ANL-ART-23

Status Report on the Water-Based NSTF RCCS Capability

Preparations and design for the transformation of the Natural convection Shutdown heat removal Test Facility (NSTF) from air to water-based cooling

Nuclear Engineering Division

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Preparations and design for the transformation of the Natural convection Shutdown heat removal Test Facility (NSTF) from air to water-based cooling

prepared by
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ABSTRACT

The following report provides an overview of the current status of the water-based transformation, including details of the design, geometry, and fabrication of the test section and network piping, for the ½ scale water-based NSTF program at Argonne National Laboratory.

In early FY2015, efforts towards a water-based design began in parallel with on-going air-based work, and began by identifying top level objectives of the transformation. Scaling studies and preparation tasks with computational modeling were carried out to guide the design decisions, minimize distortions, and ensure relevant data among scales. This entailed close collaboration with AREVA, whose water-based RCCS (included as part of their 625 MWt SC-HTGR) served as the primary design basis for incorporation into the NSTF. A literature review of previous works was made, with an emphasis placed on similar facilities, relevance to passive decay heat removal, and details pertaining to two-phase flow and measurement techniques.

The study focused on input from key designers and a thermal analysis of existing cooling panels (e.g. at TAMU and UW-Madison) and two proposed AREVA cooling panels. A base case was used as a reference point for parametric studies of effects from varying tube spacing (pitch), tube diameter, fin thickness, and materials. Then, a structural analysis was performed to ensure safe material stresses during high temperature operation. Details of the pipe network geometry and guidelines for design of the water storage tank are finally presented, followed by engineering drawings in the appendix.

The results of this study have identified a suitable configuration to support both the ANL/DOE project goals and the DOE vision to provide AREVA with data suitable for characterizing the RCCS of their full scale HTGR design. The dimensions were not selected for optimal RCCS performance, but instead to serve as a representative yet bounding configuration for future implementation into a full scale design. Scaling distortions are unavoidable; however, they can be accurately predicted based on earlier works of derived similarity solutions. Flexibility remained a primary design philosophy, and will allow the test facility to easily accommodate future alterations. The final design for the test section and network piping is summarized below:

- Riser tubes: 1.5” Schedule 160, 5.91” (150-mm) pitch, 304L stainless
- Heat transfer panels: 5/16” plates, 4.01” (102-mm) width, full penetration weld to risers, 304L stainless, split into 4 panels per riser separated by horizontal 1/8” gaps
- Test section: Eight (x8) riser tubes and nine (x9) heat transfer panels, fabricated into banks of two (x2) riser tubes and three (x3) fins, joined to form single section
- Network geometry: 4.0” Schedule 40, 304L stainless

Details of the water storage tank will reflect competing effects such as thermal hydraulic phenomena during single and two-phase operation. These considerations include mixing during single-phase jet penetration, condensation of rising bubbles during two-phase discharge, bubble entrainment into the liquid outlet, and liquid carry-over into the steam outlet.

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1 Introduction

The Natural convection Shutdown heat removal Test Facility (NSTF) program at Argonne National Laboratory (ANL) was initiated in 2010 to study the performance of passive safety systems for advanced nuclear reactors. This program is part of a broader study on the feasibility of the Reactor Cavity Cooling System (RCCS) concept. An experimental portion was first focused on air-based cooling, using a design concept by General Atomics for their MHTGR. With air-based testing anticipated to conclude by FY2016, a transition will be made to water-based cooling. The new installation will leverage the existing infrastructure of the test facility, namely the heated enclosure, electric heaters, and data acquisition system.

The purpose of this status report is to present the work done in FY2015 towards implementing a water-based test section in the NSTF. It provides background on the water-based design philosophy then introduces specific design considerations and detailed dimensions of the new water-based components. A review of the primary inputs and reference designs will be presented, followed by a thermal and structural analysis to identify expected temperatures along the cooling panels during operation. Finally, a status of procured items and planned instrumentation will be given followed by a timeline of anticipated events.

2 Design Considerations

To study the viability of water-cooled passive safety system, an experimental program is necessary to expose the complex behavior and uncertainties commonly associated with two-phase boiling phenomena. The design of the experimental test assembly should first and foremost accurately model the conditions found in a full scale reactor, e.g. heat flux and geometric constraints. Then, specifics of the cooling panels must be decided upon. Given that no formal designs have been approved by the NRC or confirmed by a US industry, a best-attempt must be made to capture the nominal design while providing key information to drive a final product. During an on-site visit to Argonne in February 2015, AREVA provided the NSTF team with several system parameters of interest to quantify performance that include, but are not limited to:

1. Heat load (integral power from RPV)
2. RCCS system flow rate
3. RCCS test section ΔT

The above parameters of interest will be measured via a suite of calibrated instruments. The heat load requirements will be met with the existing infrastructure of the air-based NSTF, which includes 40 independent control zones for heater shaping and power adjustment (220 kW at 21.6 kW/m^2 maximum) Measurements of RCCS system flow rate will be accomplished via volumetric flow meters, e.g. non-intrusive magnetic, and test section ΔT via minimally intrusive thermocouples, e.g. 1/16” Type-K.

Additionally, AREVA provided the NSTF team with “expectations for discovery”, or results from the water-based program that would be beneficial to the AREVA team and other future water-cooled RCCS designers in refining their water-based design. These include but are not limited to:

1. Impact of riser tube dimensions – inner diameter, wall thickness, panel web thickness, etc.

2. Need for inlet orificing, at riser inlet above inlet header
3. Materials - mild steel for optimal conduction, or stainless steel for water chemistry

Lastly, the AREVA team provided two critical areas for consideration in the experimental program:

1. Capture discontinuities in hot leg piping especially, bends, elbows, dips. Such features that you otherwise would not put in a hot leg of a natural circulation loop for stability reasons.
2. Web connection (fins to tube) is critical for efficient heat conduction from fins to water tubes. This plays out in the fact that RCCS serves to also maintain safe concrete temperatures – too wide fins, or poor conduction will result in very high temperature fins (webs), which will radiate and result in high concrete temperatures.

The above items will be addressed by maintaining flexibility in design philosophy. That is, all connections will be bolted and easily disassembled and replaced with alternative configurations. This will be especially considered for the pipe network between the outlet of the test section and inlet of the water tank storage, so that sections can be easily replaced for alternative piping routes. Finally, it is anticipated that a second test section will be studied within the time frame of the overall water-based testing.

2.1 Reference Cases

The designs proposed stem from existing work at US Universities for water-cooled RCCS [1,2], and input from AREVA for their 625 MW_t SC-HTGR [3]. The US Universities collaborated with the air-based program at ANL, and thus used a similar reactor reference of the GA-MHTGR. However, unlike the program at ANL, they examined water-based cooling system and employed a hybrid design for their water cooling panels. Details of the design considerations and engineering dimensions can be found in previous works [4,5].

The design inputs and observations for the AREVA design were provided by technical reports released to the DOE [3,6]. They include information regarding the geometry of the concrete containment, heat removal requirements for the RCCS, and suggested dimensions of the cooling panels.

These designs, four in total, are summarized below in Table 1, and drawn in 2D plan view in Figure 1. They will be the reference points for thermal analysis.

Table 1: Primary dimensions and specifications for four cases studied

Design	Cooling Tube			Fin	Material
	Pitch, in	O.D., in (Nom. Size)	I.D., in (Schd.)	Thick., in	
A: TAMU	4.0	2.375 (2")	2.067 (S40)	0.250	304L
B: UW	9.45	2.375 (2")	2.067 (S40)	0.250	304L
C: AREVA, i	5.91	1.90 (1.5")	1.338 (S160)	0.3125	304L
D: AREVA, ii	5.91	2.375 (2")	1.687 (S160)	0.3125	304L

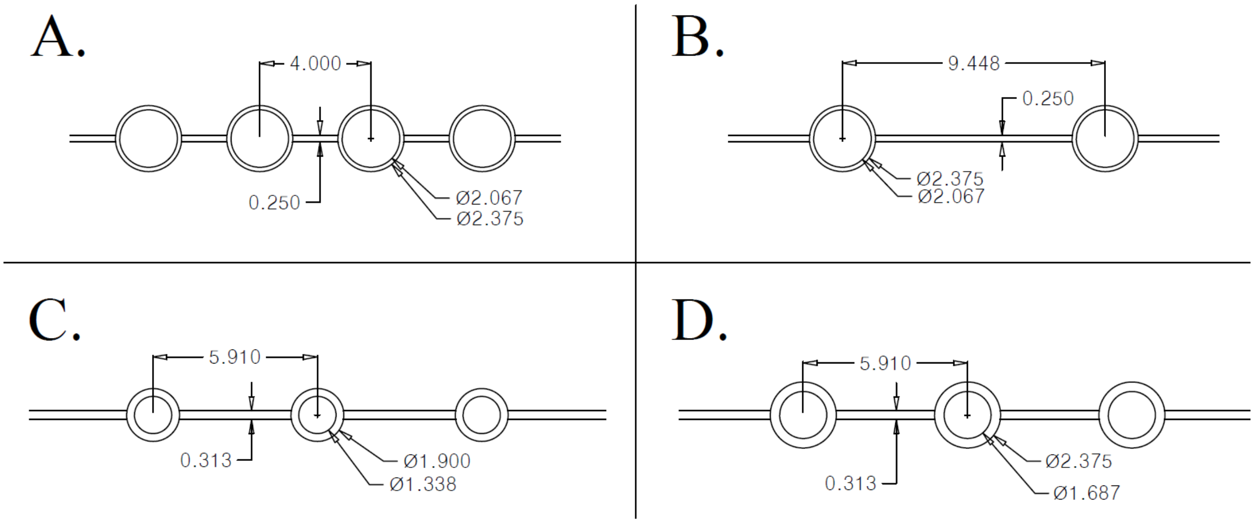

Figure 1: Geometry of four cases. A: TAMU, B: UW - Madison, C: AREVA, i D: AREVA, ii

2.2 Design Parametric

To examine the specific impacts of varying design parameters, Case C, 'AREVA i', was selected as the baseline test case. Variations on tube pitch (spacing between adjacent tubes), tube schedule (inner diameter of riser tubes), fin thickness, and test section material were performed. The ranges for these parametric variations are summarized below in Table 2.

Table 2: Parametric variables for reference Case C, 'AREVA i'

Design	**Cooling Tube**			**Fin**	**Material**
	Pitch, in	O.D., in (Nom.)	I.D., in (Schd.)	Thick., in	
Pitch	**3 - 8**	1.9 (1.5")	1.338 (S160)	0.3125	304L
Tube Sch.	5.91	1.9 (1.5")	**1.1 - 1.77 (S5 - SXXH)**	0.3125	304L
Fin Thick.	5.91	1.9 (1.5")	1.338 (S160)	**0.1 - 0.5**	304L
Material	5.91	1.9 (1.5")	1.338 (S160)	0.313	**304L, Mild Steel, 9Cr-1Mo**

3 Thermal Analysis

A thermal analysis was performed in ANSYS Workbench v15 [7] for the four design cases above, along with parametric variations of the base reference case. To provide representative boundary conditions for the thermal analysis, information from AREVA for their 625 MW_t SC-HTGR was used, Table 3. Additional boundary conditions for convective heat transfer coefficients were pulled from earlier works [8, 9]. The model summary with all boundary conditions is shown below in Figure 2.

