BNL-224219-2023-TECH

EIC-ADD-TN-051

# Site Ambient Temperatures and Operating Schedules for EIC - Utility CW Considerations

R. Srinivasan

November 2021

Electron-Ion Collider

**Brookhaven National Laboratory**

**U.S. Department of Energy**

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

# DISCLAIMER

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## Introduction/Background

The heat dissipated by the EIC accelerator system and components is ultimately removed by the conventional water-cooling systems that will be ultimately dissipated the waste heat to the atmosphere. An estimated 45 MW of heat will be dissipated to water during full beam operation and that will need to be effectively rejected to the atmosphere.

Approximately 50% of the heat is required to be rejected to a low temperature heat sink that cannot be achieved by an evaporative cooling tower during summer. To operate during these summer months, a secondary chilled water refrigeration system will be required that would increase the cost of the cooling water system. Further, operating chiller compressor in the summer months will increase the energy consumption of the machine.

This analysis is being prepared to evaluate the impact on operating and capital costs on the cooling system for various summer operating schedules while utilizing the most cost-effective scenario of an evaporative cooling system.

The technology selection for the various heat sinks is addressed in a separate write-up and are not expected to change the conclusions of this write-up.

## Evaporative Cooling Supply Temperature Limitations

When designing a new system, the cooling water system supply temperature can be determined from the ambient conditions and reasonable design parameters.

The cooling water supplied at the machine interface ($T_{CW}$) is determined as the sum of the temperature at the outlet of the tower ($T_{TWR}$) and the associated system inefficiencies for the heat exchanger ($T_{TTD}$) as well as loss of performance due to degradation ($T_{Degr}$). These consider the limitations in the heat transfer process as well as operating and maintenance practices.

$$T_{CW} = T_{TWR} + T_{TTD} + T_{Degr}$$

The cooling tower performance can be simplified utilizing reasonable design parameters as

$$T_{CW}\ (F) = T_{WB} + 10$$

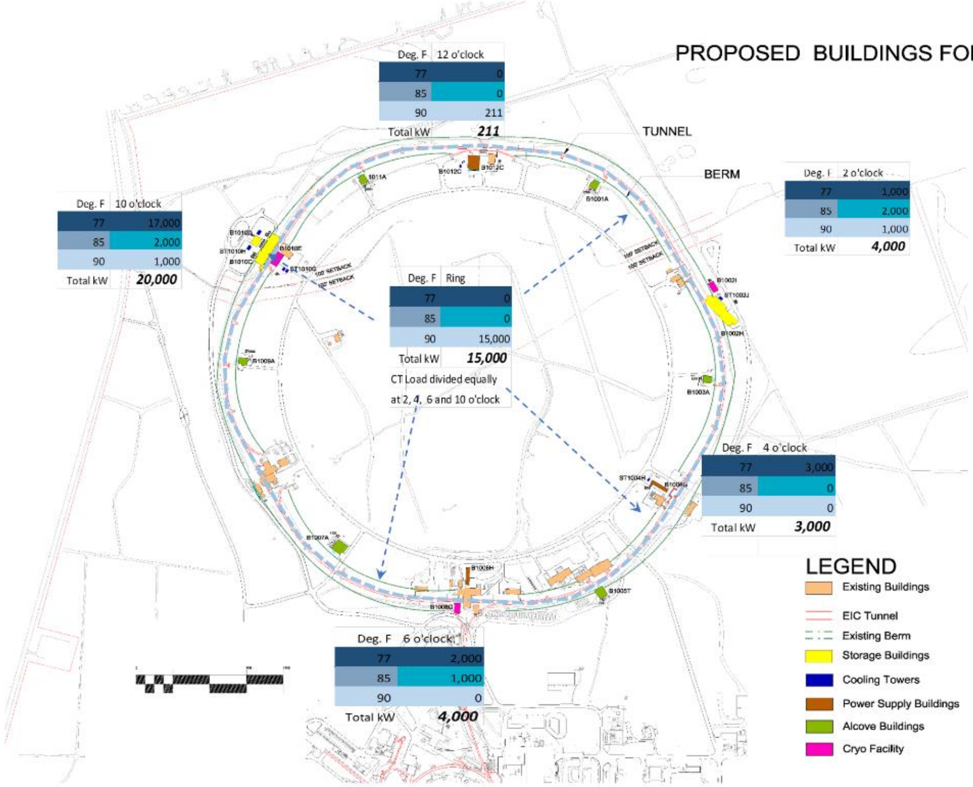
See Appendix 1 for a detailed explanation.

## CW Temperature Profile of EIC Loads

The distribution of EIC machine heat loads at various locations are shown below. Of the 46 MW water heat rejection for the EIC, roughly 23 MW is rejected at a water temperature of 77 Deg. F. The remaining is at either 85 Deg. F or above. An alternative scenario is evaluated where the RF PA is rejected at 86 Deg. F temperature.



R. Srinivasan




At the lower temperature (77F), the critical component is the cooling water for the RF Power Amplifer as required to cool the solid state electronics

| LOCATION | SYSTEM | COOLING LOAD, TONS | CW INLET TEMPERATURE, F |
|---|---|---|---|
| **1010** | ESR H1 RF 591 MHz | 4828 tons | 77 F |
| **1006** | Crab 197 MHz RF System | 610 tons | 77 F |
| **1004** | RCS Bunch Merge 1 RF System [295 MHz]<br>SHC ERL Injector Booster [197 MHz] | 767 tons | 77 F |
| **1002** | SHC ERL H1 RF System [591 MHz] | 399 tons | 77 F |
| | | **6604 TONS** | |

The required inlet and outlet cooling water temperatures are as follows.

| | |
|---|---|
| $T_{CW}, Inlet$ | 77F |
| $\Delta T \quad Rise$ e | 12 F |
| $T_{CW}, Outlet$ | 89 F |

Utilizing the previously derived equation to determine a limiting ambient wet bulb condition,

$$T_{WB}(F) = T_{CW} - 10 = 67 \, Deg. F$$

This is limiting wet bulb is the threshold above which a reasonably designed cooling tower alone is not sufficient to generate 77 Deg. F water and chillers are required to provide the additional cooling water.

