NATIONAL BUREAU OF STANDARDS REPORT

10 070

SIXTEENTH REPORT ON
A SURVEY OF THERMODYNAMIC PROPERTIES OF THE
COMPOUNDS OF THE ELEMENTS CHNOPS

Progress Report for the Period 1 January to 30 June 1969

to

National Aeronautics and Space Administration

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards[1] was established by an act of Congress March 3, 1901. Today, in addition to serving as the Nation's central measurement laboratory, the Bureau is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. To this end the Bureau conducts research and provides central national services in four broad program areas. These are: (1) basic measurements and standards, (2) materials measurements and standards, (3) technological measurements and standards, and (4) transfer of technology.

The Bureau comprises the Institute for Basic Standards, the Institute for Materials Research, the Institute for Applied Technology, the Center for Radiation Research, the Center for Computer Sciences and Technology, and the Office for Information Programs.

THE INSTITUTE FOR BASIC STANDARDS provides the central basis within the United States of a complete and consistent system of physical measurement; coordinates that system with measurement systems of other nations; and furnishes essential services leading to accurate and uniform physical measurements throughout the Nation's scientific community, industry, and commerce. The Institute consists of an Office of Measurement Services and the following technical divisions:

> Applied Mathematics—Electricity—Metrology—Mechanics—Heat—Atomic and Molecular Physics—Radio Physics[2]—Radio Engineering[3]—Time and Frequency[2]—Astrophysics[2]—Cryogenics.[2]

THE INSTITUTE FOR MATERIALS RESEARCH conducts materials research leading to improved methods of measurement standards, and data on the properties of well-characterized materials needed by industry, commerce, educational institutions, and Government; develops, produces, and distributes standard reference materials; relates the physical and chemical properties of materials to their behavior and their interaction with their environments; and provides advisory and research services to other Government agencies. The Institute consists of an Office of Standard Reference Materials and the following divisions:

> Analytical Chemistry—Polymers—Metallurgy—Inorganic Materials—Physical Chemistry.

THE INSTITUTE FOR APPLIED TECHNOLOGY provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government; cooperates with public and private organizations in the development of technological standards, and test methodologies; and provides advisory and research services for Federal, state, and local government agencies. The Institute consists of the following technical divisions and offices:

> Engineering Standards—Weights and Measures — Invention and Innovation — Vehicle Systems Research—Product Evaluation—Building Research—Instrument Shops—Measurement Engineering—Electronic Technology—Technical Analysis.

THE CENTER FOR RADIATION RESEARCH engages in research, measurement, and application of radiation to the solution of Bureau mission problems and the problems of other agencies and institutions. The Center consists of the following divisions:

> Reactor Radiation—Linac Radiation—Nuclear Radiation—Applied Radiation.

THE CENTER FOR COMPUTER SCIENCES AND TECHNOLOGY conducts research and provides technical services designed to aid Government agencies in the selection, acquisition, and effective use of automatic data processing equipment; and serves as the principal focus for the development of Federal standards for automatic data processing equipment, techniques, and computer languages. The Center consists of the following offices and divisions:

> Information Processing Standards—Computer Information — Computer Services — Systems Development—Information Processing Technology.

THE OFFICE FOR INFORMATION PROGRAMS promotes optimum dissemination and accessibility of scientific information generated within NBS and other agencies of the Federal government; promotes the development of the National Standard Reference Data System and a system of information analysis centers dealing with the broader aspects of the National Measurement System, and provides appropriate services to ensure that the NBS staff has optimum accessibility to the scientific information of the world. The Office consists of the following organizational units:

> Office of Standard Reference Data—Clearinghouse for Federal Scientific and Technical Information[3]—Office of Technical Information and Publications—Library—Office of Public Information—Office of International Relations.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT

316-11-0429

28 July 1969

NBS REPORT

10 070

SIXTEENTH REPORT ON
A SURVEY OF THERMODYNAMIC PROPERTIES OF THE
COMPOUNDS OF THE ELEMENTS CHNOPS

George T. Armstrong and Eugene S. Domalski

<NBS>

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

FOREWORD

A study at the National Bureau of Standards (NBS), of which this is the sixteenth progress report, has been undertaken to meet the need of the National Aeronautics and Space Administration (NASA) for thermodynamic information on biologically related materials important to the space program for several reasons. Among these reasons are the necessity of inferring the maximum account of useful chemistry of incompletely accessible environments, for which only limited information is available, the possibility of the occurrence of organic compounds naturally synthesized under primitive conditions, and the possibility of theoretically recovering part of the pre-biological history of the earth.

This program is being carried out under the technical supervision of Dr. George Jacobs of NASA, and with the consultation of Dr. Harold Morowitz of the Yale University, Department of Molecular Biology and Biophysics, and Dr. C. W. Beckett of the NBS. The contract (Contract No. R-138) was initiated 1 May 1964 and extended by Amendments 1, 2, 3, and 4. This report covers a portion of work under Amendment 4. A significant change in the direction of the project occurred with the initiation of Amendment 3. The work is now directed toward the presentation of the material in the form of a Handbook of Thermodynamic Data of Interest in the Biological Sciences. In this effort the work at NBS is coordinated with a related task at the Texas A and M Thermodynamic Properties Center under Dr. R. A. Wilhoit.

TABLE OF CONTENTS

Report of Progress

George T. Armstrong

During this reporting interval further progress was made on the selection of heats of combustion of organic substances relevant to the program. This work was done largely by Dr. E. S. Domalski and his results for 115 organic compounds are presented as a chapter of this progress report, beginning on page 2.

During this interval arrangements were made to have much of the tabulated results of this work published by Academic Press, Inc. A manuscript deadline of July 1970 was accepted.

A portion of the funds of this contract are being used to obtain evaluations of thermodynamic properties of aqueous solutions of biologically important compounds from the Texas A and M Thermodynamics Research Center. Dr. R. A. Wilhoit is the scientist in charge of their contributions. This work was initiated in May 1969. The thermodynamics Research Center has submitted two monthly progress reports. The first reports consist of bibliographies on activity coefficients, partial molal enthalpies, partial molal heat capacities, and osmotic coefficients of the simpler organic acids and alcohols.

Selected Heats of Combustion and Heats of Formation of
Organic Compounds of Biological Interest

Eugene S. Domalski

I. Introduction

We report here selected values for the heats of combustion and
formation at 298°K for the following classes of organic compounds:
aliphatic hydrocarbons, alicyclic hydrocarbons, aromatic hydro-
carbons, aliphatic alcohols, phenols, aliphatic di- and polyols,
aldehydes, ketones, n-aliphatic acids, hydroxy aliphatic acids, and
unsaturated aliphatic acids. The total number of compounds for which
selected values have been made in this report is 115. Adding to this
total, the compounds similarly treated in NBS Report 9883 (73 organic
compounds), and NBS Report 9968 (321 organic compounds), we obtain
509 for a final total to date. A final portion of about 100 compounds
will be processed for the next report.

II. Data on the Heats of Combustion and Formation of Various Classes of Organic Compounds

Aliphatic Hydrocarbons

Compound	State	ΔH_c° 298°K kcal mol^{-1}	ΔH_f° 298°K kcal mol^{-1}	Reference
methane	g	-212.80	-17.88	[1,2,3,32,237,240,243]
ethane	g	-372.82	-20.23	[1,4,32,245]
propane	g	-530.60	-24.81	[1,4,32,245]
n-butane	g	-687.64	-30.14	[1,4]
n-pentane	g	-845.16	-34.99	[1,4,143]
n-pentane	liq	-838.69	-41.46	[1,5,246,248]
ethylene	g	-337.23	+12.50	[1,6,7,32,237,242,244,245,252]
acetylene	g	-310.62	+54.20	[1,8,32,33,244,245,252]

Alicyclic Hydrocarbons

Compound	State	ΔH_c° 298°K kcal mol^{-1}	ΔH_f° 298°K kcal mol^{-1}	Reference
cyclopropane	g	-499.85	+12.75	[1,9,244,245,253]
cyclobutane	liq	-650.22	+0.76	[1,10,11]
cyclopentane	liq	-786.55	-25.28	[1,11,12,13,17,254]
cyclohexane	liq	-936.87	-37.33	[1,10,12-20]
cycloheptane	liq	-1099.09	-37.47	[1,10,12,16,17]
cyclooctane	liq	-1258.58	-40.35	[1,10,12,21,22]

Aromatic Hydrocarbons

Compound	State	ΔH_c^o 298°K kcal mol^{-1}	ΔH_f^o 298°K kcal mol^{-1}	Reference
benzene	g	-789.06	+19.81	[1,23-37]
benzene	liq	-780.96	+11.71	[1,18,20,38-47]
naphthalene	g	-1249.4	+35.6	[48-58]
naphthalene	c	-1231.8	+18.0	[18,42,59-87]
anthracene	g	-1714.7	+53.7	[48,55,57,88-92]
anthracene	c	-1687.3	+29.0	[38,59,60,65,77, 78,80,83,86,87,93-100]
phenanthrene	g	-1706.7	+48.4	[48,55,90]
phenanthrene	c	-1685.6	+27.3	[38,65,80,83,87, 94-97,99,100]
pyrene	c	-1873.83	+27.44	[97,101]
triphenylene	c	-2136.53	+33.72	[99,101]
chrysene	c	-2137.8	+35.0	[99,102]
1,2-benzanthracene	c	-2144.0	+41.2	[99]
3,4-benzphenanthrene	c	-2147.3	+44.5	[99]
tetracene	c	-2141.1	+38.3	[99]
perylene	c	-2334.60	+43.69	[101,103]
fluoranthrene	c	-1892.14	+45.75	[101,104]