Table 3: AREVA boundary conditions, 625 MW_t SC-HTGR

Operating Mode	RCCS Cooling	No. of active risers	Power to RCCS	Heat flux to RCCS[1,2]
Nominal	Active	x230	1.4 MWt	4.1 kW/m^2
Passive	Passive	x230	2.1 MWt	6.1 kW/m^2
Passive, DBA	Passive	x115	2.1 MWt	11.1 kW/m^2

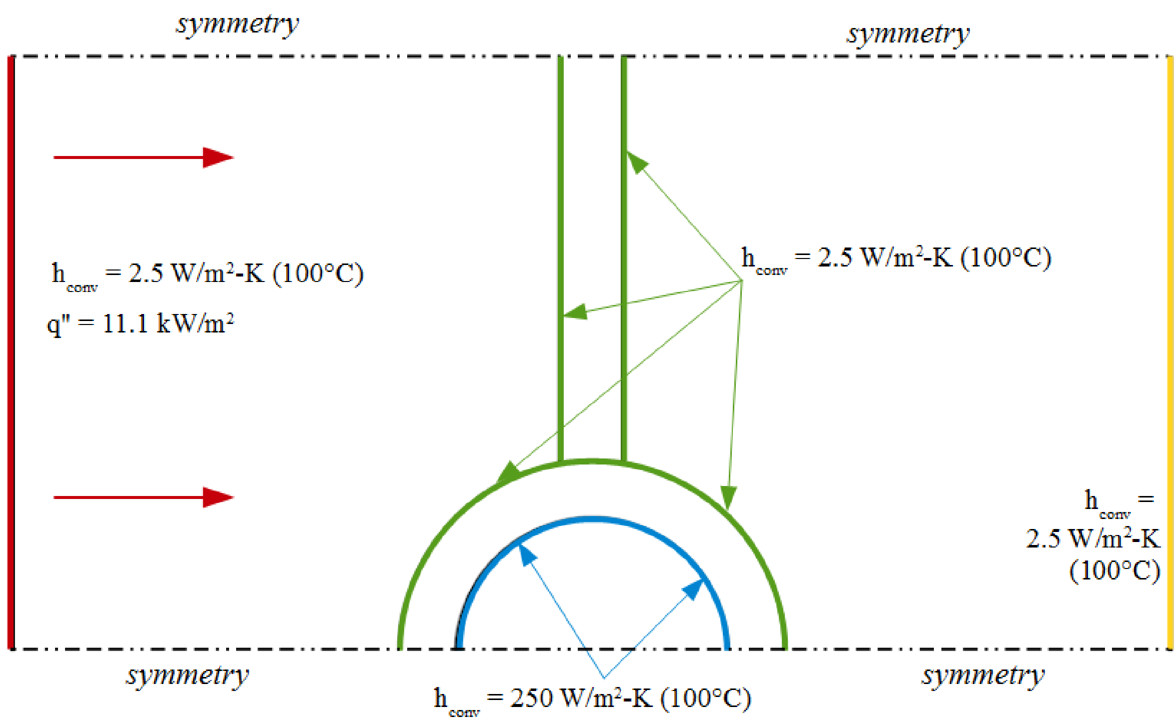

Figure 2: Overview of thermal analysis boundary conditions, 2D ANSYS model

The geometry and mesh were generated in ANSYS Workbench, and shown below in Figure 3Figure 3. The model was created in a 2D form, and utilized 8,447 nodes.

[1] Heat flux calculated based on nominal RCCS surface area. Designer inputs: 11-m overall RCCS cylinder diameter, 10-m heated length

[2] Passive, DBA heat flux of 11.1 kW/m^2 calculated based on conservative, worst-case scenario to establish peak temperatures for computational thermal and structural analysis

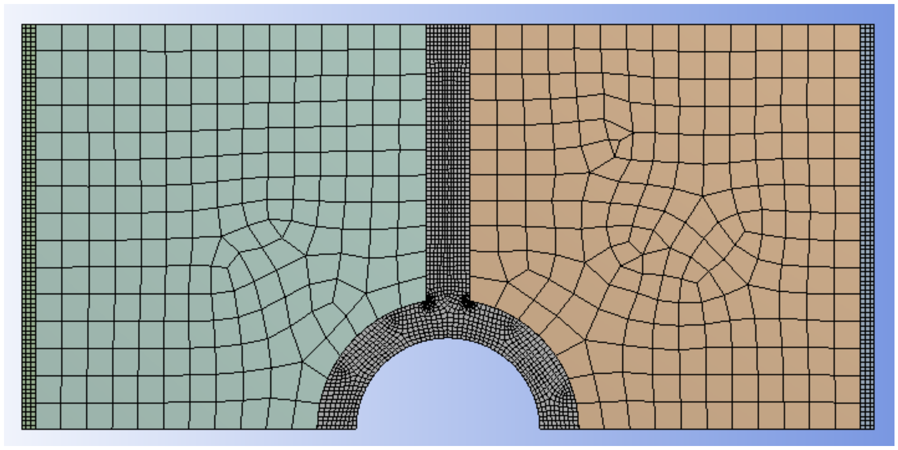

Figure 3: Mesh of thermal analysis, 2D ANSYS. Thermal simulation only thus no considerations were made for near wall boundary / inflation layers. Note mesh refinement at point of contact between fin and water tube. Cavity meshed for radiative heat transfer.

3.1 Thermal Results

The temperature profile for the baseline test Case C, 'AREVA i', is shown below in Figure 4. Clearly visible is the highest temperature observed at the centerline of the fin, 245 °C with decreasing temperatures along the fin towards the cooling tubes. Across the water tube, the coolest temperature observed for this reference case is 134 °C at the inner surface of the concrete side of the tube.

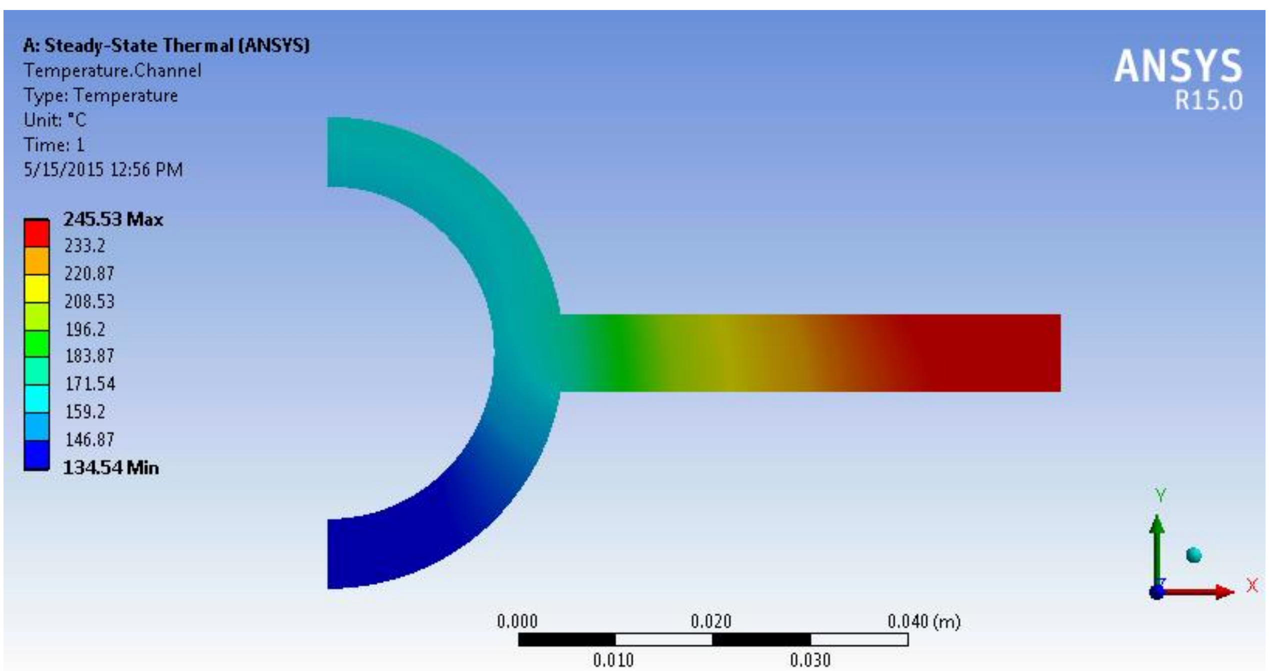

Figure 4: Temperature (°C) profile, Case C, at 11.1 kW/m^2

An overview of the temperatures of interest for the four cases is provided below in Table 4. Case B, 'UW – Madison', sees the highest temperature across the entire test section and concrete wall.

This is largely due to their high pitch or tube spacing. Among the two AREVA designs, Case C sees higher temperatures than Case D due to the smaller cooling tube diameter and subsequent smaller surface area for convective heat removal by the working fluid.

Table 4: Comparison of key *maximum* temperatures (°C) for cases at 11.1 kW/m^2

Design Case	Panel front (RPV side)	Panel back (concrete side)	Water tube (interior)
Case A – TAMU	148.50	146.93	141.92
Case B – UW-Madison	341.72	307.27	179.38
Case C – AREVA, i	245.53	243.31	163.21
Case D – AREVA, ii	213.28	211.10	152.05

3.2 Thermal Results, Parametric

A reference case, Case C, was selected as the baseline for parametric variations. The results, plotted against the range of values examined, are shown in Figure 5 below, with the baseline values for each parameter indicated by a dashed line. The majority suggest intuitive trends, e.g. with increasing tube spacing or pitch, maximum observed temperatures increase. Similarly, reduction in fin thickness results in a smaller conduction heat transfer area and thus higher temperatures. Interestingly however, is a local minimum or optimal value for the tube inner diameter. This was observed to be Schedule 40 for the 1.5" tube – the ratio of tube thickness for heat transfer, and tube inner diameter for convective heat removal is optimal for reduced temperatures. This phenomenon is analogous to the classic heat transfer problem of determining a critical radius for pipe insulation. Finally, the concrete temperature is a function of distance, and the simulated domain may not necessary reflect the dimensions of the full or NSTF scale designs so only relative trends should be considered for the concrete domain.

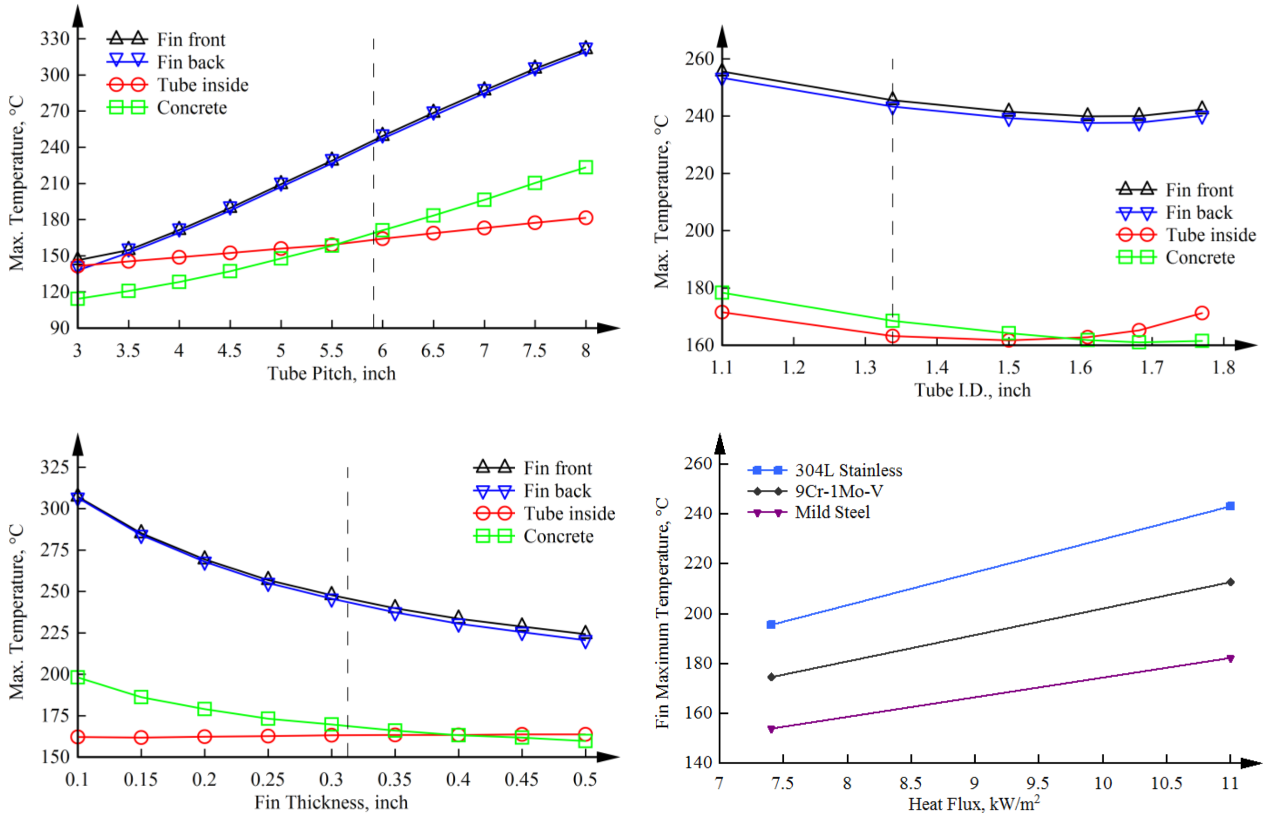

Figure 5: Four parametric test cases. i) Tube spacing, ii) Tube inner diameter, iii) Fin thickness, iv) Materials

4 Structural Analysis

A structural analysis was performed with a 3D model of the full length of the proposed riser – fin test section, Case C – AREVA, i. Shell elements were used in ANSYS to reduce computational effort, and body loads (i.e. temperature profiles) were imported from the thermal analysis. Two models were examined: the first with full length fins, and a second with split fins. The split fin model created 1/8" gaps at three points along the fin, resulting in a total of four separate heat transfer panels. The analysis was performed at the bounding scenario of 2.1 MW_t full scale heat load and resulted in a 2.24 cm thermal expansion of the fin-riser tube assembly. The stresses and deformed models (non-deformed outlined in background) are shown below in Figure 6.