At the higher allowable CWIT, the WB threshold becomes

$$T_{WB}(F) = T_{CW} - 10 = 86 - 10 = 76\ Deg.F$$

## Ambient Wet Bulb Temperature and Climatic conditions

It is impractical to utilize an absolute maximum climatic condition for any site and hence statistical methods must be applied to determine the maximum wetbulb temperatures. For this evaluation, the statistical maximum wet bulb temperatures were determined utilizing the methods from Climate Design Conditions in ASHRAE (1). These maximums were determined based on monthly values that are exceeded on average 0.4% (3 hours per month) and 10% (75 hours per month) respectively.

Weather conditions at the BNL site have been recorded locally since August 1948. Temperature measurements are recorded at 85-meter, 10-meter and 2-meter elevations. Temperature and humidity probes located at the 2-m elevation were provided John Heiser (4) and were utilized to determine the 3-hour and 75-hour exceedance values.

### Climate Impacts

To account for changes to the ambient conditions through the estimated operation of the EIC, changes were determined over a 30-year period through to 2050 utilizing the.guidance was provided by Michael Jensen (4). The entire reference is included in Attachment 2A.

Two different Representative Concentration Pathways (RCP) were considered in the analysis each of which represents a different future climate (4). RCP8.5 is often referred to as the “business as usual” scenario and assumes that emissions of greenhouse gases continue to rise at their current rates through the end of the 21st century. RCP4.5 is often described as an intermediate scenario and assumes that mitigation measures are put in place and greenhouse gas emissions peak around the year 2040 and then start to decline.

Incorporating the ambient data and climate change impacts, the maximum ambient temperatures were evaluated in Attachment 3. These values are compared to the Wetbulb threshold for evaporative cooling for both the 25C(77F) and 30C (86F) CWIT and are presented below. Note that the intermediate scenario is shown in parenthesis. Although the RCP 4.5 wet bulb maximums are lower, these were not large enough to change the monthly exceedances.

SCENARIO A (RF POWER AMPLIFIER INLET CW TEMPERATURE MAX =25C (77F)

| | Wetbulb Threshold for Evap. Cooling Deg. F | BNL Site Ambient Projected to 2050* | | | | | |
|---|---|---|---|---|---|---|---|
| | | Max Wet Bulb Deg. F 0.4 % Level Exceeded <3 hrs/month | | | Max Wet Bulb Deg. F 10% Level Exceeded <75 hrs/month | | |
| 1-Jan | **67** | 58.7 | (58.6) | | 44.6 | (44.5) | |
| 1-Feb | **67** | 58.6 | (58.7) | | 47.4 | (47.5) | |
| 1-Mar | **67** | 58.2 | (56.7) | | 48.8 | (47.2) | |
| 1-Apr | **67** | 66.8 | (66.4) | | 56.5 | (56.0) | |
| 1-May | **67** | 73.3 | (73.1) | Exceeded | 65.9 | (65.6) | |
| 1-Jun | **67** | 77.0 | (76.5) | Exceeded | 71.9 | (71.4) | Exceeded |
| 1-Jul | **67** | 82.0 | (81.4) | Exceeded | 77.8 | (77.1) | Exceeded |
| 1-Aug | **67** | 82.2 | (81.4) | Exceeded | 78.4 | (77.6) | Exceeded |
| 1-Sep | **67** | 80.0 | (79.1) | Exceeded | 74.0 | (73.1) | Exceeded |
| 1-Oct | **67** | 74.9 | (73.9) | Exceeded | 68.5 | (67.5) | Exceeded |
| 1-Nov | **67** | 68.1 | (67.7) | Exceeded | 57.1 | (56.7) | |
| 1-Dec | **67** | 60.9 | (60.0) | | 48.1 | (47.3) | |

*Values in parenthesis are based on RCP 4.5 an intermediate scenario with climate mitigation measures in place and assumes that mitigation measures are put in place and greenhouse gas emissions peak around the year 2040 and then start to decline.

As seen in the table above with the lower CWIT of 77F, the threshold Wetbulb for evaporative cooling operation is exceeded (7) months in a year at the 0.4% level and this threshold is exceeded (5) months in a year based at the 10% level and a chiller system would be required for operation during the periods where the cooling tower system is not able to handle.

SCENARIO B (RF POWER AMPLIFIER INLET CW TEMPERATURE MAX =30C(86F))

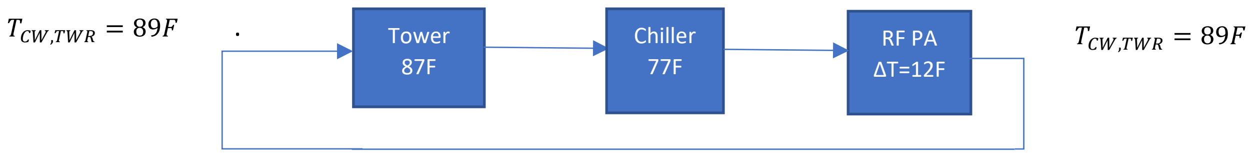
| | eQ RFPA CW Temperature <86F | Equipment Option B RFPA Max Temperature <77F |
|---|---|---|
| Jan | 58.7 | 58.7 |
| Feb | 58.6 | 58.6 |
| Mar | 58.2 | 58.2 |
| Apr | 66.8 | 66.8 |
| May | 73.3 | 73.3 E |
| Jun | 77.0 | 77.0 E |
| Jul | 82.0 E | 82.0 E |
| Aug | 82.2 E | 82.2 E |
| Sep | 80.0 E | 80.0 E |
| Oct | 74.9 E | 74.9 E |
| Nov | 68.1 | 68.1 E |
| Dec | 60.9 | 60.9 |

As seen in the table above with the higher CWIT of 86F, the threshold Wetbulb for evaporative cooling operation is exceeded (4) months in a year at the 0.4% level and this threshold is exceeded (1) months in a year based at the 10% level and a chiller system would be required for operation during the periods where the cooling tower system is not able to handle.

## Chilled Water System

The conventional alternative to a cooling tower system is to utilize a chilled water system to cool the water to the desired temperature. This can be either a stand-alone chiller that takes the entire cooling load or a supplemental chiller such as in NSLSII where part of the cooling is done in a cooling tower and the rest is done by a chiller.

