

La Jolla Blueprint  
7438 Girard Av.



**GENERAL ATOMIC**  
DIVISION OF GENERAL DYNAMICS CORPORATION  
POST OFFICE BOX 608  
SAN DIEGO 12, CALIFORNIA

To

*Amesbury*

*L. Bickland  
1155 E 57th Str  
Chicago 37*

**NARROW RULED MARGINAL**

**SIZE 11 x 8½**

**No. P-2713**

Current

Jan 30 (59) H

Ball Ni cathode at 750°C

draws half sat. current at 1 Volt loss - sat. current = 1 Amp/cm<sup>2</sup>  
Anode Temp 180°C

Cs pressure ~ 0.035 mm  
(B.P. m.p. 28.5°C  
p.p. = 670°C)

W<sup>o</sup>

Ba m.p. 850°C  
b.p. 1140°C

$$I_{up} = \frac{Q}{T} \times C_{anode}$$

Ba

$$\ln \frac{p_1}{p_2} = Q \left( \frac{1}{T_{up}} - \frac{1}{T} \right) = \frac{\Delta K}{K} \frac{Q}{K_0}$$

$$(b.p.)_{abs} = K_0$$
  
$$p = e^{-\frac{\Delta K}{K} \frac{Q}{K_0}}$$

Ba has high vapour pressure as oxidized.

K<sub>0</sub>

700 mmHg

Solvents.

~~600°C~~  
Cs in  
600°C

solvent, at 600°C

at 600°C Bi 10<sup>-3</sup>

Ba - hottest  
at cathode 500°C

$$\frac{\text{Heat con.}}{\sigma T} = \frac{k}{2} = \text{Touch}$$

$$\frac{\text{Heat con.}}{\sigma T} = \frac{k}{2} = \frac{\beta + 5}{2} \left( \frac{h}{e} \right)^2$$

$\tau$  = all done. = const. v p.

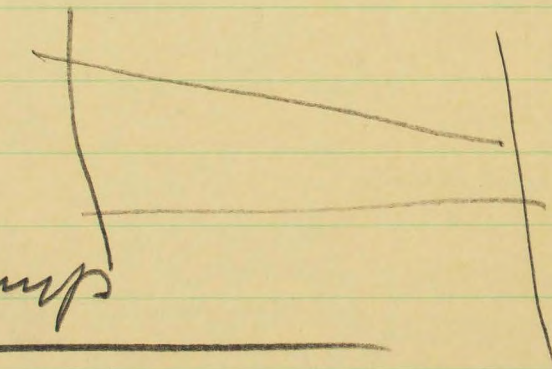
~~$\tau = \frac{h}{e} \omega$~~

definition of p

$$\lambda = \frac{1}{v^2}$$

$\beta = 3$  for  
anisotropic scattering

coeff. 4

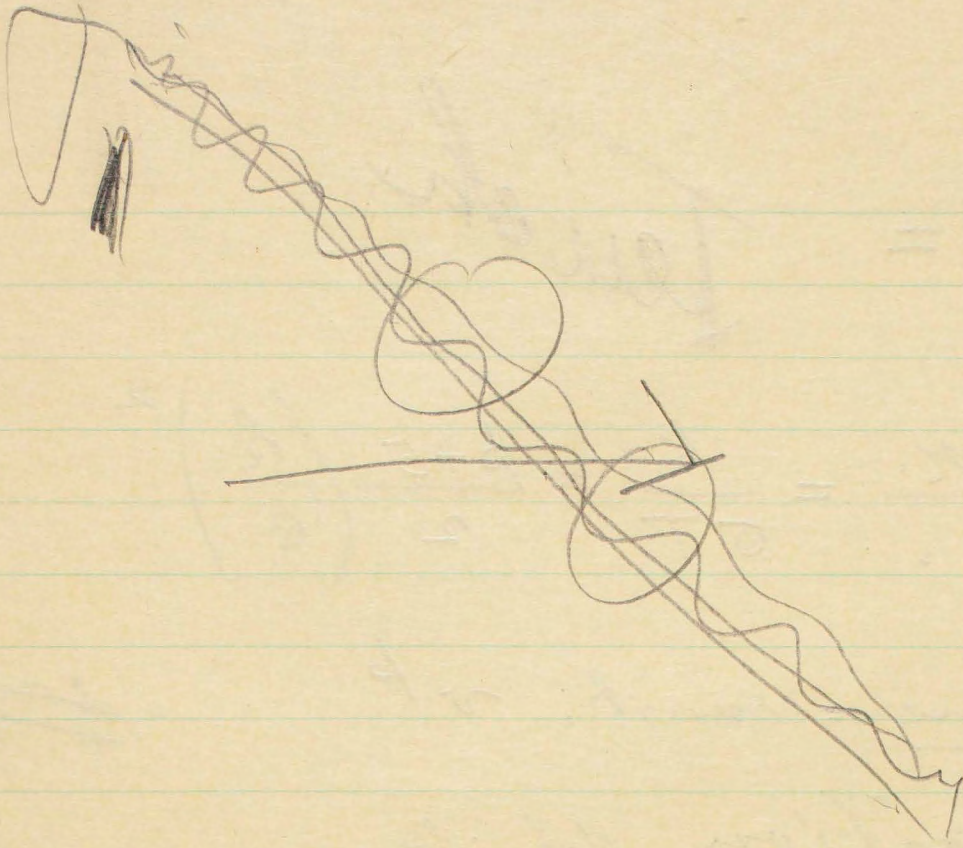


1 Volt 30 Amp

copper more favorable

$$\frac{\pi^2}{3} =$$

P.T.O.

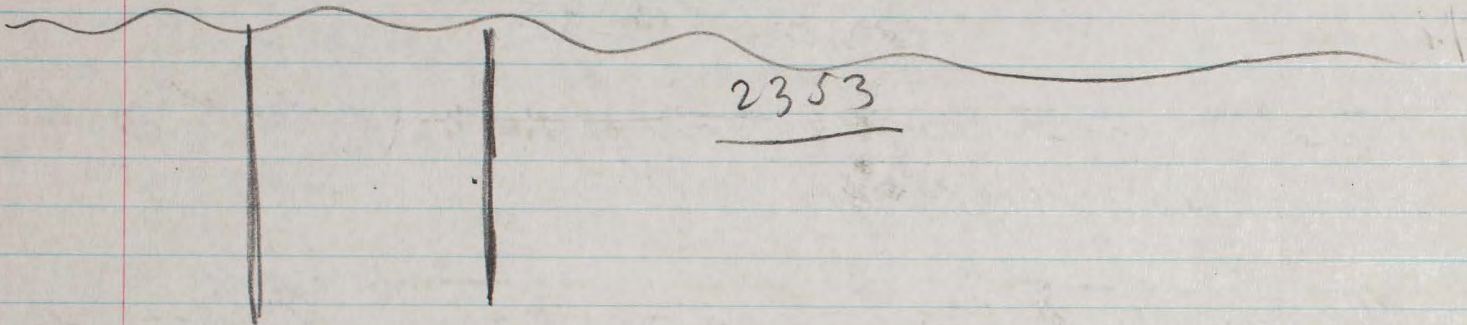


T<sub>2</sub>

vap. press. Baute page

Vapor pressure tables

$$\left. \begin{array}{l} A_2O = 1 \\ C_6 = 10 \\ B_a = 1 \end{array} \right\}$$



$$B_a \text{ (2.5)}$$

$$B_a \text{ (1.6)}$$

$$\left. \begin{array}{l} C_{s_2}O = 1 \\ C_6 = 1.4 \end{array} \right\}$$

At 600°C vapour pressure

$$Li = 0.1 \text{ mmHg (at } 540^\circ\text{C)}$$

$$Ba \approx 10^{-3} \text{ mmHg}$$

1) could be alloy of Ba and Cs.

2) Ba and sep. solution (or alloy) of say tin and Cs

Ce<sub>2</sub>O ANL 5107 / Alven Glassner)

Working p 1500 K (1200°C)  
mp. 763 K

heat of evap 37 kJ/mol

heat of fusion 7 " "

$$Q = 44000 \text{ cal}$$

$$\ln p = \frac{44}{1.987} \left( \frac{1}{K_{\text{amb}}} - \frac{1}{K} \right)$$

gases  $\sim 10^{-6.5}$  atm per  
 $R = 750 \text{ (} 450^\circ\text{C)}$

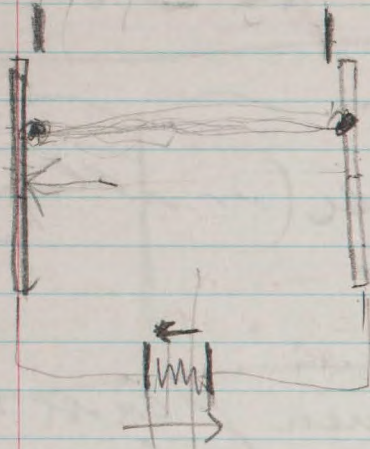
Aim:  $W_1 = 2.3$

$$W_2 = 1.00$$

gain 1 Volt "fall" 0.3 Volts  
High Temp = 1500°C (1800 K)

# Optimum

$$V \left( -\frac{W_1}{eRT_1} - e^{-\frac{W_2 + W_1 - W_2 - V - R_S}{RT_2}} \right)$$



$$Q_1 - Q_2 = \frac{T_1 - T_2}{T_2}$$

$$\frac{W_1 - W_2}{Q_1} = \frac{1}{2}$$

$$\frac{Q_1}{Q_2} = \frac{A}{Q_2} = \frac{T_1 - T_2}{T_2}$$

$$Q_1 = 2Q_2$$

$$W_1 = 2W_2$$

$$A = \frac{2000 - 500}{500} = 3$$

$$\frac{A + \text{Loss} + W_2}{W_1} = \frac{W_1 - W_2}{W_1}$$

$$\frac{A + \text{Loss}}{W_1} = \frac{W_1 - W_2}{W_1}$$

$$Q_2 = 1 \text{ Volt}$$

$$W_1 - W_2 \geq \frac{A}{T_2}$$

Wilson 2305 Calle de Oro



# Bismuth

Na marginal at  $(1500-32) \frac{5}{9} \approx 815^\circ\text{C}$  <sup>±0</sup> <sub>9</sub> <sup>H</sup>

probably usable with Ni and Ta  
Na<sub>2</sub>O dangerous

good idea in temp. 1200 F°

g.A. gas 1400 F°  
steam 1600 F°

Na 1000 F° SRE Aluminics just  
 $\frac{5000}{9} = 550^\circ\text{C}$  (North American)

Magnesium in Steel mp 650

indium undesirable?

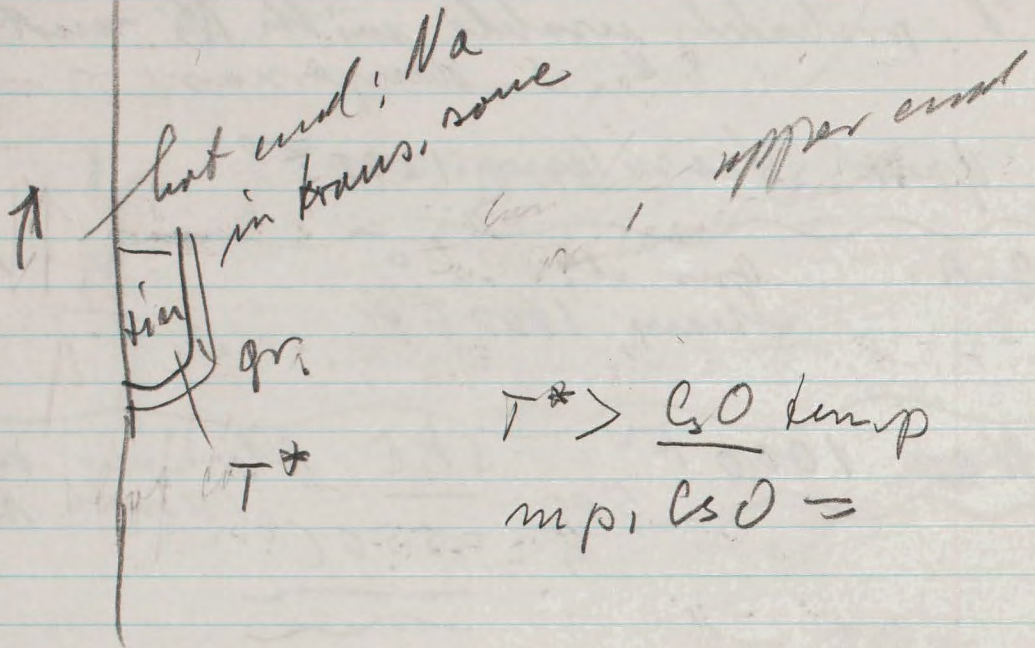
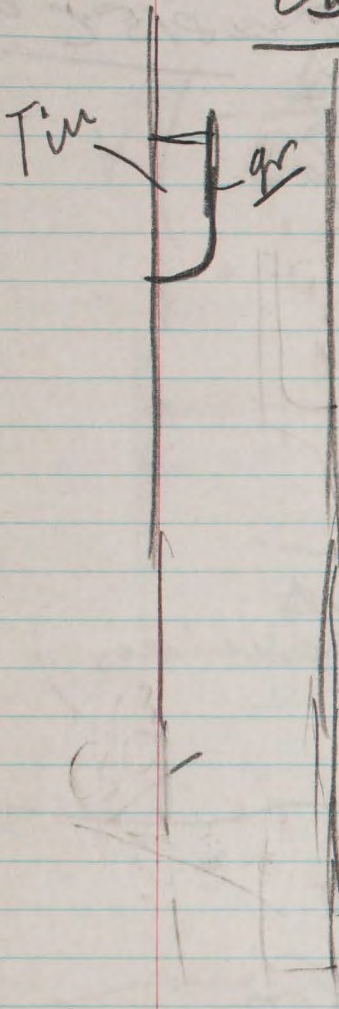
Lead in Steel in Graphite

tin in graphite

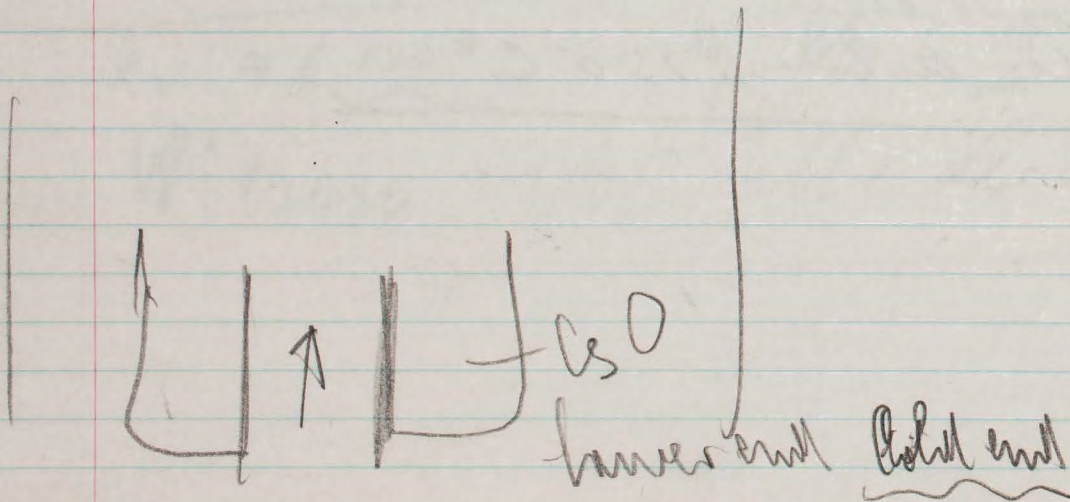
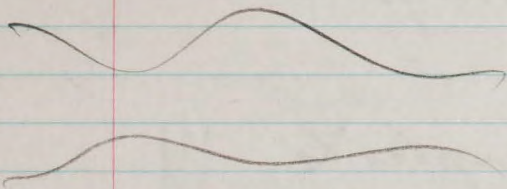
Thermal prop. of oxides,

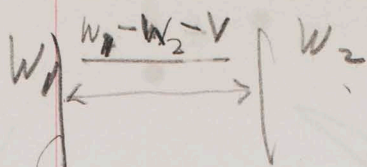
U Carbide below 1750 C°

# CS leach in Tin



$$T^* > \frac{C_2O \text{ temp}}{m p_1 C_2O} =$$





AA

$$A J_1^2 e^{-\frac{W_1}{kT_1}} = A T_2^2 e^{-\frac{(W_2 + W_1 - W_2 - V)}{kT_2}}$$

$$2 \ln T_1 - \frac{W_1}{kT_1} = 2 \ln T_2 - \frac{W_1}{kT_2} + \frac{V}{kT_2}$$

~~2 ln T1~~

~~$$\frac{V}{kT_2} = \frac{W_1}{kT_1} - \frac{W_2}{kT_2} - 2 \ln \frac{T_1}{T_2}$$~~

~~$$T_2 = \frac{T_1}{p} \quad V = \frac{W_1}{p} - W_2 - 2kT_2 \ln \frac{T_1}{T_2}$$~~

$$\left\{ \begin{aligned} 2 \ln \frac{T_1}{T_2} + \frac{W_1}{kT_2} - \frac{W_1}{kT_1} &= \frac{V}{kT_2} \\ V &< W_1 - W_2 \end{aligned} \right.$$

$$2kT_2 \ln \frac{T_1}{T_2} + W_1 - \frac{W_1}{p} = V = W_1 - W_2 + kT_1$$

$$-kT_1 + 2kT_2 \ln \frac{T_1}{T_2} + W_2 = \frac{W_1}{p}$$

if  $W_2$  is lowered  $p$  can be made higher

$$p \approx \frac{W_1}{W_2}$$

Half tennis

2 Volt

demand  $\frac{1}{2}$  Sat current

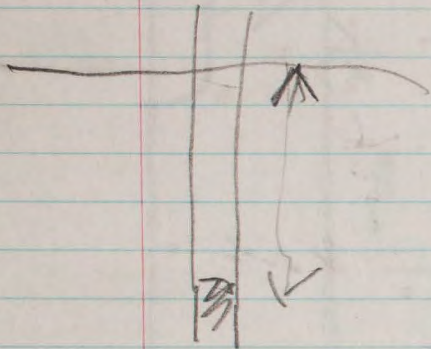
$$\frac{1}{2} A T_1^2 e^{-\frac{W_1}{kT_1}} = A T_2^2 e^{-\frac{W_1 - V}{kT_2}}$$

~~$$\frac{1}{2} 2 \ln p - \ln 2 - \frac{W_1}{kT_1} = -\frac{W_1}{kT_2} + \frac{V}{kT_2}$$~~

$$2kT_2 \ln p - kT_2 \ln 2 - \frac{W_1}{p} + W_1 = V$$

~~Maxwell's Equations~~

Capillary depression



$$h = \frac{2\gamma}{r \rho g}$$

$\gamma \approx 520$

$$h \approx \frac{2}{r \rho}$$

$$r = \frac{1}{1000} \text{ cm} \quad h = 200 \text{ cm}$$

$$d = 10$$

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Jim Arnold 4-17-46

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Comp.  $e^{-\frac{WV}{kT}} \approx e^{-\frac{PVT}{P}}$

# General

be now from theorem 1  
dynamics

$$\frac{A}{Q_1} = \frac{T_1 - T_2}{T_1}$$

$$e^{-\frac{w+x}{RT}} = \frac{1}{e} e^{-\frac{w}{RT}} \quad || \quad e^{-\frac{x}{RT}} = \frac{1}{e}$$

$$RT = \frac{1}{6} \text{ Volt} \quad \frac{x}{RT} = 1 \quad x = \frac{1}{6} \text{ Volt}$$

$$Q_1 = W_1 + \frac{1}{6} \text{ Volt}$$

$$A = Q_1 - Q_2$$
$$A = W_1 + \frac{1}{6} - W_2$$

$$\frac{W_1 + \frac{1}{6} - W_2}{W_1 + \frac{1}{6}} = \frac{T_1 - T_2}{T_1} = \frac{p-1}{p}$$

$$p(W_1 + RT - W_2) = p(W_1 + RT) - W_1 - RT$$
$$+ W_2 p = +W_1 + RT$$

$$p = \frac{W_1 + \frac{3}{2} RT}{W_2} \quad p \approx \frac{W_1}{W_2}$$

$$W_2 = 1 \quad W_1 = 2$$

$$\left. \begin{array}{l} K_1 = 1800 \\ K_2 = 900 \end{array} \right\}$$

$$\left. \begin{array}{l} W_2 = 1.00 \\ W_1 = 1.80 \\ \frac{3}{2} RT_1 = 0.20 \end{array} \right\}$$

Hull

No cathode at  $750^{\circ}\text{C}$

Anode at  $180^{\circ}\text{C} \sim 0.035 \text{ mg of Cs}$

$\frac{1}{2}$  Saturation at 1 Volt "loss"

Int. emission  $1 \text{ Amp/cm}^2$

$W = 1.63$  Work function ( $A = 120$ )

✓ D. S. Epstein Textbook of  
Thermodynamics (John Wiley & Sons)

N.Y. 1937 p. 365

A.W. Wilson The Theory of  
Metals Cambridge Press  
Cambr., Engl. 1953, second ed.  
pp. 119-120. —

Abstracts of Raye

Proc. Y.R.F.

p. 1574 (Sept) 1952

1) J. B. Taylor and I Langmuir  
Phys. Rev. 44, 423-452, 1933

see fig 15 p. 438.

2) Taylor and Langmuir Phys  
Rev 51 753-760; 1937

3) R.J. Bunday Electronics 20 Pt 2

July 47 97-99

Richard S. Frankel; Nuclear Science  
and Eng. Corp. || Dr. Paul Kruger; for permeability  
permeability. — || Dr. Ely " "

German Graphite: De Gussa with  
Brown Boveri ~ Krupp. —

Kaiser ~ A. C. F. [Am Car and Foundry] Washington  
Eng. (Oakland) Harold Abshire, in charge; Wash. D.C.  
Stenographic

~~Abstract~~ Dr. Allan Schoen Currier, Sr. Res Lab.  
fundamental work of diff. in solids. —

Hal Lewis  $Q_{MT} = R(T_1 - T_2) \ln \frac{T_1}{T_2}$   
 $T_d \approx 6$

G. M. Grover, D. J. Ruchling, and  
E. W. Salmi and R. W. J. Pidd  
p. 1011 [Vol 29, Nov 1957]

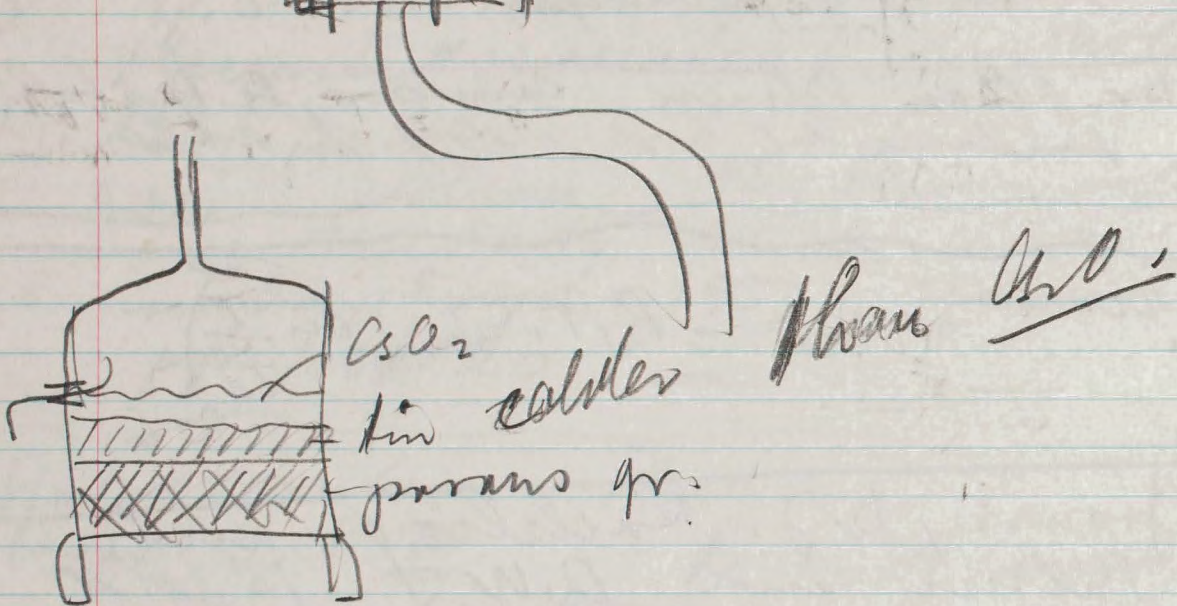
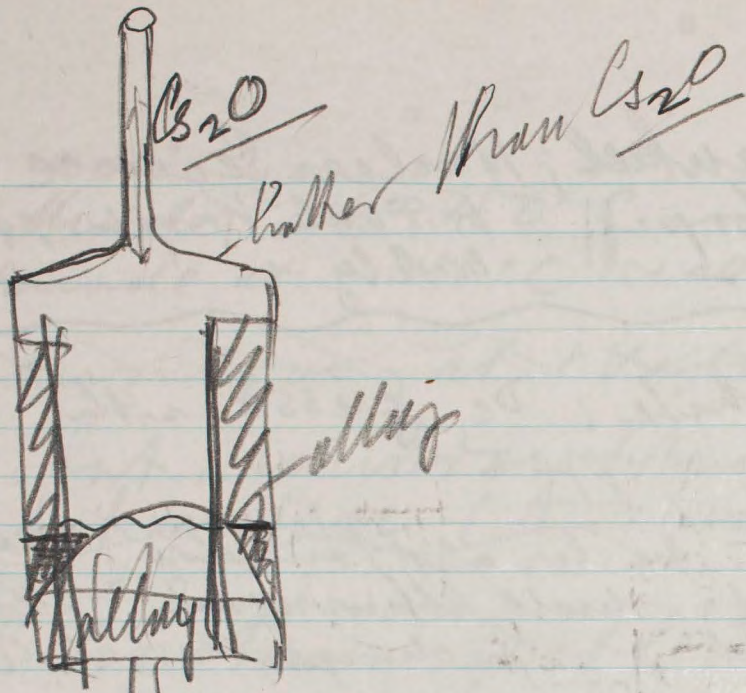
Journal of Applied Phys

