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Net Positive Suction Head Available (NPSH_a) Analysis for Phase 1 Waste Tanks

CH2MHILL
Hanford Group, Inc.

Richland, Washington

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC06-99RL14047

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Net Positive Suction Head Available (NPSHa) Analysis for Phase 1 Waste Tanks

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Abstract:

This document identifies the means to determine NPSHa for Hanford waste tanks. It presents the values of vapor pressure and density of Hanford double-shell tank waste as they relate to temperature.

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Net Positive Suction Head Available (NPSH_a) Analysis for Phase 1 Waste Tanks

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COGEMA Engineering Corporation

Date Published
March 2000

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

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TERMS

HLW	high-level waste
LAW	low-activity waste
NPSH _a	net positive suction head available
NPSH _r	net positive suction head required

1.0 INTRODUCTION

Net positive suction head (NPSH) is a measure of the pressure energy available at the suction eye of a pump impeller. As fluid enters the impeller, it accelerates and its pressure drops, as predicted by the Bernoulli equation. If the fluid pressure drops below the vapor pressure, vapor bubbles form and are carried to a region of higher pressure within the pump, where they violently collapse; this is called cavitation. Cavitation has many effects on a pump. Cavitation will limit the pump's output capacity or liters per second (gallons per minute). The collapse of vapor bubbles erodes the metal from the impeller and also causes the pump to vibrate. Vibration will greatly reduce the life of the pump seals and bearings.

The laws of physics governing the operation of pumps require that the NPSH available ($NPSH_a$) be greater than or equal to the NPSH required ($NPSH_r$) to avoid cavitation. Only the pump user can determine $NPSH_a$, because $NPSH_a$ is a function of such process system features as hardware architecture, fluid properties, and fluid temperature. The manufacturer determines a pump's $NPSH_r$, by such features as impeller design and operating radians per second (revolutions per minute). When a pump is procured, the user specifies the discharge pressure, output capacity, and $NPSH_a$, among other requirements. The manufacturer designs, builds, and tests a pump ensuring that the requirements are satisfied. One of the tests that a manufacturer can perform, if requested, is to determine the onset of cavitation, thereby establishing the $NPSH_r$. If the $NPSH_r$ is not less than the $NPSH_a$, the pump does not meet the user's requirements.

Exact values of $NPSH_a$, especially in Hanford waste tanks, are subject to uncertainty; therefore some margin must be applied when the user specifies a pump for a specific application. The margin for $NPSH_r$ can be reduced by having the pump manufacturer conduct a test, as outlined in the *Hydraulic Institute Standards*, if the first stage impeller is of new design configuration. Even pumps of standard design can have $NPSH_r$ variations from unit to unit. Reducing uncertainty for $NPSH_a$ is a function of increased knowledge of waste constituents for specific tanks and the capability to control the waste temperature.

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2.0 PURPOSE

A means to determine $NPSH_a$ for Hanford waste tanks is presented in this document. Appendix A presents the values of vapor pressure and density of Hanford double-shell tank waste as they relate to temperature. This information is to be used by the projects and design agents to calculate the $NPSH_a$ for the mixer-pump and transfer-pump detail-design specifications. For a companion document that aids in calculating $NPSH_a$, see RPP-5637, *A Parametric Study to Characterize Alternatives Generation and Analysis Alternatives for Removal of Heat from High-Level Waste Tanks*.

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3.0 SCOPE

Analysis results of waste vapor pressure and density verses temperature are based on best-basis inventory data from a limited number of tanks (i.e., Tanks 241-AN-102, -103, -104, and -105 for low-activity waste (LAW) and Tank 241-AZ-101 for high-level waste (HLW). These results are presented in Appendix A. The relationships of vapor pressure and density verses temperature change as the waste is diluted with water. Appendix A presents cases for many dilution ratios. If the user of this document determines that the $NPSH_a$ is marginal when compared to the candidate pump's $NPSH_r$ for a specific tank pumping application, caution should be used, and it is recommended that a waste analysis be performed for the tank in question with tank-specific waste property data.

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4.0 NET POSITIVE SUCTION HEAD

4.1 NET POSITIVE SUCTION HEAD EQUATION

$NPSH_a$ is the total suction head in meters (feet) of liquid absolute, determined at the pump suction nozzles and referenced to a datum, less the absolute vapor of the liquid in meters (feet) of liquid pumped.

Calculation of $NPSH_a$ is as follows.

$$NPSH_a = \frac{g_c}{g} \left(\frac{p_a - p_v}{\rho} - h_{fs} \right) \pm Z_a$$

where

- g_c = gravitational acceleration of 9.8 m/s^2 (32.174 ft/s^2)
- g = Newton's law proportionality factor of 9.8 m/s^2 ($32.174 \text{ ft-lb/lb}_f\text{-s}^2$)
- p_a = absolute pressure at the fluid surface of 703 Pa (14.696 lbf/in^2)
- p_v = vapor pressure of fluid in pascals (lbf/in^2)
- ρ = density of fluid in kg/m^3 (lb/ft^3)
- h_{fs} = fiction loss in suction line in meters (feet)
- Z_a = height of fluid surface above suction in meters (feet).