Illustrating the NSLS-II supplemental chiller concept 77F water leaving the chiller returns at a temperature of 89F as shown. The cooling tower can supply only as good as 87F on a hot summer day.




| | |
|---|---|
| *Maximum Heat Rejection Across Cooling Tower* | 15% |
| *Remaining Heat Rejected by Chiller* | 85% |

Utilizing the NSLSII concept, the cooling tower would only be able to reject about 15% of the load on a hot summer day where the wetbulb temperature is at or above 78 Deg. F Incorporating such a loop would incur additional capital expenditure and introduce a complex system with many operating parts which would not improve the reliability of the system for a 15% reduction in chiller cost. Furthermore, for a given load, the cooling tower operating on a narrow 2F temperature rise is significantly more costly compared to a higher range according to reference 5. This option is not considered and a stand-alone chiller is considered.

## Capital Costs

For the purpose of this analysis, the additional capital cost to supply 77 Deg. F during the summer was determined based on installing new chillers instead of the plate and frame heat exchanger system. This change essentially comprises of the following.

### The differential cost of installing the new chillers in place of the heat exchangers

This was estimated based on unit costs for a horizontal centrifugal water cooled chiller system including the associated pumps and piping scaled to the required tonnage. Since the chiller system essentially replaces the plate and frame heat exchanger system, the cost for a plate and frame heat exchanger based system from was subtracted from the chiller cost. Details of the estimate are shown in Appendix 5.

### Additional substation to handle the additional power requirements of the chillers were added as follows.

(1) 2500 kVA/480V Substations were assumed to handle the additional auxiliary power at Bldg 1010

(3) 1000 kVA/480V Substations were assumed to handle the additional auxiliary power at Bldg 1002, 1004 and 1006.

These costs were determined from the HDR (3).

### Additional building square footage due to the installed chillers.

An additional 2,000 sq.ft additional space for 4000 tons of chilling at building 1010 based on TRANE'S Centravac model CVVH with direct drive compressors. The other buildings are estimated to require 400 sq. ft additional space. The unit cost of the additional square footage of $382 was determined and used for this purpose based on the HDR estimate(3).

Utilizing the basis described above, the differential cost estimate was developed and summarized below more details can be found in appendix 5

| LOCATION | SYSTEM | COOLING LOAD, TONS | AUX PWR ADD, KW | INCREMENTAL COST FOR CHILLED WATER SYSTEM * |
|---|---|---|---|---|
| **1010** | ESR H1 RF 591 MHz | 4828 tons | 2400 kW | |
| **1006** | Crab 197 MHz RF System | 610 tons | 500 kW | |
| **1004** | RCS Bunch Merge 1 RF System [295 MHz] | 767 tons | 600 kW | |
| | SHC ERL Injector Booster [197 MHz] | | | |
| **1002** | SHC ERL H1 RF System [591 MHz] | 399 tons | 300 kW | |
| | | **6604 TONS** | **3700 KW** | **$ 13.9 MIL** |

## Additional Electricity Consumption Costs due to the Chiller Compressors.

Furthermore, operating the chiller compressors requires additional electrical energy translated to present value cost of $3.2 million over a 20-year operating life (7).

## Analysis of Historical CW Operating Data from RHIC

A comparison was made looking at existing cooling tower performance from Summer 2020 at RHIC. The performance of these cooling towers track well with the Wetbulb determined from Brookhaven Met. Data (5) and the effective approach of the cooling towers to the ambient wet bulb seems to mostly fall within a 5 to 10 Deg. F approach. Various factors such as the load on the system, prevailing wind, recirculation excessive makeup flow and other conditions as well as general performance degradation can affect these operating parameters. See Appendix II cooling tower benchmark with operating performance.

## Results and Conclusion

The low cooling water inlet temperature required by the RF power amplifier will require additional installation costs for the chilled water system to be able to operate for year-round operation.

Alternatively, if a decision is made to limit the operation of the chiller, that will require the EIC operation to be curtailed during the summer months. This decision will need to be made in conjunction with the acceptable monthly exceedance.

| | With Chillers | Without Chillers | |
|---|---|---|---|
| Scenario A | IA | IIA | IIIA |
| **Desired CW Inlet Temp at RF PA** | **77F** | | |
| Wetbulb Threshold | 67F | | |
| Average Monthly Exceedance | None | <3 hrs/month | <72 hrs/month |
| Available Weeks | 52 | 22 | 30 |
| Months Above WB Threshold | None | May to Nov | Jun to Oct |
| Additional Costs Above CD-1 ($ mil) | $13.9 mil | $ - | $ - |
| PV of addnl energy consumption | $3.2 mil | $ - | $ - |

| | With Chillers | Without Chillers | |
|---|---|---|---|
| Scenario B | IB | IIB | IIIB |
| **Desired CW Inlet at RF PA** | **86F** | | |
| Wetbulb Threshold | 76F | | |
| Average Monthly Exceedance | None | <3 hrs/month | <72 hrs/month |
| Available Weeks | 52 | 34 | 43.3 |
| Months Above WB Threshold | None | Jun to Sep | Jul to Aug |
| Additional Costs Above CD-1 ($ mil) | $13.9 mil | $ - | $ - |
| PV of addnl energy consumption | $3.2 mil | $ - | $ - |

## References.

1. ASHRAE Fundamentals, 2017 Chapter 14: Climatic design information.
2. Power Burns and Roe (2014), Final Report Satellite chiller plant feasibility study prepared for Brookhaven National Lab
3. HDR Estimate HDR BNL Ion Collider - 100% Budget REV3.4 11.05.2020
4. Heiser, John H. Environmental and Climate Sciences Department, RE: Meterological Data at Brookhaven, Hourly Data, Message to Ram Srinivasan. 7 March 2021
5. SPX Cooling Technologies, Inc., Cooling Tower Fundamentals (2009), Second Edition
6. Jensen, Mike. Environmental and Climate Sciences Department, Climate Projections for BNL Electron Ion Collider Cooling Tower Consideration Message to Ram Srinivasan, 3 May 2021)
7. Life Cycle cost evaluation basis for cooling system EIC (In progress)

# Appendix 1
# Cooling Tower Performance

When designing a new system, the cooling water supplied at the machine interface ($T_{CW}$) is determined as the sum of the Wet Bulb temperature and the reasonable design parameters for the heat exchangers..