They quote:

V. C. Wilson  
Bull Am. Phys. Soc. Ser II  
3. 266, 1957.

J. Medeiros, G. Welner  
J. Applied Phys 22  
p. 1329, 1951. —  
Holary Mass insert.

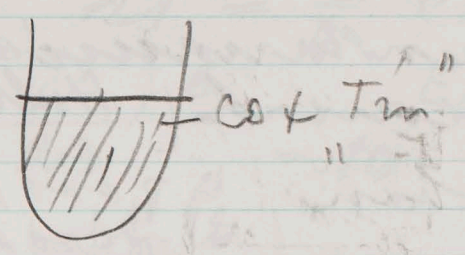
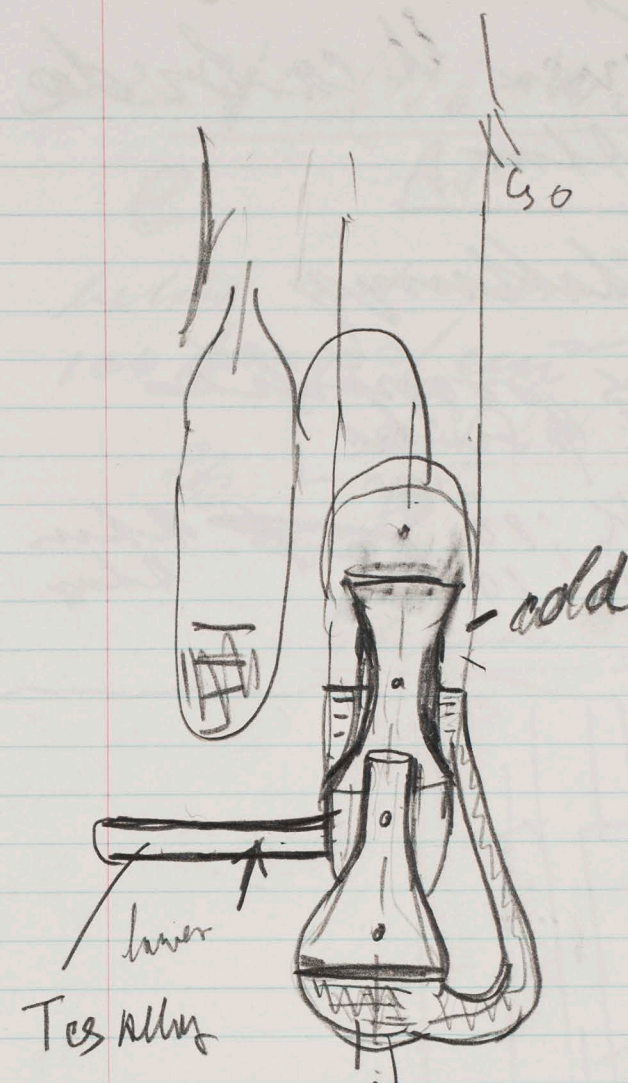
J. N. Matsopoulos MIT June 57  
June 56



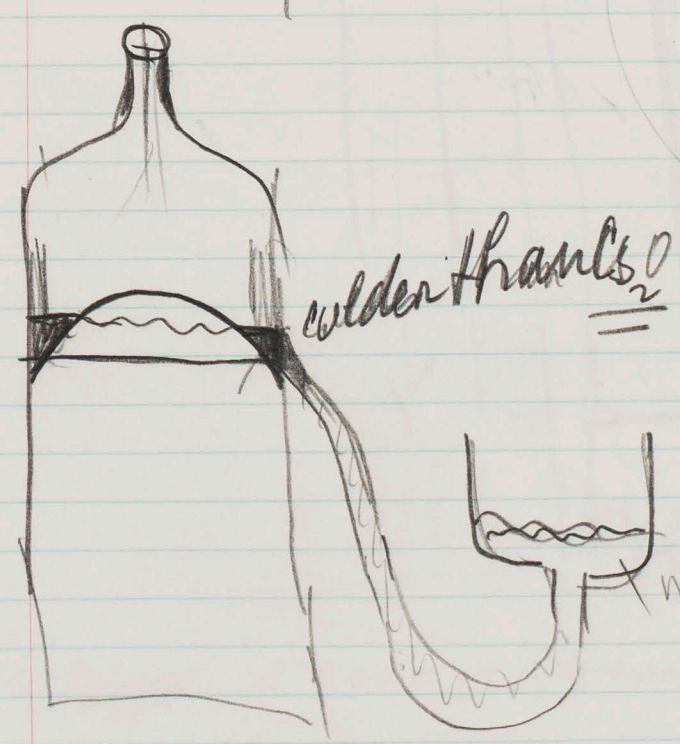
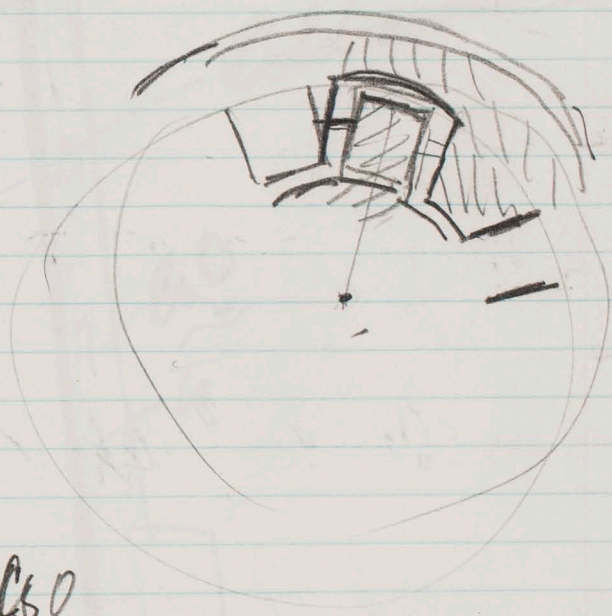
$\text{Cs}_2\text{O}$  holder than inside?



calder h



$$T_{CS} > T_{CS_2} < \text{Watt Snuck}$$



Ed Anderson

U pressure ~~at~~ over U carbide  
at 1900K.  $10^{-10}$  atm

Chemistry and Metallurgy

Thermodynamic properties  
of elements [ Still p. 516 ]

Carbon  $2,000\text{K}$ ;  $10^{-10.5}$  atm  
 $2,500\text{K}$ ;  $10^{-6.7}$  atm

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June 25 52

$$\frac{-V - (W_1 - W_2)}{e RT}$$

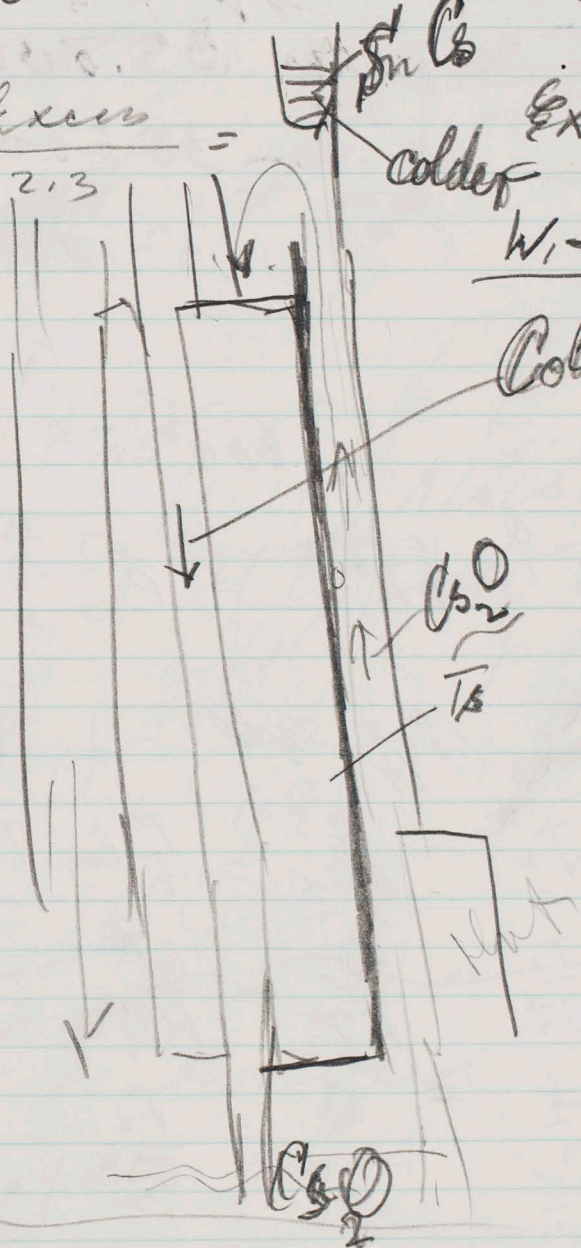
H

below sat currents

100 Amps/cm<sup>2</sup>  $RT = \frac{1}{6} \text{ eV}$

~~2.3~~  $\frac{-V - (W_1 - W_2)}{10 \cdot 2.3} \cdot 6 = 10$  - Excess  $\frac{6}{2.3}$

6 Excess =  $\frac{2.3}{2.3} = 1$  Excess =  $\frac{2.3}{6} = 0.4$   
 " 6" Volt  
 $W_1 - W_2$ , exceeds 20%  
 Cold coolant



1 Volt = 11,600  
2000

~~12,000~~ 2 2000 = ~~4000~~  $\frac{16,000}{6 \cdot 10^{23}}$

Sr. 77.4 kcal/mol ads layer  
 Ba 80.7 " " ads layer

1 e volt =  $1.6 \cdot 10^{-12}$  erg =  $1.6 \cdot 10^{-19}$  joule  
 =  $4 \cdot 10^{-20}$  cal  
 $4 \cdot 10^{-20} \times 6 \times 10^{23} = 24,000$  cal per mol  
 for 1 Volt

$Q^*$ for Ba at $\theta = p$	35.700
$Q^*$ for Ca " "	38.600
$Q^*$ for Sr " "	33.800

$T_2$  1400 K  
 2000 K

$600^* = T_2^*$

$T_2 \parallel \quad e^{-\frac{Q}{T_2}} \sqrt{T_2^*} = e^{-\frac{Q}{T_2^*}} \sqrt{T_2}$

$Q^* = \frac{1}{2} Q$  *Mag. 1/2*

$\frac{1}{2} \ln T_2^* - \frac{Q^*}{RT_2^*} = \frac{1}{2} \ln T_2 - \frac{Q}{RT_2}$

$\frac{1}{2} \ln \frac{T_2}{T_2^*} = \frac{Q}{RT_2} - \frac{Q^*}{RT_2^*}$

order of  $\frac{1}{2} = \frac{Q}{Q^*} = \frac{T_2}{T_2^*}$

W-Ba

H

James Ba on W

$Q = 3.7 \text{ Volt}$

for 0.3 coverage

$10^{11} \cdot e - \frac{Q}{RT}$

$(\text{or } 10^{10} - 10^{12})$

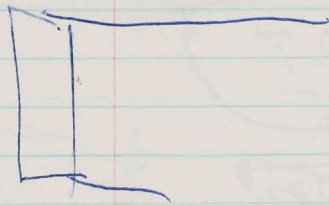
$0.5 \text{ p dynes}$

$\sqrt{20 \text{ m bar}}$

steric hindrance prob.

$\frac{p}{RT MRT}$

$\frac{2}{3} \cancel{N} m v^2 = p$



Paper J. E. Moore  
H. W. Allison

J. of Chem Phys.

Vol 23 p 1609 / 55

Mono layer  $\phi$  2.2V Work functions  
Ba 1.9V

$A = 60$

extrapolation

if T is doubled

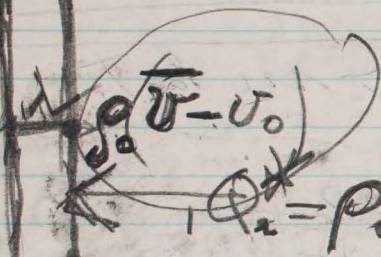
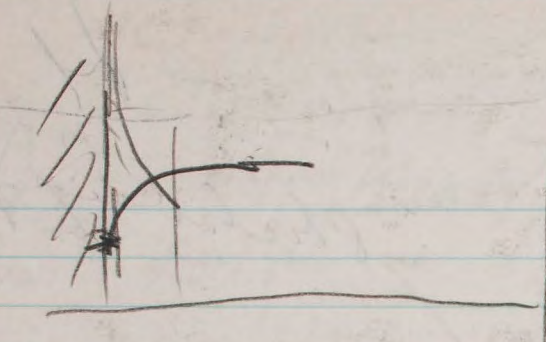
$\frac{p_1}{p_2}$  p dynes with

$\frac{e^{-\frac{Q}{RT_1}} \sqrt{T_1}}{e^{-\frac{Q}{RT_2}} \sqrt{T_2}}$

$\frac{p_1}{p_2} = \frac{e^{-\frac{Q^*}{T_1^*}} \sqrt{T_1^*}}{e^{-\frac{Q^*}{T_2^*}} \sqrt{T_2^*}}$

$\frac{e^{-\frac{Q^*}{T_1^*}} \sqrt{T_1^*}}{e^{-\frac{Q^*}{T_2^*}} \sqrt{T_2^*}}$

for ads.



$$\frac{e(\rho_0 - \Delta) v_0 = i}{e \rho_0 \bar{v} = j_0}$$

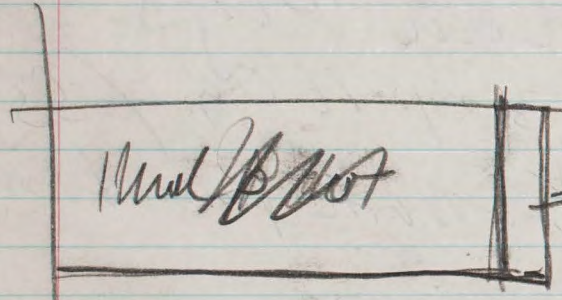
$$Q_x = \rho_0 (\bar{v} - v_0) \frac{m(\bar{v} - v_0)^2}{2}$$

$$Q = \rho_0 \bar{v} \frac{m \bar{v}^2}{2}$$

$$j_0 = \frac{1}{3} \bar{v} \rho_0 e = \frac{1}{\sqrt{3}} \frac{RT}{m} \rho_0 \frac{m \bar{v}^2}{2} = \frac{3}{2} RT$$

$$\bar{v} = \sqrt{\frac{3RT}{m}}$$

$$v_x = \sqrt{\frac{RT}{m}}$$



~~Unal pot~~

~~$$RT dv = \frac{3}{2} R dT$$~~

~~$$\frac{dT}{dv} = \frac{2}{3} T$$~~

~~pot~~

~~$$\frac{RT}{v} dv = \frac{3}{2} R dT \quad \frac{dT}{T} = -\frac{2}{3} \frac{dv}{v}$$~~

~~$$\frac{dv}{v} = \frac{3}{2} \frac{dT}{T} \quad v = \frac{3}{2} \log T$$~~

~~$$\ln v = \frac{3}{2} \ln T$$~~

~~$$\frac{1}{v^2} = \frac{1}{T}$$~~

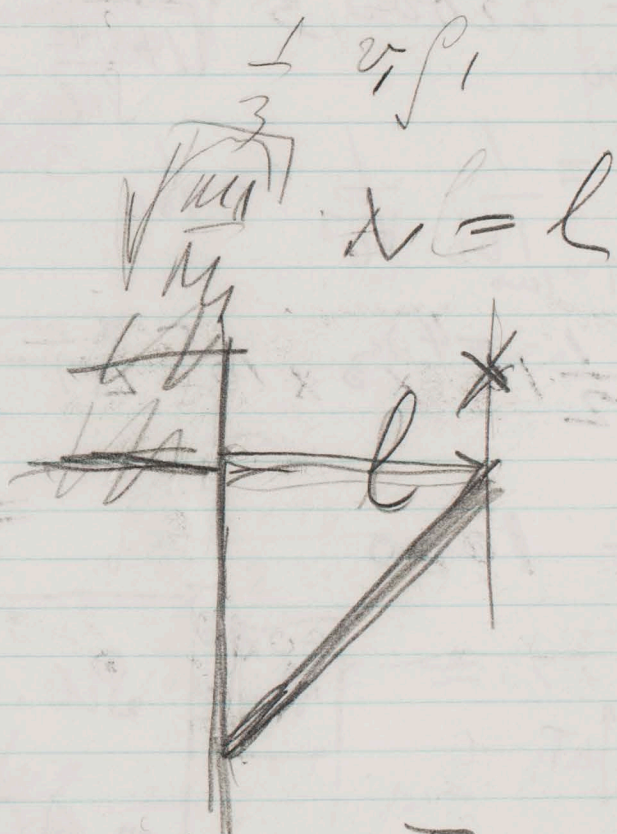
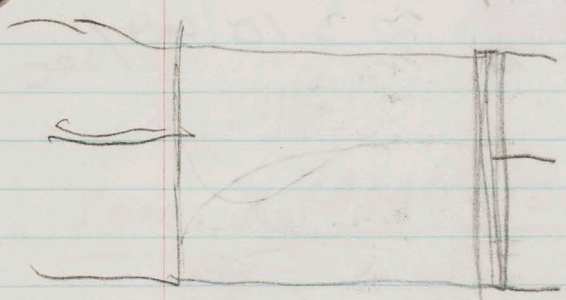
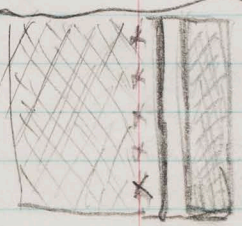
~~pot~~

Arnold <sup>1934</sup> Redman [p. 135 to 187]  
 London, Chapman & Hall Ltd 11 Henrietta St  
 W ~ Cs 1.54 Volt Pr. W.C. 2  
 or W ~ Cs 1.36 Volt  $A = 3.2$

Kingdon & Langmuir Phys Rev. 21. p. 380/23

Oxygen not lost from W. at ~~755~~

1550° K [J. A. Becker. Trans. Am. Electrochem. Soc. 55 p. 153, 1929]



Rond.

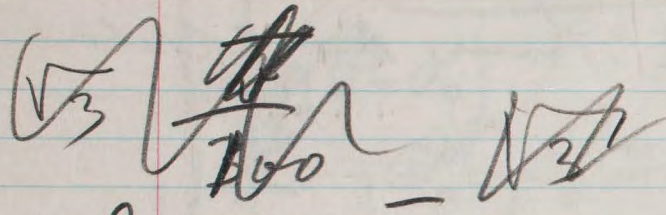
$$\Delta T \frac{3}{2} RT = \text{Kond } \Delta T$$

for the

-Ax

$$\lambda = \frac{1}{\sqrt{3}} \sqrt{\frac{\sigma_{sc}}{\sigma_a}} \approx \frac{1}{\sqrt{3}} 100$$

$$\frac{dJ}{dx} = \frac{\sqrt{3}}{100} \quad \text{diff} \left| \frac{1}{3} \times \rho \Delta T \frac{3}{2} R \right.$$



$$\frac{3}{2} R \Delta T \rho \frac{2}{3} \quad \rho = N/cc \text{ (atoms)}$$

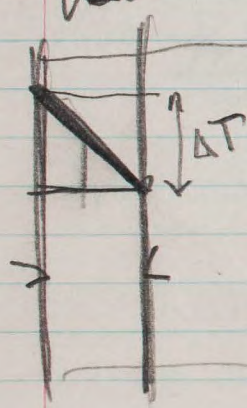
$$\frac{3}{2} R \frac{\rho_{atm}}{T/300} \frac{1}{22000} \frac{1}{3} \frac{\Delta T}{\sqrt{1 + \frac{\rho_{H_2}}{\rho_{el}}}}$$

$$\bar{v} = \frac{1}{100} \frac{1}{\sqrt{6}} \approx \frac{1}{100} 3 \cdot 10^{+7} \approx 3 \cdot 10^5 \text{ cm/sec}$$

$$\rho = 1 \quad \Delta T = 100 \quad \sqrt{6}$$

$$\frac{1}{2} \frac{R}{6} \frac{1}{2} 10^{-4} \times 3 \times 10^5 \Delta T =$$

$$4 \frac{1}{2} \frac{200}{10} \cdot 1000 = \text{watts}$$



$$\frac{30 \times 10^7}{10^4} =$$

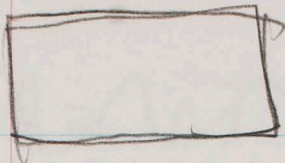
$$\rho_{el} \cdot \frac{3 \cdot 10^7}{10^4} \times \frac{1}{10^4} \frac{3}{2} R \Delta T l$$

$$= \frac{\Delta T}{l} \rho_{el} \frac{3}{2} R \frac{3 \cdot 10^5}{3} \frac{1}{10^4} l$$

$$\frac{1}{l} = \frac{\rho_{el}}{10} \frac{3 \cdot 10^7}{10^4} \frac{3}{2} \times 100'' R$$

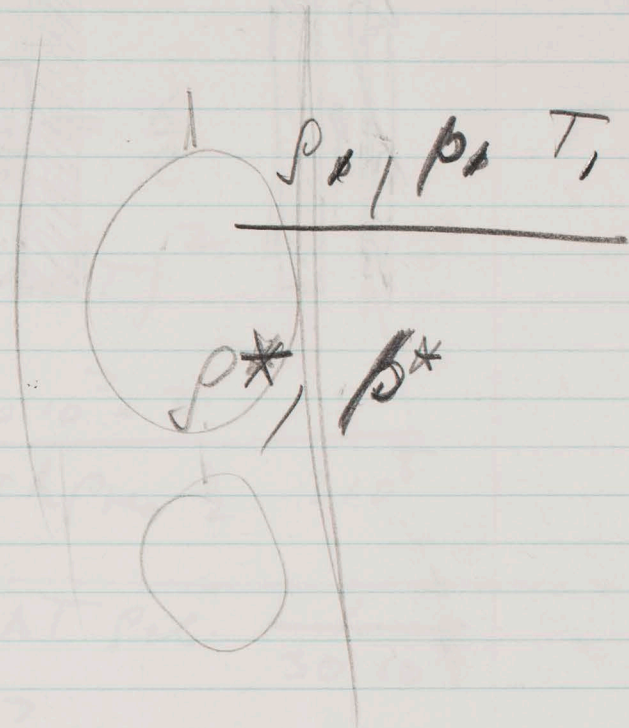
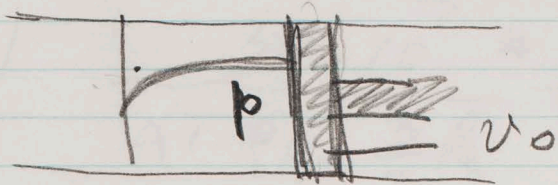
$$= \rho_{el} = \frac{10^5}{10^4} \frac{1}{10^4} \frac{1}{10^4}$$





M

$$\frac{RT}{2} = \frac{1}{2} RT$$



$$\rho v_0 =$$

$$\Delta T \approx \frac{1}{10}$$

$$\text{per collision } \frac{1}{20}$$

$$\frac{3}{2} RT$$

Pressure X 20 collisions X

$$\frac{\bar{v}}{6} \rho = \frac{1}{3}$$

$$\rho = \frac{6 \times 10^{23}}{22,400}$$

$$p = kT \rho = \frac{6 \rho_0}{\bar{v}} kT$$

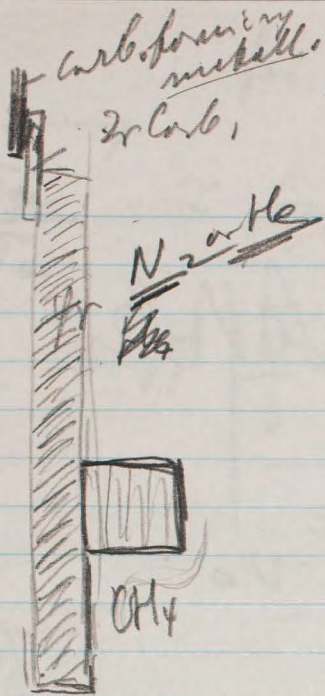
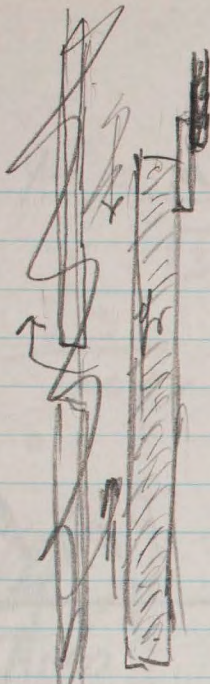
$$22,400 p \bar{v} = RT$$

