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A BIBLIOGRAPHY OF THE PHYSICAL EQUILIBRIA AND RELATED PROPERTIES OF SOME CRYOGENIC SYSTEMS

BY
THOMAS M. FLYNN

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS

Technical Note

56

May 1960

A Bibliography of the Physical Equilibria and Related Properties of Some Cryogenic Systems

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Thomas M. Flynn

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Abstract

A bibliography of approximately 700 references is presented on the physical equilibria and related properties of several important cryogenic systems. The systems considered are the pure components and mixtures of: Hydrogen, Helium, Nitrogen, Carbon Dioxide, Carbon Monoxide, Methane, Ethane, and Propane.

1. Introduction

1.1 Purpose

Gases to be liquefied are frequently obtained as by-products from some parent source, and may contain very large amounts of impurities. Determining the method of removal of the impurities is difficult since the systems are seldom ideal, and may deviate from some theoretical models by factors of several thousand. Research in the area of physical equilibria attempts to present the problem from a fundamental viewpoint so that accurate predictions and designs can be made.

Any serious effort to predict physical equilibria demands at least two types of information, sine qua non. First, a precise description of the P-V-T behavior of the pure components. Second, a precise description of the mixture: the P-V-T behavior, or the interaction of the different molecular species, and the like.

Information in these categories appears in several forms and in many places in the scientific literature. It is the purpose of this paper to present results of a literature search in this field. The search was intended to discover, as completely as possible, that work in phenomena and properties, experimental and theoretical, related to the physical equilibria of a few selected systems.

The systems selected were those of primary interest in cryogenics. They included the pure components and mixtures of: Hydrogen, Helium, Nitrogen, Carbon Dioxide, Carbon Monoxide, Methane, Ethane, and Propane.

Oxygen and the higher hydrocarbons were deliberately excluded as primary systems since their behavior has already been thoroughly reported in the literature of air separation and petroleum, respectively. They were included, however, as "Other Components" within the primary systems.

1.2 Organization

The information is presented in three principal parts: I. Phenomena, II. Properties, and III. Bibliography of References.

The following outline delineates the arrangement. For the sake of brevity, the sub-headings are given only once in each principal part. They are, of course, repeated for each component.

Organization Outline

I. Phenomena
- A. Hydrogen
  1. Phase equilibria
  2. Fugacity, activity
  3. Adsorption, on charcoal
  4. Adsorption, on silica gel
  5. Adsorption, on other adsorbents
- B. Helium
  1. -- 5.
- C. Nitrogen
  1. -- 5.
- D. Carbon Dioxide
  1. -- 5.
- E. Carbon Monoxide
  1. -- 5.
- F. Methane
  1. -- 5.
- G. Ethane
  1. -- 5.
- H. Propane
  1. -- 5.

II. Properties

A. Hydrogen

1. P-V-T General
2. Vapor pressure
3. Critical constants, and triple point
4. Compressibility isotherms
5. Density, molar volume (of a condensed phase)
6. Equations of state, general
7. Corresponding states
8. Beattie - Bridgeman
9. Benedict - Webb - Rubin
10. Potential forms, general
11. Virial coefficients
12. Lennard - Jones 6 - 9 potential
13. Lennard - Jones 6 - 12 potential

B. Helium

1. -- 13.

C. Nitrogen

1. -- 13.

D. Carbon Dioxide

1. -- 13.

E. Carbon Monoxide

1. -- 13.

F. Methane

1. -- 13.

G. Ethane

1. -- 13.

H. Propane

1. -- 13.

III. Bibliography of References
(Listed alphbetically by first author)

1.3 Scope

I. Areas Searched

Indexes, when available, were searched under the following headings:

1. acetylene
2. adsorbents
3. adsorption
4. carbon dioxide
5. carbon monoxide
6. ethane
7. ethene (ethylene)
8. gases
9. helium
10. hydrogen
11. methane
12. nitrogen
13. propane
14. propene (propylene)
15. purification
16. solubility

The sub groups searched within these general headings were:

1. Analysis: detection, determination, chromotography, mass spectrometry
2. Adsorption: by various agents, of mixtures
3. Absorption
4. Cryostat: cryogenics
5. Distillation

