacity: sufficient capacity to cool the liquid-cooled component of hybrid-cooled servers

Flow rate: sufficient flow rate to provide the desired uniform liquid temperature to the servers being tested
Supply Temperature: The system shall be capable of supplying water (or a water/glycol mixture) at the S-Class temperatures defined in the latest ASHRAE Liquid Cooling datacom book.
Failure Simulation: the cooling system shall be capable of operating at 0%, 25%, 50%, 75%, and 100% of specified server flow rates. It is expected that transitions will occur within a 2-second period. Thus, multiple pumps are expected to be better components than variable frequency pumps for modeling flow failure. Variable speed capability, however, is desirable for tuning in specific flow rates.
Measurements: ability to measure inlet temperature, discharge temperature, and flow rate to determine liquid-cooled cooling component of heat rejection
Liquid Cooling Source: Ideally, the system should include a FWS cooling loop, Cooling Distribution Unit (CDU), and TCS cooling loop. It should be possible to fail the FWS loop, the TCS loop, or both. The TCS loop should have at least 3 minutes of thermal storage built into the loop.

Servers and Racks
The testing lab shall have at least one 40U or larger rack capable of housing servers or realistic server simulators during testing. It is expected that at least 4 different servers (or simulated servers) will be tested, and that all can be stored on the single rack.

Measurements: The lab shall be capable of measuring all appropriate processor temperatures. Obtaining these measurements through a DCIM system is acceptable if actual servers are used. The lab shall also be able to determine the time that it takes for a processor to throttle its frequency to avoid overheating. If server simulators are used, the time that it takes between the initiation of a failure test and the time for the simulated CPU or GPU to reach 80ºC (176ºF) shall be considered the equivalent of 'time to throttle'.
Measurement frequency: One-second intervals will be used for data collection, unless initial testing determines that a faster or slower frequency is more desirable. Any proposed changes to measurement frequency shall be approved in advance by the PMS.

Treatment with regard to particulate and biological contamination
The heat exchangers associated with high-density direct-to-chip liquid cooling will typically have small openings and will thus be more susceptible to particulate and biological fouling than larger heat exchangers. Bidders should propose a system to assure uniform TCS loop liquid quality for the duration of the Phase 3 research. This shall include regular testing to assure that cold plate (or cold plate simulator) heat exchange performance stays constant for all tests.

Tests to be performed

Tests will first be run to determine the impact of individual variables on rate-of-rise and time to processor throttling.

Test #1 Processor power as the independent variable. Using design processor power as the variable, determine the rate of rise and time to full throttle. For the 'baseline run' align with the Binghamton University study1 server with a thermal design power (TDP) of 160 watts. Subsequent runs shall incorporate server processors with higher TDP, up to the maximum currently available on the market. Test at least 4 high-power servers from at least 2 manufacturers (or the equivalent server simulators). Server weight and thermal capacitance shall be measured and recorded as part of the test.

Test #2 TCS loop liquid inlet temperatures as the independent variable. Using TCS loop liquid inlet temperatures as the as the variable, determine the rate of rise and time from failure to full processor throttle (or 80ºC (176ºF) with server simulators). Vary the inlet temperatures to align with the most recent ASHRAE Liquid Cooling S-classes (20ºC [68ºF], 25ºC [77ºF], 30ºC [86ºF], 35ºC[95ºF], 40ºC[104ºF], 45ºC[113ºF] and 50ºC[122ºF]). Test with the highest-power processor available unless the testing cannot be performed at all S-classes with that processor.

Test #3 TCS loop liquid delta t as the independent variable. Using TCS loop liquid delta t as the variable, determine the rate of rise and time from failure to full processor throttle. Run these tests only with the S-20 and S-50 classes. The server manufacturer will likely specify the minimum flow rate. These full-failure tests should be run at 1.0x this rate, 1.5x this rate, and 2x this rate. Test with the highest-power processor available.

Test #4 Percentage of server power absorbed by liquid cooling as the independent variable. Using the percentage of server power absorbed by liquid cooling as the independent variable, determine the rate of rise and time from failure to full processor throttle. During these tests, server (or server simulator) power should initially be at 100%. To the extent possible, processor power will then be lowered to 75%, 50%, and 25% of peak power. This test should be performed on all servers (or server simulators) tested, with instrumentation as required to determine the percentage of heat rejected via the liquid and air pathways.