Rate of energy influx  $\frac{6 \times 10^{23}}{\bar{v}} p = RT$  must be

$$\frac{6 \rho_0}{\bar{v}} kT v_0 = 6 \rho_0 \frac{kT}{10}$$

$$\frac{v_0}{\bar{v}} = \frac{1}{10}$$

$$p = kT \rho$$



$$W = \rho \Delta T$$

$$1.) \quad \frac{1}{\rho} = \rho_{cl} \frac{1}{10^5} \frac{3}{2} h \Delta T$$

$$2.) \quad \frac{30 \cdot 10^7 \cdot 3}{4T \rho_{He} \frac{3}{2} R} = \frac{1}{\rho}$$

$$30 \cdot 10^7 \cdot 3 = (h \Delta T)^2$$

$$\rho_{cl} h \Delta T \frac{3}{2} \frac{1}{10^5} = \frac{30 \cdot 10^7 \cdot 3}{4T h \rho_{He} \frac{3}{2} 3 \cdot 10^5}$$

$$\frac{\lambda_{cl}}{\rho} = 3 \cdot 10^7 \frac{1}{10^4} \frac{3}{2} h \Delta T \rho_{cl} \frac{1}{30 \cdot 10^7}$$

$$\frac{\lambda_{He}}{\rho} = \frac{30 \cdot 10^7}{h \Delta T \frac{3}{2} \rho_{He}}$$

$$\frac{1}{10^5} \frac{3}{2} h \Delta T \rho_{cl} = \frac{3 \cdot 10^3}{B h \Delta T \rho_{He}}$$

$$\lambda_{cl} = \frac{\lambda_{He}}{B} (h \Delta T)^2 \rho_{cl} \rho_{He} = 2 \cdot 10^8$$

$$(h \Delta T)^2 \frac{\rho_{cl} \rho_{He}}{6 \cdot 6} \left( \frac{1}{2 \cdot 2 \cdot 10^4} \right)^2 = 2 \cdot 10^8$$

$$\frac{4 \times (100)^2 (4 \cdot 10^7)^2 \rho_{cl} \rho_{He}}{36} \frac{1}{4 \cdot 10^8} = 2 \cdot 10^8$$

$$\rho_{cl} \rho_{He} = \frac{8 \times 36 \times 10^{16}}{4 \cdot 10^8}$$

$$\rho_{cl} \rho_{He} = \frac{2 \cdot 36}{16} 10^{-2} = \frac{5 \cdot 10^{-2}}{B}$$

Test body assumption from H  
at little recombination in  
case of  $K = 2000$  at kat trade

$$\text{Rec at } t = \frac{1}{10} \quad \left| \quad \frac{2 \times 10^{19} \text{ l}}{10^3} = 2 \cdot 10^{16} \text{ l}$$

5 kat trade in 5 years

$$v = 10^5 \quad \frac{1}{L} \frac{10^5}{\sigma} = \frac{1}{3} 10^{16}$$

$$L = 3 \cdot 10^{12} \quad \text{perm } \sigma = 10^{-11}$$

$$l = 3 \cdot 10^{12}$$

$$= 6 \cdot 10^{14}$$

# Testing wrong branch of little recombination:

ionization ~~rate~~ per sec per cc

$$\nu f \rho e^{-\frac{\nu}{kT}} (1-f) \rho \sigma = A(\rho \rho)^2$$

$$\sigma = 3 \cdot 10^{-14} \text{ cm}^2 \quad \text{rather large unphysical assumption}$$

$$\frac{125}{5} \cdot \frac{\text{cm}^3}{\text{sec cm}^3} \cdot 3 \cdot 10^7 \cdot \frac{1}{5} \cdot 10^{-6.5} \cdot \rho^2 \cdot \left[ \frac{3 \cdot 10^{-14}}{5} \right] = A \rho^3$$

change  $\sigma = 3 \cdot 10^{-15}$

$$125 \cdot 3 \cdot 10^7 \cdot \frac{1}{5} \cdot 10^{-6.5} \cdot \left(\frac{1}{2}\right)^2 \cdot \left(\frac{1}{10}\right)^2 \cdot 3 \cdot 10^{-15} = A \rho^3$$

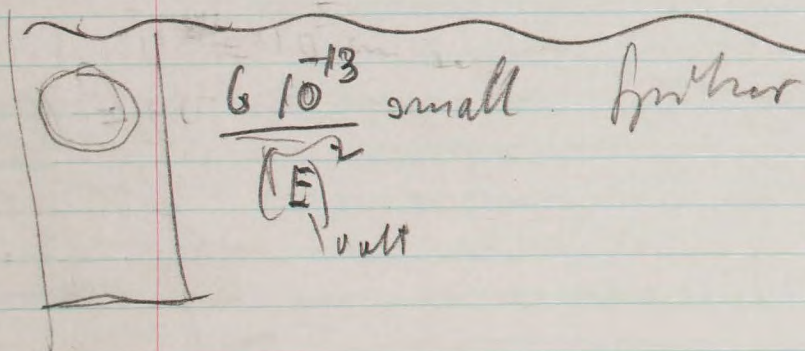
$$\frac{3 \cdot 7.5 \cdot 10^8}{4 \cdot 3} \cdot 10^{16} \cdot 10 \cdot 10^{-6} \approx 2 \cdot 10^{19} = A \rho^3$$

Recomb at  $f = \frac{1}{2}$   $\frac{2 \cdot 10^{19} \cdot \rho}{8} \text{ l/sec} = \frac{2 \cdot 10^{19}}{8} \text{ l/sec}$

Diff of Cs. ions.  $\left[ \sigma = 2 \cdot 10^{-12} \right]$  "optimistic"

$$\rho \frac{v_{eff}}{3} \frac{1}{l} \approx \frac{v_{eff}}{3} \frac{1}{\sigma l} = \frac{10^5}{3} \frac{10^{12}}{2} \frac{1}{l} = \frac{1}{6} \cdot 10^{17} \frac{1}{l}$$

$\sigma = 10^{-11}$  pessimistic



Call transfer from He to electrons.

3000°K

assume  $\sigma_{He} = 36 \cdot 10^{-16} \sim 4 \cdot 10^{-15}$

loss of factor  $\frac{1}{5 \times 2} 10^{-4}$  or  $10^{-3}$

gain of factor 35

total loss of factor  $30$

At pressure of He 1000 times higher gain of factor 30 gives  $l = 10^{-1}$  cm

In He; heat transfer by conduction to Cs

2 low temp by factor 6

$$\frac{3}{2} \frac{v^*}{3} \frac{1}{\sigma} kAT \frac{1}{l} \times 1.6 \cdot 10^{-12}$$

$$v^* = 4 \cdot 10^5 \text{ cm/sec} \quad k = 3000$$

$$\sigma = \frac{1}{50} \cdot 3 \cdot 10^{-16}$$

$$v = 1.25 \cdot 10^5 \text{ cm/sec} \text{ room temp}$$

$$\frac{1}{2} \frac{4}{3} \cdot 10 \cdot 10^{16} \frac{1}{50} \frac{1}{l} \cdot 1.6 \cdot 10^{-12} =$$

$$\frac{6.4}{6 \times 5} \frac{10^8}{l} = 2.1 \frac{10^7}{l}$$

to get  $6 \cdot 10^8$  we need  $l \leq \frac{2.1 \cdot 10^7}{6 \cdot 10^8} \leq 3 \cdot 10^{-2}$  cm

In Cs

$$6 \times \sqrt{130} = 30 \text{ times worse! at } l \leq 10^{-3} \text{ cm}$$

This is neglecting electron exchange between Cs-He

$$K = 3000$$

$$\rho_{cs} = \frac{1}{8} 10^{32}$$

$$\text{Transf.} = \frac{3}{2} \frac{1}{5} \frac{2.45}{\sqrt{2}} \cdot \frac{1.6}{2.35} \frac{1}{5} \frac{2}{5} 10^{32} 10^6 10^{-12} 10^{-5} 10^{-11} \times l$$

$$= \frac{3 \times 2.45}{10} \frac{3.2 \times 1.22}{25 \times 2.35} \times \frac{1}{2} \times 10^{26} \times 10^{-16} =$$

$$= \frac{2.29}{1200} = 2.4 \times 10^8 \quad \text{corrected value for } K=3000 \quad l \frac{1}{\sqrt{\rho_{cs}}} = 6 \times 10^8$$

Excited transfer:

3000K // per transfer  $\frac{3.8}{2}$  excited fraction  $2 \times 10^{-2.4}$  }  $3.8 \times 10^{-2.4} \times 1.6 \times 10^{-12}$  per cell

$$\text{Transf.} = \frac{1}{5} \times 3.8 \times 1.6 \times 10^{-12} \frac{1}{2.8} 10^{16} \times \frac{1}{2.8} 10^{16} \times 3 \times 10^{-14} \frac{1}{\sqrt{2}} 2.45$$

$$= \frac{3.8}{5} \times \frac{1.6}{2.8} \frac{3}{2.8} \frac{\sqrt{3}}{2} 2.45 \times \left\{ \frac{1}{3} 10^5 10^{32} 10^{-26} \right\}$$

$$\frac{1}{3} \frac{55}{40} 10^{10} = 4.5 \times 10^{10} \quad \frac{1}{\sqrt{\rho_{cs}}} l = 10^{10}$$

$$l \approx 10^{-2} \text{ cm} \quad 6 \times 10^8$$

$10^8$  is the bubble  $6 \times 10^8$  desired.

$K=2000$   $10^{-2}$  et dens.  $10^1$  etc. probable

$K=3000$  heat transfer in  $\mu\text{m}$   
 $\frac{1}{\sigma} \frac{3}{2} \frac{1}{3} \frac{1}{K} \Delta T$   
 $h = \frac{1}{\rho \sigma} \frac{1}{50}$

$l = 10^{-2} \text{ cm}$   
 $1.6 \times 10^{-12} \times 100$   
 $20 \times 10^{-16}$

$$= \frac{3}{2} \frac{1}{5} 10^5 \frac{1}{50} \times 1.6 \times 10^{-12} \frac{1}{20} 10^{16} \times 100$$

$$v = \frac{3 \times 10^7}{\sqrt{1301800}} = \frac{3 \times 10^7}{\sqrt{23.5 \times 10^5}}$$

Expected transfer for Bel Nour

H

$p = 1 \text{ m}$

$$\frac{1}{\sqrt{p_m}} 2 \times 10^{-3} p_0^2 v_0^* 2 \times 10^{-3.65} \quad \ell \times \frac{1}{2} 3 \times 10^{-12} \quad \text{B} 10^8$$

$$v_0^* = 25 \times 10^{-16} = 2.5 \times 10^{-15}$$

$$p_0 = \frac{1}{2} 10^{16}$$

$$\ell = 2 \times 10^{12} \times \frac{6 \times 10^{10}}{2 \times 2.25} \times \frac{10^3}{2 \times 2.45} \times 4 \times 10^{-32} \times 10^{15} \times 10^{3.65}$$

$$\ell = \frac{6}{5} \frac{4}{5} \times 2 \times 10^{2.65} \text{ cm} \quad -39$$

Waka:

$$\frac{f^2}{1-f^2} = 2.4 \times 10^4 T^{5/2} p^{-1} \ell \quad -\frac{3.8}{kT}$$

$k = 2000$	$10^{-10} \times 10^{-1} \times 10^{-4} \times 4 \times 10^6 \times 45 \times 2.4 = p^{-1} 4.3 \times 10^{-6}$	$f = \sqrt{\frac{\ell}{p_m}} \times 10^{-3}$
$k = 2500$	$10^{-8.25} \times 10^{-1} \times 10^{-4} \times 6.25 \times 10^6 \times 50 \times 2.4 =$	$f = \sqrt{\frac{\ell}{p_m}} \times 10^{-2}$
$k = 3000$	$10^{-6.6} \times 10^{-1} \times 10^{-4} \times 9 \times 10^6 \times 55 \times 2.4 =$	$f = \sqrt{\frac{\ell}{p_m}} \times 10^{-1}$

$$\frac{10^{-6} \times 5 \times 10^{-4} \times 10^8 \times 5}{3.1} = 4 \times 10^{-2}$$

$$3.1 \frac{10^{-8}}{1.8} \times 10^{-4} \times 10^8 \times 2.4 = 4.5 \times 10^{-4}$$

K=3000 call transfer

$$\frac{3}{2} \frac{1}{\sqrt{p_m}} \frac{1}{5} p_0^2 2.45 \times 10^7 \sqrt{\frac{3}{2}} \frac{1}{50} 1.6 \times 10^{-12} \times \frac{2 \times 10^{-11}}{5} \ell$$

$$p = \frac{1}{760} \frac{1}{2.2 \times 10^{10}} \times 6 \times 10^{18} = \frac{6}{7.6 \times 2.2} \times 10^{16} = \frac{1}{2.8} \times 10^{16}$$



Lufffeld

$$K = 2000$$

$$\rho = \frac{1}{1000} \text{ Atm}$$

$$\rho_0 = \frac{6 \times 10^{23}}{1000 \cdot 22400} \cdot \frac{1}{6}$$

$$\rho = \frac{1}{2.24} \cdot 10$$

$$\sqrt[3]{\rho_0} \frac{v^* \Delta T}{3} \frac{3}{2} k v = z$$

$$\frac{1}{\sqrt[3]{z}} = \rho_0^* \quad 2) \frac{1}{\sigma^*} \frac{v^* \Delta T}{3} \frac{3}{2} k = z$$

$$\frac{1}{3} \rho_0^2 (2) 10^{-7.3} \frac{\sigma}{\sigma^*} v \left( \frac{3}{2} k \Delta T \right) v v^* = z^2$$

$$\frac{1}{\sqrt[3]{3}} \rho_0 2 \times 10^{-3.65} \sqrt{v v^*} \frac{3}{2} k \Delta T \sqrt{\frac{\sigma \Delta T}{\sigma^*}} = z = 6 \cdot 10^{10}$$

$$\sigma = 20 \cdot 10^{-16} = 2 \cdot 10^{-15}; \sqrt{\frac{\sigma \Delta T}{\sigma^*}} = 100$$

$$\frac{v}{v^*} = \sqrt{\frac{130 \cdot 1800}{2.3 \times 10^5}} = 500$$

$$\sqrt{v v^*} = \sqrt{\frac{v^2}{500}} = \sqrt{\frac{2.45^2}{500}} \cdot 10^{14}$$

$$\sqrt{v v^*} = 1.1 \times 10^6 \quad k \Delta T = \frac{1}{60}$$

$$\sqrt[3]{\frac{1.1}{2} \cdot 10^{16} \cdot 10^{-3.65} \times 10^6 \cdot 3 \cdot \frac{1}{60} \cdot 10^2 \cdot 10^{-12}} =$$

$$\Rightarrow \frac{\sqrt[3]{3 \times 1.1 \times 4.8}}{2 \times 6} \cdot 10^{\text{Exp}\{10 - 1 + 2 - 3.65\}} = 10^{+7.35}$$

$$3 \times 10^{-19.3} \rho^2 = \frac{1}{e}$$

ionic transfer Krypton ~ Cl

W

thus 1)  $\frac{3}{2} k \frac{v^*}{3} \rho^* \frac{\Delta T}{l} = \text{exp/ann} \sim \text{rec}$

$v^*$  for  
 $N^*$  is the in the

2)  $\frac{3}{2} k \rho \frac{v}{N} \frac{1}{10^4} \frac{\Delta T}{30} = \text{?}$

$\frac{1}{3} \left( \frac{3}{2} k \Delta T \right)^2 (\rho \rho^*) (v v^*) \frac{l^*}{N} = \text{?}^2$

$\sigma$  for

Yielded transfer :

$K=2000 \sim \frac{1}{2} 210^{-3.65}$  per collision  $\sim 10^{-3.65} \times 3.8 \text{ Valt}$   
Number of collisions/sec

$K=3000 \sim 10^{-2.4} \times 3.8 \text{ Valt}$  per collision  
 $K=2000 \rho = \rho_0 210^{-3.65}$        $K=3000 \rho^* = \rho_0 210^{-2.4}$

$\frac{1}{N} = \sigma u \rho$

number of coll/sec

$\rho \frac{v}{N} = \rho^2 v \sigma l$

$= \rho_0^2 (2)^2 (10)^{-7.3} \sigma v l$

$E$ -transfer ed

$\rho_0 (2)^2 10^{-7.3} \sigma v l = 60 \times 10^7 = 6 \times 10^8 / \text{ann} \sim \text{rec}$

$v = \frac{2 \times 3 \times 10^{10}}{10^{-3}} = 2.45 \times 10^7$

$u = \frac{2.45 \times 10^7}{\sqrt{6}} = 2.10^{11}$

$\rho_0^2 \times \frac{4 \times 2}{6} 10^{-7.3} 10^{11} \times 2.45 \times 10^7 \times 10^{-8} = \frac{1}{\rho}$

# Excited States Transfer

$$\frac{9000}{2500} = \frac{5}{4} + 10\% = 1.25 = \boxed{1.4 \text{ Volts in } C_2}$$

Number of excited states at  $n=2$ :  $-2.4$

$$2 e^{-8.4} \rho^* = 2 \times 10^{-3.65} \rho^* \quad \left| \quad 2 e^{-5.6} \rho^* = 10$$

$$K = 2000$$

$$K = 3000$$

Intermediate He  $\rightarrow$  C<sub>2</sub>

however,  $f_{21}$  would be better  
 $\frac{1}{20} \times \frac{30}{4}$  was a factor 2 because of velocity

## Yonic transfer

$$\frac{f^2}{1-f^2} = 2.4 \times 10^{-4} \times T^{5/2} \rho^{-1} e^{-\frac{3.8}{KT}}$$

$$\frac{1}{6} = 0.167 \quad K = 2000$$

$$0.25 \text{ at } K = 3000$$

at  $K=11$  600 °C

$$2000K e^{-\frac{3.8}{KT}} = 10^{-10} ; \quad f^2 = 4 \times 10^6 \times 45 = 1.8 \times 10^8$$

$$3000K \sim 10^{-6.6}$$

$$9 \times 10^6 \times 55 = 5 \times 10^8$$

$$\frac{f^2}{1-f^2} = 4.3 \rho^{-1} 10^4 \times 10^{-10}$$

$$2.4 \times 5 \times \rho^{-1} 10^4 10^{-6.6} = 1.2 \rho^{-1} 10^{-1.6}$$

$$f \ll 1 \quad f = \sqrt{4.3 \rho^{-1} 10^{-6}} \quad f = \sqrt{\rho^{-1} 2 \times 10^{-3}}$$

$$f \approx 1.1 \sqrt{\rho^{-1} 10^{-0.8}}$$

$$\rho_{\text{min}} \approx \sqrt{\rho_{\text{min}} 2 \times 10^{-3}}$$

$$f_{\rho} = 1.1 \sqrt{\rho^{-1} 10^{-0.8}}$$

$$\rho_{\text{min}}^* = f \rho_{\text{min}} = \frac{1}{760} \sqrt{\rho_{\text{min}} 2 \times 10^{-3}}$$

$$\rho_{\text{min}}^* = \frac{1.1}{760} \sqrt{\rho_{\text{min}} 2 \times 10^{-0.8}}$$

$$\bar{z} = \frac{4\sqrt{3}}{1.3} \sqrt{\rho p^*} \sqrt{v v^*} \Delta T \sqrt{\frac{A^*}{L}} \quad H$$

$$v = 1.25 \cdot 10^5 \times 2.5 = 3.1 \times 10^5$$

$$v^* = 0.5 \times 3.1 \cdot 10^5 = 2.6 \cdot 10^5$$

$$v v^* = 8 \times 10^{12} \quad \parallel \quad \sqrt{v v^*} = 2.8 \cdot 10^6$$

$$\bar{z} = \frac{4\sqrt{3}}{1.3} \times 2.8 \times 10^6 \Delta T \sqrt{\rho p^*} \sqrt{\frac{A^*}{L}}$$

$$\bar{z} = 30 \cdot 10^7 = 3 \cdot 10^8$$

$$\sqrt{\rho p^*} = \frac{\bar{z} \times 10^{-6}}{\Delta T \sqrt{\frac{A^*}{L}}} \times \frac{1}{15}$$

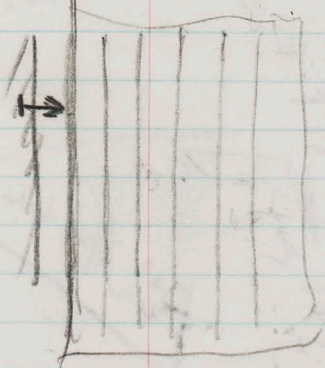
$$\sqrt{\rho p^*} = \frac{300}{\Delta T} \times \frac{1}{15} \times \frac{1}{\sqrt{\frac{A^*}{L}}}$$

Febr 9./59.

Check! O.K.

Repeat - in absence of Heat Transfer

$$\frac{1}{2} \frac{v}{3} \rho_0 \approx \frac{y_0}{3} ;$$



$$m 2k \Delta T = V$$

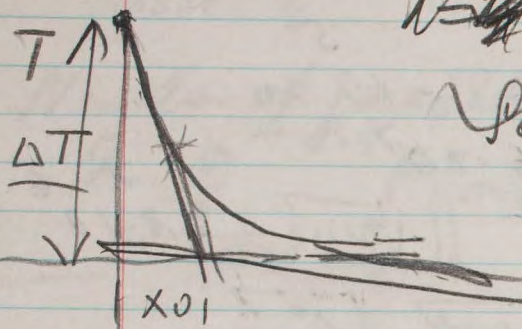
$$\Delta T = 200 \quad \frac{1}{60} \quad m = 30 V$$

$$V = 2 \quad \boxed{m = 60}$$

OR

$$V = 2 \quad \Delta E = kT \quad \frac{1}{V} e^{-\frac{\Delta E}{RT}} = \frac{1}{12} e^{-1} = 32.6$$

De Novo



~~$T_1 - T_0 = \frac{\Delta T}{x_0} x$~~   
 ~~$T_1 - T_0 = \frac{\Delta T}{x_0} x$~~   
 ~~$T_1 - T_0 = \frac{\Delta T}{x_0} x$~~

~~$v^*$  is  $\rho v$~~

~~$T_1 - T_0 = \frac{\Delta T}{x_0} x$~~   
 $T_1 - (1 - e^{-x/x_0}) \Delta T$

$\frac{dT}{dx} = -\frac{1}{x_0} e^{-x/x_0} \Delta T$

$\frac{dT}{dx}$  (initially) =  $\frac{\Delta T}{x_0} = \frac{\Delta T}{l}$   $x_0 = l$

$\frac{3k v^*}{2} \frac{\rho \Delta T}{3} = 2 \text{ ergs/sec}$

$\frac{3k \Delta T}{2} \frac{v}{l} \frac{\rho l}{10^4} = 2 \text{ ergs/sec}$   $\int_0^\infty x e^{-x} = 1$

1)  $\frac{3}{2} k \frac{v^*}{3} \rho \frac{\Delta T}{2} = \frac{2}{l^*}$

2)  $\frac{l}{l^*} = \frac{1}{l^*} \frac{l}{l} = 2 \cdot 10^4 \frac{1}{v \rho R \frac{3}{2} \Delta T} \frac{1}{l^*}$

$\frac{1}{3} \frac{3}{2} k v^* \rho \Delta T = 2 \cdot 10^4 \frac{1}{v \rho R \frac{3}{2} \Delta T} \frac{1}{l^*}$

$2^2 = \frac{1}{3} 10^{-4} v v^* \rho \rho^* \left(\frac{3}{2} R\right)^2 (\Delta T)^2 \frac{1}{l^*}$

$2 = \frac{1}{\sqrt{3}} 10^{-2} \sqrt{v v^*} \sqrt{\rho \rho^*} \times \frac{3}{2} R \Delta T \times \sqrt{\frac{1}{l^*}}$

$2 = \frac{1}{\sqrt{3}} 10^{-2} \sqrt{v v^*} \sqrt{\frac{\rho \rho^*}{N_0 N_0}} \frac{3}{2} R \Delta T \times \sqrt{\frac{1}{l^*}}$

Pinthun

$\frac{1}{6} \frac{\rho \rho^*}{22409} = \frac{\rho}{N_0}$

$2 = \frac{3}{\sqrt{3}} \frac{\sqrt{\rho \rho^*}}{1.3} 10^{-2} \sqrt{v v^*} 4 \times 10^7 \sqrt{\frac{1}{l^*}} \Delta T$

$2 = \frac{\sqrt{3} \times 4}{1.3} \sqrt{\rho \rho^*} \sqrt{v v^*} \Delta T \sqrt{\frac{1}{l^*}}$

Mean free paths  
 Esbeman

14

0°C / 1 atm	He	18	10 cm
	Ne	12.6	"
	A	6.4	"

Assumed: He on Pt  $450 \text{ K} = 0.21$   
 A on Pt  $650 \text{ K} = 0.65$

$$M \left( \frac{m v}{M} \right)^2 = \frac{m v^2}{M} \quad M v^2$$

Ramsey scattering large angle neutrons

$$\sigma = \frac{6 \cdot 10^{-20}}{\left( \frac{e \text{ Volts}}{1000} \right)^2} = \frac{6 \cdot 10^{-14}}{(\text{Volts})^2}$$

$K=2000$   $\left( \frac{+ \text{ Volt}}{6} \right)$   $\sigma = 36 \times 6 \cdot 10^{-14} = 2.15 \times 10^{-12} \text{ cm}^2 \times 10$

$K=3000$   $\frac{1}{4} \text{ Volt}$   $\sigma = 16 \times 6 \cdot 10^{-14} = 9.5 \times 10^{-13} \times 10$   
 $\sim 10^{-12} \times 10$

~~Wade~~ Wade  
~~Fyke~~ Fyke

Murray - 3 back

Murray

Murray, Burhop.