6. Liquefaction: condensation, melting point, solidification
7. Mists: analysis of, formation, separation, supersaturation
8. Physical equilibria: phase diagrams
9. Purification: impurities, separation, removal, drying
10. P-V-T: equations of state, critical constants, compressibility, vapor pressure, specific volume, fugacity
11. Reviews: bibliographies
12. Solubility: dissolved, determination, theory of, laws of
13. Thermodynamic properties

For the years of Chemical Abstracts for which no indexes are available, the following sections were searched:

a. (1) Apparatus, plant equipment and Unit Operations
b. (2) General and Physical Chemistry
c. (6) Inorganic Chemistry
d. (7) Analytical Chemistry
e. (13) Miscellaneous and Industrial Products
f. (22) Petroleum

II. The Abstracts, Indexes, and Lists searched were:

1. Chemical Abstracts, 1907 to date.*
2. British Chemical Abstracts, 1926 through 1953.
3. FIAT Review of German Science, 1936-1946, Vols. 27b (Inorganic Chemistry, Part V; Equilibrium Investigation on Inorganic Substances); Gas Analysis); and 30a (Physical Chemistry; adsorption and desorption).
4. Chemisches Zentralblatl, 1955 only.
5. Doctoral Dissertations accepted by American Universities, 1949-1955.
6. Index to American Doctoral Dissertations, Combined with Dissertation Abstracts, 1955 to date.*
7. Index to theses accepted for Higher Degrees in the Universities of Great Britain and Ireland. 1951 to date.*
8. Bibliography of Translations from Russian Scientific and Technical Literature. 1953-1956 (no more published).
9. Translation Monthly. 1955-1958.
10. Monthly List of Russian Accessions. 1948 to date.*
11. Deitz, V. R., Bibliography of Solid Adsorbents, 1900 to 1942, and 1943 to 1953.
12. Rose, Arthur and Elizabeth, Distillation Literature Index and Abstract, 1946 to 1952, and 1953 to 1954.

* "to date" means through and including the most recent issue available on October 1, 1959.

13. A few selected journals were searched issue by issue from January, 1958, to date,* since it was possible that these issues had not yet been fully abstracted. The journals searched in this manner were:
    a. A.I.Ch.E. Journal
    b. Chemical Engineering Progress
    c. Industrial and Engineering Chemistry
    d. Journal of the American Chemical Society

1.4 Acknowledgements

This work simply never would have been compiled without the aid of many able persons of the National Bureau of Standards Cryogenic Engineering Laboratory staff. Recognition is due: Mr. D. E. Drayer, who performed the bulk of the search; Mr. A. J. Kidnay for help in compiling and proofing; Mrs. B. E. Douglas for typing the two principal indicies; and especially to Mrs. L. E. Merritt for the painstaking and exhausting typing of the bibliography.

The author also wishes to acknowledge the aid of the Cryogenic Engineering Laboratory Data Center, under the direction of Mr. V. J. Johnson. This able group advised the preparation of the primary information retrieval system, and supplied many of the original papers for review.

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Phenomena Index

Phenomenon

Major Component

HYDROGEN

Category	Other Components	References
Phase Equilibria	Helium	568
	Nitrogen	17, 88, 169, 205, 226, 227, 231, 374, 420, 472, 637
	Nitrogen and Carbon Dioxide	2
	Nitrogen and Carbon Dioxide and Carbon Monoxide	3
	Nitrogen and Carbon Monoxide	10, 169, 184, 204, 539, 637
	Nitrogen and Methane	131, 132, 133, 572
	Nitrogen and Methane and Carbon Monoxide	600
	Nitrogen and Methane and Ethane	131, 132, 133
	Nitrogen and Ethene	435
	Carbon Dioxide	1, 3, 186, 236, 426, 605
	Carbon Dioxide and Nitrogen	2

Phenomenon

Major Component

HYDROGEN
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Carbon Dioxide and Nitrogen and Carbon Monoxide	3
	Carbon Monoxide	169, 227, 637
	Carbon Monoxide and Nitrogen	10, 169, 184, 204, 539, 637
	Carbon Monoxide and Nitrogen and Carbon Dioxide	3
	Carbon Monoxide and Nitrogen and Methane	600
	Methane	56, 57, 58, 59, 187, 193, 194, 207, 226, 227, 653
	Methane and Nitrogen	131, 132, 133, 572
	Methane and Nitrogen and Carbon Monoxide	600
	Methane and Nitrogen and Ethane	131, 132, 133
	Methane and Ethane	353

