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DOE/MC/19239-1546
(DE84003080)

HANDBOOK OF GAS HYDRATE PROPERTIES AND OCCURRENCE

December 1983

Work Performed Under Contract No.: DE-AC21-82MC19239

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Lewin and Associates, Inc.
and Consultants
Washington, D.C.

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Office of Fossil Energy
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ABSTRACT

This handbook provides data on the resource potential of naturally occurring hydrates, the properties that are needed to evaluate their recovery, and their production potential.

The first two chapters give data on the naturally occurring hydrate potential by reviewing published resource estimates and the known and inferred occurrences.

The third and fourth chapters review the physical and thermodynamic properties of hydrates, respectively. The thermodynamic properties of hydrates that are discussed include dissociation energies and a simplified method to calculate them; phase diagrams for simple and multi-component gases; the thermal conductivity; and the kinetics of hydrate dissociation.

The final chapter evaluates the net energy balance of recovering hydrates and shows that a substantial positive energy balance can theoretically be achieved.

The Appendices of the Handbook summarize physical and thermodynamic properties of gases, liquids and solids that can be used in designing and evaluating recovery processes of hydrates.

ACKNOWLEDGEMENT

In our effort to make the document as relevant as possible to future users, we have asked several people currently performing R&D on gas hydrates to review the draft document and to augment where possible. We wish to thank the following people for their interest, time, effort, and suggestions:

- Dr. Gerald D. Holder, University of Pittsburgh
- Dr. E. Dendy Sloan, Colorado School of Mines
- Dr. Keith Kvenvolden, U.S. Geological Survey
- Mr. Tim Collett, University of Alaska
- Mr. Walt Sawyer, Mathematical and Computer Services, Inc.
- Dr. Kenneth Bird, U.S. Geological Survey
- Dr. James Brooks, Texas A&M University
- Dr. George Claypool, U.S. Geological Survey
- Dr. Sanjay Godbole, University of Alaska

PREFACE

This document is a compilation and integration of all available scientific data relevant to gas hydrates. These data are categorized within chapters on the potential of the hydrate resource, regions of confirmed and implied hydrate occurrences, hydrate physical properties, hydrate thermal properties, and energy balance equations. An appendix having numerous relative gas tables is also included. This document is intended to be an essential reference on basic scientific data, in a concise form for researchers on the subject. As new information becomes available, revisions are anticipated in order to maintain its usefulness as a basic scientific reference of gas hydrates.

Project Manager
Gas Hydrates

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HANDBOOK OF GAS HYDRATE PROPERTIES AND OCCURRENCE

FOREWORD

The purpose of this Handbook is to present information on hydrate properties that are needed to evaluate the recovery of the natural gas hydrate deposits and the production potential of gas hydrates.

The Handbook consists of five Chapters and six Appendices as follows:

Chapter 1. The Potential Natural Gas Hydrate Occurrence - summarizes data on the potential extent of the hydrate resource.

Chapter 2. Identified and Inferred Hydrate Occurrences - discusses reservoir data on onshore and offshore hydrate deposits obtained through coring, well logs and seismic interpretation.

Chapter 3. The Physical Properties of Gas Hydrates - discusses the structures and physical characteristics of hydrates.

Chapter 4. Thermodynamic Properties of Gas Hydrates - reviews theoretical models and experimental results for evaluating energy recoverability of gas hydrates.

Chapter 5. Hydrate Energy Balance - presents a theoretical examination of hydrate properties and relationships affecting dissociation in gas hydrates.

Appendix A. Hydrate Gas Summary Tables

Appendix B. Physical Properties of Gases, Liquids and Solids

Appendix C. Thermodynamic Properties of Gas, Liquids and Solids

Appendix D. Industrial Applications of Hydrates

Appendix E. Steam Tables

Appendix F. Units and Conversion Tables

CHAPTER 1

THE POTENTIAL NATURAL GAS HYDRATE RESOURCE

This chapter provides the foundation for estimating the potential of hydrates as a future natural gas resource. Gas hydrates are shown to be a potentially large source of unconventional natural gas, based on the worldwide extent of sediments where the pressure-temperature conditions are such that hydrates can form. In addition to the large areal extent where hydrates could occur, an important characteristic of gas hydrates is that a unit volume can contain 180 times as much gas as an equal volume containing gas at standard conditions.

Hydrate reservoirs have been identified or inferred worldwide both onshore and offshore, as summarized in the first section "Natural Gas Hydrate Deposits." In addition, hydrates can occur together with oil or gas, thereby increasing the attractiveness of the hydrate resource.

As discussed in the section, "Historical Hydrate R&D Development," gas hydrates were discovered in 1810 in the laboratory, but it took nearly 150 years to establish that hydrates could and do occur naturally. Potentially they can occur under a large portion of the earth's surface, under conditions of moderate to high pressures and low temperature in sediments beneath permafrost or beneath deep water offshore.

Onshore, hydrates have been identified in Alaska, Canada and the USSR, as discussed in the section entitled "Natural Occurrence of Hydrate-Favoring Areas." Offshore, known or suspected occurrences of hydrates have been identified in continental margin sediments in all the major oceans.

Gas hydrate resource estimates vary widely because of incomplete resource data and the different methodologies used in assessing the resource, as discussed in the sections "Determination of Hydrate Interval" and "Resource Estimates." Estimates of the hydrate resource range from 500 trillion cubic feet (Tcf) to 3×10^8 Tcf worldwide. The high estimate is five orders of magnitude larger than the U.S. Geological Survey's estimate of the world's natural gas reserves.

A. NATURAL GAS HYDRATE DEPOSITS

Gas hydrates are physical combinations of gas and water where the gas molecules fit into a crystalline structure similar to that of ice. Therefore, the amount of gas stored in a given volume of hydrate is much higher than when the gas occurs in gaseous form. For example, a fully saturated hydrate contains 180 standard cubic feet (scf) of gas per cubic foot of hydrate, as shown on Figure 1-1.

Naturally occurring hydrates of natural gas were discovered, starting in the 1960's, in permafrost areas and in offshore sediments under deep water. Currently known or suspected occurrences of hydrates have been identified onshore in the USSR, the United States and Canada and offshore in 24 locations, primarily along the Atlantic and Pacific Continental Shelf off North and Central America and in the Black Sea. The presence of gas hydrate has been inferred offshore Japan, Australia, Angola, Oman, and New Zealand.

Hydrate reservoirs may contain large amounts of natural gas as hydrates, but they may also be important trapping mechanisms for gas and oil reservoirs because of the low permeability of hydrate-filled sediments, i.e., when the hydrates block pore throats in hydrocarbon (oil or gas) reservoirs or form an impermeable barrier that traps gas accumulations underneath it. The different types of hydrate deposition are shown schematically on Figure 1-2. There are several instances where hydrates have been found together with oil or gas.

- At the Messioakh gas field in the USSR, hydrates occur in strata above natural gas. It is estimated that 1/3 of the reservoir is occupied by hydrates (Makogon, 1981).
- Recently, cores recovered in the Gulf of Mexico offshore Texas showed hydrates in the presence of oil.
- Offshore, a seismic phenomenon called a bottom stimulating reflector that parallels the ocean bottom has been identified in many large areas and is thought to indicate hydrate deposits. The reflector is thought to occur when free gas is trapped under an impermeable hydrate seal.

Figure 1-1

1 CUBIC FOOT OF 90% SATURATED HYDRATE CAN CONTAIN
180 STANDARD CUBIC FEET OF METHANE

SOURCE: Lewin and Associates, Inc.

Figure 1-2

DIFFERENT TYPES OF HYDRATE DEPOSITS

SOURCE: Lewin and Associates, Inc.

B. HISTORICAL HYDRATE R&D DEVELOPMENTS

Knowledge of and interest in gas hydrates have gone through four stages. A chronology of the historical developments of hydrate R&D is presented in Table 1-1. This table shows the increase in interest that occurred in the early 1960s when naturally occurring hydrates were discovered.

The first stage of hydrate research and development began in 1810 when Sir Humphrey Davy bubbled chlorine gas through water under atmospheric conditions at temperatures near the freezing point of water. This resulted in a yellow precipitate which Davy called chlorine hydrate and which Faraday subsequently analyzed in 1823. The next significant scientific studies of gas hydrates were made in the 1890s when various French scientists found that many other gases formed hydrates. However, the true nature of these compounds remained unknown until the 1950s, although substantial data on the conditions for hydrate formation were obtained from experimental studies.

The second stage began in the 1930s when the petroleum industry became interested in hydrates. Hammerschmidt showed that hydrates, rather than ice, often plugged natural gas pipelines, that hydrates could form at temperatures well above the freezing point of water, and that additives (e.g., methanol) could inhibit the formation of hydrates. Many of the properties of hydrates were determined by the U.S. Bureau of Mines and reported in the 1946 Monograph 8 by Deaton and Frost.

The third stage started in the 1950s with the X-ray diffraction determination of the crystalline structure of hydrates by Stackelberg and co-workers. This allowed development of a theoretical model for hydrates by van der Waals and Platteeuw.

The fourth stage of hydrate research began in the mid-1960s when natural gas hydrates were discovered. This was followed by theoretical studies and indications of hydrates from well drillings in Alaska, Canada, Siberia, and offshore areas that showed hydrates could be a large, naturally-occurring gas resource in and under permafrost areas and beneath ocean basins.

TABLE 1-1

CHRONOLOGY OF MAJOR EVENTS IN HYDRATE R&D

1810:	Davy discovers and names (1811) chlorine hydrate.
1823:	Faraday analyzes chlorine hydrates.
1880's-1890's:	French scientists study hydrates.
1934:	Hammerschmidt finds hydrates plugging natural gas pipelines.
1941:	Wilcox, Carson, and Katz present K-value charts.
1946:	Deaton and Frost (IISRM) do hydrate study.
1950's:	Stackelberg, Muller, Claussen, Pauling, and Marsch determine hydrate structures.
1959:	van der Waals and Platteeuw develop statistical mechanics model and publish results in 1959.
1960:	Kobayashi and co-workers show gas hydrates can exist at conditions as high as 116.4°F at 57,580 psia using non-visual methods.
1960's:	Kobayashi and co-workers determine parameters in a statistical mechanics model.
1960's:	Robinson and co-workers study hydrates.
1964:	USSR discovers gas hydrate fields.
1970:	Katz predicts the existence of hydrate deposits and intervals.
1971:	Stoll, Ewing, and Bryan find hydrates in ocean sediments.
1972:	Parrish and Prausnitz use statistical mechanics to describe equilibria in hydrate forming mixtures.
1972-1975:	Katz, Hand, and co-workers form hydrates from organic compounds.
1974:	Hydrates found in McKenzie Delta described by Bily and Dick.
1976:	Katz, Hand, and Holder study H_I - H_{II} equilibria and liquid denuding.
1976:	Sloan, Parrish, and co-workers determine Δu and Δh for statistical mechanics model.
1979:	Workshop conducted on gas hydrates in the National Petroleum Reserve of Alaska*.
1979:	Samples of gas hydrate recovered in sediment offshore Mexico and Guatemala.
1980:	Kobayashi and co-workers study hydrate systems formation.
1980:	Sloan and co-workers and Holder and co-workers study hydrate systems formation.
1980:	Franklin (Panarctic) studies in-situ hydrates in U.S. and Canadian Arctic areas.
1981:	Hydrate Program created at Morgantown Energy Technology Center (METC) to study gas hydrates and their recovery.
1982:	Core of massive gas hydrate recovered off the Guatemalan Coast.
1982:	Methane Hydrates Workshop conducted at Morgantown Energy Technology Center, March 29 and 30.
1983:	Holder and co-workers created fully saturated methane hydrate cores.
1983:	Gas hydrate associated with petroleum recovered in Gulf of Mexico.

* Bowsher, A., 1981, "Proceedings of a Workshop on Clathrates (Gas Hydrates) in the National Petroleum Reserve in Alaska," July 16-17, 1979, Menlo Park, California, U.S. Geological Survey Open-file Report 81-1298.

C. NATURAL OCCURRENCE OF HYDRATE-FAVORING AREAS

Natural gas can combine with water to form solid hydrates in areas of low temperatures and moderate to high pressures. Geographically, these conditions occur onshore in sediments in and beneath thick permafrost and offshore beneath water deeper than 1,500 feet. In addition to favorable temperature and pressure regimes, the formation of hydrates requires a source of hydrocarbons.

1. Onshore Hydrate-Favoring Areas

Terrestrial zones of hydrate stability occur in and under permafrost regions. Permafrost, or perennially frozen ground, is naturally occurring material that has been colder than 32°F (0°C) continuously for two or more years. Since this definition relies exclusively on temperature, part or all of the moisture may be unfrozen, depending upon the chemical composition of the water or depression of the freezing point by capillary forces.

Permafrost covers more than 23 percent of the earth's land area and is chiefly restricted to Alaska (75 percent of total area), Canada (63 percent), the USSR (47 percent), the polar regions of Scandinavia, Greenland, and Antarctica. Figure 1-3 is a map showing the extent of permafrost in the Northern Hemisphere. Figure 1-4 is a map showing areas in North America where gas hydrates may potentially occur and where they have been detected.

2. Offshore Hydrate-Favoring Areas

Hydrates of natural gas may occur naturally in sediments beneath the world's oceans where a water depth of approximately 1,500 feet or more exists. Thus, offshore the areal extent of potential hydrate occurrence is $3 \times 10^8 \text{ km}^2$ (or 115 million square miles) -- more than 90 percent of the ocean basins.

The nature and extent of a zone of hydrate stability in the marine environment are different than for onshore occurrences. Ocean surface temperatures generally average slightly above those of the ambient air,

Figure 1-3

MAP SHOWING EXTENT OF PERMAFROST

Base: Lambert's Azimuthal Equal-Area Projection from Goode's Series of Base Maps, No. 201P, Univ. of Chicago Press.

0 500 1000 1500 2000 2500 MILES
0 1000 2000 3000 KILOMETERS

EXTENT OF PERMAFROST

- Zone of continuous permafrost
- Zone of discontinuous permafrost
- Zone of sporadic permafrost

SOURCE: IGT, 1980.

Figure 1-4

UNCONVENTIONAL NATURAL GAS
GAS HYDRATE RESOURCES OF NORTH AMERICA

LEGEND

- Gas Hydrates Potential Onshore
- Gas Hydrates Potential Offshore
- Areas Where Hydrates Have Been Detected

SOURCE: Malone, 1982.

whereas bottom water temperatures in the open ocean generally range from 30° to 35°F. This decrease in temperature with depth is the opposite of what occurs on land and tends to greatly increase the vertical extent of a potential zone of hydrate stability. Once the water/sediment interface is crossed, however, normal geothermal gradients are encountered and the temperature generally increases with depth as it would onshore.

D. DERIVATION OF HYDRATE INTERVALS STABILITY ZONES

The theoretical maximum thickness of natural hydrate occurrences can be derived from pressure and temperature gradients and a knowledge of the pressure-temperature combinations where hydrates are stable. This methodology can be used to derive maximum hydrate intervals for onshore areas and for the offshore basins. Recently, it has been found that the presence of very fine granular material may depress the hydrate formation temperature slightly (early results show less than 1°F), thus reducing the zone of hydrate stability (Rueff, 1983).

The volumes of sediments where hydrates can occur is very large because the intervals with hydrate-favoring conditions in permafrost areas and in ocean basins are very thick. This analysis thus illustrates the potentially large hydrate resource, although it must be stressed that for hydrates to occur in a zone where the temperature and pressure are such that hydrates are stable, both gas and water had to have been present at some point in geologic history.

1. Methodology of Determining Hydrate Stability Intervals

The intervals of potential hydrate formation can be estimated by superimposing the:

- Temperature Gradient - The average subsurface temperature gradient depends on the geographical location, but is often assumed to be 1°F per 100 feet in permafrost and 1.5°F per 100 feet under permafrost and offshore. Actual data should be used when available, as gradients can vary considerably. Thus, thermal gradients of northern Canada range between -0.5° and 5.0°C per 330 ft.

- Pressure Gradient - Fluid pressures in the earth normally correspond to a hydraulic gradient from the surface or outcrop. This is 43.5 psi for fresh water and about 45 psi for salt water per 100 feet of head. Using these hydraulic gradients, the pressure in the earth can be calculated as a function of depth.
- Phase Diagram for Hydrates - The combination of pressure and temperature where hydrates can form are delineated in the phase diagram. These diagrams are presented and discussed in Chapter 4, "Thermodynamic Properties of Hydrates."

This methodology will give the maximum depth range where hydrates can theoretically exist (Katz, 1971). The methodology is illustrated in the following examples for both onshore and offshore reservoirs.

2. Example Calculations

The example below shows how the permafrost and hydrate intervals are estimated for the Mackenzie Delta of Canada (Bily and Dick, 1974).

- The average surface temperature is 12°F (-11°C). The average thermal gradient is 1.0°F per 100 feet in the permafrost, increasing to 1.5°F per 100 feet below the permafrost.
- The pressure gradient is 0.435 psi per foot (0.84 kPa/m) of depth, assuming fresh water.
- The stability zone for hydrates can be determined by superimposing the phase diagram on a pressure-temperature graph, Figure 1-5.

The methane hydrate stability zone, shown in Figure 1-5, ranges from 300 to 3,500 feet. Within this interval, methane hydrate will occur in permafrost down to 2,000 feet.

Calculated zones of hydrate stability for 0.6 gravity natural gas are shown on Table 1-2 for permafrost areas in Alaska, Canada, and the USSR.

Offshore, hydrate intervals can be estimated using the same methodology as for the onshore. The difference is that the hydrate interval starts close to the sea bottom, often in unconsolidated sediments, instead of at depths of 500 feet or more.

Figure 1-5

DETERMINATION OF GAS-HYDRATE ZONE, MACKENZIE DELTA, CANADA

SOURCE: Bily and Dick, 1974.

TABLE 1-2

CALCULATED ZONE OF HYDRATE STABILITY (ZHS)FOR NATURAL GAS

	<u>Depth To Bottom Of Permafrost</u>		<u>Top Of ZHS</u>		<u>Bottom Of ZHS</u>		<u>Stratigraphic Thickness of ZHS</u>	
	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
Alaska								
Cape Simpson	950	(290)	950	(290)	2,070	(630)	1,120	(340)
Cape Thompson	1,180	(360)	1,180	(360)	4,660	(1,420)	3,480	(1,060)
Point Barrow	1,310	(400)	1,310	(400)	3,350	(1,020)	2,030	(620)
Prudhoe Bay	2,000	(610)	690	(210)	4,000	(1,220)	2,000	(610)
Canada								
Resolute, N.W.T.	1,210	(370)	1,210	(370)	2,490	(760)	1,280	(390)
Mackenzie Delta	1,770	(610)	620	(190)	6,100	(1,860)	5,980	(1,670)
Sverdrup Basin	--	(--)	460	(140)	4,170	(1,270)	3,710	(1,130)
W. Arctic Islands	--	(--)	460	(140)	3,610	(1,100)	3,150	(960)
E. Arctic Islands	--	(--)	590	(180)	3,150	(960)	2,560	(780)
USSR								
Messoiakh	1,480	(450)	820	(250)	2,850	(870)	2,030	(620)
Viliui	1,500	(500)	1,080	(330)	3,870	(1,180)	2,790	(850)
Markhin	4,720	(1,440)	330	(100)	7,220	(2,200)	6,890	(2,100)
Namanin	280	(85)	660	(200)	5,410	(1,650)	4,760	(1,450)
Olekmin	330	(100)	490	(150)	6,560	(2,000)	6,070	(1,850)
Ilychir	330	(100)	330	(100)	1,640	(500)	1,310	(400)
Sredne-Botuobin	2,030	(620)	330	(100)	6,560	(2,000)	6,230	(1,900)

Source: after Barracough, 1980.

Figure 1-6 shows estimated hydrate-favoring zones in sediments of Outer Continental Shelf margins. The assumptions are: a 1.5°F temperature gradient per 100 feet from the mud line downward, and a subsurface pressure increase of 45 psi per 100 feet (saline water).

3. Discussion of Examples

The examples can be used to illustrate some important considerations for evaluating the recoverability of hydrates.

When natural gas contains gases heavier than methane, such as ethane, the zone of hydrate stability increases, so hydrates can form at greater depths, Figures 1-5 and 1-6. In the onshore example, the zone of hydrate stability increases from 3,500 feet to 4,500 feet. These curves are not unique for a given gravity gas, since the zone of hydrate stability depends on the gas composition.

The zone of hydrate stability is dependent on surface temperature as well as gas composition. The example for the Mackenzie Delta shows that for an average surface temperature of -11°C , methane hydrates are stable. However, at average surface temperatures higher than -2°C , methane hydrates could not occur, although other natural gas hydrates could be stable, Figure 1-5.

The onshore example illustrates that hydrates may occur both in and below permafrost. Therefore, had gas initially occurred in the sediments that are now in the permafrost layer, it could have been converted to hydrate in the cooling process and still occur as such within the permafrost.

Establishing the depth of the permafrost is important when assessing the recoverability of hydrates. If the reservoir is to be produced through depressurization, the dissociation products in the permafrost region will be gas and ice, which may not have sufficient permeability for gas to flow to a wellbore. At sufficient depths below the permafrost interval, the dissociation products may be gas and water which are mobile and can be produced.*

*Depressurization causes cooling of the reservoir and consequently zones directly below the permafrost will freeze when the hydrates decompose.

Figure 1-6
HYDRATE-FORMING ZONES UNDER THE OCEAN BOTTOM

SOURCE: Scott, M.I., et al. IGT, 1980.

E. RESOURCE ESTIMATES

Because such large areas of sedimentary basins are underlain by permafrost or are covered by water, the volumes of gas locked in hydrates may be enormous. The largest estimates (by Dobrynin) have indicated that up to 3×10^8 trillion cubic feet (Tcf) of natural gas may exist in hydrate form (Milton, 1976). This quantity is six times greater than the total amount of methane previously estimated to exist in the combined lithosphere and hydrosphere, and it is five orders of magnitude greater than the U.S. Geological Survey's estimate of the world's proven reserves of natural gas.

Gas hydrate resource estimates, both onshore and offshore, are shown on Table 1-3 for the world and the U.S., respectively. Because of the little resource data available, the estimates vary widely.

TABLE 1-3
GAS HYDRATES - RESOURCE ESTIMATES, Tcf

<u>Reference</u>	<u>Onshore</u>		<u>Offshore</u>	
	<u>World</u>	<u>United States</u>	<u>World</u>	<u>United States</u>
Dobrynin, 1979	1.2×10^6	25,000	2.7×10^8	6.7×10^6
McIver, 1979	1,100	23	1.1×10^5	2,700
Meyer, 1979	500	11		
Trofimuk, 1980	2,010	42	$2-9 \times 10^5$	4-21,000

Source: McIver, Methane Hydrates Workshop, 1982.

Dobrynin's estimate of about 3×10^8 Tcf of methane in hydrate form assumes that fully saturated hydrates exist wherever sediments are in a temperature and pressure domain appropriate to hydrate formation. Ocean bottom temperature and geothermal gradients are then used to estimate the total volume of sediments having the combination of pressure and temperature required for hydrate formation. These estimates assume typical sediment porosity for that volume and further assume that the corresponding pore volume is completely filled with hydrates having the maximum ratio of 8 methane molecules in the cages formed by 46 water molecules (Scott, 1980).

McIver's estimate assumes conservatively, but arbitrarily, that the organic carbon content of young, unconsolidated sediment is 0.5 percent and that only 1% or 22 Bcf per cubic mile of sediment is converted to methane. This methane content of sediments is then applied to hydrate-forming sediments, and a worldwide resource estimate of 1.1×10^5 Tcf of methane is calculated. If only one percent of this were accumulated in reservoir-type rocks onshore, the hydrate resource onshore would be 1,100 Tcf.

Meyer's estimate of 500 Tcf onshore is based on a literature review of identified occurrences and a subjective interpretation of this data.

Trofimuk's estimate is based on an analysis of hydrate-favoring zones by temperature zones (polar, temperate, subtropical, and tropical). This analysis suggests that there are sufficient organic accumulations to generate methane and create fully-saturated hydrates in hydrate-favoring zones. The analysis also shows that hydrates can form under more than 90 percent of the world ocean area to an average thickness of 1,000 feet.

* * * * *

The remaining Chapters and Appendices of this Handbook provide data on hydrate properties that are needed to evaluate the recoverability and production potential of the resource and information on known or inferred hydrate deposits.

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CHAPTER 2

IDENTIFIED AND INFERRED OCCURRENCES OF GAS HYDRATES

An accurate assessment of the recoverability of natural gas hydrates requires considerable knowledge of the reservoir and hydrate properties. However, very little information is currently available on these items because hydrates are located in hard-to-access places and interest in them as a resource is recent. Thus, until the necessary reservoir data are obtained, estimates of reservoir characteristics must be based on extrapolations from the geology of the limited number of hydrate occurrences that have been identified or inferred to exist.

This chapter assembles data on known and inferred occurrences of natural gas hydrates, the reservoir properties and lithology of the recovered well cores, and the geology of the formations where the hydrates occur. Documented hydrate deposits have been identified through coring, well logs and seismic interpretation.

The discussion of hydrate occurrences is organized by onshore and offshore areas:

- Onshore Areas. Gas hydrates have been identified on the North Slope of Alaska, the Mackenzie Delta of Canada and in the Messoiaikh gas field in the USSR.
- Offshore Areas. The Deep Sea Drilling Project has recovered hydrate cores from the Atlantic offshore the U.S. East Coast, and the Pacific offshore Guatemala. Hydrates have also been identified in the Gulf of Mexico offshore Texas, and in the Black Sea.

The recoveries of gas hydrate in pressure cores demonstrate that hydrates occur in nature. However, additional information is required to delineate the extent of the individual deposits and the amount of gas hydrate contained in them. Thus, current resource estimates of methane hydrates need to be tempered with proper qualifications and have broad boundaries or limits of uncertainty.

The geographical location of known and inferred occurrences of gas hydrates are shown on Figure 2-1 and summarized on Tables 2-1 (onshore) and 2-2 (offshore) (Kvenvolden, 1980).

A. ONSHORE OCCURRENCES OF HYDRATES

The natural presence of gas hydrates in permafrost regions has been established in the Arctic areas of Alaska, Canada, and the USSR.

1. Alaska

The first confirmation that gas hydrates occur naturally in sediments under permafrost was obtained in 1972 from the North Slope of Alaska. The Arco-Exxon N.W. Eileen State No. 2 wildcat well in the West Prudhoe Bay field encountered hydrates at a depth of 666 feet. The presence of hydrates at this site was established by well logs, and cores recovered with a pressurized core barrel. Strong mud-gas shows suggested free gas in the formation, but high resistivities and high velocities on the sonic log indicated ice or icelike materials. The density log also responded as if there was ice rather than gas in the formation.

Recently, logs from 125 wells on the North Slope of Alaska were examined for potential hydrate occurrences (Collett, 1983). This analysis identified 102 possible hydrate occurrences at 32 sites. In addition, the analysis indicated that the bulk of hydrate occurrences appears to be geographically restricted to the Kuparuk River Field to the west of Prudhoe Bay, as shown in Figure 2-2. This area contains four laterally continuous hydrate-saturated units and two less extensive units. The lateral extent of each hydrate-saturated unit is shown in the block diagram of Figure 2-3. The individual hydrate accumulations and inferred environments of deposition of the associated sedimentary rocks are shown on the east-to-west cross section through the Kuparuk River oil field of Figure 2-4.

In this particular area, the gas hydrates are found exclusively in M, N, O, P, Q, and R (refer to Figure 2-3) of the Saganavirktok Formation, of Tertiary and late Cretaceous age. The formation is a poorly consolidated,

Figure 2-1
KNOWN AND INFERRED LOCATIONS OF GAS HYDRATES

SOURCE: Kvenvolden, et al., 1982.

TABLE 2-1

EVIDENCE OF GAS HYDRATES BENEATH THE PERMAFROST

<u>Number on Figure</u>	<u>Location</u>	<u>Permafrost Thickness (ft)</u>	<u>Predicted Depth Range of Hydrate (ft)</u>	<u>Geophysical Evidence</u>	<u>Geochemical Evidence</u>	<u>Research Organization</u>
A	Messoyakha gas field and northwestern Siberia, U.S.S.R.	1,480	820-2,850		90% or more methane in gas analysis; large volume of gas from thawed cores	U.S.S.R.
B	Mackenzie Delta, Northwest Territories, Canada	2,000	2,690-3,610	Well logs; small deflection in SP; high resistivity; high velocity sonic log; over-gage caliper log.	90% or more methane in gas analysis; large volume of gas from thawed cores	Imperial Oil, Ltd.
C	West Prudhoe Bay, Alaska, U.S.A.	2,000	690-3,610	Well logs; high resistivities; high velocity sonic log; gas kicks in mud logs; neutron porosity very useful in recent work.	3 sets of gas data analyzed, indicating 90% or more methane.	Exxon
D	Arctic Archipelago, Northwest Territories, Canada	1,740	No data in print		No data in print	Dome Petroleum, Ltd.
E	Vilyoy Basin, Yakutia, U.S.S.R.	1,640	No data in print		No data in print	U.S.S.R.

TABLE 2-2
GAS HYDRATES IN OCEANIC SEDIMENTS

Designation On Figure 2-1	Location	Depth of Water f = feet s = seconds (2-Way)	Subbottom Depth of Inferred Base of Gas Hydrates f = feet s = seconds (2-Way)
1	Blake Bahamas Outer Ridge, Western Atlantic Ocean off Southwestern U.S.A.	6,200-13,000 f	1,500-2,000 f
2	Continental Rise, Western Atlantic Ocean off New Jersey and Delaware	6,200-12,500 f	1,500-2,000 f
3	Labrador Shelf, Northwestern Atlantic Ocean off Newfoundland	6,600 f	Not Given
4	Beaufort Sea, Arctic Ocean off Alaska	1,300-6,200 f	300-2,600 f
5	Continental Slope, Bering Sea near Navarin Basin	1,600-10,000 f	600-1,600 f
6	Norton Sound, Bering Sea off Alaska	Not Given	Not Given
7	North Pacific Ocean, South of Aleutian Islands	14,800 f	0.5-0.7s
8	North Pacific Ocean, South of Aleutian Islands	Not Available	Not Available
9	Pacific Ocean off Northern California	2,600-3,900 f	0.3s
10	Pacific Ocean off Mexico	2.5-5.0 s	0.5-0.7 s
11	Pacific Ocean off Guatemala	Not Given	Not Given
12	Pacific Ocean off Guatemala	6,600-18,000 f	Not Observed
13	Pacific Ocean off Nicaragua	2,600-8,000 f	0.4-0.5 s
14	Pacific Ocean off Costa Rica	1.0-1.8 s	0.2-0.5 s

TABLE 2-2 (Cont'd)
GAS HYDRATES IN OCEANIC SEDIMENTS

Designation On Figure 2-1	Location	Depth of Water f = feet s = seconds (2-Way)	Subbottom Depth of Inferred Base of Gas Hydrates f = feet s = seconds (2-Way)
15	Pacific Ocean off Southern Panama	2.5-2.8 s	0.4-0.5 s
16	Caribbean Sea off Panama and Columbia	3,900-7,200 f	Not Given
17	Western Gulf of Mexico off Mexico	3,900-6,600 f	Not Given
18	Western Gulf of Mexico, Location Unspecified	2.7-3.1 s	0.5 s
19	Western Pacific, Nankai Trough off Japan	Not Available	Not Available
20	Timor Trough off Northern Australia	5,600 f	Not Given
21	Eastern Atlantic Ocean off Angola	Not Available	Not Available
22	Northwest Indian Ocean, Gulf of Oman	10,000 f	2,000-2,200 f
23	Black Sea, U.S.S.R.	6,600 f	Not Given
24	Offshore New Zealand	3,200 f	0.4-0.8 s

Figure 2-2

GEOGRAPHIC DISTRIBUTION OF HYDRATE OCCURRENCES

SOURCE: Collett, 1983.

Figure 2-3

BLOCK DIAGRAM SHOWING HYDRATE OCCURRENCE IN THE KUPARUK OIL FIELD,
AND LATERAL EXTENT OF HYDRATE SATURATION IN UNITS, M, N, O, P, Q AND R

SOURCE: Collett, 1983.

Figure 2-4

EAST TO WEST CROSS SECTION THROUGH THE KUPARUK OIL FIELD, SHOWING HYDRATE OCCURRENCES AND DEGREE OF SATURATION.

SOURCE: Collett, 1983.

massive deposit of interbedded shale, sandstone, conglomerate, mudstone and siltstone. Deposition took place in a low relief, semi-submerged deltaic system consisting of three large-scale coarsening-upward sequences. This suggests a series of three deltaic systems, each sequence prograding laterally to the northeast. Due to the interbedded nature of porous and non-porous sediments, the hydrates appear to occur in multiple, discrete units.

The presence of structural-stratigraphic control on the occurrence of hydrate is apparent upon close examination of the hydrate zones. The hydrate occurrences are below the base of a non-porous prodelta shale, with only a few exceptions. Further, within the 300-meter thick sediment interval there are several impermeable shale beds which serve as caps for the porous underlying hydrate-saturated sand units.

2. Canada

Naturally occurring hydrates were encountered at two exploratory wells drilled in 1972 by Imperial in the Mackenzie Delta, Figure 2-5 (Bily and Dick, 1974). The unconsolidated sands of Tertiary age were characterized by high porosity, but very low permeability due to the presence of gas hydrates.

Based on wireline logs, it is estimated that one of the wells, Mallik L-38, has 325 feet and the other well, Ivik J-26, has about 80 feet of hydrate-bearing sand. The identified hydrate zones are below the permafrost, but within the estimated zone of hydrate stability which extends about 1,500 feet below the bottom of the permafrost, Figure 2-6.

The main characteristics of the hydrate zones at Mallik L-38 are illustrated in Figure 2-7. The hydrate-bearing sands occur from 2,690 feet to 3,630 feet, and are interspersed with layers of mudstone and a few very thin coal beds. The sands are fine-grained to conglomeratic, unconsolidated and very porous. On the basis of log response, three of the sands are interpreted to contain free gas overlying water. The presence of free gas on water within the hydrate regime is anomalous, and may be due to recent hydrate decomposition caused by migration of slightly warmer water. The hydrate-bearing sands have a relatively high resistivity, as indicated on Figure 2-7.

Figure 2-5

SOURCE: Bily and Dick, 1974.

Figure 2-6

Mallik - Iviik hydrate zones.

SOURCE: Bily and Dick, 1974.

Figure 2-7

Figure 2-8

SOURCE: Bily and Dick, 1974.

The most pronounced characteristic of the hydrate-bearing zones of the two wells in the Mackenzie Delta was the significant amount of gas liberated as they were penetrated. A sharp increase in total mud gas at 2,700 feet was recorded and the total mud gas readings strongly indicate that hydrate zones were penetrated. The next interval tested, at 3,030 to 3,040 feet, was believed to be a hydrate-filled sand with porosity as good as the previously tested gas-bearing sand. The pressure of hydrate is inferred from tests that indicate the reservoir permeability to be very low.

The characteristics of the hydrate-bearing zones at Ivik J-26, shown in Figure 2-8, are similar to those at Mallik L-38. The sands are fine-grained, to conglomeratic, unconsolidated, and very porous.

Formation tests were performed in the lowest portion of the hydrate-bearing intervals at Ivik J-26. The hydrate zone was perforated from 3,338 to 3,348 feet, immediately above the hydrate-water interface. Pressure build-up tests indicated a very poor permeability of the hydrate-filled sand. In an attempt to stimulate the hydrate zone, 1,000 gallons (4.5 m³) of methanol were circulated into the hole and squeezed into the perforated hydrate zone. Following this treatment the zone was retested; however no improvement in productivity was obtained.

Analyses of the gas recovered from the Mallik and Ivik wells are shown in Table 2-3. These analyses show that methane is the main component (over 99%) of the gas with traces of ethane, nitrogen, and other gases. This composition would be expected from decomposed hydrates.

TABLE 2-3
GAS ANALYSES - MALLIK AND IVIK WELLS

Interval Tested (feet)	MALLIK L-38		IVIK J-26	
	3030-3040	3622-3632	3300-3310	3338-3348
Gas Composition				
Methane, %	99.19	99.25	99.31	99.53
Ethane, %	0.07	0.01	TRACE	TRACE
Propane, %	0.01	-	TRACE	TRACE
Iso-butane, %	0.03	-	-	TRACE
Nitrogen, %	0.64	0.66	0.48	0.46
CO ₂ , %	0.05	0.08	0.21	-
Helium, %	0.01	TRACE	-	0.01
TOTAL, %	100.00	100.00	100.00	100.00

3. USSR

The most explored of the prospective gas-hydrate deposits is the Messoiakh field. This field was discovered in 1967 in the Yenisei-Khatung Trough in the northeastern part of Western Siberia (Makogon, 1981).

