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CHEMICAL AND PHYSICAL PROPERTIES OF HUMAN URINE CONCENTRATES

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CHEMICAL AND PHYSICAL PROPERTIES OF HUMAN URINE CONCENTRATES

By David F. Putnam
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SUMMARY

The experimental work reported here was done to provide much needed data on the concentrative properties of human urine.

Determinations were made in the ranges 4 to 90 per cent solutes and 70 to 140 degrees Fahrenheit for solute weight fraction, vapor pressure, density, solute concentration, water concentration, solute to water ratio, osmolality, osmotic pressure, differential heat of vaporization, differential heat of solution, surface tension, specific conductivity, viscosity, weight fraction of precipitated solids, weight fraction of extracted water, refractive index, and pH.

The results are presented in plots of unsmoothed data, empirical equations, and tables of nominal values. Sample calculations and examples illustrating the consideration of these data in engineering design applications are included.

INTRODUCTION

The reclamation and reuse of water from human urine becomes mandatory for long duration space missions due to the severe restrictions imposed on launch weight. Engineering studies show that the equivalent weight of most urine purification equipment is significantly lower than the weight of drinking water that would have to be launched as stored water, if no water recovery system were used (see ref. 1-2).

The many different urine purification systems that are under investigation have at least one point in common; all must deal with urine that becomes progressively more concentrated as drinking water is extracted (see ref. 3-11). It is clear, therefore, that knowledge of the physical properties of urine concentrates, for which there is very little reference information, is required for the satisfactory analysis and design of all urine processing systems. It is hoped that the data reported here will fulfill this need.

The physical properties of urine concentrates, determined in the ranges 4 to 90 per cent solutes and 70 to 140 degrees Fahrenheit, are: solute weight fraction, vapor pressure, density, solute concentration, water concentration, solute to water ratio, osmolality, osmolarity, osmotic pressure, differential heat of vaporization, differential heat of solution, surface tension, specific conductivity, viscosity, weight fraction of precipitated solids, weight fraction of extracted water, refractive index and pH. There is a section devoted to the discussion of each of these properties. Included are experimental methods, plots of unsmoothed data, and smoothed plots representing nominal values. The nominal values for all of the above listed properties are summarized in Tables II, III and IV.

SYMBOLS

C = solute concentration, g of solutes per ml of urine
Cw = water concentration, g of water per ml of urine
Hw = differential heat of dilution, BTU per lb of water increase
Hs = differential heat of solution, BTU per lb of solute increase
Hu = differential heat of vaporization of urine, BTU per pound of urine
k = specific conductivity, μ mho-cm^{-1}
L = differential heat of vaporization of urine, BTU per pound of water evaporated
Lu = differential heat of vaporization of urine, BTU per pound of urine
L^* = differential heat of vaporization of water, BTU per pound of water evaporated
M = apparent average molecular weight of solute particles as calculated from vapor pressure data and Raoult's Law
N = number of moles of solvent = $\frac{Ww}{18}$
n = number of moles of solute particles = $\frac{Ws}{M}$
n_i = refractive index at 70°F relative to air for sodium yellow light
O = osmolality, apparent g-moles of solute particles per 1000 g of water
Or = osmolarity, apparent g-moles of solute particles per liter of urine
p = vapor pressure of urine concentrate, psia
p^* = vapor pressure of pure water, psia
pH = hydrogen ion concentration, $\log_{10}$ of the recriprocal of the molar concentration of hydrogen ions (H^+)

$$10^{-pH} = \frac{\text{g-moles of hydrogen ions } (H^+)}{\text{liter}}$$

R = gas constant, 8.3144 $\frac{\text{Joules}}{\text{g-mole x } {}^{\circ}K}$
S = entropy, BTU/lb x $^{\circ}$F
T = temperature degrees Rankine, Fahrenheit or Kelvin

$\bar{v}$ = molar volume of water, 18 $\frac{cm^3}{g\text{-mole}}$

Ww = weight of solvent, g

Wp = weight of precipitate, g

Ws = weight of solutes, g

Wu = weight of urine, g

x = solute weight fraction, g of solutes per g of urine

$1 - x$ = water weight fraction, g of water per g of urine

x_o = original solute weight fraction, g of solutes per g of urine, initially before concentration

$1 - x_o$ = original water weight fraction, g of water per g of urine, initially before concentration

y = weight fraction of extracted water, g of water extracted from urine during concentration per g of initial water content before concentration

$1 - y$ = weight fraction of unextracted water, g of water in urine concentrate per g of initial water content before concentration

γ = surface tension, dynes $-cm^{-1}$

μ = dynamic viscosity, centipoise

π = osmotic pressure, psia

ρ = density, g of urine per ml of urine

PHYSICAL PROPERTIES

Urine is not a unique solution. Its composition differs considerably from individual to individual and with variations in diet. (See ref. 12.) Normally its solute weight fraction ranges between 0.032 and 0.046. The physical properties reported here were determined for the mixed urine of forty to fifty male subjects over a period of several months. Six batches of urine, containing 19 liters per batch, were each concentrated by evaporation to approximately 200 milliliters, at which point the liquors of similarly pretreated batches were mixed and concentrated further. The physical properties were measured at discrete intervals during the concentration process. A summary of the initial conditions of the different batches of urine for which data were obtained is presented in Table I. Four different chemical pretreatments were investigated as follows: (1) H_2SO_4 + CrO_3, (2) H_2SO_4 + CrO_3 + $CuSO_4$, (3) $Ca(ClO)_2$, and (4) electrochemical oxidation. (See ref. 2 and 13.)

Pretreatments are used in most urine processing systems to stabilize urine with respect to microbes, odors and free ammonia (see ref. 13), and these four pretreatments are the most widely used. Physical property data were not obtained for untreated urine because bacterial action always developed within the first few days of the one to two month period in which the progressive concentration of the urine and physical measurements were made. This bacterial action resulted in the decomposition of urea and the evolution of large amounts of ammonia.

Most of the physical properties are not sensitive to the first three pretreatments, in which less than 10 g per liter of chemical are involved. Only precipitate, viscosity and pH are noticeably affected. The electrochemical pretreatment which converts most of the organic material in urine to useful cabin gases, has a noticeable impact on many of the concentrative properties, but not on vapor pressure and the other colligative properties.

Symbols are assigned in Table I to each batch of urine and these symbols are used consistantly throughout the report. Deviations in the data can be readily determined from the individual plots that are presented in each section.

Nominal values for the physical properties, which are intended for use in engineering calculations, are presented in Tables II, III and IV. The following examples are given to illustrate the usefulness of these data, and underscore several often neglected design considerations.

Example 1, Vapor Compression System

In a vapor compression system latent heat is conserved by compressing the evolved water vapor to a higher pressure. This allows it to condense at a temperature that is higher than the boiling temperature of urine, thereby

TABLE I

INITIAL CONDITIONS OF URINE BATCHES BEFORE CONCENTRATION

Symbol	Batch #	Pretreatment	x	ρ	n_i	k	γ	μ	pH	Batch Size, ℓ
✳	1.	H_2SO_4 = 2.57 g/l CrO_3 = 0.63 g/l H_2O = 2.56 g/l	.04174	1.012		24000		.957	2.3	19
○	2.	H_2SO_4 = 2.57 g/l CrO_3 = 0.63 g/l H_2O = 2.56 g/l	.03550	1.010		21300			2.0	19
△	3.	H_2SO_4 = 2.26 g/l CrO_3 = 0.56 g/l $CuSO_4$ = 0.18 g/l H_2O = 2.68 g/l	.04342	1.015	1.3396	22900		.951	2.7	19
□	4.	$Ca(ClO)_2 \cdot 4H_2O$ = 10 g/l	.03232	1.010	1.3378	18800	70.6	.950	5.4	18
◇	5.	$Ca(ClO)_2 \cdot 4H_2O$ = 10 g/l	.03407	1.010	1.3383	19500	68.4		6.0	19
+	6.	$Ca(ClO)_2 \cdot 4H_2O$ = 10 g/l	.03376	1.014	1.3389	21500	65.3		6.1	19
⊘	7.	Mixture of Batches 1, 2 and 3 after concentration to approximately x = 0.8.								
⧄	8.	Mixture of Batches 4 and 5 after concentration to approximately x = 0.6.								
▽	9.	Before Electrochemical Pretreatment (treated with: ROCCAL = .05 g/l H_2O = .20 g/l	0.03227	1.011	1.3380	17000	43.3	.950	6.2	2
		After Electrochemical Pretreatment	.01707	1.004	1.3352	13800	71.7		8.7	2

Table Headings:

x,	solute weight fraction, g of solutes per g of urine
ρ,	density at 70°F, g of urine per ml of urine
n_i,	refractive index at 70°F relative to air for sodium yellow light
k,	specific conductivity at 70°F μmho-cm^{-1}
γ,	surface tension at 70°F, dyne -cm^{-1}
μ,	dynamic viscosity at 70°F, centipoise
pH,	hydrogen ion concentration at 70°F, $\log_{10}$ of the reciprocal of the molar concentration of hydrogen ions
ℓ,	liter

TABLE II

TABLE HEADINGS

x = solute weight fraction, g of solutes per g of urine

M = apparent average molecular weight of solute particles at 100°F

ρ = urine density at 70°F, g of urine per ml of urine

C = solute concentration at 70°F, g of solutes per ml of urine

Cw = water concentration at 70°F, g of water per ml of urine

$\frac{x}{1 - x}$ = solute to water ratio, g of solutes per g of water

O = osmolality at 100°F, apparent g-mole of solute particles per 1000 g of water

Or = osmolarity at 100°F, apparent g-mole of solute particles per liter of urine

$\frac{p}{p^* - p}$ = ratio of vapor pressure to vapor pressure lowering at 100°F

π = osmotic pressure at 100°F, psia

γ = surface tension at 70°F, dyne $-\text{cm}^{-1}$

k = specific conductivity at 70°F, μ mho-cm^{-1}

μ_1 = viscosity of $H_2SO_4 + CrO_3$ treated urine at 70°F, centipoise

μ_2 = viscosity of $Ca(ClO)_2$ treated urine at 70°F, centipoise

$\left(\frac{Wp}{Ws_o}\right)_1$ = Weight fraction of precipitated solids of $H_2SO_4 + CrO_3$ treated urine, g of precipitate per g of original solute content

$\left(\frac{Wp}{Ws_o}\right)_2$ = Weight fraction of precipitated solids of $Ca(ClO)_2$ treated urine, g of precipitate per g of original solute content

y_1 = Weight fraction of extracted water for $H_2SO_4 + CrO_3$ treated urine, g of extracted water per g of original water content

y_2 = Weight fraction of extracted water for $Ca(ClO)_2$ treated urine, g of extracted water per g of original water content

n_i = refractive index at 70°F relative to air for sodium yellow light

Hs = differential heat of solution of urine solutes at 90°F, BTU per lb of solutes

L = differential heat of vaporization of urine at 90°F, BTU per lb of water evaporated

Lu = differential heat of vaporization of urine at 90°F, BTU per lb of urine

TABLE II

PHYSICAL PROPERTIES OF HUMAN URINE CONCENTRATES

(Nominal Values)

x	M	ρ	C	ρ-C	$\frac{x}{1-x}$	O	Or	$\frac{p}{p^*-p}$	π	γ	k	μ_1	μ_2	$\left(\frac{Wp}{Ws_o}\right)_1$	$\left(\frac{Wp}{Ws_o}\right)_2$	y_1	y_2	n_i	Hs	L	Lu
.05	52	1.017	.0509	.9663	.0526	1.012	.9780	54.89	347.8	67.5	28000	.974	.974	.002	.012			1.340	-23.8	1042	990
.10	63	1.041	.1041	.9369	.1111	1.764	1.652	31.50	602.0	61.7	54000	1.06	1.06	.007	.038			1.348	-16.2	1041	937
.15	70	1.065	.1597	.9051	.1765	2.521	2.282	22.04	854.8	57.2	75000	1.17	1.17	.008	.044			1.356	-12.9	1041	885
.20	72	1.089	.2177	.8710	.2500	3.472	3.024	16.00	1168	53.6	90000	1.31	1.31	.009	.052			1.364	-12.1	1040	832
.25	70	1.113	.2783	.8345	.3333	4.762	3.974	11.67	1584	51.0	101000	1.48	1.48	.011	.060	.895	.912	1.372	-12.5	1039	779
.30	67	1.137	.3409	.7955	.4286	6.397	5.089	8.685	2099	48.8	108000	1.71	1.71	.015	.068	.910	.932	1.380	-13.3	1037	726
.35	63	1.160	.4061	.7542	.5385	8.547	6.447	6.500	2756	47.0	111000	2.02	2.02	.019	.077	.927	.947	1.388	-14.5	1035	673
.40	60	1.184	.4737	.7105	.6667	11.11	7.895	5.000	3512	45.2	113000	2.45	2.45	.021	.083	.941	.959	1.396	-15.3	1033	620
.45	58	1.208	.5437	.6645	.8182	14.11	9.373	3.938	4359	43.7	112000	3.07	3.07	.023	.100	.953	.968	1.404	-15.7	1030	567
.50	56	1.232	.6160	.6160	1.000	17.86	11.00	3.111	5369	42.8	107000	4.03	4.03	.029	.128	.962	.975	1.412	-16.0	1027	514
.55	55	1.256	.6907	.5651	1.222	22.22	12.56	2.500	6481	42.4	98000	4.79	5.27	.043	.170	.969	.980	1.423	-15.6	1024	461
.60	55	1.280	.7678	.5119	1.500	27.27	13.96	2.037	7693	42.4	85000	5.98	7.45	.065	.243	.974	.984	1.435	-14.7	1021	408
.65	56	1.304	.8474	.4563	1.857	33.16	15.13	1.675	9016	42.5	67000	7.95	11.6	.092	.358	.979	.988	1.447	-13.2	1018	356
.70	59	1.328	.9292	.3983	2.333	39.55	15.75	1.405	10355	42.7	45000	11.6	21.1	.132	.515	.984	.991	1.459	-11.2	1017	305
.75	64	1.351	1.014	.3378	3.000	46.87	15.84	1.185	11785	43.3	29000	19.8	48.6	.187		.988		1.471	- 8.8	1016	254
.80	71	1.375	1.100	.2751	4.000	56.34	15.50	.9861	13487	44.4	16000	44.2		.266		.992		1.483	- 6.6	1017	203
.85	78	1.399	1.189	.2099	5.667	72.65	15.25	.7647	16108	46.6	7500	168		.419		.966		1.496	- 4.8	1016	152
.90	86	1.423	1.281	.1423	9.000	104.7	14.89	.5309	20400	50.5	1800	2410				.998		1.508	- 3.2	1015	101

TABLE III

VAPOR PRESSURE OF HUMAN URINE CONCENTRATES
(NOMINAL VALUES) (PSIA)