Phenomenon

Major Component

HYDROGEN
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Methane and Ethane and Propane	56, 57, 58, 59
	Methane and Propane	56, 57, 58
	Methane and Propene	57, 58
	Ethane	352, 612, 663
	Propane	59, 96, 663
	Propene	59
Fugacity, Activity		605
	Helium	370
Adsorption, Charcoal		32, 97, 118, 140, 158, 159, 161, 164, 214, 237, 315, 325, 326, 351, 367, 395, 475, 499, 527, 580, 588, 595, 610, 611, 618, 624
	Nitrogen	12
	Carbon Dioxide	268, 366, 372
Adsorption, Silica Gel		140, 408, 512, 513, 616
	Nitrogen	12, 290

Phenomenon

Major Component

HYDROGEN
(continued)

Category	Other Components	References
Adsorption, Other Adsorbents		23, 33, 86, 202, 274, 289, 363, 373, 440, 463, 487, 489, 622, 623

Phenomenon

Major Component

HELIUM

Category	Other Components	References
Phase Equilibria	Hydrogen	568
	Nitrogen	79, 80, 198, 228, 320, 536, 537
	Nitrogen and Methane and Ethane	79, 80, 583
	Nitrogen and Methane and Ethane and Propane	79, 80
	Carbon Dioxide	186, 603
	Methane	229, 230
	Propane	604
	Argon	300, 301
Fugacity, Activity		370
	Nitrogen	228
Adsorption, Charcoal		118, 127, 159, 181, 192, 238, 297, 396, 403, 551, 615, 620, 621, 626
	Nitrogen	346, 430, 678
	Methane	346

Phenomenon

Major Component

HELIUM
(continued)

Category	Other Components	References
Adsorption, Silica Gel		614
	Oxygen	345
Adsorption, Other Adsorbents		206, 312, 386

Phenomenon

Major Component

NITROGEN

Category	Other Components	References
Phase Equilibria	Hydrogen	17, 88, 169, 205, 226, 227, 231, 374, 420, 472, 637
	Hydrogen and Carbon Dioxide	2
	Hydrogen and Carbon Dioxide and Carbon Monoxide	3
	Hydrogen and Carbon Monoxide	10, 169, 184, 204, 539, 637
	Hydrogen and Carbon Monoxide and Methane	600
	Hydrogen and Methane	131, 132, 133, 572
	Hydrogen and Methane and Ethane	131, 132, 133
	Helium	79, 80, 198, 228, 320, 536, 537
	Helium and Methane and Ethane	79, 80, 583
	Oxygen	25, 31, 166, 167, 168, 334, 341, 497, 498, 534, 538
	Oxygen and Argon	257, 347, 651

Phenomenon

Major Component

NITROGEN
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Carbon Dioxide	1, 3, 200, 426, 605
	Carbon Dioxide and Hydrogen	2
	Carbon Dioxide and Hydrogen and Carbon Monoxide	3
	Carbon Dioxide and Argon	648
	Carbon Monoxide	169, 203, 294, 334, 534, 538, 558, 570, 571, 637
	Carbon Monoxide and Hydrogen	10, 169, 184, 204, 539, 637
	Carbon Monoxide and Hydrogen and Methane	600
	Methane	71, 72, 113, 114, 195, 197, 199, 404, 581, 598, 599, 635
	Methane and Hydrogen	131, 132, 133, 572
	Methane and Helium and Ethane	583
	Methane and Ethane	131, 132, 133

Phenomenon

Major Component

NITROGEN
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Methane and Ethane and Propane and Butane	584
	Ethane	137, 176, 507
	Ethene	137, 606, 607
	Acetylene	200, 286
	Propane	635
	Propene	137, 607
	Butane	9
	Benzene	518, 519
	Argon	163, 196, 277
	Argon and Oxygen	257, 347, 651
Fugacity, Activity		75, 370
	Helium	228
	Methane	75
	Ethane	492

Phenomenon

Major Component

NITROGEN
(continued)

