LA--11896-MS

DE90 014409

A Literature Review on the Chemical and Physical Properties of Uranyl Fluoride (UO_2F_2)

*W. L. Myers**

**Staff Research Assistant at Los Alamos. Department of Nuclear Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801.*

MASTER

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

A LITERATURE REVIEW ON THE CHEMICAL AND PHYSICAL PROPERTIES OF URANYL FLUORIDE (UO_2F_2)

by

W. L. Myers

ABSTRACT

This report reviews the preparation and properties of uranyl fluoride. Data are given on the crystal structure, solubility in water, specific gravity, density, specific heat, enthalpy, entropy, acidity, corrosion properties, and refractive indices. Empirical formulas are given to calculate specific gravity, density of aqueous solutions, molal volume, and refractive indices.

INTRODUCTION

This report reviews the literature on uranyl fluoride in order to consolidate the information in a reference that could be of aid in studying and designing the reactor SHEBA II. The main emphasis of the search is the physical and chemical properties of uranyl fluoride that would be of interest from a practical engineering standpoint. Some important physical properties of uranyl fluoride solutions, where no data were found, were viscosity, thermal conductivity, and surface tension. It will be difficult to accurately model the hydrodynamic and reactor kinetic feedback characteristics of SHEBA II without these properties.

GENERAL DESCRIPTION

Anhydrous difluorouranyl (UO_2F_2) is a light-yellow, very hygroscopic substance[1,2,3] that is stable in air up to ~300°C.[1] Upon heating, it undergoes thermal decomposition, so its melting point is not known.[1] It decomposes completely to U_3O_8 at temperatures of about 800°C.[1] Uranyl fluoride is a very attractive fuel solute because of the low neutron-capture cross section of fluorine.[4]

CRYSTAL STRUCTURE

Early work[5] with uranyl fluoride indicated that two forms had been isolated: α-uranyl fluoride, having the formula $UO_2F_2 \cdot 2H_2O$ (diaquodifluorouranyl), and the β form, UO_2F_2 (anhydrous difluorouranyl). I. I. Chernyaev[6] suggested that other crystalline forms can exist. These include $UO_2F_2 \cdot H_2O$ (monoaquodifluorouranyl), $UO_2F_2 \cdot 3H_2O$ (triaquodifluorouranyl), and possibly $UO_2F_2 \cdot 4H_2O$ (tetraaquodifluorouranyl).

Anhydrous UO_2F_2 crystallizes in sheets[6] that have a structure similar to the $UO_2O_2^{--}$ layers in calcium urinate, except that the UO_2F_2 layer is slightly more expanded than the $UO_2O_2^{--}$ layer. The structure consists of layers of uranium atoms 5.22 Å apart.[2,3] Each uranium atom is thus surrounded by two oxygen atoms at a distance of 1.91 Å and by six fluorine atoms at a distance of 2.50 Å.[2,3,6] M. S. Katz[5] described the structure as a stack of identical layers having a separation of 5.228 Å, with each uranium atom surrounded by two oxygen atoms at a distance of about 1.3 Å and by six fluorine atoms at a distance of 2.42 Å. The uranium layers are held together by weak O-O and O-F bonds.[2,3,6] Actual samples of UO_2F_2 all show varying degrees of stacking disorder with the planes displaced relative to each other.[3]

The ideal crystal structure of UO_2F_2 is rhombohedral[1,3,6] with one molecule per unit cell. The unit cell has dimensions a = 5.755 ± 0.003 Å and α = 42°47′ ± 3′.[1,3] Chernyaev[6] gave a slight variation in the unit cell dimensions as a = 5.764 ± 0.001 Å and α = 42°43′ ± 3′. The space group is $R\bar{3}m$,[1,3,6] with the following atomic positions[3]:

1 U in (0 0 0),

2 O in ± (u u u) with u = 0.122, and

2 F in ± (v v v) with v = 0.294

A clever interpretation of the structure of UO_2F_2 was proposed by Belov[6] (see Fig. 1).