For mixer pumps, h_{fs} will effectively be zero and p_a is atmospheric pressure for Hanford tanks; therefore, $NPSH_a$ is a function of waste depth, temperature, vapor pressure, and density.

For transfer pumps, h_{fs} must be calculated for any devices such as a hose that may be ahead of the impeller inlet.

4.2 EXAMPLES FOR USING DATA

Figures 1 and 2 illustrate the utility of the data presented in Appendix A. These figures present the relationship of submergence and waste temperature to $NPSH_a$ for mixer pumps, using two likely waste-dilution scenarios: HLW with no dilution and LAW with 1:1 dilution, respectively. Similar figures can be constructed for other dilutions. Note: *Impeller submergence is not the same as tank-waste level, because the impeller inlet is located above the tank bottom.*

Figure 1. High-Level Waste With No Dilution.

Figure 2. Low-Activity Waste With 1:1 Dilution.

All of the following examples use Figure 1, High-Level Waste With No Dilution.

4.2.1 Example 1

Q: I wish to operate the pump at full power with 2 m of waste remaining, and I've limited the temperature to 80 °C. What is the $NPSH_a$?

A: Assuming that the impeller is 0.5 m above the tank bottom, subtract 0.5 from 2.0 m and read across the 1.5 m line until it intersects the 80 °C line. Then read down to 6.7 m $NPSH_a$.

4.2.2 Example 2

Q: I have a pump with 7.0 m of $NPSH_r$ and wish to operate at full power with a 1.5 m waste level. Assuming that the impeller is 0.5 m from the tank bottom, what is the maximum waste temperature allowed?

A: Find the intersection of the vertical line of $NPSH_a = 7.0$ and the horizontal line of Submergence = 1.0. The maximum temperature is approximately 73 °C.

4.2.3 Example 3

Q: Can I operate a pump at full power with $NPSH_r = 5.0$ m at the 1.0 m waste level at 90 °C?

A: No, with 0.5 m impeller submergence at 90 °C, the $NPSH_a = 4.3$. This would not satisfy $NPSH_a > NPSH_r$.

5.0 REFERENCES

Hydraulic Institute Standards, Hydraulic Institute, Cleveland, Ohio.

RPP-5637, 2000, draft, *A Parametric Study to Characterize Alternatives Generation and Analysis Alternatives for Removal of Heat from High-Level Waste Tanks*, prepared by Numatec Hanford Corporation for CH2M HILL Hanford Group, Inc., Richland, Washington.

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APPENDIX A

**NET POSITIVE SUCTION HEAD AVAILABLE (NPSH_a)
ANALYSIS FOR PHASE 1 WASTE TANKS**

D. J. Geniesse
COGEMA Engineering Corporation

February 2000

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TERMS

BBI	best-basis inventory
ESP	Environmental Simulation Program
HLW	high-level waste
LAW	low-activity waste
NPSH	net positive suction head
NPSH _a	net positive suction head available
NPSH _r	net positive suction head required
ORP	Office of River Protection
RPP	River Protection Project
WFD	waste feed delivery

A1.0 SUMMARY

The Environmental Simulation Program (ESP)¹ was used to estimate the liquid properties of low-activity waste (LAW) and high-level waste (HLW). The liquid properties were estimated over temperature and dilution ranges to determine the effects of vapor pressure and liquid density on available net positive suction head (NPSH_a). Estimates of vapor pressure and liquid density versus temperature and dilution are presented in Tables A1a,b through A4a,b and Figures A1 through A4.

NPSH_a is a measure of the total amount of liquid pressure at the intake of a pump. NPSH_a must exceed the pump's required net positive suction head (NPSH_r) to prevent impeller cavitation. NPSH_a is expressed in meters (feet) of fluid.

The LAW chemistry was estimated from best-basis inventory (BBI) values for Tanks 241-AN-102, -103, -104, and -105. The concentrations of 13 major components were averaged to reduce inaccuracies in inventory data. The HLW chemistry was estimated from the BBI values of Tank 241-AZ-101. The concentrations of 24 compounds were used to increase the accuracy of physical property estimation.

Chemical process modeling is performed using ESP aqueous chemistry software. ESP software is leased from OLI Systems, Inc., of Morris Plains, New Jersey. ESP software is Hanford Site-approved for simulation of waste-tank chemistry.

The ESP model for the waste-tank system ("GENTANK" chemistry model) is updated continuously to improve accuracy in the thermodynamic prediction of chemical speciation and physical properties. The GENTANK chemistry model used to generate the liquid properties is current as of January 2000.

¹ Environmental Simulation Program is a trademark of OLI Systems, Inc.