Bushman will account for  
with

Heat conductivity.  
Sewer Rd A. 519

$$\overline{v}^2 = .88 \times 10^{-16}$$

Al, Zn, Fly

H<sub>2</sub> 4.4 volt to smash

N.Y. Under  
Electric scattering  
Mel. G. et al.  
Bery, Bearden et al

In camp analysis

p. 36

$$\frac{\pi d^2}{4}$$

$$He = 2.18 \times 10^{-8}$$

$$Ne = 2.6$$

$$Ar = 3.67$$

$$Kr = 4.15$$

$$Xe = 4.91$$

Electron aff.  
0.5 - 0.7 Volt  
for electron pos.

<sup>↑ D.A.</sup>  
Lynch, Becher Val 7

Alldan, Moore 1 -

Advises  
on July 1955

Devil Hill

Wayne Bell  
L: 152

L: Bld 636



Pearsons J.A.  
Ted Taylor  
Turoulin for Proves.

Rosenbluth } Reactors  
Mark Nelkin }

Bob Wilson

{ Simrad  
Juminsky  
Walker Wallace

Oxley  
Cunningham

Mary Lou Stearns }  
I Cutler  
I Victor Lind  
Park Miller

Buffield  
Sumwalt  
Merten

Pigford }  
Forbes }  
Bill Thompson }

Werner B. Teutsch  
Edward C. McIrvine

{ Home: DOR 3134  
{ Gomer Ext 2552  
Chicago

D. recommendations: Leo Brewer  
Berkeley; Reactor physics: Pearson J.A.

13-23 Feb 1951

Helman Miner 468 W. Dubois Bang  
Art Thomson (draftsman) hart  
645

Estimate

Est 751  
BR 26161

Chesterton 53506  
L x A x

$$\frac{LJ}{S} = W_1 - W_2 - V$$

where J and S are measured  
in amp/cm<sup>2</sup>; W<sub>1</sub>, W<sub>2</sub>, V in volts.

$$\eta = \frac{JV}{R + JW_1}$$

$$R = 16 \left( \frac{T}{2000} \right)^4 \text{ watts/cm}^2$$

fix J<sub>0</sub> = 30 amp/cm<sup>2</sup>

W<sub>2</sub> = 1.5V

T = 2000K =  $\frac{1}{6}$  eV.

what is W<sub>1</sub> for η max; what is η max?

$$\eta S = 120 \cdot 4 \cdot 10^6 e^{-6W_1} = 4.8 \cdot 10^8 e^{-6W_1}$$

$$V = W_1 - W_2 - \frac{LJ}{S} = W_1 - 1.5 - \frac{120 \cdot 10^{-8}}{4.8} e^{+6W_1}$$

$$V = W_1 - 1.5 - 2.5 \cdot 10^{-7} e^{+6W_1}$$

$$\eta = \frac{W_1 - 1.5 - 2.5 \cdot 10^{-7} e^{6W_1}}{\frac{1.6}{30} + W_1}$$

η has a essentially a maximum where its numerator has a max.

i.e. where  $1 = 2.5 \cdot 2.6 \cdot 10^{2.6W_1 - 7}$

$$10^{2.6W_1} = \frac{10^7}{2.5 \cdot 2.6} = 0.15 \cdot 10^7 = 1.5 \cdot 10^6$$

$$2.6W_1 = 6 + \log_{10} 1.5 = 6 + 0.2$$

$$W_1 \approx 2.4 \text{ V}$$

$$W_1 - W_2 = 2.4 - 1.5 = 0.9 \text{ V.}$$

$$2.5 \cdot 10^{-7} \cdot 1.5 \cdot 10^6 = 0.37$$

$$V = 0.9 - 2.5 \cdot 10^{6 \cdot 2 - 7} = 0.9 - 2.5 \cdot 10^{5} = 0.9 - 0.4 = 0.5 \text{ V.}$$

$$W = \frac{1}{6}(1+r)$$

$$0,9 - \frac{36 \cdot 7 \cdot 10^{-7}}{(1+r)^2} = \frac{(0,9 + W_2)6}{213(1+r)}$$

---

$$\frac{19}{36} (1+r)^2 + 0,9 + W_2$$

$$0,9 - \frac{2,5 \cdot 10^{-5}}{10} \frac{36(0,9 + W_2)(1+r)}{(1+2r)}$$

---

$$0,5(1+2r) + 0,9 + W_2$$

$$\eta = \frac{0,5}{\frac{1,6}{30} + 2,4} = \frac{0,5}{0,53 + 2,4} = \frac{0,5}{2,9} = \frac{1}{5,8} = 0,17 \quad 17\%$$

Now fix  $W_1, -W_2 =$  and  $J$ ; find  $\eta = \eta(W_2, T)$ ;  
for given  $W_2$  find optimal  $T$ .

$$\eta = \frac{J(W_1 - W_2 - \frac{4J}{5})}{116 \left(\frac{T}{2000}\right)^2 + JW_1} \quad \begin{array}{l} W_1 - W_2 = 0,9 \\ W_1 = W_2 + 0,9 \end{array}$$

$$\eta = \frac{30 \left( 0,9 - \frac{120}{120T^2} e^{\frac{W_2}{kT}} e^{\frac{0,9}{kT}} \right)}{116 \left(\frac{T}{2000}\right)^2 + 27 + 30W_2}$$

$$= \frac{0,9 - T^{-2} e^{\frac{0,9}{kT}} e^{\frac{W_2}{kT}}}{0,53 \left(\frac{T}{2000}\right)^2 + 0,90 + W_2} \quad \left(\frac{T}{2000}\right)^2 = \left(\frac{6(kT)_{ev}}{12000}\right)^2$$

$$\eta = \frac{0,9 - (12,000 \text{ ④})^{-2} e^{\frac{0,9}{\text{④}}} e^{W_2/\text{④}}}{0,53 (6 \text{ ④})^2 + 0,9 + W_2}$$

$$\frac{T^0}{12,000} = T_{ev} = \text{④}$$

④ = temp. in d.V.

$$= \frac{0,9 - \text{④}^{-2} \cdot 17 \cdot 10^{-3} \cdot 10^{\frac{0,9}{\text{④}}} \cdot 10^{\frac{W_2}{2,13 \text{ ④}}}}{19 \cdot \text{④}^2 + 0,9 + W_2}$$

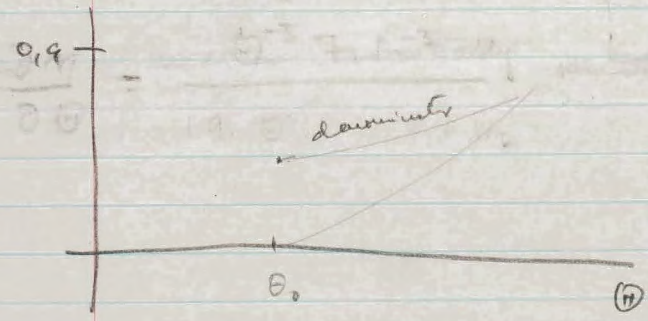
$$\left(\frac{1}{12 \cdot 10^4}\right)^2 = \frac{1}{12} \cdot 10^{-2} = \frac{1}{12} \cdot 10^{-2} = 7 \cdot 10^{-3}$$

$$0,9 - \frac{7 \cdot 10^{-3}}{\text{④}^2} \cdot 10^{\frac{0,9 + W_2}{2,13 \text{ ④}}}$$

$$\text{④}^2 \cdot 9 \cdot 10^1 = 7 \cdot 10^{-3} \cdot 10^{\frac{0,9 + W_2}{2,13 \text{ ④}}}$$

$$\text{④}^2 \approx 7 \cdot 10^{-3} \cdot 10^{\frac{0,9 + W_2}{2,13 \text{ ④}}}$$

$$2 \log \text{④} \sim 0,8 - 3 + \frac{0,9 + W_2}{2,13 \text{ ④}}$$



Low Betson per Reader  
P.W. Carpenter matter

---



**GENERAL ATOMIC**

DIVISION OF GENERAL DYNAMICS CORPORATION

POST OFFICE BOX 608

SAN DIEGO 12, CALIFORNIA

To

*Materials*  
*Leon Silard*  
*1155 E 57th St*  
*Chicago 37 Ill*

*rd*

*Dr*

# COMPOSITION BOOK

**NARROW RULED MARGINAL**

SIZE 11 x 8½

No. P-2713

Jan 31/53

# Simrad Materials I.

Na marginal at 1500F = 811C ||  
in steel (probably also Ni, Ta)

[quad temp for steam 1200F = 640C]  
g.A. gas 1400F Steam 1100F  
SRE (Krom's det [North American])  
Na at 1000F ~ 540C

compatibility alloys for Cs

Bath for Cs  
should have  
vapour

mp in steel mp. 650

Lead in steel and fr.  
Tin in graphite

} mp. vapour pressure too high  
} mp at 620C (mbl.)

Lead is better ~  $\frac{1}{40}$  mp at 640C

Tin; satisfactory

What about Lithium? mp at 723  
~~or solid alloys of Cs~~

? Al alloy if it can be  
contained what about BeO2

Solid alloys of Cs look up

Ba mp 710  $\frac{1}{400}$  mp at 650C

? Bi in steel?  $\frac{1}{400}$  mp at 650C

C<sub>2</sub>O<sub>4</sub>. ANL 5107 Alven plummer

{ B.p. 1500 K = 1227°C  
heat 37000 cal/mol  
m.p. 763 K = 490°C  
heat of fusion

$$\ln p = \frac{\Delta H}{1.987} \left( \frac{1}{K_{bp.}} - \frac{1}{K} \right)$$



D

Compatibility

M

Rubthreneum forms no carbonate  
hold  $UO_2$  | m.p.  $2500^\circ C$

$UO_2$  in graphite o.k.  
 $UO_2$  in graphite below melting point; may be?  
no Carbide on graphite vice

U metal in graphite

Ni might not form carbonate  
may react in  $UO_2$ .

Leaching (knobs)

$PuO_3$  above  $1520^\circ C$   
by formula  $= \frac{28,000}{T + 11}$

$PuF$  m.p.  $1425^\circ C$

$PuOF$  m.p.  $> 1635$

PVC stable in vacuum at  $2000^\circ C$   
dens. 14 g/cc

PuN stable in vacuum at  $1500^\circ C$   
dens. 14.2

see Katz & Leachman. The Chem of  
the actinide elements.]

$\left(\frac{a}{V} + e^{-\frac{a}{RT}}\right)$  where is maximum?

$\frac{1}{\frac{a}{V} e^{\frac{a}{RT}} + 1} = \text{fraction}$

$-\frac{1}{RT} \frac{d}{dV} \left( \frac{a}{V} e^{-\frac{a}{RT}} + \frac{1}{V} e^{-\frac{a}{RT}} \right) \sim \frac{1}{V} e^{-\frac{a}{RT}}$

Lithium in Fe o.k.

Lith. o.k. in expensive Metall

Kand Na ~ Ta o.k.  
 also W, Mo and Nb up 800°C  
 probably o.k. in Ni and  
 Stainless Steel

See for Ca, Mn Sr in Fe  
 Mellor,

$\frac{1}{V} \frac{a}{RT} = \frac{1}{V}$

$a = RT$

$\frac{1}{20}$  0.5 Volt

$\frac{RT}{V} e^{-1} = \frac{1}{2.7} \times \frac{1}{3} = \frac{1}{8}$



<sup>0.2</sup>  
 Gurnitsky from Hansen  
 BaSO<sub>4</sub>, no lamination of melt p.  
 Ca Ba 605

Tu-Ba [Paper  
 J.E. Moore  
 W.W. Allison

Q =

0.3 coverage

3.7 Volt

Tu 1000°C

J. of Chem. Phys.  
 Vol 23 p. 1609, 1955.

$$\frac{V = 10^{10} - 10^{12} \frac{Q}{2T}}{10^{11}} - e$$

0.5 sheets ;

$$\frac{p \text{ in dynes/cm}}{\sqrt{20 m k T}}$$

Book (from summer) H  
 Chemistry and Metallurgy  
 of some materials:  
 Thermodynamics  
 edited: Lawrence L. Gull  
 first ed.  
 McGraw Hill (1950)

CS<sub>2</sub>O Heat of form at 298°K  
 kcal/mol = -75.9

Heat of fusion at m.p. 7  
 " " evap. & b.p. 35

Free energy of formation:

298°K = -64      500°K = -56.5      1000°K = -35.1  
 1500°K = -3.6      2000°K = +15.7      2500°K = +36  
 mp 763 K bp 1500 K

summary

U pressure over U carbonate  
 at 1800 K 10<sup>-10</sup> Atm

Carbon at 2000 K 10<sup>-10.5</sup> Atm  
 " " 2500 K 10<sup>-6.7</sup> Atm.

Thermodynamic properties  
 of elements (Shull & Sinko)

fr Bip, 338

fr Ca p, 410

fr Mg 420

fr Temp 1207 ✓

fr

fr Tin at 580 eutectic with 27% Sr  
for more strontium go up with temp  
goes up very fast

fr Mg

70% fr at eutectic 426 °C  
at 700 °C 90% Sr

fr Pb at 676 °C 25% Sr (fr Pb<sub>3</sub>)

Ca Bi 302

Mg 401

Tin 409

Na 404

Ca Na eutectic  
700 °C 80% Ca

Ca Tin 80% Ca at 760 °C

Ca Mg 72% Ca at 445 °C

Ca Pb<sub>2</sub> at 700 °C eutectic 90% Ca  
sublimates with biphase (1100 °C)  
Ca<sub>2</sub>Pb

liquidus up to  $425^{\circ}\text{C}$   
20% Ba than %  
 $600^{\circ}\text{C}$  30% Ba

H

BA

Ba Sr any ratio

Ba Ti at  $675^{\circ}\text{C}$  20% Ba

confinement  
above  $700^{\circ}\text{C}$  graphite?

Ba My any ratio?

[if there is  
solid Ti + Ba  
compound  
with high m.p.]

My in Fe OK

eutectic at  $359^{\circ}\text{C}$  65% Ba

(than %)

Above  $700^{\circ}\text{C}$  any ratio

Ba Ca low point 50%  
 $600^{\circ}\text{C}$

at high temp. below m.p. of Ca  
small Ba concentrations

Ba Pb p 272

(?) there seems to be solid up to ~~425~~

$928^{\circ}\text{C}$  around 70% Ba

see at  $600^{\circ}\text{C}$  80% Ba liquid

Hummer, ~~Hummer~~

Graphite 2500K  
 $10^{-6.8}$  Kcal  
~~manufacture~~  
~~adhesive~~  
~~mechanic~~  
 $10^{-7.7}$  Kcal  
 $10^{-6.3}$  Kcal

In Corbide  
 $\text{pot } p_2 = 10^{-7.5}$  Kcal

Thermodynamic properties  
of elements Special Publ. sept.  
Am. Chem. Soc. 1155 16th Str.  
Wash D.C.

$\text{W, Ta, Nb, V, Ti, Zr, Hf, Th, U, Pu, Am, Cm, No}$

Corbide form F

WC	8.6 Kcal	per carbon
wc	11.7	
Mo <sub>2</sub> C	5.1	
Mo <sub>2</sub> C	2.1	
HfC	45.8	
NGC	33.3	
TaC	38.9	
W at 2500 K	10	
Ta <sub>2</sub> C	44.9	
Nb <sub>2</sub> C	37.7	
V <sub>2</sub> C	small	
ZrC	small	
BaC	small	

Hy  $\Delta F$  at 2500K  
87 Kcal/mol  
 $p = 10^{-7.6}$  Kcal at 2500K



Quasistatic experiment H

$M = 100$  density 10 maximum pressure ~~10~~

$p = 10^{-x}$  atm • permit 1 gm in 20 years

$K = 9 \times 300$  for  $v$  and density

$v = 25000$  cm/sec +

$$\rho = \frac{M}{22000} 10^{-x} \frac{1}{9} = \frac{100}{2105} 10^{-x} = 10^{-2} \frac{10^{-x}}{10^2}$$

$$\text{time} = 20 \times 3.16 \cdot 10^7 \approx 6 \cdot 10^8 \text{ sec}$$

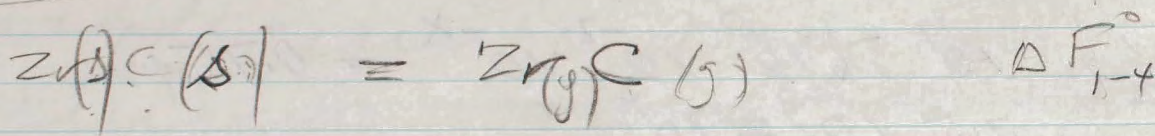
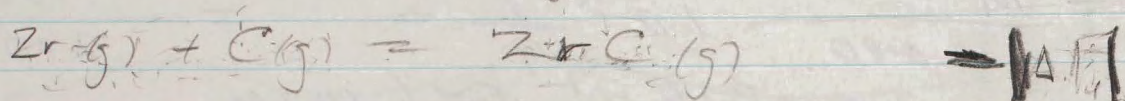
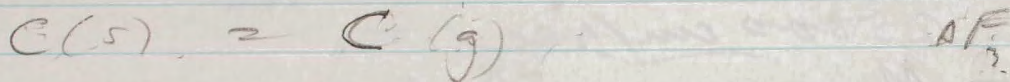
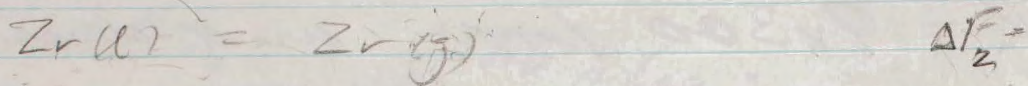
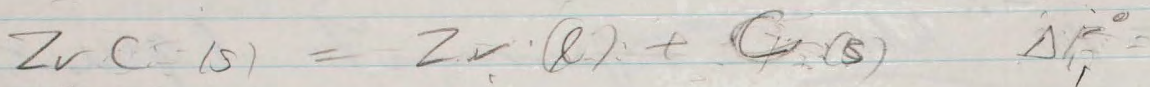
$$\frac{1}{2} \frac{2.5 \cdot 10^4 \times 6 \cdot 10^8 \cdot 10^{-3} \cdot 10^{-x}}{7.5 \cdot 10^9} = 0.75 \mu\text{m}$$

$$x \approx 10 \quad p = 10^{-10} \text{ atm or } 0.76 \times 10^{-7} \mu\text{m}$$

400° factor 10 in pressure for W

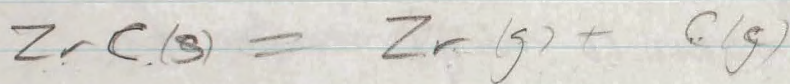
safe  
limit  
density

$$\Delta F^\circ = \Delta H^\circ - T\Delta S^\circ$$



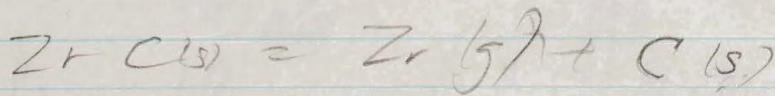
$$\Delta F_{1-4}^\circ = -RT \ln p_{\text{ZrC}}$$

$$\Delta F = -RT \ln K_p$$



$$K_p = (p_{\text{Zr}})(p_{\text{C}})$$

$$p_{\text{Zr}} = p_{\text{C}}$$



$$K_p = p_{\text{Zr}}$$

Zr

$$Q^4 = \frac{Q_1 + Q_2 + Q_3}{2} \quad W$$

For full Corbridge formula

$$Q^4 = \frac{Q_1 + Q_2 + Q_3}{3}$$

$$Q_1 \quad W = 113$$


---


$$L = 77$$

Corbridge

High Temperature Studies

O. H. Krikorian

UCRL-2000

pages 72 to 90

$$\ln p_{2r} = \frac{40}{RT} + 2 \ln p_{2r}^2$$

$$- RT \ln p_{2r} = -40 + -RT \ln p_{2r}^2$$

$$- RT \ln p_{2r} + 40 = -2 RT \ln p_{2r}^2$$

$$(120) + 40$$

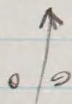
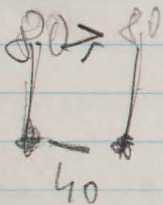
$$160$$

$$\Delta F^\circ = - RT \log_e K_p$$

$$R = 1.99 \frac{\text{cal}}{\text{gmole}^\circ\text{K}}$$

$$= - 4.57 T \log_{10} p$$

$$K_p = p \text{ (atm)}$$



$$\frac{80+40}{}$$

$$\frac{160-40}{10} = \frac{120}{150}$$

$$x - 40 = 150$$

$$x = 190$$

# Moleculare

$$\Delta F_{zc} = \Delta F_{zc}^0 + \Delta F_c$$

~~$$-RT \ln K_p = -RT \ln (p_{zc}) - RT \ln P$$~~

~~$$-RT \ln K_p = \Delta F_{zc}^0$$~~

$$-RT \ln p_{zc} = \Delta F_{zc}^0$$

$$\Delta F_1 - |\Delta F_4| = \Delta F_{zc}^0 < \underline{40000}$$

$$p_1 + p_2 + 40 = -RT \ln p_{zc} \quad \text{---}$$

$$p_1 + p_2 + (0.49) = -RT \ln p_{zc} \quad \text{---}$$

$$160 = -RT \ln p_{zc} \quad \text{---}$$

$$100 = -RT \ln p_{zc}$$

$$p_{zc} = p_c$$

$$\Delta F_1 - \Delta F_2 = 200 - 160 = -RT \ln \frac{p_{zc}}{p_{zc}} = 40$$

$$-RT \ln \frac{(p_{zc})^2}{p_{zc}} = 40$$

$$\frac{(2p_{zc})^2}{p_{zc}} = e^{-\frac{40}{RT}}$$

$$p_{zc} = e^{-\frac{40}{RT}} (p_{zc})^2$$

$$RT \ln_{10} 10^{+7.5}$$

14

$$RT \frac{2.3 \times 7.5}{\phantom{2.3 \times 7.5}} \gg 30000$$

$$J \approx 2.3 \times 7.5$$

*Glastone*  
*Chemical Thermodynamics*

REFRACTORY HARD METALS

Borides, Carbides, Nitrides, and Silicides

The Basic Constituents of Cemented Hard Metals and Their Use as  
High-Temperature Materials

by Dr. Paul Schwarzkopf and Dr. Richard Kieffer  
in collaboration with  
Dr. Werner Leszynski and Dr. Fritz Benesovsky

New York - The MacMillan Company

Pu Ni<sub>5</sub> 1350  
 Pu Os<sub>2</sub> 1500  
 Pu Ruth 1600?

Battelle  
Memorial  
Institute Report # 1300

Pu BMI Gust

total mem 1300 / 1950

The cost of production of

U and Th alloys

Rough p price. —

U Be <sub>13</sub>	was
U Co <sub>2</sub>	1200
U Au <sub>3</sub>	1450
U Fe <sub>2</sub>	1235
U Ni <sub>5</sub>	1300
U Pd <sub>3</sub>	1640
U Pt <sub>3</sub>	1700
U Si <sub>2</sub>	1700

U } Bob Gibney  
 carbide  
 article

CMF 13





$\text{VO}_2$

$\rho = 8.0$

0.0061

some units  
 some units

Cal  $\text{m}^{-1} \text{cm}^{-1}$   $\text{cm}^{-1}$   $\text{cm}^{-2}$

at  $1000^\circ \text{C}$

---

$\rho = 10.9$

0.00815

some units.

Report No. BMI-1300  
UC-25 Metallurgy and Ceramics  
(TID-4500, 13th Ed., Rev.)

CONSTITUTION OF URANIUM AND THORIUM ALLOYS

by Frank A. Rough, Arthur A. Bauer

June 2, 1958

Battelle Memorial Institute  
505 King Avenue  
Columbus 1, Ohio

Printed in USA, Price \$2.75

Available from the

Office of Technical Services  
U. S. Department of Commerce  
Washington 25, D. C.

SUBJECT

Vapor pressure of ZrC

W.O.

BY

SHEET

①

DATE

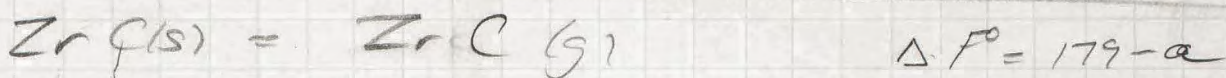
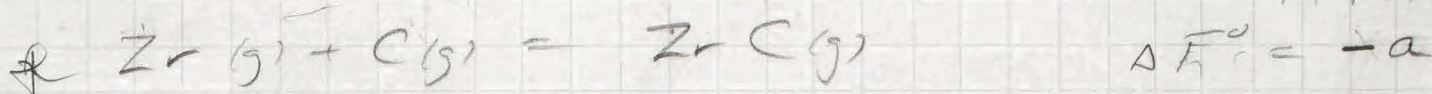
3/23/59

LOCATION

2500°K



$$\Delta F^\circ = \frac{\Delta H_{900}}{6.8} - T \frac{\Delta S_{900}}{2.7} = 37.6$$



$$\log_{10} p_{\text{ZrC}} = -\frac{\Delta F^\circ}{4.57T} = -\frac{(179 - a)}{4.57T}$$

$$p_{\text{ZrC}} = 10^{-\frac{(179 - a)}{4.57T}}$$

$$\log_{10} \frac{p_{\text{ZrC}}}{(p_{\text{Zr}})(p_{\text{C}})} = \frac{a}{4.57T}$$

$$p_{\text{Zr}} = p_{\text{C}} \quad (p_{\text{C}}) = 10^{-\frac{a}{(4.57)T}} (p_{\text{ZrC}})$$

$$p_{\text{Zr}} = p_{\text{C}} = p_{\text{ZrC}} = p_{\text{Zr}} = 10^{-\frac{a}{4.57T}}$$

SUBJECT

BY

DATE 3/28

W.O.