Aliphatic Alcohols

Compound	State	ΔH^o_c, 298°K kcal mol^{-1}	ΔH^o_f, 298°K kcal mol^{-1}	Reference
methanol	g	-182.72	-47.96	[32,105,112,237,238,239]
methanol	liq	-173.64	-57.04	[42,106-111]
ethanol	g	-336.86	-56.19	[32,105,237,239,240,241]
ethanol	liq	-326.68	-66.37	[42,109,111,113-117]
1-propanol	liq	-482.75	-72.66	[17,42,111,118-120]
2-propanol	liq	-479.44	-75.97	[17,111,118-120,126,127]
1-butanol	liq	-639.53	-78.25	[17,42,111,120-124,247]
2-butanol	liq	-635.90	-81.88	[111,121]
2-methyl-1-propanol	liq	-637.93	-79.85	[17,42,111,118,120,121]
2-methyl-2-propanol	liq	-631.92	-85.86	[17,120,121,128,129]
1-pentanol	liq	-795.25	-84.90	[17,111,118,120,123,125]
1-hexanol	liq	-951.70	-90.81	[111,123]

Phenols

Compound	State	ΔH^o_c, 298°K kcal mol^{-1}	ΔH^o_f, 298°K kcal mol^{-1}	Reference
phenol	c	-729.80	-39.45	[59,60,63,65,102,130-138]
pyrocatechol	c	-683.0	-86.3	[60,102,137]
resorcinol	c	-681.30	-87.95	[60,102,139]
hydroquinone	c	-681.78	-87.47	[63,102,134-137, 140-142,144,145]
o-cresol	c	-882.72	-48.90	[130-132,146]
m-cresol	c	-885.25	-46.37	[130-132,138,146,147]
p-cresol	c	-883.99	-47.63	[130-132,146]
2-ethyl phenol	c	-1044.07	-49.92	[148]
3-ethyl phenol	c	-1042.77	-51.22	[148]
4-ethyl phenol	c	-1040.35	-53.64	[148]

Aliphatic Di- and Polyols

Compound	State	ΔH_c°, 298°K kcal mol^{-1}	ΔH_f°, 298°K kcal mol^{-1}	Reference
1,2-ethanediol (ethylene glycol)	liq	-284.35	-108.70	[98,137,149,150,151]
1,2-propanediol	liq	-435.8	-119.6	[150,152]
1,3-propanediol	liq	-431.0	-124.4	[152]
1,2,3-propanetriol (glycerol)	liq	-395.65	-159.76	[60,98,115,149,153]
1,2,3,4-meso-butanetetrol (meso-erythritol)	c	-500.22	-217.56	[60,98,102, 137,155,156]
pentaerythritol	c	-660.1	-220.0	[137,157]
xylitol	c	-612.8	-267.3	[158]
L-arabitol	c	-611.4	-268.7	[137]
D-mannitol	c	-722.97	-319.54	[59,60,98,102,137, 153,159-161]
dulcitol	c	-720.68	-321.83	[59,60,98,137, 153,161]
D-perseitol	c	-835.2	-369.7	[137]
D-gluco-α-heptite	c	-840.4	-364.5	[162]
1,10-decanediol	c	-1526.20	-165.78	[163]
dipentaerythritol	c	-1315.1	-375.9	[164]

Aldehydes

Compound	State	$\Delta H_c^o, 298°K$ kcal mol^{-1}	$\Delta H_f^o, 298°K$ kcal mol^{-1}	Reference
methanal	g	-134.4	-28.0	[165]
ethanal	g	-258.01	-39.72	[166,167]
ethanal	liq	-278.77	-45.96	[168-171]
1-propanal	liq	-434.1	-53.0	[170-172]
1-butanal	liq	-592.2	-57.3	[172,173]
1-pentanal	liq	-742	-70	[174]
5-hydroxy-1-pentanal	liq	-697.1	-114.7	[175]
paraldehyde	liq	-810.0	-164.2	[176-178]
heptanal	liq	-1062.2	-74.4	[118,173]
octanal	liq	-1218.9	-80.0	[179]
benzaldehyde	liq	-843.2	-20.0	[180,181]
salicylaldehyde	liq	-796.4	-66.9	[182-184]

Ketones

Compound	State	$\Delta H_c^o, 298°K$ kcal mol^{-1}	$\Delta H_f^o, 298°K$ kcal mol^{-1}	Reference
2-propanone	g	-435.32	-51.78	[32,185]
2-propanone	liq	-427.92	59.18	[115,170,171, 186, 187]
2-butanone	g	-590.20	-59.27	[188]
2-butanone	liq	-584.17	-65.30	[17,19,189-191]
2,3-butanedione	liq	-493.71	-87.44	[135,192-194]
3-pentanone	liq	-736.5	-75.3	[17,120,168,195]
acetophenone	liq	-991.60	-34.07	[196-199]
benzophenone	c	-1556.2	-8.0	[77,78,127, 198-201]

7

n-Aliphatic Acids

Compound	State	ΔH°_{c}, 298°K kcal mol^{-1}	ΔH°_{f}, 298°K kcal mol^{-1}	Reference
methanoic acid (formic acid)	liq	-60.86	-101.51	[113,114,202-205]
ethanoic acid (acetic acid)	liq	-209.02	-115.71	[113,114,205-210]
propanoic acid (propionic acid)	liq	-365.03	-122.07	[209,205,211-213]
n-butanoic acid (n-butyric acid)	liq	-521.87	-127.59	[205,212,213]
n-pentanoic acid (n-valeric acid)	liq	-678.12	-133.71	[205,212-215]
n-hexanoic acid (n-caproic acid)	liq	-834.49	-139.71	[66,128,205,214]
n-heptanoic acid (enanthic acid)	liq	-990.81	-145.75	[205,214]
n-octanoic acid (caprylic acid)	liq	-1147.00	-151.93	[205,214,216,217]
n-nonanoic acid (pelargonic acid)	liq	-1303.62	-157.67	[205,212-214,216,217]
n-decanoic acid (capric acid)	liq	-1460.10	-163.56	[214,222]
n-decanoic acid (capric acid)	c	-1453.07	-170.59	[60,153,212-214]
n-dodecanoic acid (lauric acid)	liq	-1772.02	-176.37	[214,222]
n-dodecanoic acid (lauric acid)	c	-1763.25	-185.14	[154,214-219]
n-tetradecanoic acid (myristic acid)	liq	-2084.59	-188.53	[214,222]
n-tetradecanoic acid (myristic acid)	c	-2073.91	-199.21	[59,60,153,154, 214,216-218,220]
n-hexadecanoic acid (palmitic acid)	liq	-2397.52	-200.34	[205,215,222]
n-hexadecanoic acid (palmitic acid)	c	-2384.76	-213.10	[60,115,205,212,213, 214,216,217,220]

8

n-Aliphatic Acids
(continued)

Compound	State	ΔH_c^o, 298°K kcal mol^{-1}	ΔH_f^o, 298°K kcal mol^{-1}	Reference
n-octadecanoic acid (stearic acid)	liq	-2710.12	-212.47	[205,214,222]
n-octadecanoic acid (stearic acid)	c	-2696.12	-226.47	[59,60,62,115,153,205, 212-214,217,220,221]
n-eicosanoic acid (arachidic acid)	liq	-3022.71	-224.61	[214,222]
n-eicosanoic acid (arachidic acid)	c	-3005.50	-241.82	[212-214]
n-docosanoic acid (behenic acid)	c	-3337.3	-234.8	[154]

Hydroxy Aliphatic Acids

Compound	State	ΔH_c°, 298°K kcal mol^{-1}	ΔH_f°, 298°K kcal mol^{-1}	Reference
glycolic acid (hydroxyacetic acid)	c	-166.1	-158.6	[102,223]
glyoxylic acid (dihydroxyacetic acid)	c	-125.0	-199.7	[202,224]
D-lactic acid	c	-321.22	-165.86	[225]
DL-lactic acid	c	-326.8	-160.3	[115,223]
mesoxalic acid	c	-128.1	-290.7	[226]
DL-β-hydroxybutyric acid	liq	-487.2	-162.3	[115]
hydroxyisobutyric acid	c	-471.6	-177.9	[223,227]
levulinic acid (4-ketovaleric acid)	c	-576.9	-166.6	[228]
D-gluconic acid	c	-594.9	-379.3	[229]
D-galactonic acid	c	589.4	-384.8	[229]
dihydroxybehenic acid	c	-3235.3	-336.8	[154]