A2.0 DISCUSSION

Calculation of $NPSH_a$ is as follows.

$$NPSH_a = \frac{g_c}{g} \left(\frac{p_a - p_v}{\rho} - h_{fs} \right) \pm Z_a$$

where

- g_c = gravitational acceleration of 9.8 m/s^2 (32.174 ft/s^2)
- g = Newton's law proportionality factor of 9.8 m/s^2 ($32.174 \text{ ft-lb/lb}_f\text{-s}^2$)
- p_a = absolute pressure at the fluid surface of 703 Pa (14.696 lbf/in^2)
- p_v = vapor pressure of fluid in pascals (lbf/in^2)
- ρ = density of fluid in kg/m^3 (lb/ft^3)
- h_{fs} = fiction loss in suction line in meters (feet)
- Z_a = height of fluid surface above suction in meters (feet).

In the case where the fluid surface is above the pump impeller (flooded suction), Z_a is positive. Where the fluid surface is below the pump suction, Z_a is negative.

The LAW chemistry was estimated from BBI values of Tanks 241-AN-102, -103, -104, and -105. The concentrations of major components were averaged to reduce inaccuracies in inventory data. The BBI values were reconciled for charge and for free hydroxide, then compounded into molecular species. The concentrations of 13 major compounds were averaged for input to ESP molecular species; those concentration averages for Tanks 241-AN-102, -103, -104, and -105 are as follows.

Compound	Tank				
	AN-102 (g/L)	AN-103 (g/L)	AN-104 (g/L)	AN-105 (g/L)	Average (g/L)
H ₂ O	499.40	376.50	513.56	532.68	480.53
Al(OH) ₃	44.44	179.14	107.04	105.42	109.01
HCl	3.85	8.19	7.96	9.81	7.45
Na ₂ CO ₃	120.42	45.14	98.78	81.53	86.47
Cr(OH) ₃	0.44	1.36	2.66	1.97	1.61
NaF	4.01	2.17	1.40	2.22	2.45
KOH	5.40	19.29	9.25	8.53	10.62
NaOH	378.70	487.86	399.20	356.76	405.63

Compound	Tank				
	AN-102 (g/L)	AN-103 (g/L)	AN-104 (g/L)	AN-105 (g/L)	Average (g/L)
HNO ₂	82.41	140.49	95.04	120.62	109.64
HNO ₃	223.76	204.38	143.29	173.38	186.20
Na ₃ PO ₄ ·0.25NaOH	8.77	4.57	8.11	8.71	7.54
Na ₃ H(SO ₄) ₂	21.64	4.30	13.07	7.30	11.58
Acetic Acid	62.15	5.81	6.41	17.58	22.99
Oxalic Acid	49.08	2.18	9.60	0.00	15.21
Total	1,507.34	1,483.53	1,417.81	1,426.49	1,456.94

The HLW chemistry was estimated from Tank 241-AZ-101 BBI. Values were reconciled for charge and for free hydroxide, then compounded into molecular species. The concentrations of 24 major compounds are as follows.

Compound	g/L
Al(OH) ₃	39.02
Bi(OH) ₃	0.01
Ca(OH) ₂	0.29
HCl	0.18
Na ₂ CO ₃	52.10
Cr(OH) ₃	0.17
H ₂ (CrO ₄)	1.45
CsOH	0.08
NaF	3.69
Fe(OH) ₃	12.34
KOH	6.21
La(OH) ₃	0.33
NaOH	134.34
Ni(OH) ₂	0.59
HNO ₂	58.76

Compound	g/L
HNO ₃	67.58
Pb(OH) ₂	0.15
Na ₃ PO ₄ ·0.25NaOH	2.38
Pu(OH) ₄	0.01
SiO ₂	0.81
Na ₃ H(SO ₄) ₂	21.61
Sr(OH) ₂	0.04
Acetic Acid	1.31
Oxalic Acid	1.96
Total	405.45

A3.0 RESULTS

The ESP-estimated liquid physical properties for LAW and HLW are as follows.

Liquid Properties	Low-Activity Waste	High-Level Waste
Temperature (°C)	40	40
pH	15.3	13.9
Vapor pressure, Pa (lbf/in ² absolute)	0.486	0.855
Boiling point (°C)	121.0	106.7
Solids fraction (wt%)	0.068	0.046
Liquid density (g/cm ³)	1.457	1.264
Solid density (g/cm ³)	2.514	3.331
Electrical conductivity (1/Ω-cm)	0.31	0.31
Viscosity, Pa·s (cP)	7.86	2.59
Ionic strength (molality)	18.43	8.04

Liquid properties were estimated over a temperature range from 5 to 120 °C and dilution ranges from 0 to 16 volumes of water per volume of original solution (V_w/V_o). Vapor-pressure and liquid-density data are shown in Tables A1a,b through A4a,b.

A3.1 EXAMPLE

Determine the NPSH available for LAW with 1:1 water to waste dilution (V_w/V_o) at 50 °C with the pump impeller 3.66 m (12 ft) below the fluid surface.

From Table 1a, LAW vapor pressure (p_v) at 1:1 dilution and 50 °C = 1.378 lbf/in².