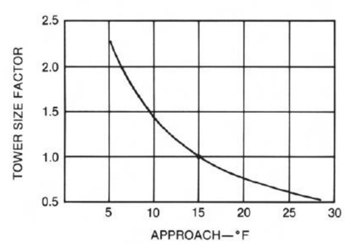
$$T_{CW} = T_{TWR} + T_{TTD} + T_{Degr}$$

The evaporative cooling tower temperature performance $T_{TWR}$ can be determined as the sum of the Air Inlet at the Tower $T_{WB}$, recirculation effects $T_{RCW} = 2F$, and the cooling tower approach to this temperature $T_{Appr}$ which is a heat exchanger inefficiency.

$$T_{TWR} = T_{WB} + T_{RCW} + T_{Appr}$$

In selecting the design of the cooling tower, its size increases asymptotically as $T_{Appr}$ reaches 5F. Furthermore, cooling tower vendors do not guarantee values less than 5 F. A value of 5F is utilized for the design of the cooling tower and that determines the cooling tower heat exchange/fill surface area.

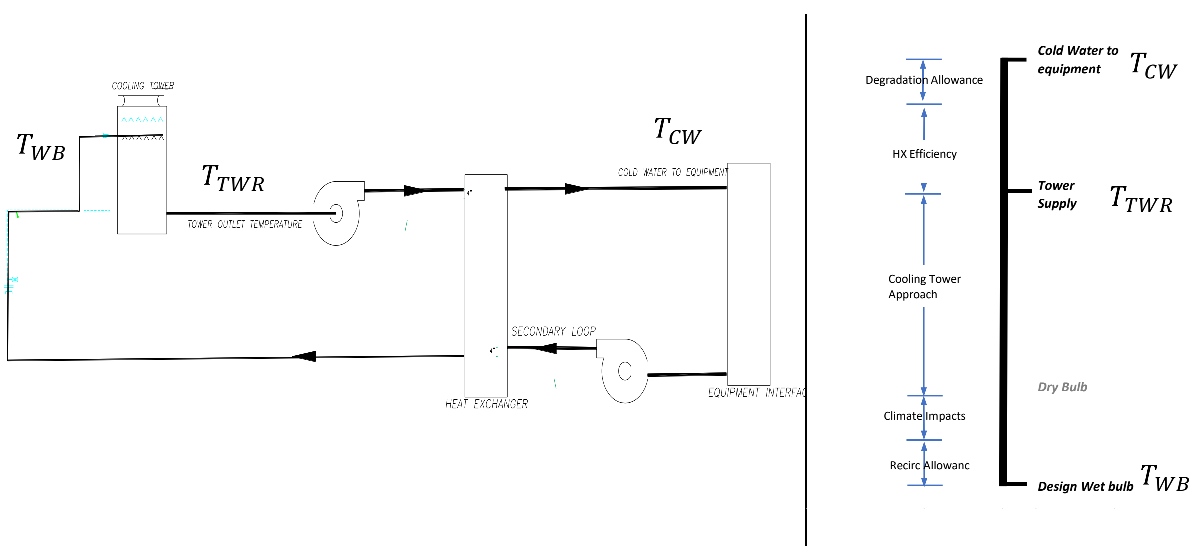
<u>Cooling Tower Size As A Function of Design Cooling Tower Approach SPX Cooling Technologies(5).</u>




Finally, adding a reasonable design efficiency of the plate and frame heat exchanger $T_{TTD} = 2F$ and degradation effects $T_{Degr} = 1F$, we can determine the CW supply temperature $T_{CW}$ as

$$T_{CW}\ (F) = T_{WB} + T_{RC} + T_{App} + T_{TTD} + T_{Degr} = T_{WB} + 11$$

These cumulative impacts are shown in the typical cooling tower configuration shown in the figure below.



# Appendix II

## Determination of Maximum Wetbulb Temperatures (Through 2050)

Weather conditions at the Brookhaven National Laboratory (BNL) site have been recorded since August 1948. Monitoring of current weather conditions at BNL is maintained by Meteorology Services and is reported in real-time. Temperature measurements are recorded at 85-meter, 10-meter and 2-meter elevations. Hourly data for the Temperature and humidity probes located at the 2-m elevation were provided by John Heiser (3).

The dry-bulb temperature and relative humidity values were used to calculate the wet-bulb temperature using the method described in Appendix IIA. These values were compared to the ASHRAE 0.4% and 10% exceedances for the region from the 20-year data for Suffolk County as measured at Long Island McArthur Airport ASHRAE (1). The BNL values bound the ASHRAE values and were utilized in determining the maximum wet bulb temperatures. Furthermore, the BNL meterological data is local to the intended cooling tower location and tracks fairly well with the performance of the existing cooling towers around the RHIC facility.

| | **ASHRAE Suffolk County Wet Bulb Maximum Historical** | | **BNL Met (1) Wet Bulb Maximum Historical 2016-2020** | |
|---|---|---|---|---|
| | **< 3 hrs/mth** | **< 75 hrs/ mth** | **< 3 hrs/mth** | **< 75 hrs/ mth** |
| **1-Jan** | 54.9 | 43.3 | 56.8 | 42.7 |
| **1-Feb** | 51.3 | 41.5 | 57.0 | 45.7 |
| **1-Mar** | 58.6 | 46.9 | 55.9 | 46.3 |
| **1-Apr** | 63.3 | 53.4 | 65.0 | 54.5 |
| **1-May** | 71.8 | 62.4 | 71.5 | 63.8 |
| **1-Jun** | 76.1 | 70.3 | 74.8 | 69.8 |
| **1-Jul** | 79.3 | 74.1 | 80.1 | 75.8 |
| **1-Aug** | 78.3 | 73.8 | 80.0 | 76.1 |
| **1-Sep** | 75.6 | 70.3 | 77.4 | 71.5 |
| **1-Oct** | 71.8 | 63.0 | 72.1 | 65.7 |
| **1-Nov** | 62.4 | 55.4 | 65.8 | 54.9 |
| **1-Dec** | 57.2 | 47.3 | 58.7 | 44.6 |

(1) BNL Met Twr 2m Hrly data (5)