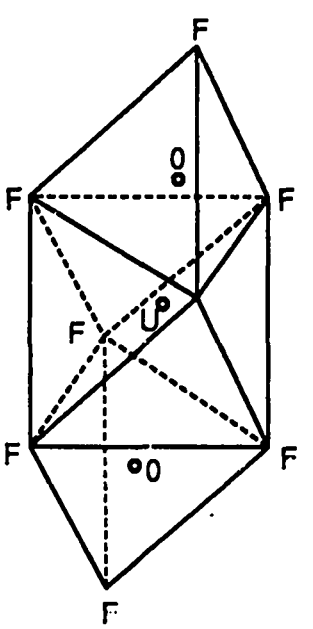

Fig. 1. The Rhombohedral Crystal Structure of Anhydrous Uranyl Fluoride.[6]

M. S. Katz[5] reported the UO_2F_2 compound is hexagonal with two molecules of uranyl fluoride in the ideal cell. This ideal cell has dimensions $a_1 = 4.198 \pm 0.002$ Å and $a_3 = 10.456 \pm 0.006$ Å. The atomic positions are

2 U in $\pm$(1/3 2/3 1/4),

4 O in $\pm$(1/3 2/3 u) (1/3 2/3 1/2-u) with u ≈ 0.08,

2 F in $\pm$(0 0 1/4), and

2 F in $\pm$(1/3 2/3 3/4) .

PREPARATION

Chemically pure anhydrous uranyl fluoride is prepared on a commercial scale by passing anhydrous HF gas over chemically pure anhydrous uranium trioxide at 350-500°C.[3,5,6]

$$UO_3 + 2HF \xrightarrow{350\text{-}500^\circ C} UO_2F_2 + H_2O$$

The reaction takes place in a reactor[5] that is a horizontal iron tube (~7 in. i.d. by 9 ft long) with a magnesium liner. The liner (a 1/8-in. magnesium sheet) has a crack running the length of the bottom to allow for heat expansion. For operation, four 9-ft trays of aluminum containing the uranium trioxide are slid into the tube through the rear end, which is then closed by a removable cap grooved to receive the end of the tube. A calcium fluoride paste in the groove seals the cap in place. The front end is closed except for a 1/2-in. feedline for the HF gas. Once the gas enters the reaction chamber, it passes through a baffle system, flows over the trays, and finally exits through the rear of the chamber.

The reactor is introduced into a furnace, and the process is started by warming the furnace to ~300°C, while CO_2 gas passes through the chamber. The HF gas is then turned on, and the temperature is slowly allowed to approach 400°C in the hottest part of the furnace. After the reaction is complete, the HF gas is displaced by CO_2, and the reactor tube (through which CO_2 is constantly passing) is removed from the hot furnace and placed on a rack to cool. After the mass has cooled to room temperature, the rear cap is removed, and the trays are quickly taken out and emptied into a receptacle.

In another reaction, a known amount of U_3O_8 or of hydrated peroxide is dissolved in a calculated amount of hydrofluoric acid,[3,6]

$$U_3O_8 + 8HF \rightarrow UF_4 + 2UO_2F_2 + 4H_2O \quad ,$$

and the resulting solution is evaporated to dryness. The product (UO_2F_2) ordinarily has a higher uranium content[3] than that calculated for a neutral salt. Therefore, hydrofluoric acid is added to the product in an amount equal to the uranium excess, and water in an amount sufficient to dissolve the salt. Then the salt is recrystallized. The crystals obtained by this method are apparently the dihydrate $UO_2F_2 \bullet 2H_2O$.

Uranyl fluoride is difficult to crystallize[3] because viscous syrups are formed on concentration. Even if uranyl fluoride dihydrate crystals can be induced to form, separation of the crystals from the mother liquor is usually very difficult. The crystals of uranyl fluoride dihydrate are soft, thin, pale-yellow plates that are so hygroscopic that it is difficult to dry them.

Some other reactions where uranyl fluoride is one of the products are

$$Na_2UO_4 + 4HF \rightarrow UO_2F_2 + 2NaF + 2H_2O$$

and

$$2UF_4 + O_2 \rightarrow UF_6 + UO_2F_2 \quad .$$

For further details about preparation and other reactions with UO_2F_2 as the product, consult Refs. 1, 2, 3, 5, and 6.

SOLUBILITY

Uranyl fluoride is readily soluble in water, methyl alcohol, and ethyl alcohol[2,5,6]; unlike the other uranyl halides, it is insoluble in ether or amyl alcohol.[2] The solubility of uranyl fluoride in water was reported by Kunin[3,7] (see Table I) for the SAM carbide and carbon 1 study, by Eidinoff[5] (see Table II) for the SAM Columbia 2 study, and in a much more complete manner by Marshall, Gill, and Secoy[7] (see Table III and Fig. 2).