Category	Other Components	References
Adsorption, Charcoal		20, 21, 22, 97, 109, 118, 149, 150, 159, 161, 180, 201, 215, 218, 275,278, 279, 283, 296, 302, 314, 365, 400, 405, 436, 499, 508, 511, 525, 527, 595, 609, 640, 641, 664, 665
	Hydrogen	12
	Helium	346, 430, 678
	Oxygen	12
	Carbon Dioxide	268
Adsorption, Silica Gel		90, 108, 145, 172, 173, 179, 222, 296, 330, 337, 376, 480, 565, 589, 616, 665
	Hydrogen	290
	Oxygen	345, 366
	Carbon Dioxide	673
	Carbon Monoxide	666
	Methane	666
Adsorption, Other Adsorbents		23, 33, 86, 433, 546, 622, 644, 677

Phenomenon

Major Component

CARBON DIOXIDE

Category	Other Components	References
Phase Equilibria	Hydrogen	1, 3, 186, 236, 426, 605
	Hydrogen and Nitrogen	2
	Hydrogen and Nitrogen and Carbon Monoxide	3
	Helium	186, 603
	Nitrogen	1, 3, 200, 426, 605
	Nitrogen and Hydrogen	2
	Oxygen	200
	Carbon Monoxide	1, 3
	Carbon Monoxide and Nitrogen	3
	Methane	170, 171, 500, 605
	Ethane	117, 502, 529
	Ethene	110, 117, 124, 256, 529, 606
	Ethene and Propane	564
	Acetylene	116

Phenomenon

Major Component

CARBON DIOXIDE
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Propane	8, 144, 488, 506
	Propane and Ethene	564
	Butane	450, 488
	Butanes and Higher Hydrocarbons	406, 407, 470, 488, 575
Fugacity, Activity		152, 375
Adsorption, Charcoal		67, 208, 215, 217, 278, 279, 367, 368, 499, 511, 516, 525, 526, 595, 609
	Hydrogen	268, 366, 372
	Nitrogen	268
	Oxygen	268
	Carbon Monoxide	366
	Ethene	67, 366
	Acetylene	557
Adsorption, Silica Gel		108, 632
	Nitrogen	673
	Oxygen	673

Phenomenon

Major Component

CARBON DIOXIDE
(continued)

Category	Other Components	References
Adsorption, Other Adsorbents		288, 451, 644

Phenomenon

Major Component

CARBON MONOXIDE

Category	Other Components	References
Phase Equilibria	Hydrogen	169, 227, 637
	Hydrogen and Nitrogen	10, 169, 184, 204, 539, 637
	Hydrogen and Nitrogen and Carbon Dioxide	3
	Hydrogen and Nitrogen and Methane	600
	Nitrogen	169, 203, 294, 334, 534, 538, 558, 570, 571, 637
	Nitrogen and Hydrogen	10, 169, 184, 204, 539, 637
	Carbon Dioxide	1, 3
	Methane	674
	Propane	659
	Propene	659
	Other Hydrocarbons	470, 659
Fugacity, Activity		370
Adsorption, Charcoal		97, 180, 215, 278, 279, 499, 525, 527, 625

Phenomenon

Major Component

CARBON MONOXIDE
(continued)

Category	Other Components	References
Adsorption, Charcoal (continued)	Carbon Dioxide	366
Adsorption, Silica Gel		480, 513, 589
	Nitrogen	666
	Methane	666
Adsorption, Other Adsorbents		23, 216, 363, 486, 487, 644

Phenomenon

Major Component

METHANE

Category	Other Components	References
Phase Equilibria	Hydrogen	56, 57, 58, 59, 187, 193, 194, 207, 226, 227, 653
	Hydrogen and Nitrogen	131, 132, 133, 572
	Hydrogen and Nitrogen and Carbon Monoxide	600
	Hydrogen and Nitrogen and Ethane	131, 132, 133
	Hydrogen and Ethane	353
	Hydrogen and Ethene	362
	Hydrogen and Propane	56, 57, 58
	Hydrogen and Propene	56, 57, 58
	Helium	229, 230
	Helium and Nitrogen and Ethane	583
	Helium and Nitrogen and Hydrocarbons	79, 80