SOLUTE FRACTION

DEG F	0	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75	.80	.85	.90
80.	.5069	.4982	.4918	.4856	.4779	.4681	.4561	.4414	.4250	.4074	.3873	.3663	.3445	.3222	.3008	.2793	.2557	.2233	.1788
81.	.5237	.5147	.5081	.5016	.4937	.4835	.4712	.4559	.4390	.4207	.4000	.3782	.3557	.3326	.3105	.2884	.2640	.2305	.1846
82.	.5410	.5317	.5249	.5182	.5100	.4994	.4866	.4709	.4533	.4345	.4130	.3905	.3672	.3433	.3205	.2977	.2725	.2379	.1905
83.	.5588	.5492	.5421	.5352	.5267	.5158	.5026	.4862	.4681	.4486	.4264	.4031	.3791	.3544	.3308	.3072	.2812	.2455	.1966
84.	.5771	.5671	.5598	.5527	.5439	.5326	.5189	.5020	.4833	.4631	.4401	.4160	.3912	.3657	.3414	.3170	.2902	.2534	.2029
85.	.5959	.5856	.5780	.5706	.5616	.5499	.5358	.5183	.4989	.4780	.4542	.4294	.4037	.3773	.3522	.3271	.2994	.2614	.2093
86.	.6152	.6045	.5967	.5891	.5798	.5676	.5530	.5349	.5149	.4933	.4687	.4430	.4165	.3893	.3634	.3374	.3089	.2697	.2159
87.	.6351	.6240	.6160	.6081	.5985	.5859	.5708	.5521	.5314	.5091	.4837	.4571	.4297	.4016	.3748	.3481	.3186	.2782	.2227
88.	.6556	.6442	.6358	.6277	.6177	.6048	.5891	.5698	.5484	.5253	.4990	.4716	.4433	.4142	.3866	.3590	.3286	.2869	.2297
89.	.6766	.6648	.6562	.6477	.6374	.6241	.6079	.5879	.5658	.5419	.5148	.4864	.4572	.4272	.3987	.3702	.3389	.2959	.2369
90.	.6982	.6860	.6771	.6684	.6577	.6439	.6272	.6066	.5837	.5590	.5310	.5016	.4715	.4405	.4111	.3818	.3495	.3051	.2442
91.	.7204	.7078	.6986	.6896	.6786	.6643	.6470	.6257	.6020	.5766	.5476	.5173	.4861	.4542	.4239	.3936	.3603	.3145	.2518
92.	.7432	.7301	.7207	.7113	.7000	.6852	.6674	.6453	.6209	.5946	.5646	.5334	.5012	.4682	.4369	.4057	.3714	.3242	.2595
93.	.7666	.7531	.7433	.7337	.7220	.7067	.6883	.6655	.6402	.6131	.5821	.5498	.5166	.4826	.4503	.4182	.3828	.3341	.2675
94.	.7906	.7766	.7665	.7566	.7445	.7287	.7097	.6862	.6601	.6320	.6001	.5667	.5324	.4973	.4641	.4309	.3944	.3443	.2756
95.	.8153	.8009	.7904	.7802	.7677	.7514	.7318	.7074	.6805	.6515	.6185	.5841	.5487	.5125	.4782	.4440	.4064	.3548	.2840
96.	.8407	.8258	.8150	.8044	.7915	.7747	.7544	.7293	.7015	.6715	.6375	.6019	.5654	.5280	.4927	.4575	.4188	.3655	.2925
97.	.8668	.8514	.8403	.8293	.8160	.7987	.7777	.7518	.7230	.6921	.6569	.6202	.5826	.5440	.5076	.4713	.4314	.3765	.3014
98.	.8935	.8776	.8661	.8548	.8411	.8232	.8015	.7747	.7451	.7131	.6768	.6390	.6001	.5604	.5228	.4854	.4443	.3878	.3104
99.	.9210	.9046	.8927	.8811	.8669	.8484	.8261	.7984	.7677	.7348	.6973	.6582	.6182	.5772	.5384	.4999	.4577	.3994	.3197
100.	.9492	.9322	.9200	.9080	.8934	.8743	.8512	.8226	.7910	.7570	.7183	.6780	.6367	.5944	.5545	.5148	.4713	.4113	.3292
101.	.9781	.9606	.9480	.9356	.9205	.9008	.8770	.8475	.8148	.7797	.7398	.6982	.6556	.6120	.5709	.5301	.4852	.4235	.3389
102.	1.0078	.9897	.9767	.9639	.9483	.9280	.9034	.8730	.8393	.8031	.7619	.7190	.6750	.6301	.5878	.5457	.4996	.4360	.3489
103.	1.0382	1.0195	1.0061	.9929	.9769	.9559	.9305	.8991	.8643	.8270	.7845	.7402	.6949	.6486	.6050	.5617	.5142	.4488	.3591
104.	1.0695	1.0502	1.0364	1.0228	1.0062	.9846	.9584	.9260	.8901	.8516	.8077	.7621	.7154	.6677	.6227	.5782	.5293	.4619	.3696
105.	1.1016	1.0817	1.0674	1.0534	1.0363	1.0140	.9870	.9536	.9165	.8768	.8316	.7845	.7363	.6872	.6409	.5950	.5447	.4754	.3803
106.	1.1345	1.1139	1.0992	1.0848	1.0672	1.0441	1.0163	.9818	.9436	.9026	.8560	.8074	.7578	.7071	.6595	.6123	.5605	.4892	.3914
107.	1.1683	1.1471	1.1319	1.1170	1.0988	1.0751	1.0464	1.0108	.9714	.9291	.8810	.8310	.7798	.7276	.6786	.6300	.5768	.5033	.4027
108.	1.2029	1.1810	1.1654	1.1500	1.1313	1.1068	1.0772	1.0405	.9998	.9562	.9066	.8551	.8023	.7486	.6981	.6481	.5933	.5178	.4142
109.	1.2384	1.2158	1.1997	1.1839	1.1646	1.1393	1.1087	1.0709	1.0290	.9840	.9329	.8798	.8254	.7701	.7181	.6667	.6103	.5326	.4261
110.	1.2748	1.2515	1.2349	1.2186	1.1987	1.1726	1.1411	1.1021	1.0589	1.0125	.9598	.9051	.8491	.7921	.7386	.6857	.6278	.5478	.4382
111.	1.3121	1.2881	1.2709	1.2541	1.2336	1.2068	1.1743	1.1341	1.0895	1.0417	.9874	.9310	.8733	.8146	.7596	.7052	.6456	.5633	.4506
112.	1.3504	1.3256	1.3080	1.2907	1.2695	1.2418	1.2084	1.1669	1.1210	1.0717	1.0157	.9576	.8982	.8377	.7811	.7251	.6639	.5793	.4634
113.	1.3896	1.3640	1.3458	1.3280	1.3062	1.2777	1.2432	1.2004	1.1531	1.1023	1.0447	.9847	.9236	.8614	.8031	.7456	.6826	.5956	.4764
114.	1.4298	1.4034	1.3847	1.3663	1.3439	1.3145	1.2789	1.2349	1.1861	1.1337	1.0743	1.0126	.9496	.8856	.8256	.7665	.7017	.6123	.4897
115.	1.4709	1.4437	1.4244	1.4055	1.3824	1.3521	1.3155	1.2700	1.2198	1.1658	1.1046	1.0411	.9762	.9103	.8487	.7878	.7213	.6294	.5034
116.	1.5130	1.4850	1.4651	1.4456	1.4218	1.3906	1.3529	1.3061	1.2542	1.1987	1.1356	1.0702	1.0034	.9356	.8722	.8097	.7413	.6468	.5173
117.	1.5563	1.5274	1.5069	1.4869	1.4624	1.4302	1.3913	1.3431	1.2897	1.2325	1.1675	1.1001	1.0314	.9616	.8964	.8322	.7619	.6648	.5316
118.	1.6006	1.5708	1.5497	1.5291	1.5038	1.4707	1.4306	1.3810	1.3260	1.2670	1.2001	1.1307	1.0600	.9882	.9211	.8551	.7829	.6831	.5463
119.	1.6459	1.6152	1.5935	1.5723	1.5462	1.5121	1.4709	1.4197	1.3630	1.3023	1.2334	1.1620	1.0892	1.0153	.9464	.8785	.8044	.7018	.5612
120.	1.6924	1.6608	1.6384	1.6166	1.5898	1.5546	1.5121	1.4594	1.4011	1.3385	1.2676	1.1940	1.1191	1.0432	.9723	.9026	.8264	.7210	.5766
121.	1.7400	1.7074	1.6844	1.6619	1.6343	1.5981	1.5544	1.5001	1.4400	1.3756	1.3025	1.2268	1.1498	1.0716	.9988	.9272	.8489	.7407	.5923
122.	1.7888	1.7552	1.7315	1.7084	1.6800	1.6427	1.5977	1.5417	1.4799	1.4136	1.3384	1.2604	1.1811	1.1008	1.0259	.9523	.8720	.7608	.6083
123.	1.8387	1.8041	1.7797	1.7559	1.7267	1.6883	1.6419	1.5843	1.5206	1.4524	1.3749	1.2948	1.2132	1.1305	1.0536	.9781	.8956	.7813	.6247
124.	1.8897	1.8540	1.8290	1.8045	1.7744	1.7349	1.6871	1.6278	1.5623	1.4920	1.4123	1.3298	1.2459	1.1609	1.0819	1.0043	.9196	.8023	.6415
125.	1.9420	1.9053	1.8795	1.8543	1.8233	1.7827	1.7335	1.6725	1.6049	1.5326	1.4506	1.3657	1.2794	1.1921	1.1109	1.0312	.9442	.8238	.6586
126.	1.9955	1.9577	1.9312	1.9052	1.8734	1.8315	1.7809	1.7181	1.6486	1.5742	1.4898	1.4024	1.3137	1.2239	1.1405	1.0587	.9694	.8457	.6762
127.	2.0503	2.0113	1.9841	1.9574	1.9246	1.8816	1.8295	1.7648	1.6933	1.6167	1.5298	1.4400	1.3488	1.2565	1.1708	1.0868	.9952	.8682	.6941
128.	2.1064	2.0663	2.0382	2.0108	1.9771	1.9328	1.8792	1.8126	1.7390	1.6602	1.5708	1.4784	1.3846	1.2897	1.2018	1.1155	1.0215	.8911	.7124
129.	2.1638	2.1225	2.0936	2.0654	2.0307	1.9852	1.9300	1.8615	1.7857	1.7047	1.6127	1.5177	1.4213	1.3238	1.2334	1.1449	1.0484	.9146	.7312
130.	2.2225	2.1800	2.1503	2.1213	2.0856	2.0387	1.9820	1.9115	1.8335	1.7501	1.6556	1.5578	1.4587	1.3585	1.2658	1.1749	1.0759	.9386	.7503
131.	2.2826	2.2388	2.2083	2.1785	2.1418	2.0936	2.0352	1.9626	1.8824	1.7967	1.6994	1.5989	1.4970	1.3941	1.2988	1.2056	1.1041	.9631	.7699
132.	2.3440	2.2989	2.2676	2.2369	2.1992	2.1496	2.0895	2.0149	1.9324	1.8442	1.7441	1.6408	1.5361	1.4304	1.3326	1.2369	1.1328	.9881	.7899
133.	2.4069	2.3605	2.3283	2.2967	2.2580	2.2069	2.1451	2.0684	1.9835	1.8928	1.7899	1.6837	1.5761	1.4675	1.3671	1.2690	1.1621	1.0137	.8103
134.	2.4712	2.4235	2.3903	2.3579	2.3180	2.2656	2.2020	2.1231	2.0358	1.9425	1.8367	1.7275	1.6170	1.5054	1.4024	1.3017	1.1921	1.0399	.8312
135.	2.5370	2.4879	2.4538	2.4205	2.3795	2.3256	2.2602	2.1790	2.0892	1.9933	1.8846	1.7723	1.6587	1.5442	1.4384	1.3352	1.2228	1.0666	.8525
136.	2.6042	2.5537	2.5186	2.4844	2.4423	2.3868	2.3196	2.2361	2.1438	2.0452	1.9334	1.8181	1.7013	1.5837	1.4752	1.3693	1.2541	1.0939	.8743
137.	2.6729	2.6209	2.5849	2.5497	2.5065	2.4494	2.3803	2.2945	2.1996	2.0982	1.9833	1.8647	1.7449	1.6241	1.5127	1.4042	1.2860	1.1217	.8966
138.	2.7432	2.6897	2.6527	2.6166	2.5721	2.5135	2.4424	2.3542	2.2566	2.1524	2.0343	1.9125	1.7893	1.6653	1.5511	1.4398	1.3187	1.1502	.9193
139.	2.8151	2.7601	2.7221	2.6850	2.6392	2.5790	2.5060	2.4152	2.3149	2.2078	2.0864	1.9613	1.8348	1.7075	1.5903	1.4762	1.3520	1.1793	.9425
140.	2.8886	2.8320	2.7930	2.7548	2.7079	2.6459	2.5709	2.4776	2.3745	2.2643	2.1396	2.0111	1.8812	1.7506	1.6303	1.5133	1.3861	1.2090	.9662
141.	2.9637	2.9055	2.8654	2.8262	2.7780	2.7143	2.6372	2.5413	2.4353	2.3221	2.1940	2.0620	1.9286	1.7945	1.6712	1.5512	1.4208	1.2393	.9904
142.	3.0404	2.9806	2.9394	2.8991	2.8496	2.7842	2.7049	2.6063	2.4974	2.3811	2.2494	2.1138	1.9769	1.8393	1.7129	1.5899	1.4563	1.2702	1.0151
143.	3.1188	3.0573	3.0150	2.9737	2.9227	2.8555	2.7741	2.6727	2.5608	2.4414	2.3061	2.1668	2.0263	1.8851	1.7554	1.6294	1.4925	1.3018	1.0403
144.	3.1990	3.1357	3.0923	3.0499	2.9976	2.9285	2.8448	2.7407	2.6257	2.5030	2.3640	2.2210	2.0767	1.9318	1.7989	1.6698	1.5295	1.3340	1.0660

TABLE IV

TABLE HEADINGS

x = solute weight fraction, g of solutes per g of urine

L/L^* = ratio of heat of vaporization of urine to heat of vaporization of pure water

Lu = differential heat of vaporization of urine, BTU/lb of urine

Hw = differential heat of dilution, BTU/lb of water increase

Hs = differential heat of dilution, BTU/lb of solute increase

L = differential heat of vaporization of urine, BTU/lb of water evaporated

TABLE IV

Differential Heats of
Vaporization, Solution and Dilution
(Nominal Values)

x	L/L*	Lu	Hw	Hs	L
.05	.9989	994.0	1.181	-22.436	1046.3
.10	.9984	941.2	1.696	-15.268	1045.8
.15	.9979	888.5	2.161	-12.248	1045.3
.20	.9973	835.7	2.861	-11.444	1044.6
.25	.9962	782.7	3.946	-11.839	1043.6
.30	.9949	729.5	5.383	-12.561	1042.1
.35	.9930	676.1	7.367	-13.681	1040.1
.40	.9908	622.7	9.655	-14.483	1037.8
.45	.9884	569.5	12.130	-14.825	1035.4
.50	.9856	516.2	15.081	-15.081	1032.4
.55	.9828	463.3	18.039	-14.759	1029.5
.60	.9801	410.7	20.824	-13.883	1026.7
.65	.9778	358.5	23.276	-12.533	1024.2
.70	.9764	306.8	24.688	-10,580	1022.8
.75	.9760	255.6	25.181	- 8.394	1022.3
.80	.9760	204.5	25.125	- 6.281	1022.4
.85	.9753	153.2	25.883	- 4.568	1021.6
.90	.9740	102.0	27.215	- 3.024	1020.3

TEMPERATURE OF URINE CONCENTRATE = 82.0

x	L/L*	Lu	Hw	Hs	L
.05	.9988	991.8	1.214	-23.064	1044.0
.10	.9983	939.1	1.744	-15.695	1043.5
.15	.9979	886.5	2.230	-12.639	1043.0
.20	.9972	833.8	2.938	-11.753	1042.3
.25	.9961	780.9	4.052	-12.157	1041.1
.30	.9947	727.8	5.529	-12.901	1039.7
.35	.9927	674.5	7.584	-14.085	1037.6
.40	.9905	621.2	9.937	-14.906	1035.3
.45	.9881	568.0	12.478	-15.251	1032.7
.50	.9852	514.8	15.512	-15.512	1029.7
.55	.9822	462.0	18.562	-15.187	1026.6
.60	.9795	409.5	21.415	-14.277	1023.8
.65	.9771	357.4	23.932	-12.887	1021.3
.70	.9757	306.0	25.353	-10.866	1019.8
.75	.9753	254.8	25.838	- 8.613	1019.4
.80	.9754	203.9	25.743	- 6.436	1019.5
.85	.9747	152.8	26.484	- 4.674	1018.7
.90	.9734	101.7	27.805	- 3.090	1017.4

TEMPERATURE OF URINE CONCENTRATE = 86.0

TABLE IV (Continued)

x	L/L*	Lu	Hw	Hs	L
.05	.9988	989.6	1.254	-23.827	1041.6
.10	.9983	937.0	1.799	-16.189	1041.1
.15	.9978	884.5	2.285	-12.948	1040.6
.20	.9971	831.9	3.018	-12.072	1039.9
.25	.9960	779.1	4.162	-12.485	1038.7
.30	.9945	726.1	5.685	-13.264	1037.2
.35	.9925	672.8	7.793	-14.472	1035.1
.40	.9902	619.6	10.215	-15.323	1032.7
.45	.9877	566.5	12.832	-15.683	1030.1
.50	.9847	513.5	15.963	-15.963	1026.9
.55	.9817	460.7	19.093	-15.622	1023.8
.60	.9789	408.3	22.031	-14.687	1020.9
.65	.9764	356.4	24.597	-13.244	1018.3
.70	.9750	305.1	26.037	-11.159	1016.9
.75	.9746	254.1	26.498	- 8.833	1016.4
.80	.9747	203.3	26.367	- 6.592	1016.5
.85	.9740	152.4	27.099	- 4.782	1015.8
.90	.9728	101.4	28.418	- 3.158	1014.5

TEMPERATURE OF URINE CONCENTRATE = 90.0

x	L/L*	Lu	Hw	Hs	L
.05	.9988	987.4	1.297	-24.639	1039.4
.10	.9982	935.0	1.843	-16.585	1038.9
.15	.9977	882.6	2.358	-13.360	1038.3
.20	.9970	830.1	3.100	-12.401	1037.6
.25	.9959	777.3	4.282	-12.847	1036.4
.30	.9944	724.4	5.839	-13.625	1034.9
.35	.9923	671.2	8.015	-14.884	1032.7
.40	.9899	618.1	10.520	-15.779	1030.2
.45	.9873	565.1	13.220	-16.158	1027.5
.50	.9842	512.1	16.437	-16.437	1024.3
.55	.9811	459.5	19.662	-16.087	1021.0
.60	.9782	407.2	22.671	-15.114	1018.0
.65	.9757	355.4	25.302	-13.624	1015.4
.70	.9743	304.2	26.753	-11.466	1013.9
.75	.9739	253.4	27.193	- 9.064	1013.5
.80	.9740	202.7	27.030	- 6.758	1013.7
.85	.9733	151.9	27.741	- 4.895	1013.0
.90	.9721	101.2	29.056	- 3.229	1011.6

TEMPERATURE OF URINE CONCENTRATE = 94.0

TABLE IV (Continued)

x	L/L^*	Lu	Hw	Hs	L
.05	.9987	985.2	1.339	-25.432	1037.1
.10	.9982	932.8	1.906	-17.154	1036.5
.15	.9977	880.6	2.412	-13.670	1036.0
.20	.9969	828.2	3.180	-12.719	1035.2
.25	.9958	775.5	4.389	-13.168	1034.0
.30	.9942	722.7	6.002	-14.005	1032.4
.35	.9921	669.6	8.241	-15.306	1030.2
.40	.9896	616.6	10.803	-16.205	1027.6
.45	.9869	563.6	13.582	-16.600	1024.8
.50	.9837	510.8	16.896	-16.896	1021.5
.55	.9805	458.2	20.210	-16.536	1018.2
.60	.9776	406.0	23.293	-15.529	1015.1
.65	.9750	354.3	25.982	-13.990	1012.4
.70	.9736	303.3	27.448	-11.763	1011.0
.75	.9732	252.6	27.860	- 9.287	1010.5
.80	.9734	202.2	27.649	- 6.912	1010.8
.85	.9727	151.5	28.343	- 5.002	1010.1
.90	.9714	100.9	29.653	- 3.295	1008.7

TEMPERATURE OF URINE CONCENTRATE = 98.0

x	L/L^*	Lu	Hw	Hs	L
.05	.9987	983.0	1.386	-26.334	1034.7
.10	.9981	930.7	1.956	-17.602	1034.1
.15	.9976	878.6	2.485	-14.080	1033.6
.20	.9968	826.3	3.276	-13.102	1032.8
.25	.9956	773.7	4.513	-13.540	1031.6
.30	.9940	721.0	6.168	-14.392	1029.9
.35	.9918	668.0	8.471	-15.731	1027.6
.40	.9893	615.0	11.130	-16.695	1025.0
.45	.9865	562.2	13.982	-17.090	1022.1
.50	.9832	509.3	17.403	-17.403	1018.7
.55	.9799	456.9	20.806	-17.023	1015.3
.60	.9769	404.8	23.977	-15.985	1012.1
.65	.9742	353.3	26.720	-14.388	1009.4
.70	.9728	302.4	28.203	-12.087	1007.9
.75	.9724	251.9	28.593	- 9.531	1007.5
.80	.9726	201.6	28.339	- 7.085	1007.8
.85	.9720	151.1	29.013	- 5.120	1007.1
.90	.9707	100.6	30.316	- 3.368	1005.8

TEMPERATURE OF URINE CONCENTRATE = 102.0

TABLE IV (Continued)

x	L/L^*	Lu	Hw	Hs	L
.05	.9986	980.8	1.423	-27.033	1032.4
.10	.9981	928.6	2.011	-18.098	1031.8
.15	.9975	876.6	2.551	-14.455	1031.2
.20	.9968	824.4	3.352	-13.408	1030.4
.25	.9955	771.9	4.639	-13.917	1029.2
.30	.9939	719.2	6.329	-14.768	1027.5
.35	.9916	666.3	8.708	-16.172	1025.1
.40	.9889	613.4	11.427	-17.141	1022.4
.45	.9861	560.7	14.366	-17.559	1019.4
.50	.9827	508.0	17.877	-17.877	1015.9
.55	.9793	455.6	21.382	-17.494	1012.4
.60	.9762	403.7	24.623	-16.415	1009.2
.65	.9735	352.2	27.436	-14.773	1006.4
.70	.9720	301.5	28.922	-12.395	1004.9
.75	.9717	251.1	29.284	- 9.761	1004.5
.80	.9720	201.0	28.983	- 7.246	1004.8
.85	.9713	150.6	29.636	- 5.230	1004.2
.90	.9701	100.3	30.926	- 3.436	1002.9

TEMPERATURE OF URINE CONCENTRATE = 106.0

x	L/L^*	Lu	Hw	Hs	L
.05	.9986	978.6	1.469	-27.908	1030.1
.10	.9980	926.6	2.068	-18.612	1029.5
.15	.9975	874.6	2.617	-14.827	1029.0
.20	.9967	822.5	3.442	-13.769	1028.2
.25	.9954	770.1	4.749	-14.248	1026.9
.30	.9937	717.6	6.513	-15.198	1025.1
.35	.9913	664.7	8.938	-16.600	1022.7
.40	.9886	611.9	11.752	-17.628	1019.8
.45	.9857	559.2	14.791	-18.078	1016.8
.50	.9822	506.6	18.405	-18.405	1013.2
.55	.9787	454.3	22.000	-18.000	1009.6
.60	.9754	402.5	25.330	-16.887	1006.3
.65	.9727	351.2	28.196	-15.182	1003.4
.70	.9712	300.6	29.696	-12.727	1001.9
.75	.9709	250.4	30.035	-10.012	1001.6
.80	.9712	200.4	29.680	- 7.420	1001.9
.85	.9706	150.2	30.310	- 5.349	1001.3
.90	.9694	100.0	31.502	- 3.510	1000.0