SHEET

2

LOCATION

For  $a = 37.6$  kcal

$$p_c = 10^{-\frac{37.6}{4.57(2.5)}} = 10^{-3.3}$$

For  $p_c = 10^{-6.8}$  (vapor pressure of C)

and  $p_c = p_{zc}$

$$p_{zrc} = 10^{\frac{a}{4.57T}} (p_c)^2$$

$$p_{zrc} = 10^{3.3} (10^{-6.8})^2$$

$$\begin{array}{r} -13.6 \\ 3.3 \\ \hline -10.3 \end{array}$$

$$p_{zrc} = 10^{-10.3}$$

Calc of a for  $p_z = p_{zc} = p_{zr} = p_c = 10^{-6.6} = 10^{-\frac{a}{4.57T}}$

$T = 2500^\circ K$

$$\Delta F_F^\circ = a = 6.6(4.57)(2.5) = 75.5 \text{ kcal}$$

(Zr + C = ZrC) gas

Thus  $a < 75.5$  kcal

$$p_{zrc} < p_c = p_{zr}$$

696  
Sizel

SUBJECT

Vapor Pressure of Carbides

BY LRR

W.O.

SHEET 1

DATE 3/13/59

LOCATION

ZrC at 2500°K

From UCRL-2085 }  $ZrC(s) = Zr(l) + C(s) \quad \Delta F^\circ = 37.6$   
 (Ker Karian)

$$(\Delta F_{2500}) = \Delta H_{298} - 2500 \frac{\Delta S_{298}}{103} = 44.4 - 2.5(2.7) = 39.2$$

From Thermo Prop of }  $Zr(l) = Zr(g) \quad (p = 10^{-5.6} \text{ atm}) \quad \Delta F^\circ = +64.5$   
 Elements, Stull & }  
 Smith

---


$$ZrC(s) = Zr(g) + C(s) \quad \Delta F^\circ = 102.1$$

2500°K

$$p_{Zr} = 10^{-\frac{\Delta F^\circ}{4.57 T}} = 10^{-\frac{102.1}{4.57(2.5)}} = 10^{-8.9} \text{ atm}$$

$$p_{C1} = C(s) = C_1(g)$$

$$p_{C1} = 10^{-6.8} \text{ atm}$$

$$2C(s) = C_2(g)$$

$$p_{C2} = 10^{-7.7} \text{ atm}$$

$$3C(s) = C_3(g)$$

$$p_{C3} = 10^{-6.3} \text{ atm}$$

$$Zr(s) = Zr(g)$$

$$p_{Zr} = 10^{-5.6} \text{ atm}$$

SUBJECT Vapor Pressure of Carbides

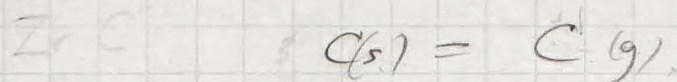
BY LRZ

W.O.

SHEET 2

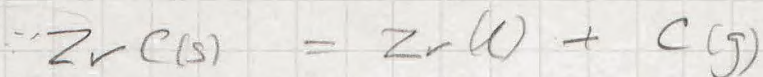
DATE 3/13/59

LOCATION



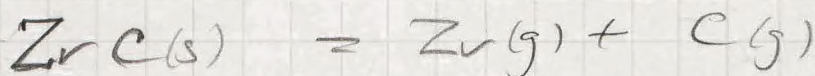
$\Delta F^\circ = 37.5$

$\Delta F_{2500}^\circ = 77.3$



$\Delta F_{2500}^\circ = 114.8$

$p_c = 10^{-\frac{\Delta F^\circ}{4.57(T)}} = 10^{-\frac{114}{4.57(2.5)}} = 10^{-10.0}$



+ 37.5

+ 64.5

+ 77.3

$\Delta F_{2500}^\circ = 179.3$

$(p_{Zr})(p_c) = 10^{-\frac{179.3}{4.57(2.5)}} = 10^{-15.67}$

Now

$p_{Zr} = p_c$

$(p_{Zr})^2 = 10^{-15.67} = 10^{-7.84}$

$p_{Zr} + p_c = 10^{-7.84} \times 10^{0.30}$

$= 10^{-7.54} \text{ atm}$

SUBJECT

Vapor pressure of carbides

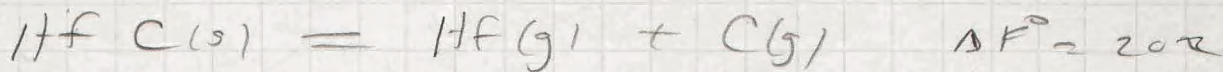
BY LRCZ

W.O.

SHEET 3

DATE 3/1955

LOCATION

25VV<sup>012</sup>From  
Kirkorian

$$HfC(s) = Hf(l) + C(s) \quad \Delta F^\circ = 37$$

$$\Delta F = +47 - 2.5(4.0) = 37$$

$$Hf(l) = Hf(g) \quad \Delta F^\circ = 87.3$$

$$C(s) = C(g) \quad \Delta F^\circ = 77.3$$

$$p_{Hf} = p_c$$

$$\underline{202}$$

$$(p_{Hf}) = 10^{-\frac{202}{4.57(25)^2}} = 10^{-8.8} \text{ atm}$$

$$p_{Hf} + p_c = 10^{-8.8} \times 10^{0.3} = \underline{10^{-8.5}}$$



$$\Delta F_{2900} = 3815 - 2.5(1.2) = 35.5$$



$$p_{Ta} = p_c$$

$$\underline{215.4}$$

$$p_{Ta} = 10^{-\frac{215.4}{4.57(25)^2}} = 10^{-9.4}$$

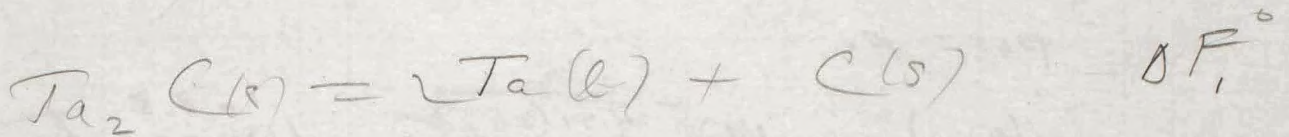
$$p_{Ta} + p_c = 10^{-9.4} \times 10^{0.3} = \underline{10^{-9.1}}$$



NO. \_\_\_\_\_  
SHEET \_\_\_\_\_  
LOCATION \_\_\_\_\_

DATE \_\_\_\_\_

~~W~~  
Ta  
NB



$$p_{Ta} = \frac{1}{2} p_c$$

$$(p_{Ta})^2 (p_c) = e^{-\frac{\Delta F_+^{\circ}}{RT}}$$

# GENERAL PHYSICAL PROPERTIES

MANY physical properties depend on the purity and physical state (annealed, hard drawn, cast, *etc.*) of the metal. The data in Tables 1 and 2 refer to metals in the highest state of purity available, and are sufficiently accurate for most purposes. The reader should, however, consult the references before accepting the values quoted as applying to a particular sample.

TABLE I. THE PHYSICAL PROPERTIES OF PURE METALS AT NORMAL TEMPERATURES

<i>Metal</i>	<i>Melting point</i> (°C)	<i>Boiling point</i> (°C)	<i>Density</i> (g/cc) (20°C)	<i>Thermal conductivity</i> (cgs units) (0-100°C)	<i>Mean specific heat</i> (cal/g°C) (0-100°C)	<i>Resistivity</i> (microhm. cm) (20°C)	<i>Temp. coeff. of resistivity</i> × 10 <sup>3</sup> (0-100°C)	<i>Coefficient of expansion</i> × 10 <sup>6</sup> (0-100°C)
Aluminium	660·1	(2500)	2·70	0·57	0·219	2·69	4·2	23·5
Antimony	630·5	1640	6·68	0·042	0·050	42	5·1	8·11
Barium	710	(1700)	3·75	—	0·068	50	—	(18)
Beryllium	1284	2967	1·848	0·40	0·481	4·6	6·0	13
Bismuth	271	1560	9·80	0·019	0·0298	116	4·2	13·4
Cadmium	320·9	765	8·64	0·20	0·0557	7·4	4·3	31
Calcium	850	1690	1·54	—	0·159	4·1 (soft) 4·37 (hard)	4·6	22
Cerium	(800)	(2500)	6·75	—	0·045	—	—	—
Caesium	29·7	700	1·87	—	0·056	78	—	—
Chromium	1850	2430	7·1	0·165	0·110	21	4·8	97
Cobalt	1492	(2900)	8·71	0·165	0·104	6·24	6·04	12·5
Copper	1083	2590	8·96	0·94	0·0922	1·673	4·3	17·0
Gallium	29·8	2070	5·91	—	0·091	see Table I, p. 673	—	18·3
Germanium	959	(2700)	5·32	—	0·074	(100 × 10 <sup>3</sup> )	—	(6)
Gold	1063	(2950)	19·3	0·70	0·031	2·3	3·9	14·1
Hafnium	(2130)	—	13·1	—	—	(32)	(4·4)	(6)
Indium	157	2075	7·3	0·06	0·058	9·0	4·7	24·8
Iridium	2443	(5300)	22·4	0·14	0·0312	5·3	3·9	6·8
Iron	1537	(3070)	7·87	0·17	0·109	9·71	6·51	12·1
Lead	327·3	1740	11·34	0·082	0·0310	20·6	3·36	29·0
Lithium	180	1370	0·534	0·17	0·84	9·35	4·75	56
Magnesium	650	1103	1·74	0·40	0·248	4·4	4·2	26·0
Manganese	1243	2150	7·4	—	0·117	160(2)	—	23
Mercury	-38·87	357	13·546	0·022	0·033	95·8	0·9	61
Molybdenum	2610	(4700)	10·3	0·34	0·062	5·7	4·6	5·1
Nickel	1453	(3000)	8·9	0·21	0·108	6·84	6·8	13·3
Niobium	2410	(3000)	8·6	—	0·064	14·1	3·95	7·2
Osmium	(2700)	(5500)	22·5	—	0·031	9·5	4·2	6·6
Palladium	1552	(3900)	11·9	0·17	0·059	10·8	3·8	11·0
Platinum	1769	(4500)	21·45	0·17	0·0321	10·6	3·92	9·0
Potassium	63·7	775	0·86	0·22	0·180	6·86	5·8	83
Radium	960	1140	(5)	—	—	—	—	—
Rhenium	3145	—	21·0	0·17	0·033	21·1	3·11	12·4    c-axis 4·7 ⊥ c-axis 8·5 90
Rhodium	1960	4500	12·4	0·20	0·060	4·7	4·57	—
Rubidium	38·8	680	1·53	—	0·085	12·5	5·53	8·5 90
Ruthenium	(2500)	(4900)	12·2	—	0·056	7·6 (0°C)	—	9·6
Silicon	1440	2600	2·34	0·2	0·174	85 × 10 <sup>3</sup>	—	7·6
Silver	960·8	2210	10·5	1·00	0·054	1·6	4·1	19·1
Sodium	97·8	883	0·97	0·30	0·293	4·6	5·0	71
Strontium	770	(1360)	2·63	—	—	22·8	—	—
Tantalum	2977	—	16·6	0·130	0·034	13·5	3·8	6·5 1·7    c-axis 27·5 ⊥ c-axis
Tellurium	450	990	6·24	0·014	0·049	(100 × 10 <sup>3</sup> )	—	30 11·2 23·5
Thallium	303	1460	11·85	0·094	0·033	16·6	5·2	—
Thorium	1850	(3500)	11·5	—	—	18·6	2·3	—
Tin	231·9	(2200)	7·30	0·155	0·054	12·8	4·2	—
Titanium	1730	(3260)	4·5	0·036	0·126	55	3·5	8·8
Tungsten	3380	(6700)	19·3	0·394	0·033	5·5	4·6	4·5

SOURCE: METALS REFERENCE BOOK, Volume II

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New York-Interscience Publishers Inc.

London - Butterworths Scientific Publications

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TABLE 3. THE PHYSICAL PROPERTIES OF PURE MOLTEN METALS

Vapour pressures will be found in Table 14, p. 613.

Metal	Temp. (°C)	Density (g/cc) (d)	Electrical resistivity (microhm cm) ( $\sigma$ )	Thermal conductivity (cgs units) ( $k$ )	Specific * heat (cal/gm) (°C)	Viscosity (cp) ( $\eta$ )	Surface tension (dynes/cm) ( $\gamma$ )	References
Aluminium	660.1 †	2.37	(20)	(0.20)	0.259	(4.5)	(915)	41, 5 (k), 43 (η), 42 (γ)
	700	2.36	(21)	(0.20)		(2.9)	900	
	800	2.31	(22.5)	(0.20)		(2.5)	865	
	900	2.31	(23.5)	(0.20)		—	—	
Antimony	630.5 †	6.50	110	0.052	0.0587	—	383	41, 5 (k), 45 (η), 44 (γ), 28 (σ)
	700	6.45	111	0.05		1.30	383	
	800	6.38	114	0.05		1.12	380	
	900	6.32	118	—		1.00	—	
	1000	6.28	124	—		0.91	—	
Bismuth	271 †	10.06	—	—	0.0359	—	—	41, 5 (k), 46 and 47 (η)
	300	10.03	128.9	0.04		1.63	376	
	400	9.91	134.2	0.038		1.39	370	
	600	9.66	145.2	0.037		1.00	356	
	800	9.40	158.5	—		—	—	
Cadmium	320.9 †	8.02	33.7	—	0.0632	—	(550)	41, 5 (k), 48 (η), 44 (γ)
	350	7.99	33.7	0.11		2.37	586	
	400	7.93	33.7	0.11		2.17	605	
	500	7.82	34.1	0.11		1.86	600	
	600	7.72	34.8	0.12		1.63	—	
Caesium	29.7 †	1.84	36.6	0.06	0.0602	0.684 ‡	—	41, 49 (d), 50 (η)
	50	1.82	$\sigma_{37} = 37.0$	—		0.607	—	
	100	—	—	—		0.474	—	
	200	—	—	—		0.344	—	
Copper	1083 †	—	—	—	0.118	—	—	45 (η)
	1100	—	—	—		—	—	
	1150	—	—	—		3.4	—	
	1200	—	—	—		3.2	—	
Gallium	29.8 †	(6.10)	25.9	(0.08)	0.0975	—	(735)	41, 51 (d and η)
	50	6.08	$\sigma_{48} = 28.4$	—		1.92	(735)	
	100	6.04	—	—		1.64	—	
	200	5.97	—	—		1.24	—	
	600	5.72	—	—		0.756	—	
	1000	5.50	—	—		0.592	—	
Indium	157 †	7.03	(29.1)	(0.10)	0.0654	—	—	41
	200	7.00	30.9	—		—	—	
	300	6.92	36.2	—		—	—	
Lead	327.3 †	10.60	94.6	0.039	0.0364	—	444	41, 5 (k), 45 and 48 (η), 52 (γ)
	400	10.51	98.0	0.038		2.32	438	
	500	10.39	104.6	0.037		1.85	431	
	600	10.27	107.2	0.036		1.54	426	
	800	10.04	116.4	—		—	409	
	1000	9.81	125.7	—		—	—	
Lithium	180 †	0.508	—	(0.10)	1.01	0.60	—	41, 50 (η)
	200	0.507	$\sigma_{230} = 45.2$	—		0.566	—	
	300	0.498	—	—		(0.444)	—	
	500	0.482	—	—		—	—	
Magnesium	650 †	1.572	—	—	0.333	—	556	41, 42 (γ)
	700	1.536	—	—		—	542	
	750	1.47	—	—		—	526	
Mercury	20	13.55	$\sigma_{40} = 98.4$	0.020	0.0329	1.554	465	41, 53 (η)
	100	13.35	103.2	0.025		1.240	456	
	200	13.12	114.2	0.030		1.052	436	
	300	12.88	127.5	—		0.950	405	
	350	(12.76)	135.5	—		0.914	395	
Potassium	63.7 †	—	13.2	—	—	0.534	—	41, 54 (d and k), 48, 55, 56 and 57 (η)
	100	0.819	15.4	—		0.450	—	
	200	0.795	21.8	0.107		0.187	0.327	
	300	0.771	28.2	0.101		0.185	0.259	
	500	0.723	—	0.090		0.182	0.184	
	700	0.676	—	$k_{600} = 0.085$		0.185	0.140	
Rubidium	38.8 †	1.475	—	(0.10)	0.0918	0.673	—	41, 50 (η)
	50	—	23.2	—		0.625	—	
	100	—	27.5	—		0.484	—	
	200	—	—	—		0.342	—	
Silver	960.8 †	9.30	—	—	0.0677	—	—	18 (d), 48 and 58 (η)
	1000	9.26	17.0	—		3.89	—	
	1100	9.18	18.2	—		3.39	—	
	1200	9.09	19.4	—		2.99	—	
	1300	9.01	20.5	—		(2.73)	—	

\* For references, see Table 11, p. 604.

† Melting point.

‡ 28.4 °C was temperature recorded.

SOURCE: METALS REFERENCE BOOK, Volume II

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London - Butterworths Scientific Publications

Second Edition, 1955

TABLE I. THE PHYSICAL PROPERTIES OF PURE METALS AT NORMAL TEMPERATURES—*continued*

Metal	Melting point (°C)	Boiling point (°C)	Density (g/cc) (20°C)	Thermal conductivity (cgs units) (0-100°C)	Mean specific heat (cal/g/°C) (0-100°C)	Resistivity (microhm. cm) (20°C)	Temp. coeff. of resistivity $\times 10^3$ (0-100°C)	Coefficient of expansion $\times 10^6$ (0-100°C)
Uranium	1133	(4200)	$\left\{ \begin{array}{l} 19.05(\alpha) \\ 18.89(\beta) \end{array} \right.$	$\left\{ \begin{array}{l} 0.060- \\ 0.065 \end{array} \right.$	0.028	29( $\alpha$ )	3.4	*
Vanadium	1750	(3350)	6.0	—	0.119	26	2.8	—
Zinc	419.5	907	7.14	0.265	0.094	5.9	4.2	31
Zirconium	1845	(4900)	6.49	(0.04)	0.069	44.6	4.4	(5)

\*  $\alpha$ -Uranium,  $\left. \begin{array}{l} 23 \parallel a\text{-axis} \\ -3.5 \parallel b\text{-axis} \\ 17 \parallel c\text{-axis} \end{array} \right\} 25-300^\circ\text{C}$        $\beta$ -Uranium,  $\left. \begin{array}{l} 4.6 \parallel c\text{-axis} \\ 23.0 \perp c\text{-axis} \end{array} \right\} 20-720^\circ\text{C}$

## References :

Electrical resistivity, see Table I, p. 673.

Specific heat, see Table II, p. 604.

1 and 2 (general); 3 and 4 (melting and boiling points); 5 (thermal conductivities); 6 (Al); 7 and 8 (Be); 9 (Cu); 10 and 11 (Fe); 12, 13 and 14 (Hf); 15 (Ni); 16 (Pt, Os, Ir, Pd, Ru, and Rh); 17 (Re); 18 (Ag); 19, 20 and 21 (Ti); 22 (W); 7, 23 and 24 (U); 12, 25 and 26 (Zr).

TABLE 2. THE PHYSICAL PROPERTIES OF PURE METALS AT ELEVATED TEMPERATURES

Metal	Temperature (°C)	Coefficient of expansion ( $\alpha \times 10^6$ ) (20-1°C)	Resistivity ( $\sigma$ ) (microhm. cm) (at 1°C)	Thermal conductivity (k) (cgs units) (at 1°C)	Specific heat (cal/g/°C) (at 1°C)	References (see also references to Table 1)
Aluminium	20	—	2.69	0.57	0.215	2, 27 ( $\sigma$ and k)
	100	23.9	3.64		0.224	
	200	24.3	4.78		0.235	
	300	25.3	5.99		0.246	
	400	—	7.30		0.257	
Antimony	20	—	42	0.043	0.049	2, 28 ( $\sigma$ ), 5 (k)
	100	8.4-11.0	61	0.040	0.051	
	500	9.7-11.6	154	0.047	0.057	
Beryllium	20	—	4.4*	0.43	0.472	8 ( $\sigma$ and k)
	100	13	7.0	0.363	0.497	
	200	—	10.5	0.311	0.529	
	300	—	14.1	0.281	0.562	
	500	—	21.8	0.246	0.626	
	700	—	32.6	0.205	0.690	
Bismuth	20	—	116	0.019	0.029	2, 29 ( $\sigma$ ), 5 (k)
	100	13.4	152	0.018	0.031	
	250	—	260	0.018	0.035	
Cadmium	20	—	7.4	0.20	0.055	2, 30 and 31 ( $\sigma$ )
	100	31.8	9.6	0.21	0.057	
	300	(38)	18.0	0.25	0.062	
Chromium	20	—	21	—	0.106	2
	100	6.6	—	—	0.117	
	400	8.4	—	—	0.139	
	700	9.4	—	—	0.155	
Copper	20	—	1.696	0.94	0.092	2, 32 ( $\sigma$ )
	100	17.1	—	0.94	0.093	
	200	17.2	2.93	0.93	0.096	
	500	18.3	—	—	0.102	
	1000	20.3	—	—	0.113	
Gold	20	—	2.3	0.70	0.030	2
	100	14.2	3.0	0.70	0.031	
	500	15.2	6.8	—	0.034	
	900	16.7	11.8	—	0.036	
Iridium	20	—	5.3	0.141	0.031	16
	100	6.8	6.8	0.135	0.032	
	500	7.2	15.1	—	0.034	
	1000	7.8	—	—	0.038	
Iron	20	—	9.7	0.175	0.106	2, 11 (k and $\sigma$ )
	100	12.2	15.0	0.163	0.114	
	200	12.9	22.0	0.147	0.125	
	400	13.8	43.1	0.116	0.146	
	600	14.5	69.8	0.093	0.167	
	800	14.6	105.5	0.071	0.189	

\* The values quoted were obtained on chill cast bars which had been heat treated in the region of 700°C. Before heat treatment the resistivities of the same bars were about 2 microhm. cm higher at temperatures up to 600°C.

TABLE 2. THE PHYSICAL PROPERTIES OF PURE METALS AT ELEVATED TEMPERATURES—continued

Metal	Temperature (t°C)	Coefficient of expansion ( $\alpha \times 10^6$ (20-t°C)	Resistivity ( $\rho$ ) (microhm. cm) (at t°C)	Thermal conductivity ( $k$ ) (cgs units) (at t°C)	Specific heat (cal/g°C) (at t°C)	References (see also references to Table 1)
Lead	20	—	20.6	0.083	0.031	2, 5 (k)
	100	29.1	27.0	0.080	0.032	
	200	30.0	36.0	0.075	0.032	
	300	31.3	50	0.071	0.033	
Magnesium	20	—	4.4	0.40	0.244	2
	100	26.1	5.6	0.40	0.254	
	200	27.0	7.2	0.39	0.265	
	400	28.9	12.1	0.31	0.286	
Molybdenum	20	—	5.7	0.34	0.061	2, 33 ( $\sigma$ ), 34 (k)
	100	5.2	7.6	0.33	0.062	
	500	5.7	17.6	0.29	0.068	
	1000	—	31	0.25	0.074	
	1500	—	46	0.20	0.081	
	2500	—	77	—	—	
Nickel	20	—	6.84	0.21	0.104	15
	100	13.3	10.3	0.198	0.114	
	200	13.9	15.8	0.175	0.126	
	300	14.4	23.0	0.152	0.138	
	400	14.8	30.6	0.142	0.124	
	500	15.2	34.2	0.148	0.128	
	900	16.3	45.5	—	0.142	
	—	—	—	—	—	
Palladium	20	—	10.8	0.168	0.058	16
	100	11.1	14.3	0.177	0.059	
	500	12.4	27.5	—	0.064	
	1000	13.6	40	—	0.071	
Platinum	20	—	10.6	0.166	0.032	2, 16
	100	9.1	13.6	0.172	0.032	
	500	9.6	27.9	—	0.035	
	1000	10.2	43.1	—	0.038	
	1500	—	55.4	—	0.042	
Rhenium	20	{ 12.4   -axis 4.7 I-axis	21.1	0.17	0.032	17
	100		25		0.033	
	2500		132		—	
Rhodium	20	—	4.7	0.210	0.059	16
	100	8.5	6.2	0.192	0.061	
	500	9.8	14.6	—	0.069	
	1000	10.8	—	—	0.079	
Silver	20	—	1.59	1.00	0.054	2, 18
	100	19.6	2.1	1.00	0.053	
	500	20.6	4.7	(0.9)	0.055	
	900	22.4	7.6	—	0.058	
Tantalum	20	—	13.5	0.130	0.033	2, 35 and 36 ( $\sigma$ )
	100	6.5	17.2	0.129	0.034	
	500	6.6	35	—	0.036	
	1500	—	71	—	0.040	
	2500	—	102	—	—	
	—	—	—	—	—	
Thallium	20	—	16.6	0.093	0.031	1, 5 (k)
	100	30	—	0.097	0.032	
	200	—	—	0.10	0.034	
Tin	20	—	12.8	0.156	0.053	2, 37 ( $\sigma$ and k)
	100	23.8	16.8	0.151	0.057	
	200	24.2	23.0	0.144	0.062	
Titanium	20	—	55	0.037	0.124	20 ( $\alpha$ and $\sigma$ ), 21 (k)
	100	8.8	70	0.036	0.120	
	200	9.1	88	0.035	0.136	
	400	9.4	119	0.033	0.148	
	600	9.7	152	0.032	—	
	800	9.9	165	(0.030)	—	
Tungsten	20	—	5.5	0.40	0.032	22 ( $\alpha$ and $\sigma$ ), 1 (k)
	100	4.5	7.2	0.38	0.033	
	500	4.6	18	(0.29)	0.034	
	1000	4.6	33	(0.25)	0.036	
	2000	5.4	65	(0.29)	—	
	3000	6.6	100	(0.36)	—	
Zinc	20	—	5.9	0.270	0.093	38 ( $\alpha$ ), 29, 39 and 40 ( $\sigma$ ), 5 (k)
	100	31	8.2	0.261	0.096	
	200	33	11.0	0.250	0.099	
	300	34	13.7	0.240	0.103	
	400	—	16.5	0.228	0.106	

U B<sub>13</sub> mols C 2000

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$$\text{gm of U/cm}^3 = 0.15$$



# GENERAL ATOMIC

DIVISION OF GENERAL DYNAMICS CORPORATION

To Dr. Czilard

11 Feb. 1959

M. SIMNAD

With my compliments.

is evidence that electrons can interchange or oscillate<sup>23</sup> in a manner similar to that of benzene. It is known that the presence in high polymers of benzene or of other resonating groups inhibits the effects of high-energy radiation, and this has been attributed to the action of these resonating groups as energy sinks absorbing the energy which would otherwise produce the effects found in irradiated polymers that do not contain these groups.<sup>24</sup>

In any case, the investigation of the magnetic properties of the glasses as affected by radiation should lead to a clarification of the results, particularly if the unpaired electrons of the transition elements pair with free electrons produced by radiation. Ordinarily paramagnetic resonance is produced in glass by radiation,<sup>25</sup> and it would be interesting to know if this is altered when coloration is prevented.