10

Unsaturated Aliphatic Acids

Compound	State	ΔH_c°, 298°K kcal mol^{-1}	ΔH_f°, 298°K kcal mol^{-1}	Reference
acrylic acid	liq	-327.0	-91.8	[67,230]
cis-crotonic acid	liq	-498	-83	[231]
trans-crotonic acid	c	-478.2	-102.9	[199]
tiglic acid (cis-α,β-dimethylacrylic acid)	c	-626.2	-117.3	[199,232]
angelic acid (trans-α,β-dimethylacrylic acid)	c	-634.6	-108.9	[199,232]
sorbic acid	c	-744.2	-93.4	[66,199,233]
hydrosorbic acid	liq	-795.7	-110.2	
undecylenic acid	c	-1579.6	-138.1	[199]
oleic acid	liq	-2675.4	-178.9	[234]
oleic acid	c	-2667.1	-187.2	[115,199,234-236]
elaidic acid	c	-2636.6	-217.7	[199,234,235]
erucic acid	c	-3297.2	-206.5	[154,232]
brassidic acid	c	-3290.1	-213.6	[154,232]

III.   Selection of the Combustion Data

Aliphatic Hydrocarbons

The heats of combustion and formation of the selected values for the aliphatic hydrocarbons are the same as those found in reference [1].

methane - The combustion data of Rossini [2,3] were used to make the selection. The early studies on the heat of combustion of methane by Andrews [240], Favre and Silbermann [237], Thomsen [32,243] and Berthelot [244] are of historical interest only.

ethane - The combustion data of Rossini [4] were used to make the selection. The early studies by Thomsen [32], and Berthelot and Matignon [245] are of historical interest only.

propane - The combustion data of Rossini [4] were used to make the selection. The early studies of Thomsen [32], and Berthelot and Matignon [245] are of historical interest only.

n-pentane (g) - The combustion data of Rossini [4] were used to make the selection. The more recent data of Pilcher and Chadwick [143] are in very good agreement with the selection.

n-pentane (liq) - The combustion data of Prosen and Rossini [5] were used for the selected value. The recent data of Good [248] are in very good agreement with the selection. The earlier work of Roth and Macheleidt [246] was not used.

ethylene - The combustion data Rossini and Knowlton [6], and the heat-of-hydrogenation data of Kistiakowsky, Romeyn, Ruhoff, Smith, and Vaughan [7] as corrected by Prosen and Rossini [249] were used to obtain the selected value. The early studies of Dulong [250], Grassi [251], Favre and Silbermann [237], Andrews [242], Berthelot [244], Berthelot and Matignon [245], Thomsen [32], and Mixter [252] are of historical interest only.

12

acetylene - The unpublished combustion data of Prosen and Rossini
cited in Wagman, Kilpatrick, Pitzer, and Rossini [8] were chosen for
the selected value. The early studies of Thomsen [32], Berthelot [33,
244], Berthelot and Matignon [245], and Mixter [252] are of historical
interest only.

Alicyclic Hydrocarbons

The selected values for the heats of combustion and formation of
the alicyclic hydrocarbons are the same as those found in reference [1].

cyclopropane - The combustion data of Knowlton and Rossini [9] were
chosen in preference to the earlier work by Berthelot [244], and
Berthelot and Matignon [245,253].

cyclopentane - The combustion data of Johnson, Prosen, and Rossini
[13] were used in preference to the data of Kaarsemaker and Coops
[10], and Spitzer and Huffman [12]. The work of Zubov [254] as corrected
by Swietoslawski [17] is of historical interest only.

cyclohexane - The combustion data of Good and Smith [20] and Johnson,
Prosen, and Rossini [13] were used to make the selection. The data
of Kaarsemaker and Coops [10], Spitzer and Huffman [12], and Moore,
Renquist and Parks [19] were in good agreement with the selection.
The works of Stohmann and Langbein [14,15], Zubov [16] as corrected by
Swietoslawski [17], Roth and von Auwers [18] are of historical
interest only.

cycloheptane - The combustion data of Spitzer and Huffman [12] and
Kaarsemaker and Coops [10] were averaged to obtain the selected value.
The data of Zubov [16] as corrected by Swietoslawski [17] was not used.

cyclooctane - The combustion data of Kaarsemaker and Coops [10], and
Spitzer and Huffman [12] were averaged to obtain the selected value.
The data of Schläpfer [21] and Ruzicka and Schläpfer [22] were not used.

Aromatic Hydrocarbons

benzene (g) - References [23] to [30] provided experimental data on the determination of the heat of vaporization of benzene. We have used the ideal heat of vaporization at 25°C of 8.10 kcal mol^{-1} as in reference [1]. By combining the latter value with the $\Delta H_c^o[C_6H_6(liq)]=$ -780.96 kcal mol^{-1}, we calculate ΔH_c^o = -789.06 kcal mol^{-1} for gaseous benzene. The early studies on the heat of combustion of gaseous benzene, references [32] to [37] were not used and are of historical interest only.

benzene (liq) - The combustion data of Good and Smith [20], and Prosen, Gilmont, and Rossini [47] were used to obtain the selected value. The data of Coops, Mulder, Dienske, and Smittenberg [45,46] were not used. References [38] to [44] summarize the early studies, and are of historical interest only.

naphthalene (g) - The sublimation pressures of naphthalene were measured by Bradley and Cleasby [48], Sherwood and Bryant [49], Miller [50], Zil'berman-Granovskaya [51], Swan and Mack [52], Winstrom and Kulp [53], Allen [54], Hoyer and Peperle [55], Aihara [56], Sears and Hopke [57], and Shlyarenko, Martin, and Belyaeva [58]. When plotted individually as log P vs 1/T, these sets of data show generally poor agreement, but when considered as a whole, good agreement results, giving a reasonably straight line. Using a least squares treatment of the vapor pressure data, we obtain for the heat of sublimation, 17.6 kcal mol^{-1} at 25°C. Combining this with our selection, $\Delta H_c^o[C_{10}H_8(c)]=$ -1231.8 kcal mol^{-1}, we calculate ΔH_c^o = -1249.4 kcal mol^{-1} for gaseous naphthalene.

naphthalene (c) - The heat of combustion of naphthalene (c) was
measured by von Rechenberg [59], Stohmann [60,61], Rübner [62],
Berthelot and Louguinine [63], Berthelot and Recoura [64], Berthelot
and Vieille [65], Fischer and Wrede [66], Riiber and Schetelig [67],
Wrede [68], Dickinson [69], Karrar and Fioroni [71], Verkade and Coops
[75,76], Beckers [77], Burriel [78], Keffler [79], Milone and
Rossignoli [80], Schläpfer and Fioroni [81], Huffman and Ellis [82],
Bender and Farber [83], Speros and Rossini [84], Prosen and Colomina
[85], Mackle and O'Hare [86], and Coleman and Pilcher [87]. The value
for the heat of combustion of naphthalene relative to that of benzoic
acid was well-established by various experimenters as 1.5202 to
1.5204. For a discussion of this point see Verkade [74], Verkade,
Coops and Hartman [73], Swietoslawski [70], and Swietoslawski and
Starczewska [72]. If we take the value 1.5204, and the presently
accepted value for benzoic acid ($-\Delta U_b$=26434 Jg^{-1} (vacuum) at 25°C),
and apply the appropriate corrections (for standard state condition,
ΔnRT and calculation of ΔH_f^o), we obtain for our selected values ΔH_c^o =
-1231.8 kcal mol^{-1}, and ΔH_f^o = +18.0 kcal mol^{-1}.

anthracene (g) - Sublimation pressures have been measured by Bradley and
Cheasby [48], Stevens [88], Klochkov [89], Inokuchi, Shiba, Handa, and
Akamatu [90], Sears and Hopke [57], Nitta, Seki, and Momotani [91],
Kelly and Rice [92], and Hoyer and Peperle [55]. As a result of
examining the experimental data, we obtained a selected heat of sub-
limation of 24.7 kcal mol^{-1}. By combining the latter with
$\Delta H_c^o [C_{14}H_{10}(c)]$ = -1687.3 kcal mol^{-1}, we calculate ΔH_c^o = -1714.7 kcal mol^{-1}
for gaseous anthracene.

15

anthracene (c) - The heat of combustion of anthracene (c) was measured
by von Rechenberg [59], Stohmann [60], Stohmann, Kleber, and Langbein
[38], Berthelot and Vieille [65,100], Beckers [77], Burriel [78],
Wiegert [93], Klaproth [94], Milone andRossignoli [80], Fries, Walter,
and Schilling [95], Shchukarev and Shchukareva [96], Richardson and
Parks [97], Parks, West, Naylor, Fugii, and McClaine [98], Bender and
Farber [83], Magnus, Hartmann, and Becker [99], Mackle and O'Hare
[86], and Coleman and Pilcher [87]. An average heat of combustion
derived from the data of the last six investigations [83,86,87,97,
98,99], mentioned constitutes our selected value. $\Delta H_c^o[C_{14}H_{10}(c)]$ =
-1687.3 kcal mol^{-1}.

phenanthrene (g) - Sublimation pressures were measured by Bradley and
Cleasby [48], Inokuchi, Shiba, Handa, and Akamatu [90], and Hoyer and
Peperle [55]. From these data we derived the heat of sublimation at
25°C of 21.1 kcal mol^{-1} from the data of Bradley and Cleasby [48].
By combining ΔH(sublimation) with $\Delta H_c^o[C_{14}H_{10}(c)]$= -1685.6 kcal mol^{-1},
we calculate ΔH_c^o = -1706.7 kcal mol^{-1} for gaseous phenanthrene.

phenanthrene (c) - The heat of combustion of phenanthrene (c) was
measured by Stohmann, Kleber, and Langbein [38], Berthelot and
Vieille [65,100], Klaproth [94], Milone and Rossignoli [80],
Shchukarev and Shchukareva [96], Fries, Walter, and Schilling [95],
Richardson and Parks [97], Bender and Farber [83], Magnus, Hartmann
and Becker [99], and Coleman and Pilcher [87]. An average heat of
combustion derived from the data of the last three investigations
[83,87,99], mentioned constitutes our selected value.
$\Delta H_c^o[C_{14}H_{10}(c)]$ = -1685.6 kcal mol^{-1}.

pyrene - The combustion data of Westrum and Wong [101] were preferred
to that of Richardson and Parks [97] in making the selection.

triphenylene - The combustion data of Westrum and Wong [101] were preferred to that of Magnus, Hartmann, and Becker [99] in making the selection.

chrysene - The combustion data of Magnus, Hartmann, and Becker [99] were preferred to that of Stohmann [102] in making the selection.

perylene - The combustion data of Westrum and Wong [101] were preferred to that of Pongratz, and Griengl [103] in making the selection.

fluoranthrene - The combustion data of Westrum and Wong [101], and Boyd, Christensen, and Pua [104] were averaged in obtaining the selected value.