From Table 2a, LAW liquid density (ρ) at 1:1 dilution and 50 °C = 78.16 lb/ft³.

At 12 feet of submergence,

$$NPSH_a = \frac{g_c}{g} \left(\frac{p_a - p_v}{\rho} - h_{fs} \right) \pm Z_a$$

Assume:

$$\begin{aligned} \rho &= 1.0 \text{ lbf/lb} \\ p_a &= 14.696 \text{ lbf/in}^2 \\ h_{fs} &= 0 \text{ ft.} \end{aligned}$$

$$\begin{aligned} \text{NPSHa} &= 1 \left(\frac{(14.696 - 1.378)(12^2)}{78.16} - 0 \right) + 12 = 36.5 \text{ ft} \\ &= 11.1 \text{ m.} \end{aligned}$$

A4.0 BIBLIOGRAPHY

1. W. L. McCabe, J. C. Smith, and P. Harriott, 1993, *Unit Operations of Chemical Engineering*, Fifth Edition, McGraw-Hill, New York, New York, pp. 191-193.

Table A1a. Low-Activity Waste Vapor Pressure.

Temp (°C)	Dilution (V/V ₀)												
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20
5	0.052	0.059	0.065	0.070	0.075	0.079	0.083	0.086	0.089	0.091	0.093	0.095	0.097
10	0.076	0.086	0.093	0.100	0.107	0.112	0.117	0.122	0.126	0.129	0.133	0.135	0.138
15	0.107	0.121	0.131	0.141	0.150	0.158	0.164	0.171	0.176	0.181	0.185	0.189	0.192
20	0.149	0.169	0.183	0.196	0.208	0.218	0.227	0.235	0.243	0.249	0.255	0.260	0.265
25	0.204	0.230	0.251	0.268	0.284	0.298	0.310	0.321	0.331	0.339	0.347	0.354	0.360
30	0.276	0.311	0.339	0.363	0.384	0.402	0.418	0.433	0.446	0.457	0.467	0.476	0.484
35	0.368	0.415	0.453	0.484	0.513	0.537	0.558	0.577	0.593	0.608	0.621	0.633	0.643
40	0.486	0.548	0.598	0.639	0.678	0.709	0.737	0.761	0.782	0.801	0.818	0.833	0.846
45	0.637	0.716	0.780	0.833	0.884	0.928	0.964	0.994	1.022	1.046	1.067	1.086	1.104
50	0.825	0.927	1.009	1.078	1.143	1.198	1.246	1.286	1.321	1.351	1.378	1.403	1.424
55	1.060	1.189	1.294	1.381	1.463	1.534	1.594	1.647	1.692	1.731	1.765	1.795	1.822
60	1.349	1.512	1.644	1.754	1.858	1.946	2.022	2.088	2.145	2.195	2.239	2.277	2.311
65	1.704	1.907	2.071	2.210	2.339	2.450	2.544	2.626	2.697	2.760	2.815	2.863	2.907
70	2.135	2.387	2.589	2.763	2.923	3.059	3.176	3.277	3.365	3.442	3.510	3.571	3.625
75	2.656	2.964	3.211	3.428	3.624	3.791	3.935	4.060	4.168	4.262	4.346	4.420	4.486
80	3.279	3.654	3.955	4.223	4.462	4.666	4.841	4.993	5.125	5.240	5.342	5.433	5.513
85	4.022	4.475	4.838	5.166	5.455	5.703	5.915	6.099	6.259	6.399	6.523	6.632	6.730
90	4.901	5.444	5.879	6.279	6.627	6.925	7.181	7.402	7.595	7.763	7.912	8.045	8.163
95	5.934	6.580	7.099	7.585	8.001	8.357	8.663	8.928	9.158	9.361	9.539	9.698	9.839
100	7.143	7.907	8.528	9.107	9.601	10.025	10.389	10.704	10.979	11.220	11.433	11.622	11.791
105	8.471	9.368	10.110	10.793	11.381	11.885	12.320	12.698	13.029	13.320	13.577	13.805	14.010
110	10.265	11.292	12.119	12.810	13.500	14.092	14.605	15.050	15.440	15.783	16.086	16.357	16.599
115	12.168	13.365	14.331	15.129	15.935	16.628	17.228	17.750	18.208	18.610	18.967	19.285	19.569
120	14.354	15.740	16.862	17.778	18.714	19.522	20.221	20.831	21.365	21.836	22.253	22.625	22.959

Note: Vapor pressure is given in lbf/in² absolute. To convert to pascals, multiply by 6.894757 E+ 03.

Table A1b. Low-Activity Waste Vapor Pressure.