The coloration measured in experiments at room temperature may have been strongly affected by the fact that many of the glasses fade rapidly. For example, a flint glass, although it becomes very intensely colored at 10<sup>6</sup> roentgens, may fade almost completely in a few hours, whereas cobalt-containing

glasses were found which show essentially no fading at room temperature. Because of the stability of the colors formed in it by radiation, a cobalt-containing glass has been developed for use as a dosimeter.<sup>26</sup> In most cases, the most exact determination of coloring characteristics requires exposure and measurement at temperatures of about 100°K.

<sup>23</sup> W. A. Weyl, "Light Absorption as Result of an Interaction of Two States of Valency of the Same Element," *J. Phys. & Colloid Chem.*, **55**, 507-12 (1951).

<sup>24</sup> K.-H. Sun, "Effects of Atomic Radiation on High Polymers," *Modern Plastics*, **32** [1] 141-50, 229-39 (1954).

<sup>25</sup> (a) E. L. Yasaitis and B. Smaller, "Paramagnetic Resonance in Irradiated Glasses," *Phys. Rev.*, **92** [4] 1068-69 (1953).

(b) Jean Combrisson and Jean Uebersfeld, "Detection of Paramagnetic Resonance in Irradiated Glass," *Compt. rend.*, **238**, 572-73 (1954).

<sup>26</sup> N. J. Kreidl and G. E. Blair, "System of Megaröntgen Glass Dosimetry"; submitted for publication in *Nucleonics*, based on N. J. Kreidl and G. E. Blair, "Irradiation Damage to Glass," NYO-3782, Contract AT(30-1)-1312, March 21, 1955.

# Thermodynamic Data on Oxides at Elevated Temperatures

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An extensive compilation of data on the free energy of formation of oxides is presented in graphic form. From these curves it is possible to obtain the free energy of most ceramic oxides in the temperature range 0° to 2400°C.

## I. Introduction

OVER the last few years, the application of thermodynamics to ceramics has received increasing attention. The greatest interest appears to have been in its use for predicting reactions in multicomponent systems. Much effort has been made to explain the nature, origin, and manner of application of these data.<sup>1-5</sup>

Portion of paper listed on the Fifty-Sixth Annual Meeting Program, The American Ceramic Society, Chicago, Ill., April 18-23, 1954 (Enamel Division, No. 6). Received November 11, 1954.

At the time this work was done, the authors were, respectively, project leader and consultant, Ceramic Division, Battelle Memorial Institute. Mr. Tripp is now with the General Electric Company, Louisville, Ky.

<sup>1</sup> Leo Brewer, "Thermodynamic Properties of the Oxides and Their Vaporization Processes," *Chem. Revs.*, **52** [1] 1-75 (1953).

<sup>2</sup> C. J. Osborn, "Graphical Presentation of Metallurgical Equilibria," *Am. Inst. Mining Met. Engrs. Tech. Pub.*, No. 2720; *J. Metals*, **188** [3] 600-607 (1950); *Ceram. Abstr.*, 1950, November, p. 229j.

## II. General Considerations

There seems to be confusion, however, in choosing the particular data on which to base assumptions regarding reactions at elevated temperatures. The driving energy which causes a reaction to take place is derived from the differences in the free energies of formation of the constituents reacting. These free energies vary with temperature. The heat of

<sup>3</sup> F. D. Richardson, J. H. E. Jeffes, and G. Withers, "Thermodynamics of Substances of Interest in Iron and Steel Making: II, Compounds Between Oxides," *J. Iron Steel Inst.*, **166** [3] 213-34, 245 (November 1950).

<sup>4</sup> (a) W. D. Kingery and J. F. Wygant, "Thermodynamics in Ceramics: I, Energy and Heat Content," *Am. Ceram. Soc. Bull.*, **31** [5] 165-68 (1952).

(b) J. F. Wygant and W. D. Kingery, "Thermodynamics in Ceramics: II, Free Energy, Entropy, and Equilibrium," *ibid.*, [6] 213-17.

(c) J. F. Wygant and W. D. Kingery, "Thermodynamics in Ceramics: III, Stability of Ceramic Materials," *ibid.*, [7] 251-55.

(d) J. F. Wygant and W. D. Kingery, "Thermodynamics in Ceramics: IV, Crystal Chemistry, Physical Processes and Surface Effects," *ibid.*, [8] 294-97.

(e) W. D. Kingery and J. F. Wygant, "Thermodynamics in Ceramics: V, Semiempirical Calculations," *ibid.*, [9] 344-47.

(f) J. F. Wygant and W. D. Kingery, "Thermodynamics in Ceramics: VI, Summary, Bibliography, and Sources of Data," *ibid.*, [10] 386-88.

<sup>5</sup> W. J. Knapp and W. D. Van Vorst, "Some Semiempirical Methods for Estimating the Entropies of Oxides, Silicates, and Titanates, and the Prediction of Reaction Equilibria and Yields," *J. Am. Ceram. Soc.*, **34** [12] 384-87 (1951).

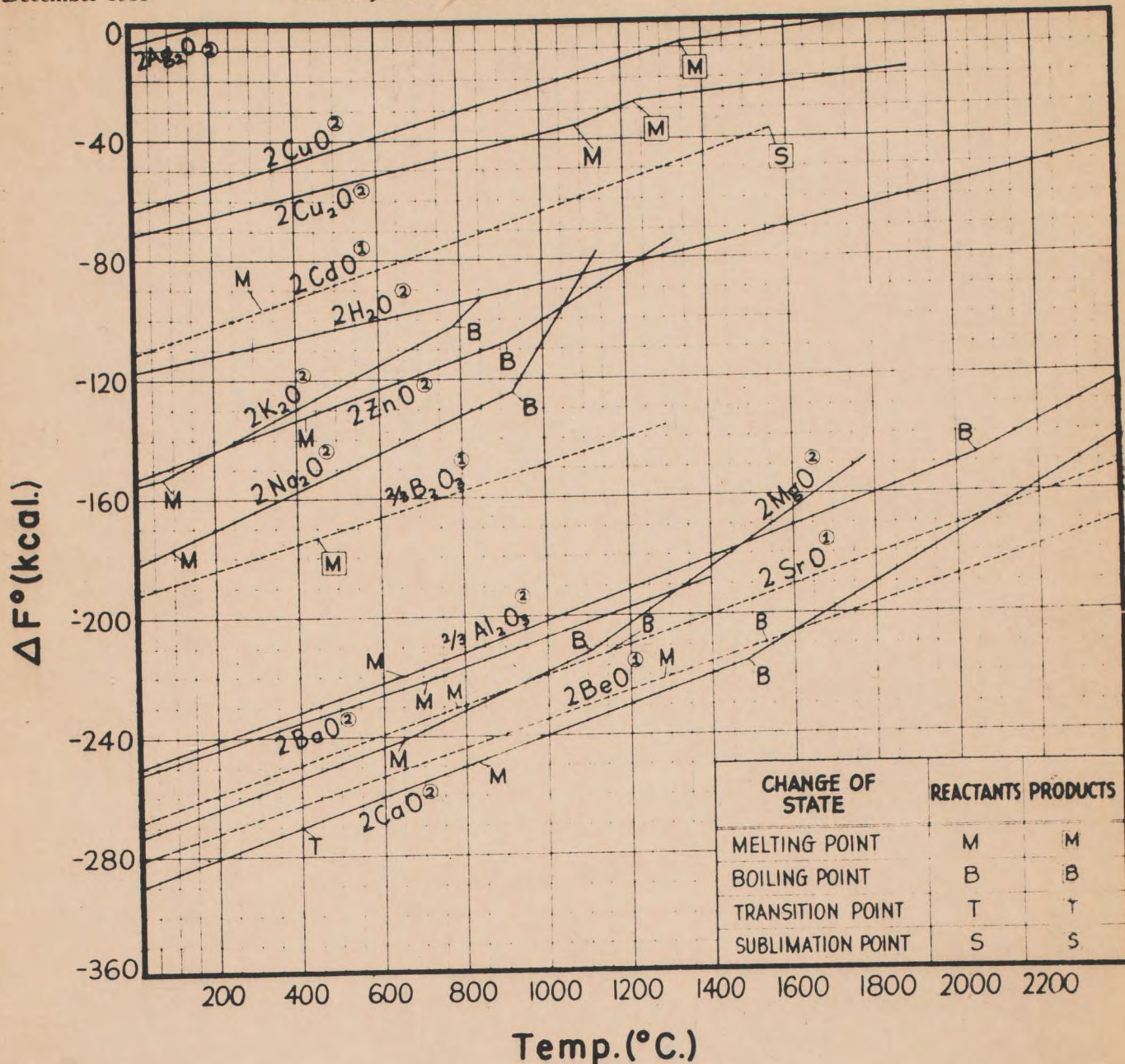


Fig. 1. Free energies of formation of metal oxides of groups 1, 2, and 3 for reactions involving 1 gram mole of oxygen.

formation includes the free energy plus a component which is related to both the temperature and the entropy of the material, and this component is not available to aid in causing a reaction to take place. Mathematically, this is stated as follows:

$$\Delta H = \Delta F + T\Delta S$$

- $\Delta H$  = change in heat of formation.
- $\Delta F$  = change in free energy of formation.
- $\Delta S$  = change in entropy.
- $T$  = absolute temperature.

For simple oxidation-reduction reactions and compound formations, the only accurate method of predicting the tendency for a reaction to occur is by the use of the free energy of formation of the various reactants and end products at the proper temperature. As explained by others,<sup>4,6</sup> the general form of this equation is

$$aA + bB = cC + dD \quad (1)$$

where  $a$ ,  $b$ ,  $c$ , and  $d$  are molar concentrations, and  $A$ ,  $B$ ,  $C$ , and  $D$  are the magnitudes of some property expressed on a

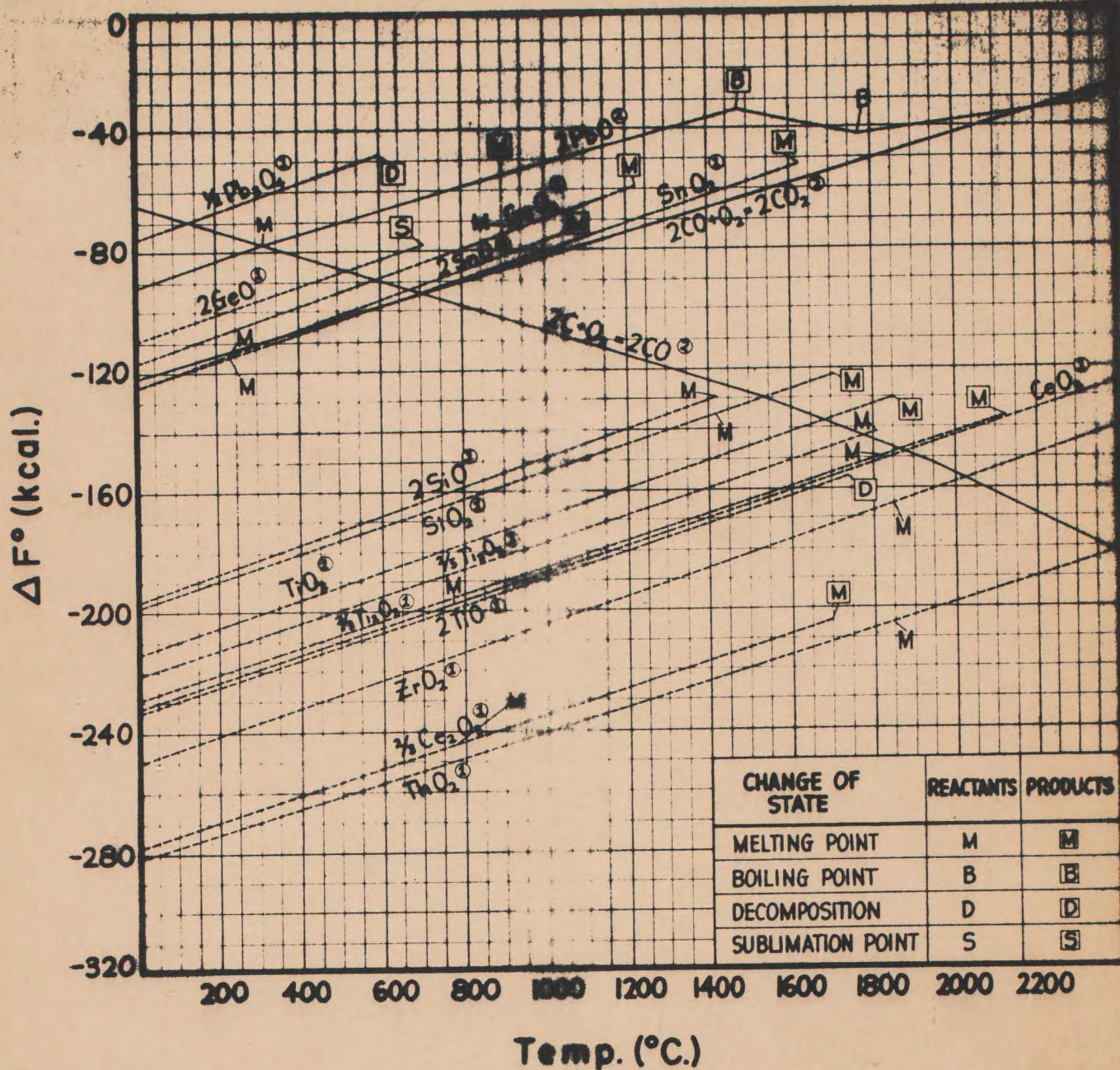


Fig. 2. Free energies of formation of metal oxides of group 4 for reactions involving 1 gram mole of oxygen.

molar basis (in this case, the free energy of formation). Therefore, the equation can be written

$$(c\Delta F_C^\circ + d\Delta F_D^\circ) - (a\Delta F_A^\circ + b\Delta F_B^\circ) = \Delta F^\circ \quad (2)$$

the superscript ( $^\circ$ ) referring to data for the standard state of the material at the particular temperature. If the subtraction results in a negative value, reaction (1) will tend to proceed to the right. The use of these data is quite simple.

### III. Use of Data

The major deterrent to the greater use of free-energy-of-formation data is probably the manner in which the available data are presented. Most of these data are in tabulated form for the temperature of 25°C. or for some specific elevated temperature. Some extra calculations often are required before they can be utilized for reactions at the temperature

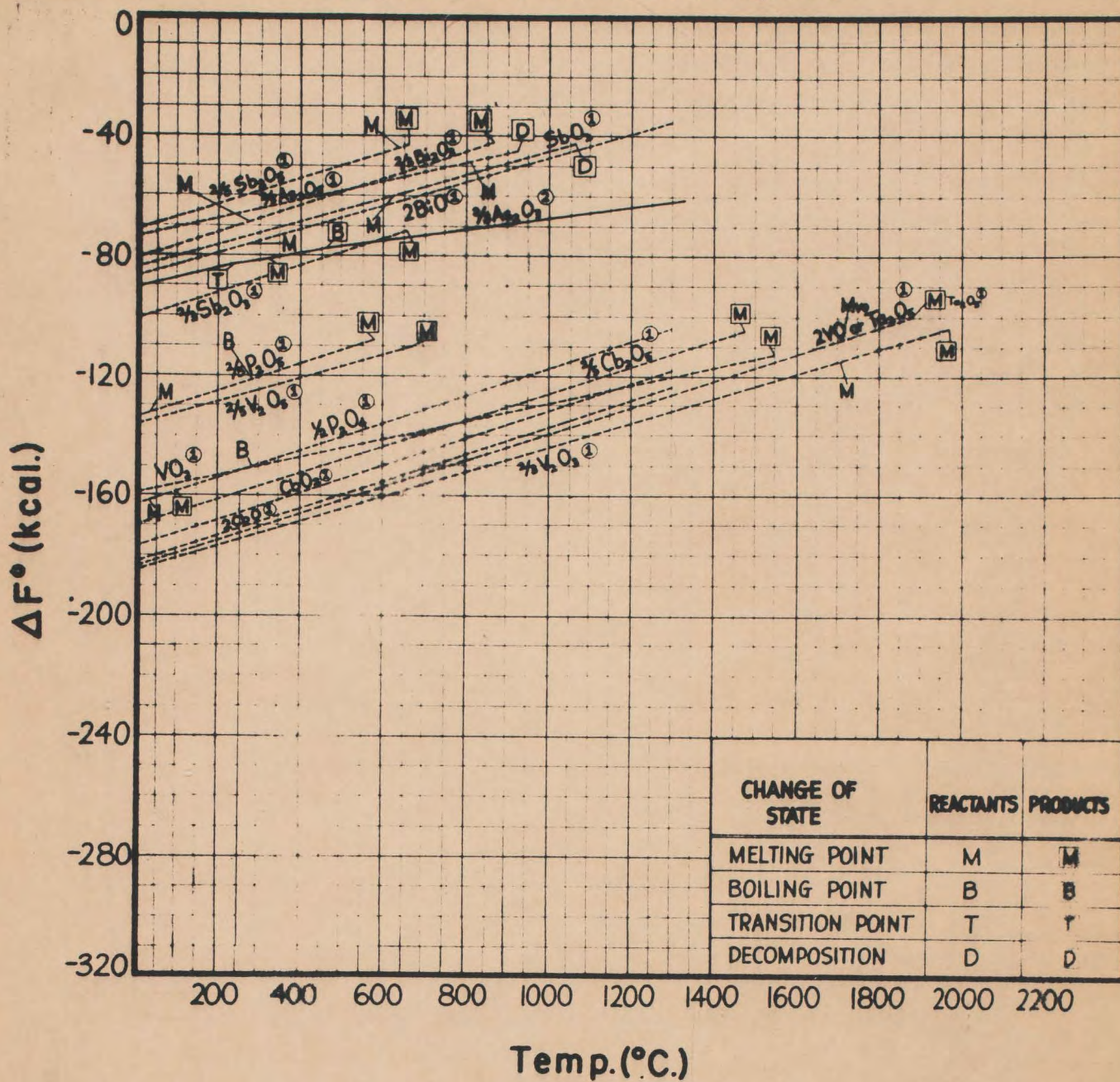


Fig. 3. Free energies of formation of metal oxides of group 5 for reactions involving 1 gram mole of oxygen.

of interest. To minimize this objection, the available data of particular interest to most ceramists are presented in graphic form in Figs. 1, 2, 3, 4, and 5, from which the values can be read directly.

These data were taken from the sources which are denoted by superscripts (footnote numbers) on the identifications for the curves. The solid curves represent data established experimentally. The dashed curves represent approximations

based on data at 25°C. for heats of formation and entropies. Such approximations are considered reasonably accurate<sup>4</sup> if carried only to the temperature at which a phase change occurs in either the compound or in the individual constituents of the compound. For this reason, the melting-point and boiling-point data are given on the dashed curves, and the curves are generally terminated at the temperature at which a physical change occurs in the oxide. In the absence

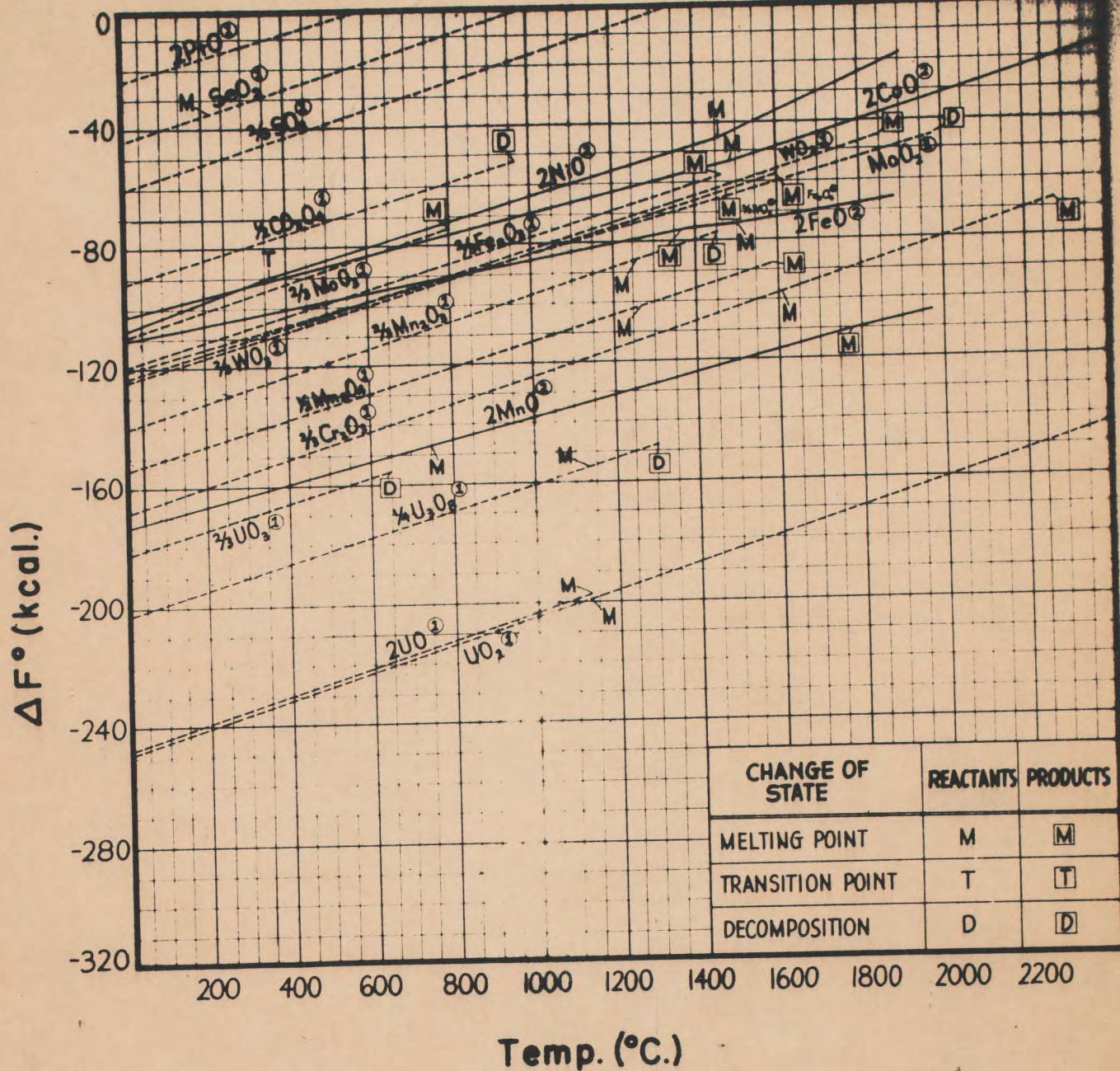


Fig. 4. Free energies of formation of metal oxides of groups 6, 7, and 8 for reactions involving 1 gram mole of oxygen.

of fairly specific data, the curves for several compounds were arbitrarily terminated at 1300°C.

Figures 1, 2, 3, and 4 give the data for the standard free energy of formation of oxides based on reactions involving one gram mole of oxygen ( $O_2$ ). This manner of presentation shows the true relationships between the relative stabilities of the various oxides. The conversion of the values from the

curves to molecular values for the oxide requires only direct multiplication by the inverse of the number preceding the identification of the curve.