Test #5 The impact of TCS loop liquid flow rate failures (0%, 25%, 50%, 75% or similar 4 values) on time to IT throttling. Tests already performed by (Alkharabsheh[1]) indicate a significant change in server failure (time to throttle) with 50% vs. 100% failure of flow. This testing will be more granular with TCS flows reduced by 25%, 50%, 75% and 100% of design. The test should be performed on all servers tested, with instrumentation as required to determine the percentage of flow reduction for each test.

Test #6 This test will be used to test the interrelationship among the various independent variables listed above. Based on the results of both modeling and the first 5 tests in this phase, a select matrix of at least 30 combinations will be recommended by the PI, and provided to the Project Monitoring Subcommittee (PMS) for review. Once a set of 30 combinations is approved by the PMS, Test #6 can be performed. (Note: this subset may differ from the initial subset of 30 combinations selected during the modeling phase due to results from Phase 3. If so, the contractor should provide an allowance to revisit Phase 2 models to align with Phase 3 tests.

Test #7 FWS loop failure. The FWS loop failure test will be performed in conjunction with a FWS cooling source and a liquid-to-liquid Coolant Distribution Unit (CDU). A total of 3 tests will be performed, with the TCS loop running at 100% capacity with each test. Test #7A will have a TCS loop tank available to provide at least 1 minute of thermal storage. Test #7B will have a TCS loop tank available to provide at least 2 minutes of thermal storage. Similarly, Test #7C will have a TCS loop available to provide at least 3 minutes of thermal storage. The impact of a 100% loss of the FWS pumps for a 75-second, a 150-second, and a 225-second period will be analyzed both for the impact on servers on the initiation of the failure, and the recovery from the failure.

A deliverable of Phase 3 is a report that summarizes all of the tests performed and results and conclusions of the effort. As part of this effort, recommendations for changes and/or refinements to the scope of subsequent phases shall be made for consideration by the PMS. (However, no changes can be made without written approval from the PMS).

Phase 4 Assembling Empirical Data from Project Partners

Assembling empirical data from existing installations of project partners, including failure and energy data, to normalize data to be manufacturer independent and publishable.

Failure Data relating to Liquid-Cooled Systems

Failure data can be difficult to come by, as companies are reluctant to admit that they have failures at all in an industry where 99.999% (5 nines) or higher on-time is the industry expectation. In light of this reluctance to provide failure data, the collection of this data will come from TC9.9 and its IT Subcommittee. The successful bidder will reach out to the current chair of the TC9.9 IT Subcommittee to coordinate data collection and then process the failure data that is returned as an input to the project's final report.

The definition of a failure for the purposes of this research shall be both the throttling of a processor that is liquid cooled, as well as the complete failure of an associated server. (Since the throttling of a processor effectively stops its ability to perform a task, this can be seen as a 'failure' by the external party being served).

The successful bidder will provide suggestions on how data will be collected and recorded in conjunction with the TC9.9 IT Subcommittee.

Energy Data relating to Liquid-Cooled Systems

Empirical energy data should be easier to obtain than failure data. First, it can be trended all the time. Second, most companies will want to advertise their 'PUE' or similar metric, and will likely be interested in providing efficiency data, especially for new energy-efficient technologies and/or cooling systems.

Data to be collected will include:

Power Utilization Efficiency (PUE) (coordinate exact definition of PUE with the PMS)
Total Utilization Efficiency (TUE) (refer to: TUE, a new energy-efficiency metric applied at ORNL's Jaguar, by Patterson, et.al. for definition)[7]

For retrofitted liquid cooling systems, the above metrics will hopefully be available on both a pre- and post-retrofit basis.
For new systems, trending will hopefully be able to differentiate the PUE and TUE for the air-cooled and liquid cooled components of the data center's heat rejection.

Where possible, both new and existing facilities shall establish and document the partial PUE and TUE of the various components of the cooling and heat rejection system to gain further insight into the aggregate PUE and TUE.

<u>Deliverables</u>:
The deliverables are defined with each task in the section above. Bidders must include an itemized checklist confirming that they have included each task/sub-task deliverable in their response.

Progress, Financial and Final Reports, Technical Paper(s), and Data shall constitute the deliverables ("Deliverables") under this Agreement and shall be provided as follows:

a. Progress and Financial Reports

Progress and Financial Reports, in a form approved by the Society, shall be made to the Society through its Manager of Research and Technical Services at quarterly intervals; specifically on or before each January 1, April 1, June 10, and October 1 of the contract period.