TEMPERATURE OF URINE CONCENTRATE = 110.0

x	L/L^*	Lu	Hw	Hs	L
.05	.9985	976.3	1.518	-28.839	1027.7
.10	.9979	924.4	2.131	-19.177	1027.1
.15	.9974	872.5	2.689	-15.236	1026.5
.20	.9966	820.5	3.541	-14.165	1025.7
.25	.9952	768.2	4.890	-14.670	1024.3
.30	.9935	715.8	6.686	-15.601	1022.5
.35	.9911	663.0	9.210	-17.105	1020.0
.40	.9882	610.3	12.106	-18.159	1017.1
.45	.9852	557.7	15.222	-18.604	1014.0
.50	.9816	505.1	18.946	-18.946	1010.3
.55	.9780	452.9	22.664	-18.543	1006.5
.60	.9747	401.2	26.084	-17.390	1003.1
.65	.9718	350.1	29.013	-15.622	1000.2
.70	.9703	299.6	30.524	-13.082	998.7
.75	.9700	249.6	30.827	-10.276	998.4
.80	.9704	199.8	30.423	- 7.606	998.8
.85	.9699	149.7	31.029	- 5.476	998.2
.90	.9686	99.7	32.297	- 3.589	996.9

TEMPERATURE OF URINE CONCENTRATE = 114.0

x	L/L^*	Lu	Hw	Hs	L
.05	.9985	974.1	1.560	-29.641	1025.3
.10	.9979	922.2	2.187	-19.680	1024.7
.15	.9973	870.5	2.754	-15.607	1024.1
.20	.9965	818.6	3.622	-14.486	1023.3
.25	.9951	766.4	5.013	-15.040	1021.9
.30	.9933	714.0	6.857	-16.000	1020.0
.35	.9908	661.3	9.455	-17.559	1017.4
.40	.9879	608.7	12.430	-18.645	1014.5
.45	.9848	556.2	15.639	-19.115	1011.3
.50	.9810	503.7	19.476	-19.476	1007.4
.55	.9773	451.6	23.275	-19.043	1003.6
.60	.9739	400.0	26.780	-17.853	1000.1
.65	.9710	349.0	29.776	-16.033	997.1
.70	.9695	298.7	31.290	-13.410	995.6
.75	.9693	248.8	31.563	-10.521	995.3
.80	.9697	199.2	31.104	- 7.776	995.8
.85	.9691	149.3	31.686	- 5.592	995.2
.90	.9679	99.4	32.940	- 3.660	994.0

TEMPERATURE OF URINE CONCENTRATE = 118.0

TABLE IV (Continued)

x	L/L*	Lu	Hw	Hs	L
.05	.9984	971.8	1.621	-30.790	1023.0
.10	.9978	920.1	2.252	-20.267	1022.3
.15	.9972	868.5	2.835	-16.066	1021.8
.20	.9964	816.7	3.730	-14.918	1020.9
.25	.9950	764.6	5.151	-15.452	1019.4
.30	.9931	712.3	7.061	-16.475	1017.5
.35	.9905	659.7	9.713	-18.039	1014.9
.40	.9875	607.1	12.786	-19.179	1011.8
.45	.9843	554.7	16.080	-19.654	1008.5
.50	.9805	502.3	20.030	-20.030	1004.6
.55	.9766	450.3	23.948	-19.594	1000.7
.60	.9731	398.8	27.545	-18.363	997.1
.65	.9701	347.9	30.604	-16.479	994.0
.70	.9686	297.7	32.135	-13.772	992.5
.75	.9684	248.1	32.374	-10.791	992.2
.80	.9689	198.6	31.848	- 7.962	992.8
.85	.9684	148.8	32.402	- 5.718	992.2
.90	.9672	99.1	33.639	- 3.738	991.0

TEMPERATURE OF URINE CONCENTRATE = 122.0

x	L/L*	Lu	Hw	Hs	L
.05	.9984	969.6	1.664	-31.610	1020.6
.10	.9977	918.0	2.312	-20.812	1020.0
.15	.9971	866.5	2.915	-16.517	1019.4
.20	.9963	814.8	3.828	-15.312	1018.5
.25	.9948	762.8	5.283	-15.848	1017.0
.30	.9929	710.5	7.237	-16.887	1015.1
.35	.9902	658.0	9.993	-18.559	1012.3
.40	.9871	605.5	13.151	-19.727	1009.1
.45	.9838	553.2	16.560	-20.240	1005.7
.50	.9798	500.8	20.618	-20.618	1001.7
.55	.9759	448.9	24.640	-20.160	997.7
.60	.9723	397.6	28.323	-18.882	994.0
.65	.9692	346.8	31.454	-16.937	990.8
.70	.9677	296.8	32.990	-14.139	989.3
.75	.9675	247.3	33.174	-11.058	989.1
.80	.9681	197.9	32.609	- 8.152	989.7
.85	.9676	148.4	33.123	- 5.845	989.2
.90	.9664	98.8	34.349	- 3.817	988.0

TEMPERATURE OF URINE CONCENTRATE = 126.0

TABLE IV (Continued)

x	L/L^*	Lu	Hw	Hs	L
.05	.9983	967.4	1.722	-32.727	1018.3
.10	.9977	915.9	2.386	-21.477	1017.6
.15	.9971	864.5	2.989	-16.936	1017.0
.20	.9962	812.9	3.921	-15.684	1016.1
.25	.9947	760.9	5.434	-16.302	1014.6
.30	.9927	708.8	7.440	-17.361	1012.6
.35	.9899	656.3	10.269	-19.070	1009.7
.40	.9867	603.9	13.524	-20.285	1006.5
.45	.9833	551.6	17.022	-20.805	1003.0
.50	.9792	499.4	21.207	-21.207	998.8
.55	.9751	447.6	25.349	-20.740	994.7
.60	.9714	396.3	29.129	-19.419	990.9
.65	.9683	345.7	32.323	-17.405	987.7
.70	.9668	295.8	33.865	-14.513	986.1
.75	.9666	246.5	34.021	-11.340	986.0
.80	.9673	197.3	33.368	- 8.342	986.6
.85	.9668	147.9	33.863	- 5.976	986.1
.90	.9656	98.5	35.065	- 3.896	984.9

TEMPERATURE OF URINE CONCENTRATE = 130.0

x	L/L^*	Lu	Hw	Hs	L
.05	.9982	965.0	1.781	-33.840	1015.8
.10	.9976	913.6	2.454	-22.086	1015.1
.15	.9970	862.4	3.069	-17.393	1014.5
.20	.9960	810.9	4.028	-16.113	1013.6
.25	.9945	759.0	5.572	-16.717	1012.0
.30	.9925	707.0	7.650	-17.850	1009.9
.35	.9896	654.6	10.555	-19.603	1007.0
.40	.9863	602.2	13.905	-20.857	1003.7
.45	.9828	550.1	17.506	-21.396	1000.1
.50	.9786	497.9	21.818	-21.818	995.8
.55	.9744	446.2	26.066	-21.327	991.5
.60	.9706	395.1	29.946	-19.964	987.7
.65	.9674	344.5	33.207	-17.881	984.4
.70	.9659	294.9	34.743	-14.890	982.9
.75	.9657	245.7	34.856	-11.619	982.7
.80	.9664	196.7	34.156	- 8.539	983.4
.85	.9660	147.4	34.605	- 6.107	983.0
.90	.9648	98.2	35.784	- 3.976	981.8

TEMPERATURE OF URINE CONCENTRATE = 134.0

TABLE IV (Continued)

x	L/L*	Lu	Hw	Hs	L
.05	.9982	962.8	1.833	-34.823	1013.5
.10	.9975	911.5	2.518	-22.659	1012.8
.15	.9969	860.3	3.154	-17.873	1012.1
.20	.9959	808.9	4.136	-16.543	1011.2
.25	.9944	757.2	5.724	-17.171	1009.6
.30	.9923	705.2	7.850	-18.316	1007.4
.35	.9893	652.9	10.849	-20.148	1004.5
.40	.9859	600.6	14.304	-21.456	1001.0
.45	.9823	548.5	18.010	-22.012	997.3
.50	.9779	496.4	22.453	-22.453	992.8
.55	.9736	444.8	26.825	-21.948	988.5
.60	.9697	393.8	30.806	-20.537	984.5
.65	.9664	343.4	34.129	-18.377	981.2
.70	.9649	293.9	35.677	-15.290	979.6
.75	.9648	244.9	35.740	-11.913	979.6
.80	.9656	196.1	34.954	- 8.739	980.3
.85	.9652	147.0	35.375	- 6.243	979.9
.90	.9640	97.9	36.537	- 4.060	978.8

TEMPERATURE OF URINE CONCENTRATE = 138.0

x	L/L*	Lu	Hw	Hs	L
.05	.9981	960.4	1.901	-36.122	1011.0
.10	.9974	909.3	2.599	-23.392	1010.3
.15	.9968	858.2	3.237	-18.342	1009.7
.20	.9958	806.9	4.246	-16.984	1008.7
.25	.9942	755.3	5.879	-17.636	1007.0
.30	.9920	703.4	8.056	-18.798	1004.8
.35	.9890	651.1	11.147	-20.702	1001.8
.40	.9855	598.9	14.708	-22.062	998.2
.45	.9817	546.9	18.530	-22.648	994.4
.50	.9772	494.9	23.099	-23.099	989.8
.55	.9728	443.4	27.597	-22.579	985.3
.60	.9687	392.5	31.670	-21.113	981.2
.65	.9654	342.2	35.082	-18.890	977.8
.70	.9638	292.9	36.623	-15.696	976.3
.75	.9638	244.1	36.633	-12.211	976.3
.80	.9647	195.4	35.775	- 8.944	977.1
.85	.9643	146.5	36.155	- 6.380	976.7
.90	.9632	97.6	37.294	- 4.144	975.6

TEMPERATURE OF URINE CONCENTRATE = 142.0

making possible the transfer of latent heat from the condensing vapor to the boiling urine. This thermodynamic process is illustrated on a T-S diagram in Figure 1 and is summarized as follows:

1-2:	boiling of urine, heat received from condensing vapor
2-4:	compression of vapor from boiling pressure to a higher condensing pressure (2-4 is for boiling of pure water, 2'-4' and 2''-4'' are for boiling of urine concentrates)
4-5-6:	cooling and condensing of vapor, heat rejected to boiling urine.

As the urine, which is fed to and contained within a vapor compression system, becomes more and more concentrated due to the extraction of water, its vapor pressure decreases as shown in Table III. The pressure ratio required to raise the pressure of the evolved vapor to a level at which its condensing temperature is just equal to the boiling temperature of the concentrated urine (illustrated in Figure 1 by the paths 2'-3' and 2''-3'') is easily calculated from Table III. It is simply the ratio of the vapor pressure at $x = 0$ to that at x. For any x, this ratio is very nearly the same in the range $80^{o}F$ to $140^{o}F$. The ratio is plotted in Figure 2.

Combining the data in Figure 2 with those in Figure 28 results in Figure 3, a plot that shows the pressure ratio versus the weight fraction of extracted water.

Figure 3 is useful when evaluating the point at which it is no longer beneficial to increase pressure ratio and hence compressor weight and power for the sake of obtaining higher water recovery efficiencies. When evaluations such as these are made, other factors that also directly or indirectly influence pressure ratio and are a function of the amount of water extracted, such as scaling due to precipitate formation and changes in transport properties, must also be evaluated.

Example 2, Vacuum Distillation System

The designer is concerned with establishing optimum boiling and condensing temperatures on the basis of heat and mass transfer with a vacuum distillation system, as with any distillation system including vapor compression. The rise in the boiling point of urine that accompanies higher concentrations must not be ignored. The increase in boiling point as a function of water extracted is shown in Figure 4 and is obtained by combining data from Figures 11 and 28.

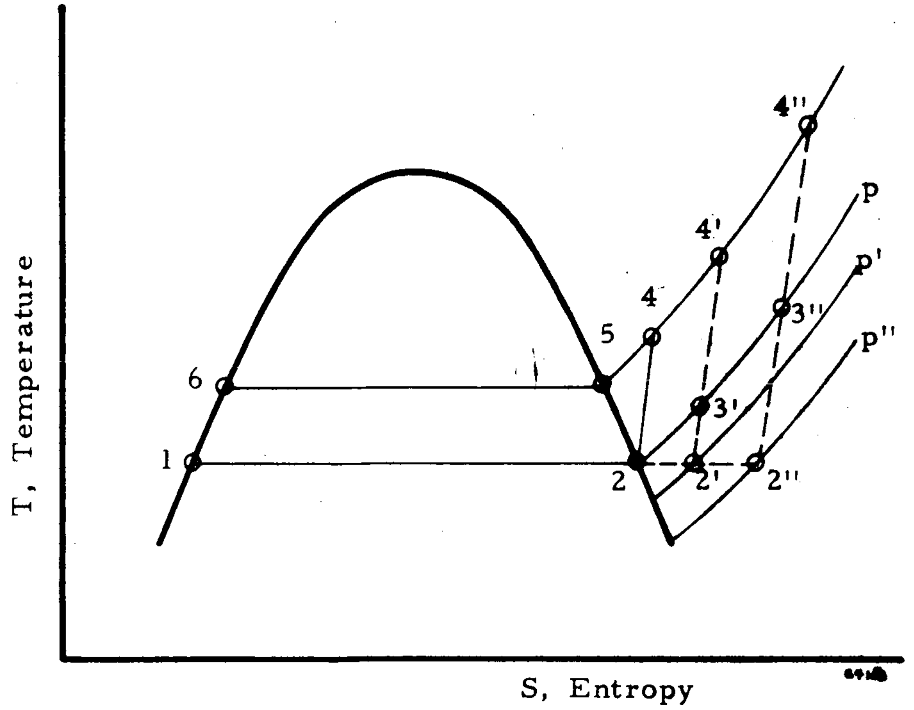

Figure 1. T-S Diagram of Vapor Compression Process

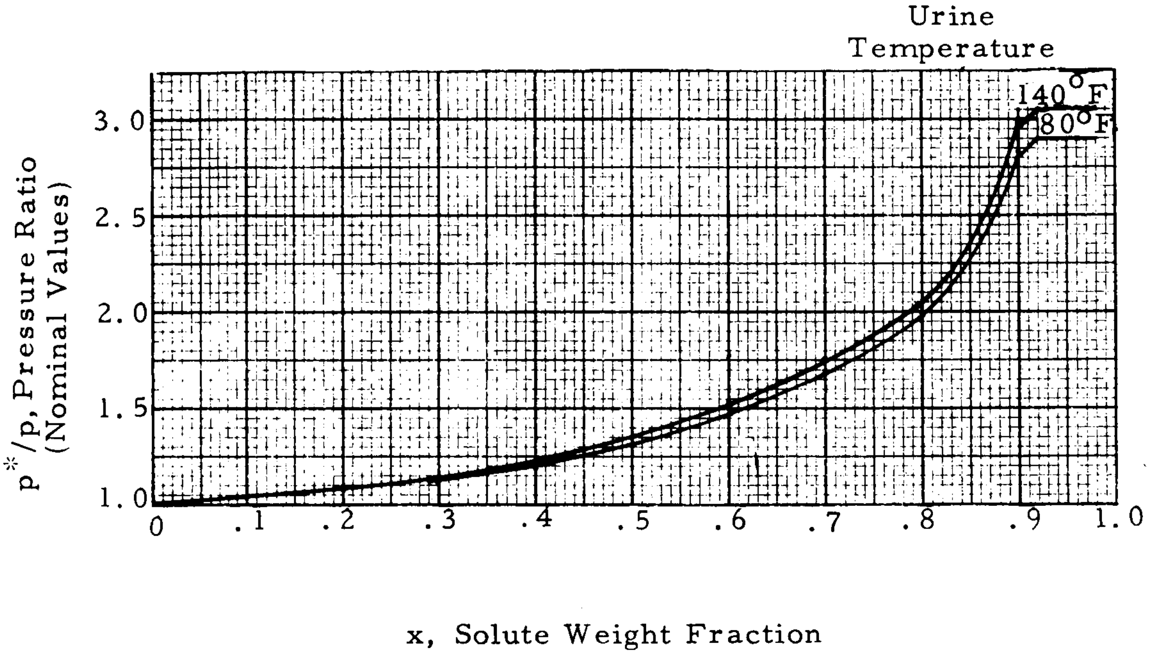

Figure 2. Ratio of the Vapor Pressure of Pure Water to the Vapor Pressure of Urine Concentrate