Phenomenon

Major Component

METHANE
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Nitrogen	71, 72, 113, 114, 195, 197, 199, 404, 581, 598, 599, 635
	Nitrogen and Hydrogen	131, 132, 133, 572
	Nitrogen and Hydrogen and Carbon Monoxide	600
	Nitrogen and Hydrogen and Ethane	131, 132, 133, 572
	Nitrogen and Helium and Ethane	583
	Nitrogen and Helium and Hydrocarbons	79, 80
	Oxygen	19, 195
	Carbon Dioxide	170, 171, 500, 605
	Carbon Monoxide	674
	Ethane	91, 251, 534, 535, 540, 612
	Ethane and Hydrogen	353

Phenomenon

Major Component

METHANE
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Ethane and Hydrogen and Nitrogen	131, 132, 133
	Ethane and Helium and Nitrogen	583
	Ethane and Ethene	246, 441
	Ethene	243, 245, 361, 441, 639
	Ethene and Hydrogen	362
	Propane	7, 251, 504, 544, 545, 612, 649
	Propane and Hydrogen	56, 57, 58
	Propene and Hydrogen	56, 57, 58
Fugacity, Activity		75, 370, 547, 605
	Nitrogen	75
	Propane	64
Adsorption, Charcoal		32, 76, 183, 214, 215, 218, 278, 279, 327, 329, 332, 354, 377, 436, 471, 499, 511, 609, 645, 650

Phenomenon

Major Component

METHANE
(continued)

Category	Other Components	References
Adsorption, Charcoal (continued)	Nitrogen	12
	Ethane	633
	Propane	633, 645
	n - Butane	633, 645
Adsorption, Silica Gel		354, 480, 513, 614
	Nitrogen	666
	Carbon Monoxide	666
	Ethane	129
Adsorption, Other Adsorbents		233, 363, 563

Phenomenon

Major Component

ETHANE

Category	Other Components	References
Phase Equilibria	Hydrogen	352, 612, 663
	Hydrogen and Nitrogen and Methane	131, 132, 133
	Hydrogen and Methane	353
	Hydrogen and Ethene	567
	Hydrogen and Hydrocarbons	56, 57, 58, 59
	Nitrogen	137, 176, 507
	Nitrogen and Helium and Hydrocarbons	79, 80
	Oxygen	19, 137
	Carbon Dioxide	117, 502, 529
	Methane	91, 251, 534, 535, 540, 612
	Methane and Hydrogen	353
	Methane and Hydrogen and Nitrogen	131, 132, 133

Phenomenon

Major Component

ETHANE
(continued)

Category	Other Components	References
Phase Equilibria (continued)	Methane and Hydrogen and Hydrocarbons	57, 58, 59
	Methane and Ethene	246, 441
	Ethene	253
	Ethene and Acetylene	397
	Acetylene	116
Fugacity, Activity		492
Adsorption, Charcoal		97, 183, 218, 278, 279, 332, 354, 436, 462, 471, 499, 643, 650
	Methane	633
Adsorption, Silica Gel		354, 643
	Methane	129
	Propane	642
Adsorption, Other Adsorbents		522, 591

Phenomenon

Major Component

PROPANE

Category	Other Components	References
Phase Equilibria	Hydrogen	59, 96, 663
	Hydrogen and Methane	56, 57, 58, 59
	Helium	604
	Helium and Nitrogen and Hydrocarbons	79, 80
	Nitrogen	635
	Nitrogen and Hydrocarbons	584
	Oxygen	19
	Carbon Dioxide	8, 144, 488, 506
	Carbon Monoxide	659
	Methane	7, 251, 504, 544, 545, 612, 649
	Propene	252, 505
Fugacity, Activity		64
Adsorption, Charcoal		62, 183, 218, 332, 354, 436, 462, 471, 499, 645, 650
	Methane	633, 645

Phenomenon

Major Component

PROPANE
(continued)

Category	Other Components	References
Adsorption, Charcoal (continued)	Propene	357
	n - Butane	645
Adsorption, Silica Gel		354, 515
	Ethane	642
	Ethene	355
	Propene	357
Adsorption, Other Adsorbents		591