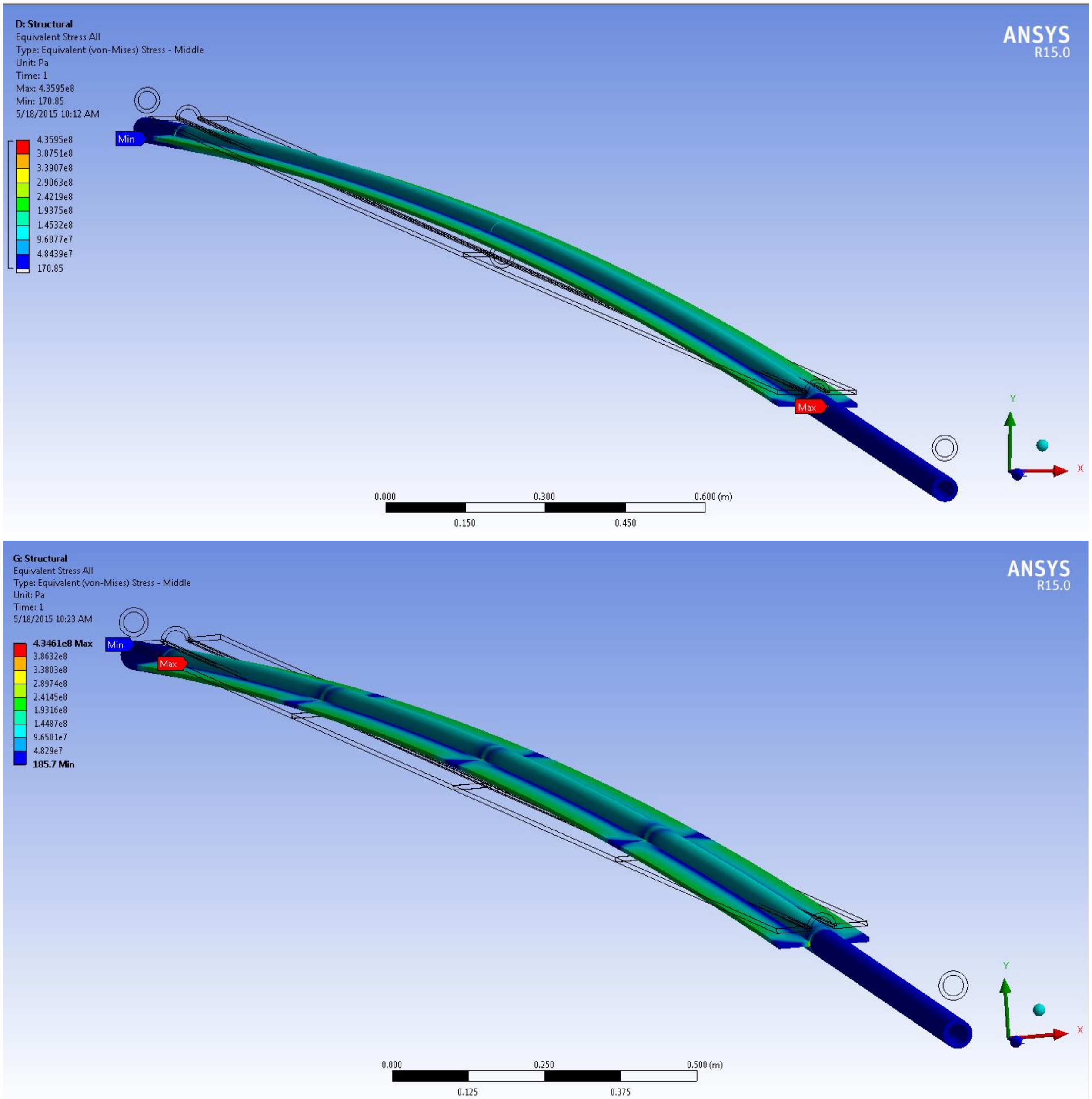

Figure 6: Thermal deformation and resulting von-Mises stress for single fin (top) and split fin (bottom) cases

Models result in an average von-Mises stress of 56 MPa across the areas of highest stress (weld of fin and riser tube), Figure 7, and is well below the generally accepted 210 MPa yield strength and 564 MPa ultimate tensile strength of 304L stainless steel [10]. Artifacts from point (non-beveled) mating resulted in local peaks that may not representative of overall stresses. Non-uniform temperature distribution on fin makes the deformation of fin as shown in Figure 8, and the deformed fin structure induces the local peaks in the structural stress. Thus, care will be taken to ensure smooth bevels and junctions during fabrication to reduce local stress concentrations at these point areas. With a split fin design resulting in slightly lower stresses and relaxing fabrication requirements, a split fin design with care of smooth bevels and junctions will be selected for the NSTF.

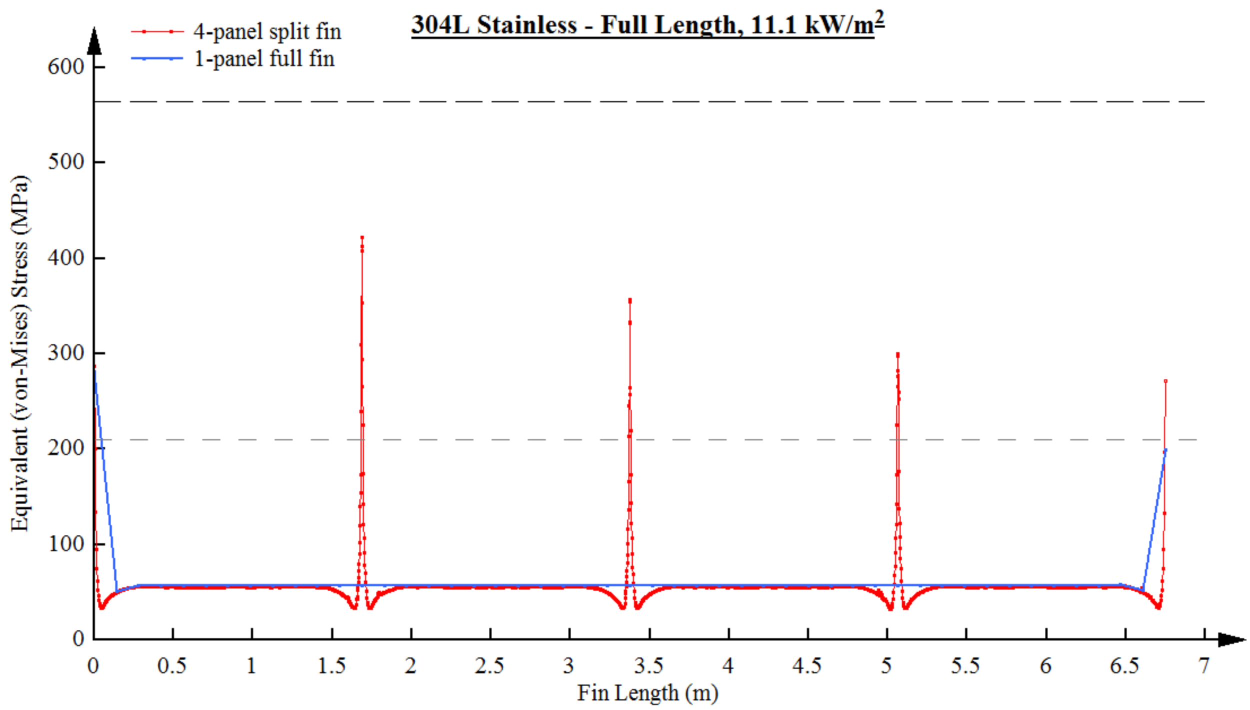

Figure 7: Stress along surface of riser tubes and fins. Dashed lines show 210 MPa yield strength (grey) and 564 MPa tensile strength (black)

Figure 8: Thermal expansion induced fin deformation at point-contact and resulting von Mises stress (MPa) along the weld of fin and riser tube

5 NSTF Implementation

5.1 Test Section

With the reference Case C, 'AREVA i', as a suitable candidate for the NSTF implementation, the amount of cooling panels was determined based on the available geometry of the existing heated enclosure. With 52" of available cavity width, eight riser tubes and cooling panel sections would fit within the enclosure. This would be installed via four banks, with each bank comprising two riser tubes and three fins (one full, two half), Figure 9. They would then be secured with plates across the back of the fins to prevent gaps in view factors and provide structural rigidity. Full penetration welds will be made between the heat transfer panels and adjacent riser tubes, Figure 10. Full details of the test section, riser banks, and joining plates can be found in the appendix. The spacing within the heated cavity is shown in Figure 11.

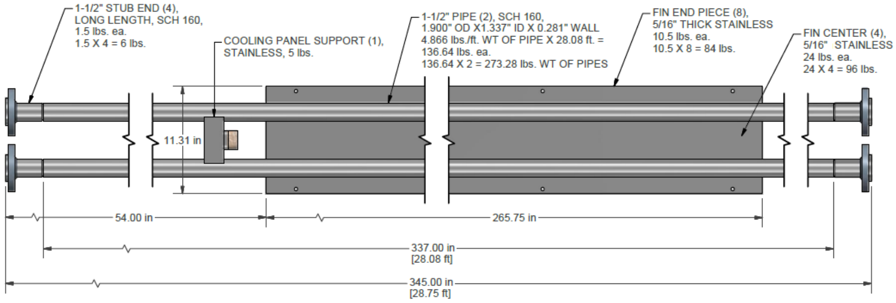

Figure 9: Single riser bank detail, 2 riser tubes

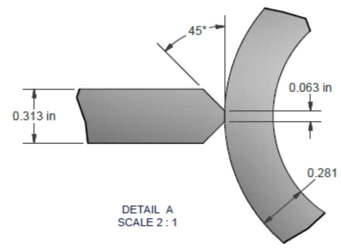

Figure 10: Bevel for full penetration weld

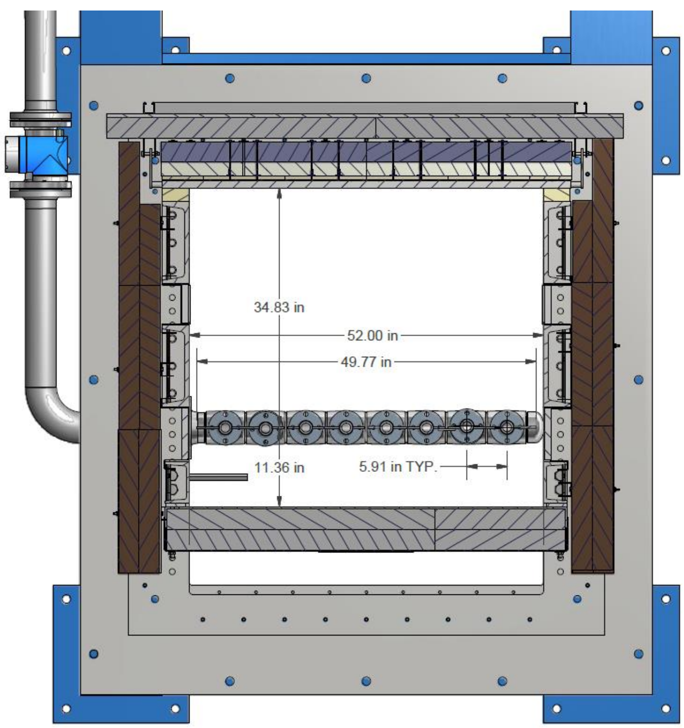

Figure 11: Plan view of heated cavity with position of test section and distance to heated surface (34.83")

5.2 Primary Network Piping

For the reference Case C, 'AREVA i', the riser tubes are constructed from 1.5" Schedule 160 pipe. Thus, each tube has an inner diameter of 1.338". To determine the minimum pipe size of the network loop, we require a constraint that the total liquid cross sectional area of the cooling panel is less than or equal to the primary network loop, Table 5.

Table 5: Flow areas for varying riser tube counts and comparison to loop flow area

No. Riser Tubes	T.S. Flow Area, in^2	Loop Pipe Size	Loop Flow Area, in^2
4	5.624	3.0", Sch. 40	7.267
6	8.436	3.5", Sch. 40	9.737
8	**11.248**	**4.0", Sch. 40**	**12.554**

Flexibility in the primary network loop will be accomplished by regular flanges at 10-ft spacing. This will allow examination of off-normal configurations for their impact on the system behavior and heat removal performance. An example is shown below in Figure 12.