TABLE I. Solubility of Uranyl Fluoride in Water[3,7,8]

Temperature °C	UO_2F_2 Wt %	UO_2F_2 Mole Fraction
1.0	61.4	0.0862
25.0	65.6	0.100
60.0	71.0	0.125
100.0	74.1	0.143

TABLE II. Solubility of Uranyl Fluoride in Water[3,5,6,7]			
Temperature °C	% by Weight	Mols/liter	Density (g/ml)
25.0	67.3	5.18 ± 0.02	2.405
75.0	69.6	5.59	2.472
99.9	72.4	6.08	2.588

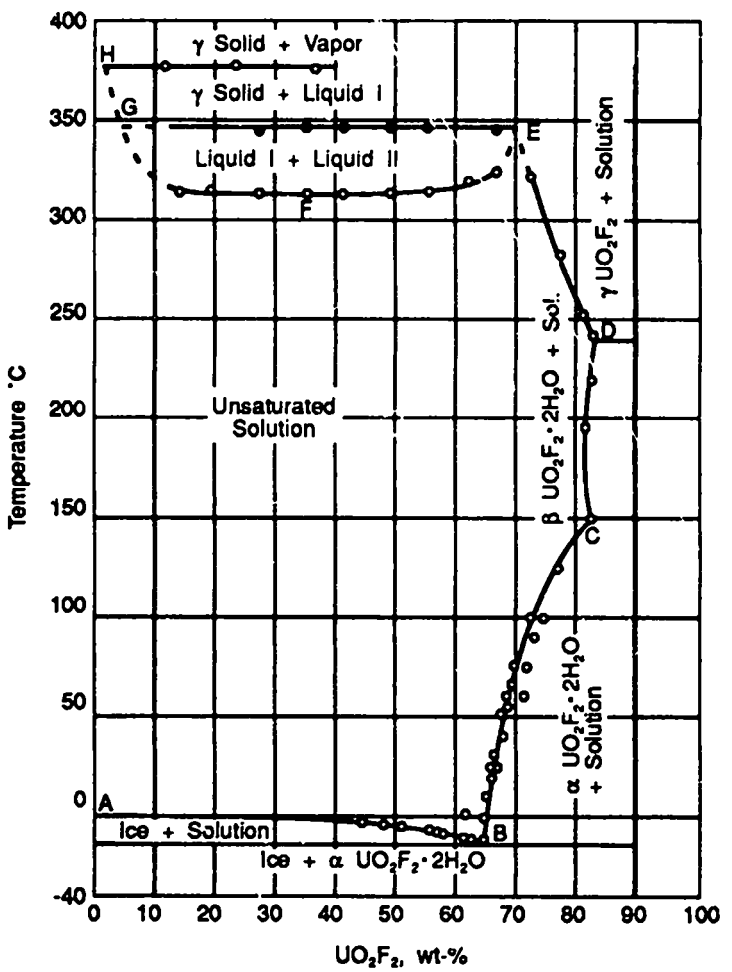

Fig. 2. The System Uranyl Fluoride - Water.[7]

TABLE III. The System Uranyl Fluoride - Water[7]				
UO_2F_2, wt-%	Temp., °C	Equilibrium phases*	Invariant temp., °C (S_α-L_1-L_2-V)	Critical temp., °C (L_1-V)
44.23	-4.2	S_I-L-V	--	--
47.72	-5.0	S_I-L-V	--	--
50.76	-5.9	S_I-L-V	--	--
55.49	-7.8	S_I-L-V	--	--
57.28	-8.1	S_I-L-V	--	--
58.54	-9.2	S_I-L-V	--	--
61.20	-10.9	S_I-L-V	--	--
62.58	-11.9	S_I-L-V	--	--
64.25†	-13.2†	S_I-S_α-L-V	--	--
64.28	-10.7	S_α-L-V	--	--
64.30	0.0	S_α-L-V	--	--
64.40	10.1	S_α-L-V	--	--
66.09	19.7	S_α-L-V	--	--
66.50	30.5	S_α-L-V	--	--
67.78	39.8	S_α-L-V	--	--
67.25	51.2	S_α-L-V	--	--
68.45	54.3	S_α-L-V	--	--
68.42	60.1	S_α-L-V	--	--
69.37	65.8	S_α-L-V	--	--
71.73	75.0	S_α-L-V	--	--
73.02	89.8	S_α-L-V	--	--
76.98	125	S_α-L-V	--	--
81.72	150	S_α-S_β-L-V	--	--
81.40	195	S_β-L-V	--	--

