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CHEMICAL STABILITY OF HIGH TEMPERATURE POWER PILE

By

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and

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MONSANTO CHEMICAL COMPANY
Clinton Laboratories

February 4, 1947

To: Dr. C. Rogers McCullough

From: S. L. Simon and J. V. Fitzgerald

Chemical Stability of High Temperature Power Pile

Summary

A preliminary study of the chemical stability of pile materials in the high temperature power pile has been made. The present memorandum includes:

1. A table of free energies, heats and entropies of formation, vapor pressures, and melting points of compounds of uranium, thorium, columbium, iron and carbon with instructions for calculating the approximate free energy of reaction at any temperature for reactions involving them.
2. A table of change in free energy at 1500°K for approximately 90 reactions involving pile constituents.
3. A discussion of the significance of these values.
4. A partial analysis of the possible reactions in a pile consisting of UO_2 , graphite, BeO , Fe and ThO_2 .

Tables

Table I has been assembled from the data of the following reports or by calculation from this data:

CC-929	CC-664
CC-2058 (A3002)	CC-1334 (A1883)
CC-3307	CC-587
CF-3626	CC-422
CC-3234	CC-672
CN-3378	

Bichowsky and Rossini - The Thermo-chemistry of Chemical Substances

An approximate value of the free energy change at any temperature for any reaction involving the compounds listed may be obtained by the following procedure:

Suppose that the reaction in question is:

we write down from the table:

and adding both equations and ΔF 's, we obtain

Note that the first two partial reactions are decompositions, not formations, and the negative of the values given in the table for ΔF , ΔH and ΔS must be used.

If the ΔF_{1500} for any of the constituents is not given in the table, it may be approximately calculated from the ΔH_{298} and ΔS_{298} for the compound by the following formula:

$$\Delta F_{1500} = \Delta H_{298} - 1500 \Delta S_{298}$$

The ΔF for any other temperature may also be calculated by using the value of the temperature in degrees Kelvin instead of 1500.

TABLE I

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Compound	$\Delta H_{298.1}$ k cal per equivalent	$\Delta H_{298.1}$ k cal per mol	$\Delta S_{298.1}$ cal per equivalent ^o	$\Delta S_{298.1}$ cal per mol ^o	$\Delta F_{298.1}$ k cal per equivalent	$\Delta F_{298.1}$ k cal per mol	ΔF_{1500} k cal per mol	T_m , melt- ing pt. ^o K	T_{10-2} ^o K	T_{10-1} ^o K	$T_{.76}$ ^o K	T_1 ^o K	T_{760} ^o K
U	----	----	----	----	----	----	----	1370	2600 2100 2000	2200	----	2400	3700 4570
UO ₂	-64.2	-256.6	-10.5	-42.1	-61.0	-244.	-193.4	2500	4200 (dec)				
U ₃ O ₈	-52.8	-845.2	-9.8	-156.7	-49.9	-798.4	-610.4	dec					
UC ₂			7.55		-8.8		-35.70	>2100					4370
U ₃ N ₄		-144.4	-20.5	-82.0	-30.	-120.0	-21.4		1140 ^o dec				
U ₅ N ₄													
UH ₄							+44.0						
Be								1570	1380	1560		1800	3240
BeO	-73.5	-147.	-11.71	-23.42	-70.0	-140.0	-111.5	2800 2820					4260 4170
Be ₂ C								>2373					
Be ₃ N ₂	-66.8		-20.3		-60.7		-72.6	2470	2000 dec 2510 dec				dec- 2510

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TABLE I, Cont'd

Compound	$\Delta H_{298.1}$ k cal per equivalent	$\Delta H_{298.1}$ k cal per mol	$\Delta S_{298.1}$ cal per equivalent ^o	$\Delta S_{298.1}$ cal per mol ^o	$\Delta F_{298.1}$ k cal per equivalent	$\Delta F_{298.1}$ k cal per mol	ΔF_{1500} k cal per mol	T _m . melt- ing pt. oK	T ₁₀₋₂ oK	T ₁₀₋₁ oK	T _{.76} oK	T ₁ oK	T ₇₆₀ oK
Th								2100	2100 2600				5300
ThO ₂	-74.2	-296.8	-10.8	- 43.0	-71.0	-284.	-232.30	3320	4700 (dec)		2700 (15 mm)		4670
ThC ₂			- 7.55		-25.1		- 68.3	3050					5270
Th ₃ N ₄	-77.6		-22.4		-70.9		-170.1		2300 dec				
Cb								2800	3000	4000		4500	6200
CbO ₂						-430							
Cb ₂ O ₅	-46.3	-463.1	-11.0	-110.0	-43.0	-430	-298.1	1790	2700 (dec)				
CbN	-59.		-20.0		-53.0		- 29.0						
Cb ₂ O ₃								2050					
CbC								3770					
Fe								1812 1808	1750	1900		2140	3010
FeO	-32.2	- 64.4	- 8.8	- 17.6	-29.6	- 59.2	- 38.0	1642 1640	2200 dec				3250 dec