Temp (°C)	Dilution (V_w/V_o)											
	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	3.00	4.00	8.00	16.00
5	0.099	0.100	0.102	0.103	0.104	0.105	0.106	0.107	0.113	0.116	0.121	0.124
10	0.140	0.142	0.144	0.146	0.147	0.148	0.150	0.151	0.159	0.164	0.171	0.175
15	0.195	0.198	0.200	0.203	0.205	0.207	0.209	0.210	0.221	0.227	0.237	0.243
20	0.269	0.272	0.276	0.279	0.282	0.284	0.286	0.289	0.304	0.312	0.325	0.333
25	0.365	0.370	0.375	0.379	0.382	0.386	0.389	0.392	0.412	0.423	0.441	0.451
30	0.491	0.497	0.503	0.509	0.514	0.518	0.522	0.526	0.552	0.567	0.591	0.604
35	0.653	0.661	0.669	0.676	0.682	0.688	0.693	0.698	0.733	0.752	0.783	0.800
40	0.859	0.869	0.879	0.888	0.897	0.904	0.911	0.918	0.962	0.987	1.028	1.050
45	1.119	1.133	1.146	1.157	1.168	1.177	1.186	1.195	1.251	1.283	1.335	1.364
50	1.444	1.462	1.478	1.492	1.506	1.518	1.529	1.540	1.612	1.652	1.719	1.755
55	1.847	1.869	1.889	1.908	1.924	1.940	1.954	1.967	2.058	2.109	2.193	2.239
60	2.342	2.370	2.395	2.418	2.439	2.458	2.476	2.492	2.605	2.669	2.775	2.832
65	2.946	2.980	3.011	3.040	3.066	3.089	3.111	3.132	3.271	3.351	3.483	3.555
70	3.673	3.716	3.755	3.791	3.824	3.853	3.880	3.905	4.077	4.176	4.339	4.427
75	4.545	4.599	4.647	4.691	4.731	4.767	4.801	4.832	5.044	5.166	5.366	5.475
80	5.586	5.651	5.710	5.763	5.812	5.857	5.898	5.936	6.197	6.345	6.590	6.722
85	6.818	6.897	6.968	7.033	7.093	7.147	7.197	7.243	7.561	7.742	8.039	8.200
90	8.268	8.364	8.450	8.529	8.600	8.666	8.726	8.781	9.166	9.386	9.746	9.941
95	9.966	10.081	10.184	10.278	10.364	10.443	10.515	10.582	11.045	11.309	11.742	11.977
100	11.942	12.079	12.202	12.315	12.417	12.511	12.597	12.677	13.232	13.548	14.067	14.349
105	14.194	14.360	14.511	14.648	14.773	14.888	14.994	15.091	15.766	16.143	16.760	17.095
110	16.816	17.013	17.191	17.353	17.502	17.638	17.763	17.879	18.680	19.127	19.861	20.260
115	19.826	20.057	20.267	20.458	20.633	20.794	20.942	21.078	22.023	22.551	23.419	23.891
120	23.259	23.530	23.776	24.000	24.206	24.394	24.568	24.728	25.839	26.460	27.481	28.037
												28.650

Note: Vapor pressure is given in lb/in^2 absolute. To convert to pascals, multiply by $6.894757 \text{ E}+03$.

Table A2a. Low-Activity Waste Liquid Density.

Temp (°C)	Dilution (V _w /V _o)												
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20
5	100.86	97.75	95.05	92.78	90.69	88.84	87.20	85.75	84.46	83.25	82.15	81.17	80.35
10	97.31	95.12	93.49	91.68	89.69	87.92	86.35	84.95	83.71	82.59	81.58	80.67	79.85
15	96.00	94.09	92.37	90.74	88.84	87.14	85.64	84.29	83.09	82.02	81.05	80.18	79.38
20	94.53	92.61	91.06	89.62	87.88	86.33	84.95	83.73	82.58	81.54	80.61	79.77	78.99
25	93.51	91.66	90.22	88.84	87.18	85.69	84.37	83.14	82.05	81.05	80.14	79.31	78.55
30	92.53	90.79	89.39	88.12	86.52	85.09	83.79	82.61	81.55	80.57	79.68	78.87	78.14
35	91.70	90.02	88.66	87.45	85.93	84.56	83.28	82.13	81.08	80.12	79.26	78.47	77.76
40	90.97	89.33	88.01	86.85	85.39	84.06	82.81	81.67	80.65	79.72	78.87	78.11	77.40
45	90.30	88.71	87.45	86.37	84.89	83.55	82.33	81.22	80.22	79.32	78.49	77.74	77.05
50	89.70	88.15	86.92	85.83	84.40	83.09	81.91	80.84	79.86	78.97	78.16	77.43	76.75
55	89.16	87.65	86.43	85.34	83.95	82.67	81.51	80.47	79.53	78.66	77.86	77.14	76.47
60	88.69	87.21	86.01	84.90	83.54	82.29	81.15	80.13	79.20	78.36	77.59	76.88	76.22
65	88.26	86.82	85.64	84.51	83.18	81.95	80.83	79.82	78.90	78.06	77.31	76.61	75.98
70	87.90	86.47	85.31	84.17	82.86	81.64	80.53	79.53	78.62	77.80	77.04	76.36	75.73
75	87.59	86.18	85.03	83.87	82.57	81.37	80.27	79.27	78.37	77.56	76.81	76.13	75.50
80	87.33	85.94	84.80	83.61	82.32	81.12	80.03	79.04	78.15	77.33	76.59	75.91	75.28
85	87.11	85.75	84.61	83.39	82.10	80.91	79.82	78.84	77.94	77.13	76.39	75.72	75.09
90	86.95	85.59	84.46	83.21	81.92	80.73	79.64	78.66	77.77	76.95	76.21	75.53	74.92
95	86.84	85.49	84.36	83.06	81.77	80.57	79.49	78.50	77.61	76.80	76.05	75.37	74.75
100	86.77	85.42	84.26	82.96	81.65	80.45	79.35	78.37	77.47	76.65	75.91	75.23	74.60
105	87.21	85.93	84.71	83.39	82.06	80.83	79.72	78.71	77.78	76.93	76.15	75.44	74.79
110	86.95	85.63	84.42	83.34	82.00	80.77	79.65	78.62	77.69	76.83	76.05	75.34	74.68
115	87.01	85.54	84.42	83.32	81.96	80.72	79.58	78.55	77.61	76.75	75.96	75.23	74.57
120	87.13	85.60	84.31	83.33	81.95	80.68	79.54	78.49	77.54	76.67	75.88	75.15	74.47