TABLE III. The System Uranyl Fluoride - Water[7] (cont)				
UO_2F_2, wt-%	Temp., °C	Equilibrium phases*	Invariant temp., °C (S_α-L_1-L_2-V)	Critical temp., °C (L_1-V)
82.61	219	S_β-L-V	--	--
83.0†	240†	S_β-S_A-L-V	--	--
82.53	243	S_α-L-V	--	--
81.22	252	S_α-L-V	--	--
77.05	283	S_α-L-V	--	--
72.31	322	S_α-L-V	--	--
70.5†	347†	S_α-L_1-L_2-V	--	--
66.46	324	L_1-L_2-V	344	--
61.98	320	L_1-L_2-V	--	--
55.13	314	L_1-L_2-V	347	--
49.24	314	L_1-L_2-V	347	--
40.98	313	L_1-L_2-V	347	--
36.1	--	--	--	376
34.76	313	L_1-L_2-V	347	--
26.75	313	L_1-L_2-V	344	--
23.0	--	--	--	378
19.36	314	L_1-L_2-V	--	--
13.86	313	L_1-L_2-V	--	--
10.85				

*S_I = solid ice; S_α = solid $\alpha \bullet UO_2F_2 \bullet 2H_2O$; S_β = solid $\beta UO_2F_2 \bullet 2H_2O$; S_A = solid $\alpha\ UO_2F_2 \bullet XH_2O$

L = saturated solution; L_1 = H_2O-rich liquid; L_2 = UO_2F_2-rich liquid; V = vapor
† Extrapolated values

A portion of the acid-rich system, UO_2F_2-HF-H_2O, has been studied at 25°C by Kunin[7] (see Table IV and Fig. 3).

TABLE IV. The System UO_2F_2-HF-H_2O at 25°C[7]

Liquid Phase			Specific Gravity	Wet Solid		
HF,%	UO_2F_2,%	H_2O,%		HF,%	UO_2F_2,%	H_2O,%
0.0	65.55	34.45	2.224	...	...	...
1.28	47.58	51.14	...	...	...	...
3.59	39.78	56.63	...	...	...	...
9.78	32.25	57.97	1.430	...	...	...
11.88	31.88	56.24	1.440	8.52	51.95	39.53
20.70	22.29	57.01	...	18.20	32.50	49.30
25.75	18.19	56.01	...	14.51	51.25	34.24
32.51	11.35	56.14	1.231	12.06	64.47	23.47
				3.50	83.76	12.74
41.70	6.10	52.20	...	8.77	75.2	16.03

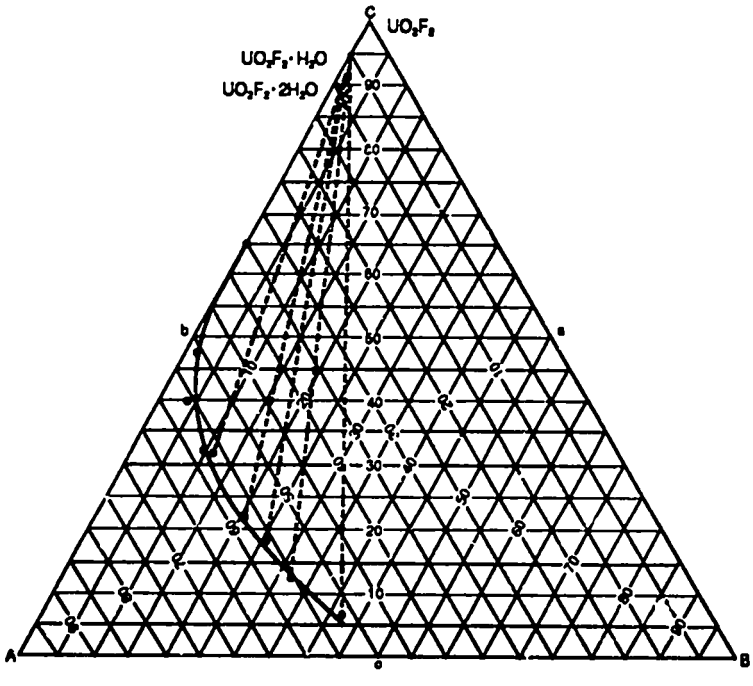

Fig. 3. The System UO_2F_2-HF-H_2O at 25°C.[7]

SPECIFIC GRAVITY

The specific gravity of uranyl fluoride water solutions at 25°C was determined by Hiskey[5] (see Table V).