The Maximum Wetbulb temperatures were projected to 2046-2050 utilizing the temperature and humidity guidance provided in Appendix II-A. The maximum wetbulb was calculated for both pathways explained in Appendix 2 A RCP 4.5 Intermediate Case and RCP 8.5 Business As Usual scenarios

| | BNL Met (1,2) Wet Bulb Maximum Projected to 2046-50 | | | |
|---|---|---|---|---|
| | **Scenario 1 RCP 8.5 “business as usual”** | | **Scenario 2 RCP 4.5 “intermediate case”** | |
| | < 3 hrs/mth | < 75 hrs/ mth | < 3 hrs/mth | < 75 hrs/ mth |
| **1-Jan** | 58.7 | 44.6 | 58.6 | 44.5 |
| **1-Feb** | 58.6 | 47.4 | 58.7 | 47.5 |
| **1-Mar** | 58.2 | 48.8 | 56.7 | 47.2 |
| **1-Apr** | 66.8 | 56.5 | 66.4 | 56.0 |
| **1-May** | 73.3 | 65.9 | 73.1 | 65.6 |
| **1-Jun** | 77.0 | 71.9 | 76.5 | 71.4 |
| **1-Jul** | 82.0 | 77.8 | 81.4 | 77.1 |
| **1-Aug** | 82.2 | 78.4 | 81.4 | 77.6 |
| **1-Sep** | 80.0 | 74.0 | 79.1 | 73.1 |
| **1-Oct** | 74.9 | 68.5 | 73.9 | 67.5 |
| **1-Nov** | 68.1 | 57.1 | 67.7 | 56.7 |
| **1-Dec** | 60.9 | 48.1 | 60.0 | 47.3 |

(1) BNL Met Twr 2m Hrly
(2) Global Warming impacts taken into account based on Appendix 2A.

# Appendix II-A

# Climate Projections for BNL Electron Ion Collider Cooling Tower Consideration

**Climate Projections for BNL Electron Ion Collider Cooling Tower Consideration**

Prepared by Michael P. Jensen (mjensen@bnl.gov)

In preparation for the construction of the Electron Ion Collider at BNL, particularly the design of the accompanying cooling tower(s), the climate in the Suffolk County region including the temperature and humidity over the projected lifetime of the towers (~30-40 years) should be considered.

**Dry-Bulb Temperature**

To provide guidance for these considerations, we have culled data from the peer-reviewed literature based on climate model simulations. Data and visualization available from the New York Climate Change Science Clearinghouse (https://nyclimatescience.org) provides information on time series of observations (past) and model-derived projections (future) of dry-bulb air temperature and precipitation amount. The “Climate Data Grapher” (https://nyclimatescience.org/highlights/data_products) is used to visualize these datasets for Suffolk County, Long Island, NY. The model projected data are from the Climate Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) downscaled using the Localized Construct4d Analog method for Suffolk County. Two different Representative Concentration Pathways (RCP) are considered in the analysis each of which represents a different future climate (Collins et al. 2013). RCP8.5 is often referred to as the “business as usual” scenario and assumes that emissions of greenhouse gases continue to rise at their current rates through the end of the 21st century. RCP4.5 is often described as an intermediate scenario and assumes that mitigation measures are put in place and greenhouse gas emissions peak around the year 2040 and then start to decline. The higher emission scenario case would be expected to result in greater climate change and warmer temperatures.

Using these the Climate Data Grapher, Table 1 summarizes the model ensemble mean dry bulb temperature projected for the period 2016-2020 and 2046-2050 for the two RCPs discussed above.

| | RCP 8.5 | | | RCP 4.5 | | |
|---|---|---|---|---|---|---|
| Month | *Temp. (16-20) | Temp. (46-50) | Increase | *Temp. (16-20) | Temp. (46-50) | Increase |
| January | 32.9 | 34.9 | 2.0 | 32.8 | 34.7 | 1.9 |
| February | 34.7 | 36.5 | 1.8 | 33.8 | 35.7 | 1.9 |
| March | 40.9 | 43.6 | 2.7 | 41.3 | 42.4 | 1.1 |
| April | 50.4 | 52.6 | 2.2 | 50.4 | 52.1 | 1.7 |
| May | 60.1 | 62.4 | 2.3 | 60.0 | 62.0 | 2.0 |
| June | 69.7 | 72.1 | 2.4 | 69.6 | 71.5 | 1.9 |
| July | 75.1 | 77.4 | 2.3 | 75.5 | 77.1 | 1.6 |
| August | 74.2 | 76.8 | 2.6 | 74.3 | 76.0 | 1.7 |
| September | 67.4 | 70.2 | 2.8 | 67.4 | 69.3 | 1.9 |
| October | 57.0 | 60.0 | 3.0 | 56.9 | 58.9 | 2.0 |
| November | 47.3 | 49.7 | 2.4 | 47.1 | 49.1 | 2.0 |
| December | 38.1 | 40.7 | 2.6 | 37.7 | 39.4 | 1.7 |

**Table 1** Model Ensemble Mean Dry-Bulb Temperature for Suffolk County, New York (Note: The small differences in the 2016-2020 temperatures for the two scenarios are because these temperatures are based on model simulations that were initialized prior to 2016-2020).

**Relative Humidity**

Unfortunately, the Climate Data Grapher does not include data on relative humidity. Instead we refer to the work of Byrne and Gorman (2018) who use the Met Office Hadley Centre's observational dataset (HadISDH; Willet et al. 2016) to analyze global trends in relative humidity over land and ocean. Their analysis suggests an decreasing trend in relative humidity of 0.22 % per decade over land.

**Methods**

These projected changes in temperature and relative humidity are applied as offsets to a 5 year dataset of dry-bulb temperature and relative humidity collected by the BNL Meteorological Services Group (https://www.bnl.gov/weather/). From these climate-adjusted dry-bulb temperature and relative humidity values the wet-bulb temperature is calculated using the empirical equation published by Stull (2011). From the climate-adjusted wet-bulb temperatures, projected times of exceedance can be determined for user defined threshold values.

**References**

Byrne, M. P. and P. A. O'Gorman, 2018: Trends in continental temperature and humidity directly linked to ocean warming. *Proc. Nat. Acad.. Sci*., **115(**19), 4863-4868. doi:10.1073/pnas.1722312115.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Com- mitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stull, R., 2011: Wet-bulb temperature from relative humidity and air temperature. *J. Appl. Meteor. Clim*., **50** (11), 2267-2269. doi:10.1175/JAMC-D-11-0143.1.