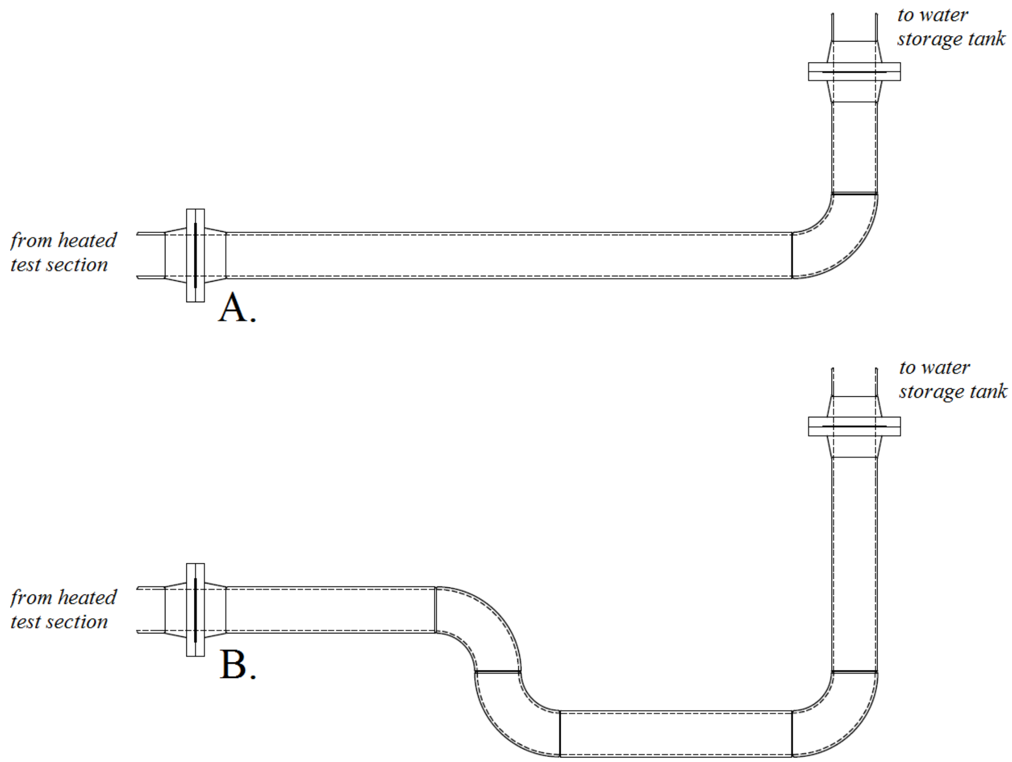

Figure 12: Flexibility in network piping. Alternative configuration (B) can be used to simulate non-ideal pipe routes to examine effects on system performance.

Based on the availability of storage and space in the existing hi-bay, the network piping would be routed to accommodate a storage tank positioned on the third (highest) floor of the mezzanine support structure. Primary elevations and lengths are shown in Figure 13.

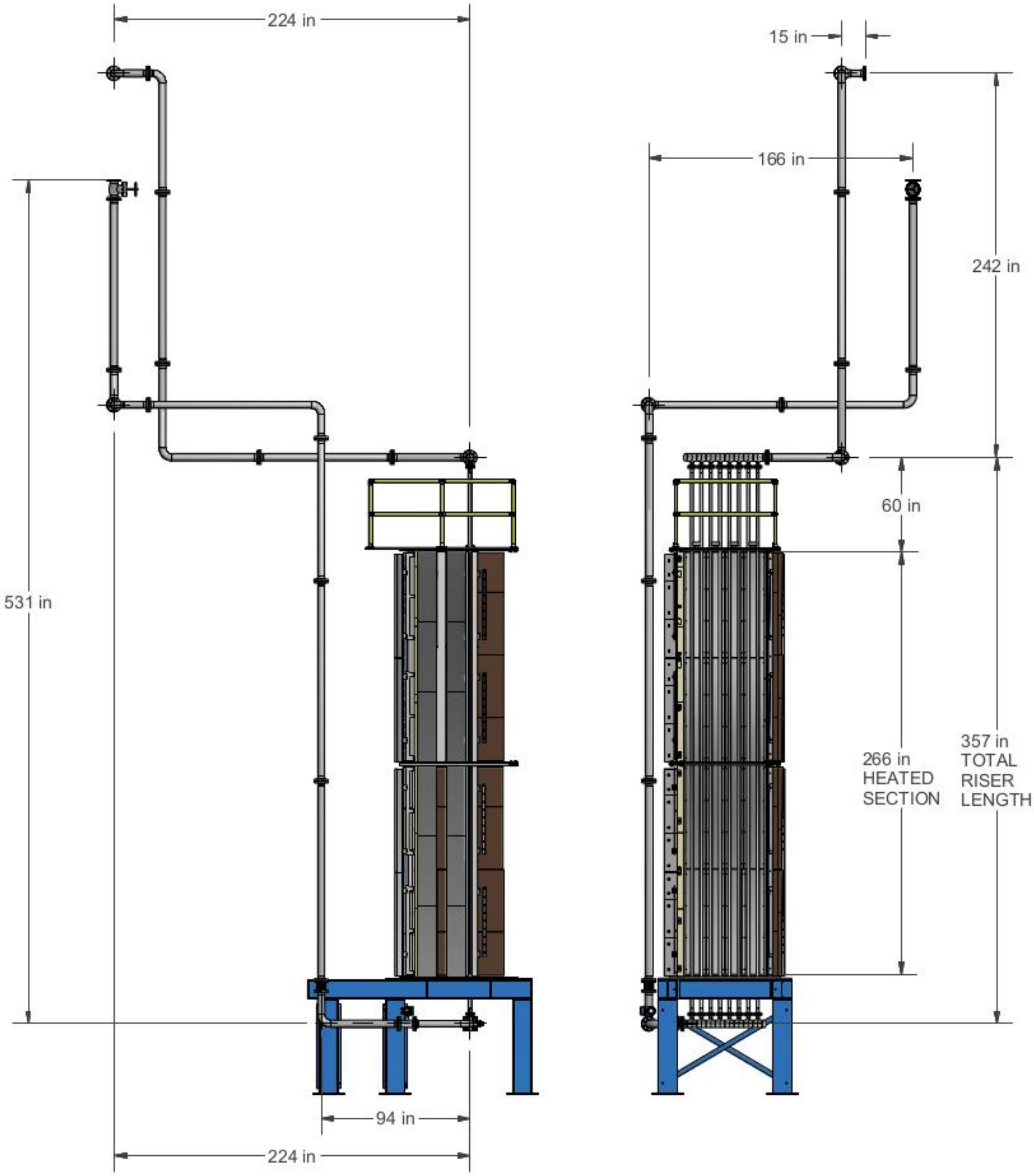

Figure 13: Elevations and horizontal runs test section and network piping. Note asymmetric routing of inlet / outlet headers, which will provide uniform flow length and frictional losses during single-phase operation. Additionally, note inclusion of butterfly valves near inlet header and exit of water storage tank, which will be adjusted to match expected system ΔT

5.3 Orificing

During fabrication of the inlet and outlet headers, grooves will be machined into the 150# 1.5” weld neck flanges to allow installation of variable sized orifice plates, Figure 14. Orifice plates may be used to either reduce the flow rate and achieve a desired heated section temperature rise, or block any desired riser tube all together. The groove will measure 0.25” deep and 2.0” diameter, and will be normally filled with a blank orifice of inner diameter equal to the nominal 1.5” Sch. 160 pipe of the test section.

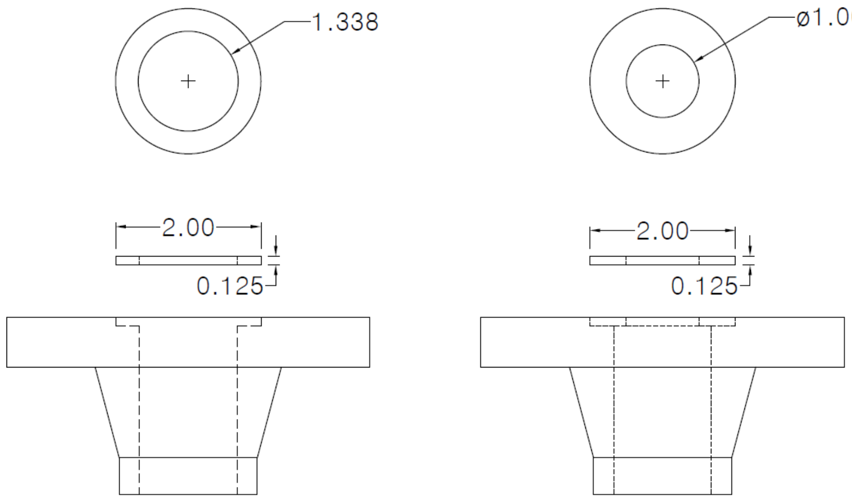

Figure 14: Machine groove in header weld neck flange to accommodate orifice plate. Left: blank used during normal operation. Right: Arbitrary orifice to increase heated temperature rise

5.4 Inlet Throttling

System wide control of the flow rate will also be possible via a butterfly valve positioned immediately prior to the inlet header pipe, Figure 15.

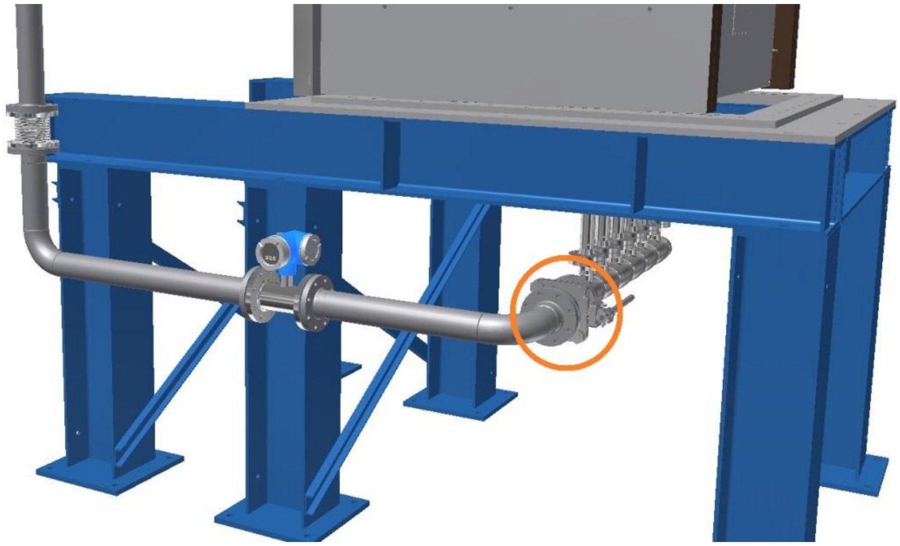

Figure 15: Lower portion of cold leg piping. Butterfly throttle valve circled in orange

5.5 Water Storage Tank

Details of the water storage tank are still being finalized, and include scaling studies of the anticipated thermal hydraulic phenomena during single-phase and two-phase operation. No baffles or conditioning will be included within the interior of the storage tank. Preliminary studies suggest the following criteria:

1. Cylindrical design with 2:1 aspect ratio (height is double tank diameter)
2. 10:1 volume ratio (volume in storage tank will be x10 of network piping).
3. Centered discharge port on lower belly
4. Two side inlet ports, one positioned along 50% mark of tank long dimension, second positioned at 5% volume of tank. Only one inlet port will be used during test operation.

Volume in water storage tank is suggested to be 10 times of networking piping including test section, upper/lower headers, and inlet/outlet piping, [11]. With known dimensions of the loop components, Table 6 summarizes each pipe volume and finally the water storage tank to be 3.93m^3 or 1,037 gal.

Table 6: Water volumes for NSTF storage tank

Component	Water Mass	Water Volume
-	lbs.	m^3
Cold Leg Pipe	195.04	0.196
Lower Header	12.11	0.012
Test Section	63.50	0.064
Upper Header	12.11	0.012
Hot Leg Pipe	108.86	0.109
Total Piping	-	0.393
Water Storage Tank	-	3.927 m^3 (1,037 gal.)

With the estimated volume of water storage tank just having 10 times of networking piping, tank dimensions are obtained for given height to diameter ratio of 2, which was used in previous experimental facilities of similar kinds from Texas A&M University and University of Wisconsin-Madison [1, 2]. The estimated dimensions for water storage tank are summarized in Table 7.

Table 7: Dimensions for NSTF Water Storage Tank

Height	2.71 m
Diameter	1.36 m
Volume	3.93 m^3 (1,037 gal.)
Height / Diameter	2

Single-phase heat removal will be performed by drawing hot water from the lower basin of the tank, cooling through a HXG, and returning via a gentle sparger by the top head of the tank. Two-phase heat removal will be performed by drawing steam off a port on the top head of the storage tank. There are two inlet ports at 50% and 5% heights as shown in Figure 16. Effects of varying inlet port heights will be studied by experiments to discover thermal-hydraulic aspects regarding single-phase and two-phase mass and enthalpy mixing in the tank and the resulting temperature difference between inlet and outlet ports of the tank, the driving force for the natural circulation through the network piping.