TABLE V. Specific Gravity of UO_2F_2 Solutions[5,7]			
Concentration	Concentration		Specific Gravity
Molar	Molar	Wt %	g/cm^3
0.50	0.502	13.62	1.136 ± 0.001
1.00	1.004	24.29	1.274
2.00	2.004	39.99	1.544
3.00	3.009	51.17	1.812
4.00	4.012	59.45	2.079
5.00	5.030	65.98	2.349
	5.180 (Sat'd)	66.40	2.400

The Reactor Handbook[7] gave the following equation from which the specific gravity can be calculated:

$$D = 0.997 + 0.277\ M - 0.0015\ M^2 \quad , \qquad (1)$$

where

M = Molarity .

This equation is valid for the range 0 - 4 M.

DENSITY

Johnson and Kraus[9] measured the density of aqueous solutions of uranyl fluoride for a wide range of concentrations at 25°C and 30°C (see Table VI).

TABLE VI. Density of Aqueous Solutions of UO_2F_2[9]		
Concentration (Wt %)	Density at 25°C (g/cm^3)	Density at 30°C (g/cm^3)
2.495	1.0202	
4.985	1.0443	1.0429
5.025	1.0448	
10.20	1.0983	1.0967
20.09	1.2164	1.2146
20.48	1.2219	
30.10	1.3632	
30.18	1.3632	1.3607
40.30	1.5509	1.5481
50.27	1.7893	1.7859
61.63	2.1627	2.1589

This density data could be fitted to the quadratic equation[9]

$$\frac{1}{d} = \frac{1}{d_o} + aF_2 + bF_2{}^2 \quad , \tag{2}$$

where

d = density of the solution,

d_o = density of the pure solvent,

F_2 = weight fraction of UO_2F_2, and

a,b = empirical constants.

The empirical constants a and b were obtained from the intercept and slope of a plot of $(1/d-1/d_o)/F_2$ vs F_2.

Temperature °C	α	β
25	-0.9120	0.0567
30	-0.9126	0.0569

Assuming that the density of uranyl fluoride solutions follow Eq. 2, the apparent molal volume Φ_v at 25°C can be calculated using the equation[9]

$$\Phi_v = M_2 (1/d_o + a + bF_2) \quad , \tag{3}$$

where

M2 = gram-molecular weight of uranyl fluoride,

d_o = density of the pure solvent,

F_2 = weight fraction of UO_2F_2, and

a,b = empirical constants (see above).

Clark[10] has incorporated these last two equations in computer codes used to calculate subcritical limits for ^{233}U and ^{235}U systems.

Katz[7] measured the densities of uranyl fluoride solutions at 25°C for various concentrations (see Table VII).

TABLE VII. Density of Uranyl Fluoride Solutions at 25°C

UO_2F_2 (Wt %)	Density (g/cm^3)	Density(g/cm^3)
2.112	1.014	1.0136
7.565	1.070	1.0699
13.86	1.135	1.1349
19.39	1.200	1.2005
26.75	1.302	1.3016
34.76	1.441	1.4412
40.98	1.575	1.5754
49.24	1.751	1.7511
55.13	1.921	1.9212
61.98	2.176	2.1764

The Reactor Handbook[7] gives a different but equivalent form of Eq. 2 as

$$\frac{1}{d} = 1.0029 - 0.9126\,F_2 + 0.0578\,F_2^{\,2} \quad , \tag{4}$$

where

d = density of the solution, and

F_2 = weight fraction of U_2F_2 .

This equation assumes water to be the solvent.

The density of anhydrous uranyl fluoride computed from x-ray diffraction studies was $\rho = 6.37$ g/cm^3 (Refs. 3,5). A direct measurement by displacement in benzene gave 5.8 g/cm^3, but this value was thought to be low because of trapped air.[3] British workers reported a pouring density of 2.95 g/cm^3 and a packing density of 2.55 g/cm^3 (Ref. 3).

