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CONVAIR ASTRONAUTICS

CONVAIR DIVISION OF GENERAL DYNAMICS CORPORATION

THE THERMODYNAMIC PROPERTIES OF SATURATED OXYGEN FROM 24°R TO 174°R

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FOREWORD

There are several problem areas in the Centaur program that require the use of the thermodynamic properties of saturated oxygen at very low temperature and pressures. The results of the study contained in this report are the graphical and tabular thermodynamic properties of saturated oxygen in the temperature range from 24°R to 174°R.

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SUMMARY

There are several problem areas in the Centaur program which require the thermodynamic properties of saturated oxygen at low pressures and temperature. The work documented in this report consists of graphical and tabular data for vapor pressures and temperatures, specific weights and volumes, specific entropy, and specific enthalpy for saturated oxygen in the temperature range from 24°R to 176°R. Figure 1 is a plot of the tabular data in Table 1 in the temperature entropy plane. The tabular data in Table 1 is presented as a function of saturation temperature in 2°R increments.

INTRODUCTION

Several problem areas in the Centaur program require knowledge of the thermodynamic properties of oxygen at low pressures and temperatures. The expansion of liquid oxygen (LOX) into extremely low back pressures results in the formation of solid oxygen (SOX) which could result in plugging valves, lines or orifices. The expansion of residual oxygen from the engine system through the engine nozzle after main engine shut down cause small additional impulses to the vehicle system. These types of problems require the use of the thermodynamic properties of saturated oxygen at low pressure.

Using experimental data contained in References (1), (2) and (3) and standard thermodynamic equations the following saturated properties were determined for the temperature range from 24°R to 174°R.

(a) Pressure
(b) Specific weight of liquid and solid
(c) Specific volume of gas
(d) Specific entropy of liquid and gas
(e) Specific enthalpy of liquid and gas

The results of this work are shown in tabular form in Table 1 and in graphical forms in the temperature entropy plane in Figure 1.

DISCUSSION

The basic equation for the relationship between temperature, pressure, specific volume, and entropy used in calculating the thermodynamic properties is

$$Tds = CpdT - \frac{\beta vTdp}{J} \qquad (1)$$

where T = Absolute temperature - °Rankine
s = Specific entropy - Btu/lb-°R
Cp = Specific heat - Btu/lb-°R
v = Specific volume - ft^3/lb.
p = Absolute pressure - lbs/ft^2
J = Mechanical equivalent of heat - 778.26 ft-lbs/Btu
$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p$

The saturation temperature-pressure relationship given in Reference 1 is

$$\ln P = 19.71451 - \frac{1738.20767}{T} - .008289T \qquad (2)$$

where
lnP = Logarithm of P to the base e
P = Saturation Pressure - lbs/ft^2 abs.
T = Absolute temperature - °R

The relation between pressure, volume, and temperature of the gas is

$$Pv = ZRT \qquad (3)$$

REFERENCES

1. Giauque, W. F. and Johnston, H. L., "The Heat Capacity of Oxygen from 12°K to its Boiling Point and its Heat of Vaporization. The Entropy From Spectrocopic" Journal of the American Chemical Society, Vol LI, July-December 1929, pages 2300-2321.

2. Tkachenko, E. A., "Pressure-Density-Temperature Relationship for Liquid Oxygen by a Generalized Equation of State" LEM 941-142, 20 Oct. 1959.

3. Liquid Propellants Handbook, Battelle Memorial Institute.

4. Sears, F. W. "An Introduction to Thermdoynamics, The Kinetic Theory of Gases, and Statistical Mechanics", Addison-Wesley Press, Inc. 1950, pgs 147-153.