Aliphatic Alcohols

methanol (g) - The combustion data of Rossini [105] on gaseous methanol were chosen in preference to the early work of Thomsen [32]. The data of Favre and Silbermann [237] are of historical interest only. The heat of vaporization of methanol at 25 °C was taken from the measurements of Fiock, Ginnings, and Holton [239], ΔHvap at 25°C = 8.95 kcal mol^{-1}. Recent vaporization data by Wadsö [112] are in very good agreement with the data of Fiock, Ginnings, and Holton [239]. A correction for dimer and tetramer formation was made to the vaporization data using the study of Weltner and Pitzer [238], amounting to 0.13 kcal mol^{-1}. This gives ΔHvap at 25°= 9.08 kcal mol^{-1} for the process: $CH_3OH(liq) = CH_3OH(g,\ monomer)$.

methanol (liq) - Our selected value for the heat of combustion of $CH_3OH(liq)$ is obtained by combining the value for the heat of combustion of $CH_3OH(g)$ with the heat of vaporization of the liquid to the gaseous monomer. The recent data of Chao and Rossini [111] is in good agreement with our selection. The earlier work of Stohmann,

17

Kleber, and Langbein [106], Richards and Davis [42], Roth [107], Roth and Banse [108], Roth and Müller [109] and I. G. Farbenfabriken [110] has not been used.

ethanol (g) - The combustion data of Rossini [105] on gaseous ethanol were chosen in preference to the earlier data of Thomsen [32]. The data of Andrews [240] and Favre and Silbermann [237] are only of historical interest. The heat of vaporization of ethanol at 25°C was taken from the measurements of Fiock, Ginnings, and Holton [239], ΔHvap at 25°C = 10.13 kcal mol^{-1}. Recent vaporization data by Wadsö [112] are in very good agreement with the data of Fiock, Ginnings, and Holton [239]. A correction for the presence of dimeric ethanol (g) was introduced from the data of Coburn, and Grunwald [241] amounting to 0.05 kcal mol^{-1}. Hence, for the process: $CH_3CH_2OH(liq)$ = $CH_3CH_2OH(g,monomer)$, ΔHvap at 25°C = 10.18 kcal mol^{-1}.

ethanol (liq) - Our selection for the heat of combustion was obtained by combining, the value for the heat of combustion of $CH_3CH_2OH(g)$ with the heat of vaporization of the liquid to the gaseous momomer. The recent data of Chao and Rossini [111] are in good agreement with our selection. The earlier data of Berthelot and Matignon [113,114], Emery and Benedict [115], Atwater and Rosa [116], Atwater and Snell [117], Roth and Muller [109] and Richards and Davis [42] were not used.

1-propanol - The combustion data of Chao and Rossini [111] and Snelson and Skinner [119] were averaged to obtain the selected value. The earlier data were not used.

2- propanol - The combustion data of Chao and Rossini [111], Snelson and Skinner [119], and Parks, Mosley and Peterson [190] were averaged to obtain the selected value. The earlier data were not used.

18

1-butanol - The combustion data of Verkade and Coops [123], Chao
and Rossini [111], Skinner and Snelson [121], Mosselman and Dekker [247],
and Gundry, Head, and Lewis [122] were averaged to obtain the selected
value. The early data of Zubov [120] and the correction of the latter
by Swietoslawski [17] was not used. The combustion data of Tjebbes
[124] appeared not negative enough by at least one kilocalorie per
mole, and hence, were not used.

2-butanol - The combustion data of Chao and Rossini [111], and Skinner
and Snelson [121] were averaged to obtain the selection.

2-methyl-1-propanol - The combustion data of Chao and Rossini [111]
and Skinner and Snelson [121] were averaged to obtain the selected
value. The earlier data was not used.

1-pentanol - The combustion data of Verkade and Coops [123], Chao and
Rossini [111], and Gundry, Harrop, Head, and Lewis [125] were averaged
to obtain the selected value. The earlier data were not used.

1-hexanol - The combustion data of Verkade and Coops [123], and Chao
and Rossini [111], were averaged to obtain the selected value.

Phenols

phenol - The heat of combustion of phenol was measured by von Rechenberg
[59], Stohmann [60,102] Berthelot and Louguinine [63], Berthelot and
Vieille [65], Andon, Biddiscombe, Cox, Handley, Harrop, Herington, and
Martin [130], Cox [131,132], Karlsson [133], Manchester [134], Parks,
Manchester, and Vaughan [135], Stohmann, Rodatz, and Herzberg [136],
Stohmann and Langbein [137], and Badoche [138]. We have used the data
of Andon, et al. [130] for our selected value.

19

pyrocatechol - The combustion data of Stohmann [102], and Stohmann and
Langbein [137] were obtained using an oxygen bomb calorimeter, and
are preferred to the data of Stohmann [60] in which the potassium
chlorate-oxidative mixture technique was used. The data in references
[102] and [137] are the same. The heat of combustion calculated from
the latter was found to be -684.9 kcal mol^{-1} after all corrections were
applied. This was reduced to -683.0 kcal mol^{-1} because the value for
the heat of combustion of phenol found by Stohmann and Langbein was 2
to 3 kcal mol^{-1} more negative than our presently selected value for
phenol.

resorcinol - The combustion data of Desai, Wilhoit, and Zwolinski
[139] was chosen in preference to the earlier combustion data.

hydroquinone - The combustion data of Pilcher and Sutton [142] was
chosen in preference to any other combustion data.

o-cresol - The combustion data of Andon, Biddiscombe, Cox, Handley,
Harrop, Herington, and Martin [130], and Cox [131,132] were chosen
in preference to the data of Stohmann, Rodatz, and Herzberg [146].

m-cresol - The combustion data of Andon, Biddiscombe, Cox, Handley,
Harrop, Herington, and Martin [130], and Cox [131,132] were chosen
in preference to the earlier data.

p-cresol - The combustion data of Andon, Biddiscombe, Cox, Handley,
Harrop, Herington, and Martin [130], and Cox [131,132] were chosen
in preference to the data of Stohmann, Rodatz and Herzberg [146].

Aliphatic Di- and Polyols

1,2-ethanediol, (ethylene glycol) - The combustion data of Parks, West, Naylor, Fujii, and McClaine [98] were preferred for the selected value to the earlier data.

1,2-propanediol - The combustion data of Moureu and Dode [150] were preferred to that of Louguinine [152].

1,2,3-propenetriol, (glycerol) - The combustion data of Parks, West, Naylor, Fujii, and McClaine [98] were chosen in preference to the earlier combustion data.

1,2,3,4-meso-butanetetrol,(meso-erythritol) - The combustion data of Parks, West, Naylor, Fujii, and McClaine [98] were chosen in preference to the earlier combustion data.

pentaerythritol - The combustion data of Medard and Thomas [157] were preferred to the data of Stohmann [137].

D-mannitol - The combustion data of Parks, West, Naylor, Fujii and McClaine [98] were preferred to any data published before 1900 (references [59,60,102,137,153,159,161]). The recent combustion data of Baer and Flehmig [160] are in poor agreement with our selected value by 6 to 7 kcal mol^{-1}. Details of their calorimetric data are scant, and the 6 to 7 kcal mol^{-1} could be the overall uncertainty in the experiment.

dulcitol - The combustion data of Parks, West, Naylor, Fujii, and McClaine [98] were chosen in preference to the earlier combustion data.

Aldehydes

ethanal (g) - The heat-of-hydrogenation data of Dolliver, Gresham, Kistiakowsky, Smith, and Vaughan [167] was used as the basis of our selected value rather than the early combustion of Berthelot and Ogier [166].

ethanal (liq) - The heat of vaporization of ethanal as determined by Coleman and DeVries [169], 6.24 kcal mol^{-1} at 25°C, was combined with the heat of formation of gaseous ethanal. The combustion data of Berthelot andDelepine [170,171], and Roth and Müller [168] was not used.

1-propanal - The combustion data of Tjebbes [172] were used to obtain the selection. The data of Berthelot and Delepine [170,171] were not used.