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Properties Index

Properties

Major Component

HYDROGEN

Category	Other Components	References
P-V-T General		235, 262, 291, 292, 656, 658, 669
	Nitrogen	34, 419, 608
	Nitrogen and Carbon Dioxide	338
	Carbon Dioxide	338
Compressibility Isotherms		4, 6, 34, 35, 52, 85, 220, 247, 272, 273, 293, 384, 424, 445, 446, 448, 452, 456, 477, 560, 576, 577, 590, 601, 638, 661, 669, 680
	Helium	52, 220, 590
	Nitrogen	34, 35, 60, 209, 338, 340, 359, 380, 418, 638, 661
	Nitrogen and Carbon Dioxide	338, 380
	Nitrogen and Methane	74, 340
	Carbon Dioxide	338, 380, 636
	Carbon Monoxide	560, 587, 601
	Methane	207, 340

Properties

Major Component

HYDROGEN
(continued)

Category	Other Components	References
Compressibility Isotherms (continued)	Methane and Nitrogen	74, 340
Vapor Pressure		27, 105, 111, 122, 190, 211, 235, 239, 270, 427, 428, 561, 656, 669
Critical Constants and Triple Point		27, 61, 211, 242, 260, 262, 271, 306, 349, 476, 477, 478, 627, 655, 656, 669, 670
Density, Molar Volume		30, 160, 387, 401, 456, 532, 552, 562, 669
	Nitrogen	75
Compressibility Factor, Z		212, 669, 675
	Nitrogen	34, 60, 543
Equation of State, General		51, 123, 213, 265, 333, 339, 438, 531, 613, 652, 669
	Nitrogen	339, 380, 466
	Carbon Dioxide	339
	Carbon Monoxide	380
Corresponding States		5, 370

Properties

Major Component

HYDROGEN
(continued)

Category	Other Components	References
Beattie-Bridgeman		43, 44, 156, 381, 585
	Nitrogen	46, 154, 169
	Nitrogen and Carbon Monoxide	169
	Carbon Monoxide	46, 169
Benedict-Webb-Rubin		17
Virial Coefficients		4, 305, 322, 379, 416, 417, 429, 444, 553, 619
	Helium	295
	Nitrogen	177, 295, 473, 515
	Carbon Dioxide	136, 177
	Carbon Monoxide	295, 473, 515
	Methane	177
Lennard-Jones 6-9 Potential		148
	Helium	590
Lennard-Jones 6-12 Potential		148

Properties

Major Component

HELIUM

Category	Other Components	References
P-V-T General		16, 235, 306, 438
	Nitrogen	335
Compressibility Isotherms		6, 85, 92, 98, 115, 272, 273, 308, 311, 384, 387, 453, 454, 474, 477, 478, 660
	Hydrogen	52, 220, 590
	Carbon Dioxide	255
Vapor Pressure		13, 14, 69, 119, 235, 242, 306, 389, 427, 583,617
Critical Constants and Triple Points		61, 262, 306, 389, 476, 477, 478, 623, 627
Density, Molar Volume		11, 77, 175, 234, 249, 264, 298, 548
Compressibility Factor, Z		79, 80, 583
	Carbon Dioxide	254
Equation of State, General		134, 148, 262, 298, 328, 382, 439, 455, 479, 533, 555, 681
Corresponding States		370

Properties

Major Component

HELIUM
(continued)

Category	Other Components	References
Beattie-Bridgeman		44, 381, 585
Virial Coefficients		4, 106, 240, 299, 309, 311, 313, 316, 323, 324, 379
	Hydrogen	295
	Nitrogen	177, 336
	Argon	295
	Carbon Dioxide	135, 177, 255, 474
Lennard-Jones 6-9 Potential		148, 299
	Hydrogen	590
	Argon	590
Lennard-Jones 6-12 Potential		148

Properties

Major Component

NITROGEN

Category	Other Components	References
P-V-T General		53, 235, 287, 349, 530
	Hydrogen	34, 419, 608
	Hydrogen and Carbon Dioxide	338
	Helium	335
	Methane	72
	Ethane	176
Compressibility Isotherms		35, 37, 41, 85, 153, 157, 272, 394, 474, 638
	Hydrogen	34, 35, 60, 209, 338, 340, 359, 380, 418, 638, 661
	Hydrogen and Carbon Dioxide	338, 380
	Hydrogen and Methane	74, 340
	Carbon Dioxide	250, 380
	Carbon Monoxide	597
	Methane	318, 340
	Methane and Hydrogen	74, 340

Properties

Major Component

NITROGEN
(continued)