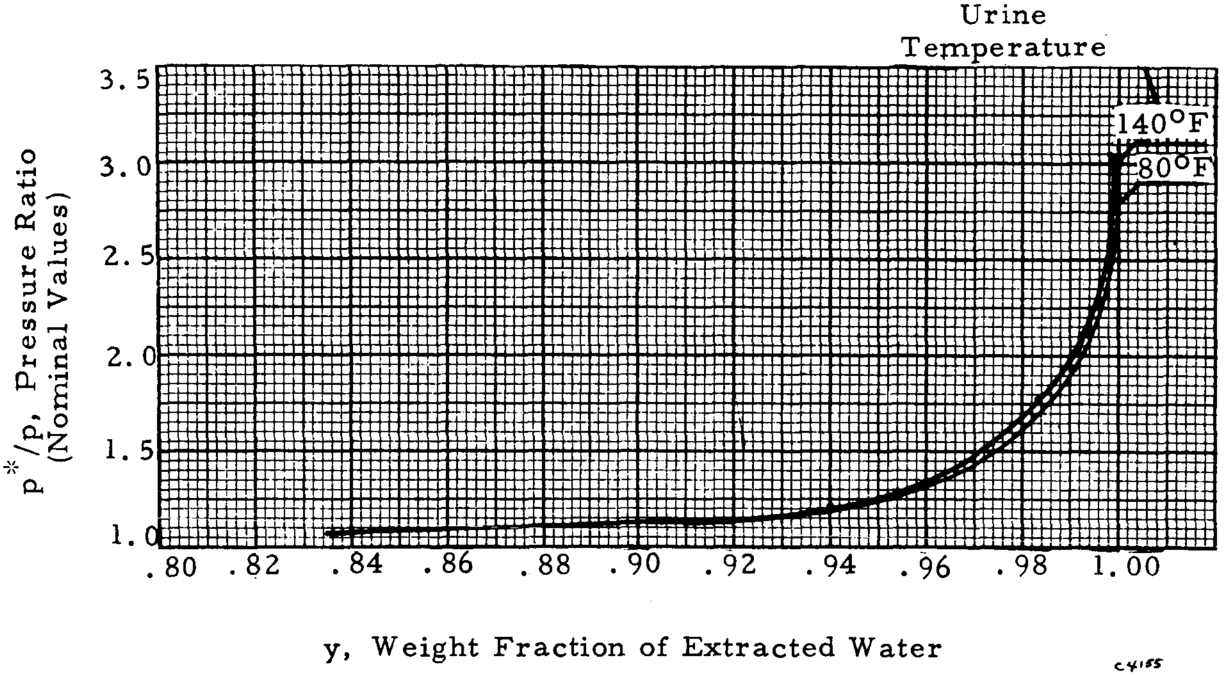

Figure 3. Pressure Ratio as a Function of the Weight Fraction of Extracted Water

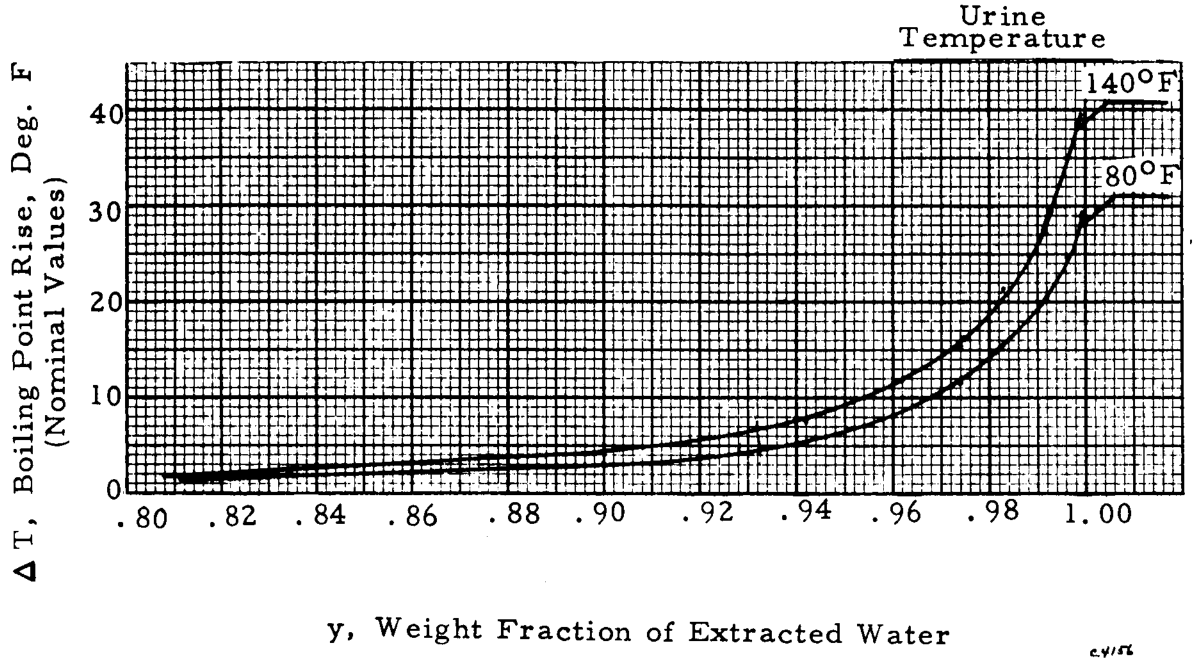

Figure 4. Boiling Point Rise as a Function of the Weight Fraction of Extracted Water

Example 3, Reverse Osmosis System

In a reverse osmosis system the pressure applied to the urine must exceed the osmotic pressure in order to achieve a reverse osmotic flow of water. As water is extracted the osmotic pressure of the remaining concentrate increases as shown in Figure 5, which was obtained by combining Figures 19 and 28.

The required increase in osmotic pressure to achieve a higher water recovery efficiency represents an increase in weight and power, so, for any mission there is an optimum operating pressure.

Example 4, Miscellaneous Considerations

Several designers have proposed urine distillation systems in which urine would be continually fed into an evaporator compartment and precipitates would be continually separated and withdrawn. Presumably this proposition is based on the mistaken belief that urine behavior is similar to that of a binary solution such as sodium chloride and water, in which the brine does not concentrate beyond the solubility limit of sodium chloride. However, urine does not behave like this. Due to the presence of many highly soluble and even some liquid species such as citric, formic and lactic acids, urine continues to get more and more concentrated as water is extracted, even as certain species are being precipitated. This behavior is indicated in Figure 26.

In most of the systems that have been proposed for extracting water from urine, the extraction process is discontinued before 100 per cent of the water is removed, i.e., before complete dryness is reached. This leaves the task of transferring the mother liquor, including entrained precipitates, from the water removal area to a holding or storage area. The viscosity and precipitate data contained here should be helpful in the design of transfer systems, and density data should aid in sizing the volume required for storing the mother liquor.

The calculations required to obtain these kinds of precipitate and volume information are illustrated in the following example.

Assume urine with the following initial conditions:

Pretreatment: $H_2SO_4 + CrO_3 + CuSO_4$

$x_o = .042$

$\rho_o = 1.012$

Calculate the amount of precipitate contained in the urine concentrate slurry that remains after extraction of 98 per cent of the water from a liter

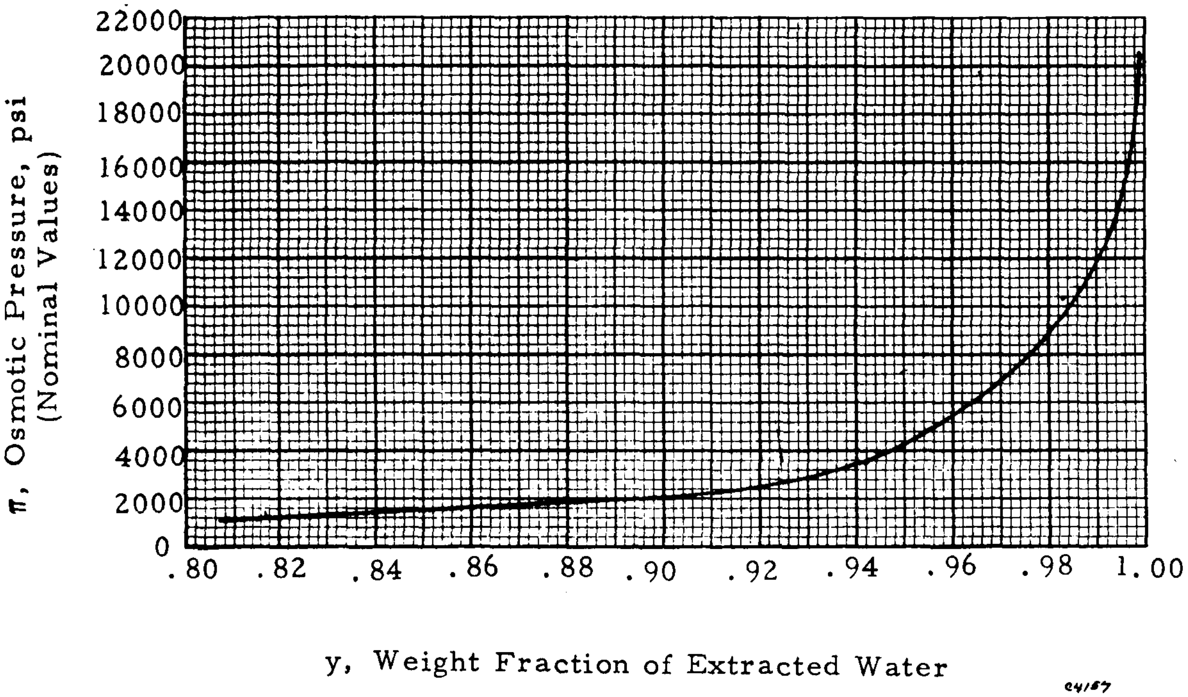

Figure 5. Osmotic Pressure as a Function of the Weight Fraction of Extracted Water

of urine with the above listed initial conditions. Also calculate the slurry's volume.

From Figure 27 for $y = .98$; $x = .665$

From Figure 13 for $x = .665$; $\rho = 1.312$

From Figure 26 for $x = .665$; $\frac{Wp}{Ws_o} = .11$

$Wu_o = \rho_o V_o = 1.012 (1000) = 1012$ g

$Ws_o = x_o Wu_o = .042 (1012) = 42.5$ g

$Wp = \frac{Wp}{Ws_o} Ws_o = .11 (42.5) = 4.675$ g

$Vp = Wp/\rho_p = 4.675/1.470 = 3.18$ ml

$Ws = Ws_o - Wp = 42.5 - 4.675 = 37.82$ g

$Wu = Ws/x = 37.82/.665 = 56.84$

$Vu = Wu/\rho = 56.84/1.312 = 43.32$ ml

weight of precipitate = $Wp = 4.675$ g

weight of slurry = $Wu + Wp = 56.84 + 4.675 = 61.52$ g

volume of slurry = $Vu + Vp = 43.32 + 3.18 = 46.50$ ml

Similar calculations for other pretreatments and various degrees of water extraction enabled construction of Figures 6 and 7.

Systems that require the removal and storage of a mother liquor need a simple way of monitoring the progress of the water extraction process to determine the proper end point. Refractive index, Figure 29 deviates less between different batches of urine and different pretreatments than any other physical property. In addition, the measurement is relatively easy to make and requires only a smear of sample. It would be a relatively simple, direct, and accurate means of monitoring and controlling water recovery processes.

Solute Weight Fraction

Solute weight fraction is the total weight of dissolved substances in urine per unit weight of urine. It does not include precipitated solids. As urine is concentrated some of the original solids are normally precipitated, as shown in Figure 26. The solute weight fraction includes only those species which remain in solution. It was determined by drying an aliquot of concentrate to

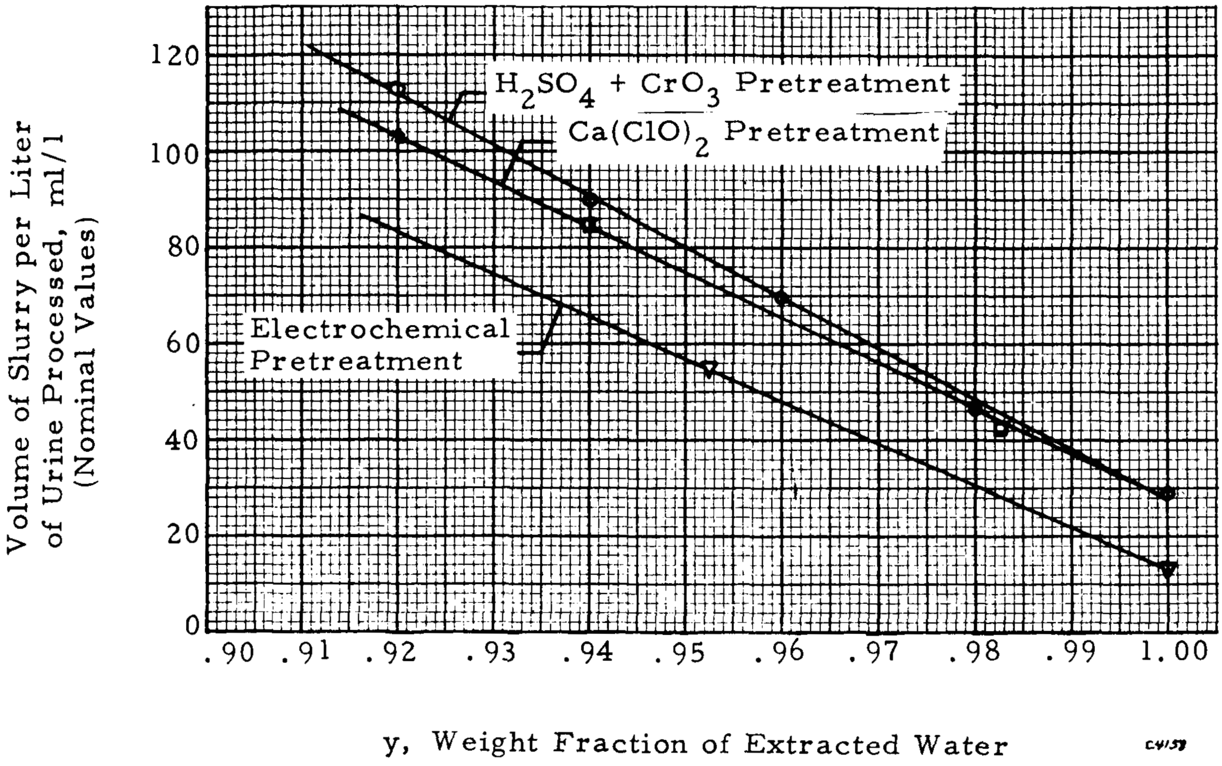

Figure 6. Volume of Urine Concentrate Slurry as a Function of the Weight Fraction of Extracted Water

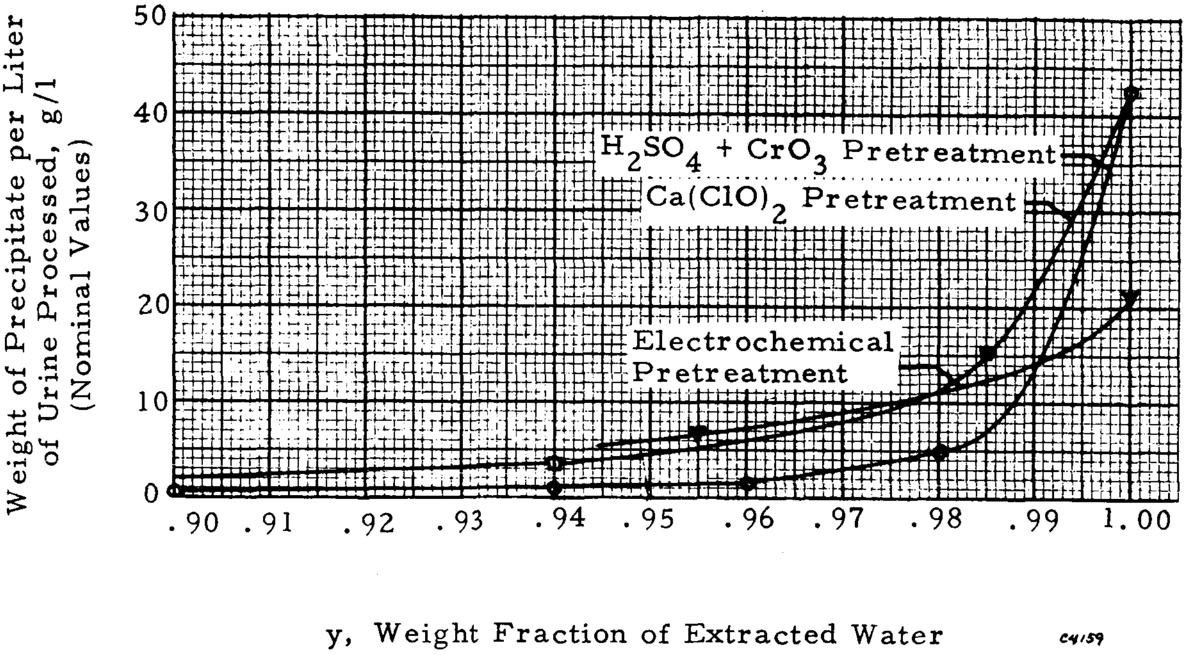

Figure 7. Weight Fraction of Precipitated Solids as a Function of the Weight Fraction of Extracted Water

approximately a -40°F dew point with a dry air purge at room temperature. With this technique there is a minimal loss of high vapor pressure solutes such as NH_3, CO_2, HCl, formic acid, amines, and phenols. Solute weight fraction is the property against which all of the other physical properties are correlated.

Vapor Pressure

Vapor pressure was determined with an Othmer vapor-liquid equilibrium still (see ref. 14). The data were smoothed in a two-step procedure in which Raoult's law was utilized. First, the apparent average molecular weight of solute particles, M, was calculated with Raoult's equation and the values were plotted against the boiling temperature, T, of the urine concentrate. The apparent average molecular weight is equal to the true average molecular weight of solute particles only at infinite dilution where intermolecular actions between solute particles is minimal. The term "particle" includes both molecules and ions and is a necessary dictinction because a mole of ions lowers vapor pressure as much as a mole of undissociated molecules. The equation used to compute M is derived as follows:

Raoult's law states that the ratio of the amount of vapor pressure lowering to the vapor pressure of the pure solvent is equal to the ratio of the number of moles of solute particles to the number of moles of solution:

$$\frac{p^* - p}{p^*} = \frac{n}{N + n}$$

rearranging terms:

$$\frac{p}{p^*} = \frac{N}{N + n}$$

$$\frac{p^* - p}{p} = \frac{n}{N} = \frac{Ws/M}{Ww/18} = \frac{x}{1 - x} \quad \frac{18}{M}$$

$$M = 18 \; \frac{x}{1 - x} \quad \frac{p}{p^* - p}$$

where:

p^* = vapor pressure of solvent

p = vapor pressure of solution

Ws = weight of solute

Ww = weight of solvent

N = number of moles of solvent = $\frac{Ww}{18}$

n = number of moles of solute particles = $\frac{Ws}{M}$

M = apparent average molecular weight of solute particles

x = solute weight fraction

T = boiling temperature of urine

The values for x, p, and T were measured. p^* was obtained from published data (see ref. 15).

For most urine samples the plot of M vs. T had a small negative slope with the following mean value:

$$\frac{dM}{dT} = -0.1145$$

The second step in the two-step procedure for smoothing vapor pressure data was carried out next. From the plots of M vs. T, M at 100°F was plotted against the solute fraction, x, as shown in Figure 8.

The mean line shown in Figure 8 was then fitted, and points from it were used as input to a computer program that calculated the nominal values of vapor pressure and the other colligative properties that are presented in Tables II, III and IV.

The following equations were used:

$$p = \frac{p^*}{\left(\frac{18}{M} \quad \frac{x}{1 - x}\right) + 1} ,$$

$$M_T = M_{100} - 0.1145 \ (T-100)$$

where:

T = degrees Fahrenheit and all other parameters are as previously defined

This method of smoothing vapor pressure data is advantageous for computing the colligative properties as compared to standard smoothing techniques such as plotting of Dürhing lines and graphing ln p versus ln p^*.