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Willett KM, et al., 2014: HadISDH land surface multi-variable humidity and temperature record for climate monitoring. *Clim Past,* **10**,1983–2006.

# Appendix 3
# Comparison of Current Operating Data

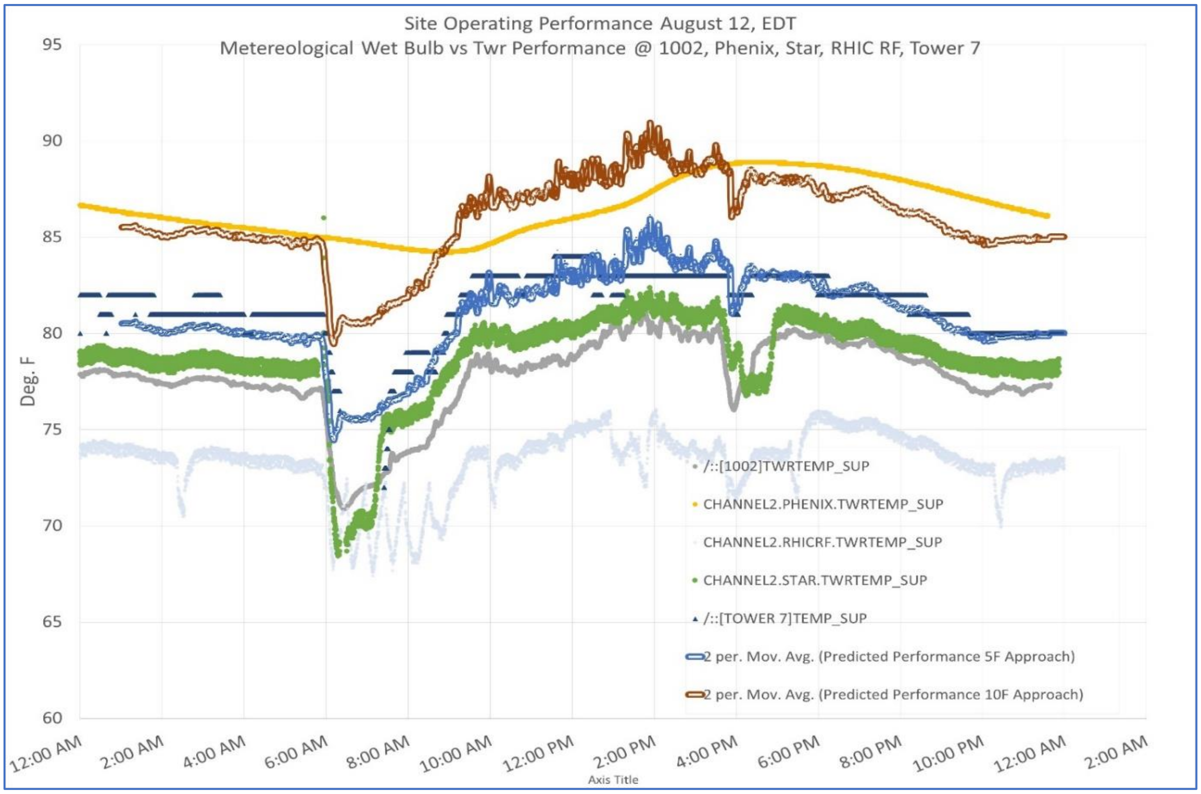
Recent operating performance for the cooling towers at RHIC were compared to a hypothetical cooling tower simulation based on a 5 Deg. F approach and a 10 Deg.F approach to Wet Bulb for that day. The performance of the existing cooling towers closely track the site ambient wet bulb (BNL met data) and the CW supply temperatures generally bounded within the 5 Deg. F to 10 Deg. F approach to Wet Bulb temperature.

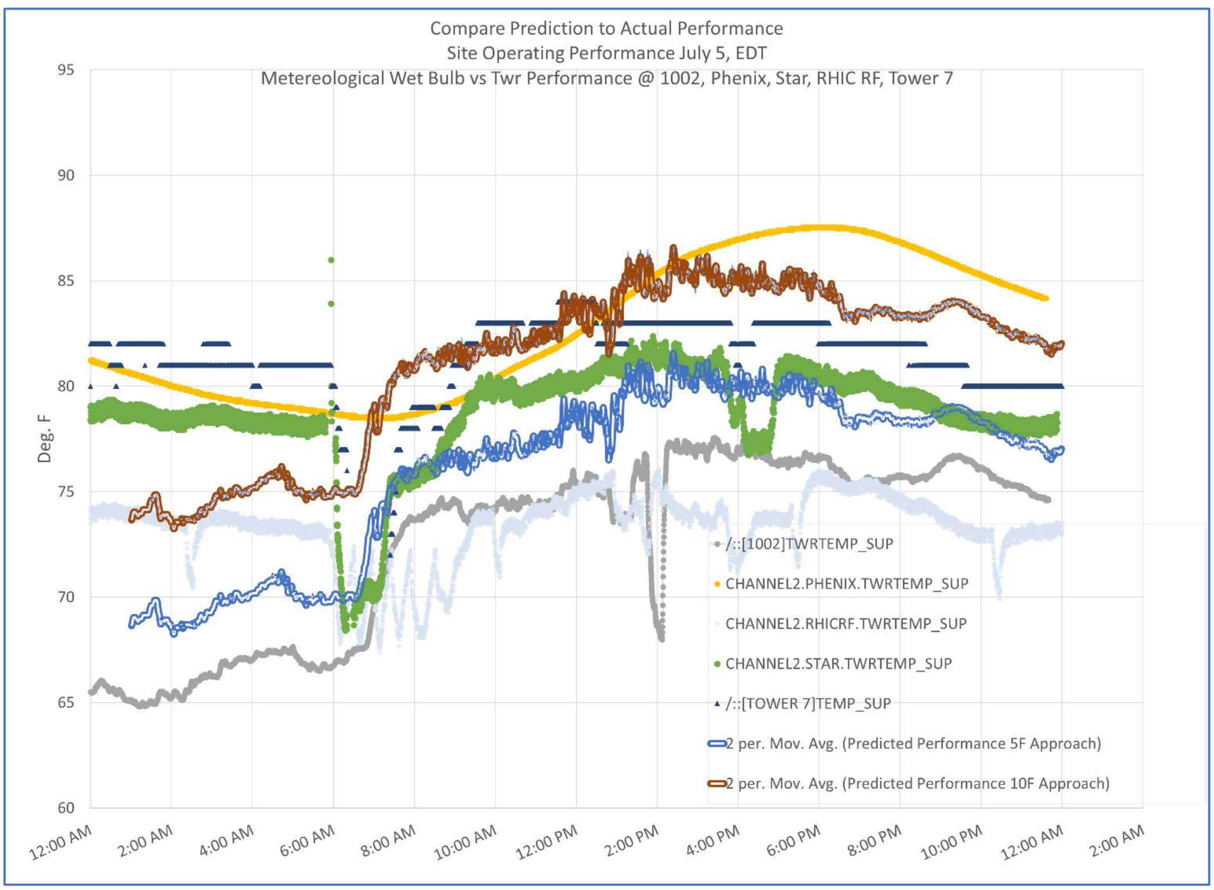
Various factors such as the load on the system, prevailing wind, recirculation excessive makeup flow and other conditions as well as general performance degradation can effect these operating parameters. Of these towers, the Phenix Tower which does not perform as the other towers has consistently shown to have operating performance issues for various factors that are not considered to impact this evaluation.