THERMODYNAMIC PROPERTIES

Wacker and Cheney[11] measured the specific heat, enthalpy, and entropy of uranyl fluoride for the temperature range 13-418K (see Table VIII). O'Hare and Malm[12] at Argonne National Laboratory reported a standard enthalpy of formation for UO_2F_2 of $\Delta H_f^\circ(UO_2F_2,c,298.15K) = -(1654.8 + 2.1)$ KJ • mol^{-1}.

ACIDITY

Table IX gives the acidity of stoichiometric uranyl fluoride as reported by Marshall, Gill, and Secoy.[7]

CORROSION PROPERTIES

Uranyl fluoride solutions are acidic, and the corrosivity of the fluoride solutions is generally greater than other uranyl solutions. Corrosion rates were dependent upon flow rate, concentration, and temperature of the solution. Tests performed at Oak Ridge National Laboratory revealed that all the stainless steels except type 416 showed adequate corrosion rates (see Table X).[4] Other experiments showed that most of the corrosion occurred in about the first 100 h of exposure, during which time a protective coating formed on the steel. Titanium demonstrated high resistance to uranyl fluoride solutions. However, in crevices where oxygen depletion occurred, titanium and its alloys are severely attacked. Zirconium is completely incompatible with uranyl fluoride solutions[13] or with the vapor phase above such solutions (which may contain a high concentration of HF gas that is very corrosive towards zirconium). Gold, platinum, and tantalum were barely affected[4] by the uranyl fluoride solution at 250°C. Niobium was heavily attacked.

TABLE VIII. Heat Capacity, Enthalpy, Entropy, and Free Energy of Uranyl Fluoride[11]

T	C°	$H^\circ - H^\circ_0$	S°	$-(F^\circ - H^\circ_0)$
(°K)	(Int. j/g)°K^{-1}	Int. j/g	(Int. j/g)°K^{-1}	Int. j/g
0	0.00000	0.00000	0.00000	0.00000
5	0.00051	0.00064	0.00017	0.00021
10	0.00403	0.01014	0.00135	0.00339
15	0.01231	0.0492	0.00440	0.01690
20	0.02333	0.1378	0.00943	0.0508
25	0.03386	0.2803	0.01575	0.1133
30	0.04478	0.4768	0.02288	0.2096
35	0.05567	0.7280	0.03060	0.3431
40	0.06637	1.0331	0.03874	0.5163
45	0.07747	1.3925	0.04719	0.7310
50	0.08909	1.8086	0.05595	0.9887
55	0.10191	2.2855	0.06503	0.2910
60	0.11549	2.8292	0.07448	1.6396
65	0.12713	3.4371	0.08420	0.0363
70	0.13573	4.0951	0.09395	0.4817
75	0.14362	4.7933	0.10358	0.9756
80	0.15261	5.5333	0.11313	0.5174
85	0.16310	6.3220	0.12269	0.1070
90	0.17378	7.1647	0.13232	0.7443
95	0.18226	8.0560	0.14196	0.4302
100	0.18847	8.9834	0.15147	6.1638
105	0.19439	9.9404	0.16081	6.9446
110	0.2007	10.928	0.16999	7.7713
115	0.2070	11.947	0.17905	8.6443
120	0.2132	12.998	0.18800	9.562
125	0.2193	14.079	0.19682	10.524
130	0.2252	15.190	0.20554	11.530

TABLE VIII. Heat Capacity, Enthalpy, Entropy, and Free Energy of Uranyl Fluoride[11] (cont)

T	C°	H°–H°$_0$	S°	–(F°–H°$_0$)
(°K)	(Int. j/g)°K^{-1}	Int. j/g	(Int. j/g)°K^{-1}	Int. j/g
135	0.2308	16.331	0.21415	12.579
140	0.2362	17.498	0.22264	13.671
145	0.2413	18.692	0.23102	14.806
150	0.2463	19.911	0.23928	15.981
155	0.2510	21.154	0.24743	17.198
160	0.2556	22.421	0.25547	18.455
165	0.2598	23.710	0.26340	19.752
170	0.2640	25.019	0.27122	21.089
175	0.2679	26.349	0.27893	22.464
180	0.2717	27.698	0.28653	23.878
185	0.2753	29.066	0.29403	25.330
190	0.2788	30.451	0.30141	26.818
195	0.2822	31.854	0.30870	28.343
200	0.2854	33.273	0.31589	29.906
205	0.2886	34.708	0.32297	31.502
210	0.2917	36.159	0.32997	33.135
215	0.2949	37.626	0.33687	34.802
220	0.2979	39.107	0.34368	36.503
225	0.3008	40.604	0.35041	38.233
230	0.3037	42.116	0.35705	40.006
235	0.3064	43.641	0.36361	41.808
240	0.3090	45.179	0.37009	43.643
245	0.3116	46.731	0.37649	45.518
250	0.3142	48.295	0.38281	47.400
255	0.3166	49.872	0.38905	49.337
260	0.3190	51.462	0.39523	1.298
265	0.3214	53.063	0.40133	3.29
270	0.3237	54.676	0.40735	5.31