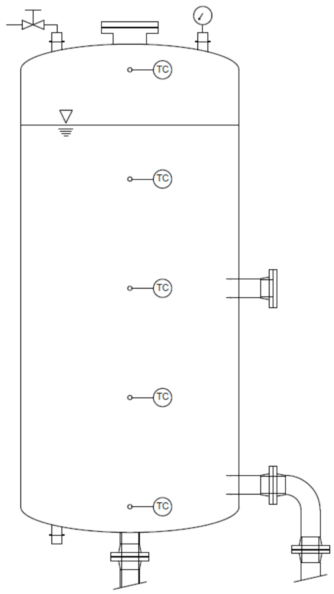

Figure 16: Dual inlet water storage tank. Left: 5% volume; Right: 50% volume.

For a given water volume and constant heater power, water depletion time is estimated by assuming that the initial water temperature is 30°C and the final steam quality is 1.0, that is, pure saturated steam. Figure 17 summarizes the water depletion time for give water volume and heater power. Water depletion time increases as water volume increases and as heater power rate decreases. For example, it takes 2 days for complete depletion of a 1,000 gallon tank and 52 kW_t, equivalent to 3 days and 2.1 MW_t in HTGR RCCS design according to the scaling relationship.

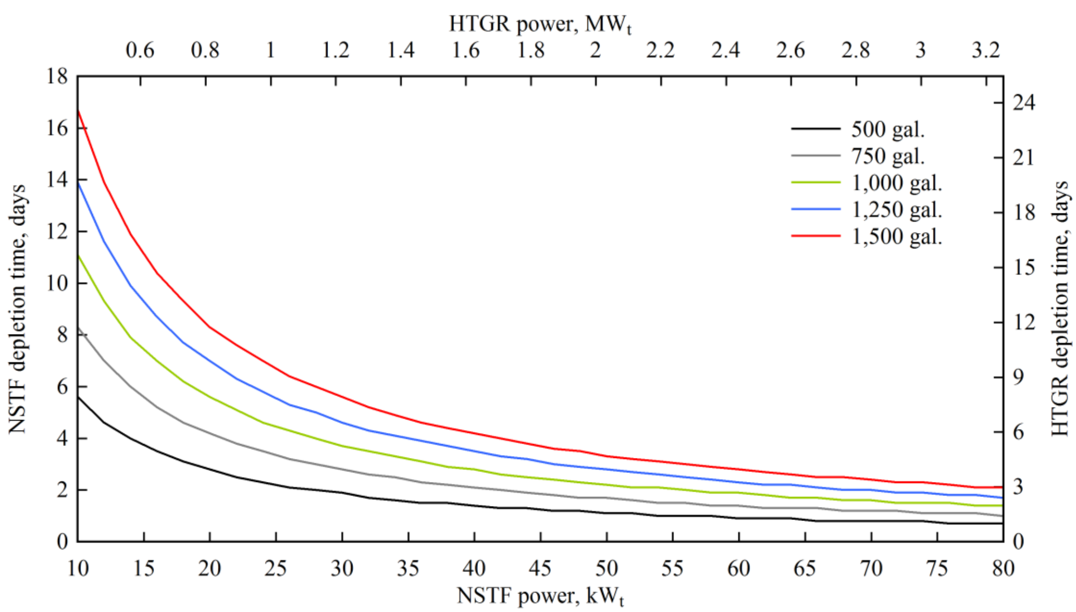

Figure 17: Water depletion time for NSTF and HTGR at varying tank volumes

5.6 Operating Conditions

Based on an eight riser tube test section, anticipated operating conditions for the ½ scale test facility at Argonne can be determined. The NSTF heat load was derived based on 230 riser tubes in the AREVA plant [3] and scaling similarity relations [12] assuming a length scale of ℓ_R =0.5. The test section temperature rise was based on the AREVA designer input reference of "…ΔT is on the order of 10 – 20 °C…" [3]. For the test facility at Argonne, which will have half scale in axial and full scale in the other directions compared to the RCCS, scaling ratio for heater power, heat flux, water mass flow rate and physical time are obtained from single phase scaling relationships [12]. A summary of the scaling ratios are provided in Table 8.

Table 8: Scaling ratio for NSTF compared to RCCS

	Relationship	Ratio
Axial Length	ℓ_R	0.5
Radial Length	1	1.0
Power	$\sqrt{\ell_R}$	0.707
Heat Flux	$\ell_R^{-0,5}$	1.414
Flow Rate	$\sqrt{\ell_R}$	0.707
Temperature	1	1.0
Time	$\sqrt{\ell_R}$	0.707

With the scaling ratio shown above, Table 9 - Table 12 summarize four anticipated operating conditions for NSTF: normal, subcooled accident, transient accident and limiting design condition.

Table 9: Normal operating condition for NSTF

	RCCS	NSTF
Number of Risers	x230	x8
Power	1,400 kW_t	34.4 kW_t
T_{in}	30.0 °C	30.0 °C
T_{out}	45.2 °C	45.2 °C
Exit Quality	0.0	0.0
Mass Flow Rate	22.0 kg/s (total) 11.0 kg/s (each loop)	0.54 kg/s (total) 0.27 kg/s (each loop)

Table 10: Subcooled accident condition for NSTF

	RCCS	NSTF
Number of Risers	x230	x8
Power	2,100 kW_t	51.6 kW_t
T_{in}	80.0 °C	80.0 °C
T_{out}	95.1 °C	95.1 °C
Exit Quality	0.0	0.0
Mass Flow Rate	33.0 kg/s (total) 16.5 kg/s (each loop)	0.81 kg/s (total) 0.41 kg/s (each loop)

Table 11: Transient accident condition for NSTF

	RCCS	NSTF
Number of Risers	x230	x8
Power	2,100 kW_t	51.6 kW_t
T_{in}	95.0 °C	95.0 °C
T_{out}	100.0 °C	100.0 °C
Exit Quality	0.000076	0.000076
Mass Flow Rate	98.8 kg/s (total) 49.4 kg/s (each loop)	2.43 kg/s (total) 1.22 kg/s (each loop)

Table 12: Limiting design condition for NSTF

	RCCS	**NSTF**
Number of Risers	x115	x4
Power	2,100 kW kW_t	51.6 kW_t
T_{in}	100.0 °C	100.0 °C
T_{out}	100.0 °C	100.0 °C
Exit Quality	0.013480	0.013480
Mass Flow Rate	69.0 kg/s (total) 69.0 kg/s (each loop)	1.70 kg/s (total) 1.70 kg/s (each loop)

5.7 Length Scaling

The exact scale from the proposed AREVA plant layout to the NSTF is provided below in Table 13. A revision to the initial proposed design now includes placing the water storage tank on the highest level of the structural mezzanine. Given the large loading of the storage tank, seismic and structural concerns are non-negligible. Finally, provisions can be made to reduce the length of the heated section to lessen the 0.68 scale closer to the other network components. This could be accomplished by zoning off the top bank of heaters and fabricating a shorter heated panel section.

Table 13: Comparison of elevations between full plant AREVA and NSTF scales

	AREVA (m)	**NSTF (m)**	*Scale (-)*
Total Riser	14.0	9.07	0.65
Heated Panel	10.0	6.76	0.68
Upper Chimney	13.8	6.15	0.45
Downcomer	32.8	13.5	0.41

5.8 Choice of Materials

The materials for all piping components, including the riser tubes, fins, primary network loop, and water storage tank will comprise an austenite stainless steel. Grades 304, 304L, 316, and 316L will be considered based on strength requirements, pricing, and weld ability. This selection facilitates experiment practices and maintaining acceptable water chemistry due to the corrosion resistance of stainless metals. Additionally, the low surface emissivity and conductivity (compared to mild steel) allows us to establish a bounding condition for maximum component temperatures.

6 Planned Components

6.1 Instrumentation

Efforts are in-progress to select a suite of sensors to best capture the thermal hydraulic behavior anticipated to occur within the water-cooled test facility. Measurements of system flow rate, temperatures, pressure drop, among others, will be considered and optimal choices selected for final installation. A summary of the planned sensors is provided in Table 14.

Table 14: Anticipated requirements for water-based NSTF instrumentation

Measurement	Sensor Type	Location	Quantity	Span
Flow rate	Magnetic	Inlet header	x1	± 5 kg/s
Temperature	TC, type-K / T	Liquid / surface	x300+	0 – 1,250 °C
Temperature	DTS (LUNA)	Test section wall	x20+	0 – 300
Different pressure	Strain	Risers, chimney	x4+	4,000 Pa
Heat flux	Thermopile	Riser surface	x16	0 – 10 kW/m^2
Water level	Strain (ΔP)	Storage tank	x1	0 – 3 m
Void fraction	Capacitance	Riser exit, chimney	x4+	0 – 100%
Steam quality	Conductivity	Steam exit	x1	0 – 1

6.2 Heat Removal System

Currently we have procured our chiller that will be used to maintain a constant temperature of the system inventory during steady-state test conditions, as well as serve as the heat sink for steam condensation during two-phase transients. The chiller, model NQR20 from ThermalCare, Figure 18, has a cooling capacity of 20RT (70.3 kW) and features a remote air-cooled condenser united that will be mounted outside the laboratory space.

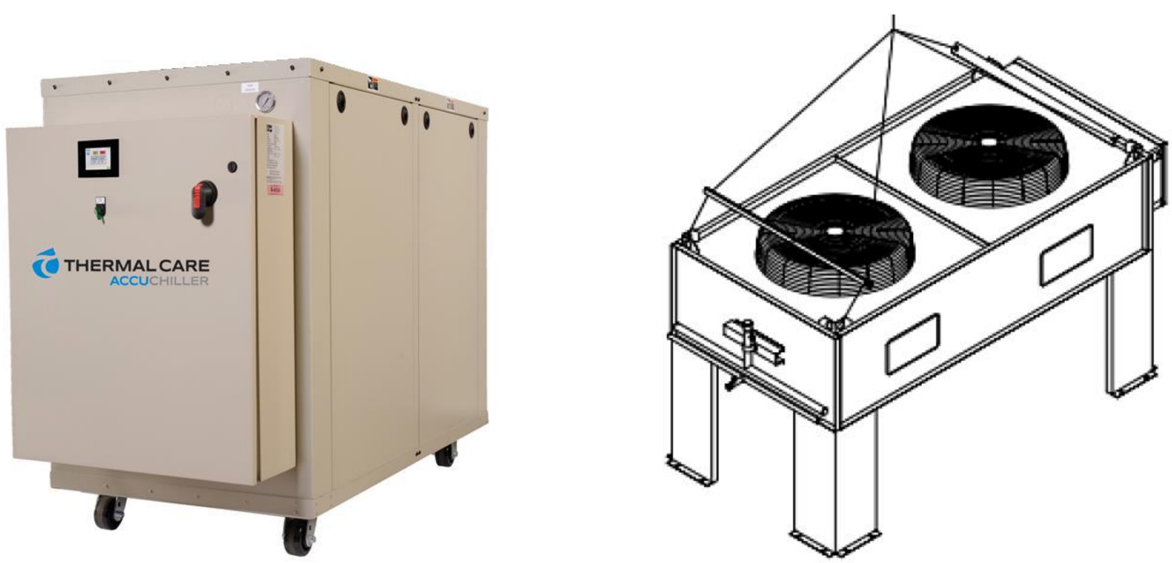

Figure 18: Portable chiller (left) and remote air-cooled condenser (right)

7 Conclusion

Due to the boiling flow that is anticipated to occur in this scaled water-based test facility design, the system will exhibit complex and uncertain thermal hydraulic behavior commonly associated with two-phase phenomena. Flashing, system-wide flow oscillations, and geysering are a few of the instabilities that are likely to be observed, and demand unique requirements for both instrumentation and structural considerations. Collaboration with modeling and simulation teams will be instrumental in the design of the test facility, as they will aid in identifying nominal system behavior and mapping relevant piping sections for instrumentation placement. Moreover, specific considerations will be made to characterize the anticipated instability modes. By obtaining knowledge of their behavior and magnitude over a broad range of conditions, the project can meet the ultimate goal of creating a shift from uncertainty to predictability. To ensure a successful application of these systems to a full sized reactor design, the impact of these instabilities on the thermal hydraulic behavior and heat removal performance must be quantified. The water-based design work that was performed over the reporting period has made best efforts to consider the needs and interests of the overall RCCS initiative. The project team and their collaborators feel confident that the final constructed test facility is well poised to support the overall DOE objectives in developing inherently safe and fully passive means of decay heat removal in advanced reactor designs. Furthermore, the design has been reviewed by AREVA and their feedback indicates their support of the designs ability to provide important data for future design and licensing activities of their 625 MW_t SC-HTGR. The results of this study have identified a configuration to support both the ANL/DOE project goals and the DOE vision to provide AREVA with data suitable for characterizing the RCCS of their full scale HTGR design. Flexibility remained a primary design philosophy, and will allow the test facility to easily accommodate future alterations.