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TABLE I, Cont'd

Compound	$\Delta H_{298.1}$ k cal per equivalent	$\Delta H_{298.1}$ k cal per mol	$\Delta S_{298.1}$ cal per equivalent ^o	$\Delta S_{298.1}$ cal per mol ^o	$\Delta F_{298.1}$ k cal per equivalent	$\Delta F_{298.1}$ k cal per mol	ΔF_{1500} k cal per mol	Tm. melt- ing pt. oK	T ₁₀₋₂ oK	T ₁₀₋₁ oK	T ₇₆ oK	T ₁ oK	T ₇₆₀ oK
Fe ₂ O ₃	-33.1	-198.5	-10.8	-65.0	-29.9	-179.1		dec 1830					
Fe ₃ O ₄	-33.1	-266.9	-10.3	-82.47	-30.8	-242.3		1811 dec 1663					
Fe ₃ C			3.05 3.5		4.61 4.73		+ .523	2110					
Fe ₂ N								dec >830					
Fe ₄ N	- 2.6		-11.5		0.89		+14.71		unstable				

Table 2 has been calculated by this method. The solid constituents which have been considered are U, UO_2 , UO_3 , U_3O_8 , Be, BeO, C, Th, ThO_2 , Fe and Cb. Gases which have been considered are CO, O_2 , H_2 , H_2O , N_2 and CH_4 . The first column gives ΔF_{1500} for the reaction as written. The ΔF_{1500} for the reverse reaction is the negative of this value. The remaining columns are self-explanatory.

TABLE 2

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No.	Reaction U	ΔF_{1500} k cal	ΔH_{298} k cal/mol	ΔS_{298} cal/mol deg	ΔF_{298} k cal/mol
1	$U + 2C \rightarrow UC_2$	- 35.70	- 13.10	+ 15.10	- 17.5
2	$U + 2CO \rightarrow UC_2 + O_2$	+ 82.1	296.36	+ 17.80	
3	$U + 2CO \rightarrow UO_2 + 2C$	- 75.4	-203.7	- 81.5	
4	$U + 3CO \rightarrow UO_3 + 3C$	- 26.0			
5	$3U + 8CO \rightarrow U_3O_8 + 8C$	-139.0			
6	$U + 2H_2 \rightarrow UH_4$	+ 44.0	- 40	- 56	- 23.2
7	$U + 2H_2O \rightarrow UO_2 + 2H_2$	-114.9	-141.0	+263.9	
8	$U + 4H_2O \rightarrow U(OH)_4 + 2H_2$				
9	$3U + 2N_2 \rightarrow U_3N_4$	- 21.4	-144.4	- 82.0	-120
10	$U + O_2 \rightarrow UO_2$	-193.4	-256.6	- 42.1	-244
11	$U + \frac{3}{2} O_2 \rightarrow UO_3$	-203.0	-293.0	- 60.0	-274.8
12	$3U + 4O_2 \rightarrow U_3O_8$	-610.4	-845.2	-156.7	-798.4
13	$U + 2CH_4 \rightarrow UC_2 + 4H_2$				- 7.0