For example, the  $\Delta F^\circ_{870^\circ C.}$  for  $\frac{1}{2}Cr_2O_3$  is read from Fig. 4 as  $-130$  kcal. per gram mole of  $O_2$ . The  $\Delta F^\circ_{870^\circ C.}$  for one mole of  $Cr_2O_3$  would be  $(\frac{1}{2})(-130)$  or  $-195$  kcal. Similarly,  $\Delta F^\circ_{870^\circ C.}$  for one mole of  $CoO$  would be  $(\frac{1}{2})(-74)$  or

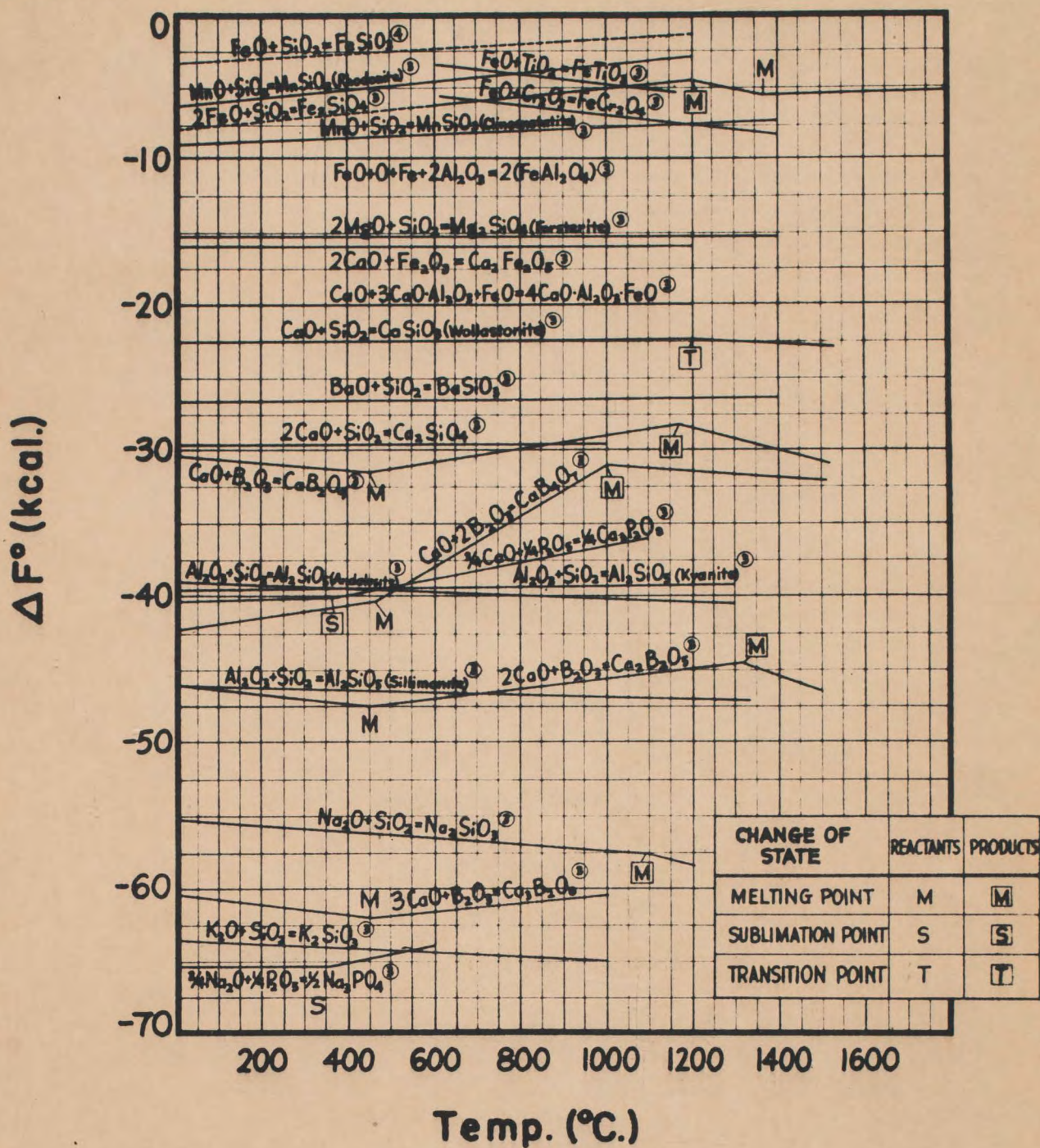
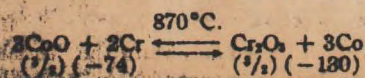


Fig. 5. Free energies of formation of various compounds between oxides.

These data can be used in the manner



$$\text{Reaction} = -185 - (-111) = -84 \text{ kcal./}\frac{1}{2} \text{ mole O}_2$$

Figure 5 gives data for the formation of complex compounds from component oxides, and not from their elements as was the case with the previous data.

# Summary

Cr - Rh (556) prob. 3 phases

Cr - Ru (554)  $5\text{Cr}_2\text{Ru}_3$   $10\%$   $\text{RCr}_3\text{Ru}$  CrRu

Cr - Ir 535 3 phases

---

Nb Rh 1014  $\text{Nb}_3\text{Rh}$   $\text{Nb}_3\text{Rh}_2$  (?)

Nb Ru (1014) S.S. up to 32% Ru RuRh (?) Nb in Ru  $< 23\%$

Nb Ir  $\frac{2}{3}$   $\text{Nb}_3\text{Ir}$

---

Ta Rh 1156  $-\text{Ta}_3\text{Rh}_2-$

Ta Ru 1159 2 phases

Ta Ir  $\frac{2}{3}$

---

Mo Rh (972) Sol. of Mo in Rh 7% at 1300,  $\epsilon$  phase 15-52.5% Mo 1400°C

$\epsilon + \text{Mo}$  form eutectic

Mo Ru 972 Mo in Ru - 800-1600 35%  $\text{Mo}_5\text{Ru}_3$

Mo Ir 869 S.S.,  $\epsilon$  etc,  $\text{Mo}_3\text{Ir}$



$\begin{matrix} & \text{Co} \\ \text{Rh} & \\ \text{Ru} & \\ \text{Ir} & \end{matrix} \left. \vphantom{\begin{matrix} \text{Rh} \\ \text{Ru} \\ \text{Ir} \end{matrix}} \right\} \text{Carbides}$

reactions with  $\checkmark$ Nb,  $\checkmark$ Cr,  $\checkmark$ Ti,  $\checkmark$ Zr,  $\checkmark$ Ta,  $\checkmark$ Mo-Ni  
 05

Rh-Nb (1014) two cpds formed  $\text{Nb}_3\text{Rh}$   $\text{Nb}_3\text{Rh}_2$ (?)

Rh-Cr (556) probably 3 phases

Rh-Ta (1156)

374  
11

Rh-Ti 1157

Rh-Zr -

Rh-Mo 972

Nb-Ru- S.S. up to 32% Ru  $\text{Ru}_{48}\text{Nb}_{52}$  Nb in Ru  $\approx 22\%$

Cr-Ru  $\text{Cr}_2\text{Ru}$ ,  $\text{Cr}_3\text{Ru}$ ,  $\text{Cr}_4\text{Ru}$

Cr-Ir - 3 phases

# GENERAL ATOMIC

DIVISION OF GENERAL DYNAMICS CORPORATION

To L. Szilard

2/6/55

From L. R. Zumwalt

Prof Szilard

Perhaps this  
will be of interest to  
you. It has data  
on the reparation of  
U, Th, rare earths, etc.  
in it.

L. R. Zumwalt

A SELF-PURIFYING HIGH-TEMPERATURE BREEDING POWER REACTOR

Leo Brewer

August, 1956

ABSTRACT

The thermodynamic calculations for the behavior of fission products in a high temperature carbide pile are presented. Even though many of the data have to be estimated and the calculations are reliable only within orders of magnitude, they clearly indicate the excellent possibility of a self-purifying reactor that can be run to high burn-up. The need for experimental determination of more thermodynamic properties is emphasized.

## A SELF-PURIFYING HIGH-TEMPERATURE BREEDING POWER REACTOR

It is clear that the first power piles will be run at relatively low temperatures until more experience has been gained, but there is no question that one should be aiming ultimately for breeders that can operate at least in the range of 2000 to 3000°K. In order to minimize the cost of processing, the piles should be designed for high burn-up.

Although a greater efficiency of conversion of thermal energy to electrical energy results from operation at high temperatures, this is not the main reason for the desire for higher temperatures. To remove energy at a high power rate, one must use high temperature gradients. A pile which can withstand a very high maximum temperature is essential for high power generation in the typically small volume of a nuclear pile. Also, high operating temperatures offer the possibility of self-purification by vaporization of most of the fission products during operation of the pile. The importance of these factors makes it desirable to aim research programs toward such a type of pile. Such piles will certainly supersede any of the lower temperature designs that have been considered for power production.

The principles of high temperature purification of nuclear fuels have been outlined previously.<sup>1</sup> The experimental data reviewed in Vol. 9, Reactor Technology and Chemical Processing, of the Geneva Proceedings<sup>2</sup> confirm that high temperature techniques can provide purification of nuclear fuels.<sup>2-8</sup> For most efficient utilization of fissile nuclear resources, we should be using power piles that can breed and use  $U^{238}$  and  $Th^{232}$ . To make the discussion more concrete, let us consider a specific nuclear fuel element and examine the possibilities of high temperature purification by vaporization of the fission product poisons. Similar examination of other fuel elements can be made using the methods described by Brewer.<sup>1</sup> For example, a liquid fuel element could be subjected to rather complete high temperature

purification by the various methods outlined above.<sup>1-8</sup>

Let us consider a pile that is converting  $\text{Th}^{232}$  to  $\text{U}^{235}$ . The uranium and thorium are present as carbides in a graphite matrix. The graphite fuel elements must be threaded so as to fit into one another and then they could be coated with niobium or zirconium carbide by a vapor deposition method.<sup>9</sup> We can imagine these coated fuel elements being cooled by some coolant, undoubtedly a liquid metal. As the graphite is normally fairly porous, the graphite fuel element within its zirconium or niobium carbide jackets can transmit a gas. The heat is extracted from the fuel element by means of the coolant outside the jacket. Through the interior of the fuel element passes a gas, e.g., helium, that removes volatile fission products as they are formed. This gas flows at a slow rate and is kept at a pressure that equalizes the pressure exerted by the coolant.

The maximum temperature to be allowed in the fuel element may be fixed by one of several factors. It is desired to have the temperature as high as possible, to have the greatest possible outward heat flow, and to increase the rate of vaporization of fission products. However, it is necessary to keep the temperature low enough so that structural strength is maintained and excessive vaporization of thorium or uranium is avoided. From the Th-C and U-C phase diagrams<sup>10,11</sup> one would expect temperatures of  $2700^\circ\text{K}$  to be quite feasible. The  $\text{ThC}_2$ -graphite eutectic temperature is given as around  $2800^\circ\text{K}$ . The solubilities of  $\text{UC}_2$  and  $\text{ThC}_2$  at such temperatures in graphite are not known. It would be important to know these so that one could predict whether eutectic melting due to the two phase system of graphite and carbide would take place at  $2800^\circ\text{K}$ . If the carbides dissolve completely in the graphite, one may go to higher temperatures than  $2800^\circ\text{K}$  without liquid formation. However, temperatures much higher than  $3000^\circ\text{K}$  may not be feasible in a graphite system in any case due to decreasing strength of graphite. Let us assume a conservative temperature of  $2700^\circ\text{K}$  for the maximum temperature of the fuel elements.

The conclusions previously reached<sup>1</sup> about the volatility of fission products were based on the tabulation<sup>12</sup> of vapor pressures of the elements available in 1945. Examination of the recent compilation of vapor pressures of the elements by Stull and Sinke<sup>13</sup> shows that the recent data have not altered the previous conclusions. From Stull and Sinke's tables, we see that Zr, Nb, Mo, Tc, Ru, and Rh are so non-volatile that one could not hope to remove them from graphite by vaporization. With the possible exceptions of Pd, Sn, and the rare earth metals<sup>15</sup> all other fission products resulting from the fission of  $U^{235}$  have atmospheric boiling points below the operating temperature of  $2700^{\circ}\text{K}$  and would be expected to vaporize rapidly. Carbide formation would not decrease the vapor pressures of any of the volatile fission products appreciably. Tin has a vapor pressure of 0.3 atm and Pd has a vapor pressure of  $10^{-1.5}$  atm at  $2700^{\circ}\text{K}$ . Neither of these elements form carbides and both should also evaporate rapidly. Thus the ~~most~~<sup>most</sup> critical question is the extent of removal of the rare earth elements, ~~esp~~<sup>especially</sup> in view of the high neutron cross sections of some of these elements. To ~~predict~~<sup>predict</sup> the equilibrium behavior of a mixture of rare earths, thorium, and uranium in graphite requires knowledge of the heats of formation of the carbides and knowledge of the vapor pressures of the pure metals. Except for the data for uranium, which really need some checking before we can be confident that we know the behavior of uranium even within an order of magnitude, there are essentially no other data. Using the methods described by Brewer and Krikorian<sup>14</sup> it is possible to estimate heats of formation of  $\text{ThC}_2$  and  $(\text{R.E.})\text{C}_2$ . As there are more data for monocarbides than for dicarbides, one would start with the monocarbides. The binding ~~energies~~<sup>energies</sup> or the  $\Delta H$  values in kcal. for the reaction



are probably as follows:

Ca < 221	Sc ~ 267	Ti 327	V 309	Cr < 282
Sr < 214		Zr 361	Nb 375	Mo 330
Ba < 216		Hf 386	Ta 396	W 379
				U 322.

It is somewhat difficult to estimate the behavior of lanthanide and actinide elements from the behavior of the transition metals, but examination of data for the nitrides is also helpful. A binding energy of 331 kcals for ThC and a binding energy of 290 kcals for (R.E.) C would not be unreasonable where R. E. is one of the light lanthanides like La, Ce, Pr, Nd, or Pm. For Eu, one would assume a behavior like that of an alkaline earth and a binding energy of 220 kcal.

Taking the estimate for the MC phases and knowing that  $MC_2$  phases exist for the lanthanide and actinide metals, one can set some limits to the binding energies of the  $MC_2$  phase or the  $\Delta H$  values in kcals for the reaction



They would be listed as follows:

Ca	400.2	Ti	< 498	V	< 480				
Sr	~ 390	Zr	< 532	Nb	< 546	Mo	< 501		
Ba	~ 390	Ce	450	Hf	< 557	Ta	< 567	W	< 550
		Th	505			U	492		

It is somewhat difficult to know how to handle the important elements Sm and Eu. If one assigns some alkaline earth behavior to them, one would assign bonding energies of 420 and 400 kcal, respectively to  $EuC_2$  and  $SmC_2$ .

Finally, converting to  $\Delta H$  values for the reaction



one obtains the following values: Th, -33; U, -27; R.E., -28; Sm, -28; and Eu, -15 kcal. The uncertainties of these values are rather high, but the order of the values is probably correct. It would be of utmost importance to obtain reliable experimental values for these quantities. From these values one can calculate the metal activities relative to pure metal at 2700°K in a system consisting of graphite

and metal carbide phases assuming zero values of  $\Delta C_p$  and  $\Delta S$ . The values obtained are as follows: Th,  $10^{-2.7}$ ; U,  $10^{-2.2}$ ; R. E.,  $10^{-2}$ ; Sm,  $10^{-2}$ , and Eu,  $10^{-1}$ .

Now it is necessary to consider the vapor pressures of the metals. Because of the importance of these data for the rare earth metals, it is worthwhile to consider them in detail. Aside from a single rough measurement of the vapor pressure of cerium reported by Brewer,<sup>12</sup> there were no other data of any sort for the volatility of the rare earth metals in 1945 when the calculations of UCRL-314 were made. Fortunately, the correct average vapor pressure was guessed approximately for the rare earth metals although the lighter rare earth metals are less volatile and the heavier ones more volatile than the values guessed in 1945.

Since then the Ames group has prepared most of the rare earth metals and have at least qualitative observations for almost all of them. Daane<sup>15</sup> and Spedding and Daane<sup>16</sup> have reported their observed volatilities. Stull and Sinke<sup>13</sup> have translated even their qualitative observations into thermodynamic functions where free energy functions were available for the gases. Table I presents an extension of their tabulation to include even those elements for which one must estimate free energy functions for the gas. The values given for  $\Delta H_{298}^{\circ}$  to three figures are from the tables of Stull and Sinke. The values that are rounded off are based on the estimated free energy functions for the process  $M(l) = M(g)$  that are tabulated in the next column. The calculated vapor pressures are given at  $2000^{\circ}\text{K}$  and  $2700^{\circ}\text{K}$  in atm. Comparison of the vapor pressures tabulated by Stull and Sinke<sup>13</sup> for Sm, Eu, and Yb with the vapor pressures of Sr and Ba would indicate that their values are high by at least a factor of two and their  $\Delta H$  values low by 2 to 3 kcal, but their values have been retained here for consistency with their tables. For calculations at  $2700^{\circ}\text{K}$ , it was assumed that the  $-(\Delta F^{\circ} - \Delta H_{298}^{\circ})/T$  values were about 1 eu smaller than the values tabulated at  $2000^{\circ}\text{K}$  for those elements not covered by Stull and Sinke.



The values given for Th and U are believed preferable to those given by Stull and Sinke.

Table I

Vaporization Data for the Rare Earth Metals and Some Actinides

	$\Delta H_{298}^{\circ}$	$-(\Delta F_{2000}^{\circ} - \Delta H_{298}^{\circ})/T$	$P_{2000}^{\circ}K$	$P_{2700}^{\circ}K$
La	99.6	28.26	$10^{-4.7}$	$10^{-2}$
Ce	80.	23.	$10^{-3.7}$	$10^{-1.3}$
Pr	79.	24.	$10^{-3.4}$	$10^{-1.2}$
Nd	76.8	24.34	$10^{-3.1}$	$10^{-1.1}$
Sm	50.0	26.45	2.	35.
Eu	43.2	24.62	4.5	50.
Gd	82.5	28.74	$10^{-2.7}$	$10^{-0.6}$
Dy	70.	25.	$10^{-2.2}$	
Ho	70.	25.	$10^{-2}$	
Er	72.	25.	$10^{-2.4}$	
Tm	62.	24.	$10^{-1.5}$	
Yb	42.9	23.35	2.6	
Lu	67.2	30.86	$10^{-0.6}$	
Th	130.	31.	$10^{-7.4}$	$10^{-4}$
U	122.7	31.3	$10^{-6.6}$	$10^{-3.4}$
	kcal	eu	atm	atm

The combinations of the vapor pressures with the metal activities in the graphite system yield the following vapor pressures in equilibrium with a system containing graphite and metal carbide phases at 2700°K: Th,  $10^{-6.7}$ ; U,  $10^{-5.6}$ ; La,  $10^{-4}$ ; Ce, Pr, Nd,  $10^{-3.2}$ ; Sm, 0.35; and Eu, 5 atm.

It is to be expected that the carbides of all of these elements will be miscible with ThC<sub>2</sub>. If the ratio of Th to C is large enough that the thorium carbide does not dissolve completely in the graphite at 2700°K, one might expect the vapor pressures given above to be reduced by the mole ratio of the metal to thorium. At 2700°K, the vapor pressure of thorium is low enough that loss of thorium due to vaporization should be unimportant. One would calculate that the loss of uranium would be smaller than that of thorium unless the uranium to thorium ratio were greater than  $10^{-1.1}$  or about 8%. The uranium content should be much smaller and thus the loss of uranium may also be unimportant. It is reasonable to assume that the behavior of Pa would be intermediate between that of Th and U.

Again assuming perfect solutions for the carbides, the lanthanum would *not* be vaporizing at a rate equal to that of the thorium until the La/Th ratio had built up to  $10^{-2.7}$ . Cerium, praseodymium, and neodymium should be vaporizing at a rate equal to the thorium vaporization rate when their ratio to Th has built up to  $10^{-3.5}$  or about 0.03%. The samarium and europium should, of course, vaporize at a much more rapid rate than the thorium even when they are at very high dilution. In the lack of data for Y, one can assume that Y will behave like La.

As one lowered the temperature, the R.E./Th ratio for equal vapor pressures would decrease. If reduction of the rare earth concentration to the lowest value possible were the only factor to consider in fixing the maximum temperature of the fuel element, one would keep the temperature to as low as possible a value that would still allow a fast enough rate of vaporization of the rare earths.

In the first stages of operation of the pile, a considerable fraction of the rare earths would probably remain dissolved in the  $\text{ThC}_2$ . However, as the burn-out proceeded and as much as 0.1% of the thorium has been converted to  $\text{U}^{233}$ , the rare earths would have built up to a concentration where their vapor pressure would be higher than that of the thorium. Thus, depending upon the temperature, one might expect a steady state to be reached at some limiting concentration of the rare earths and further operation of the pile would not result in any further build up of the rare earth poisons. Thus the pile might be operated to high burn-out. The final limitation might be the accumulation of Tc and Rh in the pile which would eventually reduce the breeding ratio.

In the above discussion, no recognition of kinetic effects has been made and it has been assumed that the rates of vaporization would be proportional to the equilibrium vapor pressures. Not much is known about the vaporization of metals from carbides. McCabe and Hudson<sup>17</sup> have shown that Mn vaporizes from its carbide with a high vaporization coefficient.

Our experience with the carbon tube King furnace at Berkeley yields some information about the vaporization of metals from graphite. The temperature range is somewhat higher, namely 2700-3200°K, than the range under consideration in this paper but the metal impurities are at much smaller concentrations than the concentrations of fission products in fuel elements. The presence of minute amounts of metal impurities can be readily detected by observation of the thermal emission spectrum due to vaporized gases in the center of the hot carbon tube.

Upon heating a fresh graphite tube, one can observe the spectra due to many metals. Metals like Mn and Cr with atmospheric boiling points between 2300°K and 2900°K are completely vaporized within a few minutes. Iron with a normal boiling point of 3160°K is very rapidly reduced within ten to fifteen minutes heating time. Titanium and vanadium are among the most persistent metals. The atmospheric boiling points of the pure Ti and V are between 3550° and 3650°K, but both of these <sup>elements</sup> elements

form very stable carbides. This formation results in reduction of their vapor pressures by a factor of almost one thousand for Ti and by a factor of over 10 for V. Both Ti and V are less volatile than even La, the least volatile of the lanthanides, and the activity of Ti is reduced more in the presence of graphite than is the activity of La. Yet it is possible after 30 to 60 minutes heating to remove virtually all of the Ti and V.

Data on the rates of vaporization of rare earths from their carbides would be valuable to have.\* One fortunate factor here is that the fission fragments will for the most part end up in disturbed portions of the graphite lattice and presumably would be able to readily move out. A considerable fraction of the fission fragments may actually come to thermal energies in the gas stream. Thus one would expect the rate of vaporization of fission fragments to be much <sup>greater</sup> ~~more~~.

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\*Note in Proof:

Professor Law McCabe of Carnegie Institute of Technology (private communication August 23, 1956) has just obtained preliminary cerium vapor pressures in equilibrium with graphite. He finds values from  $1.2$  to  $1.7 \times 10^{-7}$  atm at  $1817$  to  $1858^\circ\text{K}$ . The pressure of pure cerium would be just below  $10^{-4}$  atm in the same temperature range. Warf has shown the carbide in equilibrium with graphite to be  $\text{CeC}_3$ , but the heats of formation of  $\text{CeC}_3$  and  $\text{CeC}_2$  must be very close together. Thus these results may be compared with the estimates given above. The reduction in Ce pressure by a factor of 500 corresponds to  $\Delta H = -23$  kcal for the formation of  $\text{CeC}_3$  assuming zero  $\Delta S$ . This is in excellent agreement with the estimates of  $-28$  kcal made above. These very important preliminary experiments now provide direct experimental evidence for the volatility of the rare earths from a graphite matrix.

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than the rate one might observe from a synthetic fission mixture dissolved in graphite. One might actually lose some of the non-volatile fission products as a dust in the gas stream. The loss of thorium and uranium in the gas stream may possibly be due more to dusting than to actual volatility. It would be important to design experiments to test this.

On the whole, one would be quite encouraged to expect that temperatures of  $2500^{\circ}$  to  $2700^{\circ}$ K would be adequate to remove more than 50% and possibly 75% of the fission products and all of the bad poisons for the thermal neutrons or near thermal neutrons. The large percentage removal of fission products by vaporization would indicate that such a design would be valuable even for fast neutron reactors.

One might imagine that the pile would be operated at temperatures lower than  $2700^{\circ}$ K, e.g., 2400 to  $2500^{\circ}$ K, at which temperature almost all of the volatile fission products would be removed. From time to time, one would then decrease the coolant rate slightly to allow the temperature to increase from  $2700^{\circ}$  to  $2800^{\circ}$ K to accelerate the vaporization of some of the less volatile fission products if experience indicates any appreciable hold-back of rare earth poisons. It is possible that some of the rare earths that vaporize readily from the fuel elements might condense at cooler parts of the pile. If these cooler regions were inside the reflector there might still be neutron losses due to rare earths. If this situation develops, it might be helpful to add a small amount of chloride to the helium to convert the rare earths to the more volatile chlorides that could be swept completely out of the pile. Thus a trace of HCl could be added to the helium or the helium could be saturated with  $\text{ThCl}_4$  or  $\text{UCl}_4$  at around  $700^{\circ}$ K to provide a  $\text{ThCl}_4$  or  $\text{UCl}_4$  partial pressure of around  $10^{-6}$  atm. Because of the greater stability of the rare earth halides, one might be able to insure removal of rare earths from cool parts of the pile.

The advantages of a reactor using a self-purifying fuel element of this type are so distinctive that it is hoped that an active program of determination of the missing thermodynamic data as well as testing of such fuel elements in test reactors will be undertaken.

#### Acknowledgment

I wish to thank Theodore Taylor and Ulrich Merten of General Atomic, San Diego, California, for helpful discussions.