The following deliverables shall be provided to the Project Monitoring Subcommittee (PMS) as described in the Scope/Technical Approach section above, as they are available:

Furthermore, the Institution's Principal Investigator, subject to the Society's approval, shall, during the period of performance and after the Final Report has been submitted, report in person to the sponsoring Technical Committee/Task Group (TC/TG) at the annual and winter meetings, and be available to answer such questions regarding the research as may arise.

b. Final Report

A written report, design guide, or manual, (collectively, "Final Report"), in a form approved by the Society, shall be prepared by the Institution and submitted to the Society's Manager of Research and Technical Services by the end of the Agreement term, containing complete details of all research carried out under this Agreement, including a summary of the control strategy and savings guidelines. Unless otherwise specified, the final draft report shall be furnished, electronically for review by the Society's Project Monitoring Subcommittee (PMS).

Tabulated values for all measurements shall be provided as an appendix to the final report (for measurements which are adjusted by correction factors, also tabulate the corrected results and clearly show the method used for correction).

Following approval by the PMS and the TC/TG, in their sole discretion, final copies of the Final Report will be furnished by the Institution as follows:

-An executive summary in a form suitable for wide distribution to the industry and to the public.
-Two copies; one in PDF format and one in Microsoft Word.

c. *Science & Technology for the Built Environment*

One or more papers shall be submitted first to the ASHRAE Manager of Research and Technical Services (MORTS) and then to the "ASHRAE Manuscript Central" website-based manuscript review system in a form and containing such information as designated by the Society suitable for publication. Papers specified as deliverables should be submitted to Research Papers for HVAC&R Research for ASHRAE Transactions. Research papers contain generalized results of long-term archival value, whereas technical papers are appropriate for applied research of shorter-term value, ASHRAE Conference papers are not acceptable as deliverables from ASHRAE research projects. The paper(s) shall conform to the instructions posted in "Manuscript Central" for HVAC&R Research papers. The paper title shall contain the research project number (1972-RP) at the end of the title in parentheses, e.g., (1972-RP).

All papers or articles prepared in connection with an ASHRAE research project, which are being submitted for inclusion in any ASHRAE publication, shall be submitted through the Manager of Research and Technical Services first and not to the publication's editor or Program Committee.

d. Data

Data is defined in General Condition VI, "DATA"

e. Project Synopsis

A written synopsis totaling approximately 100 words in length and written for a broad technical audience, which documents 1. Main findings of research project, 2. Why findings are significant, and 3. How the findings benefit ASHRAE membership and/or society in general shall be submitted to the Manager of Research and Technical Services by the end of the Agreement term for publication in ASHRAE Insights

In addition, this research would also allow for updates to several state-of-the-art ASHRAE special publications and standards, as listed below. The PI/ contractor will NOT be responsible for these updates. They will be performed pro-bono by TC9.9, SPCC90.4, and SPCC127 members.

ASHRAE Datacom Book 1 Thermal Guidelines for Data Processing Environments: Additional guidance, such as maximum rate-of-rise for liquid cooling, would rely on data from this research.

ASHRAE Datacom Book 2 IT Equipment Power Trends: The transition from air- to hybrid- to liquid-cooled servers is expected in future additions of Book 2. It would be aided by this research project.

ASHRAE Datacom Book 3 Design Considerations for Datacom Equipment Centers: The results of this research would provide basic technical data to aid in addressing the transition to liquid cooling.

ASHRAE Datacom Book 4 Liquid Cooling Guidelines for Datacom Equipment Centers: Technical information relating to resilient design of liquid-cooled servers is expected to be added to Book 4 because of this research.

ASHRAE Datacom Book 6 Best Practices for Datacom Facility Energy Efficiency: Chapter 9 of this publication is devoted specifically to liquid cooling. This book and Chapter 9 specifically would benefit from the results of this study.

ASHRAE Datacom Encyclopedia. The Datacom Encyclopedia is currently an on-line version of ASHRAE Datacom Books 1, 2, and 4. The Encyclopedia would be updated by TC9.9 to align with changes to Datacom Books 1, 2, and 4.

ASHRAE 90.4 Energy Standard for Data Centers: The ability of ASHRAE Standard 90.4, to make reductions in the MLC/ELC over time based on the transition from air-cooled to liquid-cooled servers would benefit from the data obtained from this research.