Note: Liquid density is given in lb/ft³. To convert to kg/m³, multiply by 1.601846 E+ 01.

Table A2b. Low-Activity Waste Liquid Density.

Temp (°C)	Dilution (V _w /N _o)												
	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	3.00	4.00	8.00	16.00	∞
5	79.55	78.84	78.19	77.59	77.06	76.56	76.11	75.69	72.506	70.590	67.156	65.002	62.48
10	79.10	78.41	77.78	77.19	76.66	76.16	75.70	75.27	72.169	70.296	66.956	64.871	62.44
15	78.66	77.99	77.38	76.82	76.30	75.82	75.37	74.94	71.876	70.059	66.788	64.759	62.38
20	78.28	77.63	77.03	76.47	75.96	75.48	75.03	74.62	71.632	69.859	66.638	64.646	62.31
25	77.86	77.23	76.64	76.10	75.60	75.13	74.70	74.30	71.382	69.653	66.475	64.521	62.23
30	77.46	76.85	76.27	75.75	75.25	74.80	74.38	73.99	71.139	69.453	66.307	64.390	62.14
35	77.09	76.50	75.93	75.42	74.94	74.50	74.09	73.70	70.914	69.266	66.145	64.253	62.04
40	76.76	76.16	75.62	75.12	74.65	74.21	73.80	73.43	70.696	69.085	65.982	64.116	61.93
45	76.41	75.83	75.30	74.80	74.35	73.92	73.52	73.15	70.471	68.885	65.801	63.966	61.81
50	76.13	75.56	75.03	74.54	74.09	73.67	73.28	72.91	70.277	68.685	65.633	63.816	61.68
55	75.86	75.30	74.78	74.30	73.85	73.44	73.06	72.69	70.090	68.492	65.464	63.660	61.54
60	75.62	75.06	74.55	74.07	73.63	73.22	72.84	72.49	69.909	68.298	65.296	63.498	61.38
65	75.39	74.84	74.34	73.87	73.43	73.02	72.65	72.29	69.741	68.117	65.121	63.329	61.22
70	75.15	74.62	74.12	73.67	73.24	72.84	72.46	72.11	69.578	67.936	64.946	63.154	61.05
75	74.92	74.39	73.90	73.45	73.03	72.64	72.27	71.93	69.416	67.762	64.771	62.979	60.87
80	74.72	74.19	73.70	73.25	72.83	72.44	72.08	71.73	69.235	67.587	64.590	62.792	60.68
85	74.52	73.99	73.51	73.06	72.64	72.25	71.89	71.55	69.041	67.406	64.415	62.605	60.49
90	74.34	73.82	73.33	72.88	72.46	72.08	71.71	71.37	68.848	67.212	64.228	62.413	60.28
95	74.18	73.65	73.17	72.71	72.29	71.91	71.54	71.20	68.661	67.019	64.028	62.212	60.06
100	74.03	73.50	73.01	72.56	72.14	71.75	71.38	71.05	68.479	66.825	63.822	61.999	59.84
105	74.19	73.62	73.11	72.62	72.18	71.76	71.37	71.00	68.292	66.632	63.610	61.776	59.61
110	74.07	73.51	72.99	72.50	72.05	71.63	71.23	70.86	68.130	66.463	63.410	61.557	59.37
115	73.95	73.39	72.86	72.37	71.91	71.49	71.09	70.72	67.980	66.282	63.198	61.329	59.12
120	73.85	73.28	72.75	72.25	71.79	71.36	70.96	70.58	67.818	66.107	62.986	61.097	58.87

Note: Liquid density is given in lb/ft³. To convert to kg/m³, multiply by 1.601846 E+01.

Table A3a. High-Level Waste Vapor Pressure.