UO₂, UO₃, U₃O₈

14	$UO_2 \rightarrow U + O_2$	+193.4	+257	+ 42.1	+244
15	$UO_2 + 2Be \rightarrow 2BeO + U$	- 29.6	- 37.4	- 4.74	
16	$UO_2 + 2C \rightarrow U + 2CO$	+ 75.4	+203.7	+ 81.5	
17	$UO_2 + 2C \rightarrow UC_2 + O_2$	+157.9	+243.5	+ 57.2	
18	$UO_2 + 4C \rightarrow UC_2 + 2CO$	+ 39.9	+190.6	+ 96.60	
19	$3UO_3 + C \rightarrow U_3O_8 + CO$	+ 61.0			
20	$UO_2 + CO \rightarrow UO_3 + C$	+ 49.0			
21	$UO_2 + 2CO \rightarrow UC_2 + 2O_2$	+275.5			
22	$UO_2 + 2CO \rightarrow U + 2CO_2$				
23	$5UO_2 + 4Cb \rightarrow 2Cb_2O_5 + 5U$	+370.8	356.8	- 9.5	
24	$UO_2 + H_2 \rightarrow U + 2H_2O$	+114.9	-141.0	-263.9	

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TABLE 2; Cont'd

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No.	Reaction	ΔF_{1500} k cal	ΔH_{298} k cal/mol	ΔS_{298} cal/mol deg	ΔF_{298} k cal/mol
25	$UO_2 + 4H_2 \rightarrow UH_4 + 2H_2O$	+198.0			
26	$3UO_2 + 2N_2 \rightarrow U_3N_4 + 3O_2$	+558.8	625.4	+ 44.3	
27	$3UO_2 + O_2 \rightarrow U_3O_8$	- 30.2	- 75.4	- 30.4	
28	$UO_2 + \frac{1}{2} O_2 \rightarrow UO_3$	- 9.6	183.4	27.1	
29	$U_3O_8 + \frac{1}{2} O_2 \rightarrow 3UO_3$	+ 2.1			
30	$UO_2 + 2Fe \rightarrow 2FeO + U$	+117.4	+127.8	+ 6.9	

GASES

31	$C + \frac{1}{2} O_2 \rightarrow CO(g)$	- 58.915	- 26.43	+ 19.7	- 32.787
32	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O(g)$	- 39.25			- 54.638
33	$C + 2H_2 \rightarrow CH_4(g)$	+ 17.35			- 12.28

Be

34	$2Be + C \rightarrow Be_2C$				
35	$4Be + 2CO \rightarrow 2Be_2C + O_2$				
36	$Be + CO \rightarrow BeO + C$	- 52.58			
37	$2Be + H_2 \rightarrow 2BeH$				
38	$Be + H_2O \rightarrow BeO + H_2$	- 72.25			
39	$Be + 2H_2O \rightarrow Be(OH)_2 + H_2$				
40	$3Be + N_2 \rightarrow Be_3N_2$	- 72.6	-133.5	- 40.6	-121.4
41	$2Be + O_2 \rightarrow 2BeO$	-223	-294	- 46.84	-280
42	$2Be + ThO_2 \rightarrow 2BeO + Th$	+ 9.3			

BeO

43	$BeO \rightarrow Be + \frac{1}{2} O_2$	+111.5	+147	+ 23.42	+140
44	$BeO + C \rightarrow Be + CO$	+ 52.58			

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TABLE 2, Cont'd

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No.	Reaction	ΔF_{1500} k cal	ΔH_{298} k cal/mol	ΔS_{298} cal/mol/deg	ΔF_{298} k cal/mol
45	$\text{BeO} + \text{CO} \rightarrow \text{Be} + \text{CO}_2$				
46	$5\text{BeO} + 2\text{Cb} \rightarrow 5\text{Be} + \text{Cb}_2\text{O}_5$	+259.4			
47	$\text{BeO} + \text{H}_2 \rightarrow \text{Be} + \text{H}_2\text{O}$	+ 72.25			
48	$2\text{BeO} + 3\text{H}_2 \rightarrow 2\text{BeH} + 2\text{H}_2\text{O}$				
49	$\text{BeO} + \text{H}_2\text{O} \rightarrow \text{Be}(\text{OH})_2$				
50	$\text{BeO} + \text{Fe} \rightarrow \text{Be} + \text{FeO}$	+ 73.5			
51	$3\text{BeO} + \text{N}_2 \rightarrow \text{Be}_3\text{N}_2 + \frac{3}{2}\text{O}_2$	+261.9			
52	$2\text{BeO} + \text{Th} \rightarrow 2\text{Be} + \text{ThO}_2$	- 9.3			
53	$2\text{BeO} + \text{U} \rightarrow \text{UO}_2 + 2\text{Be}$	+ 29.6	+ 37.4	+ 4.74	