7.1 Path forward

This water-based design process has placed an emphasis on leveraging the existing air-based infrastructure, and will re-use many components such as the heated enclosure and insulation, radiant heaters and steel plate, power controllers, communications network, and cDAQ data acquisition chassis. This design has been reviewed internally and confirmed by outside sponsors, and procurement of the materials and instrumentation is currently in-progress. After completing the air-based data review period, disassembly and storage of air-based components will be conducted in the second half of FY16. Machine work and construction is expected to be performed in parallel, and will continue through the end of FY16, after which physical installation and facility shakedowns can be anticipated by early FY17. A more detailed breakdown of the specific events in the water-based testing program is provided in Table 15.

Table 15: Timeline for water-based operations in the NSTF

	2015				2016				2017				2018				2019				2020			
Discussion & Preparation			■	■	■																			
Test Section Design				■	■	■																		
Network & Tank Design					■	■	■																	
M&E Procurement					■	■	■	■	■															
Air-based disassembly							■	■																
Fabrication & Construction							■	■	■															
Installation								■	■															
Shakedown & Testing									■	■														
Test Series #1										■	■	■	■											
Maintenance														▒	▒									
Test Series #2																■	■	■	■					
Data Review Period																				▒	▒			
Final Report																						■	■	■

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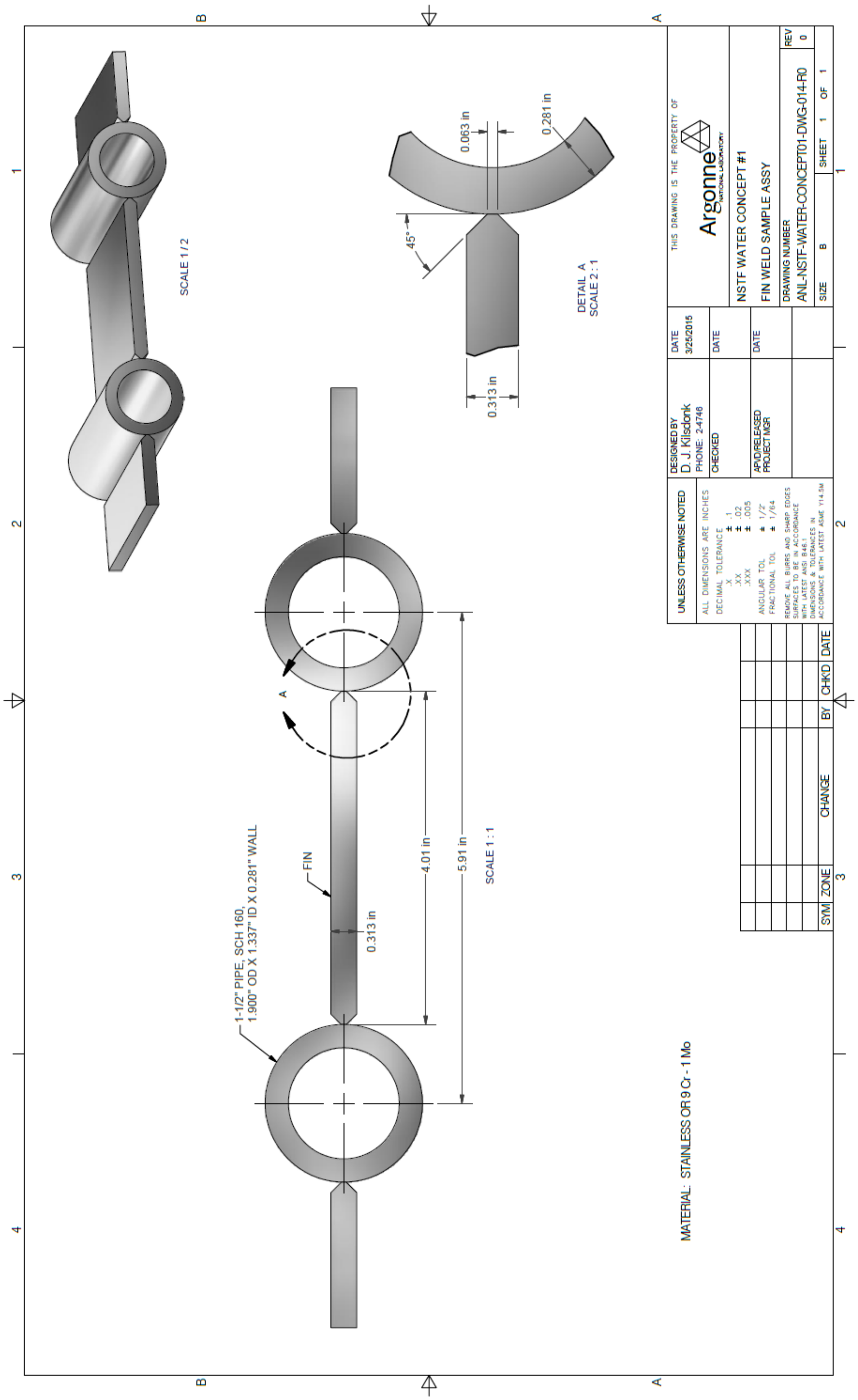
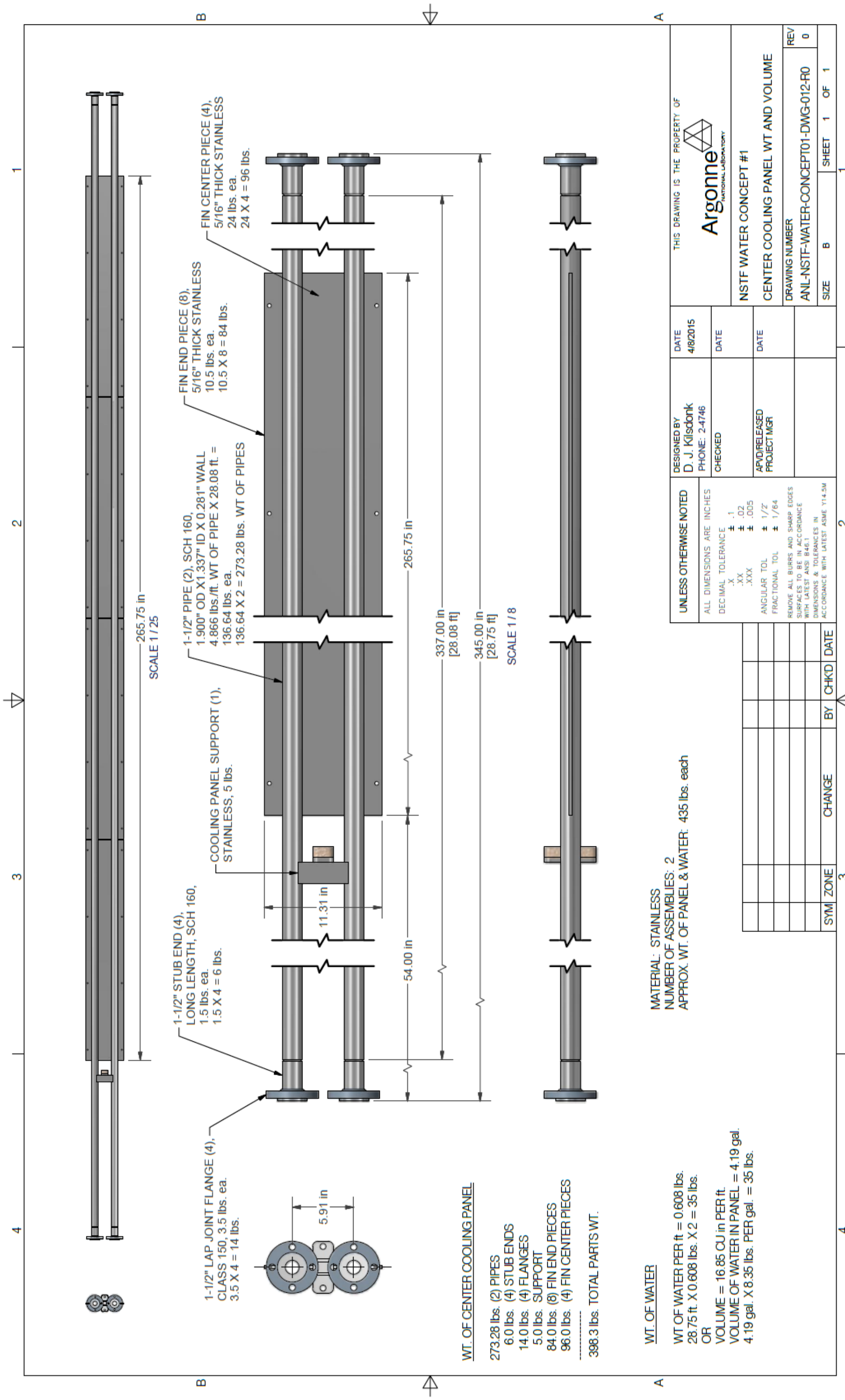
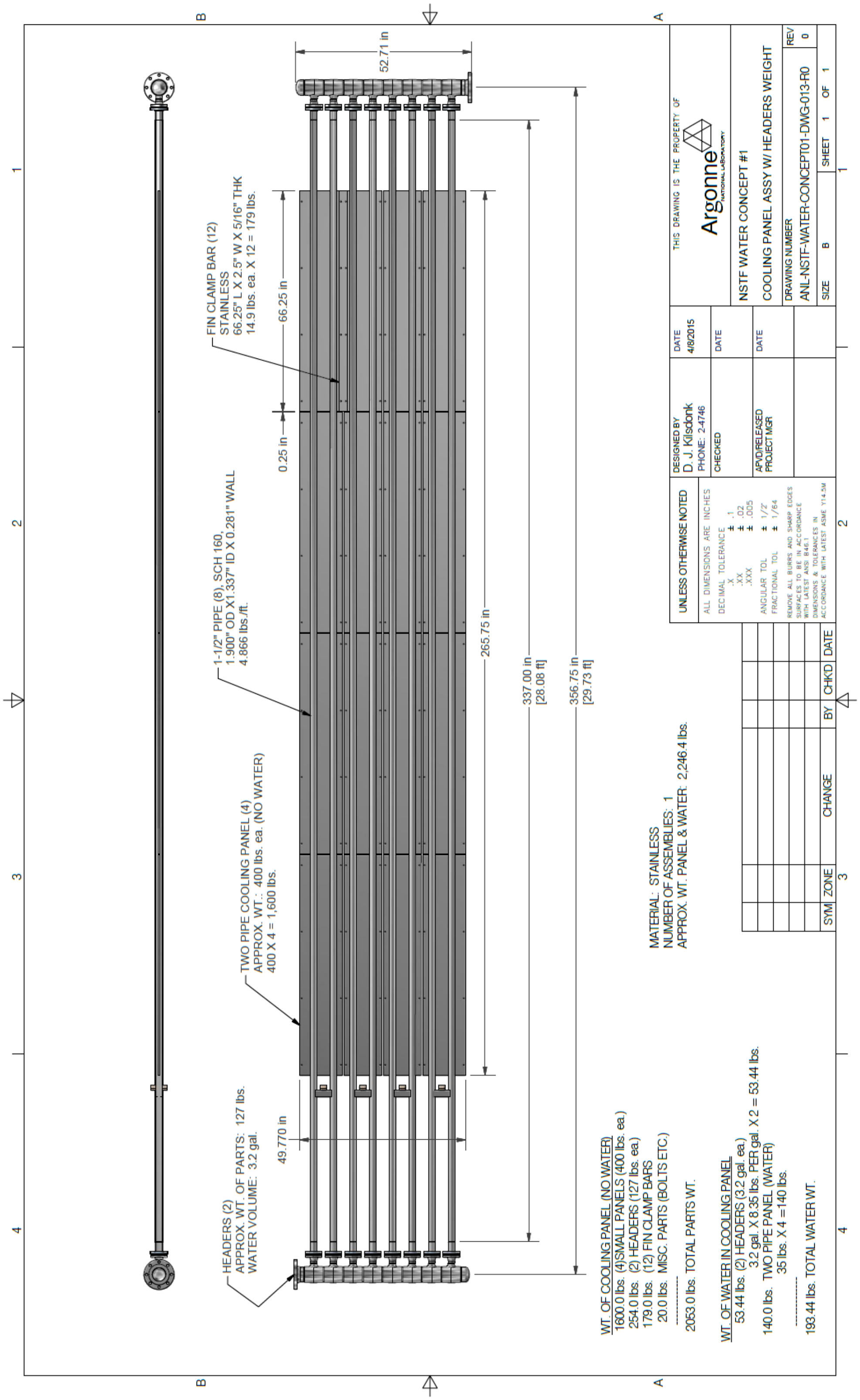
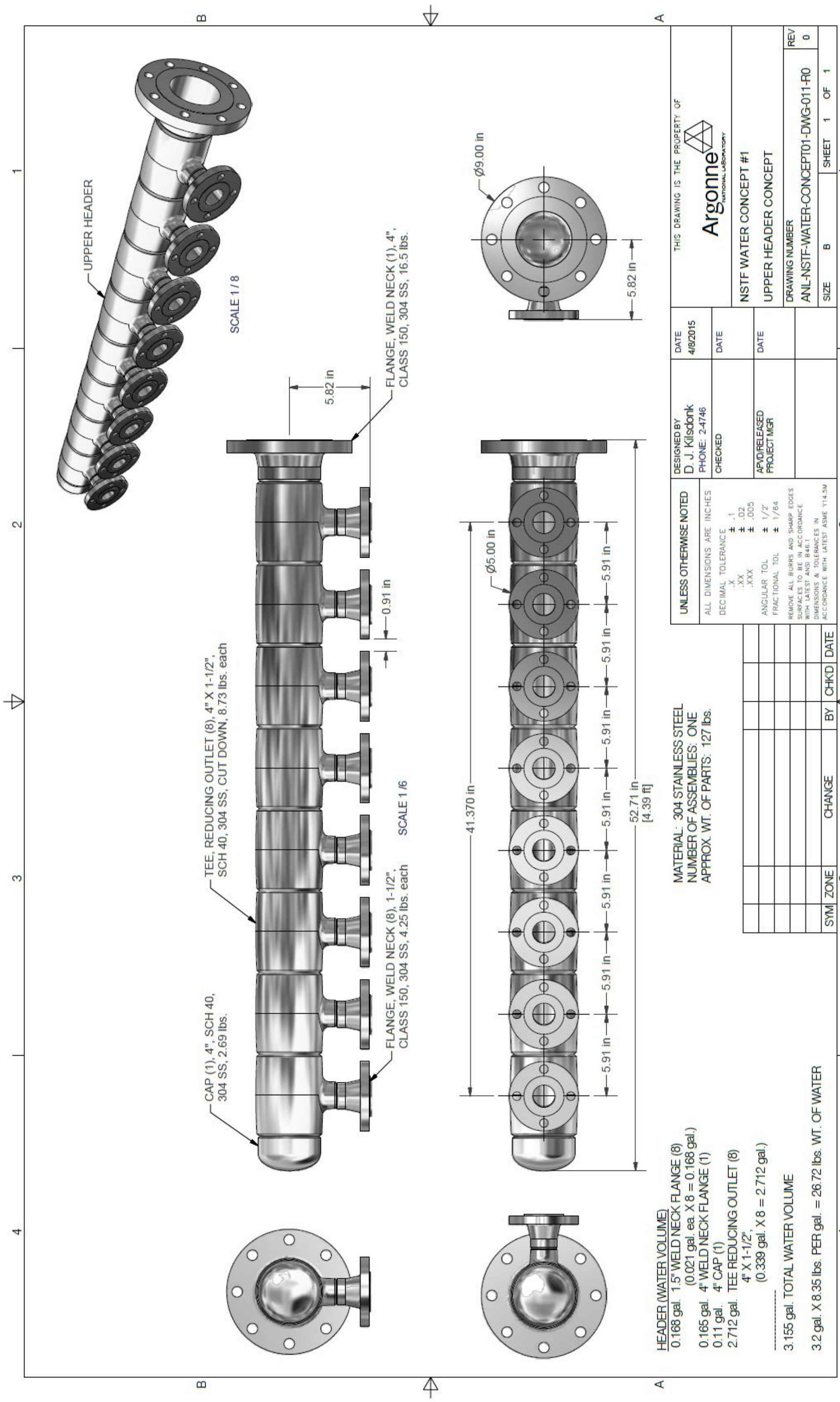
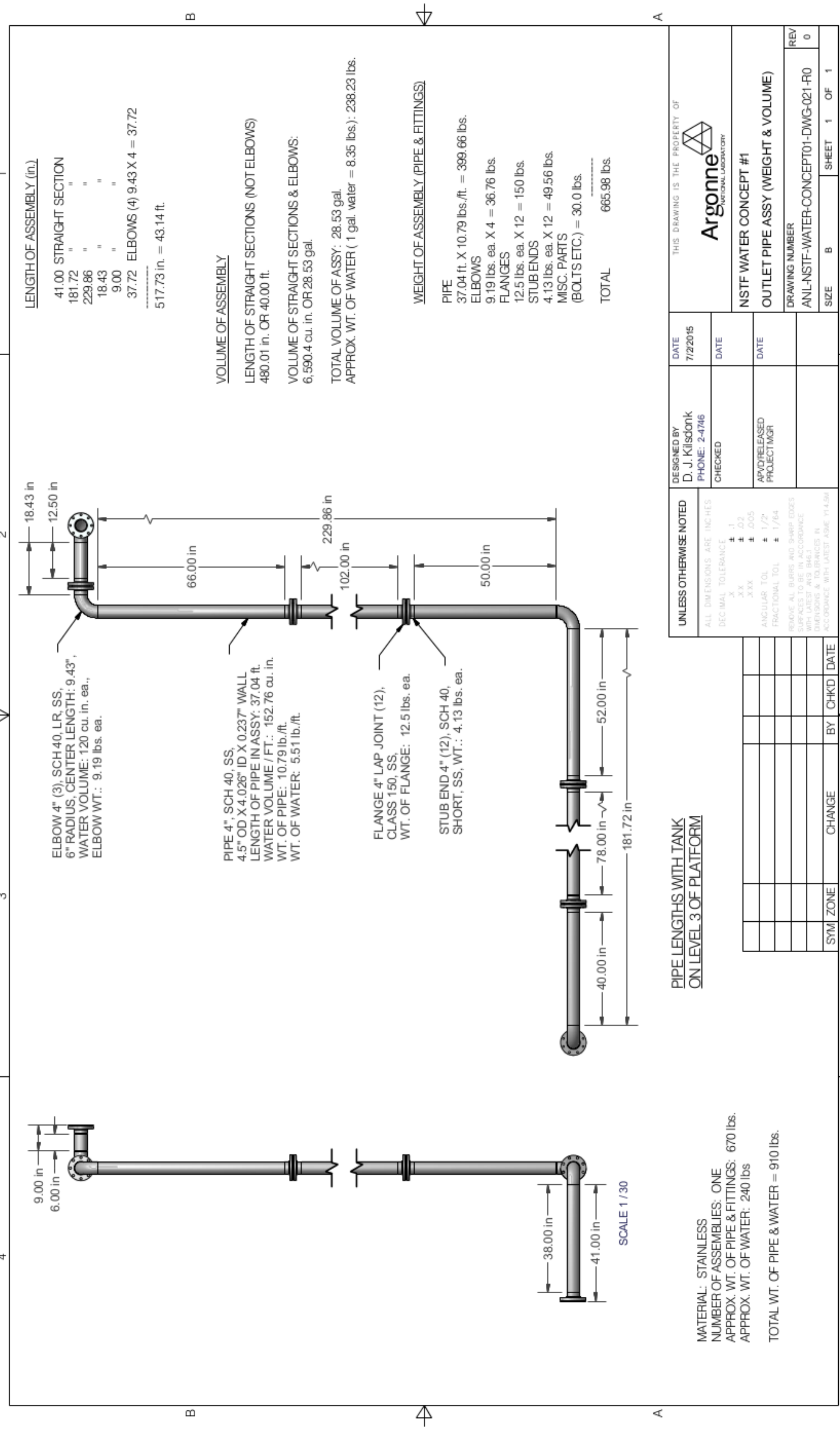
APPENDIX – ENGINEERING DRAWINGS