TABLE VIII. Heat Capacity, Enthalpy, Entropy, and Free Energy of Uranyl Fluoride[11] (cont)				
T	C°	$H^\circ - H^\circ_0$	S°	$-(F^\circ - H^\circ_0)$
(°K)	(Int. j/g)°K^{-1}	Int. j/g	(Int. j/g)°K^{-1}	Int. j/g
275	0.3259	56.300	0.41331	7.362
280	0.3280	57.934	0.41920	9.443
285	0.3300	59.579	0.42503	1.555
290	0.3320	61.235	0.43079	3.694
295	0.3339	62.900	0.43648	5.862
300	0.3357	64.574	0.44210	8.058
305	0.3374	66.256	0.44767	0.284
310	0.3390	67.947	0.45317	2.536
315	0.3406	69.647	0.45860	74.814
320	0.3422	71.354	0.46398	74.814
325	0.3438	73.069	0.46930	79.454
330	0.3454	74.792	0.47456	81.814
335	0.3470	76.523	0.47976	84.199
340	0.3486	78.262	0.48492	86.612
345	0.3502	80.009	0.49002	89.049
350	0.3517	81.764	0.49507	91.512
355	0.3532	83.526	0.50007	94.000
360	0.3546	85.296	0.50502	96.512
365	0.3560	87.072	0.50992	99.050
370	0.3572	88.855	0.51477	101.611
375	0.3584	90.645	0.51957	104.197
380	0.3596	92.440	0.52433	106.806
385	0.3607	94.241	0.52904	109.440
390	0.3617	96.046	0.53370	112.098
395	0.3627	97.858	0.53831	114.776
400	0.3638	99.674	0.54288	117.480
405	0.3648	101.495	0.54741	120.206

TABLE IX. The pH of Uranyl Fluoride Solutions at 25°C[7]		
UO_2F_2, Wt %	Density (g/cm^3)	pH, 25°C
2.112	1.0136	3.70
7.565	1.0699	3.18
13.86	1.1349	2.86
19.39	1.2005	2.69
26.75	1.3016	2.50
34.76	1.4411	2.25
40.98	1.5754	2.13
49.24	1.7511	2.05
55.13	1.9212	1.76
61.98	2.1764	1.52

REFRACTIVE INDICES

Johnson and Kraus[9] measured the refractive indices or uranyl fluoride solutions at 25°C and 30°C (see Table XI).

The results of these measurements were fitted to the equation[9]

$$n_D^t = n_D^{ot} + \alpha c + \beta c^2/2 \quad , \tag{4}$$

where

c = concentration (molarity),

α,β = emperical constants,

n_D^t = measured refractive indices of the solution at temperature t, and

n_D^{ot} = measured refractive indices of water at temperature t

TABLE X. The Corrosion Rates of Several Alloys in 0.17 m UO_2F_2 at 250°C[a]	
Metal or Alloy	**Range of average corrosion rates, mils/yr**
Austenitic stainless steels	
304,304L, 309SCb, 310, 316, 316L,318, 321, 347	4-13
Ferritic and martensitic stainless steels	
322W, 430, 443, 17-4 pH	3.5-5.0
416	>2000
Titanium and zirconium alloys	
55A, 70A, 100A, 150A	0.01-0.25
AC, AM, AT	5.6-7.7
Zirconium, Zircaloy-z	>2000
Other Metals	
Gold, platinum	<0.5
Niobium	>1000

[a]Test conditions were: pressurizing gas = 200 psi O_2; time = 200 h; flow rate = 10 to 15 ft/s.