ASHRAE Standard 127. As of this writing, the ASHRAE Standard 127 SSPC is working on adding Cooling Distribution Units (CDUs) to Standard 127, Method of Testing for Rating Air-Conditioning Units Serving Data Center (DC) and Other Information Technology Equipment (ITE) Spaces. Data from the testing of CDUs as part of this research may be of assistance to Standard 127 in establishing the test standard for CDUs.

The Society may request the Institution submit a technical article suitable for publication in the Society's ASHRAE JOURNAL. This is considered a voluntary submission and not a Deliverable. Technical articles shall be prepared using dual units; e.g., rational inch-pound with equivalent SI units shown parenthetically. SI usage shall be in accordance with IEEE/ASTM Standard SI-10.

Level of Effort

Anticipated Funding Level and Duration The estimated cost is $350,000 including the cost of the test facility, materials, and supplies, travels to ASHRAE for reporting as well as the personnel salaries, fringe benefits and overhead. Fringe and overhead cost typically are about 50% of the proposed budget in most research active universities in the U.S. The project is expected to take 36 months.

Other Information to Bidders:

Companies have offered significant in-kind contributions that consist of interaction with the successful bidder and the potential to conduct some/ all of the Phase 3 testing at corporate labs.

The level of CFD modeling required for this project is similar to the level of detail contained in the referenced papers. It is not expected to be a detailed model of the internal features of the IT equipment or piping systems, but rather high-level compact (black-box) models appropriate for data center CFD.

Modeling of air-cooled CDU's (Phase 2) is included in this research, but Phase 3 testing of air-cooled CDU's is NOT included. If bidders are set up for failure testing of air-cooled CDUs, they are free to submit an ADD-ALTERNATE to include this testing.

Evaluation of full immersion liquid cooling systems is NOT included in this RFP.
Evaluation of 2-phase or spray cooling liquid cooling is NOT included in this RFP.

Phase 2 modeling of the energy efficiency of various liquid cooling systems is included in this RFP, but Phase 3 testing of energy efficiency is NOT included.

Please provide a breakout of the cost for each of the 4 phases of this research.

Subject to the approval of the PMS, the successful bidder can undertake limited Phase 3 testing prior to the completion of Phase 2 modeling. The idea here is that testing may be able to establish constants to be used in the modeling phase that result in more accurate models.

The successful bidder is NOT expected to purchase state-of-the-art servers as part of this bid. If servers are loaned or donated, they can be used. Otherwise the successful bidder will construct one or more server simulators under the guidance of the PMS and one or more corporate co-funders for Phase 3 testing, or use server simulators loaned/ owned by the co-funders.

The successful bidder should obtain baseline air-cooled energy efficiency calculations from ASHRAE's Standing Standard Project Committee 90.4, Energy Standard for Data Centers. The contact is Thomas Loxley, Assistant Manager of Standards – Codes, TLoxley@ashrae.org 678-539-1126.

Project Milestones:

No.	Major Project Completion Milestone	Deadline Month

1	Completion of Phase 1: Literature Search and Manufacturer Equipment Surveys	6
2	Completion of Phase 2: Computer Modeling	15
3	Completion of Phase 3: Laboratory Testing	30
4	Completion of Phase 4: Industry Failure Surveys	34
5	Completion of Final Report	36

Proposal Evaluation Criteria

Proposals submitted to ASHRAE for this project should include the following minimum information:

No.	Proposal Review Criterion	Weighting Factor
1	Contractors understanding of work statement as revealed in proposal ▪ Logistical problems associated ▪ Technical problems associated	15%
2	Quality of methodology proposed for conducting research. ▪ Organization of project ▪ Management plan	20%
3	Contractor's capability in terms of facilities ▪ Managerial support ▪ Data collection ▪ Technical expertise	20%
4	Qualifications of personnel for this project ▪ Project team 'well rounded' in terms of qualifications and experience in related work ▪ Project manager directly responsible with experience ▪ Team members' qualifications and experience ▪ Time commitment of Principal Investigator	20%
5	Student Involvement ▪ Extent of student participation on contractor's team ▪ Likelihood that involvement in project will encourage entry into HVAC&R industry	5%
6	Probability of contractor's research plan meeting the objectives of the Work Statement ▪ Detailed and logical work plan with major tasks and key milestones ▪ All technical and logistic factors considered ▪ Reasonableness of project schedule	15%
7	Performance of contractor on prior ASHRAE or other projects (No penalty for new contractors)	5%