The thickness of the permafrost in the area of the Messoiakh gas deposit reaches 1,400 feet. The strata containing the hydrates lie within the zone ranging from 800 feet (250 meters) to 2,700 feet (870 meters) in depth, and the gas producing horizons lie at the base of the hydrate zone at a depth of 2,700 feet. Cross sections of the hydrate-bearing zones of the Messoiakh field are shown in Figure 2-9.

The presence of hydrates in this field was confirmed by pumping methyl alcohol, an inhibitor, into the hydrate-bearing strata of a number of the wells in this field. The resulting hydrate decomposition and gas flow from these wells are shown on Table 2-4.

TABLE 2-4
MESSIOAKH HYDRATE WELL PERFORMANCE

<u>Well Number</u>	<u>Before Alcohol Treatment</u>		<u>After Alcohol Treatment</u>	
	<u>Press. Drop</u> (kg/cm ²)	<u>Gas Production</u> (1,000 m ³ /day)	<u>Press. Drop</u> (kg/cm ²)	<u>Gas Production</u> (1,000 m ³ /day)
133	3.5	25	0.4	50
	7.0	50	0.8	100
	14	100	1.1	150
	19	150	1.5	200
	22	200	2.0	250
142	8	5	0.4	50
	13	10	0.5	100
	19.5	25	0.7	150
	25	50	1.0	200
	30	100	1.4	
	33	150		

Figure 2-9

DEPTH INTERVALS OF HYDRATE-BEARING ZONES
IN THE MESSOIYKH FIELD STRATA

- 1 -- GAS-PRODUCING BED
- 2 -- NONPRODUCING INTERLAYERS
- 3 -- ISOTHERM OF 10°C
- 4 -- WELL INTERVALS WITH COMPLETIONS

SOURCE: Makogon, 1981.

The data show that alcohol injection into the hydrate-bearing strata increased gas production two to tenfold over the prior rates.

It is conservatively estimated that 1/3 of the entire Messoiakh reservoir is occupied by gas hydrates, and the remaining 2/3 by free gas. Calculated gas reserves including gas hydrates are 54% larger than reserve estimates that assume the entire field is occupied by free gas only (Makogon, 1981).

Coring and logging have confirmed other onshore gas hydrate deposits in the USSR. For example, Makogon and others report that the Central Vilyuy gas field in Yakutia, USSR, contains gas hydrates beneath permafrost (Oil and Gas J., October 23, 1968).

B. IDENTIFIED OFFSHORE OCCURRENCES OF HYDRATES

Geologic, geochemical, and geophysical evidence suggest that gas hydrates may extend over much of the area beneath the seafloor (Kvenvolden, 1980).

- The geologic evidence for hydrates consists of theoretical evidence of widespread areas where pressures and temperatures are suitable for gas-hydrate stability. The physical evidence is the recovery of deep-sea sediment cores that have released large volumes of gas and have cooled endothermically when exposed to sea-level temperature and pressure.
- The geochemical observations include the observation of high concentrations of methane in sediment, usually accompanied by low concentrations of ethane.
- The geophysical evidence includes seismic anomalies, such as high acoustic velocity, in areas where hydrates are expected.

Identification of submarine gas hydrates are based on seismic data and coring. The major seismic evidence is the bottom-simulating reflector (BSR), Figure 2-10, although not all BSRs may be directly related to gas hydrates. Bottom-simulating reflectors have been seen only in water deeper than 1,200 feet, and are generally manifest on seismic records as an abrupt decrease in seismic velocity, Figure 2-11.

Figure 2-10

BOTTOM SIMULATING REFLECTOR -- EXAMPLE

Figure 2-11

VELOCITY ANALYSIS BY RICHARD WISE (USGS)
AT LOCATION OF ARROW IN PRECEDING FIGURE

SOURCE: Dillon and Paull, 1983.

The distribution of bottom-simulating reflectors for central America and eastern North America is shown on Figure 2-12. While the exact relationship between BSRs and gas hydrate zones is uncertain, it has been suggested that the change in seismic impedance may mark the bottom of the gas hydrate zone where free methane gas is trapped beneath the hydrate layer.

Other features on seismic records that may indicate the presence of hydrates are bottom-parallel bright spots, and deep-water velocity amplitude features (VAMP's). Such reflectors appear on seismic records from the east coast of North America, the North Pacific, the Bering Sea, and the Pacific and Atlantic coasts of Central America.

Direct evidence of offshore gas hydrates is provided by visual observations of sediments from the landward wall of the Mid-America Trench off Mexico and Guatemala, from the Gulf of Mexico off Texas, and from the Blake Outer Ridge off the southeastern U.S. At the Black Sea in the USSR, Yefremova reports having observed hydrate in gas filled cavities in a sediment core taken from 6,000 feet. The hydrate crystals were in cavities and disappeared rapidly after deposit on the deck of the ship.

1. North and Central America

Icelike material containing gas hydrates has been recovered in several cores taken in the Pacific, Atlantic, and Gulf of Mexico, Figure 2-13.

The gas hydrates in these cores were observed to be either: (1) dispersed in fine-grained sediments; (2) occupying the pore space of coarse-grained sediments; (3) as a solid, filling fractures of mudstone; or, (4) as a massive unit composed mainly of solid gas hydrate with minor amounts of sediment, Figure 2-14. Thus, numerous examples of alternative offshore hydrate reservoir settings have been observed.

Where solid gas hydrates have been sampled, the gas is composed mainly of methane accompanied by CO_2 and low concentrations of ethane and hydrocarbons of higher molecular weight. The molecular and isotopic composition of

Figure 2-12

DISTRIBUTION OF THE BOTTOM SIMULATING REFLECTOR
AS REPORTED FOR
CENTRAL AMERICA-EASTERN NORTH AMERICA

SOURCE: Dillon and Paull, 1983.

Figure 2-13

LOCATIONS WHERE SOLID GAS HYDRATES HAVE BEEN RECOVERED
FROM CONTINENTAL MARGIN SEDIMENTS BY THE
DEEP SEA DRILLING PROJECT, LEGS 66, 67, 76, and 84

SOURCE: Kvenvolden, 1983.

Figure 2-14

SOURCE: Malone, personal communication.

hydrocarbons indicates that the methane is of biological origin except for the Gulf of Mexico sample, where the methane in the hydrate appears to be of thermogenetic origin.

a. Atlantic. The widespread occurrence of BSRs indicates that gas hydrates may be present over about 80,000 km² of the Blake Outer Ridge. The Blake Outer Ridge is a major topographic feature over 310 miles in length which trends southeast from the Blake Plateau just south of Cape Hatteras, Figure 2-15. The extensive occurrence of BSRs implies that significant amounts of methane are present in these fine-grained, hemipelagic sediments that probably have very low permeability.

Hydrate gas was recovered from core samples taken on Leg 76 of the National Science Foundation's Deep Sea Drilling Project (DSDP) off the southeast coast of the U.S. in the Blake-Bahamas Outer Ridge area. At 800 feet sub-bottom, thin, mat-like layers of crushed white hydrate were recovered in semi-consolidated sediment. Vigorous outgassing from the recovered sediment was indicated by frothing. The volume of gas released upon hydrate decomposition was about 20 times the volume of pore fluid.

b. Pacific. Gas hydrates have been found in landward slope sediments of the Middle America Trench along offshore Mexico, Guatemala and Costa Rica in Legs 66, 67, and 84 of DSDP.

Gas hydrates were found in continental margin sediment during DSDP Leg 66 west of Mexico on the landward wall of the Mid-America Trench. At Site 490, gassy ice was recovered at 400 feet below the bottom. At sites 491 and 492, gassy frozen mud was collected that produced about 20 ml of gas per ml of pore fluid. The decomposed gas was mainly methane, accompanied by CO₂ and hydrocarbons of higher molecular weight, up through isobutane, although only traces of n-butane and larger molecules were observed (Barnard et al., 1981 and Kvenvolden et al., 1981). The fact that the volume of methane produced was about 5 times the amount of methane soluble in seawater at in situ pressure and temperature conditions, indicated the presence of gas hydrates (Moore et al., 1979).

Figure 2-15

DISTRIBUTION OF BOTTOM SIMULATING REFLECTOR
OFF THE SOUTHEASTERN UNITED STATES

Deep Sea Drilling Project (DSDP) drillsites in the Blake Ridge are also indicated.

SOURCE: Kvenvolden, 1983.

On DSDP Leg 67, west of Guatemala, also on the landward wall of the Mid-America Trench, gas hydrates were recovered in vitric sands near the bottom of the holes at Sites 497 and 498 (von Huene et al., 1980). The existence of gas hydrates is based on the following: (1) decomposition produced greater quantities of methane than are soluble in sea water at the given pressures and temperatures; (2) methane was abundant in gas samples from Site 496; and, (3) the high gas pressures in cores at all three holes.

Six sites were drilled on Leg 84. Gas hydrates were recovered at three sites and were inferred, from both organic and inorganic geochemical evidence, to be present at two other sites. The core at Site 570 consisted of a massive 10 to 13-foot long hydrate interval with a porosity estimated at over 90%. The well log of this massive gas hydrate is shown in Figure 2-16. The hydrate deposit was found at 816 feet beneath the seafloor. These hydrates were recovered and distributed for onshore analysis to the U.S. Department of Energy, National Bureau of Standards, SOHIO, UCLA, Texas A&M, and the Colorado School of Mines (Sloan, 1983).

c. Gulf of Mexico. Hydrates have recently been recovered in a core from a depth of 1,700 feet of water in the Gulf of Mexico, offshore Texas in the Green Canyon lease area. The gas was thermogenetic methane and had oil associated with it. The hydrate occurred in crystals of widely varying size, ranging from very small to egg size. An analysis of the gas composition is shown below in Table 2-5.

TABLE 2-5
GAS COMPOSITION OF HYDRATES - GULF OF MEXICO

<u>Gas</u>	<u>Percent</u>
Methane	67.0
Ethane	4.5
Propane	14.9
n-butane	0.1
Isobutane	4.2
Carbon Dioxide	3.9
Other	5.4
TOTAL	100.0

The existence of hydrates suggested by this analysis because the vast majority of gas components in the sample are those that can form hydrates.

Figure 2-16

WELL LOG SHOWING THE LOG RESPONSES FOR A PORTION OF THE HOLE AT SITE 570

Depth (water plus sediment) scale (m) is on the left. Each division represents one m. The top of the massive gas hydrate is indicated at a total depth of about 1,965 m. The subbottom depth of the top of the gas hydrate is at about 250 m.

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CHAPTER 3

THE PHYSICAL PROPERTIES OF GAS HYDRATES

An understanding of the physical properties of hydrates is necessary for studying the nature of hydrates, designing exploration rationales, identifying hydrates through seismic and logging techniques, and analyzing alternative hydrate recovery techniques.

The first three sections of this chapter ("Inclusion Compounds," "Hydrate Structure," and "Hydrate Numbers") discuss general structural properties of hydrates. The two basic structures of hydrates are reviewed and the amount of gas contained in hydrates is described as a function of temperature, pressure, and size of the gas molecule.

The next section, "Selected Hydrate Properties," summarizes several physical and some thermodynamic properties of hydrates. Although many properties of hydrates are not well known, the gas hydrate structures are very similar to that of ice, and therefore, many physical properties that depend on the structure are expected to be similar. However, this is not the case for some important properties, particularly electrical properties and the thermal conductivity.

The next part of this chapter, "Properties for Indirect Measurement of Hydrates," summarizes physical properties required for indirect measurements and identification of hydrates. These properties include elastic properties, sonic velocities in hydrate sediments, hydrate density, and density of hydrate deposits.

In "Production (Dissociation) Properties of Hydrates," the properties of hydrates required for production analyses are discussed. The volumes of gas and water that are obtained when hydrates dissociate and the corresponding increase in pressure are derived. The pressure may be very high, possibly leading to casing collapse. It is also shown that hydrates may form in oil or gas reservoirs containing water and hydrate-forming gases, thereby reducing the expulsion energy of the reservoir and possible blocking pore throats with low permeability hydrates. Moreover, free gas may exist in hydrate reservoirs if the water saturation is sufficiently low as it might be in gas reservoirs.

A. STRUCTURAL DESCRIPTION OF HYDRATES

1. Inclusion Compounds

Inclusion compounds are physical combinations of at least two kinds of molecules, in which one set of "guest" molecules fits into cavities of a crystalline lattice formed by another set of "host" molecules without ordinary chemical bonding. When the size and shape of the cavity in the host molecule match the form of the guest, the interactions of the outer electrons in the shells of the host and guest atoms create a strong physical bond, typical of an inclusion compound.

Inclusion compounds are known to exist in six different forms, depending on the architectural structure and the cavity shape of the host. Gas hydrates are a type of inclusion compound called clathrates (from the Latin word clathratus, meaning enclosed by bars) where guest molecules (gas) fit into separate, quasi-spherical chambers of host molecules (water) within a crystal lattice. The other five types of inclusion compounds are: canal complexes, formed when the host lattice has tubular cavities; layer complexes which are crystals with alternative layers of guest and host; molecular sieves which are formed by crystals that contain interconnecting chambers and passage ways; intramolecular hollow space complexes, formed when the host is a large molecule containing a concavity; and, linear polymer complexes, produced when guest molecules fit into a tube formed by a pipeline host molecule (Brown, 1962).

2. Hydrate Structure

A gas hydrate structure consists of a network of water molecules, where the water molecules are hydrogen-bonded in a manner similar to ice.

A gas hydrate may have two different structural forms. The unit crystal structures for Structure I (body centered cubic) and Structure II (diamond lattice) hydrates are composed of polyhedral cages as shown on Figure 3-1. As indicated on the bottom half of the figure, each hydrate structure has two types of essentially spherical cavities (or cages) of differing diameter. The

Figure 3-1

UNIT CELL CONFIGURATION OF STRUCTURES I AND II

UNIT CELL OF A GAS HYDRATE OF STRUCTURE I

Black Circles indicate small cages
White Circles indicate large cages

UNIT CELL CONFIGURATION OF STRUCTURE II

SOURCE: Makogon, 1981.

POLYHEDRAL CAGES OF WATER MOLECULES IN CLATHRATE ICES OF STRUCTURES I AND II. CIRCLES REPRESENT OXYGEN ATOMS AND LINES THE HYDROGEN BONDS BETWEEN THEM.

SOURCE: Davidson, 1983.

TABLE 3-1
PROPERTIES OF HYDRATE LATTICES

Property	Structure I	Structure II
Unit Cell Size, Å	12.03	17.31
Number of Dodecahedra	2	16
Number of Tetrakaidecahedra	6	--
Number of Hexakaidecahedra	--	8
Coordination Number (number of water molecules surrounding one cavity)		
- large cavity	24	28
- small cavity	20	20
Number of Water Molecules Per Unit Cell	46	136
Number of Large Cavities Per Unit Cell	6	8
Number of Small Cavities Per Unit Cell	2	16
Large Cavity-Diameter, Å	8.6	9.46
Small Cavity-Diameter, Å	7.88	7.82
Ideal Composition*	$6M_1 - 2M_2 \cdot 46H_2O$	$8M_1 - 16M_2 \cdot 136H_2O$
Cell Size Increase Over Ice I, %	16	18

* Hydrate composition if large molecules M_1 occupy all the large cavities and small molecules M_2 occupy all the small cavities.

Source: Gas Research Institute, 1979.

properties of the hydrate lattices are shown on Table 3-1 and discussed in the following paragraphs. The table shows the unit cell sizes, the numbers of water molecules and cavities per unit cell, the diameters of the cavities, and the ideal composition of Structure I and Structure II hydrates. The cell size expansion of hydrates over ice is also shown.

The unit cell of Structure I is constructed from 46 water molecules and has eight cavities available for gas molecules, consisting of two "small" and six "large" cavities. The "small" cavities of Structure I are regular pentagonal dodecahedra with mean free diameter of 5.1 angstroms, formed by two opposing hexagons and twelve pentagons situated between them. The ideal formula of this hydrate is $8M_1 \cdot 46H_2O$ or $M_1 \cdot 5.75H_2O$ when all eight cavities are filled. When two or more species of molecules are present simultaneously in the gas mixture (a mixture of M_1 and M_2), a so-called "mixed hydrate" is formed.

In Structure II, 136 water molecules form a lattice containing eight large and sixteen smaller cavities, giving a ratio of one molecule of entrapped gas for every 5.67 water molecules. The "small" cavities, as for Structure I, are pentagonal dodecahedra, but somewhat deformed, as a result of which the mean free diameter is about 5 angstroms. The "large" cavities of Structure II are hexadecahedra, each of which is constructed from four hexagons and twelve pentagons. The mean free diameter of this cavity is 6.6 angstroms which determines the size of the largest molecules that can form gas hydrates.

The crystal structure of the gas hydrate will depend on the geometry of the gas molecule. In general, small gas molecules create Structure I hydrates and large gas molecules create Structure II hydrates because of its larger cavities. The ability of a gas to form hydrates depends not only on its maximum length, but also on the physical configuration of the molecule since it must fit into the cavities. Thus, several molecules are non hydrate-formers, even though other molecules of greater length may form hydrates.

Figure 3-2

O-SITE DESIGNATIONS OF THE SMALL AND LARGE CAGES
OF STRUCTURE I (a and b) AND OF STRUCTURE II (c and d) HYDRATES,
VIEWED ALONG AN AXIS OF GREATEST SYMMETRY

SOURCE: Davidson, 1971.

TABLE 3-2
GEOMETRY OF CLATHRATE HYDRATE CAGES

	Small Cages			Large		
STRUCTURE I: $Pm\bar{3}n$, $a = 12.03 \text{ \AA}$						
Number of cages in unit cell	2			6		
O Site Designation	i	k		i	k	k c
Number of sites in cage	8	12		8	8	4 4
Distance to center ($\text{\AA}$)	3.83	3.96		4.47	4.06	4.645 4.25
Average distance to center ($\text{\AA}$)		3.91				4.33
Average cage radius ($\text{\AA}$)			4.22			
STRUCTURE II: $Fd\bar{3}m$, $a = 17.31 \text{ \AA}$						
Number of cages in unit cell	16			8		
O Site Designation	a	e	g	e	g	g
Number of sites in cage	2	6	12	4	12	12
Distance to center ($\text{\AA}$)	3.748	3.845	3.956	4.729	4.715	4.635
Average distance to center ($\text{\AA}$)		3.902			4.683	
Average cage radius			4.162			

	Structure I			Structure II		
O Site Designation	i	k	c	a	e	g
Sites in unit cell	16	24	6	8	32	96
Average departure at site from tetrahedral angle (degree)	1.2	5.1	1.2	0	2.1	3.6
Average departure (degree)		3.7			3.0	
Average distance of site to neighbors ($\text{\AA}$)	2.769	2.802	2.811	2.767	2.774	2.795
Average O-O distance ($\text{\AA}$)		2.793			2.790	

Source: Davidson, 1971

The geometry of clathrate hydrate cages is shown on Table 3-2. In Figure 3-2, O-site designations of the small and large cages of Structure I and II hydrates, viewed along an axis of greatest symmetry are shown (Davidson, 1971). In gas hydrates, like ice, each water molecule is hydrogen-bonded to its four nearest neighbors. The hydrogen bonds average only about 1% longer than ice and the O-O-O angles defined by the oxygen atoms of adjacent water molecules differ from the tetrahedral angles found in ice by, on average, only 3.7° in Structure I and 3.0° in Structure II. Structure II is inherently more stable than Structure I, due to the approximately tetrahedral angles found in Structure II hydrates. As a consequence, Structure II hydrates can exist in deeper and warmer environments than can Structure I hydrates. The difference between hydrates and ice structure lies in the arrangement of the second nearest and most remote water molecules; these are placed to form almost planar 5- and 6-membered rings, rather than the puckered 6-membered rings of ice.

3. Hydrate Numbers

The hydrate number is defined as the number of moles of water per mole of gas in the hydrate. For hydrates of Structure I and Structure II, the hydrate numbers are at most 5.75 and 5.67, respectively. However, the amount of gas in gas hydrates will usually be less than the theoretically maximum value.

Hydrate numbers depend on the type of gas and pressure, as shown in Figure 3-3 for three Structure I gases (Saito et al., 1974). The calculated hydrate number approaches the maximum theoretical value of 5.75 at pressures of about 15,000 psi. Below that, at pressures that can be expected in the hydrate interval (1,500 to 6,000 psi), the hydrate number for methane is higher, between six and seven. These results have been verified experimentally (Galloway et al., 1970).

The hydrate structure and typical hydrate numbers for several gas hydrates are shown on Table 3-3. The hydrate numbers are determined from comparing the enthalpy of formations above and below 0°C (Holder, 1982), as calculated from dissociation pressure-temperature data using the method of Deaton and Frost (1946). Table 3-3 also shows which cavities (small and/or large) can be occupied by the gas molecule. The hydrate numbers for gas hydrates derived by different investigators are listed in Table 3-4.

Figure 3-3

VARIATION OF HYDRATE NUMBERS WITH PRESSURE

SOURCE: Saito, Marshall and Kobayashi, 1964.

TABLE 3-3
HYDRATE STRUCTURE AND NUMBERS FOR VARIOUS GASES AND MIXTURES

<u>Gases</u>	<u>Hydrate Structure</u>	<u>Calculated Hydrate Number^a</u>	<u>Cavity Code^b</u>
Ar	I	-	1
Kr	I	-	1
Xe	I	-	1
N ₂	I	6.1	1
O ₂	I	-	1
CO ₂	I	6.5	1
H ₂ S	I	6.3	1
CH ₄	I	6.3	1
C ₂ H ₄	I	-	1
C ₂ H ₆	I	8.0	2
C ₃ H ₆	II	-	2
C ₃ H ₈	II	17.1	3
Cyclo-C ₃ H ₆	I, II	7.1	2
i-C ₄ H ₁₀	II	17.1	3
<u>Mixtures</u>			
CH ₄ (85%) + C ₃ H ₈ (15%)	II	9.0	-
CH ₄ (95%) + C ₃ H ₈ (5%)	II	8.0	-
CH ₄ (95%) + C ₂ H ₆ (3%) + C ₃ H ₈ (2%)	II	7.5	-
CH ₄ (75%) + N ₂ (25%)	I	6.3	-
CH ₄ (50%) + N ₂ (50%)	I	6.3	-
CH ₄ (80%) + C ₂ H ₆ (20%)	I	6.4	-

a Hydrate numbers calculated from deriving the enthalpy of formation above and below 0°C (when available).

b Cavity codes: 1-Gas can enter all cavities; 2-Gas can enter large cavity of both structures; 3-Gas can enter large cavity of structure II only.

Source: Holder, personal communication.

TABLE 3-4
EXPERIMENTAL COMPOSITIONS OF GAS HYDRATES

<u>Gas</u>	<u>Investigator</u>	<u>Hydrate Number Mol. Water/Mol. Gas in Hydrate Phase</u>
Methane	Deaton and Frost	7.2
	Roberts et al.	7.0
	Hammerschmidt	6.0
	DeForcrand	6.0
	Kobayashi et al.	5.8-6.3
	Prediction by Holder	6.37
Ethane	Deaton and Frost	8.3
	Roberts et al.	7.0
	Hammerschmidt	6.0
	DeForcrand	7.0
	Kobayashi et al.	7.9-8.5
	Prediction by Holder	8.0
Propane	Deaton and Frost	18.0
	Hammerschmidt	7.0
	Miller and Strong	6.0
	Cecotti	19.6-19.8
	Parent	17.4
	Prediction by Holder	17.1
Isobutane	Rouher and Barduhn	17.5
	Uchida and Hayano	17.1
	Holder and Ng	15.0-17.0
	Scheider and Farar	18.0
Carbon Dioxide	Deaton and Frost	7.0
	DeForcrand	6.0
	Villard	6.0
	Prediction by Holder	7.8
Nitrogen	Prediction by Holder	6.1
H ₂ S	Prediction by Holder	6.3

Source: Holder, personal communication.

B. SELECTED HYDRATE PROPERTIES

In general, little is known about the physical properties of hydrates and much of the current data has been derived theoretically.

Many physical properties of hydrates, (for instance elasticity) depend primarily on the structure of the lattice. Because the hydrate crystalline structure resembles that of hexagonal ice, properties that are not currently known can, at a first approximation, be assumed to be similar to those of ice. Table 3-5 provides a summary comparison of selected physical and some thermodynamic properties of ice and gas hydrates. Where values depend on the gas molecule, values considered most appropriate to methane and propane hydrates have been chosen.

Although many properties of ice and hydrates are similar, such as the acoustic velocity and the infrared spectrum, several properties are distinctly dissimilar, as shown on Table 3-5. These include electrical properties, diffusional jump times and thermal conductivity of ice and gas hydrates, as discussed below:

- Electrical Properties. Dielectric constants of hydrate are relatively large, about 58 at 0°C, although not as large as for ice. The difference probably arises because of small differences in the crystalline structure (Davidson, 1982).
- Diffusional Jump Rate. It appears that the diffusional jump rate of water molecules in gas hydrates is slower than the reorientation rate, the opposite of the case for ice (Davidson, 1983). Also, the water diffusion coefficient of hydrocarbon hydrates may be several orders of magnitude smaller than of ice (Ripmeester, in press).
- Thermal Conductivity. There is experimental evidence that the thermal conductivity of hydrates is $2.2 \text{ W m}^{-1} \text{ } ^\circ\text{K}^{-1}$, or about one-quarter of ice's (Stoll, 1979). This result is unexpected since the crystalline structures are so similar.

The thermodynamic properties of hydrates are described in Chapter 4.

TABLE 3-5
COMPARISON OF SELECTED PROPERTIES OF GAS HYDRATES AND ICE

Property	Ice	Gas Hydrate	
		Structure I	Structure II
No. of water molecules	4	46	136
Lattice parameters at 0°C (Å)	a=4.52 c=7.36	11.97 to 12.15	17.14 to 17.57
Dielectric Constant at 0°C	94	ca. 58	58
Far infrared spectrum	Broad peak at 229 cm ⁻¹	Peak at 229 cm ⁻¹ with additional absorption features	
NMR rigid lattice second moment of water protons (G ²)	32		33±2
Water molecule reorientation time at 0°C (μ sec)	21		ca. 10
Diffusional jump rate of water molecules at 0°C (μ sec)	2.7	possibly	200
Volume thermal expansion (°K ⁻¹)	1.5x10 ⁻⁴	1.5 to 1.7x10 ⁻⁴ (a)	
Isothermal Young's modulus at -50°C (10 ⁹ Pa)	9.5	8.4(a)	8.2(a)
Poisson's ratio	0.33		ca. 0.33
Adiabatic bulk compressibility at 0°C (10 ⁻¹¹ Pa)	12		14(a)
Speed of longitudinal sound at 0°C (km sec ⁻¹)	4.0		3.8(a)
Thermal conductivity at 0°C (Wm ⁻¹ °K ⁻¹)	2.2		0.53
Water lattice enthalpy compared to gas at 0°C (kJ mol ⁻¹)	-51.01±0.08		-50.2±0.5
Lattice energy at 0°K (kJ mol ⁻¹)	-47.3	Slightly less negative than ice	
Residual entropy at 0°K	3.43	Similar to ice	

(a) Indicates an estimated value.

Source: Davidson, 1983

C. PROPERTIES FOR INDIRECT MEASUREMENT OF HYDRATES

1. Elastic Properties

Very few measurements of the elastic properties of gas hydrates or of their reciprocals (compliance, compressibility) have been reported. Complete characterization of the cubic gas hydrates requires three independent elastic constants; five are required for hexagonal ice (Fletcher, 1970).

Table 3-6 shows the values of bulk modulus, shear modulus, and the ratio of compressional (P) to sheer (S) wave velocities (V_p/V_s) for hydrate I and ice specimens at -16.5°C and -1.1°C , respectively.

TABLE 3-6
BULK MODULUS, SHEAR MODULUS, AND V_p/V_s FOR HYDRATE AND ICE SPECIMENS

	<u>Temp.</u>	<u>Bulk Modulus</u> K (GPa)	<u>Shear Modulus</u> (GPa)	<u>V_p/V_s</u>
Hydrate I	-16.5°C	5.8	2.3	1.96
	-1.1°C	5.6	2.4	1.95
Ice	-16.5°C	8.3	3.9	1.87
	-1.1°C	8.8	3.9	1.88

Source: Pandit and King, 1977

Compressional and shear wave velocities of propane gas hydrates and ice have been reported as a function of temperature, -16.5°C to $+2.4^{\circ}\text{C}$, and axial stress, 0.53 MPa to 2.1 MPa (Pandit and King, 1977). Below 0°C , the temperature dependence of both compressional and shear wave velocities was weak, the respective values being 3.25 km/sec and 1.65 km/sec for propane hydrate and 3.86 km/sec and 2.4 km/sec for ice, Figures 3-4 and 3-5. This is lower than predicted by theoretical analysis, which gives about the same velocity for hydrates as for ice. No significant variation of velocity with axial stress was observed below 0°C .

Figure 3-4

Figure 3-5

SOURCE: Pandit and King, 1977.

SOURCE: Pandit and King, 1977.

Fourier analysis of the signal waveforms through the specimens seems to suggest that the attenuation in hydrates may be greater than in ice, as shown in Table 3-7.

TABLE 3-7
RELATIVE ATTENUATION OF HYDRATE TO ICE
AS A FUNCTION OF TEMPERATURE AND FREQUENCY

<u>Frequency, MHz</u>	<u>Temperature, °C</u>			
	<u>-12.1</u>	<u>-8.1</u>	<u>-4.1</u>	<u>-2.3</u>
0.500	2.5	3.3	2.5	2.0
0.625	1.3	1.0	1.0	1.0
0.750	1.3	1.3	1.3	1.3
0.875	2.5	10.0	5.0	3.3
1.000	10.0	5.0	5.0	5.0

Source: Pandit and King, 1977

2. Sonic Velocity

Sonic velocity of compressional waves for dry and saturated sediments and for sediments containing hydrate are shown in Figure 3-6. The results show a wave velocity of over 2 km/sec for hydrated sediments as opposed to less than 2 km/sec for water-saturated sand. Little difference between ice- and hydrate-filled sediments is expected but water saturation and/or the presence of free gas will have relatively dramatic effects. Data from Hardin and Richart (1963) and from Whitman and Lawrence (1963) for compressional and shear wave velocity in the same standard sand is also included in Figure 3-6. The wave velocity in sediments containing naturally-occurring hydrates may vary considerably from the values shown on Figure 3-6, because these values depend on the particular set of experimental conditions (Stoll, 1974).

In Figure 3-7, calculations of sonic velocities for two sediments are shown; the first three sets of bars are an ocean floor sediment, and the last

Figure 3-6
WAVE VELOCITY IN SEDIMENT FOR VARIOUS CONDITIONS

SOURCE: Stoll, 1974.

Figure 3-7
SONIC VELOCITIES OF HYDRATED SEDIMENTS

SOURCE: Halleck, 1982.

three terrestrial. For each, calculations have been made for various ratios of hydrate and water; the percent saturation values refer to the proportion of hydrate in the pores with the balance being water. The difference between the two sediments is not significant and depends principally on the mineralogy and porosity.

The effects of different guest molecules was also investigated using pure methane hydrate, a mixture of methane and propane hydrates, and a propane hydrate with eighty percent occupancy. Differences due to changes in guest molecules are not large and thus hydrate composition probably cannot be measured by sonic methods.

3. Density of Hydrates and Hydrate Deposits

The densities of natural gas hydrates can be calculated from the unit cell dimensions or from the microscopic properties of hydrates and their components, namely water and gas. Because both Structure I and Structure II hydrates are cubic, the cell volume is the side length cubed, and the cell mass is the mass of the water making up the lattice plus the mass of the guest molecules contained in the cavities. The cell dimensions do not depend on the size of the guest (gas) molecules. Table 3-8 lists the cell mass and volumes for Structure I and Structure II hydrate crystal lattices when no gas is present.

TABLE 3-8
HYDRATE CELL MASS AND VOLUME

<u>Structure</u>	<u>Mass of Cell Lattice</u> (g $\times 10^{-24}$)	<u>Volume</u> ($\text{\AA}^3$)	<u>Empty density</u> (g/cm ³) (lb/ft ³)	
Structure I	1,358	1,741	0.780	48.7
Structure II	4,068	5,178	0.786	49.1

Source: Pearson, 1982

Densities of natural gas hydrates can be calculated by adding the mass of the guest molecules to the lattice mass and dividing by the cell volume. Typical densities for various constituents of natural gas and occupancy ratios are listed in Table 3-9.

TABLE 3-9
DENSITIES OF NATURAL GAS HYDRATES

<u>Guest</u>	<u>Structure</u>	<u>Occupancy</u> <u>100 Percent</u>		<u>Occupancy</u> <u>90 Percent</u>	
		<u>g/cm³</u>	<u>lb/ft³</u>	<u>g/cm³</u>	<u>lb/ft³</u>
CH ₄	I	0.90	56.2	0.89	55.7
C ₂ H ₆ *	I (large)	0.95	63.1	0.93	58.2
CO ₂	II	1.12	70.0	1.09	68.1
C ₃ H ₈ *	II (large)	0.87	58.7	0.86	54.0
H ₂ S	II	1.04	65.0	1.01	63.1

* Ethane and propane only enter large cavities

Source: Holder, personal communication.

Hydrates can cause a small but measurable effect on bulk density of water-saturated rocks. Typical densities for marine and terrestrial sediments containing natural gas hydrates are listed in Table 3-10.

TABLE 3-10
DENSITIES OF SOME MARINE AND TERRESTRIAL SEDIMENTS

<u>Sediment</u>	<u>Hydrate Saturated</u> <u>(g/cm³)</u>	<u>Water Saturated</u> <u>(g/cm³)</u>
Abyssal Plain Sandy Silt	1.58	1.65
Clay	1.15	1.26
Abyssal Hill Clay	1.32	1.42
Shelf Sand (coarse)	2.02	2.07
Berea Sandstone	2.40	2.42

Source: Pearson, 1982

D. PRODUCTION (DISSOCIATION) PROPERTIES OF HYDRATES

This section derives the volumes of water and gas liberated when hydrates are dissociated. It is shown that the pressure increase can be very substantial, which might lead to operating problems. This section also shows that free gas may exist in a reservoir if the initial water content is low enough and that hydrates can form in oil reservoirs under certain conditions.

1. Dissociation Relationships

When a gas hydrate dissociates, the majority of the original volume will be filled with water and the remainder with gas. The gas volume and the mass of gas and water per cubic foot of hydrate (and the hydrate density) may be calculated using the following procedure:

Step 1. Using water properties and the hydrate expansion factor ($E = \text{ft}^3 \text{ hydrate} / \text{ft}^3 \text{ water}$), calculate the gas volume in standard cubic feet (scf) per ft^3 of hydrate from the following relationship:

$$\frac{\text{gas (scf)}}{\text{ft}^3 \text{ hydrate}} = \frac{379}{n} \times \frac{\text{water density (lb/ft}^3\text{)}}{\text{water mole-weight (lb)}} \times \frac{1}{E} \frac{(\text{ft}^3 \text{ water})}{(\text{ft}^3 \text{ hydrate})} \quad (3-1)$$

where: 379 = the standard cubic feet (14.7 psia, 60°F) of gas per pound-mole and
n = the hydrate number.

The hydrate expansion factor may be calculated from Table 3-1 where the cell size increase over ice is given as 16% and 18%, respectively.

$$E = (\text{hydrate-ice expansion}) \cdot (\text{ice-water expansion})$$

$$\text{Structure I: } E = 1.16 \times 1.10 = 1.28 \quad (3-2)$$

$$\text{Structure II: } E = 1.18 \times 1.10 = 1.30 \quad (3-3)$$

Thus, when hydrate dissociates, 78% (1/1.28) of the original volume will be filled with water and 22% with gas.

Step 2. Calculate the mass of gas and water per cubic foot of hydrate from the following:

$$\frac{1 \text{ b gas}}{\text{ft}^3 \text{ hydrate}} = \frac{\text{gas(scf)}}{\text{ft}^3 \text{ hydrate}} \times \frac{\text{gas mole-weight}}{379} \quad (3-4)$$

$$\frac{1 \text{ b water}}{\text{ft}^3 \text{ hydrate}} = \frac{\text{water density}}{\text{E}} \quad (3-5)$$

Step 3. Calculate hydrate density from

$$\text{hydrate density (lb/ft}^3\text{)} = 1 \text{ b gas/ft}^3 + 1 \text{ b water/ft}^3$$

Example: Assume methane hydrate with $n=6.3$ (90% occupancy), a water density of 62.4 lb/ft^3 , and an expansion factor of 1.28 (Structure I).

The gas volume, mass components, and hydrate density for these conditions are:

(1) Gas Volume

$$\frac{379}{6.3} \times \frac{62.4}{18} \times \frac{1}{1.28} = \frac{163 \text{ scf methane}}{\text{ft}^3 \text{ hydrate}}$$

When 1 cubic foot of methane hydrate (90% occupancy) dissociates, 163 scf of methane is liberated.