TABLE I

Temp T-°R	Pressure P-lbs/ft^2	Specific Wt. Solids ρ_s-lbs/ft^3	Specific Volume v_g-ft^3/lb	Entropy Btu/lb-°R s_s	s_{sg}	s_g	Enthalpy Btu/lbs. h_s	h_{sg}	h_g
24	1.0510×10^{-23}	91.166	1.10232×10^{26}	0	4.593973	4.593973	0	110.255352	110.255352
26	2.7160×10^{-21}	91.014	4.62191×10^{23}	.003520	4.263269	4.266789	0880	110.844994	110.932994
28	3.1667×10^{-19}	90.862	4.26905×10^{21}	007409	3.980280	3.987689	.193	111.447840	111.640840
30	1.9533×10^{-18}	90.710	7.45153×10^{20}	.011685	3.735291	3.746976	.317	112.058730	112.375730
32	7.1824×10^{-16}	90.558	2.15109×10^{18}	.016362	3.521026	3.537388	.462	112.672283	113.134283
34	1.7248×10^{-14}	90.406	9.51709×10^{16}	021423	3.331955	3.353378	.629	113.286470	113.915470
36	2.9042×10^{-13}	90.254	5.98488×10^{15}	027052	3.163587	3.190639	.826	113.889132	114.715132
38	3.6264×10^{-12}	90.102	5.05926×10^{14}	033187	3.012573	3.045760	1.053	114.477774	115.530774
40	3.5120×10^{-11}	89.950	5.49900×10^{13}	039777	2.876296	2.916073	1.310	115.051840	116.361840
42.59	4.8296×10^{-10}	89.753	4.25770×10^{12}	048988	2.718122	2.767110	1.691	115.764816	117.455816
42.59	4.8296×10^{-10}	89.753	4.25770×10^{12}	038596	2.688514	2.767110	2.952	114.503811	117.455816
44	1.7655×10^{-9}	89.646	1.20327×10^{12}	083807	2.609976	2.693783	3.178	114.838944	118.016944
46	9.6732×10^{-9}	89.494	2.29597×10^{11}	091274	2.506650	2.597924	3.514	115.305900	118.819900
48	4.5936×10^{-8}	89.342	5.04506×10^{10}	098827	2.411707	2.510534	3.869	115.761936	119.630936
50	1.9232×10^{-7}	89.190	1.25523×10^{10}	.106439	2.324141	2.430580	4.242	116.207050	120.449050
52	7.2031×10^{-7}	89.038	3.48549×10^{9}	.114106	2.243084	2.357190	4.633	116.640368	121.273368
54	2.4434×10^{-6}	88.886	1.06703×10^{9}	.121842	2.167780	2.289622	5.043	117.060120	122.103120
56	7.5868×10^{-6}	88.734	3.56376×10^{8}	.129660	2.097582	2.227242	5.473	117.464592	122.937592
58	2.1762×10^{-5}	88.582	1.28679×10^{8}	.137572	2.031930	2.169502	5.924	117.851940	123.775940
60	5.8123×10^{-5}	88.430	4.98405×10^{7}	.145589	1.970342	2.115931	6.397	118.220520	124.617520
62	1.4555×10^{-4}	88.278	2.05664×10^{7}	.153687	1.912429	2.066116	6.891	118.570598	125.461598
64	3.4379×10^{-4}	88.126	8.98805×10^{6}	.161846	1.857852	2.019698	7.405	118.902528	126.307528
66	7.7006×10^{-4}	87.974	4.13807×10^{6}	.170092	1.806270	1.976362	7.941	119.213820	127.154820
68	1.6433×10^{-3}	87.822	1.99789×10^{6}	.178435	1.757394	1.935829	8.500	119.502792	128.002792
70	3.3552×10^{-3}	87.670	1.00730×10^{6}	.186870	1.710984	1.897854	9.082	119.768880	128.850880
72	6.5777×10^{-3}	87.518	5.28490×10^{5}	.195405	1.666813	1.862218	9.688	120.010536	129.698536
74	1.2423×10^{-2}	87.366	2.87596×10^{5}	.204021	1.624706	1.828727	10.317	120.228244	130.545244
76	2.2672×10^{-2}	87.214	1.61846×10^{5}	.212741	1.584467	1.797208	10.971	120.419492	131.390492
78.77	4.9524×10^{-2}	87.003	7.67933×10^{5}	.223262	1.533261	1.756523	11.783	120.774969	132.557969
78.77	4.9524×10^{-2}	87.003	7.67933×10^{5}	.350087	1.406436	1.756523	21.773	110.784964	132.557969
80	6.8820×10^{-2}	86.910	5.61247×10^{4}	.355425	1.384052	1.739477	22.197	110.724160	132.921160
82	1.150×10^{-1}	86.758	3.44266×10^{4}	.363931	1.349069	1.713000	22.886	110.623658	133.509658
84	1.874×10^{-1}	86.606	2.16416×10^{4}	.372232	1.315727	1.687959	23.575	110.521068	134.096068
86	2.981×10^{-1}	86.454	1.39288×10^{4}	.380337	1.283914	1.664251	24.264	110.416604	134.680604
88	4.643×10^{-1}	86.302	9.15087×10^{3}	.388257	1.253525	1.641782	24.953	110.310200	135.263200
90	7.083×10^{-1}	86.150	6.13484×10^{3}	.395999	1.224469	1.620468	25.642	110.202210	135.844210
92	1.0601	85.998	4.19006×10^{3}	.403570	1.196494	1.600064	26.331	110.077448	136.408448
94	1.5586	85.846	2.91187×10^{3}	.410979	1.169853	1.580832	27.020	109.966182	136.986182
96	2.2534	85.694	2.05689×10^{3}	.418232	1.144308	1.562540	27.709	109.853568	137.562568
97.9	3.1522	85.549	1.49950×10^{3}	.424983	1.121997	1.546490	28.364	109.843506	138.207506

TABLE I (CONT.)