1-butanal - The combustion data of Tjebbes [172] and Nicholson [173] were averaged to make the selection.

paraldehyde - The combustion data of Fletcher, Mortimer, and Springall [178] were used to obtain the selected value. The same data are given earlier by Cass, Springall, and White [177], but show ΔH_c to be more negative by 0.2 kcal mol^{-1}. The combustion data of Louguinine [176] were not used.

heptanal - The combustion data of Nicholson [173] were chosen in preference to the data of Louguinine [118].

benzaldehyde - The combustion data of Landrieu, Baylocq, and Johnson [180] were chosen in preference to the data of Stohmann, Rodatz, and Herzberg [181].

22

salicylaldehyde - The combustion data of Delepine and Rivals [182] were
chosen in preference to the data of Berthelot and Rivals [183] and
Rivals [184].

Ketones

2-propanone (g) - The combustion data of Miles and Hunt [185] were
chosen in preference to the early data of Thomsen [32].

2-propanone (liq) - The heat of vaporization was taken from the data
of Pennington and Kobe [187], ΔH^0_{vap} at 25°C = 7.40 kcal mol^{-1}. The
latter value was combined with the heat of combustion of gaseous
2-propanone. The combustion data of Berthelot and Delepine [170,171],
Emery and Benedict [115], and Taylor, Hall, and Thomas [186] were not
used.

2-butanone (liq) - The combustion data of Sinke and Oetting [191]
were chosen in preference to any previous work.

2,3-butanedione - The combustion data of Nicholson, Szwarc, and Taylor
[193], and Parks, Manchester, and Vaughan [135] were averaged to make
the selection. The data of Springall and White [194] and Landrieu
[192] were not used.

3-pentanone - The combustion data of Roth and Müller [168] and
Louguinine [195] were averaged to obtain the selected value. The
data of Zubov [120] as corrected by Swietoslawski [17] were not used.

acetophenone - The combustion data of Colomina, Latorre, and Perez-
Ossorio [196,197] were chosen in preference to the early combustion
data of Stohmann [199], and Stohmann, Rodatz, and Herzberg [198].

23

benzophenone - The combustion data of Colomina, Cambeiro, Perez-Ossorio, and Latorre [200], and Parks, Mosley, and Peterson [127] were averaged for the selection. The data of Beckers [77], Burriel [78], Landrieu, and Blatt [201], Stohmann, Rodatz, and Herzberg [198], and Stohmann [199] were not used.

n-Aliphatic Acids

methanoic acid, (formic acid) - The combustion data of Sinke [204] were used to obtain the selected value. The data of Lebedeva [205] are in excellent agreement with the selection. The data of Berthelot [202], Berthelot and Matignon [113,114], and Jahn [203] were not used.

ethanoic acid, (acetic acid) - The combustion data of Evans and Skinner [206] were used to obtain the selected value. The data of Lebedeva [205] are in excellent agreement with the selection. The data of Berthelot and Matignon [113,114], Roth [207], Schjanberg [208,209] and Stull [210] were not used, although only the data of Roth [207] appeared to deviate from the selection by more than 0.3 kcal mol^{-1}.

propanoic acid, (propionic acid) - The combustion data of Lebedeva [205] were chosen in preference to the previous data.

n-butanoic acid, (n-butyric acid) - The combustion data of Lebedeva [205] were chosen in preference to the early data.

n-pentanoic acid, (n-valeric acid) - The combustion data of Lebedeva [205], and Adriaanse, Dekker, and Coops [214] were averaged to obtain the selected value. The data of Hancock, Watson, and Gilby [215] agree well with the early work of Stohmann, Kleber, Langbein, and Offenbauer [212,213]. Data from the latter three references were not used.

n-hexanoic acid, (n-caproic acid) - The combustion data of Lebedeva [205], and Adriaanse, Dekker, and Coops [214] were averaged to obtain the selected value. The data of Fischer and Wrede [66], and Louguinine [128] were not used.

n-heptanoic acid, (enanthic acid) - The combustion data of Lebedeva [205], and Adriaanse, Dekker, and Coops [214] were averaged to obtain the selection.

n-octanoic acid, (caprylic acid) - The combustion data of Lebedeva [205] and Adriaanse, Dekker, and Coops [214] were averaged to obtain the selected value. The data of Louguinine [216,217] were not used.

n-nonanoic acid, (pelargonic acid) - The combustion data of Lebedeva [205], and Adriaanse, Dekker, and Coops [214] were averaged to obtain the selection. The early data [212,213,216,217] were not used.

n-decanoic acid, (capric acid)(c) - The combustion data of Adriaanse, Dekker, and Coops [214] were chosen in preference to the earlier data.

n-dodecanoic acid, (lauric acid)(c) - The combustion data of Adriaanse, Dekker, and Coops [214] were chosen in preference to the earlier data.

n-tetradecanoic acid, (myristic acid)(c) - The combustion data of Adriaanse, Dekker, and Coops [214] was used to obtain the selected value. The data of Swain, Silbert, and Miller [220], although not as precise, are in good agreement with the selection. The early combustion data [59,60,153,154,216,217,218] were not used.

n-hexadecanoic acid, (polmitic acid)(liq) - The heat of fusion as determined by Adriaanse, Dekker, and Coops [214,222] was selected in preference to the data of Lebedeva [205].

n-hexadecanoic acid, (palmitic acid)(c) - The combustion data of
Adriaanse, Dekker, and Coops [214] were used to obtain the selected
value in preference to the data of Lebedeva [205]. The data of
Swain, Silbert, and Miller [220], although not as precise as either
of the above data is in good agreement with the data of Adriaanse,
Dekker and Coops [214]. Data prior to the above [60,115,212,213,
216,217] were not used.

n-octadecanoic acid, (stearic acid)(liq) - The fusion data of
Lebedeva [205], and Adriaanse, Dekker, and Coops [214,222] were
averaged to obtain the selected value, ΔH(fusion) at 25°C = 14.0 kcal
mol^{-1}.

n-octadecanoic acid, (stearic acid)(c) - The combustion data of
Lebedeva [205], and Adriaanse, Dekker, and Coops [214] were averaged
to obtain the selected value. The combustion data of Swain, Silbert,
and Miller [220] are too positive by about 2.2 kcal mol^{-1}. Data prior
to the above [59,60,62,115,153,212,213,217,221] were not used.

n-eicosanoic acid, (arachidic acid)(c) - The combustion data of Adriaanse,
Dekker, and Coops [214] were preferred to the earlier work.

Hydroxy Aliphatic Acids

glycolic acid, (hydroxyacetic acid) - The combustion data of Louguinine
[223], and Stohmann [102] were averaged to obtain the selected value.

glyoxylic acid, (dihydroxyacetic acid) - The combustion data of
Berthelot [202] are the same as Berthelot and Matignon [224].

DL-lactic acid - The combustion data of Emery and Benedict [115] and
Louguinine [223] were averaged to obtain the selected value.

hydroxyisobutyric acid - The later combustion data of Louguinine [223] was preferred to the earlier work by the same author [227].

Unsaturated Aliphatic Acids

acrylic acid - The combustion data of Moureu and Boutaric [230], and Riiber and Schetelig [67] were averaged to obtain the selected value.

tiglic acid - The combustion data of Stohmann [199] and Stohmann [232] are the same.

angelic acid - The combustion data of Stohmann [199] and Stohmann [232] are the same.

sorbic acid - The combustion data of Fischer and Wrede [66] were chosen in preference to the data of Stohmann [199] and Osipov [233].

oleic acid (c) - The combustion data of Keffler and McLean [236] were chosen in preference to previous data.

elaidic acid - The combustion data of Keffler [234,235] were chosen in preference to the data of Stohmann [199].

erucic acid - The combustion data of Stohmann and Langbein [154] are the same as Stohmann [232].

brassidic acid - The combustion data of Stohmann and Langbeing [154] are the same as Stohmann [232].

IV. References

[1] "Selected Values of Hydrocarbons and Related Compounds", American Petroleum Institute Research Project 44, Thermodynamics Research Center, Texas A and M University, College Station, Texas (Loose-leaf data sheets, extant 1969).

[2] Rossini, F. D., J. Research NBS 6, 37-49 (1931).

[3] Rossini, F. D., J. Research NBS 7, 329-330 (1931).

[4] Rossini, F. D., J. Research NBS 12, 735-750 (1934).

[5] Prosen, E. J. and Rossini, F. D., J. Research NBS 33, 255-272 (1944).

[6] Rossini, F. D. and Knowlton, J. W., J. Research NBS 19, 249-262 (1937).

[7] Kistiakowsky, G. B., Romeyn, Jr., H., Ruhoff, J. R., Smith, H. A., and Vaughan, W. E., J. Am. Chem. Soc., 57, 65-75 (1935).

[8] Wagman, D. D., Kilpatrick, J. E., Pitzer, K. S., and Rossini, F. D., J. Research NBS 35, 467-496 (1945).

[9] Knowlton, J. W., and Rossini, F. D., J. Research NBS 43, 113-115 (1949).

[10] Kaarsemaker, S. and Coops, J., Rec. trav. chim. 71, 261-276 (1952).

[11] Coops, J. and Kaarsemaker, S., Rec. trav. chim. 69, 1364 (1950).

[12] Spitzer, R. and Huffman, H. M., J. Am. Chem. Soc. 69, 211-213 (1947).

[13] Johnson, W. H., Prosen, E. J., and Rossini, F. D., J. Research NBS, 36, 463-468 (1946).