C

54	$\text{C} + \text{Cb} \rightarrow \text{CbC}$				
55	$\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$	+ 17.85			- 12.28
56	$\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2$	- 19.67			
57	$\text{C} + 3\text{Fe} \rightarrow \text{Fe}_3\text{C}$	+ .523	+ 5.773	3.5	4.73
58	$2\text{C} + \text{N}_2 \rightarrow (\text{CN})_2$				
59	$2\text{C} + \text{O}_2 \rightarrow 2\text{CO}$	-117.83	- 52.86	+ 39.4	- 63.58
60	$2\text{C} + \text{Th} \rightarrow \text{ThC}_2$	- 32.1	- 45.7	7.55	- 25.1
61	$2\text{C} + \text{ThO}_2 \rightarrow \text{Th} + 2\text{CO}$	+114.47			

Th

62	$\text{Th} + 2\text{CO} \rightarrow \text{ThO}_2 + 2\text{C}$	-114.47			
63	$\text{Th} + 2\text{CO} \rightarrow \text{ThC}_2 + \text{O}_2$	+ 85.7			
64	$\text{Th} + \text{H}_2 \rightarrow \text{Th}_x\text{H}_y$				
65	$3\text{Th} + 2\text{N}_2 \rightarrow \text{Th}_3\text{N}_4$	-176.1	-310.3	- 89.6	-283.6
66	$\text{Th} + \text{O}_2 \rightarrow \text{ThO}_2$	-232.30	-296.8	- 43.0	-284.0

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TABLE 2, Cont'd

No.	Reaction	ΔF_{1500} k cal	ΔH_{298} k cal/mol	ΔS_{298} cal/mol deg	ΔF_{298} k cal/mol
<u>ThO₂</u>					
67	$\text{ThO}_2 \rightarrow \text{Th} + \text{O}_2$	+232.30	+296.8	+ 43.0	+284.0
68	$\text{ThO}_2 + 2\text{Fe} \rightarrow \text{Th} + 2\text{FeO}$				
69	$\text{ThO}_2 + 2\text{CO} \rightarrow \text{Th} + 2\text{CO}_2$				
70	$\text{ThO}_2 + 2\text{CO} \rightarrow \text{ThC}_2 + 2\text{O}_2$	+318.2			
71	$\text{ThO}_2 + 2\text{H}_2 \rightarrow \text{Th} + 2\text{H}_2\text{O}$	+153.8			
72	$\text{ThO}_2 + \text{H}_2 \rightarrow \text{Th}_x\text{H}_y + \text{H}_2\text{O}$				
73	$3\text{ThO}_2 + 2\text{N}_2 \rightarrow \text{Th}_3\text{N}_4 + 3\text{O}_2$	+520.8			
74	$5\text{ThO}_2 + 4\text{Cb} \rightarrow 5\text{Th} + 2\text{Cb}_2\text{O}_5$	+565.3			

Fe

75	$\text{Fe} + \frac{1}{2} \text{O}_2 \rightarrow \text{FeO}$	- 38.0	- 64.4	- 17.6	- 59.2
76	$8\text{Fe} + \text{N}_2 \rightarrow 2\text{Fe}_4\text{N}$	+ 29.42	- 2.54	- 11.5	0.89
77	$\text{Fe} + \text{H}_2\text{O} \rightarrow \text{FeO} + \text{H}_2$	+ 1.25			
78	$\text{Fe} + \text{CO} \rightarrow \text{Fe}(\text{CO})_5$		-180		
79	$\text{Fe} + \text{CO} \rightarrow \text{FeO} + \text{C}$	+ 20.92			
80	$3\text{Fe} + 2\text{O}_2 \rightarrow \text{Fe}_3\text{O}_4$		-266.9	- 82.47	-242.3
81	$2\text{Fe} + \frac{3}{2} \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3$		-198.5	- 65.0	-179.1

Cb

82	$\text{Cb} + \text{CO} \rightarrow \text{Cb}_x(\text{CO})_y$				
83	$\text{Cb} + \text{CO} \rightarrow \text{CbC} + \frac{1}{2} \text{O}_2$				
84	$2\text{Cb} + 5\text{CO} \rightarrow \text{Cb}_2\text{O}_5 + 5\text{C}$	- 3.52			
85	$\text{Cb} + \text{H}_2 \rightarrow \text{Cb}_x\text{H}_y$				
86	$2\text{Cb} + 5\text{H}_2\text{O} \rightarrow \text{Cb}_2\text{O}_5 + 5\text{H}_2$	-101.85			