The following cooling tower performance were compared.

- Cooling Tower at 2’ O Clock (1002)
- Cooling Tower near 4’ O Clock (RHIC RF Tower)
- Cooling Tower near 6’ O’ Clock (Star Tower and Tower 7)
- Cooling Tower near 8’ O Clock (Phenix Tower)


The operating performance of the cooling towers was downloaded from the historical operating data and the comparisons are shown below.


Site Operating Performance August 12, EDT
Metereological Wet Bulb vs Twr Performance @ 1002, Phenix, Star, RHIC RF, Tower 7
95
90
85
80
75
70
65
60
Deg. F
/::[1002]TWRTEMP_SUP
CHANNEL2.PHENIX.TWRTEMP_SUP
CHANNEL2.RHICRF.TWRTEMP_SUP
CHANNEL2.STAR.TWRTEMP_SUP
/::[TOWER 7]TEMP_SUP
2 per. Mov. Avg. (Predicted Performance 5F Approach)
2 per. Mov. Avg. (Predicted Performance 10F Approach)
12:00 AM
2:00 AM
4:00 AM
6:00 AM
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM
6:00 PM
8:00 PM
10:00 PM
12:00 AM
2:00 AM
Axis Title


Compare Prediction to Actual Performance
Site Operating Performance July 5, EDT
Metereological Wet Bulb vs Twr Performance @ 1002, Phenix, Star, RHIC RF, Tower 7
95
90
85
80
75
70
65
60
Deg. F
/::[1002]TWRTEMP_SUP
CHANNEL2.PHENIX.TWRTEMP_SUP
CHANNEL2.RHICRF.TWRTEMP_SUP
CHANNEL2.STAR.TWRTEMP_SUP
/::[TOWER 7]TEMP_SUP
2 per. Mov. Avg. (Predicted Performance 5F Approach)
2 per. Mov. Avg. (Predicted Performance 10F Approach)
12:00 AM
2:00 AM
4:00 AM
6:00 AM
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM
6:00 PM
8:00 PM
10:00 PM
12:00 AM
2:00 AM

# Appendix 4

## Chiller Differential Cost Estimate Summary

| Location/Machine | Column1 | Item | Size | Units | Unit Rate | Cost | Reference |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| **1010 ESR H1 RF 591 MHz** | Add | Horizontal Centrifugal Chiller with pumps and Piping | 4828 | tons | $ 1,681 | $ 8,115,743 | Ref, 1 |
| | Subtract | DI With Plate and Frame HX, Piping and Pump System | 4828 | tons | $ 329 | $ (1,588,243) | Ref, 2 |
| | Add | 2500 KVA Unit Substation | 1 | | $ 1,061,299 | $ 1,061,299 | Ref, 3 |
| | Add | For Addnl Building Space | 2000 | sq.ft | $ 382 | $ 764,000 | Ref, 5 |
| | | | | | | | $ 8,352,798 |
| | | | | | | | |
| | | | | | | | |
| **1006 Crab 197 MHz RF System** | Add | Horizontal Centrifugal Chiller with pumps and Piping | 611 | tons | $ 1,681 | $ 1,026,403 | Ref, 1 |
| | Subtract | DI With Plate and Frame HX, Piping and Pump System | 611 | tons | $ 329 | $ (200,866) | Ref, 2 |
| | Add | 1000 KVA Unit Substation | 1 | | $ 909,563 | $ 909,563 | Ref, 4 |
| | Add | For Addnl Building Space | 400 | sq.ft | $ 382 | $ 152,800 | Ref, 5 |
| | | | | | | | $ 1,887,900 |
| | | | | | | | |
| | | | | | | | |
| **1004 RCS 295 MHz SHC 197 MHz** | Add | Horizontal Centrifugal Chiller with pumps and Piping | 767 | tons | $ 1,681 | $ 1,288,971 | Ref, 1 |
| | Subtract | DI With Plate and Frame HX, Piping and Pump System | 767 | tons | $ 329 | $ (252,250) | Ref, 2 |
| | Add | 1000 KVA Unit Substation | 1 | | $ 909,563 | $ 909,563 | Ref, 4 |
| | Add | For Addnl Building Space | 400 | sq.ft | $ 382 | $ 152,800 | Ref, 5 |
| | | | | | | | $ 2,099,083 |
| | | | | | | | |
| | | | | | | | |
| **1002 SHC ERL H1 RF 591 MHz** | Add | Horizontal Centrifugal Chiller with pumps and Piping | 399 | tons | $ 1,681 | $ 670,742 | Ref, 1 |
| | Subtract | DI With Plate and Frame HX, Piping and Pump System | 399 | tons | $ 329 | $ (131,264) | Ref, 2 |
| | Add | 1000 KVA Unit Substation | 1 | | $ 909,563 | $ 909,563 | Ref, 4 |
| | Add | For Addnl Building Space | 400 | sq.ft | $ 382 | $ 152,800 | Ref, 5 |
| | | | | | | | $ 1,601,842 |
| | | | | | | | |
| | | | | | | | |
| **Total** | | | | | | | **$ 13,941,623** |