[14] Stohmann, F. and Langbein, H., J. prakt. Chem. [2] 48, 447-453 (1893).

[15] Stohmann, F. and Langbein, H., Ber. Verhandl. K. sächs Ges. Wiss. Math. Phys. Kl. 45, 477-484 (1893).

[16] Zubov, P., Zhur. Russ. Fiz. Khim. Obshchestva, 33, 708-722 (1901).

[17] Swietoslawski, W., J. Am. Chem. Soc. 42, 1092-1100 (1920).

[18] Roth, W. A., and von Auwers, K., Ann. 407, 145-175 (1915).

[19] Moore, G. E., Renquist, M. L., and Parks, G. S., J. Am. Chem. Soc. 62, 1505-1507 (1940).

[20] Good, W. D. and Smith, N. K., J. Chem. Eng. Data 14, 102-106 (1969).

[21] Schläpfer, P., quoted in H. O. Boekenoogen, Diss. Utrecht, 1930.

[22] Ruzicka, L. and Schläpfer, P., Helv. chim. Acta. 16, 162-168 (1933).

[23] Cox, J. D. and Andon, R.J.L., Trans. Faraday Soc. 54, 1622-1629 (1958).

[24] Fiock, E. F., Ginnings, D. C., and Holten, W. B., J. Research NBS 6, 881-900 (1931).

[25] Mathews, J. H., J. Am. Chem. Soc. 48, 562-576 (1926).

[26] Waddington, G. and Douslin, D. R., J. Am. Chem. Soc. 69, 2275-2279 (1947).

[27] Hales, J. L., Cox, J. D. and Lees, E. B., Trans. Faraday Soc. 59, 1544-1554 (1963).

[28] Hildenbrand, D. L., Kramer, W. R., MacDonald, R. A., and Stull, D. R., J. Am. Chem. Soc. 80, 4129-4132 (1958).

[29] Williamson, K. D. and Harrison, R. H., J. Chem. Phys. 26, 1409-1411 (1957).

[30] Kolosovskii, N. and Teodorovich, R. L., Bull. soc. chim. France [5] 2, 692-700 (1935).

[31] Rossini, F. D., Pitzer, K. S., Arnett, R. L., Braun, R. M., Pimentel, G. C., et al., "Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds", American Petroleum Institute Research Project 44, Carnegie Press, Pittsburgh, 1953.

[32] Thomsen, J., Thermochemische Untersuchungen, Vol. IV, (J.A. Barth, Leipzig, 1886).

[33] Berthelot, M., Ann. chim. phys. [5] 13, 5-20 (1878).

[34] Berthelot, M., Ann. chim. phys. [5] 23, 188-197 (1881).

[35] Berthelot, M. and Ogier, J., Compt. rend. 91, 781-787 (1880).

[36] Stohmann, F., Rodatz, P., and Herzberg, H., Ann. chim. phys.
      [6] 8, 253-267 (1886).

[37] Stohmann, F., Rodatz, P., and Herzberg, H., J. prakt. Chem. [2]
      33, 241-259 (1886).

[38] Stohmann, F., Kleber, C., and Langbein, H., J. prakt. Chem. [2]
      40, 77-95 (1889).

[39] Roth, W. A. and von Auwers, K., Ann. 407, 145-175 (1915).

[40] Richards, T. W. and Jesse, Jr., R. H., J. Am. Chem. Soc. 32,
      268-298 (1910).

[41] Richards, T. W. and Barry, F., J. Am. Chem. Soc. 37, 993-1020
      (1915).

[42] Richards, T. W. and Davis, H. S., J. Am. Chem. Soc. 42, 1599-1617
      (1920).

[43] Richards, T. W., Henderson, L. J., and Frevert, H. L., Proc. Am.
      Acad. 42, 573-593 (1907).; ibid. Z. physik. Chem. 59, 532-552 (1907).

[44] Drucker, C. and Flade, T., Z. Wiss. Phot. 29, 29-42 (1930).

[45] Coops, J., Mulder JMzn., D., Dienske, J. W., and Smittenberg,
      J., Rec. trav. chim. 65, 128 (1946).

[46] Coops, J., Mulder JMzn., D., Dienske, J. W., and Smittenberg, J.,
      Rec. trav. chim. 66, 153-160 (1947).

[47] Prosen, E. J., Gilmont, R., and Rossini, F. D., J. Research NBS
      34, 65-71 (1945).

[48] Bradley, R. S. and Cleasby, T. G., J. Chem. Soc. 1953, 1690-1692.

[49] Sherwood, T. K., and Bryant, Jr., H. S., Can. J. Chem. Eng. 35,
      51-57 (1957).

[50] Miller, G. A., J. Chem. Eng. Data, 8, 69-72 (1963).

[51] Zil'berman-Granovskaya, A. A., Zhur. Fiz. Khim. 14, 759-767 (1940).

[52] Swan, T. H. and Mack, Jr., E., J. Am. Chem. Soc. 47, 2112-2116 (1925).

[53] Winstrom, L. O. and Kulp, L., Ind. Eng. Chem. 41, 2584-2586 (1949).

[54] Allen, R. W., J. Chem. Soc. 77, 400-412 (1900).

[55] Hoyer, H. and Peperle, W., Z. Electrochem. 62, 61-66 (1958).

[56] Aihara, A., Bull Chem. Soc. Japan, 32, 1242-1248 (1959).

[57] Sears, G. W. and Hopke, E. R., J. Am. Chem. Soc. 71, 1632-1634 (1949).

[58] Shlyarenko, S. I., Markin, B. I., and Belyaeva, L., Zhur. Fiz. Khim. 32, 1916-1921 (1958).

[59] von Rechenberg, C., J. prakt. Chem. [2] 22, 1-45 (1880).

[60] Stohmann, F., J. prakt. Chem. [2] 31, 273-306 (1885).

[61] Stohmann, F., J. prakt. Chem. [2] 36, 131-141 (1887).

[62] Rübner, M., Z. Biol. 21, 251-334 (1885).

[63] Berthelot, M., and Louguinine, W., Ann. chim. phys. [6] 13, 321-329 (1888).

[64] Berthelot, M., and Recoura, A., Ann. chim. phys. [6] 13, 289-304 (1888).

[65] Berthelot, M., and Vieille, P., Ann. chim. phys. [6] 10, 433-455 (1887).

[66] Fischer, E. and Wrede, F., Sitzber. preuss. Akad. Wiss. Physik. Math. Kl. 1904, 687-715.

[67] Riiber, C. N. and Schetelig, J., Z. physik. Chem. 48, 345-352 (1904).

[68] Wrede, F., Z. physik. Chem. 75, 81-94 (1910).

[69] Dickinson, H. C., Bur. Standards Bull. 11, 189-257 (1915).

[70] Swietoslawski, W., J. Am. Chem. Soc. 39, 2595-2600 (1917).

[71] Karrer, P., and Fioroni, W., Ber. 55B, 2854-2863 (1922).

[72] Swietoslawski, W., and Starczewska, H., Bull. soc. chim. France, [4] 31, 654-667 (1922).

[73] Verkade, P. E., Coops, Jr., J., and Hartman, H., Rec. trav. chim. 41, 241-277 (1922).

[74] Verkade, P. E., Chem. Weekblad, 21, 13-20 (1924).

[75] Verkade, P. E., and Coops, Jr., J., Rec. trav. chim. 47, 709-714 (1928).

[76] Verkade, P. E., and Coops, Jr., J., Rec. trav. chim. 52, 747-767 (1933).

[77] Beckers, M., Bull. soc. chim. Belg. 40, 571-610 (1931).

[78] Burriel, F., Anales soc. espan. fis. y quim. 29, 89-125 (1931); (unpublished data of M. Beckers).

[79] Keffler, L. J. P., J. chim. phys. 28, 457-469 (1931).

[80] Milone, M. and Rossignoli, P., Gazz. chim. ital., 62, 644-655 (1932).

[81] Schläpfer, P., and Fioroni, W., Helv. Chim. Acta, 6, 713-729 (1923).

[82] Huffman, H. M. and Ellis, E. L., J. Am. Chem. Soc. 57, 41-46 (1935).

[83] Bender, P. and Farber, J., J. Am. Chem. Soc. 74, 1450-1452 (1952).

[84] Speros, D. M. and Rossini, F. D., J. Phys. Chem. 64, 1723-1727 (1960).

[85] Prosen, E. J. and Colomina, M., unpublished data quoted in Experimental Thermochemistry, Vol. I, p. 134, (Interscience Publishers, (1956)).

[86] Mackle, H. and O'Hare, P.A.G., Trans. Faraday Soc. 59, 2693-2701 (1963).

[87] Coleman, D. J. and Pilcher, G., Trans. Faraday Soc. 62, 821-827 (1966).

[88] Stevens, B., J. Chem. Soc. 1953, 2973-2974.

[89] Klochkov, V. P. Zhur. Fiz. Khim. 32, 1177 (1958).

[90] Inokuchi, H., Shiba, S., Handa, T., and Akamatu, H., Bull. Chem. Soc. Japan, 25, 299-302 (1952).

[91] Nitta, I., Seki, S., and Momotani, M., Nippon Kagaku Zasshi, 71, 430-433 (1950).

[92] Kelly, J. D. and Rice, F. O., J. Phys. Chem. 68, 3794-3796 (1964).