(2) Mass Components

Methane:

$$163 \times \frac{16}{379} = \frac{6.9 \text{ lb methane}}{\text{ft}^3 \text{ hydrate}}$$

Water:

$$\frac{1}{1.28} \times 62.4 = \frac{48.8 \text{ lb water}}{\text{ft}^3 \text{ hydrate}}$$

This is equivalent to $48.8/18 = 2.7 \text{ lb mole of water}$.

(3) Hydrate Density

$$\begin{aligned} 6.9 \text{ lb methane/ft}^3 &+ 48.8 \text{ lb of water/ft}^3 = \\ 55.7 \text{ lb of hydrate/ft}^3 \end{aligned}$$

The density of hydrate in this example is 55.7 pounds per cubic foot. The density of hydrate (about 56 pounds per cubic foot) is very similar to that of ice; 56.7 pounds per cubic foot.

2. Calculation of Dissociated Gas Pressure

In a constant volume system, the gas from the dissociated hydrate will increase the pressure in the formation significantly and may lead to collapse of the casing. It is, therefore, important to know the maximum pressure that can be expected when hydrates dissociate.

The pressure in psia of the dissociated gas per mole can be calculated from:

$$\begin{aligned} P &= \frac{Z N_g RT}{V} = \frac{Z (2.7/n) (10.73)T}{0.22} & (3-7) \\ &= 131.69 \left(\frac{ZT}{n} \right) \end{aligned}$$

where:

Z = compressibility factor (Figure 3-10)

T = reservoir temperature, in $^{\circ}R$

N_g = mole of gas (2.7/n)

P = pressure of dissociated gas, psia

0.22 = volume of gas

R = gas constant $(10.73 \frac{\text{psia} \cdot \text{ft}^3}{\text{lb-mole} \cdot ^{\circ}R})$

The compressibility factor Z is a function of P and T , so either the solution to this equation can be determined iteratively using Figure 3-8 or the value of P/Z can be determined from Figure 3-9.

Figure 3-8

GAS DEVIATION (COMPRESSIBILITY) FACTORS

SOURCE: Slider, 1976.

Figure 3-9
GAS DEVIATION FACTOR, z vs. (P_r/z)

SOURCE: Slider, 1976.

Example. Calculate the pressure increase when hydrate ($n = 6.3$) dissociates in a reservoir with a temperature of 8°C (506°R) and pressure of 1,500 psi.

The reservoir pressure does not affect the final pressure if no free gas is initially present. The calculations are as follows:

(1) For methane, $T_c = 343^{\circ}\text{R}$, $P_c = 673$ psia, so

$$(\text{Reduced } T) = 506/343 = 1.48$$

$$(\text{Reduced } P) = P/673$$

(2) We can calculate

$$P = \frac{131.69 (Z) (506)}{6.3} = 10,580 Z \text{ psia}$$

$$P_r (P = 10,580) = \frac{10,580}{673} = 15.7$$

(3) From Figures 3-8 and 3-9, we find that a Z value cannot be determined for $P_r/Z = 15.7$, but that the value of P_r/Z increases exponentially for P_r/Z greater than 8 when T_r is 1.48. For a T_r of 1.48, the highest P_r/Z value shown is 10. For this value of P_r/Z , $Z = 1.5$

(4) For $Z = 1.5$, the pressure of the formation can be calculated as

$$P = (1.50) (10,580) = 16,000 \text{ psia}$$

Upon dissociation of hydrate, the pressure in the formation and wellbore will, therefore, increase beyond 16,000 psi in a constant volume system, possibly resulting in casing collapse or fracturing of the formation. However, with the increase in pressure, hydrates will probably form again, so that the final increase in pressure is less.

The preceding example assumes that there is no free gas initially present in the reservoir and that the hydrate occupies 100% of the pore volume. If the hydrate occupies less than 100% of the pore volume, the pressure increase will be less. The general formula is

$$P = Z \frac{\left(\frac{2.7}{n} + n_{go}\right) 10.73 T}{\left[0.22 + \frac{f_g}{f_H}\right]} \quad \text{and} \quad n_{go} = \frac{P_o \left(\frac{f_g}{f_H}\right)}{10.73 T} \quad (3-8)$$

where f_H is the fraction of the pore volume occupied by hydrate and f_g is the fraction occupied by gas ($1-f_H$). P_o is the original reservoir pressure (1,500 psia in the example) and n_{go} is the number of moles of free gas per ft^3 of hydrate. Units of P are psia, T are $^{\circ}\text{R}$.

Example. Calculate the resulting pressure when hydrates dissociate for the example reservoir when hydrates occupy 50% of the reservoir pore volume and methane gas, at 1,500 psia, occupies the remainder.

$$(1) \quad n_{go} = \frac{1,500 \left(-\frac{1/2}{1/2}\right)}{10.73 \times 506} = 0.276$$

$$(2) \quad P_r = 1,500/673 = 2.23$$

(3) The value of Z can be determined from Figure 3-9 as 0.85 for $P_r/Z = 2.23$ and $T_c = 1.48$.

$$p = (0.85) \frac{(2.7/6.3) + (0.276) (10.73 \cdot 506)}{(0.22 + 0.05/0.05)} = 2,660 \text{ psia}$$

For this example, the pressure will be 2,660 psia when the hydrates have dissociated.

3. Equilibrium Saturation of Hydrates

Hydrate reservoirs may be oversaturated (contain gas and hydrate) or undersaturated (contain water and hydrate), depending on the original gas and water saturation. The previous calculations have shown that one cubic foot of 90% saturated hydrate I is formed from 0.78 ft³ of water (2.7 pound-mole) and 163 scf of methane (0.43 pound-mole). Should there be an excess of water or gas when hydrate is formed, the excess water or gas will not be hydrated.

4. Denuding

Gas hydrates may form from natural gas and liquids containing dissolved hydrate-forming gases. Thus, if hydrate-forming conditions exist in oil fields, the lighter (methane through n-butane) hydrocarbons can be removed from the crude oil. Such denuded crudes will have little dissolved gases to expel the crude and will have high viscosity. Production problems can be further complicated by the blockage of pores by hydrates.

Laboratory experiments showing the denuding effect of hydrate formation on a North Slope of Alaska crude oil containing dissolved gases is shown in Table 3-11. The table shows how the mol percent of methane (CH₄) in crude oil was decreased significantly from 32.8% to 17.0% by the formation of hydrates from the gases dissolved in the crude oil.

TABLE 3-11

DENUDING OF METHANE-PROPANE GASES FROM NORTH SLOPE CRUDE OIL*

<u>Component</u>	<u>Liquid Composition (mol percent)</u>			<u>Hydrate Composition (mol percent)</u>	
	<u>Initial</u> ¹	<u>Final</u> ²	<u>Change</u>	<u>Measured</u> ³	<u>Calculated</u> ⁴
CH ₄	32.8	17.0	-60.3%	85.9	84.6
C ₃ H ₈	14.5	14.2	-25.0%	14.1	15.4
Crude Oil	52.7	68.8	----		
<u>Quadruple Point</u> ⁵		<u>Initial</u>	<u>Final</u>		<u>Change</u>
Temperature, °F		74.3	63.2		-11.1
Pressure, psia		1,475	930		-545

*Crude Oil properties

Molecular weight
(Benzene freezing point method) 260
Specific gravity 0.932

1. Synthesized composition.
2. By flashing technique.
3. From gas evolved by melting hydrate crystals.
4. Amount denuded, calculated by material balance.
5. Four-phase (vapor, liquid hydrocarbon, liquid water, and hydrate) equilibrium point.

Source: Verma et al., 1975

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CHAPTER 4

THERMODYNAMIC PROPERTIES OF GAS HYDRATES

Evaluating the recoverability of the hydrate resource requires knowledge of hydrate thermodynamic properties, since they determine the energy required to dissociate gas hydrates and the rates at which dissociation can take place.

The first section, "Thermodynamic Models," shows that results from current theoretical models match experimentally determined hydrate property values. Based on the models, a simplified method to calculate the dissociation pressure as a function of temperature is given. A tabulation of experimental data for gas and gas mixture hydrates is included as an attachment to this chapter. This attachment is intended to serve as a reference to which theoretical results can be compared.

The second section contains phase diagrams for a wide variety of gas hydrates in graphical form, including single component gases, multi-component gases and gases with hydrate inhibitors.

The third section, "Hydrate Dissociation Energy," discusses the energy required to dissociate gas hydrates into its components, gas and water (or ice). Equations for calculating the dissociation energy of hydrates are given, and simple correlations are presented for single gas hydrates at temperatures near 0°C. The calculated dissociation energy for several multi-component gases is also given.

The fourth section discusses the thermal conductivity of pure hydrates and hydrate-impregnated sediments. This physical parameter governs heat flow in the hydrate reservoir and is important for evaluating hydrate producibility.

The fifth section discusses the kinetics of hydrate formation and dissociation. Little is known about hydrate kinetics, but experimental data to date on pure hydrates indicate that the dissociation rate of hydrates will depend on the previous thermal history of the deposit.

The final section contains data on hydrate heat capacities. Preliminary experimental results show that it is slightly higher than the heat capacity of ice.

A. THERMODYNAMIC MODELS

1. Model Description

The initial framework for calculating hydrate dissociation energy was developed by Van der Waals and Platteeuw (1959). It is based on the following assumptions:

- (a) The contribution of the water molecules to the free energy is independent of the mode of occupation of the cavities. This excludes clathrates in which the dimensions of the encaged molecules seriously distort the host lattice; e.g., CO_2 or CH_3CN in hydroquinone;
- (b) The encaged molecules are localized in the cavities, which can only contain one solute molecule,
- (c) The mutual interaction of the solute molecules is neglected; i.e., the partition function for the motion of a solute molecule in its cage is independent of the number and types of solute molecules present, and,
- (d) Classical statistical thermodynamics are valid.

Under these assumptions, the chemical potential of a water molecule in the clathrate phase can be expressed as:

$$\Delta\mu_H = \mu_\beta - \mu_H = -RT \sum_{j=1}^2 v_j \ln (1 - \sum_i \theta_{ij}) \quad (4-1)$$

where μ_β and μ_H are the chemical potential of the occupied and unoccupied lattice water, respectively; R is the gas constant, T is temperature, and v_j is the ratio of the number of j cavities to number of water molecules in the hydrate phase. The variable θ_{ij} is the fraction of the j cavities which are occupied by an i type gas molecule. (For a binary water-gas mixture, methane-water, for example, only one gas is in the lattice and θ_j represents the occupancy of the j type cavities by the gas.)

The fraction of the cavities occupied by gas is given by the Langmuir isotherm

$$\theta_{ij} = C_{ij}f_i / (1 + \sum_i C_{ij}f_i) \quad (4-2)$$

where C_{ij} are constants and f_i is the gas-phase fugacity of the i th gas species and is calculated using a modern equation of state, such as the Perry-Robinson equation (1976).

The Langmuir coefficient, C_{ij} , is determined by integrating the gas-water potential interaction function over the volume of the cavity:

$$C_{ij} = \frac{4\pi}{RT} \int_{\text{volume}}^{\text{cell}} \exp(-w(r)/RT) r^2 dr \quad (4-3)$$

In this expression, r is the distance of an enclathrated gas molecule from the center of the cell, and the term $w(r)$ is the intermolecular potential function, which is discussed below.

The Langmuir coefficient, C_{ij} , depends on cavity size, temperature, and the value of the potential function, $w(r)$. Thus, the value of C_{ij} is different for each cavity type, and the fractional occupancy θ of the large and small cavities by any gas species will be different.

Many functions have been used for expressing the intermolecular potential in the theoretical model, reflecting advances in the understanding of hydrates.

- Van der Waals and Platteeuw (1959) used the Lennard-Jones 6-12 potential and had mixed results in predicting hydrate dissociation pressures. McKoy and Sinanoglu (1963) tried other potential functions and found that the interaction of water with rod-like molecules, such as ethane, could be more accurately described by the Kihara line core potential.

- Instead of using calculated potential parameters, Kobayashi and co-workers determined potential parameters for methane, nitrogen and argon hydrates (Marshall et al., 1964) by fitting experimental and calculated hydrate dissociation pressures. In this manner, accurate hydrate dissociation pressures could be predicted for the first time. Errors in predicted dissociation pressures were reduced from as much as one hundred percent to less than five percent.
- Parrish and Prausnitz (1972) expanded the concept of fitting hydrate parameters to develop a generalized method for predicting hydrate dissociation pressures of fifteen different gases and mixtures. This work yielded excellent results for hydrate dissociation pressures of binary gas-water mixtures but gave erratic results for dissociation pressures of the few multi-component mixtures that were studied.
- Ng and Robinson (1976) added an empirically adjustable parameter to this algorithm and improved the prediction of specific multi-component dissociation pressures. This modified algorithm also predicts the conditions for hydrate formation from condensed systems.
- Recently, Dharmawardhana, Parrish and Sloan (1981), and John and Holder (1982) improved this model by optimizing the experimentally undetermined zero-point properties (the enthalpy and chemical potential differences between the unoccupied hydrate lattice and ice at 273°K and zero pressure).

With the most recent advances, hydrate models are now able to predict the phase behavior and the combinations of pressure-temperature at which hydrates form within 5 percent for single and multi-component gas hydrates at pressures below 2,000 psi. Above this pressure, the accuracy slowly decreases.

2. Model Results

The theoretical models match experimental results well, as shown on Figures 4-1, 4-2, and 4-3 for mixtures of methane, ethane, and propane. The model used in these calculations was developed by Holder and Hand. The figures illustrate the capacity to predict dissociation pressures and phases as a function of temperature for single and multi-component systems. Smoothed experimental data for single gas and multi-gas hydrates are presented in the Attachment 3-1 at the end of the chapter and can be used to verify the model results in Figures 4-1 and 4-2.

Based on the model and its match with experimental results, simplified correlations can be derived for the dissociation pressure as a function of temperature as follows:

$$P = \exp [a + b/T] \quad (4-4)$$

where the temperature, T , is in $^{\circ}\text{K}$, the pressure, P , is in kPa, and a and b are empirically derived constants. The values for a and b and the range in which these coefficients apply is shown on Table 4-1.

Example

Experimental values of the dissociation pressure for methane hydrate are compared below with calculated values using the correlation equation:

<u>Gas Hydrate</u>	<u>Temperature</u> ($^{\circ}\text{K}$)	<u>Dissociation Pressure (kPa)</u>		<u>Difference</u>	
		<u>Exp. Smoothed</u> (kPa)	<u>Correlation</u> (kPa)	<u>kPa</u>	<u>%</u>
Methane	256.8	1,520	1,587	(67)	4
Methane	263.2	1,860	1,898	(38)	2
Methane	273.2	2,570	2,467	(103)	4
Methane	293.2	6,950	6,952	2	-

The dissociation pressures calculated using the correlation match the smoothed experimental data to within 4%.

Figure 4-1

COMPARISON OF EXPERIMENTAL
AND CALCULATED DISSOCIATION
PRESSURES OF VL₁H HYDRATE CURVES OF
METHANE-PROPANE-WATER MIXTURES

Figure 4-2

COMPARISON OF EXPERIMENTAL
AND CALCULATED DISSOCIATION
PRESSURES OF VL₁H HYDRATE CURVES OF
METHANE-ETHANE-WATER MIXTURES

Figure 4-3

COMPARISON OF EXPERIMENTAL AND
CALCULATED DISSOCIATION PRESSURE
OF VL₁L₂H, VL₁H₁H₂ AND
VL₁L₂H₁H₂ HYDRATE CURVES OF METHANE-
ETHANE-PROPANE-WATER MIXTURES

TABLE 4-1
CORRELATION COEFFICIENTS FOR CALCULATING
DISSOCIATION PRESSURES

<u>Gas</u>	<u>Hydrate Structure</u>	<u>a*</u>	<u>b*</u>	<u>Temperature range, °C</u> (°K = 273 + °C)
CH ₄	I	14.7170	-1886.79	-25 to 0°C
CH ₄	I	38.9803	-8533.80	0 to 25°C
C ₂ H ₆	I	17.5110	-3104.535	-25 to 0°C
C ₂ H ₆	I	44.2728	-10424.248	0 to 14°C
C ₃ H ₈	II	17.1560	-3269.6455	-25 to 0°C
C ₃ H ₈	II	67.1301	-16921.84	0 to 5°C
CO ₂	I	18.5939	-3161.41	-25 to 0°C
CO ₂	I	44.5776	10245.01	0 to 11°C
N ₂	I	15.1289	-1504.276	-25 to 0°C
N ₂	I	37.8079	-7688.6255	0 to 25°C
H ₂ S	I	16.5597	-3270.409	-25 to 0°C
H ₂ S	I	34.8278	8266.1023	0 to 25°C

* a and b are empirically derived constants.

Source: Holder, personal communication.

B. PHASE DIAGRAMS

This section contains phase diagrams of hydrates for single-gas and multi-gas systems. These phase diagrams show which phases (gas, liquid, solid, hydrate) are stable as a function of temperature and pressure. The diagrams can be used to determine the phases in a reservoir when the temperature and pressure are known.

1. Single Gas Systems

The phase diagram of methane hydrate for a single gas system is shown in Figure 4-4. At temperatures just below 0°C (32°F) and at low pressures, ice and methane gas co-exist. The quadruple point, where ice, CH_4 hydrate, water, and $\text{CH}_4(\text{g})$ are in equilibrium is slightly below 0°C (-0.19°C) and 25.3 atm (372 psia). As the pressure is increased above 25.3 atmospheres, the stable phases become hydrate and gas. The phase diagram also shows that hydrates may form at temperatures above 0°C , at higher pressures. Since these conditions are encountered under permafrost, gas can be expected to exist in hydrate form there.

Predicted and measured phase diagrams for various gas hydrates are shown in Figure 4-5. With the exception of nitrogen, these gases form hydrates at higher temperatures than methane. Thus, these gas hydrates may exist at greater depths than methane hydrates. Data on the dissociation temperature of 69 simple hydrates at a pressure of one atmosphere and other phase data, such as the quadruple points, are given in Attachment 4-2.

2. Multi-gas Systems

The overall phase diagram for (methane + ethane) hydrate equilibria is shown on Figure 4-6 (Holder and Grigoriou, 1980). It has two points of interest. The first is that the curve containing $(0.10 \text{ CH}_4 + 0.90 \text{ C}_2\text{H}_6)$ crosses the curve for pure ethane; and the second is that at temperatures higher than about 281°K , the mixture has lower dissociation pressures than pure ethane. The reason some (methane + ethane) hydrate dissociation-pressure curves cross the dissociation-pressure curve of ethane hydrate is that some

Figure 4-4

PHASE DIAGRAM OF METHANE HYDRATE

THE LINE HYDRATE + CH₄(l) + CH₄(g) ENDS VERY CLOSE TO THE CRITICAL POINT OF METHANE (191 °K). Q IS THE QUADRUPLE POINT (ICE + HYDRATE + WATER + CH₄(g)).

SOURCE: Miller, 1974.

Figure 4-5

DISSOCIATION PRESSURES OF CH₄, C₂H₆, C₃H₈, CO₂, H₂S AND N₂ HYDRATES

SOURCE: Holder, 1983.

Figure 4-6
METHANE AND ETHANE HYDRATE EQUILIBRIUM

SOURCE: Holder and Grigoriou, 1980.

mixtures have dissociation pressures lower, and some higher, than those of ethane hydrate. For dissociation-pressure curves not to cross, all curves would have to be parallel or asymptotic and one mixture curve would be required to have exactly the same dissociation pressure as ethane hydrate at every temperature. In fact, the curve of any mixture with less than about 0.15 to 0.20 percent methane will cross the curve for pure ethane at some temperature; the temperature of intersection increasing as the percent of methane increases.

The figure also shows that ethane-methane hydrate mixtures form at lower pressures (at the same temperature) than pure methane hydrates. Thus, the presence of ethane will increase the zone of hydrate stability.

Hydrate phase diagrams for natural gas mixtures are shown in Figure 4-7. The curves exhibit two characteristics, namely: (1) hydrates form at lower pressure than for methane, and (2) the slope changes as the temperature increases.

Phase diagrams for hydrate mixtures of methane and other gases are shown in Figure 4-8. These figures illustrate how sensitive dissociation pressures can be to the vapor phase composition, particularly for propane and hydrogen sulfide.

3. Gas Hydrate Phase Diagrams with Inhibitors

While the addition of other gases generally increases the range of hydrate stability, the role of inhibitors is to reduce the range of hydrate stability, thus preventing hydrates from forming (for example in transmission facilities).

The higher the gas gravity, the lower the amount of inhibitor needed for a change to occur. The depression of hydrate formation temperature for various inhibitors (methanol, sodium and calcium chloride) is dependent on the amount of inhibitor (Figure 4-9 and Figure 4-10). The figures show that the hydrate formation temperature can be depressed as much as 20°F for a 20 weight percent solution of inhibitor.

Figure 4-7

SOURCE: GRI, 1979.

Figure 4-8

EFFECT OF OTHER GAS COMPONENTS ON METHANE HYDRATE EQUILIBRIUM

(1 psi = 6.8947 kPa)

SOURCE: Goodman, 1982.

Figure 4-9

DEPRESSION OF HYDRATE-FORMATION TEMPERATURES BY INHIBITORS

SOURCE: Scott, IGT, 1980.

FIGURE 4-10
EFFECT OF SALT SOLUTION ON HYDRATE FORMATION

SOURCE: GRI, 1979.

C. HYDRATE DISSOCIATION ENERGY

Hydrate dissociation energy is defined as the energy required to create a phase change and thus dissociate hydrate into its components, gas and water or ice. This energy is a function of pressure, temperature, and gas composition.

The decomposition energy of the hydrate equals the energy of its formation for single-component gases. However, this may not be the case for multi-component gas hydrates where the formation of hydrates may result in different compositions of the gas in the solid and gaseous phases. Figure 4-11 shows the difference between the energy of formation and decomposition of gas hydrates of the Shebelin and Orenburg fields in the USSR. Also, the pressure-temperature conditions at which the hydrate formation process starts and at which decomposition of the hydrate gas mixtures ends, are not the same, because of the different compositions of gas.

The hydrate dissociation energy, or the enthalpy of formation, is calculated from

$$\Delta H_D = T \cdot \Delta V \cdot \frac{dP}{dT} \quad (4-5)$$

where ΔV is the change in volume due to hydrate formation. This can be modified to

$$\Delta H_D = ZRT^2 \frac{d \ln P}{dT} - n \Delta V_w T \frac{dP}{dT} \quad (4-6)$$

where:

Z = the compressibility factor of the gas in equilibrium with the hydrate,

R = the gas constant,

ΔV_w = the volume change, Table 4-2, and

n = the hydrate number.

At low pressures ($P < 1,000$ kPa) the second term of Equation 4-5 can be neglected.

FIGURE 4-1

COMPARISON OF EXPERIMENTAL AND CALCULATED
DISSOCIATION PRESSURES OF VL₁H HYDRATE CURVES OF METHANE-PROPANE-WATER
MIXTURES

HEAT OF HYDRATE FORMATION OF INDIVIDUAL
GASES AT EQUILIBRIUM CONDITIONS.
FIELDS: I-ORENBURG, II-SHEBELIN

HEAT OF FORMATION (1)
AND OF DECOMPOSITION (2)
OF GAS HYDRATES AT THE SHEBELIN (a)
AND (b) FIELDS (4.5% H₂S)

PRESSURE-TEMPERATURE CONDITIONS
OF FORMATION(1) AND
OF DECOMPOSITION (2) OF
GAS HYDRATES AT THE SHEBELIN FIELD

SOURCE: MaKogon, 1981.

TABLE 4-2
VOLUME CHANGES ΔV_w UPON CONVERTING WATER TO HYDRATE
 (cm³/gmol-water)

<u>Structure</u>	<u>T < 273.15°K</u>	<u>T > 273.15°K</u>
I	3.0	4.6
II	3.4	5.0

By inserting Equation 4-4 into Equation 4-6, a straight-line correlation can be developed for the dissociation energy of single-component gas hydrates as follows:

$$\Delta H_D \text{ (cal/mole)} = c + d \cdot (273+T) \text{ T in } ^\circ\text{C} \quad (4-7)$$

where values of c and d are shown on Table 4-3.

TABLE 4-3
COEFFICIENTS FOR CALCULATING DISSOCIATION ENERGY

<u>GAS</u>	<u>c</u>	<u>d</u>	<u>Temperature range</u>
CH ₄	6,534	-12.0	-25 to 0°C
	13,521	-4.0	0 to 25°C
C ₂ H ₆	8,458	-9.6	-25 to 0°C
	13,254	15.0	0 to 14°C
C ₃ H ₈	7,609	-4.9	-25 to 0°C
	-37,752	250.1	0 to 5°C
CO ₂	9,290	-12.9	-25 to 0°C
	19,199	-15.0	0 to 11°C
N ₂	493,424	-9.0	-25 to 0°C
	6,188	18.4	0 to 25°C
H ₂ S	8,488	-7.8	-25 to 0°C
	6,782	31.5	0 to 25°C

Calculated values of the dissociation energy for various gas mixtures are shown on Figures 4-12 and 4-13. The figures show that for multi-component gas hydrates, the dissociation energy may not be a linear function of temperature.

Figure 4-12

ENTHALPY-TEMPERATURE DIAGRAM FOR CH₄/C₃H₈ AND CH₄/C₂H₆ HYDRATES

Figure 4-13

ENTHALPY-TEMPERATURE DIAGRAMS FOR CH₄/C₂H₆/C₃H₈ HYDRATES

Example

The dissociation energy to produce one mole of methane gas from methane hydrate at 0°C can be calculated as

$$\Delta H_D \text{ (cal/g mole)} = 6,534 - 12 (273 + 0) = 3,258 \quad T = 0-^{\circ}\text{C}$$

$$\Delta H_D \text{ (cal/g mole)} = 13,520 - 4 (273 + 0) = 12,428 \quad T = 0+^{\circ}\text{C}$$

The energy required to dissociate hydrate into ice and gas at 0°C is 3,258 cal per gram-mole of gas dissociated, while 12,428 cal per gram-mole are required to dissociate hydrate into gas and water.

D. THERMAL CONDUCTIVITY

The thermal conductivity of pure natural gas hydrates is approximately 0.94×10^{-3} cal/cm/s/°K (Stoll and Bryan, 1979). This is surprisingly low, only about 1/5 that of ice and the reason for this difference in the thermal conductivities of two very similar substances is not clear.

Dharmawardhana (1983) suggests that the difference is due to stretching from the angles found normally in ice. Other investigators, such as Ross and Andersson (1982), believe that a phonon scattering mechanism is involved.

Calculated conductivities of several composite materials, are listed in Table 4-4.

TABLE 4-4
THERMAL CONDUCTIVITIES OF NATURAL GAS HYDRATES^{a/}

<u>Rock Type</u>	<u>k_s</u>	<u>Φ</u>	<u>Conductivity Water-Saturated</u>	<u>Conductivity Hydrate-Saturated</u>	<u>Conductivity Ice-Saturated</u>
Sandstone	19.2	13	16.0	15.9	16.8
	20.4	29	13.3	13.1	15.0
Iwahi Sandstone	3.5	20	3.0	2.9	3.1
Limestones	12.0	21	9.1	8.9	10.4
Ocean Sediments	9.2	68	3.4	3.0	6.2

^{a/} All thermal conductivities in 10^{-3} cal/cm/s/°K where k_s is the matrix thermal conductivity, and Φ is porosity, percent.

Source: Pearson, 1982

E. KINETICS OF HYDRATE FORMATION/DECOMPOSITION

Under rapid dissociation conditions, both heat transfer and mass transfer limitations across the hydrate-gas-water interfaces will be important. Only a few results have been obtained in the Western world on mass transfer kinetics, by Bishnoi and Vysniauskus (1983), and on heat transfer rates, by Holder (1982). While the exact formation process is still unknown with respect to quantitative rates, the Russians under the leadership of Y.F. Makogon (1974) have studied this subject extensively, and they have developed an extensive qualitative model of hydrate kinetics. Their model explains much of the behavior of hydrates and is discussed below.

A knowledge of the formation of hydrates is closely allied to the structure of water (and its solid form - ice) since water accounts for 78 to 87 percent of the total mass of the gas hydrate.

In ice, each water molecule is hydrogen bonded to four other water molecules to form a larger tetragon. This hydrogen bonding gives a very open structure for ice, shown in Figure 4-14, as well as to water and the hydrate structures. The water molecules occupy 33.9%, 37%, 29.4%, and 28.1% of the total volume in ice, water, hydrate structure I, and hydrate structure II, respectively.

In the liquid state many water molecules are usually bonded together as shown by the groups of 2 to 20 molecules in Figure 4-15. These bonds normally occur and disappear on a very short time scale. Table 4-5 shows the average number of clustered molecules as a function of temperature. In order to crystallize to a hydrate cell nucleus, a guest molecule, such as methane, must attract and stabilize a group of clusters as shown in the middle of Figure 4-15, resulting in a basic hydrate cell like that at the bottom right of the figure.

Figure 4-14
STRUCTURAL MODEL OF ICE

Figure 4-15
FORM OF WATER MOLECULE AGGREGATES

SOURCE: Sloan, 1983.

TABLE 4-5
AVERAGE NUMBER OF WATER MOLECULES IN CLUSTER
AS A FUNCTION OF TEMPERATURE

<u>Temperature</u> <u>°C</u>	<u>Number of Molecules</u> <u>in Cluster</u>
0	860
25	455
50	288
100	70
150	37
200	16
250	8
300	4
350	1-2

Upon dissociation of hydrates, the guest molecules are freed, but many of the hydrogen bonds remain, so that it is easier to form hydrates the second time than initially, when substantial subcooling is required. This is dramatically illustrated in the cooling curves of Schroeter and Kobayashi (1982) in Figure 4-16 for H₂S-methane-propane hydrates. The region near the hydrate formation point shows a hysteresis curve in pressure versus temperature, whose magnitude depends on the number of previous hydrate formations. Curve S₁ is the first hydrate formation, S₂ is the second formation, and S₃ the third. Systems containing a smaller number/size of nucleating micro-crystals would exhibit a greater amount of supercooling. This figure also illustrates that water clusters, or micro-crystals, are broken by raising the resultant liquid to a higher temperature before reforming the hydrates. The "remembered hydrate" structure of the water is almost completely eroded when the water is heated above 30°C (86°F).

The following three quantitative statements concerning the rate of formation or dissociation of hydrate crystal nuclei appear true, based on the current state of knowledge.

1. The process of hydrate formation occurs at on the gas-water interface.
2. In a volume of water, the forming of hydrate nuclei is hindered by the extremely low molar content of guest gases in the water. The nuclei must reach a critical size (requiring many gas molecules) to be thermodynamically stable.

Figure 4-16

SOURCE: Schroeter, J. P., et al., 1982.

3. In the hydrocarbon vapor or liquid phase, the clustering of water molecules is unlikely in the absence of complete saturation of the hydrocarbon phase with moisture. In completely saturated hydrocarbons, the water molecules do cluster into fixed bonds that form the basis for hydrate centers.

F. HEAT CAPACITIES

Heat capacities as a function of temperature, and heats of dissociation for tetrahydrofuran (THF) II, ethylene oxide (EtO)I, and cyclopropane (Cy) I and II have recently been reported (Callanan and Sloan, 1983). The heat capacities were found to vary both with structure and with guest molecule.

It seems that the dramatic effects of hydrate formation noted in the thermal conductivity are not reflected in heat capacity. Average heat capacity values for four hydrates and water are shown in Figure 4-17. The curves for ethylene oxide (I) and cyclopropane (II) lie close to that of water. The curve for tetrahydrofuran (II) lies about 3 to 6 percent lower; that for cyclopropane (I), 9 to 12 percent lower. Figure 4-14 also shows that for Structure II hydrates the guest causes a difference of 5 to 8 percent in the measured heat capacities. For Structure I hydrates the difference is greater (9 to 11 percent).

The heat capacities obtained by Callanan and Sloan for the tetrahydrofuran specimens, are about 13 to 14 percent higher than those of Cook and Laubitz (1981) which are considered to be pure hydrates. They are 10 percent higher than those established from the curves given by Ross and Andersson (1982) at 260°K. However, these specimens contained admixed ice. The experimental results of specimens studied by Leaist et al., (1982) with less admixed ice agree with the results within the combined experimental error. However, the values given by Leaist for the ethylene oxide hydrate are about five percent lower than those of Callanan and Sloan.

Figure 4-17
HYDRATE HEAT CAPACITY

CI, CYCLOPROPANE I;
CII, CYCLOPROPANE II;
T, TETRAHYDROFURAN;
E, ETHYLENE OXIDE;
W, WATER

SOURCE: Callanan and Sloan, 1983.

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ATTACHMENT 4-1
EXPERIMENTAL HYDRATE DATA

Experimental data for various gas hydrates are shown on the following tables, "Temperature Pressure Dissociation Relationships for Various Hydrates, Experimental Hydrate Data (Smoothed)," (Attachment 4-1A) and "Temperature Pressure Dissociation Relationships for Various Hydrates, Experimental Data," (Attachment 4-1B). The measured data (smoothed) in Attachment 4-1A are summarized in the PhD thesis of John (1981) and have been smoothed by Holder, 1983.

ATTACHMENT 4-1A

TEMPERATURE PRESSURE DISSOCIATION RELATIONSHIPS FOR VARIOUS HYDRATES
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane</u>			
CH ₄	193.2	101	I
CH ₄	256.8	1,500	I
CH ₄	263.2	1,860	I
CH ₄	273.2	2,570	I
CH ₄	283.2	6,950	I
CH ₄	290.2	15,928	I
CH ₄	301.6	65,432	I
<u>Methane-Propane</u>			
CH ₄ (23.8%)C ₃ H ₈ (76.2%)	273.2	205	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	273.2	219	II
CH ₄ (71.2%)C ₃ H ₈ (28.8%)	273.2	290	II
CH ₄ (88.3%)C ₃ H ₈ (11.7%)	273.2	441	II
CH ₄ (99.0%)C ₃ H ₈ (1.0%)	273.2	1,302	II
CH ₄ (23.8%)C ₃ H ₈ (76.2%)	274.4	256	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	275.0	297	II
CH ₄ (71.2%)C ₃ H ₈ (28.8%)	275.4	393	II
CH ₄ (88.3%)C ₃ H ₈ (11.7%)	275.4	586	II
CH ₄ (99.0%)C ₃ H ₈ (1.0%)	275.4	1,710	II
CH ₄ (23.8%)C ₃ H ₈ (76.2%)	276.1	340	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	276.7	390	II
CH ₄ (71.2%)C ₃ H ₈ (28.8%)	277.6	538	II
CH ₄ (88.3%)C ₃ H ₈ (11.7%)	277.6	772	II

Source: Holder, Personal communication.