The empirical constants are

Temperature °C	α	β
25	0.02055	-0.00185
30	0.02049	-0.00183

TABLE XI. Refractive Index of Uranyl Fluoride Solutions[9]		
UO_2F_2, Wt %	Refractive Index	
	25°C	30°C
1.002	1.33319	1.33266
2.495	1.33417	1.33366
4.985	1.33586	1.33531
5.025	1.33597	
7.481	1.33764	1.33705
9.607	1.33924	1.33864
10.20	1.33963	1.33907
15.01	1.34333	1.34275
20.09	1.34756	1.34692
20.48	1.34788	1.34721
24.89	1.35188	1.35114
30.10	1.35705	
30.18	1.35705	1.35636
33.39	1.36059	1.35988
40.27	1.36888	1.36825
46.36	1.37726	1.37647
50.27	1.38316	1.38239
50.90	1.38439	1.38370
56.90	1.39503	1.39418
57.10	1.39542	1.39457
61.12	1.40392	1.40303
61.63	1.40475	1.40407

CONCLUSION

In addition to the 13 references cited above, there are 8 sources that are also worth consulting. These sources are listed in the Appendix.

REFERENCES

1. E. H. P. Cordfunke, The Chemistry of Uranium (Elsevier Publishing Company, Amsterdam/London/New York, 1969).

2. V. M. Vdovenko, "Chemistry of Uranium and Transuranium Elements," U.S. Atomic Energy Commission report AEC-tr-6421 (1960, translation).

3. J. J. Katz and E. Rabinowitch, The Chemistry of Uranium (Dover Publications, Inc., New York, 1973).

4. J. A. Lane, H. G. MacPherson, and F. Maslan, Fluid Fuel Reactors (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1958).

5. M. S. Katz, SAM Columbia 2, Report CC-1744 (June 17, 1944).

6. I. I. Chernyaev, Complex Compounds of Uranium (Daniel Davey and Company, Inc., New York, 1966, translation).

7. The Reactor Handbook, Vol. II, U.S. Atomic Energy Commission report AECD-3646 (1955).

8. F. S. Patton, J. M. Googin, and W. L. Griffith, Enriched Uranium Processing (Macmillan Company, New York, 1963).

9. J. S. Johnson and K. A. Kraus, "Density and Refractive Index of Uranyl Fluoride," *J. Am. Chem. Soc.* **75**, 4594 (1953).

10. H. K. Clark, "Subcritical Limits for Uranium-235 Systems," *Nuclear Science and Engineering* **81**, 351-378 (1982).

11. P. F. Wacker and R. K. Cheney, *J. Research Natl. Bur. Standards* **39**, 317 (1947).

12. P. A. G. O'Hare and J. G. Malm, "Thermochemistry of Uranium Compounds XIII. Standard Enthalpies of Formation at 298.15K of α-uranium oxide Tetrafluoride (UOF_4) and Uranyl Fluoride (UO_2F_2)," *J. Chem. Thermodynamics* **14**, 331-336 (1982).

13. Reactor Handbook, Vol. I (Interscience Publishers, Inc., New York, 1960).

APPENDIX

H. K. Clark, "Subcritical Limits for Uranium-233 Systems," *Nuclear Science and Engineering* **81**, 379-395 (1982).

W. F. Finke, Solubilities, Inorganic and Metal-Organic Compounds, K-Z, Vol. II, fourth ed. (American Chemical Society, 1965), p. 1608.

J. S. Johnson and K. A. Kraus, "Activity Coefficients of Uranyl Fluoride from Freezing Point Depressions: Undissociated Species and Dimerization," *J. Am. Chem. Soc.* **74**, 4436-4439 (1952).

J. S. Johnson, K. A. Kraus, and T. F. Young, "Determination of Activity Coefficients by Ultracentrifugation. Ultracentrifugation of Uranyl Fluoride Solutions," *J. Am. Chem. Soc.* **76**, 1436-1443 (1954).

W. L. Marshall, J. S. Gill, and C. H. Secoy, "Phase Equilibria of Uranium Trioxide and Aqueous Hydrofluoric Acid in Stoichiometric Concentrations," *J. Am. Chem. Soc.* **76**, 4279-4281 (1954).

E. Rabinowitch and R. L. Belford, Spectroscopy and Photochemistry of Uranyl Compounds (Macmillan Company, New York, 1964).

M. H. Rand and O. Kubaschewski, The Thermochemical Properties of Uranium Compounds (Oliver and Boyd, Edinburgh and London, 1963).

Timmermans, The Physico-Chemical Constants of Binary Systems in Concentrated Solutions, Vol. III (Interscience Publishers, Inc., New York, 1960), p. 1008.