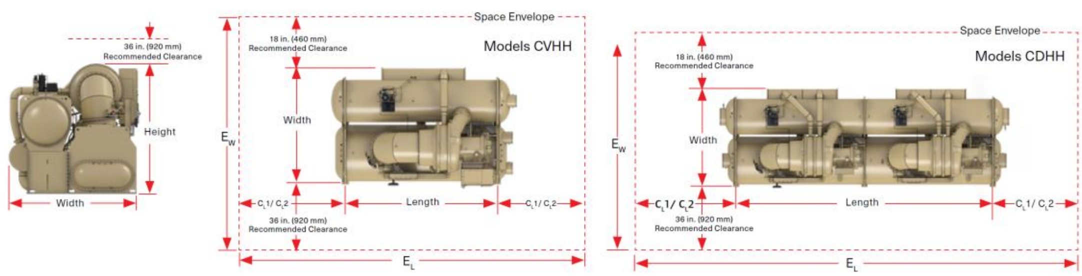
# APPENDIX 5

## Water Cooled Centrifugal Chiller Size and Performance
## TRANE® CenTraVac™ CVHH 1700

**TRANE** **Custom Unit Performance**

**Custom Unit which is outside of the scope of AHRI Water-Cooled Water Chilling Packages Using Vapor Compression Cycle Certification Program, but is rated in accordance with AHRI Standard 550/590 (I-P).**

| | Unit | 1 |
|---|---|---|
| Revision Level | | 230 |
| Unit Model | | CVHH |
| Unit Size | | 1700 |
| Refrigerant Type | | R1233zd |
| Starter Model | | AFDE |
| Starter Type | | UAFD |
| Circuit 1 Starter Size | | 1210 |
| Starter Filter | | Y |
| Circuit 1 Stage 1 IGV | ° | 90 |
| Circuit 1 Impeller Speed | rpm | 3000 |
| Circuit 1 Stage 1 Blade Diameter | inch | 25.984 |
| Circuit 1 Stage 2 Blade Diameter | inch | 25.984 |
| Circuit 1 Motor CPKW | | 743 |
| Circuit 1 Orifice ORSZ | | 212 |
| Circuit 1 Condenser Orifice ORSZ | | 223 |
| Line Hertz | Hz | 60 |
| Line Volt | V | 480 |
| Motor Hertz | Hz | 60 |
| Volt | V | 460 |
| Circuit 1 Order RLA | A | 927.8 |
| Circuit 1 Motor Order RLA | A | 1197 |
| Circuit 1 Line-Side MCA | A | 1157 |
| Circuit 1 Line-Side MOP | A | 2000 |
| Full Load Cooling Capacity | ton | 2500 |
| Circuit 1 Evaporator TONS | ton | 2500 |
| Unit Order kW | kW Input | 768.74 |
| Order kW/ton | kW/ton | 0.3075 |




### CenTraVac™ chiller Models CVHH and CDHH

| | Model | Comp Size | Shell Configuration EVAP/COND | Space Envelope: Length ($E_L$) | | Space Envelope: Terminal Box Only ($E_W$) | | Tube Pull Clearance: $C_L1$ | | Tube Pull Clearance: $C_L2$ | | Base Unit Dimensions: Length | | Base Unit Dimensions: Height | | Base Unit Dimensions: Width | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | in. | mm | in. | mm | in. | mm | in. | mm | in. | mm | in. | mm | in. | mm |
| 60 Hz | Standard CVHH | 900/1000/1200 | 100M/100M | 373.0 | 9474 | 176.0 | 4470 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 121.2 | 3078 | 122.0 | 3099 |
| | | | 100L/100L | 413.5 | 10503 | 176.0 | 4470 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 121.2 | 3078 | 122.0 | 3099 |
| | | | 130M/130M | 373.0 | 9474 | 178.0 | 4521 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 127.9 | 3248 | 124.0 | 3150 |
| | | | 160M/200M | 373.0 | 9474 | 180.1 | 4575 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 135.4 | 3439 | 126.1 | 3203 |
| | | | 200L/220L | 413.5 | 10503 | 185.2 | 4704 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 137.7 | 3498 | 131.2 | 3332 |
| | | | 220L/220L | 413.5 | 10503 | 192.1 | 4878 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 141.6 | 3597 | 138.1 | 3507 |
| | | 1500/1700 | 200L/200L | 413.5 | 10503 | 181.1 | 4600 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 137.7 | 3498 | 127.1 | 3228 |
| | | | 220L/220L | 413.5 | 10503 | 192.1 | 4878 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 141.6 | 3597 | 138.1 | 3507 |
| | Heat Recovery CVHH | 900/1000/1200 | 100M/10HM | 373.0 | 9474 | 191.8 | 4872 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 121.2 | 3078 | 137.8 | 3500 |
| | | | 130M/13HM | 373.0 | 9474 | 194.0 | 4928 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 127.9 | 3248 | 140.0 | 3556 |
| | | | 160M/20HM | 373.0 | 9474 | 200.7 | 5097 | 166 | 4216 | 47 | 1194 | 160.0 | 4064 | 135.4 | 3439 | 146.7 | 3725 |
| | | 1500/1700 | 200L/20HL | 413.5 | 10503 | 200.3 | 5177 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 137.7 | 3498 | 149.8 | 3805 |
| | | | 220L/22HL | 413.5 | 10503 | 222.0 | 5639 | 186 | 4731 | 47 | 1194 | 180.3 | 4578 | 141.6 | 3597 | 168.0 | 4267 |
| | Duplex CDHH | 2000/2600 | 400M/440M | 698.0 | 17729 | 185.2 | 4704 | 318 | 8077 | 68 | 1727 | 312.0 | 7925 | 137.7 | 3498 | 131.2 | 3332 |
| | | 2800/3300 | 440M/440M | 706.0 | 17932 | 192.1 | 4878 | 318 | 8077 | 76 | 1930 | 312.0 | 7925 | 141.6 | 3597 | 138.1 | 3507 |
| | | | 440X/440X | 802.0 | 20371 | 192.1 | 4878 | 366 | 9296 | 76 | 1930 | 360.0 | 9144 | 141.6 | 3597 | 138.1 | 3507 |



R. Srinivasan