Category	Other Components	References
Vapor Pressure		24, 79, 84, 142, 163, 210, 219, 235, 242, 260, 261, 265, 276, 287, 307, 310, 427, 451, 484, 491, 520, 583, 657, 672
Critical Constants and Triple Points		104, 261, 306, 348, 349, 457, 476, 478, 484, 657
Density, Molar Volume		75, 84, 160, 387, 532, 566, 667
	Hydrogen	75
Compressibility Factor, Z		34, 79, 80, 125, 265, 370, 421, 438, 477, 484, 528, 583, 667
	Hydrogen	34, 60, 543
	Hydrogen and Carbon Dioxide and Carbon Monoxide and Methane	543
	Methane	73, 587
	Ethane	176
	Ethene	248
	Propane	647

Properties

Major Component

NITROGEN
(continued)

Category	Other Components	References
Equation of State, General		265, 266, 321, 331, 383, 388, 421, 432, 433, 465, 467, 477, 480, 555, 582, 629, 667
	Hydrogen	339, 380, 466
	Methane	199, 318, 339, 628
Corresponding States		370, 443, 630
Beattie-Bridgeman		44, 153, 480, 585, 586
	Hydrogen	46, 169, 154
	Hydrogen and Carbon Monoxide	169
	Carbon Monoxide	169
	Methane	45, 46
Benedict-Webb-Rubin		17, 480, 581
	Hydrogen	17
	Carbon Monoxide	558
Virial Coefficients		106, 304, 305, 379, 443, 474, 581, 654
	Hydrogen	177, 295, 473, 515

Properties

Major Component

NITROGEN
(continued)

Category	Other Components	References
Virial Coefficients (continued)	Helium	177, 336
	Oxygen	295
	Carbon Dioxide	136, 177, 474
	Methane	177
Lennard-Jones 6-9 Potential		349
Lennard-Jones 6-12 Potential		221, 519, 592

Properties

Major Component

CARBON DIOXIDE

Category	Other Components	References
P-V-T General		235, 414, 496
	Hydrogen	338
	Hydrogen and Nitrogen	338
	Ethane	502
	Ethene and Propane	564
	n - Butane	450
Vapor Pressure		82, 117, 188, 235, 409, 410, 434, 458, 484, 593, 676
Critical Constants and Triple Points		102, 423, 484
Compressibility Isotherms		39, 40, 107, 247, 258, 387, 411, 412, 448, 574
	Hydrogen	338, 380, 636
	Hydrogen and Nitrogen	34, 35, 338, 359, 380, 638
	Helium	255
	Nitrogen	250, 338

Properties

Major Component

CARBON DIOXIDE
(continued)

Category	Other Components	References
Compressibility Isotherms (continued)	Nitrogen and Hydrogen	34, 35, 338, 359, 380, 638
Compressibility Factor, Z		438, 484
	Hydrogen and Nitrogen and Carbon Monoxide and Methane	543
	Helium	254
	Methane	500
Equation of State, General		139, 266, 331, 383, 432, 582, 586, 634
	Hydrogen	380
Corresponding States		125
	Ethene	110
Beattie-Bridgeman		83, 281, 381, 585
Virial Coefficients		126, 136, 304, 371, 379, 553, 592
	Hydrogen	136, 177
	Helium	135, 177, 255, 474

Properties

Major Component

CARBON DIOXIDE
(continued)

Category	Other Components	References
Virial Coefficients (continued)	Nitrogen	136, 177, 474
	Oxygen	136, 177
	Carbon Monoxide	136
	Ethene	177
Lennard-Jones 6-12 Potential		221, 519, 592

Properties

Major Component

CARBON MONOXIDE

Category	Other Components	References
P-V-T General		182, 235, 530
Vapor Pressure		120, 143, 235, 241, 265, 389, 390, 422, 672
Critical Constants and Triple Points		104, 143, 244, 389, 390, 478
Compressibility Isotherms		36, 37, 78, 223,224, 258, 394, 476, 560, 574
	Hydrogen	560, 587, 601
	Nitrogen	597
Density, Molar Volume		104, 157, 160
	Methane	103
Compressibility Factor, Z		265, 438, 517, 528
	Hydrogen and Nitrogen and Carbon Dioxide and Methane	543
Equation of State, General		155, 265, 467, 549
	Hydrogen	339