[93] Weigert, F., Z. physik. Chem. 63, 458-466 (1908).

[94] Klaproth, G., Braunschweig (1929) quoted from W. Schilling Dissertation, Braunschweig (1930) quoted in Landolt-Bornstein, 5th Ed., Ergb. II, p. 1635.

[95] Fries, K., Walter, R., and Schilling, Ann. 516, 248-285 (1935).

[96] Shchukarev, A. N. and Shchukareva, L. A., Zhur. Fiz. Khim. 3, 169-174 (1932).

[97] Richardson, J. W., and Parks, G. S., J. Am. Chem. Soc. 61, 3543-3546 (1939).

[98] Parks, G. S., West, T. H., Naylor, B. F., Fujii, P. S., and McClaine, L. A., J. Am. Chem. Soc. 68, 2524-2527 (1946).

[99] Magnus, A., Hartmann, H., and Becker, F., Z. physik. Chem. 197, 75-91 (1951).

[100] Berthelot, M., and Vieille, P., Compt. rend. 102, 1211-1217 (1886).

[101] Westrum, Jr., E. F., and Wong, S., AEC Report COO-1149-92, Contract AT(11-1)-1149, 7 pp., April 1967.

[102] Stohmann, F., Z. physik. Chem. 6, 334-357 (1890).

[103] Pongratz, A., and Griengl, F., Monatsh. Chem., 53-54, 256-262 (1929).

[104] Boyd, R. H., Christensen, R. L., and Pua, R., J. Am. Chem. Soc. 87, 3554-3559 (1965).

[105] Rossini, F. D., J. Research NBS 8, 119-139 (1932).

[106] Stohmann, F., Kleber, C., and Langbein, H., J. prakt. Chem. [2] 40, 341-364 (1889).

[107] Roth, W. A., Rec. trav. chim. 45, 248-256 (1926).

[108] Roth, W. A. and Banse, H., unpublished data in Landolt-Bornstein, 5th Ed., Ergb. II, Teil II, p. 1634 (1931).

[109] Roth, W. A. and Muller, F., unpublished data in Landolt-Bornstein, 5th Ed., 1st. suppl. p. 868 (1927).

[110] I. G. Farbenfabriken, quoted in Landolt-Bornstein, 5th Ed., Ergb. II, Teil II, p. 1636 (1931).

[111] Chao, J., and Rossini, F. D., J. Chem. Eng. Data, 10, 374-379 (1965).

[112] Wadsö, I., Acta Chem. Scand., 20, 544-552 (1966).

[113] Berthelot, M., and Matignon, C., Ann. chim. phys. [6] 27, 310-319 (1892).

[114] Berthelot, M. and Matignon, C., Compt. rend. 114, 1145-1149 (1892).

[115] Emery, A. G., and Benedict, F. G., Am. J. Physiol. 28, 301-307 (1911).

[116] Atwater, W. O. and Rosa, E. B., Phys. Rev. 9, 214-251 (1899).

[117] Atwater, W. O. and Snell, J. F., J. Am. Chem. Soc. 25, 659-699 (1903).

[118] Louguinine, W., Ann. chim. phys. [5] 21, 139-144 (1880).

[119] Snelson, A., and Skinner, H. A., Trans. Faraday Soc. 57, 2125-2131 (1961).

[120] Zubov, P., Zhur. Russ. Fiz. Khim. Obshchestva, 30, 926-950 (1898).

[121] Skinner, H. A. and Snelson, A., Trans. Faraday Soc. 56, 1776-1783 (1960).

[122] Gundry, H. A., Head, A. J., and Lewis, G. B., Trans. Faraday Soc. 58, 1309-1312 (1962).

[123] Verkade, P. E. and Coops, J., Rec. trav. chim. 46, 903-917 (1927).

[124] Tjebbes, J., Acta Chem. Scand. 14, 180-188 (1960).

[125] Gundry, H. A., Harrop, D., Head, A. J., and Lewis, G. B., private communication, 1969.

[126] Parks, G. S. and Moore, G. E., J. Chem. Phys. 7, 1066-1067 (1939).

[127] Parks, G. S., Mosley, J. R., and Peterson, Jr., P. V., J. Chem. Phys. 18, 152-153 (1950).

[128] Louguinine, W., Ann. chim. phys. [5] 25, 140-144 (1882).

[129] Raley, J. H., Rust, F. F., and Vaughan, W. E., J. Am. Chem. Soc. 70, 88-94 (1948).

[130] Andon, R. J. L., Biddiscombe, D. P., Cox, J. D., Handley, R., Harrop, D., Herington, E. F. G., and Martin, J. L., J. Chem. Soc. 1960, 5246-5254.

[131] Cox, J. D., Symposium über Thermodynamik, Fritzens-Wattens, Tirol, 1959, 7 pp., paper No. 20.

[132] Cox, J. D., Pure Appl. Chem. 2, 125-128 (1961).

[133] Karlsson, K. J., Thesis, Lund, Sweden, 1941.

[134] Manchester, K. E., Ph.D. Thesis, Stanford Univ., 1955.

[135] Parks, G. S., Manchester, K. E., and Vaughan, L. M., J. Chem. Phys. 22, 2089-2090 (1954).

[136] Stohmann, F., Rodatz, P., and Herzberg, H., J. prakt. Chem. [2] 33, 464-470 (1886).

[137] Stohmann, F., and Langbein, H., J. prakt. Chem. [2] 45, 305-356 (1892).

[138] Badoche, M., Bull. Soc. Chim. France Mem. [5] 8, 212-220 (1941).

[139] Desai, P. D., Wilhoit, R. C., and Zwolinski, B. J., J. Chem. Eng. Data, 13, 334-335 (1968).

[140] Berner, E., unpublished data, in E. Schreiner, Z. physik. Chem. 117, 57-87 (1925).

[141] Magnus, A., Z. physik. Chem. [N.F.] 9, 141-161 (1956).

[142] Pilcher, G. and Sutton, L. E., J. Chem. Soc. 1956, 2695-2700.

[143] Pilcher, G., and Chadwich, J. D. M., Trans. Faraday Soc. 63, 2357-2361 (1967).

[144] Valuer, A., Compt. rend. 125, 872-874 (1897).

[145] Swietoslawski, W. and Starczewska, H., J. chim. phys. 22, 399-401 (1925).

[146] Stohmann, F., Rodatz, P., and Herzberg, H., J. prakt. Chem. [2] 34, 311-325 (1886).

[147] Swarts, F., Rec. trav. chim. 32, 59-89 (1913); ibid. Bull. Classe sci., Acad. roy. Belg. 1912, 481-523.

[148] Biddiscombe, D. P., Handley, R., Harrop, D., Head, A. J., Lewis, G. B., Martin, J. F., and Sprake, C. H. S., J. Chem. Soc. 1963, 5764-5768.

[149] Louguinine, W., Ann. chim. phys. [5] 20, 558-562 (1880).

[150] Moureu, H. and Dode, M., Bull. Soc. chim. [5] 4, 637-647 (1937).

[151] Jung, G. and Dahmlos, J., Z. physik. Chem. A190, 230-240 (1942).

[152] Louguinine, W., Compt. rend. 91, 297-300 (1880).

[153] Stohmann, F., von Rechenberg, C., Wilsing, H., and Rodatz, P., Landw. Jahrb. 13, 549-581 (1884).

[154] Stohmann, F., and Langbein, H., J. prakt. Chem. [2] 42, 361-382 (1890).

[155] Berthelot, M., and Matignon, C., Ann. chim. phys. [6] 21, 409-416 (1890).

[156] Louguinine, W., Compt. rend. 108, 620-622 (1889).

[157] Medard, L., and Thomas, M., Mem. poudres, 36, 97-127 (1954).

[158] Obermok-Yakubova, A. P., and Balandin, A. A., Izvest. Akad. Nauk SSSR, Ser. Khim. No. 12, 2210-2211 (1963).

[159] Gibson, H. B., Storrs School of Agricultural Experiment Station, Storrs, Connecticut, 3rd Annual Rept. 182-192 (1890).

[160] Baer, E., and Flehmig, H-H., Can. J. Biochem. and Physiol. 47, 79-83 (1969).

[161] Berthelot, M. and Vieille, P., Ann. chim. phys. [6] 10, 455-463 (1887).

[162] Fogh, J., Compt. rend. 114, 920-923 (1892).

[163] Parks, G. S. and Mosher, H. P., J. Chem. Phys. 37, 919-920 (1962).

[164] Medard, L. and Thomas, M., Mem. poudres, 38, 45-63 (1955).

[165] von Wartenberg, H., and Lerner-Steinberg, B., Z. Angew. Chem. 38, 591-592 (1925).

[166] Berthelot, M. and Ogier, J., Ann. chim. phys. [5] 23, 199-201 (1881).

[167] Dolliver, M., Gresham, T. L., Kistiakowsky, G. B., Smith, E. A., and Vaughan, W. E., J. Am. Chem. Soc. 60, 440-450 (1938).

[168] Roth, W. A., and Müller, F., unpublished data in Landolt-Bornstein 5th Ed. 1st suppl., p. 869 (1927).

[169] Coleman, C. F. and DeVries, T., J. Am. Chem. Soc. 71, 2839-2841 (1949).

[170] Berthelot, M. and Delepine, M., Ann. chim. phys. [7] 21, 289-296 (1900).