Temp (°C)	Dilution (V _w /V _o)													
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20	
5	0.100	0.103	0.106	0.108	0.109	0.111	0.112	0.113	0.114	0.114	0.115	0.116	0.116	
10	0.141	0.145	0.149	0.151	0.154	0.156	0.157	0.159	0.160	0.161	0.162	0.163	0.164	
15	0.196	0.202	0.207	0.210	0.214	0.216	0.218	0.220	0.222	0.223	0.225	0.226	0.227	
20	0.270	0.277	0.284	0.289	0.293	0.297	0.300	0.302	0.305	0.306	0.309	0.310	0.312	
25	0.366	0.376	0.385	0.392	0.397	0.402	0.406	0.410	0.413	0.415	0.418	0.421	0.423	
30	0.491	0.504	0.516	0.525	0.533	0.539	0.545	0.549	0.554	0.557	0.561	0.564	0.567	
35	0.652	0.668	0.684	0.696	0.706	0.715	0.722	0.729	0.734	0.738	0.744	0.747	0.751	
40	0.855	0.877	0.898	0.914	0.927	0.938	0.948	0.956	0.963	0.969	0.976	0.981	0.985	
45	1.110	1.141	1.168	1.188	1.205	1.220	1.232	1.243	1.252	1.259	1.268	1.275	1.281	
50	1.431	1.470	1.505	1.531	1.552	1.571	1.586	1.600	1.612	1.621	1.633	1.641	1.649	
55	1.828	1.877	1.922	1.954	1.981	2.005	2.025	2.043	2.058	2.069	2.084	2.094	2.104	
60	2.316	2.378	2.433	2.474	2.508	2.538	2.563	2.585	2.605	2.618	2.637	2.650	2.663	
65	2.911	2.987	3.056	3.107	3.150	3.187	3.219	3.246	3.270	3.287	3.310	3.327	3.342	
70	3.631	3.725	3.810	3.873	3.926	3.972	4.011	4.045	4.075	4.096	4.124	4.145	4.164	
75	4.496	4.611	4.715	4.793	4.858	4.914	4.962	5.004	5.040	5.067	5.101	5.127	5.150	
80	5.528	5.668	5.795	5.889	5.969	6.037	6.096	6.147	6.191	6.224	6.266	6.298	6.326	
85	6.751	6.922	7.075	7.189	7.286	7.368	7.439	7.501	7.555	7.595	7.646	7.684	7.718	
90	8.185	8.397	8.581	8.719	8.835	8.934	9.019	9.094	9.159	9.217	9.268	9.315	9.356	
95	9.865	10.12	10.34	10.51	10.65	10.77	10.87	10.96	11.04	11.11	11.17	11.23	11.28	
100	11.82	12.13	12.39	12.59	12.76	12.91	13.03	13.14	13.23	13.31	13.38	13.45	13.51	
105	14.08	14.42	14.73		15.17				15.74		15.93	16.01	16.08	

Note: Vapor pressure is given in lbf/in² absolute. To convert to pascals, multiply by 6.894757 E+ 03.

Table A3b. High-Level Waste Vapor Pressure.

Temp (°C)	Dilution (V_w/V_o)												
	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	3.00	4.00	8.00	16.00	∞
5	0.117	0.117	0.118	0.118	0.118	0.119	0.119	0.119	0.121	0.123	0.125	0.126	0.127
10	0.164	0.165	0.166	0.166	0.167	0.167	0.168	0.168	0.171	0.173	0.175	0.177	0.179
15	0.228	0.229	0.230	0.231	0.232	0.232	0.233	0.233	0.237	0.240	0.244	0.246	0.248
20	0.313	0.315	0.316	0.317	0.318	0.319	0.319	0.320	0.325	0.329	0.334	0.337	0.341
25	0.425	0.426	0.428	0.429	0.430	0.432	0.433	0.434	0.441	0.445	0.452	0.456	0.461
30	0.569	0.571	0.573	0.575	0.577	0.578	0.580	0.581	0.591	0.596	0.606	0.611	0.618
35	0.754	0.757	0.760	0.762	0.764	0.767	0.768	0.770	0.783	0.790	0.803	0.810	0.818
40	0.990	0.993	0.997	1.000	1.003	1.006	1.008	1.011	1.027	1.036	1.053	1.062	1.073
45	1.286	1.291	1.295	1.300	1.303	1.307	1.310	1.313	1.334	1.346	1.368	1.380	1.394
50	1.656	1.662	1.668	1.673	1.678	1.682	1.686	1.690	1.717	1.733	1.760	1.776	1.794
55	2.113	2.121	2.128	2.135	2.141	2.146	2.152	2.157	2.191	2.211	2.245	2.265	2.288
60	2.674	2.684	2.693	2.701	2.709	2.716	2.722	2.729	2.772	2.797	2.840	2.866	2.895
65	3.356	3.369	3.380	3.391	3.400	3.409	3.417	3.425	3.479	3.510	3.565	3.596	3.632
70	4.181	4.197	4.211	4.224	4.236	4.247	4.257	4.266	4.333	4.372	4.440	4.479	4.524
75	5.171	5.190	5.208	5.224	5.238	5.252	5.264	5.275	5.359	5.407	5.490	5.538	5.593
80	6.352	6.375	6.396	6.416	6.434	6.450	6.465	6.478	6.580	6.639	6.741	6.800	6.868
85	7.749	7.778	7.804	7.827	7.849	7.869	7.888	7.904	8.028	8.099	8.223	8.295	8.378
90	9.394	9.428	9.428	9.488	9.514	9.538	9.561	9.582	9.730	9.817	9.97	10.05	10.16
95	11.32	11.36	11.40	11.43	11.47	11.47	11.52	11.55	11.73	11.83	12.01	12.11	12.24
100	13.59	13.61	13.66	13.70	13.74	13.77	13.80	13.83	14.05	14.17	14.39	14.51	14.66
105	16.15	16.21	16.26	16.31	16.36	16.40	16.44	16.47	16.73	16.88	17.14	17.29	17.46