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Propane (continued)</u>			
CH ₄ (99.0%)C ₃ H ₈ (1.0%)	277.6	2,227	II
CH ₄ (23.8%)C ₃ H ₈ (76.2%)	277.8	450	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	278.3	510	II
CH ₄ (23.8%)C ₃ H ₈ (76.2%)	279.4	594	II
CH ₄ (88.3%)C ₃ H ₈ (11.7%)	279.8	1,027	II
CH ₄ (99.0%)C ₃ H ₈ (1.0%)	279.8	2,958	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	280.0	665	II
CH ₄ (71.2%)C ₃ H ₈ (28.8%)	280.9	848	II
CH ₄ (37.1%)C ₃ H ₈ (62.9%)	281.7	864	II
CH ₄ (71.2%)C ₃ H ₈ (28.8%)	283.2	1,158	II
CH ₄ (88.3%)C ₃ H ₈ (11.7%)	283.2	1,544	II
CH ₄ (99.0%)C ₃ H ₈ (1.0%)	283.2	4,420	II
<u>Methane-Ethane-Propane</u>			
CH ₄ (45.4%)C ₂ H ₆ (45.7%)C ₃ H ₈ (8.9%)	275.8	917	I
CH ₄ (17.4%)C ₂ H ₆ (70.5%)C ₃ H ₈ (12.1%)	280.5	1,393	I
CH ₄ (45.4%)C ₂ H ₆ (45.7%)C ₃ H ₈ (8.9%)	280.8	1,682	I
CH ₄ (36.4%)C ₂ H ₆ (54.1%)C ₃ H ₈ (9.5%)	281.4	1,724	I
CH ₄ (17.4%)C ₂ H ₆ (70.5%)C ₃ H ₈ (12.1%)	281.4	1,586	I
CH ₄ (45.4%)C ₂ H ₆ (45.7%)C ₃ H ₈ (8.9%)	282.0	1,882	I
CH ₄ (17.4%)C ₂ H ₆ (70.5%)C ₃ H ₈ (12.1%)	282.2	1,779	I
CH ₄ (36.4%)C ₂ H ₆ (54.1%)C ₃ H ₈ (9.5%)	282.5	2,006	I
CH ₄ (36.4%)C ₂ H ₆ (54.1%)C ₃ H ₈ (9.5%)	283.8	2,275	I
CH ₄ (17.4%)C ₂ H ₆ (70.5%)C ₃ H ₈ (12.1%)	284.0	2,165	I
CH ₄ (36.4%)C ₂ H ₆ (54.1%)C ₃ H ₈ (9.5%)	285.0	2,758	I
CH ₄ (45.4%)C ₂ H ₆ (45.7%)C ₃ H ₈ (8.9%)	285.2	2,758	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Argon</u>			
CH ₄ (26.2%) Ar (73.8%)	273.2	5,750	I
CH ₄ (49.3%) Ar (50.7%)	273.2	4,160	I
CH ₄ (75.0%) Ar (25.0%)	273.2	3,180	I
CH ₄ (26.2%) Ar (73.8%)	283.2	16,359	I
CH ₄ (49.3%) Ar (50.7%)	283.2	12,700	I
CH ₄ (75.0%) Ar (25.0%)	283.2	9,600	I
CH ₄ (73.5%) Kr (26.5%)	273.2	1,780	I
CH ₄ (36.0%) Kr (64.0%)	273.2	1,550	I
CH ₄ (73.5%) Kr (26.5%)	283.2	4,750	I
CH ₄ (36.0%) Kr (64.0%)	283.2	3,950	I
<u>Ethane</u>			
C ₂ H ₆	262.1	293	I
C ₂ H ₆	267.6	375	I
C ₂ H ₆	273.2	462	I
C ₂ H ₆	278.7	944	I
C ₂ H ₆	284.3	1,943	I
<u>Ethane-Methane</u>			
C ₂ H ₆ (25.0%) CH ₄ (75.0%)	273.2	1,003	I
C ₂ H ₆ (90.0%) CH ₄ (10.0%)	273.2	441	I
C ₂ H ₆ (75.0%) CH ₄ (25.0%)	273.2	496	I
C ₂ H ₆ (50.0%) CH ₄ (50.0%)	273.2	684	I
C ₂ H ₆ (25.0%) CH ₄ (75.0%)	278.7	1,955	I
C ₂ H ₆ (90.0%) CH ₄ (10.0%)	278.7	918	I
C ₂ H ₆ (75.0%) CH ₄ (25.0%)	278.7	1,034	I
C ₂ H ₆ (50.0%) CH ₄ (50.0%)	278.7	1,351	I
C ₂ H ₆ (25.0%) CH ₄ (75.0%)	284.3	3,603	I
C ₂ H ₆ (90.0%) CH ₄ (10.0%)	284.3	1,914	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Ethane-Methane (Continued)</u>			
C ₂ H ₆ (75.0%) CH ₄ (25.0%)	284.3	2,159	I
C ₂ H ₆ (50.0%) CH ₄ (50.0%)	284.3	2,671	I
<u>Propane</u>			
C ₃ H ₈	250.0	53	II
C ₃ H ₈	252.8	62	II
C ₃ H ₈	255.6	72	II
C ₃ H ₈	258.3	84	II
C ₃ H ₈	261.1	96	II
C ₃ H ₈	263.9	111	II
C ₃ H ₈	266.7	127	II
C ₃ H ₈	269.4	146	II
C ₃ H ₈	272.2	166	II
C ₃ H ₈	273.9	195	II
C ₃ H ₈	275.0	248	II
C ₃ H ₈	276.1	315	II
C ₃ H ₈	277.2	399	II
<u>Propane-Ethane</u>			
C ₃ H ₈ (27.1%) C ₂ H ₆ (72.9%)	273.4	476	II
C ₃ H ₈ (34.2%) C ₂ H ₆ (65.8%)	273.9	434	II
C ₃ H ₈ (27.1%) C ₂ H ₆ (72.9%)	274.3	600	II
C ₃ H ₈ (26.0%) C ₂ H ₆ (74.0%)	274.5	648	II
C ₃ H ₈ (34.2%) C ₂ H ₆ (65.8%)	275.0	607	II
C ₃ H ₈ (27.1%) C ₂ H ₆ (72.9%)	275.6	862	II
C ₃ H ₈ (15.0%) C ₂ H ₆ (85.0%)	275.7	731	II
C ₃ H ₈ (54.1%) C ₂ H ₆ (45.9%)	275.8	490	II
C ₃ H ₈ (57.7%) C ₂ H ₆ (44.3%)	275.9	496	II
C ₃ H ₈ (34.2%) C ₂ H ₆ (65.8%)	276.2	820	II
C ₃ H ₈ (72.0%) C ₂ H ₆ (28.0%)	276.5	469	II

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Propane-Ethane (Continued)</u>			
C ₃ H ₈ (34.2%) C ₂ H ₆ (65.8%)	276.5	883	II
C ₃ H ₈ (55.7%) C ₂ H ₆ (44.3%)	276.7	600	II
C ₃ H ₈ (72.0%) C ₂ H ₆ (28.0%)	276.9	517	II
C ₃ H ₈ (54.1%) C ₂ H ₆ (45.9%)	277.0	655	II
C ₃ H ₈ (15.0%) C ₂ H ₆ (85.0%)	277.2	896	I
C ₃ H ₈ (55.7%) C ₂ H ₆ (44.3%)	277.4	717	II
C ₃ H ₈ (72.0%) C ₂ H ₆ (28.0%)	277.9	655	II
C ₃ H ₈ (54.1%) C ₂ H ₆ (45.9%)	278.0	848	II
C ₃ H ₈ (18.6%) C ₂ H ₆ (81.4%)	278.9	1,207	I
C ₃ H ₈ (18.6%) C ₂ H ₆ (81.4%)	279.5	1,303	I
C ₃ H ₈ (14.3%) C ₂ H ₆ (85.7%)	279.7	1,207	I
C ₃ H ₈ (14.3%) C ₂ H ₆ (85.7%)	280.2	1,303	I
C ₃ H ₈ (15.0%) C ₂ H ₆ (85.0%)	280.6	1,400	I
C ₃ H ₈ (15.0%) C ₂ H ₆ (85.0%)	280.7	1,413	I
<u>Propane-Hydrogen Sulphide</u>			
C ₃ H ₈ (98.5%) H ₂ S (1.5%)	270.2	132	II
C ₃ H ₈ (97.0%) H ₂ S (3.0%)	270.2	111	II
C ₃ H ₈ (93.0%) H ₂ S (7.0%)	270.2	86	II
C ₃ H ₈ (89.5%) H ₂ S (10.5%)	270.2	71	II
C ₃ H ₈ (77.0%) H ₂ S (23.0%)	270.2	61	II
C ₃ H ₈ (62.0%) H ₂ S (38.0%)	270.2	58	II

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Propane-Hydrogen Sulfide</u>			
C ₃ H ₈ (52.0%) H ₂ S (48.0%)	270.2	56	II
C ₃ H ₈ (27.5%) H ₂ S (72.5%)	270.2	51	II
<u>Ethylene</u>			
C ₂ H ₄	273.9	593	I
C ₂ H ₄	275.0	683	I
C ₂ H ₄	276.1	786	I
C ₂ H ₄	277.2	903	I
C ₂ H ₄	278.3	1,041	I
C ₂ H ₄	280.0	1,276	I
C ₂ H ₄	281.7	1,558	I
C ₂ H ₄	283.3	1,903	I
C ₂ H ₄	285.0	2,317	I
C ₂ H ₄	286.7	2,820	I
C ₂ H ₄	288.3	3,413	I
C ₂ H ₄	291.7	9,094	I
C ₂ H ₄	292.8	11,818	I
C ₂ H ₄	293.9	15,334	I
C ₂ H ₄	295.0	19,857	I
C ₂ H ₄	296.1	25,662	I
C ₂ H ₄	297.2	33,102	I
C ₂ H ₄	298.3	42,617	I
C ₂ H ₄	299.4	54,759	I
C ₂ H ₄	300.6	70,237	I
C ₂ H ₄	301.7	89,922	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Propylene</u>			
C ₃ H ₆	272.8	465	II
C ₃ H ₆	272.9	470	II
C ₃ H ₆	272.9	475	II
C ₃ H ₆	273.4	524	II
C ₃ H ₆	273.6	547	II
C ₃ H ₆	273.7	569	II
C ₃ H ₆	273.9	592	II
Cyclo - C ₃ H ₆	263.9	42	II
Cyclo - C ₃ H ₆	266.1	46	II
Cyclo - C ₃ H ₆	268.3	51	II
Cyclo - C ₃ H ₆	270.6	56	II
Cyclo - C ₃ H ₆	272.2	61	II
Cyclo - C ₃ H ₆	273.9	76	II
Cyclo - C ₃ H ₆	243.6	13	I
Cyclo - C ₃ H ₆	249.3	19	I
Cyclo - C ₃ H ₆	260.1	35	I
Cyclo - C ₃ H ₆	276.0	103	I
Cyclo - C ₃ H ₆	277.7	125	I
Cyclo - C ₃ H ₆	278.8	146	I
Cyclo - C ₃ H ₆	280.0	172	I
Cyclo - C ₃ H ₆	281.6	210	I
<u>n-Butane-Methane</u>			
n-C ₄ H ₁₀ (1.5%) CH ₄ (98.5%)	252.8	778	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	252.8	648	II
n-C ₄ H ₁₀ (3.5%) CH ₄ (96.5%)	252.8	574	II

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>n-Butane-Methane (continued)</u>			
n-C ₄ H ₁₀ (7.5%) CH ₄ (92.5%)	252.8	441	II
n-C ₄ H ₁₀ (10.5%) CH ₄ (89.5%)	252.8	392	II
n-C ₄ H ₁₀ (1.5%) CH ₄ (98.5%)	258.3	1,023	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	258.3	852	II
n-C ₄ H ₁₀ (3.5%) CH ₄ (96.5%)	258.3	752	II
n-C ₄ H ₁₀ (7.5%) CH ₄ (92.5%)	258.3	574	II
n-C ₄ H ₁₀ (10.5%) CH ₄ (89.5%)	258.3	508	II
n-C ₄ H ₁₀ (1.5%) CH ₄ (98.5%)	263.9	1,331	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	263.9	1,105	II
n-C ₄ H ₁₀ (3.5%) CH ₄ (96.5%)	263.9	975	II
n-C ₄ H ₁₀ (7.5%) CH ₄ (92.5%)	263.9	738	II
n-C ₄ H ₁₀ (10.5%) CH ₄ (89.5%)	263.9	654	II
n-C ₄ H ₁₀ (10.5%) CH ₄ (89.5%)	266.7	738	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	269.4	1,419	II
n-C ₄ H ₁₀ (3.5%) CH ₄ (96.5%)	269.4	1,249	II
n-C ₄ H ₁₀ (7.5%) CH ₄ (92.5%)	269.4	940	II
n-C ₄ H ₁₀ (1.5%) CH ₄ (98.5%)	272.2	1,936	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	272.2	1,602	II
n-C ₄ H ₁₀ (3.5%) CH ₄ (96.5%)	272.2	1,409	II
n-C ₄ H ₁₀ (7.5%) CH ₄ (92.5%)	272.2	1,056	II
n-C ₄ H ₁₀ (1.6%) CH ₄ (98.4%)	275.0	2,066	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	275.0	1,862	II
n-C ₄ H ₁₀ (3.9%) CH ₄ (96.1%)	275.0	1,566	II
n-C ₄ H ₁₀ (1.6%) CH ₄ (98.4%)	277.8	3,099	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	277.8	2,774	II
n-C ₄ H ₁₀ (3.9%) CH ₄ (96.1%)	277.8	2,391	II

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>n-Butane-Methane (continued)</u>			
n-C ₄ H ₁₀ (1.6%) CH ₄ (98.4%)	280.6	4,608	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	280.6	4,100	II
n-C ₄ H ₁₀ (3.9%) CH ₄ (96.1%)	280.6	3,619	II
n-C ₄ H ₁₀ (1.6%) CH ₄ (98.4%)	283.3	6,801	II
n-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	283.3	6,015	II
n-C ₄ H ₁₀ (3.9%) CH ₄ (96.1%)	283.3	5,434	II
<u>Isobutane</u>			
i-C ₄ H ₁₀	252.8	35	II
i-C ₄ H ₁₀	261.1	57	II
i-C ₄ H ₁₀	269.4	90	II
i-C ₄ H ₁₀	273.2	113	II
i-C ₄ H ₁₀	273.3	118	II
i-C ₄ H ₁₀	273.9	132	II
i-C ₄ H ₁₀	274.4	148	II
i-C ₄ H ₁₀	275.0	166	II
<u>Isobutane-Methane</u>			
i-C ₄ H ₁₀ (0.8%) CH ₄ (99.2%)	275.0	1,168	II
i-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	275.0	757	II
i-C ₄ H ₁₀ (15.2%) CH ₄ (84.8%)	275.0	343	II
i-C ₄ H ₁₀ (65.1%) CH ₄ (34.9%)	277.0	254	II
i-C ₄ H ₁₀ (0.8%) CH ₄ (99.2%)	280.6	2,412	II
i-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	280.6	1,537	II
i-C ₄ H ₁₀ (15.2%) CH ₄ (84.8%)	280.6	714	II
i-C ₄ H ₁₀ (23.8%) CH ₄ (76.2%)	284.7	1,000	II
i-C ₄ H ₁₀ (0.8%) CH ₄ (99.2%)	286.1	4,840	II
i-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	286.1	3,036	II
i-C ₄ H ₁₀ (15.2%) CH ₄ (84.8%)	286.1	1,443	II

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Isobutane-Methane (continued)</u>			
i-C ₄ H ₁₀ (0.8%) CH ₄ (99.2%)	273.2	912	II
i-C ₄ H ₁₀ (1.2%) CH ₄ (98.8%)	273.2	795	II
i-C ₄ H ₁₀ (2.5%) CH ₄ (97.5%)	273.2	594	II
i-C ₄ H ₁₀ (6.0%) CH ₄ (94.0%)	273.2	405	II
i-C ₄ H ₁₀ (15.2%) CH ₄ (84.8%)	273.2	265	II
i-C ₄ H ₁₀ (28.6%) CH ₄ (71.4%)	273.2	185	II
i-C ₄ H ₁₀ (63.6%) CH ₄ (36.4%)	273.2	141	II
i-Cyclo-C ₃ H ₆	273.2	63	II
<u>Carbon Dioxide</u>			
CO ₂	276.7	1,896	I
CO ₂	277.8	2,199	I
CO ₂	278.9	2,544	I
CO ₂	280.0	2,944	I
CO ₂	281.1	3,406	I
CO ₂	282.2	3,930	I
<u>Carbon Dioxide-Methane</u>			
CO ₂ (60.0%) CH ₄ (40.0%)	275.5	1,993	I
CO ₂ (12.5%) CH ₄ (87.5%)	276.4	3,199	I
CO ₂ (34.0%) CH ₄ (66.0%)	277.0	2,841	I
CO ₂ (36.0%) CH ₄ (64.0%)	278.9	3,434	I
CO ₂ (71.0%) CH ₄ (29.0%)	279.5	2,999	I
CO ₂ (7.0%) CH ₄ (93.0%)	281.0	5,102	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Carbon Dioxide-Methane (continued)</u>			
CO ₂ (28.0%) CH ₄ (72.0%)	282.9	5,171	I
CO ₂ (52.0%) CH ₄ (48.0%)	283.8	5,275	I
CO ₂ (41.0%) CH ₄ (59.0%)	285.9	6,998	I
<u>Carbon Dioxide-Propane</u>			
CO ₂ (92.0%) C ₃ H ₈ (8.0%)	273.9	676	II
CO ₂ (79.0%) C ₃ H ₈ (21.0%)	274.0	359	II
CO ₂ (40.0%) C ₃ H ₈ (60.0%)	274.8	324	II
CO ₂ (28.0%) C ₃ H ₈ (72.0%)	275.2	303	II
CO ₂ (94.0%) C ₃ H ₈ (6.0%)	276.3	1,151	II
CO ₂ (16.0%) C ₃ H ₈ (84.0%)	277.8	476	II
CO ₂ (35.0%) C ₃ H ₈ (65.0%)	278.3	579	II
CO ₂ (90.0%) C ₃ H ₈ (10.0%)	278.3	1,204	II
CO ₂ (52.5%) C ₃ H ₈ (47.5%)	278.6	689	II
CO ₂ (18.0%) C ₃ H ₈ (82.0%)	279.0	592	II
CO ₂ (86.0%) C ₃ H ₈ (14.0%)	279.4	1,207	II
CO ₂ (37.0%) C ₃ H ₈ (63.0%)	279.6	752	II
CO ₂ (74.0%) C ₃ H ₈ (26.0%)	281.8	1,303	II
<u>Hydrogen Sulphide</u>			
H ₂ S	252.8	39	I
H ₂ S	255.6	44	I
H ₂ S	258.3	50	I
H ₂ S	261.1	57	I
H ₂ S	263.9	65	I
H ₂ S	266.7	72	I
H ₂ S	269.4	82	I
H ₂ S	272.2	92	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Hydrogen-Sulphide (continued)</u>			
H ₂ S	275.0	114	I
H ₂ S	280.6	212	I
H ₂ S	286.1	387	I
H ₂ S	291.7	691	I
H ₂ S	297.2	1,206	I
<u>Hydrogen Sulphide-Methane</u>			
H ₂ S(5.7%) CH ₄ (94.3%)	279.3	2,206	I
H ₂ S(21.4%) CH ₄ (78.6%)	279.8	1,034	I
H ₂ S(9.5%) CH ₄ (90.5%)	284.3	2,540	I
H ₂ S(1.1%) CH ₄ (98.9%)	284.8	6,688	I
H ₂ S(2.9%) CH ₄ (97.1%)	287.6	6,653	I
H ₂ S(8.2%) CH ₄ (91.8%)	288.7	4,826	I
H ₂ S(6.6%) CH ₄ (93.4%)	290.4	6,378	I
H ₂ S(11.5%) CH ₄ (88.5%)	292.0	5,998	I
H ₂ S(19.8%) CH ₄ (80.2%)	295.4	5,068	I
<u>Nitrogen</u>			
N ₂	268.9	13,100	I
N ₂	270.0	13,534	I
N ₂	271.1	13,983	I
N ₂	272.2	14,438	I
N ₂	273.9	17,527	I
N ₂	276.1	22,119	I
N ₂	277.8	26,276	I
N ₂	280.6	34,846	I
N ₂	283.3	45,947	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Nitrogen (continued)</u>			
N ₂	286.1	60,274	I
N ₂	288.9	78,649	I
<u>Oxygen</u>			
O ₂	267.8	9,880	I
O ₂	269.4	10,315	I
O ₂	270.6	10,611	I
O ₂	271.7	10,914	I
O ₂	272.8	11,225	I
O ₂	273.3	11,976	I
O ₂	275.0	14,645	I
O ₂	276.7	17,858	I
O ₂	277.8	20,353	I
O ₂	278.9	23,180	I
O ₂	280.6	28,117	I
O ₂	281.7	31,937	I
O ₂	283.3	30,583	I
O ₂	286.1	52,628	I
<u>Argon</u>			
Ar	148.8	97	I
Ar	263.2	1,860	I
Ar	273.2	9,250	I
Ar	279.4	16,996	I
Ar	283.2	27,400	I
Ar	291.0	66,914	I

ATTACHMENT 4-1A (Cont'd)
EXPERIMENTAL HYDRATE DATA (SMOOTHED)

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Krypton</u>			
Kr	273.2	1,470	I
Kr	283.2	3,700	I
Kr	202.9	111	I
<u>Xenon</u>			
Xe	216.7	9	I
Xe	222.2	13	I
Xe	227.8	18	I
Xe	233.3	24	I
Xe	238.9	32	I
Xe	244.4	42	I
Xe	250.0	55	I
Xe	255.6	71	I
Xe	261.1	90	I
Xe	266.7	114	I
Xe	272.2	143	I

ATTACHMENT 4-1B
TEMPERATURE PRESSURE DISSOCIATION RELATIONSHIPS
FOR VARIOUS HYDRATES, EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane</u>			
CH ₄	285.833	9,618.246	I
CH ₄	285.889	9,342.454	I
CH ₄	286.278	10,100.882	I
CH ₄	286.444	10,307.726	I
CH ₄	289.167	13,961.970	I
CH ₄	292.222	21,132.562	I
CH ₄	296.111	34,749.792	I
CH ₄	298.889	48,677.288	I
CH ₄	301.056	62,397.940	I
CH ₄	301.778	68,086.150	I
<u>Methane-Ethane</u>			
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	285.111	68,430.890	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	288.111	62,225.570	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	289.833	48,229.126	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	293.778	34,439.526	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	296.722	24,235.222	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	299.222	13,893.022	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	301.333	10,445.622	I
CH ₄ (94.6%) C ₂ H ₆ (5.4%)	302.167	6,929.274	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	289.000	6,998.222	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	291.889	10,445.622	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	293.500	13,893.022	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	296.556	23,476.794	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	299.167	35,611.642	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	301.500	48,642.814	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	303.278	61,949.778	I
CH ₄ (80.9%) C ₂ H ₆ (19.1%)	304.222	68,568.786	I

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Propane</u>			
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	290.667	6,929.274	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	290.833	6,929.274	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	292.778	62,466.888	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	293.444	10,445.622	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	294.667	13,893.022	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	296.778	20,856.770	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	299.278	34,508.474	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	301.722	48,367.022	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	303.833	62,294.518	II
CH ₄ (96.5%) C ₃ H ₈ (3.5%)	304.611	68,982.474	II

Methane-Isobutane

CH ₄ (98.6%) i-C ₄ H ₁₀ (1.4%)	300.056	49,125.450	II
CH ₄ (98.6%) i-C ₄ H ₁₀ (1.4%)	288.776	6,791.378	II
CH ₄ (98.6%) i-C ₄ H ₁₀ (1.4%)	302.278	62,225.570	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	294.444	6,722.430	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	294.000	6,722.430	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	296.667	13,893.022	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	297.222	13,961.970	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	298.333	23,269.950	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	300.667	34,577.422	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	302.722	48,367.022	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	305.167	63,328.738	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	303.278	49,056.502	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	298.500	23,821.534	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	296.833	13,961.970	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	295.500	10,583.518	II
CH ₄ (95.4%) i-C ₄ H ₁₀ (4.6%)	294.778	7,687.702	II

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-n-Butane</u>			
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	276.222	2482.266	II
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	279.622	3823.511	II
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	283.603	6656.102	II
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	286.233	10,089.161	II
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	287.603	12,071.071	II
CH ₄ (98.36%) n-C ₄ H ₁₀ (1.64%)	288.706	13,732.373	II
CH ₄ (97.52%) n-C ₄ H ₁₀ (2.48%)	276.533	2,302.105	II
CH ₄ (97.52%) n-C ₄ H ₁₀ (2.48%)	279.906	3,593.294	II
CH ₄ (97.52%) n-C ₄ H ₁₀ (2.48%)	282.533	5,134.695	II
CH ₄ (97.52%) n-C ₄ H ₁₀ (2.48%)	284.933	7,476.721	II
CH ₄ (97.52%) n-C ₄ H ₁₀ (2.48%)	286.583	10,409.562	II
CH ₄ (96.09%) n-C ₄ H ₁₀ (3.91%)	277.094	2,152.005	II
CH ₄ (96.09%) n-C ₄ H ₁₀ (3.91%)	279.922	3,142.857	II
CH ₄ (96.09%) n-C ₄ H ₁₀ (3.91%)	283.306	5,094.637	II
CH ₄ (96.09%) n-C ₄ H ₁₀ (3.91%)	286.133	8,167.511	II
CH ₄ (96.09%) n-C ₄ H ₁₀ (3.91%)	287.733	11,060.156	II
CH ₄ (94.18%) n-C ₄ H ₁₀ (5.82%)	278.172	2,051.892	II
CH ₄ (94.18%) n-C ₄ H ₁₀ (5.82%)	281.611	3,293.025	II

Methane-Ethane-Propane-Isobutane-n-Butane

CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	293.778	13,548.282	II
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	297.667	27,682.622	II
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	300.167	41,334.326	II

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Ethane-Propane-Isobutane-n-Butane</u> (continued)			
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	301.833	52,159.162	II
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	303.222	62,846.102	II
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	296.000	20,236.238	II
CH ₄ (90.6%) C ₂ H ₆ (6.6%) C ₃ H ₈ (1.8%) i-C ₄ H ₁₀ (.50%) n-C ₄ H ₁₀ (.50%)	298.778	33,750.046	II
<u>Methane-Pentane</u>			
CH ₄ (98.64%) C ₅ H ₁₂ (1.36%)	276.383	3,563.233	II
CH ₄ (98.64%) C ₅ H ₁₂ (1.36%)	279.683	4,954.603	II
CH ₄ (98.64%) C ₅ H ₁₂ (1.36%)	282.456	6,676.235	II
CH ₄ (98.64%) C ₅ H ₁₂ (1.36%)	284.933	8,750.051	II
CH ₄ (97.4%) NC ₄ (2.6%)	285.167	7,687.702	II
CH ₄ (97.4%) NC ₄ (2.6%)	287.889	12,445.114	II
CH ₄ (97.4%) NC ₄ (2.6%)	295.833	34,577.422	II
CH ₄ (97.4%) NC ₄ (2.6%)	301.222	65,948.762	II
CH ₄ (97.4%) NC ₄ (2.6%)	286.500	10,445.622	II
CH ₄ (97.4%) NC ₄ (2.6%)	285.889	9,066.662	II
CH ₄ (97.4%) NC ₄ (2.6%)	282.722	5,757.158	II
CH ₄ (94.7%) NC ₄ (5.3%)	287.667	10,652.466	II
CH ₄ (94.7%) NC ₄ (5.3%)	292.611	23,890.482	II
CH ₄ (94.7%) NC ₄ (5.3%)	295.278	34,163.734	II

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
CH ₄ (94.7%) NC ₄ (5.3%)	298.111	48,229.126	II
CH ₄ (94.7%) NC ₄ (5.3%)	300.278	61,605.038	II
CH ₄ (94.7%) NC ₄ (5.3%)	301.222	68,430.890	II
CH ₄ (94.7%) NC ₄ (5.3%)	290.444	17,960.954	II
CH ₄ (94.7%) NC ₄ (5.3%)	289.000	13,893.022	II
CH ₄ (94.7%) NC ₄ (5.3%)	287.722	10,652.466	II
CH ₄ (94.7%) NC ₄ (5.3%)	286.778	8,687.448	II
CH ₄ (94.7%) NC ₄ (5.3%)	285.500	6,998.222	II
CH ₄ (98.6%) IC ₄ (1.4%)	300.167	47,677.542	II
CH ₄ (98.6%) IC ₄ (1.4%)	298.000	34,508.474	II
CH ₄ (98.6%) IC ₄ (1.4%)	297.778	33,612.150	II
CH ₄ (98.6%) IC ₄ (1.4%)	295.389	21,063.614	II

Methane-Carbon-dioxide-Hydrogen-sulfide

CH ₄ (68.6%) CO ₂ (24.9%) H ₂ S (6.5%)	279.333	1,475.487	I
CH ₄ (69.9%) CO ₂ (24.1%) H ₂ S (6.0%)	282.222	2,033.966	I
CH ₄ (70.5%) CO ₂ (23.5%) H ₂ S (6.0%)	284.167	2,771.710	I
CH ₄ (71.5%) CO ₂ (22.8%) H ₂ S (5.7%)	286.556	3,743.876	I
CH ₄ (72.5%) CO ₂ (22.0%) H ₂ S (5.5%)	288.611	4,929.782	I
CH ₄ (72.5%) CO ₂ (22.0%) H ₂ S (5.5%)	290.167	6,184.636	I
CH ₄ (72.5%) CO ₂ (22.0%) H ₂ S (5.5%)	291.111	7,549.806	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	293.167	11,224.734	I
CH ₄ (72.3%) CO ₂ (22.2%) H ₂ S (5.5%)	293.889	12,010.742	I
CH ₄ (69.9%) CO ₂ (12.7%) H ₂ S (17.4%)	287.611	2,020.176	I
CH ₄ (70.0%) CO ₂ (12.3%) H ₂ S (16.7%)	290.111	2,647.603	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	291.667	3,330.188	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	293.500	4,391.988	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	294.833	5,122.836	I

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Carbon-dioxide-Hydrogen-sulfide</u>			
(continued)			
CH ₄ (71.1%) CO ₂ (11.9%) H ₂ S (17.0%)	295.556	6,494.902	I
CH ₄ (70.8%) CO ₂ (12.1%) H ₂ S (17.1%)	296.667	7,384.331	I
CH ₄ (72.5%) CO ₂ (11.9%) H ₂ S (15.6%)	297.778	8,404.761	I
CH ₄ (68.8%) CO ₂ (13.6%) H ₂ S (17.6%)	297.778	8,004.863	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	277.778	1,241.064	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	280.556	1,751.279	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	283.333	2,482.128	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	286.111	3,619.770	I
CH ₄ (72.0%) CO ₂ (22.3%) H ₂ S (5.7%)	288.889	5,274.522	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	277.778	758.428	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	280.556	965.272	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	283.333	1,275.538	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	286.111	1,723.700	I
CH ₄ (72.0%) CO ₂ (12.0%) H ₂ S (16.0%)	288.889	2,378.706	I
CH ₄ (82.0%) CO ₂ (11.5%) H ₂ S (7.5%)	277.778	1,034.220	I
CH ₄ (82.0%) CO ₂ (11.5%) H ₂ S (7.5%)	280.556	1,434.118	I
CH ₄ (82.0%) CO ₂ (11.5%) H ₂ S (7.5%)	283.333	1,999.492	I
CH ₄ (82.0%) CO ₂ (11.5%) H ₂ S (7.5%)	286.111	2,826.868	I
CH ₄ (82.0%) CO ₂ (11.5%) H ₂ S (7.5%)	288.889	3,998.984	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (7.5%)	277.778	1,172.116	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	280.556	1,654.752	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	283.333	2,413.180	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	286.111	3,516.348	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	288.899	5,240.048	I
CH ₄ (78.5%) CO ₂ (13.9%) H ₂ S (7.6%)	281.222	1,675.436	I
CH ₄ (80.3%) CO ₂ (13.0%) H ₂ S (6.7%)	282.667	2,275.284	I
CH ₄ (81.0%) CO ₂ (13.0%) H ₂ S (6.0%)	286.667	3,867.983	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	287.500	4,557.463	I

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Methane-Carbon-dioxide-Hydrogen-sulfide</u> (continued)			
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	289.611	5,888.159	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	290.944	6,881.010	I
CH ₄ (82.0%) CO ₂ (12.5%) H ₂ S (5.5%)	292.389	8,652.974	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	293.056	9,632.036	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	293.778	10,790.362	I
CH ₄ (82.5%) CO ₂ (12.1%) H ₂ S (5.4%)	294.889	12,341.692	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	295.722	14,079.182	I
CH ₄ (82.0%) CO ₂ (12.6%) H ₂ S (5.4%)	296.556	15,706.354	I
CH ₄ (81.0%) CO ₂ (11.8%) H ₂ S (7.2%)	284.333	1,902.965	I
CH ₄ (81.0%) CO ₂ (11.8%) H ₂ S (7.2%)	285.556	2,764.815	I
CH ₄ (80.0%) CO ₂ (12.0%) H ₂ S (8.0%)	289.278	4,254.092	I
CH ₄ (80.0%) CO ₂ (12.0%) H ₂ S (8.0%)	290.556	4,978.046	I
CH ₄ (80.0%) CO ₂ (12.0%) H ₂ S (8.0%)	292.222	5,943.318	I
CH ₄ (81.6%) CO ₂ (11.1%) H ₂ S (7.3%)	293.222	6,984.432	I
CH ₄ (83.9%) CO ₂ (9.4%) H ₂ S (6.7%)	294.167	7,529.122	I

Propane-Methane-Hydrogen-sulfide

C ₃ H ₈ (88.654%) CH ₄ (7.172%) H ₂ S (4.174%)	275.950	561.237	II
C ₃ H ₈ (88.654%) CH ₄ (7.172%) H ₂ S (4.174%)	277.750	693.151	II
C ₃ H ₈ (88.654%) CH ₄ (7.172%) H ₂ S (4.174%)	284.150	1,393.070	II
C ₃ H ₈ (88.654%) CH ₄ (7.172%) H ₂ S (4.174%)	287.35	1,986.718	II
C ₃ H ₈ (88.654%) CH ₄ (7.172%) H ₂ S (4.174%)	291.150	3,305.330	II

ATTACHMENT 4-1B (Cont'd)

EXPERIMENTAL DATA

<u>Gas</u>	<u>Temperature</u> (°K)	<u>Pressure</u> (kPa)	<u>Structure</u>
<u>Propane-Methane-Hydrogen-sulfide</u> (continued)			
C ₃ H ₈ (81.009%) CH ₄ (7.016%) H ₂ S (11.975%)	275.850	339.224	II
C ₃ H ₈ (81.009%) CH ₄ (7.016%) H ₂ S (11.975%)	283.550	817.034	II
C ₃ H ₈ (81.009%) CH ₄ (7.016%) H ₂ S (11.975%)	292.650	2,813.079	II
C ₃ H ₈ (31.71%) CH ₄ (7.402%) H ₂ S (60.888%)	280.350368.182		II
C ₃ H ₈ (31.71%) CH ₄ (7.402%) H ₂ S (60.888%)	286.250	686.033	II
C ₃ H ₈ (31.71%) CH ₄ (7.402%) H ₂ S (60.888%)	297.450	2,554.524	II
C ₃ H ₈ (31.71%) CH ₄ (7.402%) H ₂ S (60.888%)	300.950	4,274.777	II

Hydrogen - Methane - Ethane - Ethene - Propane - Isobutane - n-Butane -
Pentane - Carbon-dioxide - Hydrogen-sulfide

H ₂ (78.4%) CH ₄ (13.1%) C ₂ H ₆ (4.33%) C ₂ H ₄ (.05%) C ₃ H ₈ (2.26%) i-C ₄ H ₁₀ (.10%) n-C ₄ H ₁₀ (.50%) C ₅ H ₁₂ (.11%) CI ₂ (.12%) H ₂ S (.71%)	276.128	6,726.153	II
same as above	276.128	6,215.938	II
same as above	275.911	5,765.294	II
same as above	275.633	5,505.015	II
same as above	275.511	5,304.859	II
same as above	274.122	3,508.212	II

ATTACHMENT 4-2

STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

The structure and stability properties of 69 simple clathrate hydrates are shown on tables in this attachment. For each gas, the table gives the structure (I or II), the diameter (if available), the dissociation temperature and pressures at quadruple points, and the dissociation temperature of the hydrates at a pressure of one atmosphere.

ATTACHMENT 4-2

STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

Type of Guest	Guest Molecule	Structure, Value of a, (a at °C)	T, P at Q ₁ * (°C, atm)	T, P at Q ₂ * (°C, atm)	T at 1 atm (°C)
<u>Rare Gas</u>					
	Ar	I	-0.8 ⁰ , 87	No Q ₂	-124 ⁰
	Kr	I	-0.1 ⁰ , 14.3	No Q ₂	-49.8 ⁰
	Xe	I, 12.0	0 ⁰ , 1.5	No Q ₂	-10.4 ⁰
<u>Diatomic Molecule</u>					
	N ₂	I	-1.3 ⁰ , 141.5	No Q ₂	-
	O ₂	I	-1.0 ⁰ , 109.2	No Q ₂	-
	Cl ₂	I, 12.03, 11.82(4 ⁰)	-0.22 ⁰ , 0.316	28.3 ⁰ , 8.4	9.7 ⁰
	Br ₂	4	-0.30 ⁰ , 0.0555	5.80 ⁰ , 0.127-	-
	BrCl	I, 12.02	0 ⁰ , 0.165	25 ⁰ , 2.5	18 ⁰
<u>Triatomic Molecule</u>					
	CO ₂	I, 12.07	0 ⁰ , 12.4	9.9 ⁰ , 44.4	-55 ⁰
	N ₂ O	I, 12.03	0 ⁰ , 9.7	12 ⁰ , 41	-
	H ₂ S	I, 12.02	-0.4 ⁰ , 0.918	29.5 ⁰ , 22.1	0.4 ⁰
	H ₂ Se	I, 12.06	0 ⁰ , 0.455	30 ⁰ , 11	8 ⁰
	SO ₂	I, 11.97	-2.6 ⁰ , 0.274	12.1 ⁰ , 2.33	6.8 ⁰
	ClO ₂	I	-0.79 ⁰	18.2 ⁰	15 ⁰
	COS	I, 12.14	-	-	-

* Quadruple point: Q₁ = hydrate ice, liquid₁, and gas.
Q₂ = hydrate, liquid₁, liquid₂, and gas.

Source: Davidson, D. W.: Water: A Comprehensive Treatise (vol 2). F. Franks (Ed.). Plenum Press, New York (1973) 174-179.