References

1. Failure Analysis of Direct Liquid Cooling System in Data Centers, Sami Alkharabsheh, et. all, Binghamton University, National Science Foundation Grant No. IIP-1134867
2. Transient Thermal Response of Servers Through Air Temperature Measurements, Hamza Salih Erden, H. Ezzat Khalifa, Roger R. Schmidt, ASME IPACK 2013-73281
3. Further exploration of a compact transient server model, Zachary M. Pardey, Jim VanGilder, ITHERM.2014.6892433
4. Data Center Temperature Rise During a Cooling System Outage, Paul Lin, Simon Zhang, Jim VanGilder, Schneider Electric White Paper 179 Rev. 0
5. Chip to Chiller Experimental Cooling Failure Analysis of Data Centers Part I: Effect of Energy Efficiency Practices, Alissa, H. A.; Nemati, K.; Sammakia, B. G.; Seymour, M. J.; Tipton, R.; Mendo, D.; Demetriou, D. W.; Schneebeli, K. IEEE Transactions in Components, Packaging and Manufacturing Technology , 2016
6. A Compact Cooling-System Model for Transient Data Center Simulations. James W. VanGilder, Christopher M. Healey, Michael Condor, Wei Tian, Quentin Menusier, 17th IEEE ITHERM Conference. 2018.
7. TUE, a new energy-efficiency metric applied at ORNL's Jaguar. Michael K. Patterson, Stephen W. Poole, Chung-Hsing Hsu, Don Maxwell, William Tschudi, Henry Coles, David J. Martinez, Natalie Bates.
8. Power Usage Effectiveness Analysis of a High-Density Air-Liquid Hybrid-Cooled Data Center, Ali Heydari, Bahared Eslami, Vahideh Radmard, Fred Rebarber, Tyler Buell, Kevin Gray, Sam Sather, Jeremy Rodriguez, IPACK2022-97447, 2022.

9. Guidelines and Experimental Hydraulic Performance Evaluation for Single-Phase CDUs Under Steady and Transient Events, 2023, 22nd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTHERM)
10. Advances in IBM Z Water Cooling z13, z14, z15, 2021, 20th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (iTHERM) The following ASHRAE articles/ publications have been found by utilizing the ASHRAE On-line Bookstore search features and other means:
11. Thermal Mass Availability for Cooling Data Centers During Power Shutdown Khankari, K. 2010. ASHRAE Transactions 116(2)
12. Rate of Heating Analysis of Data Centers During Power Shutdown, Khankari, K. 2011. ASHRAE Transactions 117(1)
13. A Compact Server Model for Transient Data Center Simulations, James W. VanGilder, P.E., Christopher M. Healey, Ph.D., Zachary M. Pardey, and Xuanhang Zhang, ASHRAE Technical Paper DE-13-032
14. Proposal for Standard Compact Server Model for Transient Data Center Simulations, Zachary M. Pardey, Dustin W. Demetriou, PhD, Hamza Salih Erden, PhD, James VanGilder, PE, H. Ezzat Khalifa, PhD, Roger R. Schmidt, PhD, PE. ASHRAE Technical Paper CH-15-036
15. ASHRAE Datacom Book 1 Thermal Guidelines for Data Processing Environments Part of ASHRAE TC9.9 Datacom Encyclopedia. https://datacom.ashrae.org
16. ASHRAE Datacom Book 2 IT Equipment Power Trends
17. ASHRAE Datacom Book 3 Design Considerations for Datacom Equipment Centers Part of ASHRAE TC9.9 Datacom Encyclopedia. https://datacom.ashrae.org
18. ASHRAE Datacom Book 4 Liquid Cooling Guidelines for Datacom Equipment Centers Part of ASHRAE TC9.9 Datacom Encyclopedia. https://datacom.ashrae.org
19. ASHRAE Datacom Book 6 Best Practices for Datacom Facility Energy Efficiency, 2nd Edition. (ASHRAE 2009).
20. ASHRAE 90.4 Energy Standard for Data Centers
21. ASHRAE Standard 127, Method of Testing for Rating Air-Conditioning Units Serving Data Center (DC) and Other Information Technology Equipment (ITE) Spaces.
22. ASHRAE Research Project Report 1675-RP: Guidance for CFD Modeling of Data Centers
23. ASHRAE Standard 169-2021 Climatic Data for Building Design Standards (ANSI Approved)