Note: Vapor pressure is given in lb/in^2 absolute. To convert to pascals, multiply by $6.894757 \text{ E}+03$.

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Table A4b. High-Level Waste Liquid Density.

Temp	Dilution (V _v /V _o)												
(C)	1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00	3.00	4.00	8.00	16.00	∞
5	71.27	70.91	70.57	70.27	69.98	69.72	69.47	69.26	67.58	66.58	64.78	63.70	62.48
10	71.03	70.67	70.35	70.06	69.78	69.52	69.28	69.07	67.43	66.45	64.69	63.64	62.44
15	70.78	70.44	70.12	69.83	69.56	69.31	69.08	68.87	67.27	66.31	64.59	63.55	62.38
20	70.55	70.22	69.91	69.63	69.36	69.11	68.88	68.68	67.12	66.18	64.48	63.47	62.31
25	70.32	69.99	69.69	69.41	69.15	68.91	68.68	68.50	66.96	66.03	64.37	63.37	62.23
30	70.09	69.77	69.48	69.20	68.95	68.71	68.49	68.30	66.79	65.88	64.25	63.26	62.14
35	69.87	69.55	69.26	68.99	68.74	68.51	68.29	68.10	66.62	65.72	64.12	63.14	62.04
40	69.64	69.33	69.05	68.78	68.53	68.31	68.10	67.91	66.44	65.56	63.98	63.02	61.93
45	69.42	69.11	68.83	68.57	68.33	68.10	67.89	67.71	66.26	65.40	63.83	62.89	61.81
50	69.21	68.90	68.62	68.37	68.13	67.90	67.70	67.52	66.09	65.23	63.68	62.74	61.68
55	69.00	68.70	68.42	68.17	67.93	67.71	67.50	67.33	65.91	65.06	63.52	62.59	61.54
60	68.79	68.49	68.22	67.97	67.73	67.51	67.31	67.14	65.73	64.88	63.35	62.44	61.38
65	68.58	68.29	68.02	67.77	67.54	67.32	67.12	66.95	65.54	64.70	63.19	62.27	61.22
70	68.39	68.10	67.82	67.57	67.34	67.12	66.92	66.76	65.36	64.52	63.01	62.10	61.05
75	68.19	67.90	67.63	67.38	67.15	66.94	66.73	66.57	65.17	64.33	62.83	61.92	60.87
80	68.00	67.71	67.44	67.19	66.96	66.74	66.54	66.38	64.98	64.15	62.64	61.73	60.68
85	67.82	67.52	67.25	67.01	66.77	66.56	66.36	66.19	64.79	63.96	62.44	61.53	60.49
90	67.64	67.35	67.08	66.83	66.60	66.38	66.18	66.01	64.62	63.77	62.26	61.34	60.28
95	67.47	67.17	66.90	66.65	66.42	66.20	65.99	65.82	64.42	63.58	62.05	61.13	60.06
100	67.12	66.99	66.72	66.47	66.23	66.01	65.81	65.62	64.23	63.38	61.84	60.91	59.84
105	66.98	66.69	66.42	66.17	65.94	65.73	65.53	65.34	63.96	63.12	61.60	60.67	59.61

Note: Liquid density is given in lb/ft³. To convert to kg/m³, multiply by 1.601846 E+01.

Figure A1. Low-Activity Waste Vapor Pressure Versus Temperature.

Note: To convert vapor pressure to pascals, multiply by 6.894757 E+03.

Figure A2. Low-Activity Liquid Density Versus Temperature.

Note: To convert liquid density to kg/m³, multiply by 1.601846 E+ 01.

Figure A3. High-Level Waste Vapor Pressure Versus Temperature.

Note: To convert vapor pressure to pascals, multiply by 6.894757 E+03.

Figure A4. High-Level Waste Liquid Density Versus Temperature.

Note: To convert liquid density to kg/m^3 , multiply by $1.601846 \text{ E}+01$.

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