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# Physical Properties of Selected Refractories

Compiled by Group CMB-6  
 Tabulated by Group CMB-7  
 Los Alamos Scientific Laboratory  
 Los Alamos, New Mexico

Radiation exposure for comments under "Principle Limitation":

A =  $1 \times 10^{20}$  nvt  
 B =  $2 \times 10^{20}$  nvt

Bibliography starts on page 40

	DENSITY	CRYSTALLINE FORM	TENSILE STRENGTH	COMPRESSIVE STRENGTH	MODULUS OF RUPTURE	YOUNG'S MODULUS OF ELASTICITY	MELTING POINT	SPECIFIC HEAT	LINEAR COEF. OF THERMAL EXPANSION	FREE ENERGY OF FORMATION	ENTHALPY $\Delta H$	ENTROPY $\Delta S$	THERMAL CONDUCTIVITY	THERMAL SHOCK RESISTANCE	RESISTIVITY	TYPE OF CONDUCTOR	MAGNETIC SUSCEPTIBILITY	DIELECTRIC CONSTANT	SPECTRAL EMISSIVITY	VAPOR PRESSURE	PRINCIPLE LIMITATION			
	gm/cc		M PSI	M PSI	M PSI	10 <sup>6</sup> PSI	°C	cal/gm/°C	10 <sup>-6</sup> /°C	kilo-cal/mole	298°K	298°K	cal/cm <sup>2</sup> /cm <sup>2</sup> /°C		ohm/cm		ROOM TEMP MAG UNIT /gm x 10 <sup>-6</sup>	ROOM TEMP	AS MELTED SURFACES $\lambda \times 0.65 \mu$	mm Hg				
ALUMINA Al <sub>2</sub> O <sub>3</sub>	3.97	HEXAGONAL	21 (25) 19.8 (800) 7.3 (1400) <sup>29</sup>	41.3 (20*) 20 (1200*)	46.8 (20*) <sup>32</sup>	51 (25*) 48.2 (800*) 28.0 (1300*) <sup>32</sup>	2050	.21 (20) .25 (500) .28 (1000)	5.8 (25) 7.3 (800) 10.0 (1300) <sup>29</sup> 10.2 (1500) <sup>31</sup>	-365.9	-399.09	12.19	0.017 (100) 0.015 (1000) <sup>30</sup>	GOOD	1.0 x 10 <sup>10</sup> 2.2 x 10 <sup>10</sup> (500)	NONCONDUCTOR	-.098	12.3	22-40 (2800-1200)	BP 2980 47 780 mm AT APPROX (1800) <sup>60</sup> BP 2200 47	RADIATION EXPOSURE - A=NONE B=NONE 37 TEMP LIMIT - 1950° 38	ALUMINA Al <sub>2</sub> O <sub>3</sub>		
BARYTA BaO	5.72	CUBIC					1923 210			-126.3	-133.4	16.8	325 (100) 222 (400) 0.48 (1000) <sup>30</sup>	EXCELLENT	1.0 x 10 <sup>10</sup> 2.2 x 10 <sup>10</sup> (500)	EXCESS SEMICONDUCTOR	-.13			BP 2200 47	HYDRATION TOXIC I	BARYTA BaO		
BERYLLIA BeO	3.00	HEXAGONAL	6.0 (975) <sup>43</sup> 13.8 (20*) <sup>17</sup>	10.3 (20*) 60 (1200*)	20.6 (20*) <sup>32</sup>	45 (25*) 48.2 (800*) 12 (1400*)	2570	24 (20) 50 (500) 50 (1000) <sup>34</sup>	8 (100) 8 (500) 10.0 (1300) <sup>29</sup> 10.2 (1500) <sup>31</sup>	-132.0	-146.0	3.37	500 (100) 211 (400) 0.48 (1000) <sup>30</sup> 0.55 (1600) <sup>34</sup>	EXCELLENT	8.1 x 10 <sup>3</sup> (1000) 3.5 x 10 <sup>6</sup> (1800) 8.1 x 10 <sup>7</sup> (2100) <sup>34</sup>	NONCONDUCTOR	0	118-137	37 (1470)	BP 4260 47 SLIGHT AT (1900) <sup>60</sup>	TOXIC - IN VACUO - W@2000°C - YELLOW METALLIC DEPOSIT, Mo@1900°C - SILVERY DEPOSIT, ThO <sub>2</sub> @2100°C - LIQUID FORMED, ZrO <sub>2</sub> @1900°C ADHERENCE - RADIATION EXPOSURE - A - SI EXPANSION OF Co, B-0.3% EXPANSION OF Co, NONE FOR Os 37 TEMP LIMIT 2000°C 42 CAN NOT BE USED IN VACUO ABOVE 2100°C 35	BERYLLIA BeO		
CALCIA CaO	3.32	CUBIC					2572	218 (20- 1500) <sup>34</sup>	10.2 (500) 12.8 (900) 14.7 (1500) <sup>31</sup>	-144.3	-151.9	9.5	0.53 (100) 0.20 (400) 0.17 (1000) <sup>30</sup>	FAIR	7.3 x 10 <sup>3</sup> (760) 9.6 x 10 <sup>7</sup> (1500) 1.1 x 10 <sup>10</sup> (1963) <sup>34</sup>	NONCONDUCTOR	-.27	27		BP 2850 47 60 mm AT (174*) <sup>60</sup>	HYDRATION I TEMP LIMIT - 2400°C 38	CALCIA CaO		
CERIA CeO <sub>2</sub>	7.13	CUBIC					2810	.088 (20) 8.6 (500)		-232.0	-233.0	17.7	2.2 x 10 <sup>3</sup> (800) 1.9 x 10 <sup>4</sup> (1200)	NONCONDUCTOR			39	58-8	63 mm AT (1400) <sup>60</sup>	REDUCTION I TEMP LIMIT - 2400°C 38	CERIA CeO <sub>2</sub>			
CHROMIUM OXIDE Cr <sub>2</sub> O <sub>3</sub>	5.21	HEXAGONAL					2435 ± 50	.001 (20) 24	11- (100) 13- (500) 15- (1000)	-251.1	-269.7	19.4	1.2 x 10 <sup>7</sup> (320) 7.5 x 10 <sup>7</sup> (750) 2.3 x 10 <sup>10</sup> (1200) <sup>34</sup>	DEFECT SEMICONDUCTOR			25.5	60-80 60 (1450)	BP 3000 47	REDUCTION I	CHROMIUM OXIDE Cr <sub>2</sub> O <sub>3</sub>			
COBALT OXIDE CoO	6.46	CUBIC					1800			-176.8	-57.2	10.5	1.1 x 10 <sup>10</sup> (1500) <sup>34</sup>	DEFECT SEMICONDUCTOR				74.5	77 (1320)		REDUCTION I	COBALT OXIDE CoO		
FERRIC OXIDE Fe <sub>2</sub> O <sub>3</sub>	5.20	CUBIC HEXAGONAL					1550	.149 (0) .354 (700) <sup>24</sup>	83 (40) 21	-179.1		1.7 x 10 <sup>3</sup> 001 24 92.1 19 25 34		SEMICONDUCTOR				14.20	63 (1200)		REDUCTION I	FERRIC OXIDE Fe <sub>2</sub> O <sub>3</sub>		
GALLIUM OXIDE Ga <sub>2</sub> O <sub>3</sub>	6.44	HEXAGONAL MONOCLINIC					1740 ± 25	.106 (20) 36			-258.0										REDUCTION I	GALLIUM OXIDE Ga <sub>2</sub> O <sub>3</sub>		
HAFNIA HfO <sub>2</sub>	9.68	MONOCLINIC				8.2 (20) <sup>31</sup>	2900 ± 25 37	.174 (400) .197 (1000)	5.8 (25- 1500) <sup>32</sup>	-259.0	-271.5	29.7	1.1 x 10 <sup>3</sup> (500) 5 x 10 <sup>3</sup> (400)	NONCONDUCTOR				110			BP 4200 47	HYDRATION I	HAFNIA HfO <sub>2</sub>	
LANTHANA La <sub>2</sub> O <sub>3</sub>	6.51	HEXAGONAL					2320	.075 (20) 34		-435.0	-458.0	39.9	1.1 x 10 <sup>8</sup> (550) 1 x 10 <sup>8</sup> (100)	NONCONDUCTOR							BP 4200 47	HYDRATION I	LANTHANA La <sub>2</sub> O <sub>3</sub>	
LITHIA Li <sub>2</sub> O	2.01	CUBIC					1700			-142.4													LITHIA Li <sub>2</sub> O	
MAGNESIA MgO	3.58	CUBIC	14 (25) 14.2 (800) 6 (1300) <sup>32</sup> 3.1 (975) 48	11.2 (20*)	11.7 (20*) <sup>33</sup>	30.5 (25) 27.5 (800) 4.0 (1300) <sup>32</sup>	2800	.152 (0) .163 (50) 48	11 (100) 13 (500) 15 (1000) <sup>31</sup> 16 (1500)	-138.43	-143.8	6.4	0.86 (100) 0.59 (400) 0.17 (1000) <sup>30</sup>	FAIR	1.1 x 10 <sup>10</sup> (20) <sup>4</sup>	NONCONDUCTOR	-.25	10.5-11.5	10-43 (1480-1200) <sup>42</sup>	BP 2825 47 760 mm AT (170) <sup>60</sup>	IN VACUO - BaO @ 1800°C LIQUID PHASE, W@2000°C - REDUCTION OF MgO, Mo @ 1800°C SILVERY DEPOSIT, ZrO <sub>2</sub> @2000°C LIQUID PHASE 35 RADIATION EXPOSURE - A - NO CHANGE, B-CRYSTAL BROKEN, 37, TEMP. LIMIT - 2400°C 38 CAN NOT BE USED IN VACUO ABOVE 1600°C TO 1700°C 35	MAGNESIA MgO		
MANGANOUS OXIDE MnO	5.40	CUBIC					1785		7 (20) 34	-87.8	-92.0	14.4	1.1 x 10 <sup>8</sup> (20) <sup>4</sup>	DEFECT SEMICONDUCTOR							BP 4050 47	OXIDATION I	MANGANOUS OXIDE MnO	
NIOBIA Nb <sub>2</sub> O <sub>3</sub>	4.46	RHOMBIC					1772	.101 (20) 27					5.5 x 10 <sup>6</sup> (20) <sup>4</sup>	METALLIC CONDUCTOR							BP 1450	OXIDATION I	NIOBIA Nb <sub>2</sub> O <sub>3</sub>	
NICKEL OXIDE NiO	6.8	CUBIC					1990	.183 (20) 10		-51.7	-58.4	9.22	0.22 (100) 0.14 (400) 0.075 (1000) <sup>30</sup>	DEFECT SEMICONDUCTOR							BP 1100	REDUCTION I	NICKEL OXIDE NiO	
SILICA SiO <sub>2</sub>	2.32	ISOMETRIC TRIGONAL HEXAGONAL					1728	12.80 (20) 10		-192.4 -191.9 -192.1	-205.4 -204.8 -205.0	10.3 QUARTZ 10.5 TRIMORPH 10.3 CRYSTAL REALITE 34	3.9 x 10 <sup>7</sup> 25	POOR TO 320°C EXCELLENT ABOVE 320°C 3	1.1 x 10 <sup>10</sup> (500) 1.4 x 10 <sup>7</sup> (1000) 2.4 x 10 <sup>10</sup> (1250) <sup>34</sup>	NONCONDUCTOR	-.45	QUARTZ 4.6 TRIMORPH 4.5 REALITE 3.75 4	BP 2950 47	RADIATION EXPOSURE - A=NONE B=DIMINUTION IN HALO INTENSITY 37 TEMP LIMIT - 1600°C 38	SILICA SiO <sub>2</sub>			
STRONTIUM OXIDE SrO	4.7	CUBIC					2430		13.72 (20- 300) 13.52 (20) 13.92 (20-1200) <sup>51</sup>	-133.8	-141.1	13.0		NONCONDUCTOR							BP 3050 47	HYDRATION I	STRONTIUM OXIDE SrO	
TANTALUM OXIDE Ta <sub>2</sub> O <sub>5</sub>	8.02	RHOMBIC					1875	.078 (0*) 7		-470.6	-499.9	34.2	1.1 x 10 <sup>5</sup> (20) <sup>4</sup> 20 to 1 x 10 <sup>11</sup>	EXCESS SEMICONDUCTOR							BP 3050 47	HYDRATION I	TANTALUM OXIDE Ta <sub>2</sub> O <sub>5</sub>	
THORIA ThO <sub>2</sub>	9.69	CUBIC	5 (20) 72	220 (20*) 25 (500*) 1200*	17.9 (20*) <sup>32</sup>	21 (20*) 18 (800*) 14 (1400*)	3220 ± 50 39	.055 (0-100) .058 (0-800) 0.72	7.1 (300) 9.1 (700) 10.4 (1500) 3	-296.0	-292.0	19.6	0.25 (100) 0.14 (400) 0.08 (1000) <sup>30</sup>	POOR	1.1 x 10 <sup>10</sup> (20) <sup>4</sup> 1.2 x 10 <sup>7</sup> (500) 1.9 x 10 <sup>10</sup> (1200) 1.1 x 10 <sup>8</sup> (250) <sup>34</sup>	NONCONDUCTOR	0		57 (1550)	BP 4400 47	IN VACUO - W 2200°C ThO <sub>2</sub> REDUCTION, Mo 1900°C DEPOSIT & ADHERENCE 36 RADIO ACTIVE, TEMP LIMIT 2700°C 38 ALRIGHT IN VACUO TO 2300°C 38 - MgO 2200°C VAPOR REACTION	THORIA ThO <sub>2</sub>		
STANNIC OXIDE SnO <sub>2</sub>	7.00	TETRAGONAL					1825	.090 (45) 23	3.3 (500) 5.7 (0-100) 4	-124.2	-138.8	12.5	57 (100) 4 2.6 x 10 <sup>7</sup> (800) 1.0 x 10 <sup>10</sup> (1500)	EXCESS SEMICONDUCTOR							BP 4400 47	REDUCTION & VOLATILIZATION I SUBLIMES AT 1510°C 48	STANNIC OXIDE SnO <sub>2</sub>	
TITANIA TiO <sub>2</sub>	4.17	MONOCLINIC TETRAGONAL					1830	.166 (18-49) <sup>23</sup>	7.1 (300) 8.2 (300) 9.1 (1450) 31	-205.1	-218.0	12.01	.015 (100) 0.09 (400) 0.08 (1000) 31	EXCESS SEMICONDUCTOR				117 118 89 RUTILE, 42	52 (1450)	BP 2227 47	REDUCTION I A=NONE, B=NONE 37	TITANIA TiO <sub>2</sub>		
TUNGSTITE WO <sub>3</sub>	7.16	ORTHORHOMBIC					1473	.073 (0) 23 .082 (50) 34		-59.8	-66.6	19.9	5.6 x 10 <sup>6</sup> (20) <sup>3</sup>	AMPHOTERIC SEMICONDUCTOR								OXIDATION & RADIOACTIVE I	TUNGSTITE WO <sub>3</sub>	
URANIA UO <sub>2</sub>	10.97	CUBIC	5 (20) 72	140 (20*)	12.9 (25) 13.5 (500) 14.9 (1000) <sup>44</sup>	24.6 (525) <sup>11</sup> 23.5 (825)	2878 ± 22 28	.086 (0-200) 12.9 (800-1260) <sup>45</sup>	9.1 (27-400) 10.8 (400-800)	-257	-270	18.6	0.175 (100) 0.013 (400) 0.06 (1000) <sup>33</sup>	SEMICONDUCTOR	3.8 x 10 <sup>4</sup> (20) 5 x 10 <sup>7</sup> (500) <sup>4</sup>						BP 4100 47	OXIDATION I	URANIA UO <sub>2</sub>	
VANADIUM OXIDE V <sub>2</sub> O <sub>3</sub>	4.87	HEXAGONAL					1970	256 (0-72*) 26		-271	-290	23.58	1.75 x 10 <sup>3</sup> (1967*) 5.5 x 10 <sup>3</sup> (20*) <sup>4</sup>	METALLIC CONDUCTOR							BP 3000 47	OXIDATION I	VANADIUM OXIDE V <sub>2</sub> O <sub>3</sub>	
YTRIA Y <sub>2</sub> O <sub>3</sub>	4.84	CUBIC					2410	.103 (0-100)		-429	288.8			EXCESS SEMICONDUCTOR							BP 4300 47	VOLATILIZATION I	YTRIA Y <sub>2</sub> O <sub>3</sub>	
ZINC OXIDE ZnO	5.66	HEXAGONAL					1975 ± 25	.138 (20)	3.16 (20) 21 5.85 (20-300) 6.77 (20-500) 8.10 (20-1200) <sup>52</sup>	-76.5	-83.17	10.5	.027 (200) .018 (400) 0.009 (800) <sup>33</sup>	NON-CONDUCTOR							BP 1950 47	VOLATILIZES READILY - 1700°C 44	ZINC OXIDE ZnO	
ZIRCONIA ZrO <sub>2</sub>	5.56 6.10 6.26	MONOCLINIC TETRAGONAL CUBIC	20 (25) 16 (800) 10.2 (1300)	303 (20*) 230 (500*) 100 (1200)	26.1 (20*)	21.5 (25*) 22.0 (800*) 11.8 (1300)	2690 ± 20	.16 (500)	12 20 7.6 (300) CUBIC 11.8 (1500) <sup>31</sup>	-246	-258.2	12.03	0.047 (100) 0.049 (400) 0.055 (1000) <sup>30</sup>	FAIR	1.0 x 10 <sup>6</sup> (385) 2.2 x 10 <sup>4</sup> (700) 3.6 x 10 <sup>8</sup> (1200) 1.1 x 10 <sup>7</sup> (2000) <sup>4</sup>					BP 4400 47	TEMP LIMIT - 2500°C - IN VACUO - 0° 1600°C REDUCTION, W@1800°C, YELLOW DEPOSIT, Mo @ 2200°C ADHERENCE DUE TO SINTERING; ThO <sub>2</sub> @2200°C SI ADHERENCE 35 RADIATION EXPOSURE - A= DIMINUTION IN MONOCLINIC PHASE B= MONOCLINIC DISAPPEARS, CUBIC, STABLE 37, ALRIGHT IN VACUO TO 2300° 35	ZIRCONIA ZrO <sub>2</sub>		
CARBON C			1-2-2 (20)	2-10 (20)	10-45 (20)	1.1-2.9 (20)																	THRESHOLD OXIDATION TEMPERATURE APPROX 350°C 61 STRENGTH INCREASES WITH TEMPERATURE UP TO 2500°C 63	CARBON
GRAPHITE C <sub>g</sub>	2.27-2.28		5-2.5 (20)	3-10 (20)	10-45 (20)	0.5-23 (20)	SUBLIMES 3650 64	29 (21 to 1000) <sup>38</sup>	12 (20 to 900) <sup>38</sup>	0.00	125.03 141.25 170.39 65	1.36	.426 (100) 268 (400) 149 (1000) <sup>30</sup>	EXCELLENT	0.008-0.013 (20)	DIAMAGNETIC					BP 4400 47	THRESHOLD OXIDATION TEMPERATURE APPROX 400°C 61 STRENGTH INCREASES WITH TEMPERATURE UP TO 2800°C 63	GRAPHITE	



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Merten

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Copy No. 13

BEGINNING OF A TABLE  
ON CERAMICS

Work done by:  
E. Creutz

Report written by:  
E. Creutz

Project No. 30

March 24, 1958

BEGINNING OF A TABLE ON CERAMICS

I started to collect some data on various ceramic materials. The following lattice has more vacancies than occupied sites so rather than have it sit on my desk any longer, I thought it might be worthwhile distributing it so that various people can fill in the blanks if they have pertinent data. I should appreciate any pertinent numbers that you can supply. As time goes on, I expect to have some information from Saxonburg Ceramics on the lithium complexes.

Material	Melting Point (°C)	Boiling Point (°C)	Density (gm/cm <sup>3</sup> )	Mohr Hardness	Compressive Strength (10 <sup>3</sup> psi)	Crystal Structure	Specific Heat (cal/gm/°C)	Expansion Coefficient (per °C)	Electrical Resistivity (ohm cm)	Young's Modulus (10 <sup>6</sup> psi)	Thermal Conductivity cal (sec cm <sup>2</sup> °C) <sup>-1</sup>	Pieces Fabricators are Willing to Supply	Approx. Cost per in. of 2-in.-Diam Tube	Supplier Who Has Made Samples	Main Source of Data	Thermal Shock Resistance
B	~2000	~2400	2.31	9.3		mono-clinic	.51 (900°C)	8.3 x 10 <sup>-6</sup>							Pac. Coast Borax Co.	poor
B <sub>4</sub> C	2450	>3500	2.51	9	414	rhomboidal		4.5 x 10 <sup>-6</sup>	5 x 10 <sup>-1</sup>	65C		2" long, 1/4" wall		Norton Co.	Norton Co.	fair
BN	2730 (sublimes)		2.20			hexagonal		.59 x 10 <sup>-6*</sup> 10.1 x 10 <sup>-6†</sup>	2 x 10 <sup>12</sup> 20°C 3 x 10 <sup>4</sup> 1000°C	20°C 4.9* 12.4†	.068* .036†		\$10	Carborundum Co. and Norton Co.	Carborundum Co.	good
BeO	2530	~3900	3.02		114	hexagonal	.29	5.5 x 10 <sup>-6</sup>	10 <sup>14</sup>	39	.19	3" long	\$20	Brush Be Corp.; Be Corp.		good
Li <sub>2</sub> OAl <sub>2</sub> O <sub>3</sub>	>1625		2.55	5.5										Saxonburg Ceramics		
Li <sub>2</sub> OB <sub>2</sub> O <sub>3</sub>	770													Goeddel, General Atomic		
Li <sub>2</sub> O.2B <sub>2</sub> O <sub>3</sub>	930															
2Li <sub>2</sub> O.SiO <sub>2</sub>	1256					rhomboidal										
Li <sub>2</sub> O.SiO <sub>2</sub>	1200					rhomboidal										
Li <sub>2</sub> O.SiO <sub>2</sub> B <sub>2</sub> O <sub>3</sub>	~900															
Li <sub>2</sub> O.Al <sub>2</sub> O <sub>3</sub> 4SiO <sub>2</sub> (Spodumene)	1423		2.64	6		mono-clinic										
Li <sub>2</sub> O.Al <sub>2</sub> O <sub>3</sub> 2SiO <sub>2</sub> (Eucriptite)	1390			6												
Li <sub>2</sub> O.Al <sub>2</sub> O <sub>3</sub> SiO <sub>2</sub>	~1350			8												

\*Perpendicular to forming force

†Parallel to forming force

Material	Melting Point (°C)	Boiling Point (°C)	Density (gm/cm <sup>3</sup> )	Moh Hardness	Compressive Strength (10 <sup>3</sup> psi)	Crystal Structure	Specific Heat (cal/gm/°C)	Expansion Coefficient per °C	Electrical Resistivity (ohm cm)	Young's Modulus (10 <sup>6</sup> psi)	Thermal Conductivity cal (sec cm <sup>2</sup> ) <sup>-1</sup>	Pieces Fabricators are Willing to Supply	Approx. Cost per in. of 2-in.-Diam Tube	Supplier Who Has Made Sample	Main Source of Data	Thermal Shock Resistance
Li <sub>2</sub> O.SiO <sub>2</sub> . 2Al <sub>2</sub> O <sub>3</sub>	~ 1350															
Li <sub>2</sub> O.SiO <sub>2</sub> 4Al <sub>2</sub> O <sub>3</sub>	~ 1350															
2Li <sub>2</sub> O.SiO <sub>2</sub> Al <sub>2</sub> O <sub>3</sub>	~ 1350															
Li <sub>2</sub> O.B <sub>2</sub> O <sub>3</sub> . Al <sub>2</sub> O <sub>3</sub>	?															
Al <sub>2</sub> O <sub>3</sub> (Sapphire)	2040	2980	3.98	9	300	hexagonal	.18	50°C 6.7x10 <sup>-6*</sup> 5x10 <sup>-6†</sup> 1000°C 9.03x15 <sup>6*</sup> 8.31x15 <sup>6†</sup>	10 <sup>11</sup>	50	.065 ?	14" rods 1/4" diam	Linde			
Al <sub>2</sub> O <sub>3</sub>	2040	2980	3.98					8.1x10 <sup>-6</sup>	1.4x10 <sup>5</sup> 1000°C		.091	various	McDanel Morgan			
3Al <sub>2</sub> O <sub>3</sub> .2SiO <sub>2</sub> (Mullite)	1830		3.16				.238	5.3x10 <sup>-6</sup>	8 x 10 <sup>4</sup> 1000°C		.068	various	McDanel Morgan			
SiO <sub>2</sub>	1710		2.2				.134	.54 x 10 <sup>-6</sup>	2 x 10 <sup>8</sup>		.055	various				excellent
MgO	2800		3.58				.289	14.3 x 10 <sup>-6</sup>	4 x 10 <sup>6</sup>		.11					
2MgO.SiO <sub>2</sub> (Forsterite)	1900		3.19				.22	10.5 x 10 <sup>-6</sup>			.047		Saxonburg Ceramics			
Be <sub>2</sub> C	~2150 (Disso- ciates)		2.44	9	105	cubic	.33	20°C 5.6x10 <sup>-6</sup> 600°C 10.5x10 <sup>-6</sup>	.063		.05				BMI-1165	poor

\* Parallel to C axis

† Perpendicular to C axis