FIN CENTER PIECE (4), 5/16" THICK STAINLESS 24 lbs. ea. 24 X 4 = 96 lbs.
FIN END PIECE (8), 5/16" THICK STAINLESS 10.5 lbs. ea. 10.5 X 8 = 84 lbs.
1-1/2" PIPE (2), SCH 160, 1.900" OD X1.337" ID X 0.281" WALL 4.866 lbs./ft. WT OF PIPE X 28.08 ft. = 136.64 lbs. ea. 136.64 X 2 = 273.28 lbs. WT OF PIPES
COOLING PANEL SUPPORT (1), STAINLESS, 5 lbs.
1-1/2" STUB END (4), LONG LENGTH, SCH 160, 1.5 lbs. ea. 1.5 X 4 = 6 lbs.
1-1/2" LAP JOINT FLANGE (4), CLASS 150, 3.5 lbs. ea. 3.5 X 4 = 14 lbs.
265.75 in
SCALE 1 / 25
265.75 in
337.00 in [28.08 ft]
345.00 in [28.75 ft]
SCALE 1 / 8
11.31 in
54.00 in
5.91 in
WT. OF CENTER COOLING PANEL
273.28 lbs. (2) PIPES
6.0 lbs. (4) STUB ENDS
14.0 lbs. (4) FLANGES
5.0 lbs. SUPPORT
84.0 lbs. (8) FIN END PIECES
96.0 lbs. (4) FIN CENTER PIECES
398.3 lbs. TOTAL PARTS WT.
WT. OF WATER
WT OF WATER PER ft = 0.608 lbs.
28.75 ft. X 0.608 lbs. X 2 = 35 lbs.
OR
VOLUME = 16.85 CU in PER ft.
VOLUME OF WATER IN PANEL = 4.19 gal.
4.19 gal. X 8.35 lbs. PER gal. = 35 lbs.
MATERIAL: STAINLESS
NUMBER OF ASSEMBLIES: 2
APPROX. WT. OF PANEL & WATER: 435 lbs. each
UNLESS OTHERWISE NOTED
ALL DIMENSIONS ARE INCHES
DECIMAL TOLERANCE .X ± .1 .XX ± .02 .XXX ± .005
ANGULAR TOL ± 1/2°
FRACTIONAL TOL ± 1/64
DESIGNED BY D. J. Kilsdonk PHONE: 2-4746
DATE 4/8/2015
CHECKED
APVD/RELEASED PROJECT MGR
THIS DRAWING IS THE PROPERTY OF Argonne NATIONAL LABORATORY
NSTF WATER CONCEPT #1
CENTER COOLING PANEL WT AND VOLUME
DRAWING NUMBER ANL-NSTF-WATER-CONCEPT01-DWG-012-R0
REV 0
SIZE B
SHEET 1 OF 1
SYM ZONE CHANGE BY CHK'D DATE


FIN CLAMP BAR (12)
STAINLESS
66.25" L X 2.5" W X 5/16" THK
14.9 lbs. ea. X 12 = 179 lbs.
1-1/2" PIPE (8), SCH 160,
1.900" OD X1.337" ID X 0.281" WALL
4.866 lbs./ft.
TWO PIPE COOLING PANEL (4)
APPROX. WT.: 400 lbs. ea. (NO WATER)
400 X 4 = 1,600 lbs.
HEADERS (2)
APPROX. WT. OF PARTS: 127 lbs.
WATER VOLUME: 3.2 gal.
52.71 in
66.25 in
0.25 in
265.75 in
337.00 in
[28.08 ft]
356.75 in
[29.73 ft]
49.770 in
MATERIAL: STAINLESS
NUMBER OF ASSEMBLIES: 1
APPROX. WT. PANEL & WATER: 2,246.4 lbs.
WT. OF COOLING PANEL (NO WATER)
1600.0 lbs. (4)SMALL PANELS (400 lbs. ea.)
254.0 lbs. (2) HEADERS (127 lbs. ea.)
179.0 lbs. (12) FIN CLAMP BARS
20.0 lbs. MISC. PARTS (BOLTS ETC.)
2053.0 lbs. TOTAL PARTS WT.
WT. OF WATER IN COOLING PANEL
53.44 lbs. (2) HEADERS (3.2 gal. ea.)
3.2 gal. X 8.35 lbs. PER gal. X 2 = 53.44 lbs.
140.0 lbs. TWO PIPE PANEL (WATER)
35 lbs. X 4 =140 lbs.
193.44 lbs. TOTAL WATER WT.
UNLESS OTHERWISE NOTED
ALL DIMENSIONS ARE INCHES
DECIMAL TOLERANCE
.X ± .1
.XX ± .02
.XXX ± .005
ANGULAR TOL ± 1/2°
FRACTIONAL TOL ± 1/64
DESIGNED BY
D. J. Kilsdonk
PHONE: 2-4746
DATE
4/8/2015
CHECKED
APVD/RELEASED
PROJECT MGR
THIS DRAWING IS THE PROPERTY OF
Argonne NATIONAL LABORATORY
NSTF WATER CONCEPT #1
COOLING PANEL ASSY W/ HEADERS WEIGHT
DRAWING NUMBER
ANL-NSTF-WATER-CONCEPT01-DWG-013-R0
REV
0
SIZE B
SHEET 1 OF 1
SYM ZONE CHANGE BY CHK'D DATE