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TABLE 2, Cont'd

No.	Reaction	ΔF_{1500} k cal	ΔH_{298} k cal/mol	ΔS cal/mol deg	ΔG k cal/mol
87	$\text{Cb} + 5\text{H}_2\text{O} \rightarrow \text{Cb}(\text{OH})_5 + \frac{5}{2}\text{H}_2$				
88	$\text{Cb} + \frac{1}{2}\text{N}_2 \rightarrow \text{CbN}$	- 29.0			
89	$2\text{Cb} + \frac{5}{2}\text{O}_2 \rightarrow \text{Cb}_2\text{O}_5$	-298.1	-463.1	-110	
90	$\text{Cb} + \text{O}_2 \rightarrow \text{CbO}_2$				-430.0

Significance of ΔF Values

If the ΔF for a given reaction at a given temperature is negative, the reaction will tend to proceed in the direction given. The only factor which is uncertain is the rate at which it will go, and the reaction may occur instantaneously or take an indefinite time for completion. If the ΔF is positive, and if the products are not removed, the reaction will not proceed to completion, although even small equilibrium amounts of products may be of importance for pile design.

Unfortunately, also, the conditions in the high temperature power pile are such that removal of reaction products, either by the coolant or by diffusion away from the reacting zone, is very likely.

Very little can be said about the latter; it is likely that experimental tests will have to be made for at least some of the reactions in which only solid products are formed.

There are two possible analytical approaches for reactions in which gaseous products are formed:

1. It might be assumed that the reaction is taking place in an evacuated chamber whose volume is that of the coolant volume in the pile. The amount of reaction which has taken place when the equilibrium pressure of gaseous products has been reached can then be calculated. This has been done in the example which follows.
2. The coolant gas will contain a certain amount of gaseous impurities. The minimum concentration of these impurities will be larger in most cases than the concentrations of the same gases to be expected from the reaction of the pile materials. The chief danger to pile materials appears to arise from the reaction of gases which may be expected as impurities with the solid materials of the pile. It appears to be desirable, therefore, to determine what the impurity concentrations will be in the helium and to use these concentrations in calculations to determine the chemical stability of the pile.

A report considering the problem from this angle is in preparation and will be presented later.

Preliminary Analysis of High Temperature Power Pile

We shall assume a pile of the following description:

Fuel rods - UO_2 -C - no jackets.
He coolant - no impurities.
BeO moderator.
BeO + graphite reflector.
Steel shell.
 ThO_2 breeder slugs in graphite part of reflector only.

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The following pairs of materials may react;

UO₂ - C
 UO₂ - BeO
 BeO - C
 ThO₂ - C

The following reactions will then be of interest;

14.	UO ₂ → U + O ₂	ΔF ₁₅₀₀ = +193.4	ΔF ₂₉₈ = +244.4
16.	UO ₂ + 2C → U + 2CO	+ 75.4	+179.4
17.	UO ₂ + 2C → UC ₂ + O ₂	+157.9	+226.4
18.	UO ₂ + 4C → UC ₂ + 2CO	+ 39.9	+161.8
43.	BeO → Be + $\frac{1}{2}$ O ₂	+111.5	+140.0
44.	BeO + C → Be + CO	+ 52.58	+107.7
61.	2C + ThO ₂ → Th + 2CO	+114.47	+219.3
67.	ThO ₂ → Th + O ₂	+232.30	+284.0

The ΔF₁₅₀₀'s are all positive, indicating that the reactions do not tend to proceed in the direction given unless the products are removed. Also, since 1500°K is approximately the highest temperature expected in the pile, ΔF₂₉₈ has been calculated to see whether at points of lower temperature the reaction would have more tendency to proceed. In all cases ΔF₂₉₈ is larger than ΔF₁₅₀₀, so that maximum reaction will take place at 1500.