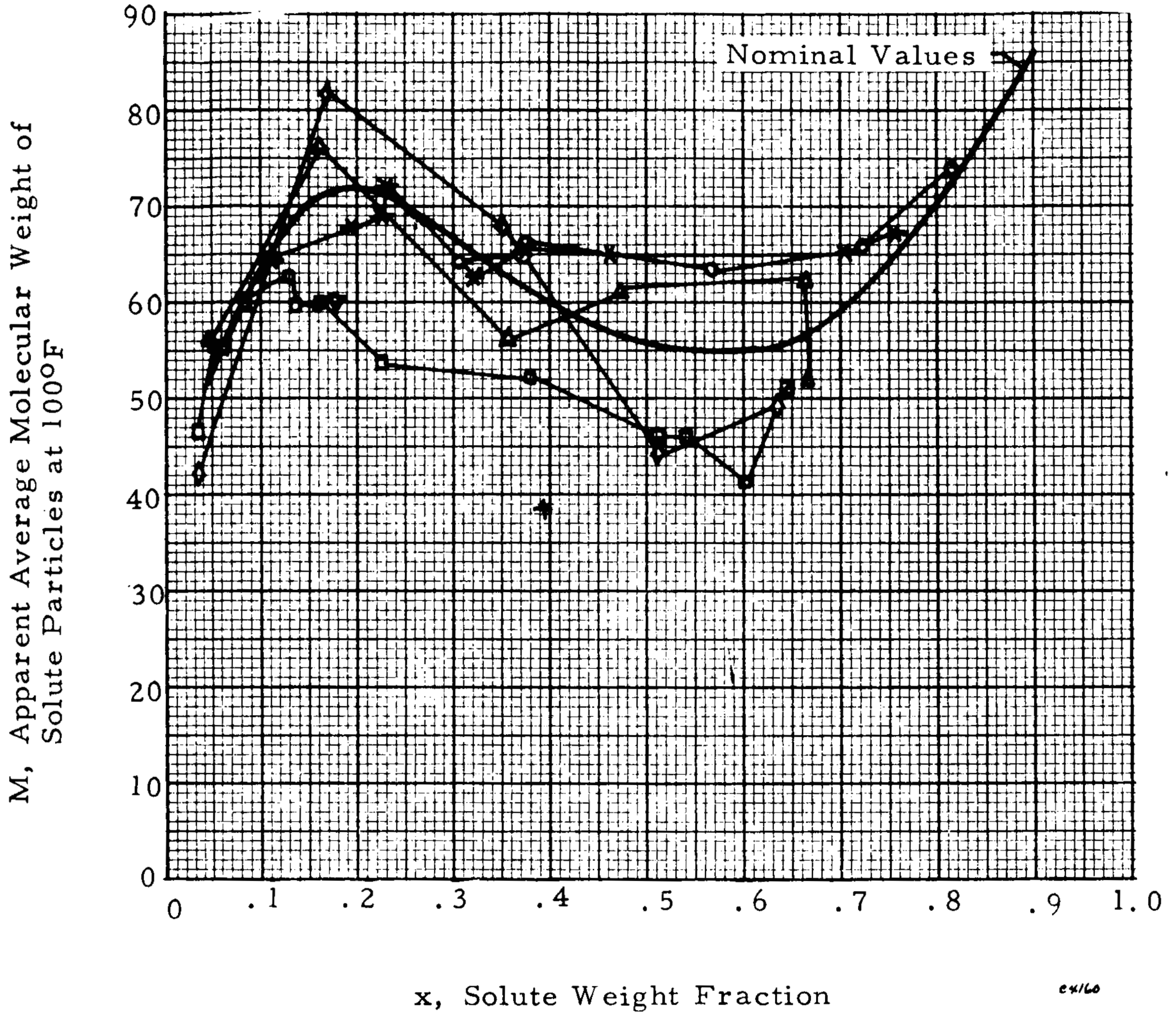

Figure 8. Apparent Average Molecular Weight of Urine Solute Particles

In addition to the table of nominal vapor pressures, Table II, the smoothed vapor pressure data are presented in three familiar forms in Figures 9, 10 and 11. In Figure 12, vapor pressure data are compared to the smoothed values and to the measured values of urea and sodium chloride solutions.

Density

Density was calculated from specific gravity measurements made with precision grade hydrometers. The data are plotted in Figure 13.

Most of the chemically treated urines scatter around a mean line within approximately ± 1 1/2 per cent. This mean line is described by the following equation:

$$\rho = 0.4775\,x + 0.99325$$

where:

ρ = density, g of urine per ml of urine

x = solute weight fraction, g of solutes per g of urine

The density of the electrochemically treated urine is slightly greater than chemically treated urine due to a substantial loss of organic solutes, and is expressed by the following equation:

$$\rho = 0.6110\,x + 0.9904$$

where:

ρ = density, g of urine per ml of urine

x = solute weight fraction, g of solutes per g of urine

Solute Concentration

The solute concentration, C, is the weight of solutes per unit volume of urine and is calculated as follows:

$$C = \rho x$$

where:

C = solute concentration, g of solutes per ml of urine

ρ = density, g of urine per ml of urine

x = solute weight fraction, g of solutes per g of urine

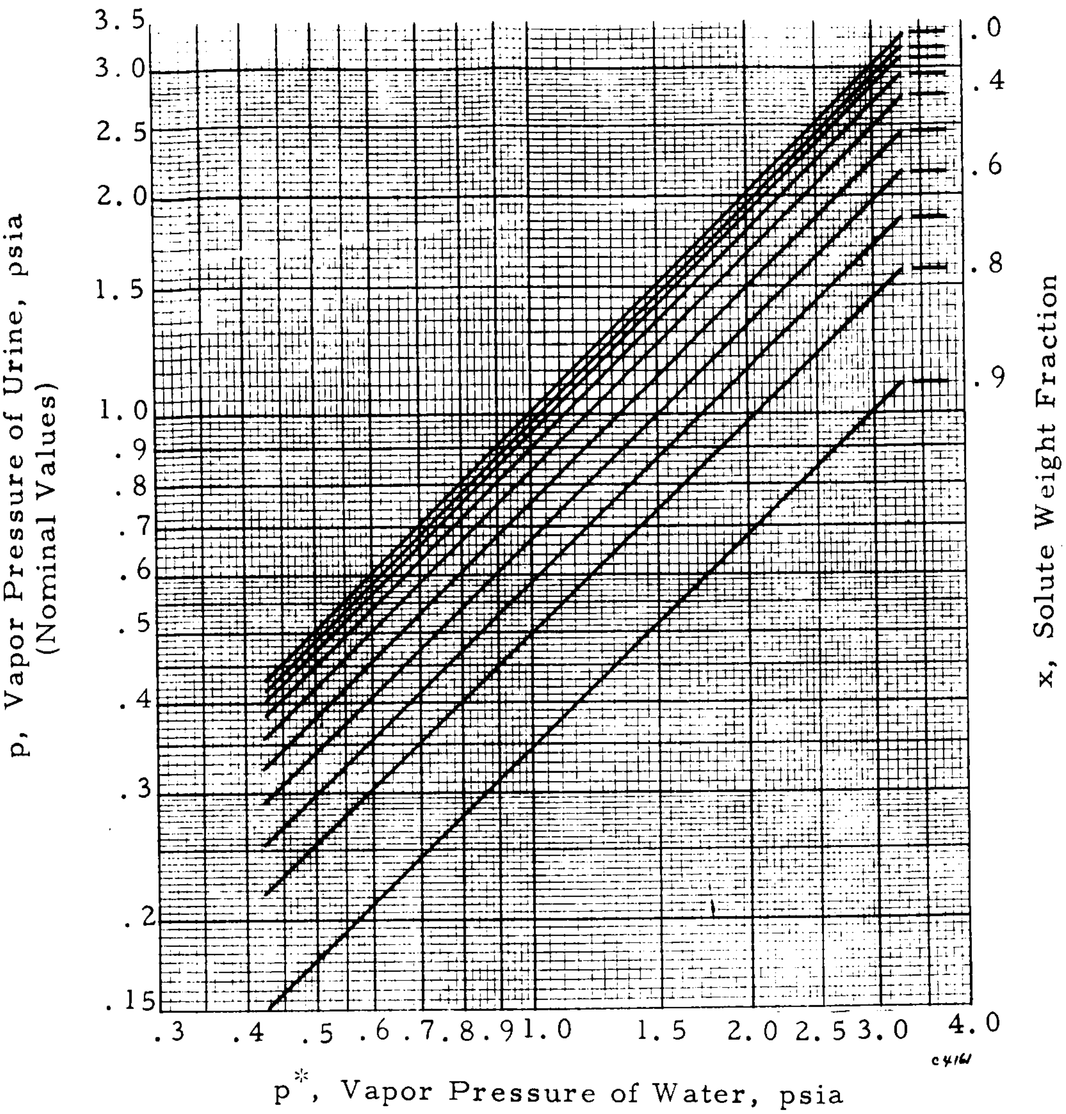

Figure 9. Logrithmic Plot of the Vapor Pressure of Urine Concentrates versus the Vapor Pressure of Pure Water

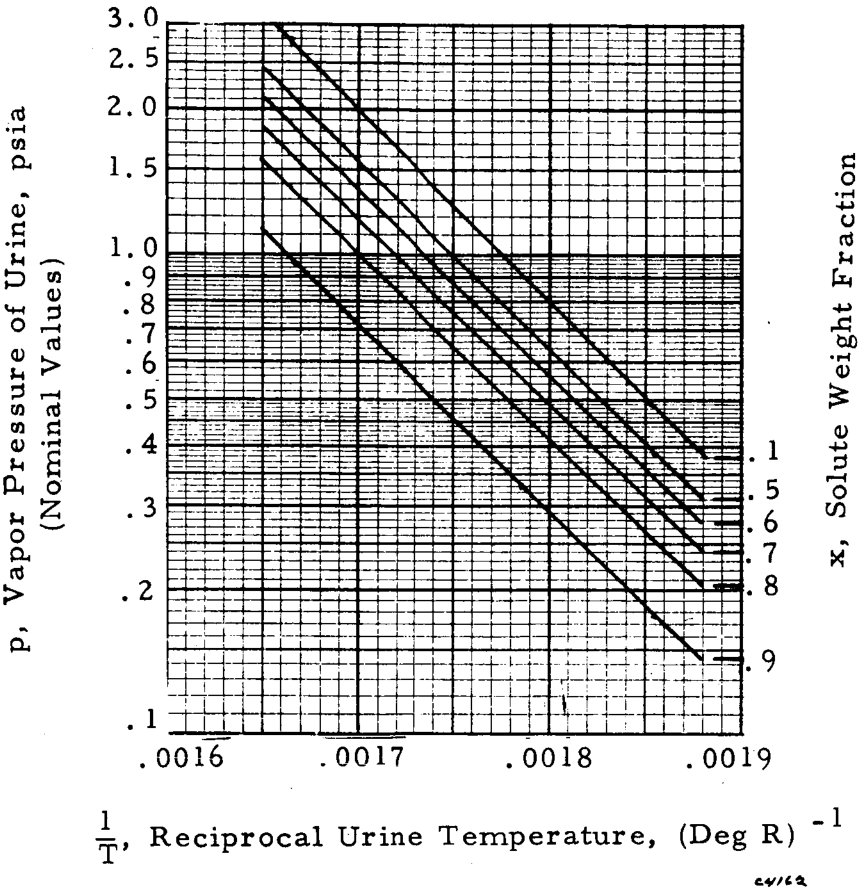

Figure 10. Semi-logrithmic Plot of the Vapor Pressure of Urine Concentrates versus the Reciprocal of the Boiling Temperature

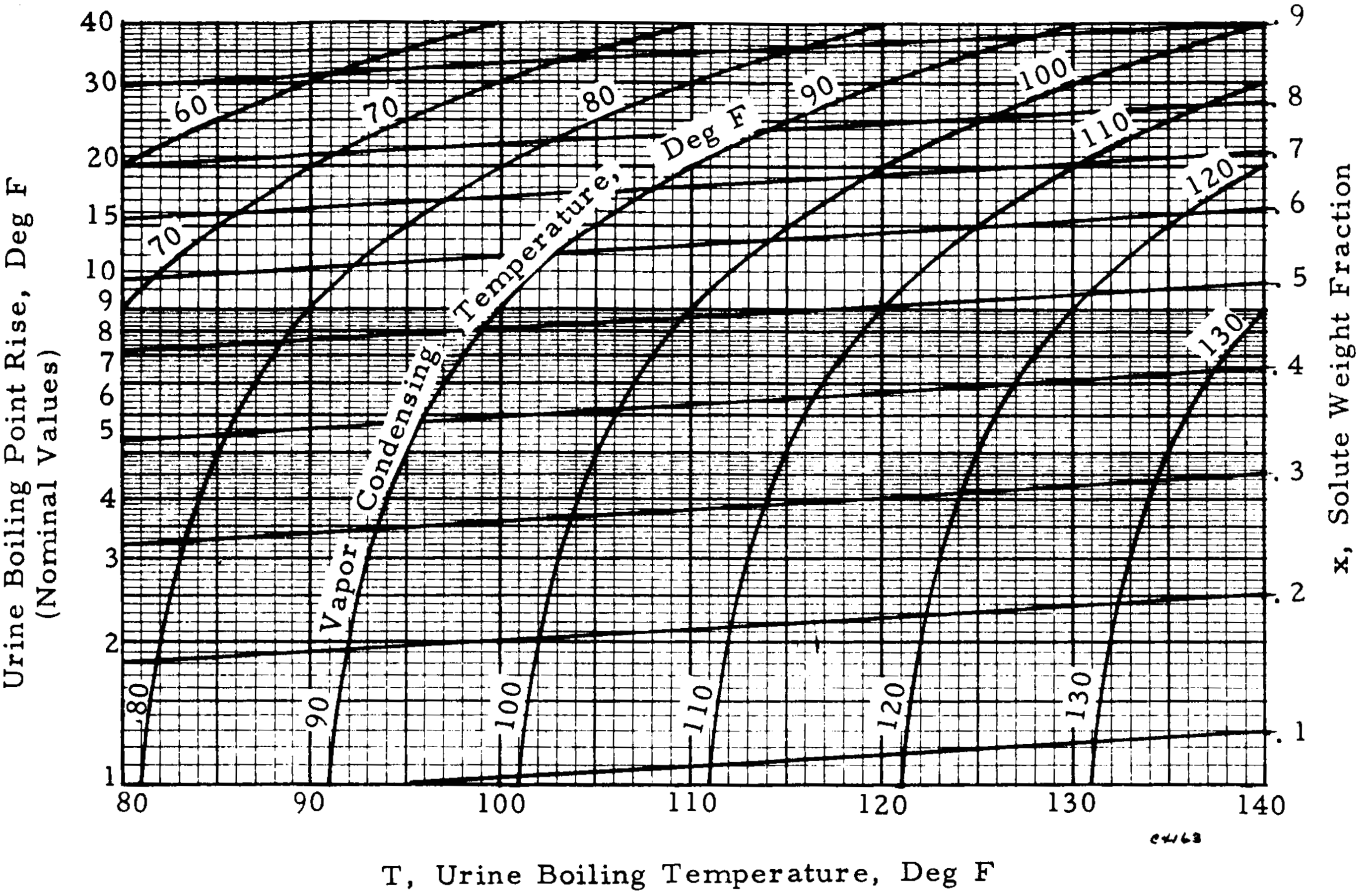

Figure 11. Boiling Point Rise as a Function of Boiling Temperature, Condensing Temperature and Solute Weight Fraction

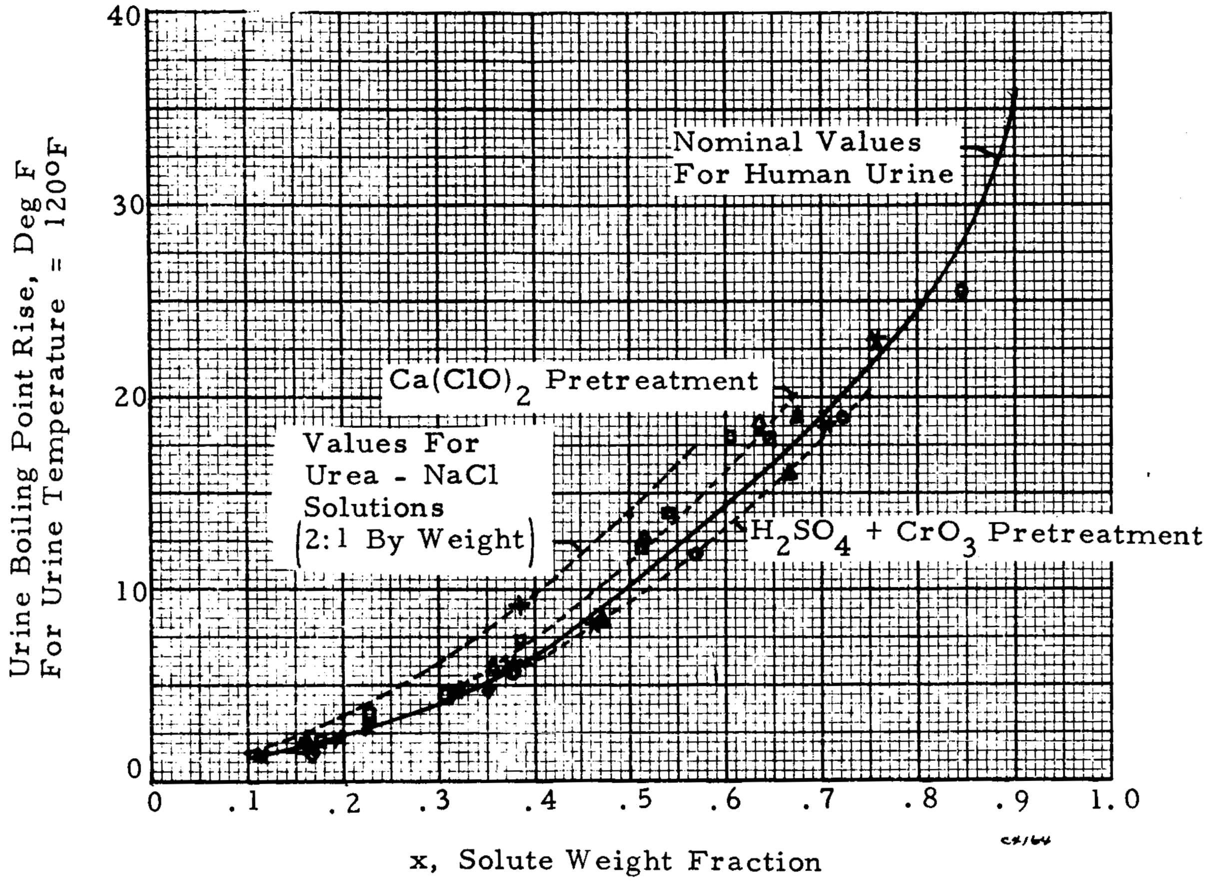

Figure 12. Boiling Point Rise of Urine Concentrate at 120°F

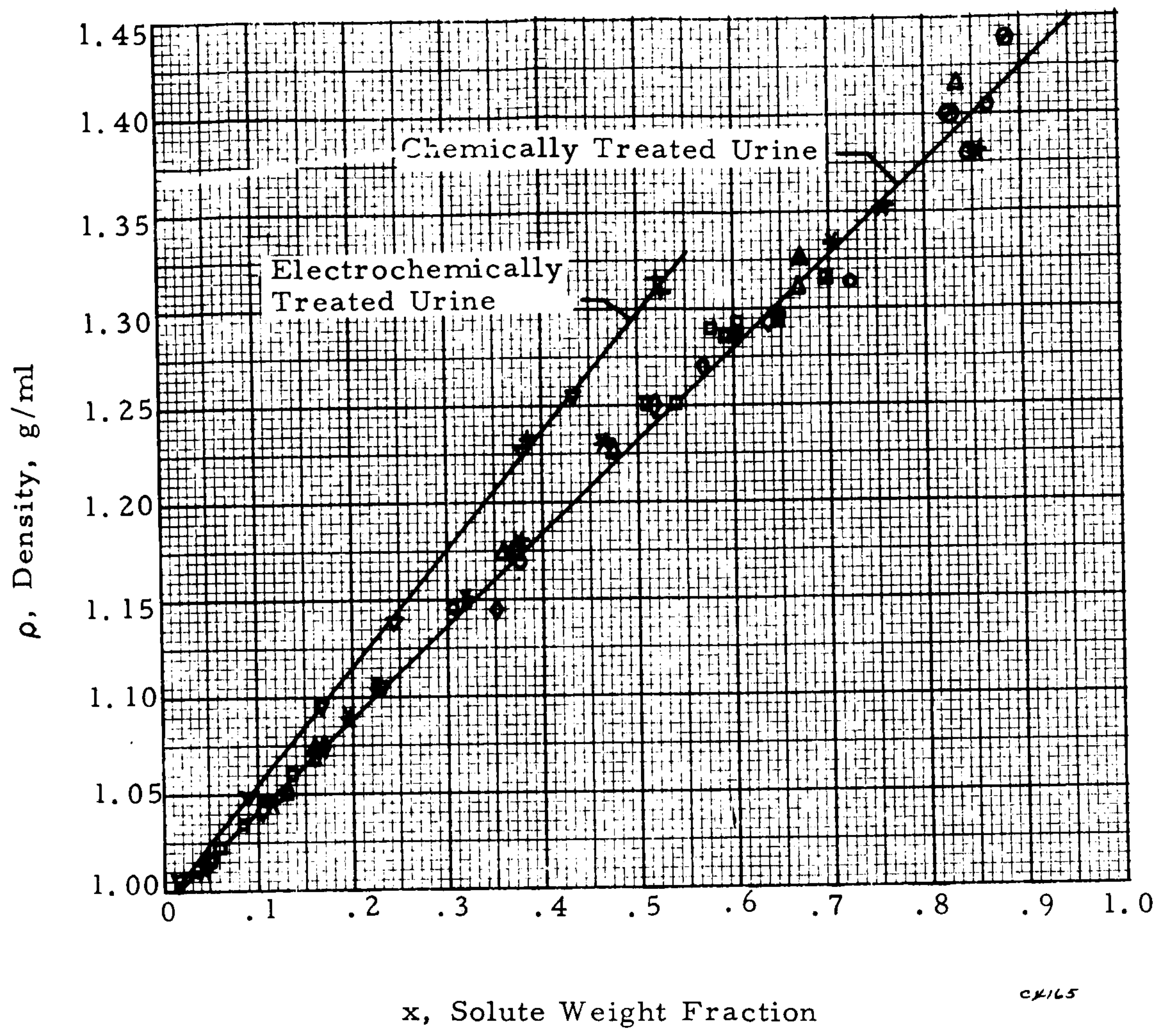

Figure 13. Density of Urine Concentrate

The nominal variation of solute concentration at 70°F with solute weight fraction is shown in Figure 14.