Properties

Major Component

CARBON MONOXIDE
(continued)

Category	Other Components	References
Corresponding States		125, 189, 244, 370
Beattie-Bridgeman		381, 549
	Hydrogen	46, 169
	Hydrogen and Nitrogen	169
	Nitrogen	169
Benedict-Webb-Rubin		549, 558
	Nitrogen	558
Virial Coefficients		391
	Hydrogen	295, 473, 515
	Carbon Dioxide	136
Lennard-Jones 6-12 Potential		221

Properties

Major Component

METHANE

Category	Other Components	References
P-V-T General		72, 87, 100, 165, 225, 232, 319, 342, 468
	Nitrogen	72
	Ethane	280
	Propane	280
	n - Butane	280, 503
Vapor Pressure		26, 70, 79, 81, 121, 130, 178, 241, 259, 303, 317, 319, 344, 360, 484, 510, 573, 579, 583, 594, 602, 672, 679
Critical Constants and Triple Point		42, 101, 103, 104, 141, 178, 225, 244, 317, 319, 425, 476, 477, 478, 481, 523, 524, 602, 623, 631
Compressibility Isotherms		207, 413
	Hydrogen	207, 340
	Hydrogen and Nitrogen	74, 340
	Nitrogen	318, 340
	Ethane	415

Properties

Major Component

METHANE
(continued)

Category	Other Components	References
Density, Molar Volume		121, 263, 387, 393, 431, 532, 541, 554, 578
	Carbon Monoxide	103
Compressibility Factor, Z		15, 79, 80, 89, 438, 477, 484, 583
	Hydrogen and Nitrogen and Carbon Dioxide and Carbon Monoxide	543
	Nitrogen	73, 587
	Carbon Dioxide	500
	Ethane	587
	n - Butane	587
Equation of State, General		258, 331, 383, 432, 464, 467, 477
	Nitrogen	199, 318, 339, 628
Corresponding States		225, 251, 285, 461, 586
Beattie-Bridgeman		43, 44, 381, 519, 585
	Nitrogen	45, 46
Benedict-Webb-Rubin		54, 55, 459, 560, 461, 482, 483, 581

Properties

Major Component

METHANE
(continued)

Category	Other Components	References
Virial Coefficients		304, 485, 556, 587
	Hydrogen	177
	Nitrogen	177
Lennard-Jones 6-12 Potential		221

Properties

Major Component

ETHANE

Category	Other Components	References
P-V-T General		100, 232
	Nitrogen	176
	Carbon Dioxide	502
	Methane	280
	Propene	378, 402, 494
Vapor Pressure		79, 94, 95, 117, 130, 151, 178, 360, 364, 490, 583, 593, 594, 679
Critical Constants and Triple Point		42, 50, 102, 524
Compressibility Isotherms		38, 47, 49, 146, 501
	Methane	415
	Propene	378, 493, 494
Density, Molar Volume		263, 578
Compressibility Factor, Z		79, 80, 333
	Nitrogen	176
	Methane	587

Properties

Major Component

ETHANE
(continued)

Category	Other Components	References
Equation of State, General		47, 139, 162, 258, 331, 383, 549, 629
Corresponding States		18, 110, 125, 284, 461, 586
Beattie-Bridgeman		381, 549, 585
Benedict-Webb-Rubin		54, 55, 459, 460, 461, 482, 549
Virial Coefficients		521

Properties

Major Component

PROPANE

Category	Other Components	References
P-V-T General		232
	Carbon Dioxide and Ethane	564
	Methane	280
	Propene	505
Vapor Pressure		79, 93, 95, 151, 178, 191, 360, 593, 594, 679
Critical Constants and Triple Point		138, 178, 343, 369, 523, 524
Compressibility Isotherms	Propene	358
Density, Molar Volume		263, 385, 578
Compressibility Factor, Z		79, 80, 191
	Nitrogen	647
Equation of State, General		258, 331, 383
Corresponding States		18, 125, 284, 461

Properties

Major Component

PROPANE
(continued)

Category	Other Components	References
Beattie-Bridgeman		48, 381, 585
Benedict-Webb-Rubin		54, 55, 459, 461, 482

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U.S. DEPARTMENT OF COMMERCE
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NATIONAL BUREAU OF STANDARDS
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THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer. Concreting Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

NBS