UPPER HEADER
SCALE 1 / 8
FLANGE, WELD NECK (1), 4", CLASS 150, 304 SS, 16.5 lbs.
5.82 in
Ø9.00 in
5.82 in
TEE, REDUCING OUTLET (8), 4" X 1-1/2", SCH 40, 304 SS, CUT DOWN, 8.73 lbs. each
CAP (1), 4", SCH 40, 304 SS, 2.69 lbs.
FLANGE, WELD NECK (8), 1-1/2", CLASS 150, 304 SS, 4.25 lbs. each
0.91 in
SCALE 1 /6
Ø5.00 in
41.370 in
5.91 in
52.71 in
[4.39 ft]
MATERIAL: 304 STAINLESS STEEL
NUMBER OF ASSEMBLIES: ONE
APPROX. WT. OF PARTS: 127 lbs.
HEADER (WATER VOLUME)
0.168 gal. 1.5" WELD NECK FLANGE (8)
(0.021 gal. ea. X 8 = 0.168 gal.)
0.165 gal. 4" WELD NECK FLANGE (1)
0.11 gal. 4" CAP (1)
2.712 gal. TEE REDUCING OUTLET (8)
4" X 1-1/2",
(0.339 gal. X 8 = 2.712 gal.)
3.155 gal. TOTAL WATER VOLUME
3.2 gal. X 8.35 lbs. PER gal. = 26.72 lbs. WT. OF WATER
UNLESS OTHERWISE NOTED
ALL DIMENSIONS ARE INCHES
DECIMAL TOLERANCE
.X ± .1
.XX ± .02
.XXX ± .005
ANGULAR TOL ± 1/2°
FRACTIONAL TOL ± 1/64
DESIGNED BY
D. J. Kilsdonk
PHONE: 2-4746
DATE
4/8/2015
CHECKED
APVD/RELEASED PROJECT MGR
THIS DRAWING IS THE PROPERTY OF
Argonne NATIONAL LABORATORY
NSTF WATER CONCEPT #1
UPPER HEADER CONCEPT
DRAWING NUMBER
ANL-NSTF-WATER-CONCEPT01-DWG-011-R0
REV
0
SIZE B
SHEET 1 OF 1
SYM ZONE CHANGE BY CHK'D DATE


ELBOW 4" (3), SCH 40, LR, SS,
6" RADIUS, CENTER LENGTH: 9.43",
WATER VOLUME: 120 cu. in. ea.,
ELBOW WT.: 9.19 lbs. ea.
PIPE 4", SCH 40, SS,
4.5" OD X 4.026" ID X 0.237" WALL
LENGTH OF PIPE IN ASSY: 37.04 ft.
WATER VOLUME / FT.: 152.76 cu. in.
WT. OF PIPE: 10.79 lb./ft.
WT. OF WATER: 5.51 lb./ft.
FLANGE 4" LAP JOINT (12),
CLASS 150, SS,
WT. OF FLANGE: 12.5 lbs. ea.
STUB END 4" (12), SCH 40,
SHORT, SS, WT.: 4.13 lbs. ea.
18.43 in
12.50 in
66.00 in
229.86 in
102.00 in
50.00 in
9.00 in
6.00 in
38.00 in
41.00 in
SCALE 1 / 30
40.00 in
78.00 in
52.00 in
181.72 in
LENGTH OF ASSEMBLY (in.)
41.00 STRAIGHT SECTION
181.72 " "
229.86 " "
18.43 " "
9.00 " "
37.72 ELBOWS (4) 9.43 X 4 = 37.72
517.73 in. = 43.14 ft.
VOLUME OF ASSEMBLY
LENGTH OF STRAIGHT SECTIONS (NOT ELBOWS)
480.01 in. OR 40.00 ft.
VOLUME OF STRAIGHT SECTIONS & ELBOWS:
6,590.4 cu. in. OR 28.53 gal.
TOTAL VOLUME OF ASSY: 28.53 gal.
APPROX. WT. OF WATER (1 gal. water = 8.35 lbs.): 238.23 lbs.
WEIGHT OF ASSEMBLY (PIPE & FITTINGS)
PIPE
37.04 ft. X 10.79 lbs./ft. = 399.66 lbs.
ELBOWS
9.19 lbs. ea. X 4 = 36.76 lbs.
FLANGES
12.5 lbs. ea. X 12 = 150 lbs.
STUB ENDS
4.13 lbs. ea. X 12 = 49.56 lbs.
MISC. PARTS
(BOLTS ETC.) = 30.0 lbs.
TOTAL 665.98 lbs.
MATERIAL: STAINLESS
NUMBER OF ASSEMBLIES: ONE
APPROX. WT. OF PIPE & FITTINGS: 670 lbs.
APPROX. WT. OF WATER: 240 lbs
TOTAL WT. OF PIPE & WATER = 910 lbs.
PIPE LENGTHS WITH TANK
ON LEVEL 3 OF PLATFORM
SYM ZONE CHANGE BY CHK'D DATE
UNLESS OTHERWISE NOTED
DESIGNED BY
D. J. Kilsdonk
PHONE: 2-4746
DATE
7/2/2015
CHECKED
APVD/RELEASED
PROJECT MGR
THIS DRAWING IS THE PROPERTY OF
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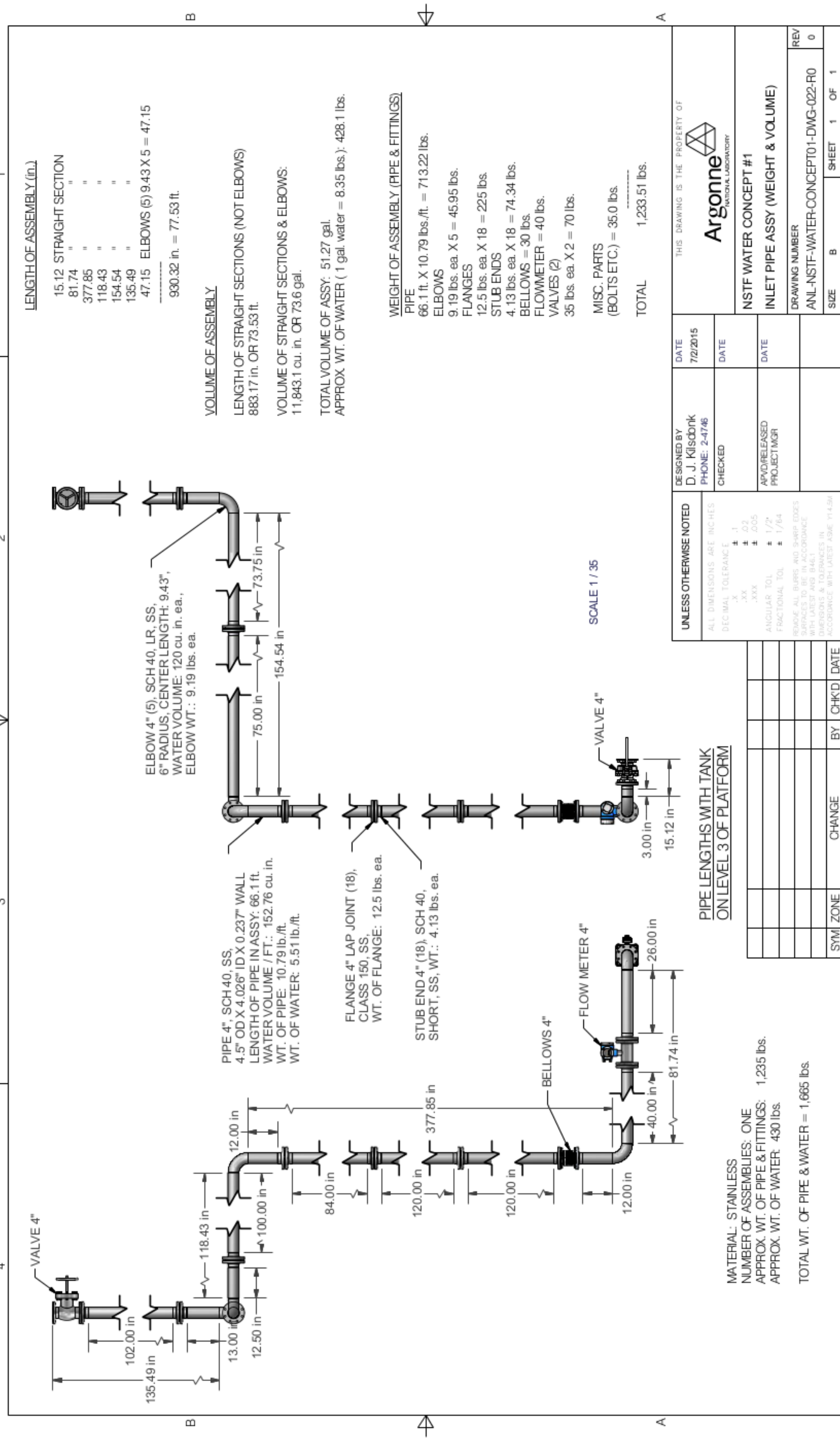
NSTF WATER CONCEPT #1
OUTLET PIPE ASSY (WEIGHT & VOLUME)
DRAWING NUMBER
ANL-NSTF-WATER-CONCEPT01-DWG-021-R0
REV
0
SIZE B
SHEET 1 OF 1


VALVE 4"
102.00 in
135.49 in
118.43 in
13.00 in
12.50 in
100.00 in
12.00 in
84.00 in
120.00 in
377.85 in
120.00 in
BELLOWS 4"
FLOW METER 4"
12.00 in
40.00 in
81.74 in
26.00 in
PIPE 4", SCH 40, SS,
4.5" OD X 4.026" ID X 0.237" WALL
LENGTH OF PIPE IN ASSY: 66.1 ft.
WATER VOLUME / FT.: 152.76 cu. in.
WT. OF PIPE: 10.79 lb./ft.
WT. OF WATER: 5.51 lb./ft.
FLANGE 4" LAP JOINT (18),
CLASS 150, SS,
WT. OF FLANGE: 12.5 lbs. ea.
STUB END 4" (18), SCH 40,
SHORT, SS, WT.: 4.13 lbs. ea.
ELBOW 4" (5), SCH 40, LR, SS,
6" RADIUS, CENTER LENGTH: 9.43",
WATER VOLUME: 120 cu. in. ea.,
ELBOW WT.: 9.19 lbs. ea.
75.00 in
73.75 in
154.54 in
VALVE 4"
3.00 in
15.12 in
SCALE 1 / 35
PIPE LENGTHS WITH TANK
ON LEVEL 3 OF PLATFORM
MATERIAL: STAINLESS
NUMBER OF ASSEMBLIES: ONE
APPROX. WT. OF PIPE & FITTINGS: 1,235 lbs.
APPROX. WT. OF WATER: 430 lbs.
TOTAL WT. OF PIPE & WATER = 1,665 lbs.
LENGTH OF ASSEMBLY (in.)
15.12 STRAIGHT SECTION
81.74 " "
377.85 " "
118.43 " "
154.54 " "
135.49 " "
47.15 ELBOWS (5) 9.43 X 5 = 47.15
930.32 in. = 77.53 ft.
VOLUME OF ASSEMBLY
LENGTH OF STRAIGHT SECTIONS (NOT ELBOWS)
883.17 in. OR 73.53 ft.
VOLUME OF STRAIGHT SECTIONS & ELBOWS:
11,843.1 cu. in. OR 73.6 gal.
TOTAL VOLUME OF ASSY: 51.27 gal.
APPROX. WT. OF WATER (1 gal. water = 8.35 lbs.): 428.1 lbs.
WEIGHT OF ASSEMBLY (PIPE & FITTINGS)
PIPE
66.1 ft. X 10.79 lbs./ft. = 713.22 lbs.
ELBOWS
9.19 lbs. ea. X 5 = 45.95 lbs.
FLANGES
12.5 lbs. ea. X 18 = 225 lbs.
STUB ENDS
4.13 lbs. ea. X 18 = 74.34 lbs.
BELLOWS = 30 lbs.
FLOWMETER = 40 lbs.
VALVES (2)
35 lbs. ea. X 2 = 70 lbs.
MISC. PARTS
(BOLTS ETC.) = 35.0 lbs.
TOTAL 1,233.51 lbs.
SYM ZONE CHANGE BY CHK'D DATE
UNLESS OTHERWISE NOTED
DESIGNED BY
D. J. Kilsdonk
PHONE: 2-4746
DATE
7/2/2015
CHECKED
DATE
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DATE
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NSTF WATER CONCEPT #1
INLET PIPE ASSY (WEIGHT & VOLUME)
DRAWING NUMBER
ANL-NSTF-WATER-CONCEPT01-DWG-022-R0
REV
0
SIZE B
SHEET 1 OF 1

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