Water Concentration

The water concentration, Cw, is the weight of water per unit volume of urine. Cw is equal to the difference between density and solute concentration, and is calculated as follows:

$$Cw = \rho - c = \rho\,(1 - x)$$

where:

Cw = water concentration, g of water per ml of urine

ρ = density, g of urine per ml of urine

C = concentration, g of solutes per ml of urine

x = solute weight fraction, g of solutes per g of urine

The nominal variation of water concentration at 70°F with solute weight fraction is shown in Figure 15.

Solute to Water Ratio

The solute to water ratio is the weight of solutes per unit weight of water, and is equal to:

$$\frac{x}{1 - x}$$

where:

$\frac{x}{1 - x}$ = g of solute per g of water

x = solute weight fraction, g of solute per g of urine

$1 - x$ = water weight fraction, g of water per g of urine

The variations of solute to water ratio with solute weight fraction is independent of the pretreatment used and is shown in Figure 16.

Osmolality

Osmolality is analogous to molality. The difference is that in osmolality, the apparent average molecular weight of solute particles as determined by measuring vapor pressure depression and applying Raoult's law, is used

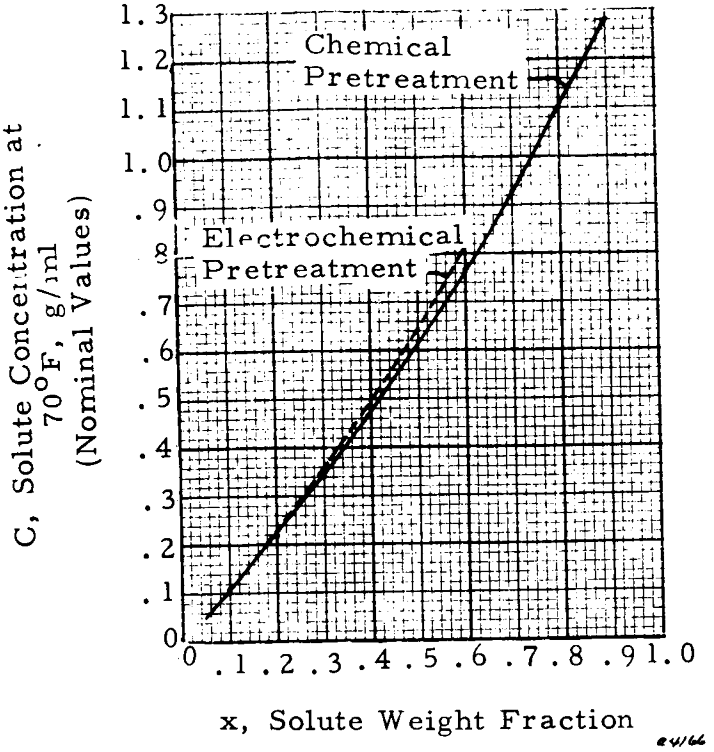

Figure 14. Solute Concentration of Urine Concentrate

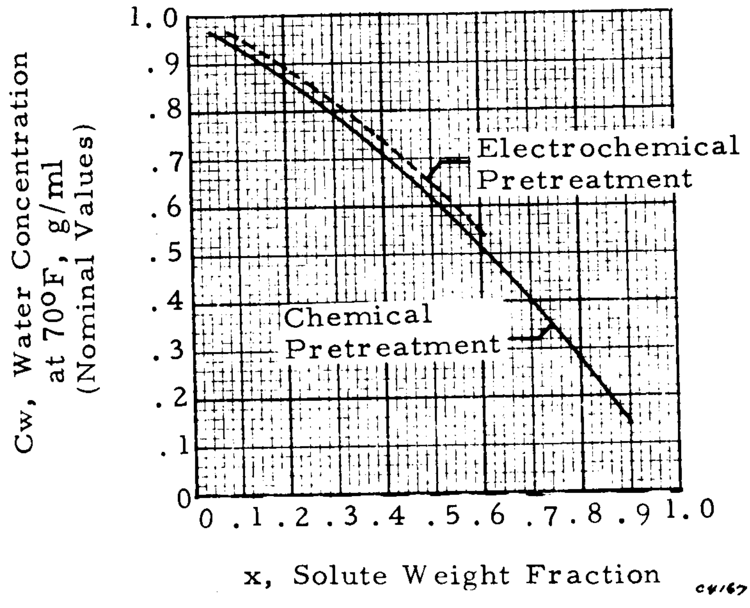

Figure 15. Water Concentration of Urine Concentrate

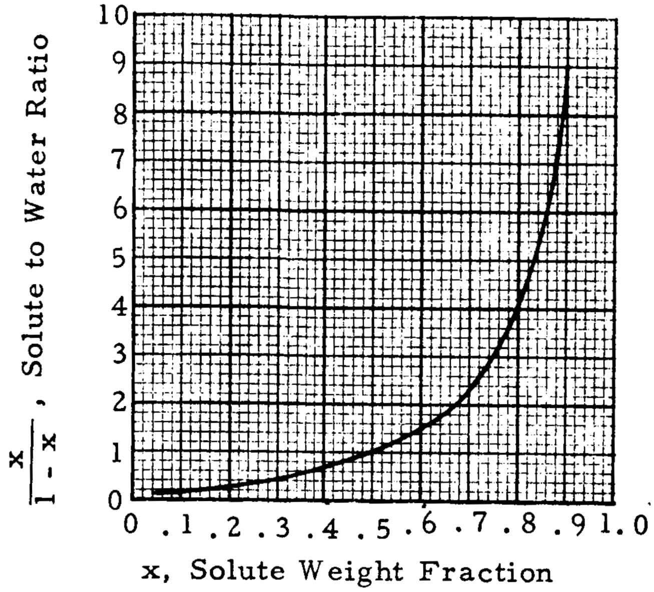

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Figure 16. Solute to Water Ratio of Urine Concentrate

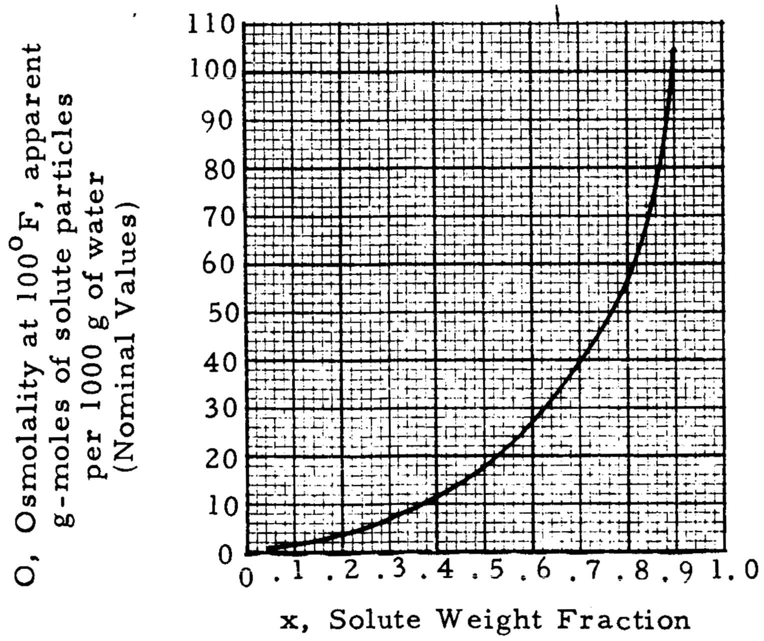

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Figure 17. Osmolality of Urine Concentrate

instead of the average molecular weight of solute molecules. The distinction between particles and molecules is important; so too is the relationship of osmolality to vapor pressure depression. For further discussion see the Vapor Pressure section.

Osmolality is defined as the number of apparent g-moles of solute particles (as calculated from vapor pressure data) per 1000 g of solvent:

$$0 = \frac{n}{Ww} 1000 = \frac{Ws/M}{Ww} 1000$$

$$= \frac{x}{1 - x} \frac{1000}{M} = \frac{p^{*} - p}{p} \frac{1000}{18}$$

where:

0 = osmolality, apparent g-moles of solute particles per 1000 g of water

n = number of solute particles = $\frac{Ws}{M}$

Ws = weight of solute, g

M = apparent average molecular weight of solute particles

Ww = weight of water, g

x = solute weight fraction, g of solutes per g of urine

p^{*} = vapor pressure of water, psia

p = vapor pressure of urine, psia

The variation of osmolality at 100°F with solute weight fraction is shown in Figure 17.

Osmolarity

Osmolarity is analogous to molarity in the same way osmolality is analogous to molality (see Osmolality section).

Osmolarity is defined as the number of apparent g-moles of solute particles (as calculated from vapor pressure data) per liter of solution:

$$\mathrm{Or} = \frac{n}{\mathrm{Wu}} \rho \quad 1000 = \frac{\mathrm{Ws}/M}{\mathrm{Wu}} \rho \quad 1000$$

$$= \frac{x \rho}{M} \quad 1000 = \frac{C}{M} \quad 1000$$

$$= \frac{p^{*} - p}{p} \quad \frac{1000}{18} \quad \rho \quad (1 - x)$$

$$= \rho \ (1 - x) \ 0 = (\rho - C) \ 0 = \mathrm{Cw} \ \ 0$$

where:

Or = osmolarity, apparent g-moles of solute particles per liter of urine

0 = osmolality, apparent g-moles of solute particles per 1000 g of water

n = number of moles of solute particles = $\frac{\mathrm{Ws}}{M}$

Ws = weight of solute, g

M = apparent average molecular weight of solute particles

Wu = weight of urine, g

ρ = density of urine, g of urine per ml of urine

C = solute concentration, g of solutes per ml of urine

Cw = water concentration, g of water per ml of urine, = ρ - C

x = solute weight fraction, g of solutes per g of urine

p^{*} = vapor pressure of water, psia

p = vapor pressure of urine, psia

The variation of osmolarity at 100°F with solute weight fraction is shown in Figure 18 for chemically pretreated urine.

Osmotic Pressure

Osmotic pressure is estimated from the vapor pressure data. In practice such estimates are found to closely approximate experimental values to osmolarities of 5 and beyond (see ref. 16). The osmotic pressure was calculated at 100°F as follows:

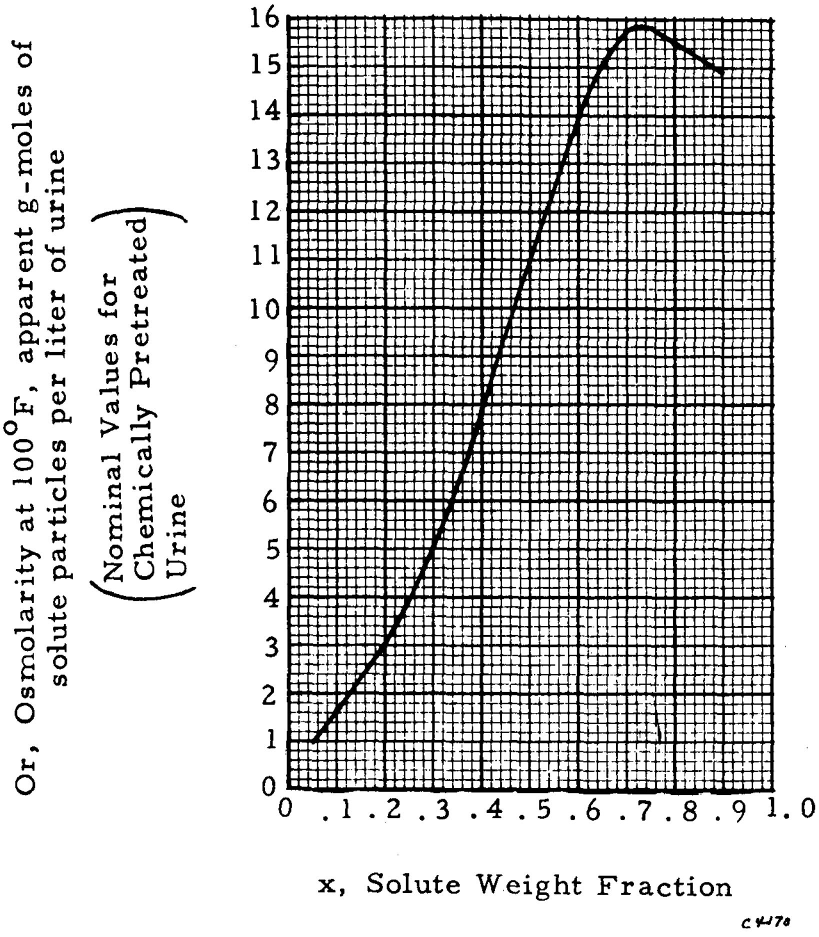

Figure 18. Osmolarity of Urine Concentrate

$$\pi = C_1 \frac{RT}{\bar{v}} \ln \frac{p^*}{p}$$

$$= 20,836 \ln \left(\frac{p^* - p}{p} + 1\right)$$

where:

π = osmotic pressure, psia

R = gas constant, $8.3144 \frac{\text{Joules}}{\text{g-mole x } ^\circ\text{K}}$

T = temperature, $311^\circ K$ ($100^\circ F$)

$\bar{v}$ = molar volume of water, $18 \frac{\text{cm}^3}{\text{g-mole}}$

C_1 = $1.4504 \times 10^{-5} \frac{\text{psia}}{\text{dyne-cm}^2}$

p^* = vapor pressure of water at $100^\circ F$, psia

p = vapor pressure of urine at $100^\circ F$, psia

The variation of osmotic pressure with solute weight fraction is shown in Figure 19.

Differential Heat of Vaporization

The following relationship between vapor pressure and heat of vaporization is derived (see ref. 17) by integration of the Clausius-Clapeyron equation:

$$\ln p = L/L^* \ln p^* + c$$

where:

p = vapor pressure of urine, psia

p^* = vapor pressure of water, psia

L = differential heat of vaporization of urine, BTU per lb of water evaporated.

L^* = heat of vaporization of pure water, BTU per lb of water evaporated

c = constant of integration

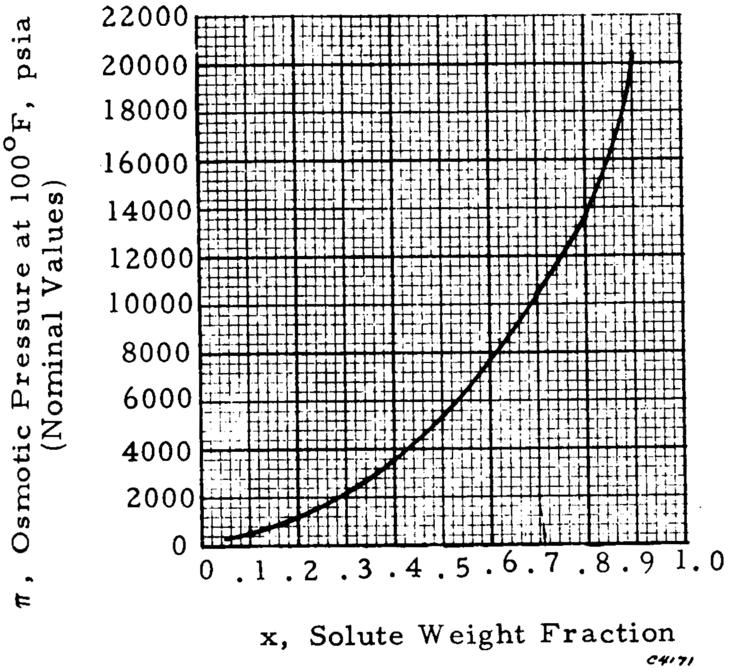

Figure 19. Osmotic Pressure of Urine Concentrate

The nominal values for L that are shown in Table IV were calculated by evaluating the above equation, over the range 80°F to 144°F, at two different pressures separated by an increment corresponding to 4°F. The calculation is made as follows:

$$\ln p_2 = L/L^* \ln p_2^* + c$$

$$\ln p_1 = L/L^* \ln p_1^* + c$$

subtracting:

$$\ln p_2 - \ln p_1 = L/L^* (\ln p_2^* - \ln p_1^*)$$

$$L/L^* = \frac{\ln (p_2/p_1)}{\ln (p_2^*/p_1^*)}$$

The differential heat of vaporization, L, is the heat required to remove a unit quantity of water from urine with an infinitesimal increase in concentration. The differential heat of vaporization, Lu, which would be required to vaporize all of the water in a unit quantity of urine without changing concentration is calculated as follows:

$$Lu = (1 - x) L$$

where:

Lu = differential heat of vaporization of urine, BTU/lb of urine

L = differential heat of vaporization of urine, BTU/lb of water

1 - x = weight fraction of water, lb of water per lb of urine

Water cannot, of course, be vaporized from urine without a change in concentration. The heat required to effect an evaporative increase in concentration is called the integral heat of vaporization, and can be evaluated by using an average value for the differential heat of vaporization in the interval of concentration under consideration.

A computer program was used to calculate nominal values of L and Lu using vapor pressure and enthalpy data for pure water (reference 15) at 4°F increments, and the equations for vapor pressure that are given in the <u>Vapor Pressure</u> section. Nominal values are tabulated in Table IV. The variation with solute weight fraction for one temperature, 90°F, is shown in Figure 20.