ATTACHMENT 4-2 (Cont'd)

STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

<u>Type of Guest</u>	<u>Guest Molecule</u>	<u>Structure, Value of a, (a at 0°C)</u>	<u>T, P at Q₁ * (°C, atm)</u>	<u>T, P at Q₂ * (°C, atm)</u>	<u>T at 1 atm (°C)</u>
<u>Inorganic Polyatomic Molecule</u>	PH ₃	I	0 ⁰ , 2.3	28 ⁰	-
	AsH ₃	I	0 ⁰ , 0.81	28.3 ⁰ , 17.5	1.6 ⁰
	SF ₆	II, 17.21	0 ⁰ , 0.80	14.0 ⁰ , 19.9	1.0 ⁰
<u>Hydrocarbon</u>	CH ₄	I	-0.2 ⁰ , 25.3	No Q ₂	-78.7 ⁰
	C ₂ H ₂	I	0 ⁰ , 5.75	15.0 ⁰ , 33	-40.2 ⁰
	C ₂ H ₄	I	-0.1 ⁰ , 5.44	No Q ₂	-36.9 ⁰
	C ₂ H ₆	I	-0.03 ^u , 5.23	14.7 ⁰ , 33.5	-32.0 ⁰
	Propylene	II	-0.134 ⁰ , 4.60	0.958 ⁰ , 5.93	-
	Cyclo- propane	I, 12.14(5 ⁰)	-	16.21 ⁰ , 5.59	2.8 ⁰
	C ₃ H ₈	II, 17.40	0 ⁰ , 1.74	5.7 ⁰ , 5.45	-11.6 ⁰
	iso- Butane	II, 17.57	0.00 ⁰ , 1.12	1.88 ⁰ , 1.653	-2.8 ⁰
	Cyclo- pentene	II	-	3.2 ⁰	-
	Cyclo- pentane	II	-	7.7 ⁰	-
<u>Fluorinated Hydrocarbon</u>	CH ₃ F	I	0. ⁰ , 2.1	18.8 ⁰ , 32	-
	CH ₂ F ₂	I	-	17.6 ⁰	-
	CHF ₃	I, 12.05	-	21.8 ^u	-

ATTACHMENT 4-2 (Cont'd)

STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

<u>Type of Guest</u>	<u>Guest Molecule</u>	<u>Structure, Value of a, (a at °C)</u>	<u>T, P at Q₁ * (°C, atm)</u>	<u>T, P at Q₂ * (°C, atm)</u>	<u>T at 1 atm (°C)</u>
<u>Fluorinated Hydrocarbon (cont'd)</u>					
	CF ₄	I	0°, 41.5	-	-
	C ₂ H ₃ F	I, 12.11	-	-	-
	C ₂ H ₅ F	I	0°, 0.7	22.8°, 8	3.7°
	C ₂ F ₄	II	-	10.5°	-
	CH ₃ CHF ₂	I, 12.12	0°, 0.54	14.9°, 4.30	4.3°
	(CH ₃) ₃ CF	II	-	-	-
<u>Chlorinated Hydrocarbon</u>					
	CH ₃ Cl	I, 12.00	0°, 0.41	20.5°, 4.9	7.5°
	CH ₂ Cl ₂	II, 17.33	0°, 0.153	1.7°, 0.211	-
	HCCl ₃	II, 17.33	-0.09°, 0.065	1.7°, 0.090	-
	C ₂ H ₃ Cl	II	-	1.15°, 1.80	-
	C ₂ H ₅ Cl	II, 17.30	0°, 0.265	4.8°, 0.77	-
	CH ₃ CHCl ₂	II	0°, 0.072	1.5°, 0.092	-
<u>Chloro-Fluorinated Hydrocarbon</u>					
	CH ₂ ClF	I	-0.2°, 0.222	17.88°, 2.825	9.83°
	CHClF ₂	I, 11.97(2°)	-0.2°, 0.84	16.3°, 7.6	0.9°
	CHCl ₂ F	II	-0.13°, 0.145	8.61°, 0.998	-
	CCl ₂ F ₂	II, 17.37 17.12(2°)	-0.1°, 0.36	12.1°, 4.27	5.2°
	CCl ₃ F	II, 17.29	-0.1°, 0.080	8.5°, 0.065	-
	CH ₃ CClF ₂	II, 17.29	-0.04°, 0.136	13.09°, 2.294	9.1°

ATTACHMENT 4-2 (Cont'd)
STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

<u>Type of Guest</u>	<u>Guest Molecule</u>	<u>Structure, Value of a, (a at 0°C)</u>	<u>T, P at Q₁ * (0°C, atm)</u>	<u>T, P at Q₂ * (0°C, atm)</u>	<u>T at 1 atm (0°C)</u>
<u>Alkyl Bromide</u>					
	CH ₃ Br	I, 12.09	-0.24 ⁰ , 0.238	14.73 ⁰ , 1.51	11.3 ⁰
	C ₃ H ₅ Br	II	0 ⁰ , 0.2	1.4 ⁰ , 0.22	-
<u>Alkyl Iodide</u>					
	CH ₃ I	II, 17.14	0 ⁰ , 0.097	4.3 ⁰ , 0.23	-
<u>Bromofluoro- Methane</u>					
	CHBrF ₂	II(?)	-	9.87 ⁰ , 2.65	-
	CBrF ₃	II	-0.1 ⁰ , 0.88	11 ⁰	0.5 ⁰
	CBr ₂ F ₂	II	-	4.9 ⁰ , 0.501	-
	CBrClF ₂	II	0 ⁰ , 0.189	9.96 ⁰ , 1.673	7.6 ⁰
<u>Mercaptan</u>					
	CH ₃ SH	I, 12.12	0 ⁰ , 0.31	12.0 ⁰ , 1.25	10.0 ⁰
<u>Ether</u>					
	Ethylene oxide	I, 12.1(-10 ⁰) 12.03(-25 ⁰)	-2.1 ⁰	11.1 ⁰	-
	Dimethyl ether	II, 17.47	-	-	-
	Propylene oxide	II, 17.124 (-138 ⁰)	-4.7 ⁰	-3.5 ⁰	-
	Tri-methylene oxide	II, 17.095 (-130 ⁰) I	- - -	-13.1 ⁰ -20.8 ⁰	- -

ATTACHMENT 4-2 (Cont'd)

STRUCTURAL AND STABILITY PROPERTIES OF SIMPLE CLATHRATE HYDRATES

<u>Type of Guest</u>	<u>Guest Molecule</u>	<u>Structure, Value of a, (a at °C)</u>	<u>T, P at Q₁ * (°C, atm)</u>	<u>T, P at Q₂ * (°C, atm)</u>	<u>T at 1 atm (°C)</u>
<u>Ether (cont'd)</u>					
	1,3-Dioxolane	II,17.118 (-138 ⁰)	-	-3.0 ⁰	-
	Furan	II,17.3 (-10 ⁰)	-	4.6 ⁰	-
	Dihydrofuran	II,17.166 (-138 ⁰)	-3.3 ⁰	-1.2 ⁰	-
	Tetrahydrofuran	II,17.18 (-10 ⁰) 17.170(-138 ⁰)	-1.0 ⁰	4.4 ⁰	-
<u>Ketone</u>					
	Acetone	II,17.16(-38 ⁰)	-	-19.8 ⁰	-
	Cyclobutanone	II,17.161(-138 ⁰)	-	0.0 ⁰	-
<u>Amine</u>					
	t-Butylamine		-	-1 ⁰	-

CHAPTER 5

HYDRATE ENERGY BALANCE

One of the most important questions when evaluating the recovery of hydrates is the net energy balance -- the extent to which the energy content of the produced methane exceeds the energy expended to dissociate the gas hydrate. This chapter evaluates the energy balance from a theoretical viewpoint, assuming there are no external heat losses to the media surrounding the hydrate reservoir.

The first section, titled "Production Mechanisms," describes the two main approaches that can be used to dissociate hydrates, namely thermal stimulation and depressurization. In thermal stimulation, energy is injected and the limiting constraint is heat transfer. In depressurization, no energy is injected and the limiting constraint is the conduction of heat in the reservoir.

The second section, "Energy Input," analyzes the sensible and latent heat requirements for hydrate dissociation. Using reservoir conditions presumed representative of the North Slope of Alaska, the analysis shows that the hydrate dissociation energy is much larger than the sensible heat required to raise the temperature of the reservoir matrix and its associated fluids to the dissociation temperature.

The next section, "Energy Output," presents the basic equations and assumptions for calculating the producible energy from hydrate dissociation. This section shows that the producible energy is a function of the porosity of the reservoir matrix, the extent of gas saturation and the nature of the gas hydrate.

The fourth section, "Energy Balance," derives two measures for quantifying the net energy balance. These are the efficiency ratio (ER), the ratio between the energy output and the energy input, and the energy balance (EB), the energy output less the energy input. Calculations for the representative hydrate reservoir show that: (1) theoretically 15 times as much energy may be produced as is injected, assuming no heat loss for thermal stimulation. (For

depressurization, the energy efficiency ratio is meaningless if no energy is injected); and, (2) the net energy balance ranges from 40,000 to 50,000 BTU per cubic foot of reservoir. This is essentially equal to the energy production per unit of reservoir rock from a high grade heavy oil deposit being developed by steam injection. A schematic diagram illustrating the energy balance is shown on Figure 5-1.

A. PRODUCTION MECHANISMS

Two fundamentally different methods are available for dissociating hydrates, Figure 5-2. These two approaches are thermal stimulation and depressurization, as further described below. The energy inputs for hydrate dissociation may differ considerably, depending on which of these methods (or combination of methods) is used.

- Thermal Stimulation of a hydrate reservoir involves injecting energy to first heat the reservoir matrix and its associated fluids to the dissociation temperature and then adding additional energy to dissociate the hydrate. This method is illustrated on the phase diagram, Figure 5-3, for a sample reservoir presumed to be characteristic of the North Slope. For simplicity, no increase in reservoir pressure is assumed from the injection of heat. To a certain extent, reservoir pressure can be controlled by the operator.
- Depressurization of a hydrate reservoir leads to the dissociation of the gas hydrates, by lowering the pressure until the phase boundary is crossed, as is illustrated on Figure 5-3. Depressurization will lead to cooling of the reservoir, although this may be limited to only a few degrees (3-10°F), depending on the rate and degree to which the reservoir is depressurized.

The composition of the reservoir fluids and the rate of gas production will differ significantly, depending on the dissociation mechanism. Although thermal stimulation requires the injection of heat into the reservoir, the advantages are that the hydrate is decomposed relatively rapidly into gas and water, both of which are mobile, so the gas can be readily produced.

Figure 5-1

SCHEMATIC OF HYDRATE ENERGY BALANCE

ENERGY RATIO (ER): $\frac{\text{energy out}}{\text{energy in}}$

ENERGY BALANCE (EB): energy out - energy in

SOURCE: Lewin and Associates, Inc.

Figure 5-2

CONCEPTUAL METHODS FOR DISSOCIATING HYDRATE DEPOSITS

SOURCE: Lewin and Associates, Inc.

Figure 5-3

PHASE DIAGRAM FOR METHANE HYDRATE SHOWING
EXAMPLE RESERVOIR PRODUCTION ALTERNATIVES

SOURCE: Lewin and Associates, Inc.

Depressurization, on the other hand, leads to a cooling of the reservoir, so the water of the hydrate may form an ice phase if the extent of the cooling is large.

The amount of reservoir cooling and the state of the water phase in the reservoir will depend on the pressure at which the hydrate interface is maintained. At 400 psi, the dissociation products will be gas and water for the sample reservoir, while at 200 psi they will be gas and ice. The rate of dissociation of hydrates in depressurization depends on the rate of heat flow from the surrounding media to the hydrate interface and this process can be slow. Thus, a viable project using depressurization for producing hydrates requires that they decompose sufficiently fast so that there is a large, steady source of gas, and that the reservoir permeability be sufficiently high for the gas to flow readily to the wellbore.

B. ENERGY INPUT

The energy input, H , required for dissociating methane consists of:
 (1) the sensible heat, H_S , required to bring the reservoir rock and fluids to the dissociation temperature from the original reservoir conditions; and,
 (2) the heat of dissociation, H_D , that effects a phase change and dissociates the hydrate into gas and water (or ice). The overall energy input requirements are expressed in Equation 5-1:

$$\begin{array}{rclcl}
 \text{Input Energy} & & \text{Sensible} & & \text{Heat} \\
 \text{Requirements} & = & \text{Heat of} & + & \text{of} \\
 & & \text{Rock + Fluids} & & \text{Dissociation} \\
 H & = & H_S & + & H_D \qquad (5-1)
 \end{array}$$

Each of these heat components is discussed in the following.

1. Sensible Heat Requirements

The sensible heat, H_S , required to raise a reservoir and its associated fluids from the initial reservoir temperature, T_R , to the dissociation temperature, T_D , is:

$$H_S = M (T_D - T_R) \quad (5-2)$$

Where:

M = The weighted heat capacity of the reservoir,
BTU/°F/ft³

T_D = Dissociation temperature, °F

T_R = Initial reservoir temperature, °F

Assuming the reservoir contains water, oil, free gas, and hydrate, the weighted heat capacity of the reservoir, M , is:

$$M = (1 - \Phi) C_r \rho_r + \Phi S_w C_w \rho_w + \Phi S_o C_o \rho_o + \Phi S_g C_g \rho_g + \Phi S_H C_H \rho_H \quad (5-3)$$

Where:

Φ = Porosity, fraction

S = Saturation (water [w], oil [o], gas [g], or hydrate [H]), fraction

C = Specific heat (rock, water, oil, gas, or hydrate), BTU/°F/lb

ρ = Density (rock, water, oil, gas or hydrate), lb/ft³

The methodology for calculating the sensible heat requirements is shown in the following example.

Example. For the purpose of illustration, a hydrate reservoir presumed representative of the North Slope is used in the energy input and balance calculations. The reservoir temperature and pressure are 46°F (8°C) and 1,500 psi, respectively. To simplify the calculations and to evaluate the attractiveness of gas hydrate deposits, the reservoir is assumed to contain no associated oil or free gas and to be 90% saturated with methane. The assumed rock, water and hydrate properties of the example reservoir and its associated fluids are shown on Table 5-1.

a. Thermal Stimulation. The sensible heat required to raise the example reservoir to the dissociation temperature is calculated as follows:

STEP 1: Establish the dissociation temperature, T_D , from the hydrate phase diagram. For this sample reservoir (where no pressure increase is assumed from heat injection) the dissociation temperature will be 55°F (13°C or 286°K), as shown on Figure 5-3.

STEP 2: Calculate the sensible heat requirements, H_S , using Equations 5-2 and 5-3, and the rock, water, and hydrate properties summarized on Table 5-1, as shown below:

$$\begin{aligned}
 H_S &= [(1 - \phi) \rho_r C_r + \phi S_{H_2O} C_H] [\Delta T], \text{ in BTU/ft}^3 \text{ of reservoir} \\
 &= [(1 - 0.3) (167 \text{ lb/ft}^3) (0.2 \text{ BTU/lb/}^\circ\text{F}) \\
 &\quad + (0.3)(1) (55.7 \text{ lb/ft}^3) (0.67 \text{ BTU/lb/}^\circ\text{F})] \\
 &\quad [55^\circ\text{F} - 46^\circ\text{F}] \\
 &= [34.58 \text{ BTU/ft}^3/^\circ\text{F}] [9^\circ\text{F}] \\
 &\cong 310 \text{ BTU/ft}^3 \text{ of reservoir}
 \end{aligned}$$

For the sample reservoir, the sensible heat required to bring the reservoir from its initial conditions to the dissociation temperature (55°F) is about 310 BTU per cubic foot of reservoir.

TABLE 5-1
ROCK, WATER AND HYDRATE PROPERTIES

Basic Properties

$$\begin{aligned}\rho_r &= 167 \text{ lb/cu ft}^3 \\ C_r &= 0.2 \text{ BTU/lb/}^\circ\text{F} \\ \rho_w &= 62.4 \text{ lb/cu ft}^3 \\ C_w &= 1.0 \text{ BTU/lb/}^\circ\text{F} \\ \rho_H &= 55.7 \text{ lb/cu ft}^3 \\ C_H &= 0.67 \text{ BTU/lb/}^\circ\text{F (Structure I)}\end{aligned}$$

Example Reservoir Variables

$$\begin{aligned}T_R &= 46^\circ\text{F}, 8^\circ\text{C}, 281^\circ\text{K} \\ \phi &= 0.30 \\ P &= 1,500 \text{ psi} \\ S_H &= 1 \\ S_w &= S_o = S_g = 0\end{aligned}$$

b. Depressurization. For the depressurization case, the change in reservoir temperature is dependent on the pressure at the hydrate interface.

If the pressure is maintained at 400 psi, the temperature change is negative, at -10°F (6°C), Figure 5-3, and the sensible heat is:

$$H_S = (34.58 \text{ BTU/ft}^3/^{\circ}\text{F}) (-10^{\circ}\text{F})$$

$$\cong 360 \text{ BTU/ft}^3$$

At 200 psi, the temperature change is -30°F (17°C), and

$$H_S = (34.58 \text{ BTU/ft}^3/^{\circ}\text{F}) (-30^{\circ}\text{F})$$

$$\cong 1,040 \text{ BTU/ft}^3$$

2. Heat of Dissociation Requirements

The heat of dissociation required to change the hydrate phase into gas and water or gas and ice are developed in Chapter 4, "Thermodynamic Properties of Hydrates." The calculation is complex, but as shown in Chapter 4, simplified regression equations can be developed that expresses the dissociation energy as a linear function of temperature, as follows:

$$H_{\text{Diss}}(\text{cal/g-mole}) = c + d \cdot T \text{ (T in Kelvin)} \quad (5-4)$$

Where for methane hydrates:

$$c = 6,534 \text{ and } d = -12; \text{ for } T \text{ between } 248^{\circ}\text{K} (-25^{\circ}\text{C}) \text{ and } 273^{\circ}\text{K} (0^{\circ}\text{C})$$

$$c = 13,521 \text{ and } d = -4; \text{ for } T \text{ between } 273^{\circ}\text{K} (0^{\circ}\text{C}) \text{ and } 298^{\circ}\text{K} (25^{\circ}\text{C})$$

Example. The dissociation energy depends on the reservoir temperature and pressure at which the hydrates dissociate. Thus, the energy requirements will differ depending on whether thermal stimulation or depressurization is used, as shown in the following examples:

a. Thermal Stimulation. For the example reservoir, the dissociation temperature is 55°F (286°K), from Figure 5-3; so the dissociation energy is:

$$\begin{aligned} H_{\text{Diss}} &= 13,521 + (-4)(286) \\ &= 12,377 \quad \text{cal/g-mole of hydrate} \end{aligned}$$

Converting the units to BTU per cubic foot of hydrate, the dissociation energy is:

$$\begin{aligned} H_{\text{Diss}} &= (12,377)(0.8) \\ &= 9,900 \quad \text{BTU/ft}^3 \text{ of hydrate} \end{aligned}$$

The hydrate dissociation energy per cubic foot of porous reservoir rock (porosity equal to 30%) is then:

$$\begin{aligned} H_D &= H_{\text{Diss}} \cdot \phi \\ &= 9,900 (0.3) \\ &= 2,960 \quad \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

b. Depressurization. The calculations for the heat of dissociation using depressurization are similar to those for the thermal stimulation case. At a reservoir pressure of 400 psi, the dissociation temperature is 36°F (275°K), so the dissociation energy per cubic foot of reservoir is:

$$\begin{aligned} H_D &= 0.3 (13,521 + (-4)(275)) \\ &= 3,726 \quad \text{cal/g-mole} \\ &= 3,726 (0.8) \\ &= 2,980 \quad \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

At a pressure of 200 psi, the dissociation temperature is 16°F (264°K), so

$$\begin{aligned} H_D &= 0.3 (6,534 + (-12)(264)) \\ &= 1,010 && \text{cal/g-mole} \\ &= 1,010 (0.8) \\ &= 810 && \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

In addition, energy may be required to maintain the lower reservoir pressure, which is not included in the calculation.

3. Total Dissociation Energy

The total dissociation energy is the sum of the sensible heat and the heat of dissociation as expressed in Equation 5-1, and shown below for the two basic production schemes.

a. Thermal Stimulation. For the example reservoir, the total dissociation energy under thermal stimulation is 3,270 BTU per cubic foot of reservoir, as calculated below:

$$\begin{aligned} H &= H_S + H_D \\ &= 310 + 2,960 && \text{BTU/ft}^3 \text{ of reservoir} \\ &= 3,270 && \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

As shown by the above example, the heat of dissociation is much larger than the sensible heat, 2,960 BTU/ft³ versus 310 BTU/ft³ of reservoir. Thus, the heat of dissociation accounts for about 90% of the total dissociation energy.

b. Depressurization. The total dissociation energy under depressurization at 400 psi is 2,620 BTU per cubic foot of reservoir as shown below:

$$\begin{aligned} H &= H_S + H_D \\ &= -360 + 2,980 && \text{BTU/ft}^3 \text{ of reservoir} \\ &= 2,620 && \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

The energy of dissociation would be taken from the reservoir matrix, and the temperature of reservoir rock at the hydrate interface would decrease. A temperature gradient would be established in the reservoir and the rate of dissociation would be controlled by the internal heat flow from the earth to the dissociation interface. This heat flux can be treated as a "free" energy input since it does not require any technology. Taking the earth's natural heat flux ($\dot{Q}$) and multiplying by time (Δt) gives the energy input:

$$\text{Energy Input} = \dot{Q} \Delta t$$

Judge (1973) estimates the heat flux in permafrost regions as 0.3 to 0.8 BTU/ft²/day. If all of this energy is absorbed by hydrates, the energy input increases with time, so the depressurization technique is time dependent. The energy balance becomes

$$H_S + H_D - \dot{Q} \Delta t = 0$$

and the time required to dissociate the hydrate becomes

$$\Delta t = \frac{H_S + H_D}{\dot{Q}}$$

where:

$$H_S = (34.58)(-10^{\circ}\text{F}) = -345.8 \text{ BTU/ft}^3$$

$$H_D = 2,620 \text{ BTU/ft}^3$$

Combining and using $\dot{Q} = 0.5 \text{ BTU/ft}^2/\text{day}$

$$\Delta t = \frac{2,620 - 345.8}{0.5}$$

$$\cong 4,548 \text{ days or 12 years.}$$

Thus, it would take 12 years to reduce the thickness of a hydrate zone by 1 foot. Greater reductions in thickness would take proportionately longer. This time estimate is conservative (long) in that it assumes that only the media containing the hydrates is cooled. In an actual situation, some of the surrounding media would also be cooled and the sensible heat that the

surrounding media loses would accelerate the hydrate dissociation. If a thickness of 5 feet, including 1 foot of hydrate, and 4 feet of overburden and underburden was cooled 10°F, then the sensible heat term, which is negative, would be five times as great and the required time would decrease to 891 days (2.4 years). Greater temperature reductions could also accelerate the process.

At 200 psi, the dissociation energy is -230 BTU per cubic foot:

$$\begin{aligned} H &= H_S + H_D \\ &= (1,040) + 810 && \text{BTU/ft}^3 \text{ of reservoir} \\ &= -230 && \text{BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

This means that if the hydrate interface is maintained at 200 psi, the sensible heat of the reservoir matrix surrounding the hydrate is sufficient to provide the energy for dissociating the hydrate into gas and ice.

C. ENERGY OUTPUT

The energy output, E, is independent of the production mechanism employed and depends solely on the amount of hydrocarbon contained in the hydrate reservoir. The energy contained in a cubic foot of reservoir rock when hydrate is dissociated into methane and water can be calculated as follows:

$$E = \Phi \cdot V_H \cdot HV \quad \text{BTU/ft}^3 \text{ of reservoir} \quad (5-5)$$

Where:

Φ = porosity, fraction

V_H = volume of hydrocarbons at standard conditions in one cubic foot of hydrate, scf/ft³

HV = heating value of gas, BTU/scf

Assuming methane with a heating value, HV, of 1,010 BTU per scf (see Appendix A) and a reservoir hydrocarbon content, V_H , of 163 scf of methane per cubic foot of hydrate (90% saturated, Structure I), the energy output equation simplifies to:

$$E = 165,000 \cdot \Phi \quad \text{BTU/ft}^3 \text{ of reservoir} \quad (5-6)$$

The energy output depends on the amount of hydrate dissociated and so is directly proportional to porosity and the gas saturation of the hydrate.

Example. For the example reservoir, assuming a reservoir with 30% porosity, the energy production from one cubic foot of reservoir is:

$$E = (0.3) (165,000) \text{ BTU/ft}^3 \text{ of reservoir}$$

$$= 49,500 \text{ BTU/cu ft of reservoir}$$

D. ENERGY BALANCE

Various measures can be used to examine the "energy balance" of hydrate recovery, including:

- Efficiency ratio (ER) defined as:

$$ER = \frac{\text{Energy Out}}{\text{Energy In}} \quad (5-7)$$

This measure is a relative one that expresses the number of times that the energy out is larger than the energy in.

- Energy balance (EB) defined as:

$$EB = \text{Energy Out} - \text{Energy In} \quad (5-8)$$

This measure is absolute and expresses the net energy gain, or the difference between Energy Out and Energy In.

For thermal stimulation, the general energy efficiency ratio (ER) for a 90 percent saturated methane hydrate with no free gas or oil can be expressed as:

$$ER = \frac{165,000 \Phi}{[(1 - \Phi) C_r \rho_r + C_H \rho_H] \Delta T + \Phi \cdot H_{Diss}} \quad (5-9)$$

For depressurization, there is no energy input (Energy In = 0), so the energy efficiency ratio is meaningless.

Similarly, the general net energy balance (EB) equation for thermal stimulation of a 90 percent saturated methane hydrate with no free gas or oil is:

$$EB = 165,000 \phi - [(1 - \phi) C_{rpr} + \phi \cdot C_H \rho_H] \Delta T - \phi \cdot H_{Diss} \quad (5-10)$$

Example

a. Thermal Stimulation. The expressions for the energy ratio and energy balance reduce to the following general equations when the basic rock, water and hydrate properties of Table 5-1 are inserted:

$$ER = \frac{165,000 \phi}{[(1 - \phi) 33.4 + \phi 37.3] \Delta T + \phi \cdot H_{Diss}} \quad (5-11)$$

$$EB = 165,000\phi - [(1 - \phi) 33.4 + \phi \cdot 37.3] \Delta T - \phi H_{Diss} \quad (5-12)$$

The energy ratio and energy balance for the sample reservoir with a porosity of 30% and a dissociation temperature of 55°F (286°K) are:

$$ER = \frac{(0.3) (165,000)}{(0.7 \cdot 33.4 + 0.3 \cdot 37.3)(9) + 2,960} = \frac{49,500}{3,280} = 15.1$$

$$EB = (0.3 \cdot 165,000) - (0.7 \cdot 33.4 + 0.3 \cdot 37.3)(9) - 2,960 = 46,220 \text{ BTU/ft}^3 \text{ of reservoir}$$

The calculations show that about 15 times more energy is produced than is used when hydrates are dissociated. The net energy gain is 46,220 BTU per cubic foot of reservoir, assuming no heat losses.

The Energy Ratio and Energy Balance are shown on Figure 5-4 as a function of the change in reservoir matrix temperature. The figure shows that even if the reservoir where the hydrate is being dissociated is heated higher than the dissociation temperature, the energy ratio is still substantial. For example, for a temperature change of 60°F, assuming the hydrates are dissociated at 69°F and 4,500 psi (or three times the original temperature), the Energy Ratio would be 5.8 and the Energy Balance would be 41,000 BTU/ft³ of reservoir. Thus, even under less efficient conditions there is still a substantial energy gain.

The change in Energy Ratio and Energy Balance with porosity is shown on Figure 5-5. There is little change in Energy Ratio as the porosity increases, because both the energy output and the energy input (the heat of dissociation) increase linearly with the porosity. However, there is a significant change in the Energy Balance.

b. Depressurization. The Energy Balance for depressurization can be calculated using the definition. The Energy Out is the same as established above, or 49,500 BTU per cubic foot of reservoir, and there is no Energy In. The Energy Balance is then:

$$\begin{aligned} \text{EB} &= \text{Energy Out} - \text{Energy In} \\ &= 49,500 - 0 = 49,500 \text{ BTU/ft}^3 \text{ of reservoir} \end{aligned}$$

Figure 5-4

ENERGY EFFICIENCY RATIO AND NET ENERGY BALANCE AS A FUNCTION OF TEMPERATURE INCREASE - THERMAL STIMULATION

SOURCE: Lewin and Associates, Inc., 1983.

Figure 5-5

ENERGY EFFICIENCY RATIO AND NET ENERGY BALANCE
AS A FUNCTION OF POROSITY - THERMAL STIMULATION

SOURCE: Lewin and Associates, Inc., 1983.

E. COMPARISON OF PRODUCTION SCHEMES

A major difference between thermal stimulation and depressurization is that in thermal stimulation, energy is injected to increase hydrate decomposition, while in depressurization, hydrate decomposition is limited by the heat flow in the reservoir.

The energy efficiency ratio (ER) and energy balance (EB) are summarized below and in Figure 5-6 for the two production schemes:

	<u>Energy Efficiency Ratio with No Heat Loss</u>	<u>Energy Balance</u>
Thermal Stimulation	15.1	46,220 (BTU/ft ³ of reservoir)
Depressurization	Not defined	49,500 (BTU/ft ³ of reservoir)

The main reason for the improvement in the Energy Balance for depressurization is that no sensible energy is required to raise the overall reservoir temperature.

Although the energy balance is about the same for the example reservoir, the reservoir conditions and fluids may be very different. For thermal stimulation, the reservoir temperature is higher than originally and, thus, the hydrates have been dissociated into gas and water, both of which are producible. For depressurization, the reservoir temperature decreases depending on the pressure at the hydrate interface and in some conditions ice may form. This technique alone is a viable recovery scheme only if the hydrate dissociation is rapid enough to give a substantial source of gas and if the potentially ice-filled reservoir has sufficient permeability for adequate gas flow to a wellbore.

Another difference between these two methods lies in the heat loss. For thermal stimulation, 25% to 75% of the injected heat may be lost which would lower the energy efficiency ratio and energy balance. In depressurization, no heat loss occurs and the energy balance will hold in the real case. However, depressurization is time limited and will not produce gas as rapidly as thermal stimulation, so a combination of techniques may be appropriate. Thermal stimulation could be used initially to prepare the hydrate zone for depressurization.

Figure 5-6

COMPARISON OF THERMAL STIMULATION AND DEPRESSURIZATION (For Sample Reservoir)

A. DISSOCIATION ENERGY

B. ENERGY EFFICIENCY RATIO

15.1

NOT DEFINED

C. ENERGY BALANCE

46,220 BTU/Ft³ OF RESERVOIR

49,500 BTU/Ft³ OF RESERVOIR

SOURCE: Lewin and Associates, Inc.

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APPENDIX A

HYDRATE GAS SUMMARY TABLES

Tables summarizing physical and thermodynamic properties of light hydrocarbons (methane through butane) and other gases that can form hydrates are contained in this Appendix.

GAS COMPONENTS OF GAS HYDRATES

HYDROCARBONS

Physical Constants		Methane	Ethane	Propane	n-Butane	Isobutane
Formula		CH ₄	C ₂ H ₆	C ₃ H ₈	n-C ₄ H ₁₀	i-C ₄ H ₁₀
Molecular Weight		16.042	30.068	44.094	58.120	58.120
Boiling Point °F, 14.696 psia		-258.68(1)	-127.53(1)	-43.73(1)	+31.10(1)	+10.89(1)
Vapor Pressure 100°F, psia		----	----	190	51.6	72.2
Freezing Point °F, 14.696 psia		-296.46 ^d	-297.89	-305.84	-217.030	-255.280
CRITICAL CONSTANTS	Pressure, psia	673.1	708.3	617.4	550.7	529.1
	Temperature, °F	-116.5	+ 90.09	206.26	305.62	274.96
	Volume, cu ft/lb	0.0993	0.0787	0.0730	0.0704	0.0725
LIQUID DENSITY 60°F 14.696 psia	Specific Gravity 60F/60F ^b	0.3(K)	0.374	0.5077 ^h	0.5844 ^h	0.563 ^h
	lb per gal ^c	2.5(K)	3.11	4.224 ^h	4.863 ^h	4.685 ^h
	gal/lb mole	6.4(14)	9.67(14)	10.44	11.95	12.40
GAS DENSITY 60°F 14.696 psia	Temp. Coefficient of Density	----	----	0.00171 ^h	0.00111 ^h	0.00123 ^h
	Specific Gravity Air = 1	0.555 ^e	1.046 ^e	1.547 ^e	2.071 ^e	2.067 ^e
	Cubic Feet Gas per Pound ^b	23.61 ^e	12.52 ^e	8.471 ^e	6.327 ^e	6.339 ^{e1}
Cubic Feet Gas/gal Liquid		----	----	35.78 ^e	30.77 ^e	29.70 ^e
Specific Heat						
60F 14.696 psia	Cp	0.5271	0.4097	0.3885	0.3920	0.3872 ⁵
	Cv	0.402	0.343	0.342	0.363	0.352
CALORIFIC VALUE 60°F	NET					
	BTU/cu ft Vapor 14.596 psia	911	1,631	2,353	3,101	3,094
	BTU/cu ft Vapor 14.696 psia	1,012 ^e	1,783 ^e	2,557 ^e	3,369 ^e	3,354 ^e
	GROSS					
	BTU/lb Liquid ^c	----	----	21,554	21,190	21,152
	BTU/gal Liquid	----	----	91,044	108,047	99,097
Heat of Vaporization 14.696 psia at						
Boiling Point BTU/lb		219.7	210.7	183.5	165.9	157.8
Air Required for Combustion cu ft/cu ft		9.53	16.67	23.82	30.97	30.97
Refractive Index ^{a,n,D} 68F		----	----	----	----	----
ASTM OCTANE NO.	Motor Method D-357	----	----	----	----	----
	Research Method D-908	+6 ^g	+6 ^g	+5.3 ^g	88 ^g	+0.2 ^g
Flammability Limits, Volume %						
in Air Mixture						
Lower		5.0	3.22	2.37	1.86	1.80
Higher		15.0	12.45	9.50	8.41	8.44

GAS COMPONENTS OF GAS HYDRATES

NATURAL GASES

Physical Constants

Formula		NH ₃	N ₂ O ₂	H ₂	O ₂	N ₂	Cl ₂	H ₂ O
Molecular Weight		17.032	28.966	2.016	32.000	28.016	70.914	18.016
Boiling Point °F, 14.696 psia		-28.1(2)	-317.7(2)	-422.9(2)	-297.4(2)	-320.4(2)	30.3(2)	212.0
Vapor Pressure 100°F, psia		-211.9(11)	----	----	----	----	154(3)	0.9492
Freezing Point °F, 14.696 psia		-107.9(2)	----	-434.4(2)	-361.1(2)	-345.6(2)	-150.9(2)	32.0
CRITICAL CONSTANTS	Pressure, psia	1,657(11)	547(2)	188(2)	730(2)	492(2)	1,120(2)	3,206(2)
	Temperature, °F	271.4(11)	-221.3(2)	-399.8(2)	-181.8(2)	-232.8(2)	291(2)	705.4(2)
LIQUID DENSITY 60°F 14.696 psia	Volume, cu ft/lb	0.0682(3)	0.0517(2)	0.5168(3)	0.0373(3)	0.0515(3)	0.0280(3)	0.0400(3)
	Specific Gravity 60F/60F ^b	.6173(11)	.856m(8)	.07m(3)	1.14m(3)	.808m(3)	1.423(10)	1.000
	lb per gal ^c	5.147	----	----	----	----	11.86	8.337
GAS DENSITY 60°F 14.696 psia	gal/lb mole	3.31	----	----	----	----	5.98	2.16
	Temp. Coefficient of Density	----	----	----	----	----	----	----
	Specific Gravity Air = 1	0.5830	1.000	0.0696	1.1047	0.9672	2.4482	0.622
IDEAL GAS	Cubic Feet Gas per Pound ^b	22.124	13.089	188.699	11.848	13.532	5.283	----
	Cubic Feet Gas/gal Liquid	113.4(11)	----	----	----	----	62.6(3)	175.44
SPECIFIC HEAT 60F 14.696 psia	Cp	.5232(3)	0.241(13)	3.408(13)	0.2188(13)	0.2482(13)	.1149(3)	0.4446(13)
	Cv	0.399	0.171	2.42	0.156	0.177	0.0841	0.332
CALORIFIC VALUE 60°F	NET	BTU/cu ft Vapor 14.696 psia	----	273(8)	----	----	----	----
	GROSS	BTU/cu ft Vapor 14.696 psia	----	324(13)	----	----	----	----
		BTU/lb Liquid ^c	----	----	----	----	----	----
		BTU/gal Liquid	----	----	----	----	----	----
Heat of Vaporization 14.696 psia at								
Boiling Point BTU/lb		589.3(11)	92(3)	192(2)	92(2)	86(3)	121(2)	970.3(9)
Air Required for Combustion cu ft/cu ft		----	----	2.39	----	----	----	----
Refractive Index ^{a,n,D} 68F		----	----	----	----	----	----	1.3330(13)
ASTM OCTANE NO.	Motor Method D-357	----	----	----	----	----	----	----
	Research Method D-908	----	----	----	----	----	----	----
Flammability Limits, Volume %								
Lower		15.50(5)	----	4.00(5)	----	----	----	----
Higher		27.00	----	74.20	----	----	----	----

GAS COMPONENTS OF GAS HYDRATES

NATURAL GASES

Physical Constants		Methyl Alcohol	Ethyl Alcohol	Carbon Monoxide	Carbon Dioxide	Hydrogen Sulphide	Sulfur Dioxide	Hydrogen Chloride	
Formula		CH ₄ O	C ₂ H ₆ O	CO	CO ₂	H ₂ S	SO ₂	HCl	
Molecular Weight		32.042	46.069	28.010	44.010	34.076	64.060	36.465	
Boiling Point °F, 14.696 psia		148.1(2)	173.3(2)	-313.6(2)	-109.3(2)	-76.5(4)	14.0(2)	-121.0	
Vapor Pressure 100°F, psia		4.6(7)	2.3(3)	----	----	554.6(6)	84.5(7)	900(T)	
Freezing Point °F, 14.696 psia		-144.0(2)	-179.1(2)	-340.6(2)	----	-121.9(4)	-98.9(2)	-173.6(u)	
CRITICAL CONSTANTS	Pressure, psia	1,157(2)	927(2)	510(2)	1,073(2)	1,306(2)	1,142(2)	1,199.2	
	Temperature, °F	464(2)	469.6(2)	-218.(2)	88.0(2)	212.7(2)	315.0(2)	124.5(s)	
	Volume, cu ft/lb	.0589(3)	.0581(3)	.0515(3)	.0348(3)	----	.0308(3)	0.0381	
LIQUID DENSITY 60°F 14.696 psia	Specific Gravity 60F/60F ^b	.796(3)	.794(3)	.801m(8)	.8159(10)	.79(6)	1.394(7)	0.8558	
	lb per gal ^c	6.637	6.619	----	6.802	6.53	11.62	7.1266	
	gal/lb mole	4.83	6.96	----	6.47	5.18	5.51	5.117(q)	
GAS DENSITY 60°F 14.696 psia	Temp. Coefficient of Density	----	----	----	----	----	----	0.003346(q)	
	Specific Gravity Air = 1	1.1062	1.5905	0.9670	1.5194	1.1764	2.2116	1.268	
	Cubic Feet Gas per Pound ^b	14.479	20.818	13.550	8.569	11.050	5.824	10.407(q)	
IDEAL GAS	Cubic Feet Gas/gal Liquid	96.097	137.794	----	58.3(2)	72.7(2)	67.7(3)	74.17(q)	
	Specific Heat Cp	0.27(13)	0.307(13)	.2484(13)	.1991(13)	.254(13)	.147(13)	0.1939(x)	
CALORIFIC VALUE 60°F	60F 14.696 psia Cv	0.446	0.368	0.177	0.153	0.192	0.118	0.1375(x)	
	GROSS	BTU/cu ft Vapor 14.696 psia	765	1446	----	----	621(15)	----	----
		BTU/cu ft Vapor 14.696 psia	865(13)	1596(13)	321(13)	----	627(13)	----	----
		BTU/lb Liquid ^c	9,750	12,755	----	----	----	----	----
ASTM OCTANE NO.	BTU/gal Liquid	64,643	84.311	----	----	----	----	----	
	Motor Method D-357	----	----	----	----	----	----	----	
Heat of Vaporization 14.696 psia at									
Boiling Point BTU/lb		473(8)	368(8)	91(8)	248n(3)	236(6)	171(8)	190.4(V)	
Air Required for Combustion cu ft/cu ft		7.15(13)	14.30(13)	2.39	----	7.2	----	----	
Refractive Index ^{a,n,D} 68F		1.3288(13)	1.3614(13)	----	----	----	----	----	
Research Method D-908		----	----	----	----	----	----	----	
Flammability Limits, Volume % Lower		6.72(5)	3.78(5)	12.50(5)	----	4.30(5)	----	----	
in Air Mixture Higher		36.50	18.95	74.20	----	45.50	----	----	

CLASSIFICATION OF LETTERS

- a. Air Saturated Hydrocarbons.
- b. Absolute values from weights in vacuum.
- c. Apparent values from weights in air.
- d. At Saturation pressure (triple point).
- e. Actual gas volumes corrected for deviation.
- g. Equivalent octane number (gas).
- h. Saturation pressure
- k. Mines octane number derived from blends with Reference 5.
- K. Values in parenthesis are estimated.
- m. Density of liquid gr./ml. @ normal boiling point.
- n. Heat of sublimation
- q. Calculated from other properties.
- s. See References 16, 18, & 20.
- t. Reference 2.
- u. References 16 & 18.
- v. References 11 & h.
- w. Reference 19.
- x. Reference 18 & p.