Temp T-°R	Pressure P-lbs/ft^2	Specific Wt. Liquid ρ_l-lb/ft^3	Specific Volume vg-ft^3/lb	Entropy Btu/lb-°R s_f	s_{fg}	s_g	Enthalpy Btu/lb h_f	h_{fg}	h_g
97.9	3.1522	81.95	1.49950×10^3	.486056	1.060924	1.546980	34.343	103.864596	138.207506
100	4.4976	81.55	1.07349×10^3	.494528	1.035017	1.529545	35.181	103.501700	138.682700
102	6.1460	81.20	8.01284×10^2	.502418	1.011319	1.513737	35.978	103.154538	139.132538
104	8.4900	80.85	5.91431×10^2	.510146	.988512	1.498658	36.774	102.805248	139.579248
106	11.447	80.50	4.47087×10^2	.517720	.966546	1.484266	37.569	102.453876	140.022876
108	15.253	80.18	3.41859×10^2	.525148	.945373	1.470521	38.364	102.100284	140.464284
110	20.102	79.90	2.64200×10^2	.532437	.924950	1.457387	39.159	101.744500	140.903500
112	26.218	79.60	2.06231×10^2	.539594	.905229	1.444823	39.953	101.385648	141.338648
114	33.856	79.20	1.62540×10^2	.546625	.887179	1.433804	40.748	101.138406	141.886406
116	43.313	78.95	1.29254×10^2	.553535	.868759	1.422294	41.543	100.776044	142.319044
118	54.918	78.62	1.03678×10^2	.560329	.850798	1.411127	42.338	100.394164	142.732164
120	69.046	78.30	83.844	.567011	.833702	1.400713	43.133	100.044240	143.177240
122	86.112	78.00	68.334	.573586	.817007	1.390593	43.929	99.674854	143.603854
124	106.58	77.65	56.105	.580060	.800830	1.380890	44.725	99.302920	144.027920
126	130.95	77.35	46.386	.586434	.785142	1.371576	45.522	98.927892	144.449892
128	159.78	77.00	38.609	.592712	.769926	1.362638	46.319	98.550528	144.869528
130	193.66	76.70	32.345	.598897	.755168	1.354065	47.117	98.171840	145.288840
132	233.25	76.35	27.260	.604992	.740836	1.345828	47.915	97.790352	145.705352
134	279.24	76.00	23.104	.611001	.726902	1.337903	48.714	97.404868	146.118868
136	332.38	75.70	19.694	.616925	.713376	1.330301	49.514	97.019136	146.533136
138	393.44	75.40	16.870	.622768	.700202	1.322970	50.316	96.627876	146.943876
140	463.26	75.03	14.525	.628530	.687391	1.315921	51.118	96.235580	147.353580
142	542.71	74.60	12.566	.634216	.674920	1.309136	51.922	95.838640	147.760640
144	632.70	74.37	10.920	.639828	.662775	1.302603	52.726	95.439600	148.165600
146	734.20	74.02	9.5319	.645367	.650944	1.296311	53.530	95.037824	148.567824
148	848.18	73.70	8.3547	.650837	.639412	1.290249	54.335	94.632976	148.967976
150	975.65	73.37	7.3509	.656239	.628156	1.284395	55.141	94.223400	149.364400
152	1117.7	73.03	6.4944	.661573	.617197	1.278770	55.948	93.813944	149.761944
154	1275.3	72.90	5.7585	.666842	.606498	1.273340	56.756	93.400692	150.156692
156	1449.6	72.54	5.1241	.672048	.596055	1.268103	57.565	92.984580	150.549580
158	1641.8	72.17	4.5744	.677193	.585853	1.263046	58.375	92.564774	150.939774
160	1852.8	71.80	4.0968	.682278	.575881	1.258159	59.185	92.140960	151.325960
162	2083.9	71.44	3.6801	.687304	.566132	1.253436	59.996	91.713384	151.709384
164	2336.2	71.08	3.3148	.692273	.556584	1.248857	60.808	91.279776	152.087776
166	2610.8	70.69	2.9946	.697187	.547411	1.244598	61.622	90.870226	152.492226
168	2908.8	70.31	2.7132	.702046	.538412	1.240458	62.437	90.453216	152.890216
170	3231.3	69.93	2.4639	.706852	.529619	1.236471	63.253	90.035230	153.288230
172	3577.0	69.55	2.2438	.711606	.520937	1.232543	64.070	89.601164	153.671164
174	3954.2	69.16	2.0460	.716310	.512447	1.228757	64.888	89.165778	153.872778
176	4356.7	68.77	1.8605	.720966			65.707		