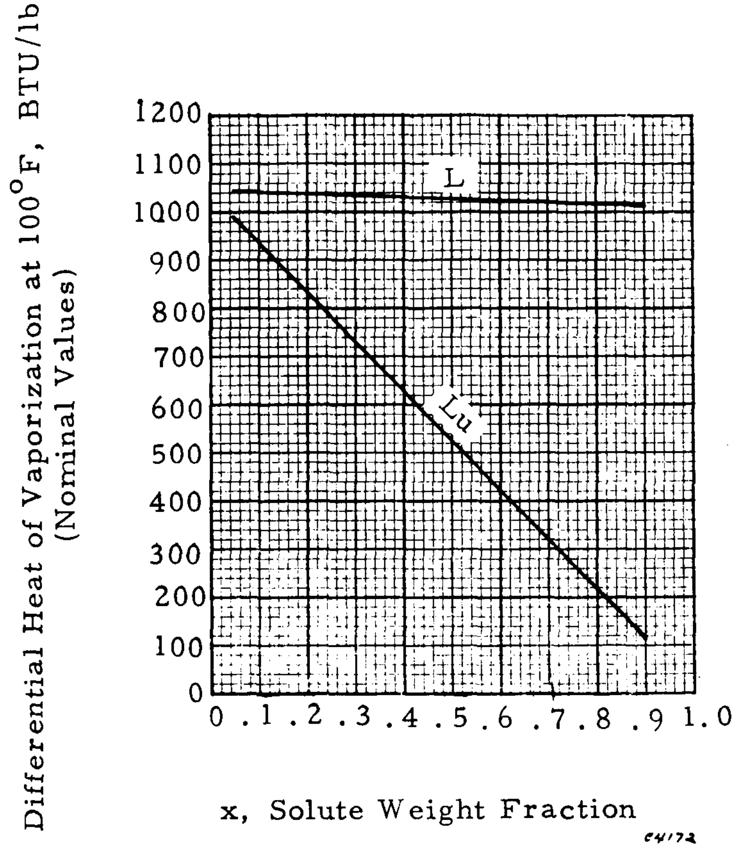

Figure 20. Differential Heat of Vaporization of Urine Concentrate

Differential Heat of Solution

The differential heat of solution and the differential heat of dilution are defined in reference 16 as follows:

> Differential heat of solution is the heat absorbed when a unit quantity of solute is added to a very large quantity of solution at a specified concentration.
>
> Differential heat of dilution is the heat absorbed when a unit quantity of solvent is added to a very large quantity of solution at a specified concentration.

The relationship between these two quantities is readily derived by considering the case in which solvent and solute are added in a proportion that causes no change in concentration. For this case the net change in energy of the solution is zero, therefore:

$$\Delta Ww \; Hw + \Delta Ws \; Hs = 0$$

and for no change in concentration, the solvent and solute must be added in the following proportion:

$$\frac{\Delta Ww}{\Delta Ws} = \frac{1 - x}{x}$$

These two expressions combine as follows:

$$Hs = -Hw \frac{1 - x}{x}$$

where:

Hs = differential heat of solution, BTU per lb of solute increase

Hw = differential heat of dilution, BTU per lb of water increase

ΔWw = water increase, lb

ΔWs = solute increase, lb

$\frac{1 - x}{x}$ = ratio of water to solutes, lb of water per lb of solute

Applying the first law of thermodynamics to the process of vaporizing water from a urine solution the following relationship is derived:

$$Hw = L^{*} - L$$

where:

H_w = differential heat of dilution, BTU per lb of water increase
L^* = heat of pure water, BTU per lb of water evaporated
L = differential heat of vaporization of urine, BTU per lb of water evaporated

The above expressions where used to compute the nominal values of Hw and Hs that are presented in Table IV. Their variation with solute weight fraction is shown in Figure 21.

Surface Tension

Surface tension was measured by the capillary rise method (see ref. 18). Nominal values of surface tension are presented in Table II. The data are plotted in Figure 22.

Specific Conductivity

The specific conductivity was measured with a small platinum electrode cell of about 5 ml capacity with a cell constant of 10 cm^{-1}. Nominal values of specific conductivity are presented in Table II. The data are plotted in Figure 23.

Viscosity

Viscosity was measured with an Ostwald viscometer (see ref. 16 and 19). Nominal values are presented in Table II. The data are plotted in Figures 24 and 25. The following empirical relationships were found:

For $x < 0.5$:

All pretreatments:

$$\mu = 0.9\, e^{\frac{3}{2}\left(\frac{x}{1-x}\right)}$$

For $x > 0.5$:

$Ca(ClO)_2$ pretreatment:

$$\mu = \frac{8}{7}\, e^{\frac{5}{4}\left(\frac{x}{1-x}\right)}$$

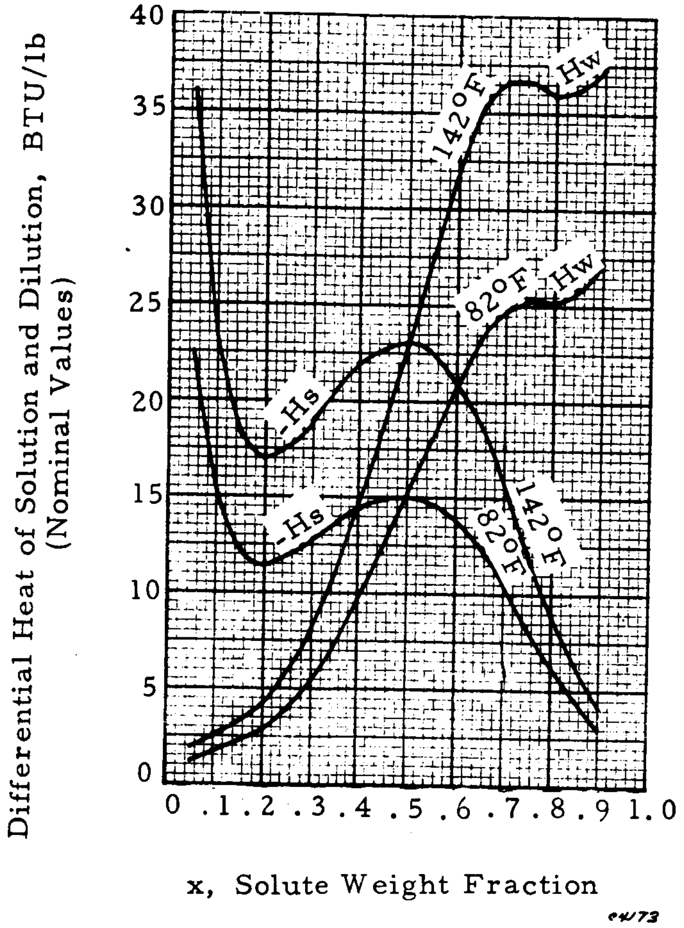

Figure 21. Differential Heat of Solution and Dilution of Urine Concentrate

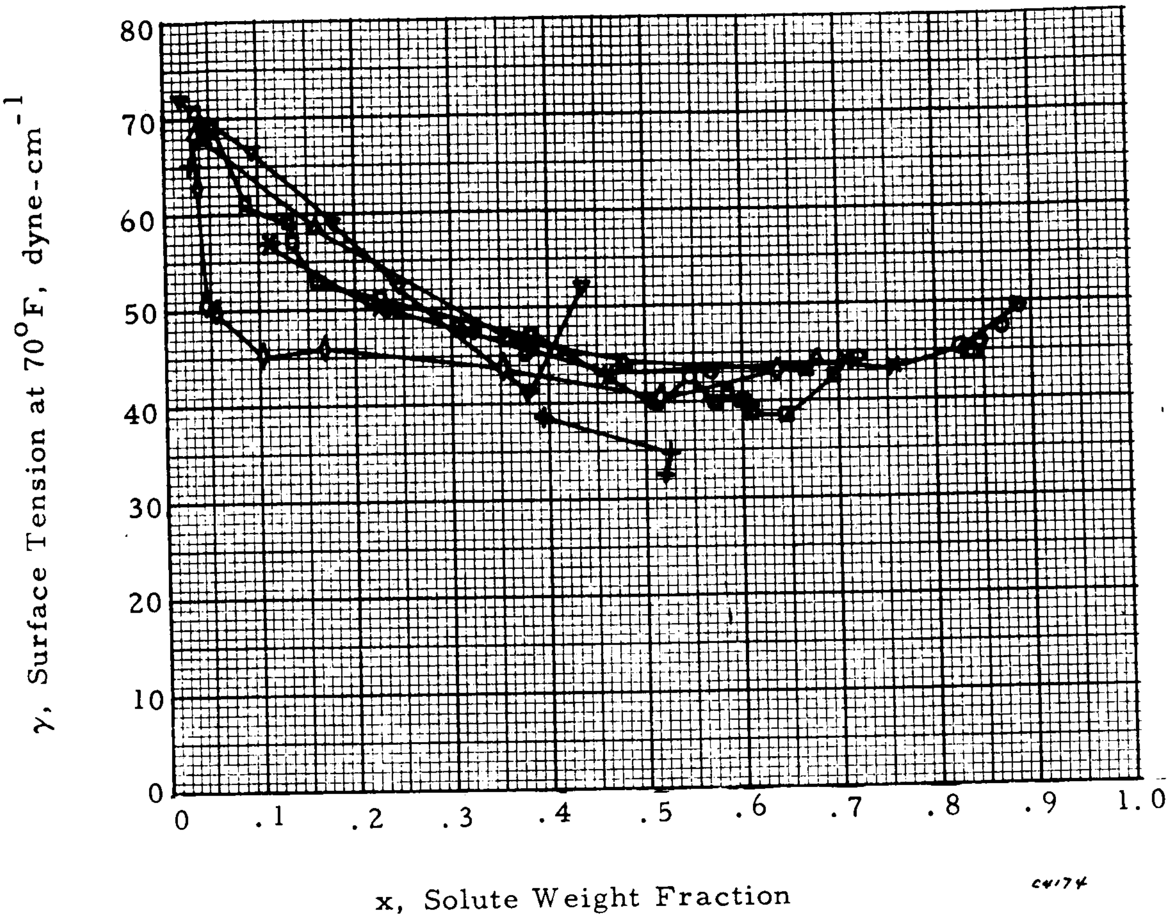

Figure 22. Surface Tension of Urine Concentrate

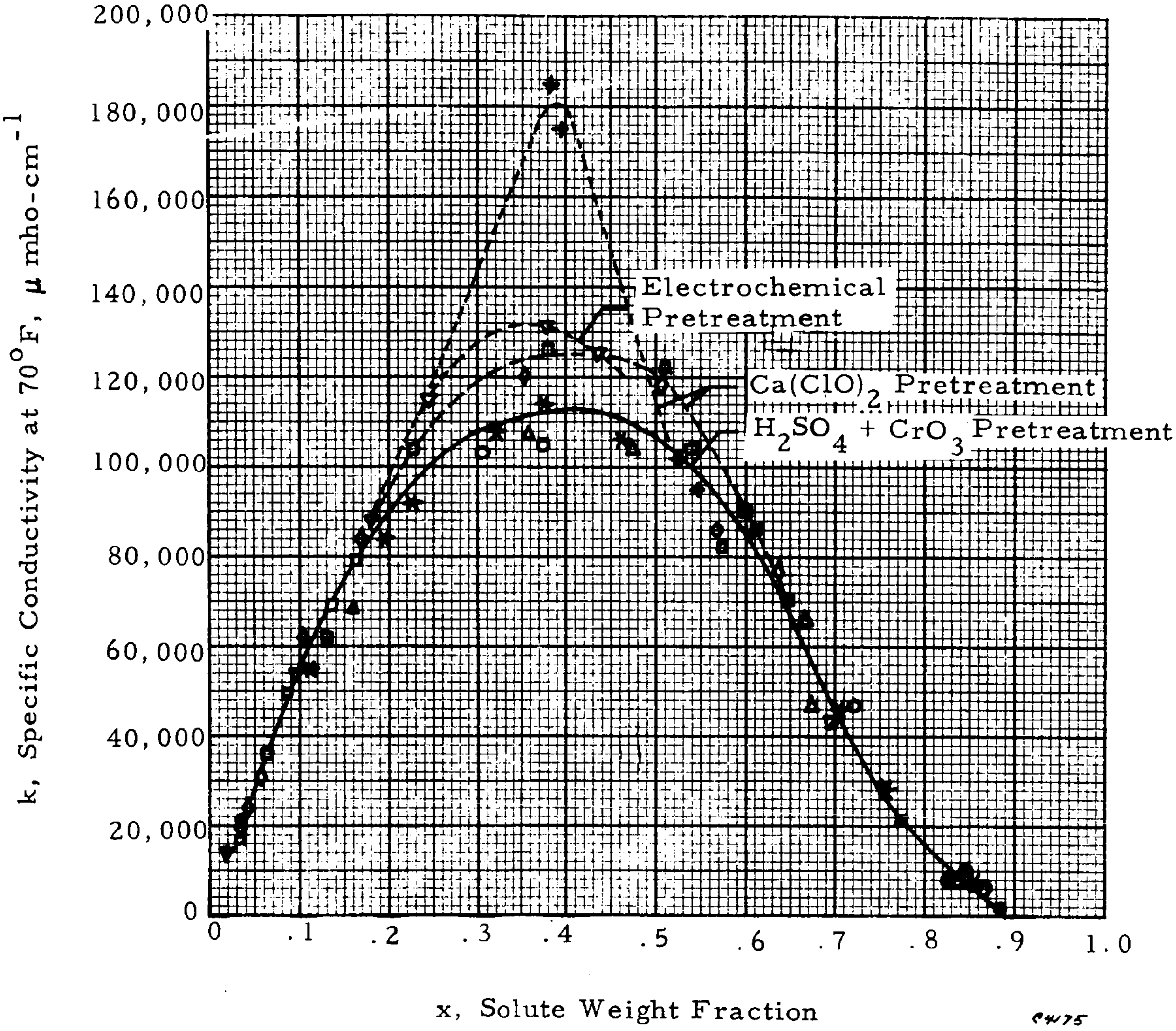

Figure 23. Specific Conductivity of Urine Concentrate

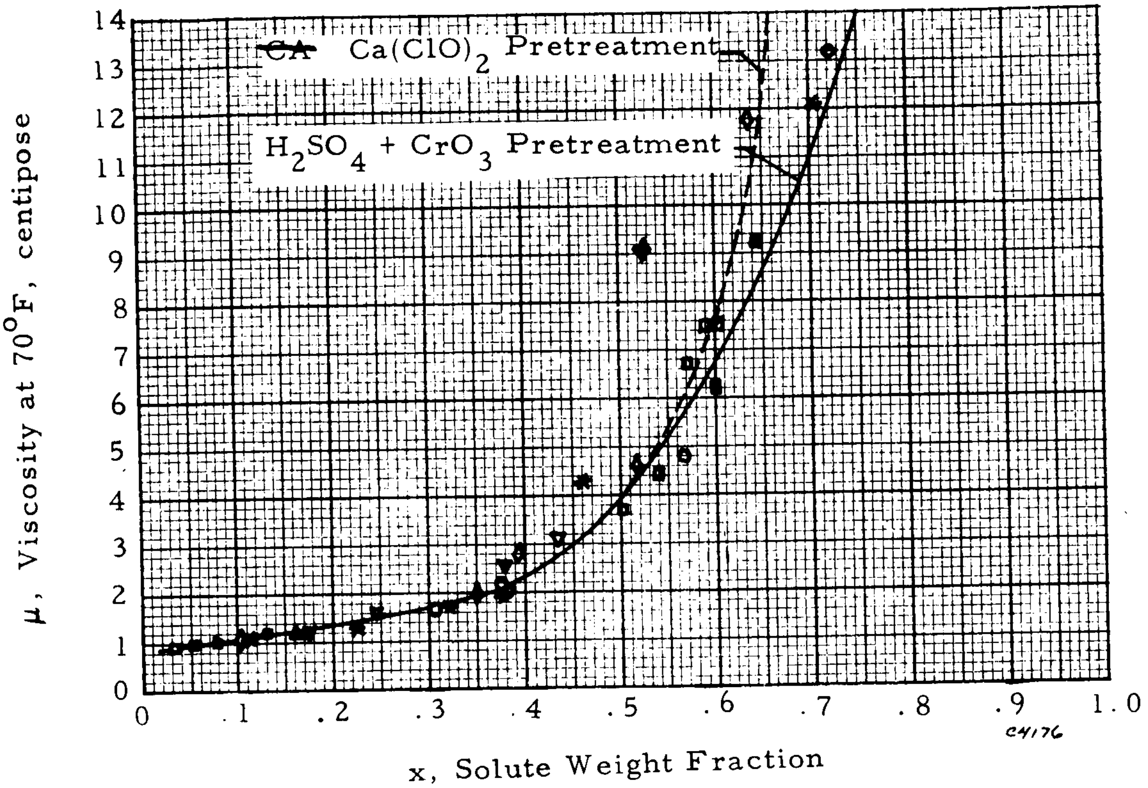

Figure 24. Viscosity of Urine Concentrate

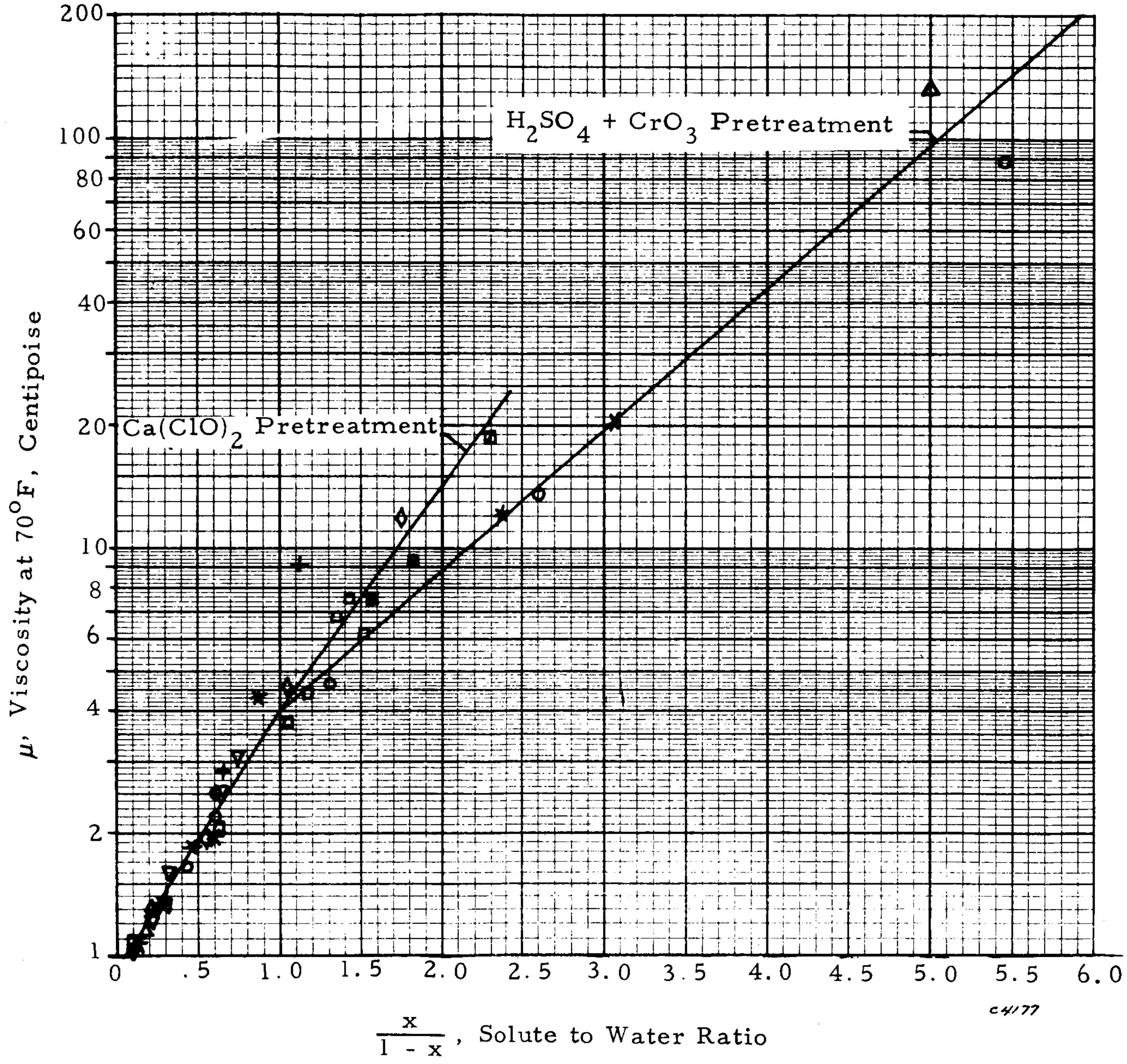

Figure 25. Viscosity as a Function of the Solute to Water Ratio

H_2SO_4 + CrO_3 pretreatment:

$$\mu = 1.8\, e^{\frac{4}{5}\left(\frac{x}{1 - x}\right)}$$

where:

μ = dynamic viscosity, centipoise

x = solute weight fraction, g of solutes per g of urine

1 - x = water fraction, g of water per g of urine

Weight Fraction of Precipitated Solids

The amount of precipitate was determined by filtering all suspended and precipitated solids from a urine sample of known size and composition. The amount of dried precipitate is reported as a fraction of the original solute content. The following definition is made:

$$\text{Weight Fraction of Precipitated Solids} = \frac{Wp}{Ws_o} = \text{g of dry precipitate per g of original solute content}$$

The data are presented in Figure 26. There is little variance in the H_2SO_4 + CrO_3 pretreatment data. $Ca(ClO)_2$ pretreatment data have a wider spread. Nominal values are presented in Table II.