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APPENDIX B
PHYSICAL PROPERTIES OF GASES, LIQUIDS, AND SOLIDS

Knowledge of the physical properties of hydrate components (gases, water, or ice) and the sediments surrounding hydrates is needed when modeling and evaluating the recoverability of hydrates.

This appendix provides data on the most important physical properties of gas, oil, water, ice, and sediment for evaluating the recoverability of hydrates.

A. DENSITY/SPECIFIC GRAVITY

The specific gravity of a substance with respect to water is the ratio of the substance's density to the density of water at the same temperature and pressure. The units of specific gravity are:

$$\gamma_o = \frac{\rho_o}{\rho_w} = \frac{1 \text{ b oil/ft}^3 \text{ oil}}{1 \text{ b water/ft}^3 \text{ water}} \quad (\text{B-1})$$

Sometimes specific gravity is given as sp gr 60°/60° which means that the densities of both the liquid and water were measured at 60°F and atmospheric pressure.

The petroleum industry uses another gravity term called API gravity which is defined as:

$$^\circ\text{API} = \frac{141.5}{\gamma_o} - 131.5 \quad (\text{B-2})$$

where γ_o is the specific gravity at 60°/60°.

Tables B-1 and B-2 show the density of water (ice) and the volume of water as a function of temperature and pressure. The density of some marine and terrestrial sediments are shown in Table B-3.

TABLE B-1
DENSITY AND VOLUME OF WATER -1° to 250°C

Temp. °C	Density	Volume	Temp. °C	Density	Volume	Temp. °C	Density	Volume
-10	0.99815	1.00186	20	0.99823	1.00177	50	0.98807	1.01207
-9	843	157	21	802	198	51	762	254
-8	869	131	22	780	220	52	715	301
-7	892	108	23	757	244	53	669	349
-6	912	088	24	733	268	54	621	398
-5	.99930	1.00070	25	.99708	1.00293	55	.98573	1.01448
-4	945	055	26	682	320	60	324	705
-3	958	042	27	655	347	65	059	979
-2	970	031	28	627	375	70	.97781	1.02270
-1	979	021	29	598	404	75	489	576
0	.99987	1.00013	30	.99568	1.00434	80	.97183	1.02899
1	993	007	31	537	465	85	.96865	1.03237
2	997	003	32	506	497	90	534	590
3	999	001	33	473	530	95	192	959
4	1.00000	1.00000	34	440	563	100	.95838	1.04343
5	0.99999	1.00001	35	.99406	1.00598	110	.9510	1.0515
6	997	003	36	371	633	120	.9434	1.0601
7	993	007	37	336	669	130	.9352	1.0693
8	988	012	38	300	706	140	.9264	1.0794
9	981	019	39	263	743	150	.9173	1.0902
10	.99973	1.00027	40	.99225	1.00782	160	.9075	1.1019
11	963	037	41	187	821	170	.8973	1.1145
12	952	048	42	147	861	180	.8866	1.1279
13	940	060	43	107	901	190	.8750	1.1429
14	927	073	44	066	943	200	.8628	1.1590

Source: Perry and Chilton, eds., 1973.

TABLE B-2
VOLUME OF WATER AS A FUNCTION OF PRESSURE AND TEMPERATURE

Temp. OF (°C)	Pressure in atmospheres						
	0	500	1,000	2,000	3,000	4,000	5,000
32(0)	1.0000	0.9769	0.9566	0.9223	0.8954	0.8739	0.8565
68(20)	1.0016	0.9804	0.9619	0.9312	0.9065	0.8855	0.8675
122(50)	1.0128	0.9915	0.9732	0.9428	0.9183	0.8974	0.8792
176(80)	1.0287	1.0071	0.9884	0.9568	0.9315	0.9097	0.8913

1 atmosphere = 14.3 psi

Source: Baumeister, 1978.

TABLE B-3
DENSITY OF SOME MARINE AND TERRESTRIAL SEDIMENTS

Sediment	Hydrate Saturated (g/cm ³)	Water Saturated (g/cm ³)
Abyssal Plain		
Sandy Silt	1.58	1.65
Clay	1.15	1.26
Abyssal Hill Clay	1.32	1.42
Shelf		
Sand (coarse)	2.02	2.07
Derea Sandstone	2.40	2.42

Source: Pearson, 1982

TABLE B-4
DENSITIES OF GASES AT STANDARD CONDITIONS (0°C, 1 atm)

Gas	Formula	Mol. wt.	gram/liter	lb./ft ³
Air	-	-	1.2928	0.0808
Argon	Ar	39.91	1.7828	0.1114
Butane	C ₄ H ₁₀	58.08	2.5985	0.1623
Carbon dioxide	CO ₂	44.00	1.9768	0.1235
Chlorine	Cl ₂	70.91	3.2204	0.2011
Ethane	C ₂ H ₆	30.05	1.3567	0.0848
Helium	He	4.00	0.1769	0.0111
Hydrogen	H ₂	2.016	0.0898	0.0056
Hydrogen sulfide	H ₂ S	34.08	1.5392	0.0961
Krypton	Kr	82.90	3.6431	0.2275
Methane	CH ₄	16.03	0.7167	0.0448
Neon	Ne	20.40	0.8713	0.0544
Nitrogen	N ₂	28.02	1.2507	0.0782
Oxygen	O ₂	32.00	1.4289	0.0892
Sulfur dioxide	SO ₂	64.06	2.9268	0.1828
Xenon	Xe	130.20	5.7168	0.3570

Source: Perry and Chilton, 1973

The density of gases can be calculated from the equation of state as

$$\rho_g = \frac{nM}{v} = \frac{pM}{ZRT}$$

The density of natural gases is shown in Figure B-1 as a function of pressure, gravity, and temperature. The densities of gases at standard conditions are shown in Table B-4.

B. VISCOSITY

The dynamic viscosity, η , of a (Newtonian) fluid is given by ζ ($\zeta = \eta/dv/dr$), where η = shearing stress between two planes parallel with the direction of flow, and dv/dr = velocity gradient at right angles to the direction of flow. The dimensions of dynamic viscosity are $ML^{-1}T^{-1}$.

Kinematic viscosity, ν , is the ratio of the dynamic viscosity to the density. The dimensions of kinematic viscosity are L^2T^{-1} .

1. Gases

The dynamic viscosity of gases is usually expressed in centipoise (μ , cp). The viscosity of gases and vapors as a function of temperature at one atmosphere are shown graphically in Figure B-2.

Kinetic theory shows that the viscosity of gases is expected to be independent of the pressure and to vary as the square root of the absolute temperature (Perry and Chilton, 1973).

The effect of pressure on gas viscosity (significant for pressures exceeding about 10 atm.) is represented by the generalized charts of Carr and co-workers, shown as Figures B-3a and B-3b. These figures, which are limited to T_r and $P_r > -1$, represent the pressure dependence of gas viscosity within average and maximum deviations of about 2 and 10 percent in most cases. In the region of the critical point, errors may be serious.

Figure B-1
DENSITY OF NATURAL GASES

SOURCE: Katz, et al., 1959.

Figure B-2

VISCOSITY OF GASES AT ATMOSPHERIC PRESSURE

SOURCE: McCain, 1973.

Figure B-3a
EFFECT OF PRESSURE ON GAS VISCOSITY

Figure B-3b
EFFECT OF PRESSURE ON GAS VISCOSITY --
HIGH PRESSURE RANGE

SOURCE: Perry and Chilton, 1973.

Presentation of Figures B-3a and b as two plots, with parametric curves and abscissa scales reversed in one, allows more accurate interpolation. If, for example, $T_r = 1.67$ and $P_r = 23$, one may read (μ_p/μ_l) values from Figure B-3a at $P_r = 23$ and at $T_r = 1.60$ and 1.75 straddling the desired but unplotted isotherm. One may then plot these points (of μ_p/μ_l vs. T_r) on Figure B-3b to construct the desired isobar for $P_r = 23$, from which μ_p/μ_l at $T_r = 1.67$ may be read.

Example

Find the viscosity of carbon dioxide at 122°F (50°C or 582°R) and 100 atmospheres:

- The viscosity at one atmosphere can be read from Figure B-2 for 122°F as 0.0163 centipoise.
- The critical pressure and temperature for carbon dioxide (Appendix A) is:

$$P_c = 1,070 \text{ psia}$$

$$T_c = 548^\circ\text{R}$$

- The reduced pressure and temperature are:

$$P_r = (100) (14.7)/1,070 = 1.37$$

$$T_r = 582/548 = 1.06$$

- The reduced viscosity can be determined from Figure B-3a as 1.95. Therefore, the viscosity of carbon dioxide at 50°C (582°R) and 100 atmospheres (1,470 psi) is:

$$\mu = (0.0163) (1.95) = 0.0318 \text{ centipoise}$$

2. Liquids

In general, the dynamic viscosity of liquids decreases with the temperature approximately according to the equation $\log \mu = A + B/T$, where A and B are characteristic constants and T is the absolute temperature. Values of A and B for a large number of liquids are given by Barrer (1943).

The viscosity of water decreases inversely with temperature and increases slightly with pressure, Figure B-4. Figure B-5 gives the viscosity-temperature relationship of typical petroleum fluids in graphical form.

C. SONIC VELOCITY

The sonic velocity in various permafrost sediments is shown on Table B-5. The sonic velocity of sediments with hydrates are discussed in Chapter 3, "Physical Properties of Hydrates."

D. GAS SOLUBILITY IN WATER

The solubility of gas in water can be expressed as

$$R \ln X_2 = A + B/T + C \ln (T/K) + D \cdot T$$

where the temperature T is in $^{\circ}\text{K}$ and X_2 is the mole fraction gas in water and the coefficients A, B, C, and D are given in Table B-6.

The solubility of methane in pure water from 70°F to 680°F and from 600 to 16,000 psi (4,137 to 110,320 kPa) is shown in Figure B-6. Modification of solubility as a function of salinity is shown in Figure B-7. Also shown in Figure B-6 is the critical point of water at 705.38°F (374.15°C) and 3,208.14 psi (218.3 atm; 22,114 kPa) where a discontinuity in properties of water-methane mixtures would occur. The distinction between liquid and vapor would disappear, so that water and methane should be completely miscible in all proportions above this point.

TABLE B-5

Seismic compressional-wave velocities measured in permafrost

Rock Types	Locality and Reference	Seismic Velocity (kilo ft/sec)		Estimated Ground Temp., °C
		Frozen	Unfrozen	
Quaternary sediments				
Silt and organic matter	Fairbanks Area, Alaska ^a	5-10	1.8-4	-1
Alluvial clay	Northway, Alaska ^b	7.8		-2
Silt and gravel	Fairbanks Area, Alaska ^c	7.7-10		-1
Aeolian sand	Tetlin Junction, Alaska ^c	8		-3
Floodplain alluvium	Fairbanks Area, Alaska ^c	8-14	6.1-7	-1
Tundra silts, sands, and peats				
(Gubik Formation, probably saline)	Barrow Area, NPR-4, Alaska	8-8.8		-9
(Gubik Formation, probably saline)	Skull Cliff Area, NPR-4, Alaska	7.4-8.9		-9
(Gubik Formation, less saline)	Topagoruk Area, NPR-4, Alaska	8-12		-9
Gravel	Fairbanks Area, Alaska ^a	13.0-15.2	6-7.5	-1
Outwash gravel	Tanacross, Alaska ^c	7.6-10		-3
Glacier moraine	Delta Junction, Alaska ^c	7.6-13.2		2
Unclassified sediments	Isachsen, Canada	8.8		-13
Glacier outwash	Thule, Greenland	14.1-15.3		-11
Glacier till	Thule, Greenland	15.4-15.5		-11
Mesozoic sediments				
Mudstone (Ogotoruk Formation) ^d	Ogotoruk Creek, Alaska	14.2	11 ^d	-5
Mudstone (Ogotoruk Formation) ^{d,e}	Ogotoruk Creek, Alaska	13.2		-5
Shale and siltstone (Schrader Bluff Formation) ^e	Fish Creek Test Well 1, NPR-4, Alaska	8.9-9.8	6.6-7.6	-8
Shale and sandstone (Chandler Formation) ^{e,f}	Umiat Test Well 2, NPR-4, Alaska	12.7		-7
Shale and sandstone (Nanushuk Group) ^{e,g}	Simpson and Minga Wells, NPR-4, Alaska	8.1-8.4	5-7	-9
Sandstone (Colville Group)	Umiat Area, NPR-4, Alaska	10.7		-7
Sandstone and shale (Nanushuk and Colville Group)	Meade-Dumalik Area, NPR-4, Alaska	10.14		-9
Sandstone (Isachsen Formation)	Isachsen, Canada	11.1		-10
Paleozoic and older sediments				
Shale (Dundas Formation)	Thule, Greenland	13.3-14		-11
Sandstone (Narssarsuk Formation)	Thule, Greenland	15.6-17.9		-11
Quartzite (Wohlstenholm Formation)	Thule, Greenland	18		-11
Dolomite (Narssarsuk Formation)	Thule, Greenland	18.9-19.5		-11
Metamorphic rocks				
Schist (Birch Creek Schist)	Fairbanks Area, Alaska ^a	13-16		-1
Gneiss	Thule, Greenland	20		-11

^a Obtained from H. G. Taylor, 1938, Report on geophysical work by the seismic method in placer deposits of Fairbanks District of Alaska, unpublished report to U.S. Smelting, Refining and Mining Company.

^b Unpublished data from J. E. Swartz and E. R. Shepard, U.S. Geol. Survey, 1946

^c Data by author in 1952

^d The Materials Testing Laboratory, U.S. Army Engineer District, Alaska, tested cores from this well and found that 5 porosity measurements averaged 6.4% and that dynamic measurements on unfrozen cores gave elastic module which may be used to compute a velocity in the unfrozen rocks of about 11,000 fps

^e Measurements by velocity logs of wells; rest measured by refraction

^f Porosity measurements of 44 cores from Umiat Test Well #2 averaged 13.5%

^g Porosity measurements of 15 cores from Simpson Test Well #1 averaged 30.8%

Source: Barnes, D.F. "A Review of Geophysical Methods for Delineating Permafrost," Proceedings of the International Permafrost Conference, National Research Council, National Academy of Sciences, Washington, D.C., Publication 1287, p. 350.

TABLE B-6

SOLUBILITY OF GASES IN WATER AT ATMOSPHERIC PRESSURE

<u>Gas</u>	$(\text{Cal } ^\circ\text{K}^{-\frac{A}{T}} \text{ mol}^{-1})$	$(\text{Cal } ^\circ\text{K} \text{ mol}^{-1})$	$(\text{Cal } ^\circ\text{K}^{-\frac{C}{T}} \text{ mol}^{-1})$	$(\text{Cal } ^\circ\text{K}^{-2} \text{ mol}^{-1})$
CH ₄	-365.183	18106.7	49.7554	-0.000285033
C ₂ H ₆	-533.392	26565.0	74.6240	-0.00457313
C ₂ H ₄	-303.888	15817.6	40.7591	-
C ₂ H ₂	-311.014	16215.8	42.5303	-
C ₃ H ₈	-628.866	31638.4	88.0808	-
C ₃ H ₆	199.656	-3940.90	-35.8336	-
N ₂	-327.850	16757.6	42.8400	0.0167645
O ₂	-286.942	15450.6	36.5593	0.0187662
H ₂ S	-297.158	16347.7	40.2024	0.00257153
CO	-341.325	16487.3	46.3757	-
CO ₂	317.658	17371.2	43.0607	-0.00219107
He	-233.163	8737.84	32.2652	-0.0119726
Ne	-310.827	12766.8	43.6185	-0.0127534
Ar	-336.760	16170.1	46.2117	-0.00608793
Kr	-270.967	15992.9	33.2892	0.0260485
Xe	-360.119	18744.6	49.0332	-0.00311323

Source: Holder, personal communication.

Figure B-4
VISCOSITY OF WATER

*(1 psi = 6.8947 kPa)

SOURCE: Katz and Coats, 1967.

Figure B-5
VISCOSITY-TEMPERATURE RELATIONSHIPS
FOR TYPICAL PETROLEUM FUELS

SOURCE: Perry and Chilton, 1973.

Figure B-6

SOLUBILITY OF METHANE IN FRESH WATER

SOURCE: Sultanov, Skripka, and Namoit, 1972.

Figure B-7

EFFECT OF SALINITY ON GAS IN SOLUTION

SOURCE: Standing and Dodson, 1944.

Example

Determine the amount of methane in water at 1,250 psi and 200°F and a salinity of 150,000 ppm.

- From Figure B-6, the amount of methane dissolved in pure water is 1,000 ft³/Bbl.
- The correction factor of Figure B-7 is 0.50.
- The amount of methane dissolved in water is:
 $1,000 \times (0.5) = 500 \text{ ft}^3/\text{Bbl}.$

1. Water Content of Hydrocarbon Gases

A general chart for the water content of various natural hydrocarbon gases is shown on Figure B-8. Recent results indicate that the curves cannot be extrapolated as shown beneath the freezing point (Aoyagi, 1979).

The dotted line in Figure B-8 shows the hydrate formation conditions. Below the hydrate formation temperatures, gas and solid hydrate co-exist rather than gas and liquid, which exist at temperatures above the hydrate formation conditions. There is a slight change in slope of the lines below the hydrate formation temperature, Figure B-9.

Hydrates may form at natural gas wellheads at temperatures above 32°F when the pressure is more than 26 atmospheres. This can hamper operation of heat exchangers, expanders, pipelines, etc.

The solubility of gases in water in the presence of gas hydrates can be estimated using the following equation and coefficients, Table B-7.

$$X_i = (\phi_i y_i P) \cdot X_0 \cdot \exp \left[\frac{-V (P-1)}{82.06 T} \right]$$

$$X_0 = \exp (A + B/T)$$

where:

P = Pressure in atmospheres

ϕ_i = fugacity coefficient

y_i = Gas phase mole fraction

V = Partial molar volume of gas in water.

Use 32 except for C_2H_4 where V = 60

T = Temperature in $^{\circ}K$

TABLE B-7
GAS SOLUBILITY IN WATER IN THE PRESENCE OF HYDRATES

<u>Gas, i</u>	<u>A</u>	<u>B</u>
CH ₄	-15.826277	1559.0631
C ₂ H ₆	-18.400368	2410.1807
C ₃ H ₈	-20.958631	3109.3918
nC ₄ H ₁₀	-22.150557	3407.2181
i-C ₄ H ₁₀	-20.108263	2739.7313
C ₂ H ₄	-18.057885	2627.6108
Cyclo C ₃ H ₈	$X_0 = 760 \exp (-67.557 + 91177.534/T + .072775 T)$	
N ₂	-17.934347	1933.381
O ₂	-17.160634	1914.144
H ₂ S	-15.103508	2603.9795
CO ₂	-14.283146	2050.3269

Figure B-8
WATER CONTENTS OF NATURAL GASES
WITH CORRECTIONS FOR SALINITY AND GRAVITY

Figure B-9
WATER CONTENT OF METHANE

SOURCE: Aoyagi, 1979.

The water content in methane is shown on Figure B-9. As shown, the curves above the freezing point of water cannot be extrapolated into the ice region because the slope changes (Sloan, 1976).

McKetta and Katz, working with the methane-butane water system, showed that the amount of water required to saturate a gas depends on the molecular weight (hence the gravity) of the gas and the temperature. A correction factor is shown on Figure B-8 under the title "Correction for Gas Gravity" and is called, C_g where:

$$C_g = \frac{\text{lbs. water in Gas of Gravity, G}}{\text{lbs. water in Gas of Gravity of 0.6}}$$

In Figure B-8, there is also a correction chart for salinity from which the salinity correction factor, C_s , is obtained.

$$C_s = \frac{\text{lb. water in gas if gas had been in contact with brine}}{\text{lb. water in gas if gas had been in contact with water}}$$

Example

A natural gas, gravity = 0.9, is in contact with brine in a reservoir. The brine contains 30,000 ppm solids (approximately 3 percent NaCl). The pressure of the gas is 3,000 psia and the gas temperature is 150°F. How much water is in the gas in pounds of water per million cubic feet of gas (measured at 60°F and 14.7 psia)?

Step 1 Follow the dashed lines on Figure B-8. At 3,000 psia and 150°F, a 0.6 gravity gas would contain 105 pounds of water per million cubic feet of 0.6 gas, if the gas had been in contact with pure water.

Step 2 Correction for gas gravity from 0.6 to 0.9: From the correction chart for gravity, follow the dashed line from the abscissa where the desired gravity is 0.9 vertically, to the 150°F isotherm. Read horizontally, the C_g correction factor for gas gravity, = 0.98.

Step 3 Correction for salinity of brine: See the second correction chart on Figure B-8. At a brine salinity of 3% go vertically to the correction line and read on the ordinate value of $C_2 = 0.93$.

Step 4 The amount of water dissolved is calculated as follows:
 $105 \text{ lbs. water} \times C_g \times C_2 = 105 \times 0.98 \times 0.93 = 95.6 \text{ lbs. water}$
in the gas. The experimental value for this gas was 96.2, which is within the desired accuracy.

APPENDIX C
THERMODYNAMIC PROPERTIES OF GASES, LIQUIDS, AND SOLIDS

This appendix reviews the thermodynamic properties of hydrate components (gases and liquids) and of the sediments that surround potential hydrate deposits.

A. HEAT CAPACITY

The heat capacity, C_p , of a substance is defined as the amount of heat required to raise the temperature of a unit mass by one degree. The specific heat of a substance is the ratio between its heat capacity and the heat capacity of water.

For most engineering purposes, heat capacities may be assumed numerically equal to specific heats because the heat capacity of water is about 1.0 BTU per pound. Two heat capacities are generally used, that at constant pressure, c_p , and that at constant volume, c_v . For unit mass, the instantaneous heat capacities are defined as:

$$\left(\frac{\partial b}{\partial t}\right)_p = c_p \quad \left(\frac{\partial u}{\partial t}\right)_v = c_v \quad (C-1)$$

1. Gases

The following expression for C_p in $\text{cal deg}^{-1} \text{ mole}^{-1}$ is in most cases applicable to gases from about 300°K to $1,500^\circ\text{K}$.

$$C_p = a + bt + cT^2 + dT^3 \quad (T \text{ in } ^\circ\text{K}) \quad (C-2)$$

Values of the constants in a , b , c , and d are shown in Table C-1 for gases and vapors at one atmosphere.

TABLE C-1
VALUES OF CONSTANTS AT ONE ATMOSPHERE

Substance	a	b x 10 ³	c x 10 ⁶	d x 10 ⁹
n-Butane	-0.012	92.506	-47.998	9.706
Carbon Dioxide	6.214	10.396	-3.545	
Carbon Monoxide	6.420	1.665	-0.196	
Ethane	1.279	42.464	-16.420	2.035
Hydrogen	6.947	-0.200	0.4808	
Hydrogen Sulphide	6.864	-0.200	0.785	-0.634
Methane	3.381	18.044	-4.300	
Nitrogen	6.524	1.250	-0.001	
Oxygen	6.148	3.102	-0.923	
Propane	-1.209	73.734	-38.666	7.961
Sulphur Dioxide	6.147	13.844	-9.103	2.057
Water	7.256	2.298	0.283	

Example. Calculate the heat capacity of methane at 32°F (273°K).

$$\begin{aligned}
 C_p &= 3.381 + 18.044(273) \cdot 10^{-3} - 4.300(273)^2 \cdot 10^{-6} \\
 &= 7.99 \text{ cal/}^{\circ}\text{K/mole}
 \end{aligned}$$

2. Liquids

The heat capacity of water at atmospheric pressure and at higher pressure is shown in Tables C-2 and C-3.

TABLE C-2
HEAT CAPACITY OF WATER AT ATMOSPHERIC PRESSURE, J/g/°C

°C	0	1	2	3	4	5	6	7	8	9
0	4.2174	4.2138	4.2104	4.2074	4.2045	4.2019	4.1996	4.1974	4.1954	4.1936
10	4.1919	4.1904	4.1890	4.1877	4.1866	4.1855	4.1846	4.1837	4.1829	4.1822
20	4.1816	4.1810	4.1805	4.1801	4.1797	4.1793	4.1790	4.1787	4.1785	4.1783
30	4.1782	4.1781	4.1780	4.1780	4.1779	4.1779	4.1780	4.1780	4.1781	4.1782
40	4.1783	4.1784	4.1786	4.1788	4.1789	4.1792	4.1794	4.1796	4.1799	4.1801
50	4.1804	4.1807	4.1811	4.1814	4.1817	4.1821	4.1825	4.1829	4.1833	4.1837
60	4.1841	4.1846	4.1850	4.1855	4.1860	4.1865	4.1871	4.1876	4.1882	4.1887
70	4.1893	4.1899	4.1905	4.1912	4.1918	4.1925	4.1932	4.1939	4.1946	4.1954
80	4.1961	4.1969	4.1977	4.1985	4.1994	4.2002	4.2011	4.2020	4.2029	4.2039
90	4.2048	4.2058	4.2068	4.2078	4.2089	4.2100	4.2111	4.2122	4.2133	4.2145

Source: Kaye and Laby, 1966.

TABLE C-3
HEAT CAPACITY OF WATER AT HIGH TEMPERATURES AND PRESSURE, BTU/lb/°F

<u>Temperature, °F</u>	<u>Pressure, psia</u>			
	<u>1,000</u>	<u>2,000</u>	<u>4,000</u>	<u>6,000</u>
200	1.002	0.998	0.992	0.986
400	1.072	1.063	1.047	1.034
600	0.888	1.453	1.295	1.211
680	0.707	1.365	1.789	1.450
800	0.605	0.800	1.967	2.872
1,000	0.566	0.633	0.829	1.110

Source: Perry and Chilton, 1973.

The specific heats of brine, sea-water, and ice are summarized in Table C-4.

TABLE C-4
SPECIFIC HEATS OF VARIOUS SUBSTANCES

<u>Substance</u>	<u>Temperature, °C</u>	<u>Specific Heat (J/g/°C)</u>
Brine	0	2.97
	15	3.01
Sea-water	17	3.93
Ice	-250	0.15
	-160	1.0
	-21 to -1	2.0 to 2.1

3. Solids

The heat capacity of naturally occurring solids (sand, crushed rock, cement mortars, etc.) may be approximated within about ± 15 -20% by the equation:

$$C_p = 0.18 + 0.00006T \quad (C-3)$$

where C_p is in Btu/(lb.)(°F) and T is in °F.

For petroleum oils, C_p may be estimated within 5 percent by the equation:

$$C_p = \frac{0.388 + 0.00045T}{s^{0.5}} \quad (C-4)$$

where C_p is in BTU/(lb)(°F), T is in °F, and s is the liquid specific gravity at 60°F/60°F. Equation (C-4) is directly applicable for temperatures between 32° and 400°F and for $0.75 < s < 0.96$. The average error is 5 percent for the extended temperature range of 400° to 750°F.

For solid compounds at about room temperature, Kopp's approximation is often useful. This states that the specific heat of a solid compound at room temperature is equal to the sum of the specific heats of the atoms forming the compound. The values given in Table C-5 can be used in connection with Kopp's Law.

TABLE C-5
CONSTANTS FOR KOPP'S LAW

<u>Elements</u>	<u>Specific Heats of the Atoms</u>	<u>Elements</u>	<u>Specific Heats of the Atoms</u>
Heavy Elements	6.4	Oxygen	4.0
Boron	2.7	Phosphorus	5.4
Carbon	1.8	Silicon	3.5
Fluorine	5.0	Sulfur	5.4
Hydrogen	2.3		

Source: Perry and Chilton, 1973.

Example. Calculate the specific heat of Na_2SO_4 .

The specific heat of the atoms of $\text{Na}_2\text{SO}_4 = 2(6.4) + 5.4 + 4(4) = 34.2$. The molecular weight of $\text{Na}_2\text{SO}_4 = 142$. Specific heat = $34.2/142 = 0.24$: (I.C.T. value = 0.20). (Errors of 20 percent are not uncommon using Kopp's Law.)

4. Heat Capacity of Mixtures

The heat capacities of mixtures (solids, liquids, or gases--singly or in combination, miscible or immiscible--) can be estimated by weighting the pure-component or phase heat capacities by weight, mole, or volume fractions. For an immiscible mixture, this approach is entirely adequate. For miscible mixtures, the accuracy of such weighting varies from excellent, in the case of low density gases, to quite poor for liquid mixtures with large heats of mixing. For liquids, the weighting rule will generally work well only for mixtures of chemically similar non-polar liquids (such as hydrocarbons or liquid metals), or for aqueous solutions of non-electrolytes. Even then, C_p values predicted in this manner exceed experimental values by a few percent. Aqueous solutions of inorganic salts are a special class for which two rules of thumb are available. The weighted specific heat can be used, where the specific heat of the salt is for the crystalline state; or, alternatively, for solutions up to about 40 weight percent solute, the assumption may be made that the dissolved salt has a negligible heat capacity. Thus, 30 weight percent solution of salt in water would have a specific heat of 0.7 cal/(g)(°C) (Perry and Chilton, 1973).

If w_1 pounds of a substance at temperature t_1 and with specific heat c_1 is mixed with w_2 pounds of a second substance at temperature t_2 and with specific heat c_2 , provided chemical reaction, heat evolution, or heat absorption do not occur, the specific heat of the mixture, c_m , is:

$$c_m = (w_1 c_1 + w_2 c_2) / (w_1 + w_2) \quad (C-5)$$

and the temperature of the mixture, t_m , is:

$$t_m = (w_1 c_1 t_1 + w_2 c_2 t_2) / (w_1 c_1 + w_2 c_2) \quad (C-6)$$

For mixing two bodies of the same (perfect) gas at constant pressure,

$$t_m = [(v_1 + v_2) / (v_1/t_1 + v_2/t_2)] - 459.69 \quad (C-7)$$

B. THERMAL CONDUCTIVITY

The thermal conductivity, k , of a substance is defined as the quantity of heat transmitted, due to a unit temperature gradient, in unit time under steady conditions in a direction normal to surface of unit area, when the heat transfer is dependent solely on the temperature gradient. Thermal diffusivity is derived from the thermal conductivity and is equal to $k/(\text{density} \cdot \text{specific heat})$. The unit of thermal conductivity is measured in $\text{J/S} \cdot \text{m} \cdot ^\circ\text{K}$ in SI units.

1. Solids, Liquids and Gases

The thermal conductivity of a material is dependent on:

- mineral composition
- grain orientation and size
- porosity
- shape and orientation number of the voids.

Data on the thermal conductivity and diffusivity are summarized on Tables C-6 through C-10 and on Figures C-1 through C-2. The content of these tables and figures is summarized below:

- Table C-6 contains the thermal conductivity of water and steam as a function of pressure and temperature.
- Table C-7 contains the thermal conductivities of solids, ice, and unconsolidated sediments.
- Table C-8 contains the thermal conductivity of permafrost zones in Northern Canada.
- Table C-9 contains the thermal conductivities of ocean sediment and water and their change with the temperature.
- Table C-10 contains the thermal diffusivity of various minerals.
- Figure C-1 shows the thermal conductivity of various sediments as a function of water saturation.
- Figure C-2 shows the effect on the thermal conductivity of hydrate formation.

TABLE C-6
THERMAL CONDUCTIVITY OF WATER AND STEAM
 mwatts/(m.) (°K)

Pressure Bars	Temperature °C										
	0	50	100	150	200	250	300	400	500	600	700
1	569	643	24.8	28.7	33.2	38.2	43.4	54.9	67.4	80.6	94.3
50	573	647	684	690	668	618	52.5	60.2	72.0	85.0	98.6
100	577	651	688	693	672	625	545	68.6	77.6	89.8	103
150	581	655	691	696	676	633	559	82.2	84.3	95.1	108
200	585	659	695	700	681	639	571	107	92.6	101	113
250	589	662	698	703	685	646	582	157	103	107	118
300	592	666	701	706	689	652	592	264	116	114	124
350	596	669	704	710	693	657	601	351	132	122	129
400	599	672	707	716	701	667	616	416	180	139	142
500	606	678	713	720	704	671	622	436	206	149	148

Source: Perry and Chilton, 1973.

TABLE C-7
THERMAL CONDUCTIVITIES OF SOLIDS

Material	Bulk Density (lb/ft ³)	Temperature (°F)	k
Ice	57.5		1.26
Soil, dry		68	0.075
Soil, dry, including stones	127	68	0.30
Sand, dry	94.8	68	0.188
Earth, plus 42% water	108	0	0.62

TABLE C-8
THERMAL CONDUCTIVITY OF PERMAFROST ZONES IN NORTHERN CANADA

Sedimentary Rocks		Metamorphic Rocks		Intrusive Rocks	
Lithology	Thermal cond. (mcal/cm. sec°C)	Lithology	Thermal cond. (mcal/cm. sec°C)	Lithology	Thermal cond. (mcal/°C cm. sec)
Shale	3.5	Gneiss	6	Gabbro	6
Limestone	7.0	Greenstone	8	Diabase	5
Sandstone					
Quartz	10	Slate	9	Granite	7
Dolomite	12	Argillite	8		
Evaporites	13	Quartzite	14		

Sources: Judge, 1973.