Since each reaction has a gaseous product, the extent to which the reaction has proceeded at equilibrium may be measured by the equilibrium pressure of this product. This pressure may be calculated from the equation:

$$\log K_p = \frac{-\Delta F}{2.3RT} \quad \log K_{p1500} = \frac{-\Delta F_{1500}}{6.87 \times 10^3}$$

The pressures calculated are given in the following table:

Reaction No.	K _{p1500}	Gas Formed	P (Atmospheres)
14	1.3 x 10 ⁻³⁰	O ₂	10 ⁻²⁸
16	1 x 10 ⁻¹¹	CO	3.46 x 10 ⁻⁶
17	1.3 x 10 ⁻²³	O ₂	1.3 x 10 ⁻²³
18	1.5 x 10 ⁻⁶	CO	1.21 x 10 ⁻³
43	6.3 x 10 ⁻¹⁷	O ₂	3.98 x 10 ⁻³³
44	2.1 x 10 ⁻⁸	CO	2.1 x 10 ⁻⁸
61	2.0 x 10 ⁻¹⁷	CO	5.6 x 10 ⁻⁹
67	1.3 x 10 ⁻³⁴	O ₂	2 x 10 ⁻³⁴

We can now calculate the total amount of reaction for reactions 17 and 18 which give the highest equilibrium pressures of CO and O₂ respectively. The following assumptions are made:

Total volume of coolant = 4100 cu. ft. = 11.6 x 10⁴ liters.
 Coolant in pile has average temperature = $\frac{1400 + 500}{2}$ = 950°F.

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Coolant in remainder of system has average temperature = 500°F.
 Volume of coolant in pile = 700 cu. ft.
 Volume of coolant in remainder of system = 3400 cu. ft.
 Pressure of coolant = 10 atmospheres.

Under these assumptions the weighted average temperature of the coolant is 559.8°F = 566.4°K.

The number of moles of gas which have been formed at equilibrium will be

$$N = 245p_{1500}$$

For the two reactions under consideration, the values are:

The amount of UO_2 decomposed in 18 is obviously negligible. The amount of UO_2 transformed in 17 is $\sim .15$ moles ~ 40.5 g $\sim 0.1\%$ of the UO_2 in the pile.

This apparently favorable result is not, however, the complete story. If the CO or O_2 were removed by other reactions as fast as it is formed, more attack of the BeO and UO_2 may be anticipated. From the list of reactions (Table 2) we might expect the following reactions to be relevant:

Reaction	ΔF_{1500}
20. $UO_2 + CO \rightarrow UO_3 + C$	+ 49.0
21. $UO_2 + 2CO \rightarrow UC_2 + 2O_2$	+275.5
27. $3UO_2 + O_2 \rightarrow U_3O_8$	- 30.2
28. $UO_2 + \frac{1}{2} O_2 \rightarrow UO_3$	- 9.6
59. $2C + O_2 \rightarrow 2CO$	-117.83
70. $ThO_2 + 2CO \rightarrow ThC_2 + 2O_2$	+318.2
75. $Fe + \frac{1}{2} O_2 \rightarrow FeO$	- 38.0
78. $Fe + 5CO \rightarrow Fe(CO)_5$	?
79. $Fe + CO \rightarrow FeO + C$	+ 20.92
80. $3Fe + 2O_2 \rightarrow Fe_3O_4$	-143.2
81. $2Fe + \frac{3}{2} O_2 \rightarrow Fe_2O_3$	-101.0

It is apparent that a consideration of this kind introduces three possibilities:

1. These reactions may cause the first group to go further towards completion by removing gaseous products.
2. The gaseous products of the first group may attack the materials in the second group.
3. Absorption of CO may give rise to O_2 and vice versa.

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Conclusions and Recommendations

1. The possible interactions are so many that it appears impossible to completely analyze the problem. The approach in which the maximum concentration of gaseous impurities is taken as fixed by the purification system will probably be more useful.

2. There will probably be a minimum desirable concentration of such impurities as O_2 and CO as well as a maximum if oxides and graphite are used in the pile. The minimum value will be set by the necessity of restraining reactions between oxides and graphite, the maximum by oxidation reactions such as $3UO_2 + O_2 \rightarrow U_3O_8$ and $C + \frac{1}{2} O_2 \rightarrow CO$ which result in volatile products.

3. It may be necessary to protect steel parts from attack by coolant impurities.

4. The chief chemical effects on pile materials will be due to impurities in the coolant.

5. Possible chemical reaction of fission products with UO_2 and fuel rod matrix material should be studied.