Weight Fraction of Extracted Water

The weight fraction of extracted water is defined as the amount of water removed from urine during dehydration per unit weight of the original water content. The following algebraic relationship applies:

$$y = 1 - \left(1 - \frac{Wp}{Ws_o}\right) \frac{x_o}{1 - x_o} \quad \frac{1 - x}{x}$$

where:

y = weight fraction of extracted water, g of water extracted from urine per g of original water content

x = solute weight fraction, g of solutes per g of urine

1 - x = water weight fraction, g of water per g of urine

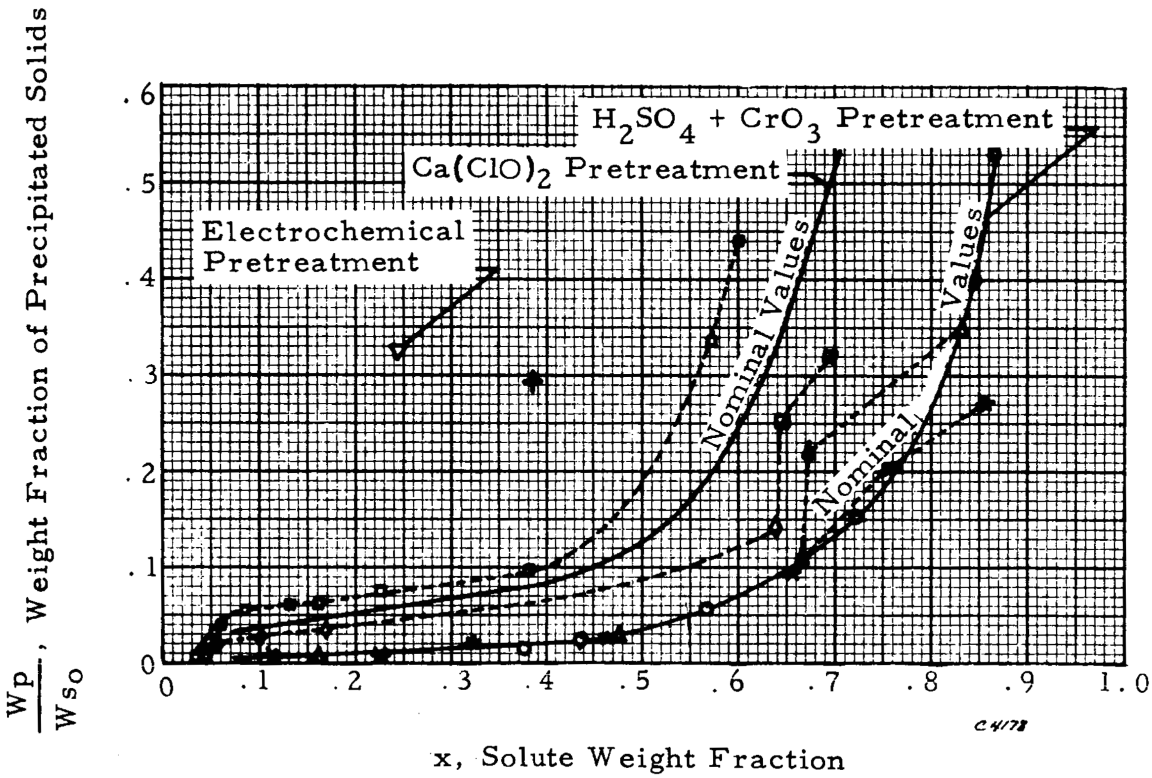

Figure 26. Weight Fraction of Solids Precipitated From Urine

x_o = original solute weight fraction, g of original solutes per g of original urine

$1 - x_o$ = original water weight fraction, g of original water per g of original urine

$\frac{Wp}{Ws_o}$ = weight fraction of precipitated solids, g of dry precipitate per g of original solute content

$1 - \frac{Wp}{Ws_o}$ = weight fraction of remaining solutes, g of solutes per g of original solute content

The data are presented in Figure 27. Nominal values are presented in Table II and in Figure 28, which shows the weight fraction of extracted water as a function of solute weight fraction for $x_o = .04$.

Refractive Index

The refractive index determinations were made at 70°F with an Abbe refractometer calibrated for sodium yellow light relative to air. The data are plotted in Figure 29 and show a straight-line relationship between refractive index and solute weight fraction up to about $x = 0.51$. At this point the slope of the line increases abruptly. Nominal values of x may be calculated with the following empirical equations and are tabulated in Table II.

For $x < 0.51$:

$$x = 6.29371\, n_i - 8.38545$$

For $x > 0.51$:

$$x = 4.12655\, n_i - 5.32242$$

where:

x = solute weight fraction, g of solute per g of urine

n_i = refractive index at 70°F relative to air for sodium yellow light

The refractive index is often plotted in the following form as shown in Figure 30:

$$\frac{1}{\rho} \quad \frac{n_i^2 - 1}{n_i^2 + 2}$$

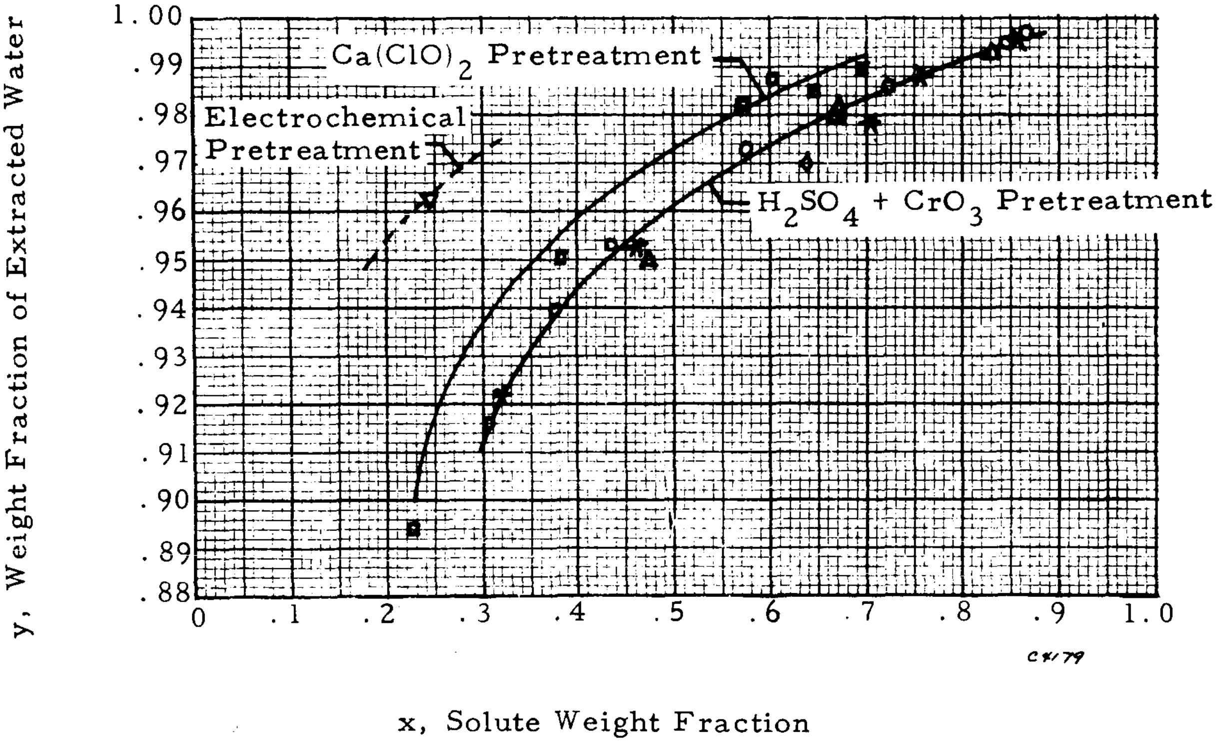

Figure 27. Weight Fraction of Water Extracted From Urine

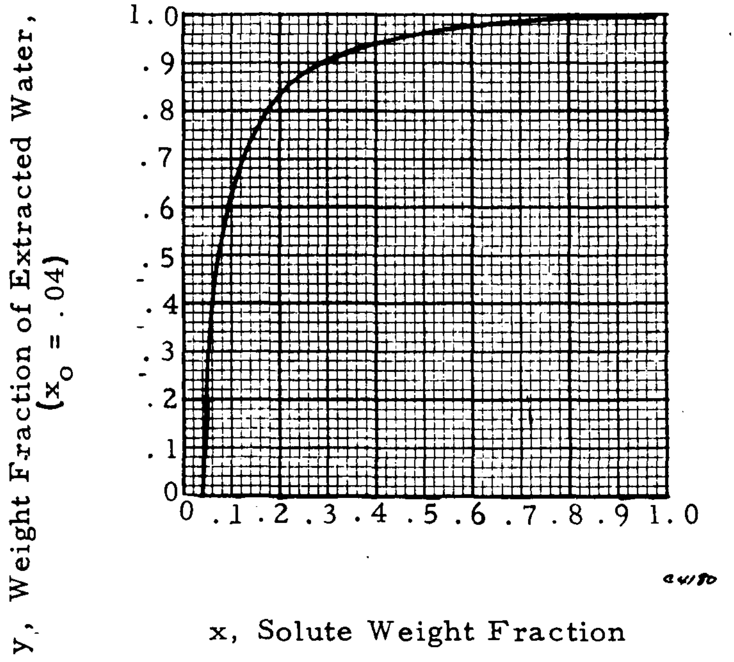

Figure 28. Weight Fraction of Extracted Water versus Solute Weight Fraction

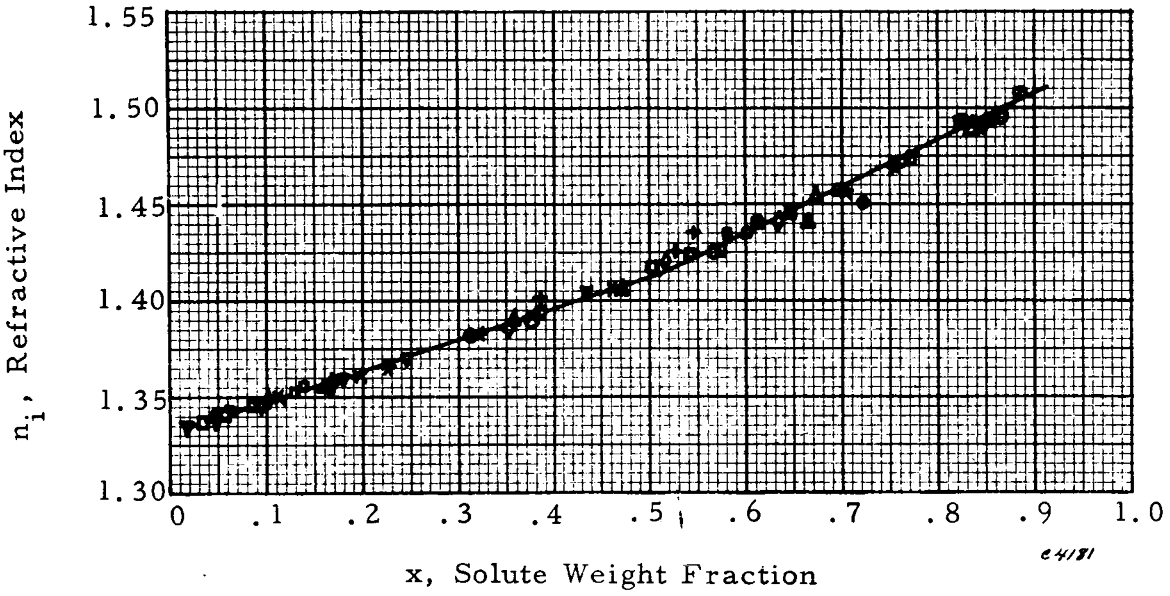

Figure 29. Refractive Index of Urine Concentrates

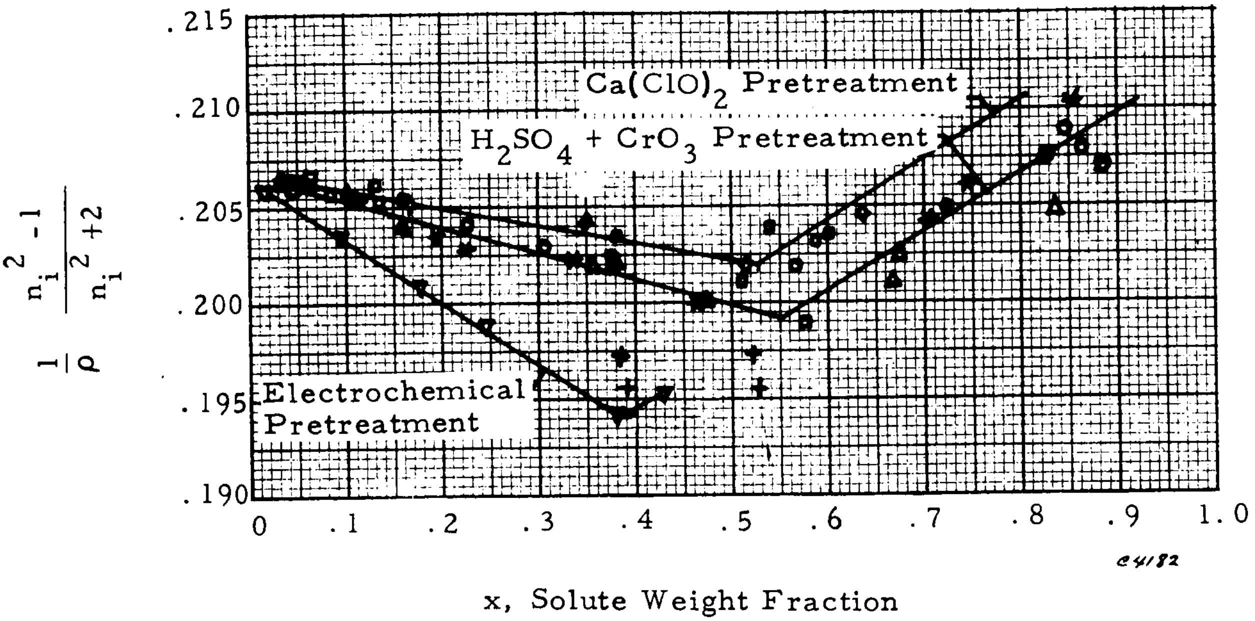

Figure 30. Linear Dependence of $\rho^{-1}\,(n_i^2-1)/(n_i^2+2)$ on Solute Weight Fraction

where:

ρ = density, g of urine per ml of urine

n_i = refractive index at 70°F relative to air for sodium yellow light

There are theoretical reasons (see ref. 20) why this parameter should exhibit linear dependence on solute weight fraction. It is interesting that for urine concentrates the parameter remains within ± 4% of the value 0.2020, for $0 < x < 0.90$, and within this narrow range it varies in straight-line relationships.

pH

pH was measured electrometrically at 70°F with a Beckman Expanded Scale pH meter. The data show that pH is primarily a function of initial pH and pretreatment. Concentration causes pH to change but little from its initial value. The data are plotted in Figure 31.

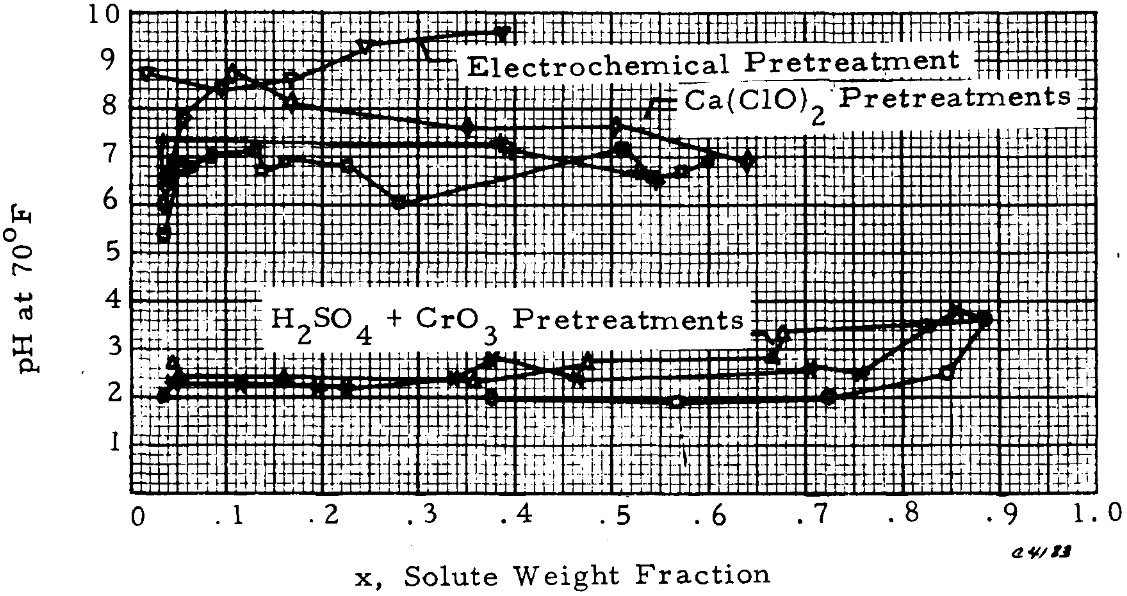

Figure 31. pH of Urine Concentrates

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