TABLE C-9
OCEAN SEDIMENT, WATER, SEA WATER:
CHANGE OF THERMAL CONDUCTIVITY WITH TEMPERATURE

Substance	Temperature, °C	Thermal Conductivity, cal cm cm ² sec°C X 10 ⁴	Decrease in Thermal Con- ductivity over Temperature Range, %	Observer
Pacific sediment (moisture content 52% of wet weight, wet density 1.40 g/cm ³)	25	19.0	5.8	Butler, 1950
	4	17.9		
Pacific sediment (moisture content 66.5% of wet weight, wet density 1.23 g/cm ³)	25	17.0	5.9	Butler, 1950
	4	16.0		
Pure water	25	14.3	4.2	Nukiyama & Yoshizawa, (1934)
	4	13.7		
Pure water	25	14.6	6.2	Challoner & Powell, (1956)
	4	13.7		
Sea water	30	14.1	4.3	Nukiyama & Yoshizawa, (1934)
	10	13.5		

Source: Ratcliffe, 1960.

Figure C-1

THERMAL CONDUCTIVITY OF
VARIOUS SATURATED SEDIMENTS

Figure C-2

THE EFFECT OF THE FORMATION OF GAS HYDRATE
COMPARED WITH THE EFFECT OF FREEZING
FOR WATER AND FOR WATER-FILLED SEDIMENT.
WATER CONTENT ON A DRY WEIGHT BASIS IS WA

SOURCE: Stoll and Bryan, 1979.

TABLE C-10
THERMAL CONDUCTIVITY OF SOLIDS

<u>Lithology</u>	<u>Temperature</u> (°F)	<u>k</u> (cm ² sec.)
Granite	60	0.011
Limestone	60	0.007
Dolomite	60	0.020
Sandstone	60	0.010
Shale	60	0.008
Ice	60	0.012

Source: Holder, personal communication.

The variation of thermal conductivity with temperature is shown on Table C-11 for selected substances.

TABLE C-11
VARIATION OF $k \times 10^4$ WITH TEMPERATURE

	<u>Temperature, °C</u>			
	<u>-100</u>	<u>0</u>	<u>100</u>	<u>1,000</u>
<u>Gases</u>				
Air	1.58	2.41	3.17	7.6
Carbon Dioxide	-	1.45	2.23	7.9
Hydrogen Sulphide	-	1.2	-	-
Methane	1.88	3.02	-	-
Water Vapor	-	1.58	2.35	5.7 (500°C)
<u>Liquids</u>				
Water		0.56	0.69	
<u>Solids</u>				
Ice	3.9	2.3		
Sand		0.3-0.4		

The effects of free gas on the thermal conductivity of frozen and unfrozen granular sediment is shown in Figure C-3. From this figure, it is obvious that relatively small amounts of gas can cause significant changes in the thermal conductivity of frozen sediments. It is likely that the same type of effect will be found in sediments containing ice-like, crystalline gas hydrate.

Figure C-3

THERMAL CONDUCTIVITY FOR FROZEN AND UNFROZEN SAND

SOURCE: Stoll, 1974.

The thermal conductivity of a gas is related to its coefficient of viscosity, μ , and specific heat at constant volume c_v , by the equation, $k = 0.25(9Y - 5) c_v$, where Y is the ratio c_p/c_v .

At normal pressures, the thermal conductivity of a gas is independent of pressure; an increase occurs at high pressures and a decrease at low pressures, e.g., below about 1 mmHg for air.

The thermal conductivities of porous media (solid + liquid or gas) can be correlated with Russel's equation:

$$\frac{k_{\text{comp}}}{k_{\text{cont}}} = \frac{vp^{2/3} + 1 - p^{2/3}}{v(p^{2/3} - p) + 1} \frac{p^{2/3} + p}{p^{2/3} + p} \quad (\text{C-8})$$

where the subscripts "comp" and "cont" denote values for the composite mixture and for the continuous phase, respectively, and where p is the porosity (volume fraction of voids or obstacles), given for a solid-gas mixture, by:

$$p = \frac{p_{\text{solid}} - p_{\text{comp}}}{p_{\text{solid}} - p_{\text{gas}}} \quad (\text{C-9})$$

The term v is the ratio of the thermal conductivity of the porosities to that of the continuous phase: $v = k_{\text{por}}/k_{\text{cont}}$. Equation (C-8) is applicable for $0 < p < 1$ when the particle size is reasonable uniform. For cellular materials (gas-solid with solid as the continuous phase, or solid-solid), average and maximum prediction errors appear to be 6 and 15 percent. If v is large, Eq. (C-8) reduces to:

$$\frac{k_{\text{comp}}}{k_{\text{cont}}} = \frac{1}{1 - p^{1/3}} \quad (\text{C-10})$$

C. HEAT OF COMBUSTION

The heat of combustion is shown below on Table C-12 for gases which can form hydrates.

TABLE C-12

HEATS OF COMBUSTION								
Compound	Formula	State	Heat of Combustion, - H_C^0 , at 25°C, and constant pressure, to form					
			H ₂ O (liq.) and CO ₂ (gas)			H ₂ O (gas) and CO ₂ gas		
			Kcal./mole	Cal./g	BTU/lb	Kcal./mole	Cal./g.	BTU/lb
Hydrogen.....	H ₂	gas	68.3174	33,887.6	60,957.7	57.7979	28,669.6	51,571.4
Carbon.....	C	solid	94.0518	7,831.1	14,086.8			
		graph.						
Carbon Monoxide.....	CO	gas	67.6361	2,414.7	4,343.6			
Paraffins								
Methane.....	CH ₄	gas	212.798	13,265.1	23,861	191.759	11,953.6	21,502
Ethane.....	C ₂ H ₆	gas	372.820	12,399.2	22,304	341.261	11,349.6	20,416
Propane.....	C ₃ H ₈	gas	530.605	12,033.5	21,646	488.527	11,079.2	19,929
Propane.....	C ₃ H ₈	liq.	526.782	11,946.8	21,490	484.704	10,922.5	19,774
n-Butane.....	C ₄ H ₁₀	gas	687.982	11,837.3	21,293	635.384	10,932.3	19,665
n-Butane.....	C ₄ H ₁₀	liq.	682.844	11,748.9	21,134	630.246	10,843.9	19,506
2-Methylpropane (Isobutane).....	C ₄ H ₁₀	gas	686.342	11,809.1	21,242	633.744	10,904.1	19,614
2-Methylpropane (Isobutane).....	C ₄ H ₁₀	liq.	681.625	11,727.9	21,096	629.027	10,822.9	19,468

Source: American Petroleum Institute Research Project 44.

APPENDIX D
POTENTIAL INDUSTRIAL APPLICATIONS OF HYDRATES

In addition to their potential as an energy source, hydrates have been investigated for various industrial applications. These include desalination of water, gas transportation and storage, and creating high pressures (Makogon, 1981 and Borg, 1983).

1. Desalination of Water. The first patent on desalination of water using hydrates was granted in the 1950s. The general principle is that when gas hydrates form from brine only the water molecules are removed, leaving the salts in solution. Subsequent hydrate decomposition provides gas and pure water.

Desalination was tested in the 1960s in two pilot plants. The Sweet Water Development Company chose propane hydrate, while the Koppers Company used Freon-12 (CCl_2F_2) (Knox, 1961). However, both tests had severe problems with growing adequately sized compact crystals to make permeable, washable beds. In addition, the slow hydration kinetics and the propensity of the mixtures to supercool raised technical concerns about the feasibility of using hydrates for desalination, and the concepts were not developed further.

2. Gas Transportation. Another application of hydrates is for gas storage. An alternative to gas hydrate storage is liquefied natural gas (LNG).

Hydrate-based gas storage appears to have certain advantages relative to LNG. Table D-1 compares gas liquefaction with hydration. The gas hydrate system allows higher temperatures and is a potentially safer system due to the relatively slow decomposition kinetics of hydrate. However, the use of hydrates for gas storage also has certain disadvantages, including greater volume, greater heat of refrigeration and regasification, slow kinetics of formation and decomposition, and supercooling/superheating of 2.8 to 11°C (5-20°F). These disadvantages have proved to be so important that LNG is the lowest cost option.

TABLE D-1
HYDRATE VS LNG STORAGE

<u>Pressure</u>	<u>Temperature</u>		<u>Vol. for 1000 scf</u>		<u>H Refrig. - BTU/1000</u>	
	(°F)	(°C)	(ft ³)	(m ³)	(scf)	(kJ/m ³)
14.7 psia (0.1 MPa)						
Liquefaction	-259	-161	1.61	0.04	15,620	582
Hydration	-146	- 99	6.25	0.18	101,500	3,781
400 psia (2.7 MPa)						
Liquefaction	-145	- 98	2.275	0.01	11,000	410
Hydration	+ 33	0.6	6.25	0.18	64,800	2,413

3. Gas Storage. Gas may potentially be stored underground in permafrost regions (even in structures without a natural caprock) due to the very low permeability of hydrates (Evrenos, 1971). If the reservoir is in a zone of hydrate stability, the injection of gas will cause hydrate to form which could serve as the caprock and plug gas leaks. Although the injection of stored gas would increase the pressure on the roof, the danger of the stored gas bursting through the roof would be reduced. As the gas pressure increases, more gas hydrate should form, thus increasing the thickness and strength of the hydrate caprock. Conversely, with removal of gas from the storage reservoir, pressure on the roof should decrease so that the lower part of the hydrate caprock would decompose.

4. Increasing Gas Pressure Without Compression. Pressures of several thousand psi can be obtained by decomposing gas hydrates in confined spaces, due to the pressure of the dissociated gas. This is demonstrated in Chapter 4, "Thermodynamic Properties of Hydrates." This method of producing high pressures can be employed in laboratory research and may also be used in industrial processes requiring high energy concentration. An example would be the compression of liquid solutions to speed up reactions during studies of various properties of materials subjected to high pressures. Refrigeration is required however to form hydrates and compression would be required in the refrigerator.

APPENDIX E

STEAM TABLES

One method of recovering hydrates may be the injection of steam to dissociate the methane. Steam tables have been included as an appendix to this Handbook to provide data on steam temperature and pressure properties.

The steam tables are arranged by temperature in Table E-1 and by pressure in Table E-2. These tables can be used to calculate both the energy required to generate steam and the energy given off by steam when it condenses.

The following symbols are used in the tables:

- h: specific enthalpy, BTU per lb
- p: pressure, lb per in²
- s: specific entropy, BTU per lb
- t: thermodynamic temperature,
- u: specific internal energy, BTU per lb
- v: specific volume, ft³ per lb

Subscripts

- f: refers to a property of fluid in equilibrium with vapor.
- g: refers to a property of gas in equilibrium with liquid.
- fg: refers to a change by evaporation.

The example below illustrates how to calculate these values.

Example: Table E-1 show that at a temperature of 340°F, the pressure is 117.93 psia and the total energy (enthalpy) of the steam is 1,190.8 BTU per pound. This energy is divided into two parts, the sensible part (saturated liquid enthalpy) of 311.3 BTU per pound required to raise the water to its boiling point, and the latent part (evaporation enthalpy) of 879.5 BTU per pound required to evaporate the boiling water.

TABLE 1 SATURATION TEMPERATURE

Temp Fahr. t	Press. Lbf. Sq.In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
32	.08859	.016022	3305.	-.01	1021.2	1021.2	-.01	1075.4	1075.4	-.00003	2.1870	2.1870
32.018	.08866	.016022	3302.	.00	1021.2	1021.2	.01	1075.4	1075.4	.00000	2.1869	2.1869
33	.09223	.016022	3181.	.99	1020.6	1021.5	.99	1074.8	1075.8	.00201	2.1815	2.1835
34	.09601	.016021	3062.	1.99	1019.9	1021.9	1.99	1074.3	1076.3	.00404	2.1759	2.1799
35	.09992	.016021	2948.	2.99	1019.2	1022.2	3.00	1073.7	1076.7	.00607	2.1704	2.1764
36	.10397	.016021	2839.	4.00	1018.5	1022.5	4.00	1073.1	1077.1	.00810	2.1648	2.1729
37	.10816	.016021	2734.	5.00	1017.9	1022.9	5.00	1072.6	1077.6	.01012	2.1594	2.1695
38	.11250	.016020	2634.	6.01	1017.2	1023.2	6.01	1072.0	1078.0	.01215	2.1539	2.1660
39	.11700	.016020	2538.	7.01	1016.5	1023.5	7.01	1071.5	1078.5	.01416	2.1484	2.1626
40	.12166	.016020	2445.	8.02	1015.8	1023.9	8.02	1070.9	1078.9	.01617	2.1430	2.1592
41	.12648	.016020	2357.	9.02	1015.2	1024.2	9.02	1070.3	1079.3	.01818	2.1376	2.1558
42	.13146	.016021	2272.	10.02	1014.5	1024.5	10.03	1069.8	1079.8	.02018	2.1322	2.1524
43	.13662	.016021	2190.	11.03	1013.8	1024.8	11.03	1069.2	1080.2	.02218	2.1268	2.1490
44	.14196	.016021	2112.	12.03	1013.1	1025.2	12.03	1068.6	1080.7	.02418	2.1215	2.1457
45	.14748	.016021	2037.	13.04	1012.5	1025.5	13.04	1068.1	1081.1	.02618	2.1162	2.1423
46	.15319	.016022	1965.	14.04	1011.8	1025.8	14.04	1067.5	1081.5	.02815	2.1109	2.1390
47	.15909	.016022	1896.	15.04	1011.1	1026.2	15.05	1066.9	1082.0	.03014	2.1056	2.1357
48	.16520	.016023	1829.	16.05	1010.4	1026.5	16.05	1066.4	1082.4	.03212	2.1003	2.1324
49	.17151	.016024	1766.	17.05	1009.8	1026.8	17.05	1065.8	1082.9	.03410	2.0951	2.1292
50	.17803	.016024	1704.2	18.06	1009.1	1027.2	18.06	1065.2	1083.3	.03607	2.0899	2.1259
51	.18477	.016025	1645.2	19.06	1008.4	1027.5	19.06	1064.7	1083.7	.03804	2.0847	2.1227
52	.19173	.016026	1588.6	20.06	1007.8	1027.8	20.07	1064.1	1084.2	.04000	2.0795	2.1195
53	.19892	.016027	1534.1	21.06	1007.1	1028.1	21.07	1063.5	1084.6	.04195	2.0743	2.1163
54	.20635	.016028	1481.7	22.07	1006.4	1028.5	22.07	1063.0	1085.1	.04391	2.0692	2.1131
55	.2140	.016029	1431.4	23.07	1005.7	1028.8	23.07	1062.4	1085.5	.04586	2.0641	2.1099
56	.2219	.016030	1382.9	24.08	1005.1	1029.1	24.08	1061.9	1085.9	.04781	2.0590	2.1068
57	.2301	.016031	1336.3	25.08	1004.4	1029.5	25.08	1061.3	1086.4	.04975	2.0539	2.1036
58	.2386	.016032	1291.5	26.08	1003.7	1029.8	26.08	1060.7	1086.8	.05169	2.0488	2.1005
59	.2473	.016033	1248.4	27.08	1003.0	1030.1	27.08	1060.2	1087.2	.05362	2.0438	2.0974
60	.2563	.016035	1206.9	28.08	1002.4	1030.4	28.08	1059.6	1087.7	.05555	2.0388	2.0943
61	.2655	.016036	1166.9	29.08	1001.7	1030.8	29.09	1059.0	1088.1	.05747	2.0338	2.0912
62	.2751	.016037	1128.5	30.09	1001.0	1031.1	30.09	1058.5	1088.6	.05940	2.0288	2.0882
63	.2850	.016039	1091.4	31.09	1000.3	1031.4	31.09	1057.9	1089.0	.06131	2.0238	2.0851
64	.2952	.016040	1055.8	32.09	999.7	1031.8	32.09	1057.3	1089.4	.06323	2.0189	2.0821
65	.3057	.016042	1021.5	33.09	999.0	1032.1	33.09	1056.8	1089.9	.06514	2.0140	2.0791
66	.3165	.016044	988.4	34.09	998.3	1032.4	34.09	1056.2	1090.3	.06704	2.0091	2.0761
67	.3276	.016045	956.5	35.09	997.7	1032.7	35.09	1055.6	1090.7	.06895	2.0042	2.0731
68	.3391	.016047	925.8	36.09	997.0	1033.1	36.09	1055.1	1091.2	.07084	1.9993	2.0701
69	.3510	.016049	896.2	37.09	996.3	1033.4	37.09	1054.5	1091.6	.07273	1.9944	2.0672
70	.3632	.016051	867.7	38.09	995.6	1033.7	38.09	1054.0	1092.0	.07463	1.9896	2.0642
71	.3758	.016053	840.2	39.09	995.0	1034.1	39.09	1053.4	1092.5	.07651	1.9848	2.0613
72	.3887	.016055	813.7	40.09	994.3	1034.4	40.09	1052.8	1092.9	.07839	1.9800	2.0584
73	.4021	.016057	788.1	41.09	993.6	1034.7	41.09	1052.3	1093.4	.08028	1.9752	2.0555
74	.4158	.016059	763.5	42.09	992.9	1035.0	42.09	1051.7	1093.8	.08215	1.9705	2.0526
75	.4300	.016061	739.7	43.09	992.3	1035.4	43.09	1051.1	1094.2	.08402	1.9657	2.0497
76	.4448	.016063	716.8	44.09	991.6	1035.7	44.09	1050.6	1094.7	.08589	1.9610	2.0469
77	.4596	.016065	694.6	45.09	990.9	1036.0	45.09	1050.0	1095.1	.08775	1.9563	2.0440
78	.4750	.016068	673.3	46.09	990.3	1036.3	46.09	1049.4	1095.5	.08961	1.9516	2.0412
79	.4909	.016070	652.7	47.09	989.6	1036.7	47.09	1048.9	1096.0	.09146	1.9469	2.0384
80	.5073	.016073	632.8	48.08	988.9	1037.0	48.09	1048.3	1096.4	.09332	1.9423	2.0356
81	.5241	.016075	613.5	49.08	988.2	1037.3	49.09	1047.7	1096.8	.09517	1.9376	2.0328
82	.5414	.016077	595.0	50.08	987.6	1037.6	50.08	1047.2	1097.3	.09701	1.9330	2.0300
83	.5593	.016080	577.1	51.08	986.9	1038.0	51.08	1046.6	1097.7	.09885	1.9284	2.0273
84	.5776	.016083	559.8	52.08	986.2	1038.3	52.08	1046.0	1098.1	.10069	1.9238	2.0245
85	.5964	.016085	543.1	53.08	985.5	1038.6	53.08	1045.5	1098.6	.10252	1.9193	2.0218
86	.6158	.016088	527.0	54.08	984.9	1038.9	54.08	1044.9	1099.0	.10436	1.9147	2.0190
87	.6357	.016091	511.4	55.07	984.2	1039.3	55.08	1044.4	1099.4	.10618	1.9102	2.0163
88	.6562	.016094	496.3	56.07	983.5	1039.6	56.07	1043.8	1099.9	.10801	1.9056	2.0136
89	.6772	.016096	481.7	57.07	982.9	1039.9	57.07	1043.2	1100.3	.10983	1.9011	2.0110

Source: Keenan, J.H. et al. Steam Tables. John Wiley & Sons, New York, 1969.

TABLE 1 SATURATION TEMPERATURE (CONT'D)

Temp Fahr. t	Press. Lbf. Sq.In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
90	.6988	.016099	467.7	58.07	982.2	1040.2	58.07	1042.7	1100.7	.11165	1.8966	2.0083
91	.7211	.016102	454.0	59.06	981.5	1040.6	59.07	1042.1	1101.2	.11346	1.8922	2.0056
92	.7439	.016105	440.9	60.06	980.8	1040.9	60.06	1041.5	1101.6	.11527	1.8877	2.0030
93	.7674	.016108	428.2	61.06	980.2	1041.2	61.06	1041.0	1102.0	.11708	1.8833	2.0003
94	.7914	.016111	415.9	62.06	979.5	1041.5	62.06	1040.4	1102.4	.11888	1.8788	1.9977
95	.8162	.016114	404.0	63.06	978.8	1041.9	63.06	1039.8	1102.9	.12068	1.8744	1.9951
96	.8416	.016117	392.4	64.05	978.1	1042.2	64.06	1039.2	1103.3	.12248	1.8700	1.9925
97	.8677	.016121	381.3	65.05	977.5	1042.5	65.05	1038.7	1103.7	.12427	1.8657	1.9899
98	.8945	.016124	370.5	66.05	976.8	1042.8	66.05	1038.1	1104.2	.12606	1.8613	1.9874
99	.9220	.016127	360.1	67.05	976.1	1043.2	67.05	1037.5	1104.6	.12785	1.8569	1.9848
100	.9503	.016130	350.0	68.04	975.4	1043.5	68.05	1037.0	1105.0	.12963	1.8526	1.9822
101	.9792	.016134	340.2	69.04	974.8	1043.8	69.04	1036.4	1105.5	.13141	1.8483	1.9797
102	1.0090	.016137	330.8	70.04	974.1	1044.1	70.04	1035.8	1105.9	.13319	1.8440	1.9772
103	1.0395	.016141	321.6	71.04	973.4	1044.4	71.04	1035.3	1106.3	.13496	1.8397	1.9747
104	1.0708	.016144	312.8	72.03	972.7	1044.8	72.04	1034.7	1106.7	.13674	1.8354	1.9722
105	1.1029	.016148	304.2	73.03	972.1	1045.1	73.03	1034.1	1107.2	.13850	1.8312	1.9697
106	1.1359	.016151	295.9	74.03	971.4	1045.4	74.03	1033.6	1107.6	.14027	1.8269	1.9672
107	1.1697	.016155	287.8	75.03	970.7	1045.7	75.03	1033.0	1108.0	.14203	1.8227	1.9647
108	1.2044	.016158	280.0	76.02	970.0	1046.0	76.03	1032.4	1108.4	.14379	1.8185	1.9623
109	1.2399	.016162	272.4	77.02	969.3	1046.4	77.02	1031.9	1108.9	.14554	1.8143	1.9598
110	1.2763	.016166	265.1	78.02	968.7	1046.7	78.02	1031.3	1109.3	.14730	1.8101	1.9574
111	1.3137	.016169	258.0	79.01	968.0	1047.0	79.02	1030.7	1109.7	.14905	1.8059	1.9549
112	1.3520	.016173	251.1	80.01	967.3	1047.3	80.02	1030.1	1110.2	.15079	1.8017	1.9525
113	1.3913	.016177	244.4	81.01	966.6	1047.6	81.02	1029.6	1110.6	.15254	1.7976	1.9501
114	1.4315	.016181	238.0	82.01	966.0	1048.0	82.01	1029.0	1111.0	.15427	1.7935	1.9477
115	1.4727	.016185	231.7	83.00	965.3	1048.3	83.01	1028.4	1111.4	.15601	1.7894	1.9454
116	1.5150	.016189	225.6	84.00	964.6	1048.6	84.01	1027.8	1111.9	.15775	1.7852	1.9430
117	1.5583	.016193	219.7	85.00	963.9	1048.9	85.01	1027.3	1112.3	.15948	1.7812	1.9406
118	1.6026	.016197	214.0	86.00	963.2	1049.2	86.00	1026.7	1112.7	.16121	1.7771	1.9383
119	1.6480	.016201	208.4	86.99	962.6	1049.6	87.00	1026.1	1113.1	.16293	1.7730	1.9359
120	1.6945	.016205	203.0	87.99	961.9	1049.9	88.00	1025.5	1113.5	.16465	1.7690	1.9336
121	1.7422	.016209	197.8	88.99	961.2	1050.2	89.00	1025.0	1114.0	.16637	1.7649	1.9313
122	1.7910	.016213	192.7	89.99	960.5	1050.5	89.99	1024.4	1114.4	.16809	1.7609	1.9290
123	1.8409	.016217	187.8	90.99	959.8	1050.8	90.99	1023.8	1114.8	.16980	1.7569	1.9267
124	1.8921	.016221	183.1	91.98	959.2	1051.1	91.99	1023.2	1115.2	.17152	1.7529	1.9244
125	1.9444	.016226	178.41	92.98	958.5	1051.5	92.99	1022.7	1115.7	.17322	1.7489	1.9221
126	1.9980	.016230	173.91	93.98	957.8	1051.8	93.99	1022.1	1116.1	.17493	1.7449	1.9199
127	2.0529	.016234	169.54	94.98	957.1	1052.1	94.98	1021.5	1116.5	.17663	1.7410	1.9176
128	2.1090	.016239	165.30	95.97	956.4	1052.4	95.98	1020.9	1116.9	.17833	1.7370	1.9154
129	2.1664	.016243	161.18	96.97	955.7	1052.7	96.98	1020.4	1117.3	.18003	1.7331	1.9131
130	2.225	.016247	157.17	97.97	955.1	1053.0	97.98	1019.8	1117.8	.18172	1.7292	1.9109
131	2.285	.016252	153.28	98.97	954.4	1053.3	98.98	1019.2	1118.2	.18341	1.7253	1.9087
132	2.347	.016256	149.51	99.97	953.7	1053.7	99.98	1018.6	1118.6	.18510	1.7214	1.9065
133	2.410	.016261	145.84	100.97	953.0	1054.0	100.97	1018.0	1119.0	.18679	1.7175	1.9043
134	2.474	.016265	142.27	101.96	952.3	1054.3	101.97	1017.5	1119.4	.18847	1.7136	1.9021
135	2.540	.016270	138.81	102.96	951.6	1054.6	102.97	1016.9	1119.8	.19015	1.7098	1.8999
136	2.607	.016275	135.44	103.96	951.0	1054.9	103.97	1016.3	1120.3	.19183	1.7059	1.8978
137	2.676	.016279	132.17	104.96	950.3	1055.2	104.97	1015.7	1120.7	.19350	1.7021	1.8956
138	2.746	.016284	128.98	105.96	949.6	1055.5	105.97	1015.1	1121.1	.19518	1.6983	1.8934
139	2.818	.016289	125.89	106.96	948.9	1055.9	106.97	1014.5	1121.5	.19685	1.6945	1.8913
140	2.892	.016293	122.88	107.95	948.2	1056.2	107.96	1014.0	1121.9	.19851	1.6907	1.8892
141	2.967	.016298	119.96	108.95	947.5	1056.5	108.96	1013.4	1122.3	.20017	1.6869	1.8871
142	3.044	.016303	117.12	109.95	946.8	1056.8	109.96	1012.8	1122.8	.20184	1.6831	1.8849
143	3.122	.016308	114.35	110.95	946.1	1057.1	110.96	1012.2	1123.2	.20350	1.6793	1.8828
144	3.203	.016313	111.66	111.95	945.5	1057.4	111.96	1011.6	1123.6	.20515	1.6756	1.8807

TABLE 1 SATURATION TEMPERATURE (CONT'D)

Temp Fahr. t	Press. Lbf. Sq. In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
145	3.285	.016318	109.04	112.95	944.8	1057.7	112.96	1011.0	1124.0	.20681	1.6718	1.8787
146	3.368	.016323	106.50	113.95	944.1	1058.0	113.96	1010.5	1124.4	.20846	1.6681	1.8766
147	3.454	.016328	104.02	114.95	943.4	1058.3	114.96	1009.9	1124.8	.21010	1.6644	1.8745
148	3.541	.016333	101.61	115.95	942.7	1058.6	115.96	1009.3	1125.2	.21175	1.6607	1.8725
149	3.630	.016338	99.27	116.95	942.0	1059.0	116.96	1008.7	1125.6	.21339	1.6570	1.8704
150	3.722	.016343	96.99	117.95	941.3	1059.3	117.96	1008.1	1126.1	.21503	1.6533	1.8684
151	3.815	.016348	94.76	118.94	940.6	1059.6	118.96	1007.5	1126.5	.21667	1.6497	1.8663
152	3.910	.016353	92.60	119.94	939.9	1059.9	119.96	1006.9	1126.9	.21831	1.6460	1.8643
153	4.007	.016358	90.50	120.94	939.2	1060.2	120.96	1006.3	1127.3	.21994	1.6423	1.8623
154	4.106	.016363	88.45	121.94	938.6	1060.5	121.96	1005.7	1127.7	.22157	1.6387	1.8603
155	4.207	.016369	86.45	122.94	937.9	1060.8	122.96	1005.1	1128.1	.22320	1.6351	1.8583
156	4.310	.016374	84.51	123.94	937.2	1061.1	123.96	1004.6	1128.5	.22482	1.6315	1.8563
157	4.416	.016379	82.62	124.94	936.5	1061.4	124.96	1004.0	1128.9	.22645	1.6279	1.8543
158	4.523	.016384	80.77	125.94	935.8	1061.7	125.96	1003.4	1129.3	.22807	1.6243	1.8523
159	4.633	.016390	78.98	126.94	935.1	1062.0	126.96	1002.8	1129.7	.22969	1.6207	1.8504
160	4.745	.016395	77.23	127.94	934.4	1062.3	127.96	1002.2	1130.1	.23130	1.6171	1.8484
161	4.859	.016400	75.53	128.94	933.7	1062.6	128.96	1001.6	1130.5	.23291	1.6135	1.8465
162	4.976	.016406	73.87	129.94	933.0	1062.9	129.96	1001.0	1131.0	.23452	1.6100	1.8445
163	5.095	.016411	72.25	130.94	932.3	1063.2	130.96	1000.4	1131.4	.23613	1.6064	1.8426
164	5.216	.016417	70.67	131.95	931.6	1063.5	131.96	999.8	1131.8	.23774	1.6029	1.8407
165	5.340	.016422	69.14	132.95	930.9	1063.8	132.96	999.2	1132.2	.23934	1.5994	1.8387
166	5.466	.016428	67.64	133.95	930.2	1064.2	133.96	998.6	1132.6	.24094	1.5959	1.8368
167	5.595	.016434	66.18	134.95	929.5	1064.5	134.97	998.0	1133.0	.24254	1.5924	1.8349
168	5.726	.016439	64.76	135.95	928.8	1064.8	135.97	997.4	1133.4	.24414	1.5889	1.8330
169	5.860	.016445	63.37	136.95	928.1	1065.1	136.97	996.8	1133.8	.24573	1.5854	1.8311
170	5.996	.016450	62.02	137.95	927.4	1065.4	137.97	996.2	1134.2	.24732	1.5819	1.8293
171	6.136	.016456	60.70	138.95	926.7	1065.7	138.97	995.6	1134.6	.24891	1.5785	1.8274
172	6.277	.016462	59.42	139.95	926.0	1066.0	139.97	995.0	1135.0	.25050	1.5750	1.8255
173	6.422	.016468	58.16	140.96	925.3	1066.3	140.97	994.4	1135.4	.25208	1.5716	1.8237
174	6.569	.016473	56.94	141.96	924.6	1066.6	141.98	993.8	1135.8	.25366	1.5682	1.8218
175	6.720	.016479	55.75	142.96	923.9	1066.9	142.98	993.2	1136.2	.25524	1.5647	1.8200
176	6.873	.016485	54.58	143.96	923.2	1067.2	143.98	992.6	1136.6	.25682	1.5613	1.8181
177	7.029	.016491	53.45	144.96	922.5	1067.5	144.98	992.0	1137.0	.25839	1.5579	1.8163
178	7.188	.016497	52.34	145.96	921.8	1067.8	145.99	991.4	1137.4	.25997	1.5545	1.8145
179	7.350	.016503	51.26	146.97	921.1	1068.1	146.99	990.8	1137.8	.26154	1.5512	1.8127
180	7.515	.016509	50.20	147.97	920.4	1068.3	147.99	990.2	1138.2	.26311	1.5478	1.8109
181	7.683	.016515	49.17	148.97	919.7	1068.6	149.00	989.6	1138.6	.26467	1.5444	1.8091
182	7.854	.016521	48.17	149.97	919.0	1068.9	150.00	989.0	1139.0	.26623	1.5411	1.8073
183	8.029	.016527	47.19	150.98	918.3	1069.2	151.00	988.3	1139.3	.26780	1.5377	1.8055
184	8.206	.016533	46.23	151.98	917.6	1069.5	152.01	987.7	1139.7	.26936	1.5344	1.8037
185	8.387	.016539	45.30	152.98	916.8	1069.8	153.01	987.1	1140.1	.27091	1.5311	1.8020
186	8.572	.016545	44.38	153.98	916.1	1070.1	154.01	986.5	1140.5	.27247	1.5277	1.8002
187	8.759	.016551	43.49	154.99	915.4	1070.4	155.02	985.9	1140.9	.27402	1.5244	1.7985
188	8.951	.016558	42.62	155.99	914.7	1070.7	156.02	985.3	1141.3	.27557	1.5211	1.7967
189	9.145	.016564	41.78	156.99	914.0	1071.0	157.02	984.7	1141.7	.27712	1.5178	1.7950
190	9.343	.016570	40.95	158.00	913.3	1071.3	158.03	984.1	1142.1	.27866	1.5146	1.7932
191	9.545	.016576	40.14	159.00	912.6	1071.6	159.03	983.4	1142.5	.28021	1.5113	1.7915
192	9.750	.016583	39.34	160.00	911.9	1071.9	160.04	982.8	1142.9	.28175	1.5080	1.7898
193	9.959	.016589	38.57	161.01	911.2	1072.2	161.04	982.2	1143.3	.28329	1.5048	1.7881
194	10.172	.016596	37.82	162.01	910.4	1072.5	162.04	981.6	1143.6	.28482	1.5015	1.7863
195	10.388	.016602	37.08	163.02	909.7	1072.7	163.05	981.0	1144.0	.28636	1.4983	1.7846
196	10.609	.016608	36.36	164.02	909.0	1073.0	164.05	980.4	1144.4	.28789	1.4951	1.7830
197	10.833	.016615	35.65	165.02	908.3	1073.3	165.06	979.7	1144.8	.28942	1.4918	1.7813
198	11.061	.016621	34.96	166.03	907.6	1073.6	166.06	979.1	1145.2	.29095	1.4886	1.7796
199	11.293	.016628	34.29	167.03	906.9	1073.9	167.07	978.5	1145.6	.29248	1.4854	1.7779

TABLE 1 SATURATION TEMPERATURE (CONT'D)