[171] Berthelot, M. and Delepine, M., Compt. rend. 130, 1045-1049 (1900).

[172] Tjebbes, J., Acta Chem. Scand. 16, 953-957 (1962).

[173] Nicholson, G. R., J. Chem. Soc. 1960, 2377-2378.

[174] Louguinine, W., Ann. chim. phys. [5] 23, 384-389 (1881).

[175] Skuratov, S. M., Strepikheev, A. A., and Kozina, M. P., Doklady Akad. Nauk SSSR 117, 452-454 (1957).

[176] Louguinine, W., Compt. rend. 101, 1061-1064 (1885).

[177] Cass, R. C., Springall, H. D. and White, T. R., Chem. and Ind. (London) 1955, 387-388.

[178] Fletcher, S. E., Mortimer, C. T., and Springall, H. D., J. Chem. Soc. 1959, 580-584.

[179] Geiseler, G. and Raetzsch, M., Ber. Bunsenges. Physik. Chem. 69, 485-488 (1965).

[180] Landrieu, P., Baylocq, F., and Johnson, J. R., Bull. soc. chim. France, [4] 45, 36-49 (1929).

[181] Stohmann, F., Rodatz, P., and Herzberg, W., J. prakt. Chem. [2] 36, 1-16 (1887).

[182] Delepine, M. and Rivals, P., Compt. rend. 129, 520-523 (1899).

[183] Berthelot, M. and Rivals, P., Ann. chim. phys. [7] 7, 29-47 (1896).

[184] Rivals, P., Ann. chim. phys. [7] 12, 501-574 (1897).

[185] Miles, C. B. and Hunt, H., J. Phys. Chem. 45, 1346-1359 (1941).

[186] Taylor, J., Hall, C. R. L., and Thomas, H., J. Phys. Colloid Chem. 51, 580-592 (1947).

[187] Pennington, R. E. and Kobe, K. A., J. Am. Chem. Soc. 79, 300-305 (1957).

[188] Crog, R. S. and Hunt, H., J. Phys. Chem. 46, 1162-1163 (1942).

[189] Renquist, M. L., Ph.D. Thesis, Stanford Univ. 1941, 76 pp.

[190] Parks, G. S. , Mosley, J. R., and Peterson, Jr., P. V., J. Chem. Phys. 18, 152-153 (1950); (corrected data in ref. [19]).

[191] Sinke, G. C. and Oetting, F. L., J. Phys. Chem. 68, 1354-1358 (1964).

[192] Landrieu, P., Compt. rend. 142, 580-582 (1906).

[193] Nicholson, G. R., Szwarc, M., and Taylor, J. W., J. Chem. Soc. 1954, 2767-2769.

[194] Springall, H. D. and White, T., J. Chem. Soc. 1954, 2764-2766.

[195] Louguinine, W., Compt. rend. 98, 94-97 (1884).

[196] Colomina, M., Latorre, C., Perez-Ossorio, R., Symposium über Thermo-dynamik in Fritzens-Wattens, Tirol, 1959, 5 pp.

[197] Colomina, M., Latorre, C., Perez-Ossorio, R., Pure Appl. Chem. 2, 133-135 (1961).

[198] Stohmann, F., Rodatz, P., and Herzberg, W., J. prakt. Chem. [2] 36, 353-370 (1887).

[199] Stohmann, F., Z. physik. Chem. 10, 410-424 (1892).

[200] Colomina, M., Cambeiro, M., Perez-Ossorio, R., and Latorre, C., Anales real soc. espan. fis. y quim. 55B, 509-514 (1959).

[201] Landrieu, P. and Blatt, H., Bull. soc. chim. France 35, 1424-1436 (1924).

[202] Berthelot, M., Ann. chim. phys. [6] 28, 126-139 (1893).

[203] Jahn, H., Ann. Physik 37, 408-443 (1889).

[204] Sinke, G. C., J. Phys. Chem. 63, 2063 (1959).

[205] Lebedeva, N. D., Zhur. Fiz. Khim. 38, 2648-2651 (1964).

[206] Evans, F. W. and Skinner, H. A., Trans. Faraday Soc. 55, 260-261 (1959).

[207] Roth, W. A., Rec. trav. chim. 45, 248-256 (1926).

[208] Schjǻnberg, E., Svensk. Kem. Tid. 44, 227-231 (1932).

[209] Schjǻnberg, E., Z. physik. Chem. A172, 197-233 (1935).

[210] Stull, D. R., Thermochemical Bulletin, No. 2, 4-5 (1956).

[211] Louguinine, W., Compt. rend. 101, 1061-1064 (1885).

[212] Stohmann, F., Kleber, C., Langbein, H., and Offenhauer, P., Ber. Verhandl. K. Sachs Ges. Wiss. Math. Phys. Kl. 45, 604-658 (1893).

[213] Stohmann, F., Kleber, C., Langbein, H., and Offenhauer, J. prakt. Chem. 49, 99-129 (1894).

[214] Adriaanse, N., Dekker, H., and Coops, J., Rec. trav. chim. 84, 393-407 (1965).

[215] Hancock, C. K., Watson, G. M., and Gibly, R. F., J. Phys. Chem. 58, 127-129 (1954).

[216] Louguinine, W., Ann. chim. phys. [6] 11, 220-234 (1887).

[217] Louguinine, W., Compt. rend. 102, 1240-1243 (1886).

[218] Stohmann, F., and Rodatz, P., J. prakt. Chem. [2] 32, 93-97 (1885).

[219] Roth, W. A., and Rist-Schumaker, E., Z. Electrochem. 50, 7-9 (1944).

[220] Swain, Jr., H. A., Silbert, L. S., and Miller, J. G., J. Am. Chem. Soc. 86, 2562-2566 (1964).

[221] Medard, L. and Thomas, M., Mem. poudres 34, 421-442 (1952).

[222] Adriaanse, N., Dekker, H., and Coops, J., Rec. trav. chim. 83, 557-572 (1964).

[223] Louguinine, W., Ann. chim. phys [6] 23, 179-231 (1891).

[224] Berthelot, M. and Matignon, C., Ann. chim. phys. [6] 28, 139-144 (1893).

[225] Saville, G., and Gundry, H. A., Trans. Faraday Soc. 55, 2036-2038 (1959).

[226] Matignon, C., Ann. chim. phys. [6] 28, 289-394 (1893).

[227] Louguinine, W., Compt. rend. 107, 597-600 (1888).

[228] Berthelot, M. and Andre, G., Compt. rend. 124, 645-648 (1897).

[229] Stroh, H. H., and Klchenmeister, W., Z. Chem. 4, 427-428 (1964).

[230] Moureu, C. and Boutaric, A., J. chim. phys. 18, 348-352 (1920).

[231] Clopatt, J. A., Soc. Sci. Fennica, Commentationes Phys. Math. 6, No. 4, 1-15 (1932).

[232] Stohmann, F., unpublished data quoted in C. Liebermann, Ber. 25, 90-95 (1892).

[233] Ossipov, I., Zhur. Russ. Fiz. Khim. Obshchestva, 20, 650-652 (1888).

[234] Keffler, L. J. P., Rev. trav. chim. 49, 415-424 (1930).

[235] Keffler, L. J. P., J. Phys. Chem. 34, 1319-1325 (1930).

[236] Keffler, L. J. P. and McLean, J. H., J. Soc. Chem. Ind. (London) 54, 178T-185T (1935).

[237] Favre, P. A. and Silbermann, J. T., Ann. chim. phys. [3] 34, 357-450 (1852).

[238] Weltner, Jr., W., and Pitzer, K. S., J. Am. Chem. Soc. 73, 2606-2610 (1951).

[239] Fiock, E. F., Ginnings, D. C., and Holton, W. B., J. Research NBS 6, 881-900 (1931).

[240] Andrews, T., Phil. Mag. [3] 32, 321-339 (1848).

[241] Coburn, Jr., W. C., and Grunwald, E., J. Am. Chem. Soc. 80, 1318-1322 (1958).

[242] Andrews, T., Phil. Mag. [3] 32, 321-339 (1848).

[243] Thomsen, J., Ber. 13, 1321-1334 (1880).

[244] Berthelot, M., Ann. chim. phys. [5] 23, 176-187 (1881).

[245] Berthelot, M., and Matignon, C., Ann. chim. phys. [6] 30, 547-565 (1893).

[246] Roth, W. A., and Macheleidt, R., unpublished data in Landolt-Bornstein 5th Ed., Vol. II, p. 1588 (1923).

[247] Mosselman, C. and Dekker, H., Rec. trav. chim. 88, 257-265 (1969).

[248] Good, W. D., Bureau of Mines, Bartlesville, Okla., private communication, January, 1969.

[249] Prosen, E. J. and Rossini, F. D., J. Research NBS 36, 269-275 (1946).

[250] Dulong, P. L., Compt. rend. 7, 872-877 (1838).

[251] Grassi, C., J. pharm. chim. [3] 8, 170-181 (1845).

[252] Mixter, W. G., Am. J. Sci., [4] 12, 347-357 (1901); see also Am. J. Sci [4] 22, 13-18 (1906).

[253] Berthelot, M., and Matignon, C., Compt. rend. 116, 1333-1339 (1893).

[254] Zubov, P., Zhur. Russ. Fiz. Khim. Obshchestva, 45, 240-251 (1913).