Temp Fahr. t	Press. Lbf. Sq. In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
200	11.529	.016634	33.63	168.04	906.2	1074.2	168.07	977.9	1145.9	.29400	1.4822	1.7762
202	12.014	.016648	32.36	170.05	904.7	1074.8	170.09	976.6	1146.7	.29704	1.4759	1.7729
204	12.515	.016661	31.15	172.06	903.3	1075.3	172.10	975.4	1147.5	.30008	1.4695	1.7696
206	13.034	.016674	29.99	174.07	901.8	1075.9	174.11	974.1	1148.2	.30310	1.4632	1.7664
208	13.570	.016688	28.88	176.08	900.4	1076.5	176.13	972.9	1149.0	.30612	1.4570	1.7631
210	14.125	.016702	27.82	178.10	898.9	1077.0	178.14	971.6	1149.7	.30913	1.4508	1.7599
212	14.698	.016716	26.80	180.11	897.5	1077.6	180.16	970.3	1150.5	.31213	1.4446	1.7567
214	15.291	.016729	25.83	182.12	896.0	1078.2	182.17	969.1	1151.2	.31513	1.4384	1.7535
216	15.903	.016743	24.90	184.14	894.6	1078.7	184.18	967.8	1152.0	.31811	1.4322	1.7504
218	16.535	.016758	24.00	186.15	893.1	1079.3	186.20	966.5	1152.7	.32109	1.4261	1.7472
220	17.188	.016772	23.15	188.17	891.7	1079.8	188.22	965.3	1153.5	.32406	1.4201	1.7441
222	17.861	.016786	22.33	190.18	890.2	1080.4	190.24	964.0	1154.2	.32702	1.4140	1.7410
224	18.557	.016801	21.55	192.20	888.7	1080.9	192.26	962.7	1154.9	.32998	1.4080	1.7380
226	19.275	.016816	20.80	194.22	887.3	1081.5	194.28	961.4	1155.7	.33292	1.4020	1.7349
228	20.015	.016830	20.08	196.24	885.8	1082.0	196.30	960.1	1156.4	.33586	1.3961	1.7319
230	20.78	.016845	19.386	198.26	884.3	1082.6	198.32	958.8	1157.1	.33880	1.3901	1.7289
232	21.57	.016860	18.723	200.28	882.9	1083.1	200.34	957.5	1157.9	.34172	1.3842	1.7260
234	22.38	.016875	18.087	202.30	881.4	1083.7	202.37	956.2	1158.6	.34464	1.3784	1.7230
236	23.22	.016891	17.476	204.32	879.9	1084.2	204.39	954.9	1159.3	.34755	1.3725	1.7201
238	24.08	.016906	16.890	206.34	878.4	1084.7	206.42	953.6	1160.0	.35045	1.3667	1.7172
240	24.97	.016922	16.327	208.36	876.9	1085.3	208.44	952.3	1160.7	.35335	1.3609	1.7143
242	25.88	.016937	15.786	210.39	875.4	1085.8	210.47	950.9	1161.4	.35624	1.3552	1.7114
244	26.82	.016953	15.267	212.41	873.9	1086.3	212.49	949.6	1162.1	.35912	1.3494	1.7085
246	27.79	.016969	14.767	214.44	872.4	1086.9	214.52	948.3	1162.8	.36199	1.3437	1.7057
248	28.79	.016985	14.287	216.46	870.9	1087.4	216.55	947.0	1163.5	.36486	1.3380	1.7029
250	29.82	.017001	13.826	218.49	869.4	1087.9	218.59	945.6	1164.2	.36772	1.3324	1.7001
252	30.88	.017017	13.382	220.52	867.9	1088.4	220.62	944.3	1164.9	.37058	1.3267	1.6973
254	31.97	.017034	12.955	222.55	866.4	1088.9	222.65	942.9	1165.6	.37342	1.3211	1.6945
256	33.09	.017050	12.544	224.58	864.9	1089.4	224.68	941.6	1166.2	.37626	1.3155	1.6918
258	34.24	.017067	12.149	226.61	863.3	1090.0	226.72	940.2	1166.9	.37910	1.3100	1.6891
260	35.42	.017084	11.768	228.64	861.8	1090.5	228.76	938.8	1167.6	.38193	1.3044	1.6864
262	36.64	.017101	11.402	230.68	860.3	1091.0	230.79	937.5	1168.3	.38475	1.2989	1.6837
264	37.89	.017118	11.049	232.71	858.8	1091.5	232.83	936.1	1168.9	.38756	1.2935	1.6810
266	39.17	.017135	10.709	234.75	857.2	1092.0	234.87	934.7	1169.6	.39037	1.2880	1.6784
268	40.49	.017152	10.382	236.78	855.7	1092.5	236.91	933.3	1170.2	.39317	1.2825	1.6757
270	41.85	.017170	10.066	238.82	854.1	1093.0	238.95	932.0	1170.9	.39597	1.2771	1.6731
272	43.24	.017187	9.762	240.86	852.6	1093.4	241.00	930.6	1171.6	.39876	1.2717	1.6705
274	44.67	.017205	9.469	242.90	851.0	1093.9	243.04	929.2	1172.2	.40154	1.2664	1.6679
276	46.13	.017223	9.186	244.94	849.5	1094.4	245.08	927.8	1172.8	.40432	1.2610	1.6653
278	47.64	.017241	8.913	246.98	847.9	1094.9	247.13	926.3	1173.5	.40709	1.2557	1.6628
280	49.18	.017259	8.650	249.02	846.3	1095.4	249.18	924.9	1174.1	.40986	1.2504	1.6602
282	50.77	.017277	8.397	251.07	844.8	1095.8	251.23	923.5	1174.7	.41262	1.2451	1.6577
284	52.40	.017296	8.152	253.11	843.2	1096.3	253.28	922.1	1175.4	.41537	1.2398	1.6552
286	54.07	.017314	7.915	255.16	841.6	1096.8	255.33	920.6	1176.0	.41812	1.2346	1.6527
288	55.78	.017333	7.687	257.21	840.0	1097.3	257.38	919.2	1176.6	.42086	1.2293	1.6502
290	57.53	.017352	7.467	259.25	838.5	1097.7	259.44	917.8	1177.2	.42360	1.2241	1.6477
292	59.33	.017371	7.254	261.31	836.9	1098.2	261.50	916.3	1177.8	.42633	1.2189	1.6453
294	61.17	.017390	7.048	263.36	835.3	1098.6	263.55	914.9	1178.4	.42906	1.2138	1.6428
296	63.06	.017409	6.849	265.41	833.7	1099.1	265.61	913.4	1179.0	.43178	1.2086	1.6404
298	65.00	.017429	6.657	267.46	832.1	1099.5	267.67	911.9	1179.6	.43449	1.2035	1.6380
300	66.98	.017448	6.472	269.52	830.5	1100.0	269.73	910.4	1180.2	.43720	1.1984	1.6356
302	69.01	.017468	6.292	271.57	828.8	1100.4	271.79	909.0	1180.8	.43990	1.1933	1.6332
304	71.09	.017488	6.119	273.63	827.2	1100.8	273.86	907.5	1181.3	.44260	1.1882	1.6308
306	73.22	.017508	5.951	275.69	825.6	1101.3	275.93	906.0	1181.9	.44530	1.1832	1.6285
308	75.40	.017528	5.789	277.75	824.0	1101.7	278.00	904.5	1182.5	.44799	1.1781	1.6261

TABLE 1 SATURATION TEMPERATURE (CONT'D)

Temp Fahr. t	Press. Lbf. Sq.In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
310	77.64	.017548	5.632	279.81	822.3	1102.1	280.06	903.0	1183.0	.45067	1.1731	1.6238
312	79.92	.017569	5.480	281.87	820.7	1102.6	282.13	901.5	1183.6	.45334	1.1681	1.6214
314	82.26	.017589	5.333	283.94	819.0	1103.0	284.21	899.9	1184.1	.45602	1.1631	1.6191
316	84.65	.017610	5.190	286.01	817.4	1103.4	286.28	898.4	1184.7	.45868	1.1581	1.6168
318	87.10	.017631	5.052	288.07	815.7	1103.8	288.36	896.9	1185.2	.46135	1.1532	1.6145
320	89.60	.017652	4.919	290.14	814.1	1104.2	290.43	895.3	1185.8	.46400	1.1483	1.6123
322	92.16	.017673	4.790	292.21	812.4	1104.6	292.51	893.8	1186.3	.46666	1.1433	1.6100
324	94.78	.017695	4.665	294.28	810.7	1105.0	294.59	892.2	1186.8	.46930	1.1384	1.6077
326	97.46	.017716	4.543	296.36	809.0	1105.4	296.67	890.7	1187.3	.47194	1.1335	1.6055
328	100.20	.017738	4.426	298.43	807.4	1105.8	298.76	889.1	1187.9	.47458	1.1287	1.6033
330	103.00	.017760	4.312	300.51	805.7	1106.2	300.84	887.5	1188.4	.47722	1.1238	1.6010
332	105.86	.017782	4.201	302.58	804.0	1106.6	302.93	885.9	1188.9	.47984	1.1190	1.5988
334	108.78	.017804	4.094	304.66	802.3	1106.9	305.02	884.3	1189.4	.48247	1.1141	1.5966
336	111.76	.017826	3.991	306.74	800.6	1107.3	307.11	882.7	1189.9	.48509	1.1093	1.5944
338	114.82	.017849	3.890	308.83	798.9	1107.7	309.21	881.1	1190.3	.48770	1.1045	1.5922
340	117.93	.017872	3.792	310.91	797.1	1108.0	311.30	879.5	1190.8	.49031	1.0997	1.5901
342	121.11	.017894	3.698	313.00	795.4	1108.4	313.39	877.9	1191.3	.49291	1.0950	1.5879
344	124.36	.017917	3.606	315.08	793.7	1108.8	315.49	876.3	1191.7	.49552	1.0902	1.5857
346	127.68	.017941	3.517	317.17	791.9	1109.1	317.59	874.6	1192.2	.49811	1.0855	1.5836
348	131.07	.017964	3.430	319.26	790.2	1109.5	319.70	873.0	1192.7	.50071	1.0807	1.5814
350	134.53	.017988	3.346	321.35	788.4	1109.8	321.80	871.3	1193.1	.50329	1.0760	1.5793
352	138.06	.018011	3.265	323.45	786.7	1110.1	323.91	869.6	1193.5	.50588	1.0713	1.5772
354	141.66	.018035	3.185	325.54	784.9	1110.5	326.02	868.0	1194.0	.50846	1.0666	1.5751
356	145.34	.018059	3.109	327.64	783.2	1110.8	328.13	866.3	1194.4	.51103	1.0619	1.5730
358	149.09	.018083	3.034	329.74	781.4	1111.1	330.24	864.6	1194.8	.51360	1.0573	1.5709
360	152.92	.018108	2.961	331.84	779.6	1111.4	332.35	862.9	1195.2	.51617	1.0526	1.5688
362	156.82	.018133	2.891	333.94	777.8	1111.8	334.47	861.2	1195.6	.51873	1.0480	1.5667
364	160.80	.018157	2.822	336.05	776.0	1112.1	336.59	859.5	1196.0	.52129	1.0433	1.5646
366	164.87	.018182	2.756	338.16	774.2	1112.4	338.71	857.7	1196.4	.52385	1.0387	1.5626
368	169.01	.018208	2.691	340.26	772.4	1112.7	340.83	856.0	1196.8	.52640	1.0341	1.5605
370	173.23	.018233	2.628	342.37	770.6	1112.9	342.96	854.2	1197.2	.52894	1.0295	1.5585
372	177.53	.018258	2.567	344.49	768.7	1113.2	345.08	852.5	1197.6	.53149	1.0249	1.5564
374	181.92	.018284	2.508	346.60	766.9	1113.5	347.21	850.7	1197.9	.53403	1.0204	1.5544
376	186.39	.018310	2.450	348.72	765.1	1113.8	349.35	848.9	1198.3	.53656	1.0158	1.5524
378	190.95	.018336	2.394	350.83	763.2	1114.1	351.48	847.2	1198.6	.53910	1.0112	1.5503
380	195.60	.018363	2.339	352.95	761.4	1114.3	353.62	845.4	1199.0	.54163	1.0067	1.5483
382	200.33	.018389	2.286	355.07	759.5	1114.6	355.76	843.6	1199.3	.54415	1.0021	1.5463
384	205.15	.018416	2.234	357.20	757.6	1114.8	357.90	841.7	1199.6	.54667	.9976	1.5443
386	210.06	.018443	2.183	359.32	755.8	1115.1	360.04	839.9	1200.0	.54919	.9931	1.5423
388	215.06	.018470	2.134	361.45	753.9	1115.3	362.19	838.1	1200.3	.55171	.9886	1.5403
390	220.2	.018498	2.087	363.58	752.0	1115.6	364.34	836.2	1200.6	.55422	.9841	1.5383
392	225.3	.018525	2.040	365.72	750.1	1115.8	366.49	834.4	1200.9	.55672	.9796	1.5363
394	230.6	.018553	1.995	367.85	748.2	1116.0	368.64	832.5	1201.1	.55923	.9751	1.5344
396	236.0	.018581	1.951	369.99	746.2	1116.2	370.80	830.6	1201.4	.56173	.9706	1.5324
398	241.5	.018609	1.908	372.13	744.3	1116.4	372.96	828.7	1201.7	.56423	.9662	1.5304
400	247.1	.018638	1.8661	374.27	742.4	1116.6	375.12	826.8	1202.0	.56672	.9617	1.5284
405	261.4	.018710	1.7663	379.63	737.5	1117.1	380.53	822.0	1202.6	.57295	.9506	1.5236
410	276.5	.018784	1.6726	385.01	732.6	1117.6	385.97	817.2	1203.1	.57916	.9395	1.5187
415	292.1	.018859	1.5848	390.40	727.6	1118.0	391.42	812.2	1203.6	.58534	.9285	1.5139
420	308.5	.018936	1.5024	395.81	722.5	1118.3	396.89	807.2	1204.1	.59152	.9175	1.5091
425	325.6	.019014	1.4249	401.24	717.4	1118.6	402.38	802.1	1204.5	.59767	.9066	1.5043
430	343.3	.019094	1.3521	406.68	712.2	1118.9	407.89	796.9	1204.8	.60381	.8957	1.4995
435	361.9	.019176	1.2836	412.14	707.0	1119.1	413.42	791.7	1205.1	.60994	.8848	1.4948
440	381.2	.019260	1.2192	417.62	701.7	1119.3	418.98	786.3	1205.3	.61605	.8740	1.4900
445	401.2	.019345	1.1584	423.12	696.3	1119.5	424.55	780.9	1205.5	.62215	.8631	1.4853

TABLE 1 SATURATION TEMPERATURE (CONT'D)

Temp Fahr. t	Press. Lbf. Sq. In. p	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
450	422.1	.019433	1.1011	428.6	690.9	1119.5	430.2	775.4	1205.6	.6282	.8523	1.4806
455	443.8	.019522	1.0471	434.2	685.4	1119.6	435.8	769.8	1205.6	.6343	.8415	1.4759
460	466.3	.019614	.9961	439.7	679.8	1119.6	441.4	764.1	1205.5	.6404	.8308	1.4712
465	489.8	.019707	.9480	445.3	674.2	1119.5	447.1	758.3	1205.4	.6465	.8200	1.4665
470	514.1	.019803	.9025	450.9	668.4	1119.4	452.8	752.4	1205.2	.6525	.8093	1.4618
475	539.3	.019901	.8594	456.6	662.6	1119.2	458.5	746.4	1204.9	.6586	.7985	1.4571
480	565.5	.020002	.8187	462.2	656.7	1118.9	464.3	740.3	1204.6	.6646	.7878	1.4524
485	592.6	.020106	.7801	467.9	650.7	1118.6	470.1	734.1	1204.2	.6707	.7770	1.4477
490	620.7	.020211	.7436	473.6	644.7	1118.3	475.9	727.8	1203.7	.6767	.7663	1.4430
495	649.8	.020320	.7090	479.3	638.5	1117.9	481.8	721.3	1203.1	.6827	.7555	1.4383
500	680.0	.02043	.6761	485.1	632.3	1117.4	487.7	714.8	1202.5	.6888	.7448	1.4335
505	711.2	.02055	.6449	490.9	625.9	1116.8	493.6	708.1	1201.7	.6948	.7340	1.4288
510	743.5	.02067	.6153	496.8	619.5	1116.2	499.6	701.3	1200.9	.7009	.7232	1.4240
515	776.9	.02079	.5872	502.6	612.9	1115.5	505.6	694.3	1200.0	.7069	.7123	1.4193
520	811.4	.02091	.5605	508.5	606.2	1114.8	511.7	687.3	1198.9	.7130	.7015	1.4145
525	847.1	.02104	.5350	514.5	599.5	1113.9	517.8	680.0	1197.8	.7191	.6906	1.4097
530	884.0	.02117	.5108	520.5	592.6	1113.0	523.9	672.7	1196.6	.7252	.6796	1.4048
535	922.1	.02131	.4878	526.5	585.5	1112.0	530.1	665.1	1195.3	.7313	.6687	1.3999
540	961.5	.02145	.4658	532.6	578.4	1111.0	536.4	657.5	1193.8	.7374	.6576	1.3950
545	1002.1	.02160	.4449	538.7	571.1	1109.8	542.7	649.6	1192.3	.7435	.6466	1.3901
550	1044.0	.02175	.4249	544.9	563.7	1108.6	549.1	641.6	1190.6	.7497	.6354	1.3851
555	1087.2	.02191	.4059	551.1	556.1	1107.2	555.5	633.4	1188.9	.7558	.6242	1.3800
560	1131.8	.02207	.3877	557.4	548.4	1105.8	562.0	625.0	1187.0	.7620	.6129	1.3749
565	1177.8	.02224	.3703	563.7	540.5	1104.2	568.5	616.4	1184.9	.7683	.6015	1.3698
570	1225.1	.02241	.3537	570.1	532.5	1102.6	575.2	607.6	1182.8	.7745	.5901	1.3646
575	1274.0	.02259	.3378	576.5	524.3	1100.8	581.9	598.6	1180.4	.7808	.5785	1.3593
580	1324.3	.02278	.3225	583.1	515.9	1098.9	588.6	589.3	1178.0	.7872	.5668	1.3540
585	1376.1	.02298	.3079	589.7	507.3	1096.9	595.5	579.8	1175.3	.7935	.5550	1.3486
590	1429.5	.02319	.2940	596.3	498.4	1094.8	602.5	570.1	1172.5	.8000	.5431	1.3430
595	1484.5	.02340	.2805	603.1	489.4	1092.5	609.5	560.0	1169.5	.8064	.5310	1.3374
600	1541.0	.02363	.2677	609.9	480.1	1090.0	616.7	549.7	1166.4	.8130	.5187	1.3317
605	1599.3	.02386	.2553	616.8	470.6	1087.4	623.9	539.1	1163.0	.8196	.5063	1.3259
610	1659.2	.02411	.2434	623.9	460.8	1084.6	631.3	528.1	1159.4	.8262	.4937	1.3199
615	1720.9	.02437	.2320	631.0	450.6	1081.7	638.8	516.8	1155.5	.8329	.4808	1.3138
620	1784.4	.02465	.2209	638.3	440.2	1078.5	646.4	505.0	1151.4	.8398	.4677	1.3075
625	1849.7	.02494	.2103	645.7	429.4	1075.1	654.2	492.9	1147.0	.8467	.4544	1.3010
630	1916.9	.02525	.2000	653.2	418.2	1071.4	662.1	480.2	1142.4	.8537	.4407	1.2944
635	1986.0	.02558	.1901	660.9	406.6	1067.5	670.3	467.1	1137.3	.8608	.4267	1.2875
640	2057.1	.02593	.1805	668.7	394.5	1063.2	678.6	453.4	1131.9	.8681	.4122	1.2803
645	2130.2	.02632	.1711	676.7	381.9	1058.6	687.1	439.0	1126.1	.8755	.3974	1.2729
650	2205.	.02673	.16206	685.0	368.7	1053.7	695.9	423.9	1119.8	.8831	.3820	1.2651
655	2283.	.02718	.15323	693.5	354.8	1048.2	705.0	408.0	1113.0	.8909	.3660	1.2569
660	2362.	.02767	.14459	702.3	340.0	1042.3	714.4	391.1	1105.5	.8990	.3493	1.2483
665	2444.	.02821	.13613	711.4	324.4	1035.7	724.1	373.2	1097.3	.9073	.3318	1.2391
670	2529.	.02882	.12779	720.9	307.5	1028.5	734.4	353.9	1088.3	.9160	.3132	1.2293
675	2616.	.02951	.11952	731.0	289.3	1020.3	745.3	332.9	1078.2	.9252	.2934	1.2186
680	2705.	.03032	.11127	741.7	269.3	1011.0	756.9	309.8	1066.7	.9350	.2718	1.2068
685	2797.	.03128	.10291	753.4	246.8	1000.2	769.6	283.9	1053.4	.9456	.2480	1.1936
690	2892.	.03248	.09428	766.4	220.8	987.2	783.8	253.9	1037.7	.9575	.2208	1.1784
695	2990.	.03410	.08506	781.6	189.2	970.8	800.5	217.4	1017.9	.9715	.1882	1.1598
700	3090.	.03666	.07438	801.7	145.9	947.7	822.7	167.5	990.2	.9902	.1444	1.1346
702	3131.	.03837	.06911	813.1	121.1	934.2	835.4	138.9	974.3	1.0008	.1196	1.1204
704	3173.	.04139	.06214	830.6	83.3	913.9	854.9	95.5	950.4	1.0173	.0821	1.0994
705	3194.	.04507	.05652	848.9	46.3	895.2	875.5	53.0	928.6	1.0349	.0455	1.0805
705.44	3204.	.05053	.05053	872.6	0	872.6	902.5	0	902.5	1.0580	0	1.0580

TABLE 2 SATURATION PRESSURES

Press. Lbf. Sq. In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
.08866	32.02	.016022	3302.	.00	1021.2	1021.2	.01	1075.4	1075.4	.00000	2.1869	2.1869
.090	32.39	.016022	3256.	.38	1021.0	1021.3	.38	1075.2	1075.6	.00077	2.1849	2.1856
.095	33.74	.016021	3093.	1.73	1020.1	1021.8	1.73	1074.4	1076.1	.00350	2.1774	2.1809
.10	35.02	.016021	2946.	3.02	1019.2	1022.2	3.02	1073.7	1076.7	.00612	2.1702	2.1764
.11	37.43	.016020	2691.	5.43	1017.6	1023.0	5.43	1072.3	1077.8	.01098	2.1570	2.1680
.12	39.65	.016020	2477.	7.66	1016.1	1023.7	7.67	1071.1	1078.8	.01547	2.1449	2.1604
.13	41.71	.016021	2296.	9.73	1014.7	1024.4	9.73	1069.9	1079.7	.01960	2.1338	2.1534
.14	43.64	.016021	2140.	11.67	1013.4	1025.1	11.67	1068.8	1080.5	.02346	2.1234	2.1469
.15	45.45	.016022	2005.	13.49	1012.2	1025.7	13.49	1067.8	1081.3	.02706	2.1138	2.1409
.16	47.15	.016022	1886.	15.20	1011.0	1026.2	15.20	1066.9	1082.0	.03044	2.1048	2.1352
.17	48.76	.016023	1780.	16.82	1009.9	1026.7	16.82	1065.9	1082.8	.03363	2.0963	2.1299
.18	50.30	.016024	1687.	18.35	1008.9	1027.3	18.36	1065.1	1083.4	.03663	2.0883	2.1250
.19	51.75	.016026	1602.	19.81	1007.9	1027.7	19.82	1064.3	1084.1	.03951	2.0808	2.1203
.20	53.15	.016027	1526.3	21.22	1007.0	1028.2	21.22	1063.5	1084.7	.04225	2.0736	2.1158
.21	54.48	.016028	1457.3	22.55	1006.1	1028.6	22.55	1062.7	1085.3	.04485	2.0667	2.1116
.22	55.76	.016029	1394.5	23.83	1005.2	1029.1	23.83	1062.0	1085.8	.04734	2.0602	2.1075
.23	56.99	.016031	1337.0	25.06	1004.4	1029.5	25.06	1061.3	1086.4	.04972	2.0540	2.1037
.24	58.17	.016032	1284.2	26.24	1003.6	1029.8	26.25	1060.6	1086.9	.05200	2.0480	2.1000
.25	59.31	.016034	1235.5	27.39	1002.8	1030.2	27.39	1060.0	1087.4	.05421	2.0422	2.0965
.26	60.41	.016035	1190.5	28.49	1002.1	1030.6	28.49	1059.4	1087.9	.05633	2.0367	2.0931
.27	61.47	.016037	1148.7	29.56	1001.4	1030.9	29.56	1058.8	1088.3	.05838	2.0314	2.0898
.28	62.50	.016038	1109.8	30.58	1000.7	1031.3	30.58	1058.2	1088.8	.06035	2.0263	2.0867
.29	63.50	.016040	1073.6	31.58	1000.0	1031.6	31.59	1057.6	1089.2	.06226	2.0214	2.0836
.30	64.46	.016041	1039.7	32.55	999.4	1031.9	32.56	1057.1	1089.6	.06411	2.0166	2.0807
.32	66.32	.016044	978.1	34.41	998.1	1032.5	34.41	1056.0	1090.4	.06765	2.0075	2.0751
.34	68.07	.016047	923.6	36.16	996.9	1033.1	36.16	1055.0	1091.2	.07098	1.9989	2.0699
.36	69.74	.016050	875.0	37.83	995.8	1033.6	37.84	1054.1	1091.9	.07414	1.9909	2.0650
.38	71.33	.016053	831.4	39.42	994.7	1034.2	39.42	1053.2	1092.6	.07713	1.9832	2.0604
.40	72.84	.016056	792.0	40.94	993.7	1034.7	40.94	1052.3	1093.3	.07998	1.9760	2.0559
.42	74.30	.016059	756.3	42.39	992.7	1035.1	42.39	1051.5	1093.9	.08270	1.9691	2.0518
.44	75.69	.016063	723.8	43.78	991.8	1035.6	43.78	1050.7	1094.5	.08531	1.9625	2.0478
.46	77.03	.016066	694.0	45.12	990.9	1036.0	45.12	1050.0	1095.1	.08780	1.9562	2.0440
.48	78.32	.016069	666.7	46.40	990.0	1036.4	46.40	1049.3	1095.7	.09019	1.9501	2.0403
.50	79.56	.016071	641.5	47.64	989.2	1036.9	47.65	1048.6	1096.2	.09250	1.9443	2.0368
.60	85.19	.016086	540.0	53.26	985.4	1038.7	53.27	1043.4	1098.6	.10287	1.9184	2.0213
.70	90.05	.016099	466.9	58.12	982.1	1040.3	58.12	1042.6	1100.7	.11174	1.8964	2.0081
.80	94.35	.016112	411.7	62.41	979.2	1041.7	62.41	1040.2	1102.6	.11951	1.8773	1.9968
.90	98.20	.016124	368.4	66.25	976.6	1042.9	66.25	1038.0	1104.3	.12642	1.8604	1.9868
1.0	101.70	.016136	333.6	69.74	974.3	1044.0	69.74	1036.0	1105.8	.13266	1.8453	1.9779
1.1	104.91	.016147	304.9	72.94	972.1	1045.1	72.94	1034.2	1107.1	.13834	1.8315	1.9699
1.2	107.88	.016158	280.9	75.90	970.1	1046.0	75.90	1032.5	1108.4	.14357	1.8190	1.9626
1.3	110.64	.016168	260.6	78.65	968.2	1046.9	78.66	1030.9	1109.6	.14841	1.8074	1.9558
1.4	113.22	.016178	243.0	81.23	966.5	1047.7	81.23	1029.4	1110.7	.15292	1.7967	1.9496
1.5	115.65	.016187	227.7	83.65	964.8	1048.5	83.65	1028.0	1111.7	.15714	1.7867	1.9438
1.6	117.94	.016196	214.3	85.94	963.3	1049.2	85.94	1026.7	1112.7	.16111	1.7773	1.9384
1.7	120.12	.016205	202.4	88.11	961.8	1049.9	88.11	1025.5	1113.6	.16485	1.7685	1.9334
1.8	122.18	.016214	191.8	90.17	960.4	1050.6	90.18	1024.3	1114.5	.16840	1.7602	1.9286
1.9	124.15	.016222	182.3	92.14	959.1	1051.2	92.14	1023.2	1115.3	.17178	1.7523	1.9241
2.0	126.04	.016230	173.75	94.02	957.8	1051.8	94.02	1022.1	1116.1	.17499	1.7448	1.9198
2.2	129.57	.016246	158.86	97.55	955.4	1052.9	97.55	1020.0	1117.6	.18100	1.7309	1.9119
2.4	132.85	.016260	146.40	100.81	953.1	1053.9	100.82	1018.1	1118.9	.18653	1.7181	1.9046
2.6	135.89	.016274	135.79	103.85	951.0	1054.9	103.86	1016.4	1120.2	.19165	1.7063	1.8980
2.8	138.75	.016288	126.67	106.70	949.1	1055.8	106.71	1014.7	1121.4	.19642	1.6954	1.8918
3.0	141.43	.016300	118.72	109.38	947.2	1056.6	109.39	1013.1	1122.5	.20089	1.6852	1.8861
3.2	143.97	.016313	111.75	111.92	945.5	1057.4	111.93	1011.6	1123.6	.20510	1.6757	1.8808
3.4	146.37	.016325	105.57	114.32	943.8	1058.1	114.33	1010.2	1124.6	.20907	1.6667	1.8758
3.6	148.66	.016336	100.05	116.61	942.2	1058.9	116.62	1008.9	1125.5	.21284	1.6583	1.8711
3.8	150.84	.016347	95.11	118.79	940.7	1059.5	118.80	1007.6	1126.4	.21642	1.6502	1.8666

TABLE 2 SATURATION PRESSURES (CONT'D)

Press. Lbf. Sq.In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
4.0	152.93	.016358	90.64	120.88	939.3	1060.2	120.89	1006.4	1127.3	.21983	1.6426	1.8624
4.2	154.93	.016368	86.59	122.88	937.9	1060.8	122.89	1005.2	1128.1	.22309	1.6353	1.8584
4.4	156.85	.016378	82.89	124.80	936.6	1061.4	124.81	1004.1	1128.9	.22621	1.6284	1.8546
4.6	158.70	.016388	79.51	126.65	935.3	1061.9	126.66	1003.0	1129.6	.22920	1.6217	1.8509
4.8	160.49	.016398	76.40	128.43	934.1	1062.5	128.45	1001.9	1130.3	.23208	1.6154	1.8475
5.0	162.21	.016407	73.53	130.15	932.9	1063.0	130.17	1000.9	1131.0	.23486	1.6093	1.8441
5.5	166.27	.016429	67.25	134.21	930.0	1064.2	134.23	998.4	1132.7	.24137	1.5949	1.8363
6.0	170.03	.016451	61.98	137.98	927.4	1065.4	138.00	996.2	1134.2	.24736	1.5819	1.8292
6.5	173.53	.016471	57.51	141.49	924.9	1066.4	141.51	994.1	1135.6	.25292	1.5698	1.8227
7.0	176.82	.016490	53.65	144.78	922.6	1067.4	144.80	992.1	1136.9	.25811	1.5585	1.8167
7.5	179.91	.016508	50.30	147.88	920.4	1068.3	147.90	990.2	1138.1	.26297	1.5481	1.8110
8.0	182.84	.016526	47.35	150.81	918.4	1069.2	150.84	988.4	1139.3	.26754	1.5383	1.8058
8.5	185.61	.016543	44.74	153.60	916.4	1070.0	153.62	986.7	1140.4	.27187	1.5290	1.8009
9.0	188.26	.016559	42.41	156.25	914.5	1070.8	156.27	985.1	1141.4	.27596	1.5203	1.7963
9.5	190.78	.016575	40.31	158.78	912.7	1071.5	158.81	983.6	1142.4	.27986	1.5120	1.7919
10	193.19	.016590	38.42	161.20	911.0	1072.2	161.23	982.1	1143.3	.28358	1.5041	1.7877
11	197.73	.016620	35.15	165.76	907.8	1073.5	165.80	979.3	1145.1	.29055	1.4895	1.7800
12	201.94	.016647	32.40	169.99	904.8	1074.7	170.03	976.7	1146.7	.29696	1.4761	1.7730
13	205.87	.016674	30.06	173.94	901.9	1075.9	173.98	974.2	1148.2	.30291	1.4637	1.7666
14	209.55	.016699	28.05	177.65	899.3	1076.9	177.69	971.9	1149.6	.30846	1.4521	1.7606
14.696	211.99	.016715	26.80	180.10	897.5	1077.6	180.15	970.4	1150.5	.31212	1.4446	1.7567
15	213.03	.016723	26.29	181.14	896.8	1077.9	181.19	969.7	1150.9	.31367	1.4414	1.7551
16	216.31	.016746	24.75	184.45	894.4	1078.8	184.50	967.6	1152.1	.31858	1.4313	1.7499
17	219.43	.016768	23.39	187.59	892.1	1079.7	187.65	965.6	1153.3	.32322	1.4218	1.7450
18	222.40	.016789	22.17	190.59	889.9	1080.5	190.64	963.7	1154.4	.32762	1.4128	1.7404
19	225.24	.016810	21.08	193.45	887.8	1081.3	193.51	961.9	1155.4	.33181	1.4043	1.7361
20	227.96	.016830	20.09	196.19	885.8	1082.0	196.26	960.1	1156.4	.33580	1.3962	1.7320
21	230.57	.016849	19.20	198.83	883.9	1082.7	198.89	958.4	1157.3	.33963	1.3885	1.7281
22	233.08	.016868	18.38	201.36	882.1	1083.4	201.43	956.8	1158.2	.34329	1.3811	1.7244
23	235.49	.016887	17.63	203.80	880.3	1084.1	203.88	955.2	1159.1	.34681	1.3740	1.7208
24	237.82	.016905	16.94	206.16	878.5	1084.7	206.23	953.7	1159.9	.35019	1.3672	1.7174
25	240.08	.016922	16.306	208.44	876.9	1085.3	208.52	952.2	1160.7	.35345	1.3607	1.7142
26	242.26	.016939	15.719	210.65	875.2	1085.9	210.73	950.8	1161.5	.35660	1.3544	1.7110
27	244.37	.016956	15.173	212.78	873.6	1086.4	212.87	949.4	1162.2	.35965	1.3484	1.7080
28	246.42	.016972	14.665	214.86	872.1	1087.0	214.95	948.0	1163.0	.36259	1.3425	1.7051
29	248.41	.016988	14.192	216.88	870.6	1087.5	216.97	946.7	1163.6	.36545	1.3369	1.7023
30	250.34	.017004	13.748	218.84	869.2	1088.0	218.93	945.4	1164.3	.36821	1.3314	1.6996
31	252.23	.017019	13.333	220.75	867.7	1088.5	220.85	944.1	1165.0	.37090	1.3261	1.6970
32	254.06	.017034	12.942	222.61	866.3	1089.0	222.71	942.9	1165.6	.37351	1.3210	1.6945
33	255.85	.017049	12.575	224.43	865.0	1089.4	224.53	941.7	1166.2	.37605	1.3160	1.6920
34	257.59	.017064	12.228	226.20	863.7	1089.9	226.31	940.5	1166.8	.37852	1.3111	1.6896
35	259.30	.017078	11.900	227.93	862.4	1090.3	228.04	939.3	1167.4	.38093	1.3064	1.6873
36	260.96	.017092	11.591	229.62	861.1	1090.7	229.73	938.2	1167.9	.38328	1.3018	1.6851
37	262.59	.017106	11.297	231.27	859.8	1091.1	231.39	937.1	1168.5	.38558	1.2973	1.6829
38	264.18	.017119	11.018	232.89	858.6	1091.5	233.01	936.0	1169.0	.38782	1.2930	1.6808
39	265.74	.017133	10.753	234.48	857.4	1091.9	234.60	934.9	1169.5	.39000	1.2887	1.6787
40	267.26	.017146	10.501	236.03	856.2	1092.3	236.16	933.8	1170.0	.39214	1.2845	1.6767
41	268.76	.017159	10.261	237.56	855.1	1092.6	237.69	932.8	1170.5	.39424	1.2805	1.6747
42	270.22	.017172	10.032	239.05	854.0	1093.0	239.18	931.8	1171.0	.39628	1.2765	1.6728
43	271.66	.017184	9.813	240.51	852.8	1093.4	240.65	930.8	1171.4	.39829	1.2726	1.6709
44	273.07	.017197	9.603	241.95	851.8	1093.7	242.09	929.8	1171.9	.40026	1.2688	1.6691
45	274.46	.017209	9.403	243.37	850.7	1094.0	243.51	928.8	1172.3	.40218	1.2651	1.6673
46	275.82	.017221	9.211	244.75	849.6	1094.4	244.90	927.9	1172.8	.40407	1.2615	1.6656
47	277.16	.017233	9.027	246.12	848.6	1094.7	246.27	926.9	1173.2	.40593	1.2579	1.6638
48	278.47	.017245	8.851	247.46	847.5	1095.0	247.61	926.0	1173.6	.40775	1.2544	1.6622
49	279.76	.017257	8.681	248.78	846.5	1095.3	248.94	925.1	1174.0	.40953	1.2510	1.6605
50	281.03	.017269	8.518	250.08	845.5	1095.6	250.24	924.2	1174.4	.41129	1.2476	1.6589
51	282.28	.017280	8.361	251.36	844.6	1095.9	251.52	923.3	1174.8	.41301	1.2443	1.6573
52	283.52	.017291	8.210	252.62	843.6	1096.2	252.78	922.4	1175.2	.41471	1.2411	1.6558
53	284.73	.017303	8.065	253.86	842.6	1096.5	254.03	921.6	1175.6	.41638	1.2379	1.6543
54	285.92	.017314	7.924	255.08	841.7	1096.8	255.25	920.7	1176.0	.41802	1.2348	1.6528

TABLE 2 SATURATION PRESSURES (CONT'D)

Press. Lbf. Sq.In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
55	287.10	.017325	7.789	256.28	840.8	1097.0	256.46	919.9	1176.3	.41963	1.2317	1.6513
56	288.26	.017336	7.658	257.47	839.8	1097.3	257.65	919.0	1176.7	.42122	1.2287	1.6499
57	289.40	.017346	7.532	258.64	838.9	1097.6	258.82	918.2	1177.0	.42278	1.2257	1.6485
58	290.53	.017357	7.410	259.79	838.0	1097.8	259.98	917.4	1177.4	.42432	1.2228	1.6471
59	291.64	.017368	7.292	260.93	837.2	1098.1	261.12	916.6	1177.7	.42584	1.2199	1.6457
60	292.73	.017378	7.177	262.06	836.3	1098.3	262.25	915.8	1178.0	.42733	1.2170	1.6444
61	293.81	.017388	7.067	263.17	835.4	1098.6	263.36	915.0	1178.4	.42881	1.2143	1.6431
62	294.88	.017399	6.960	264.26	834.6	1098.8	264.46	914.2	1178.7	.43026	1.2115	1.6418
63	295.93	.017409	6.856	265.34	833.7	1099.1	265.55	913.4	1179.0	.43169	1.2088	1.6405
64	296.98	.017419	6.755	266.41	832.9	1099.3	266.61	912.7	1179.3	.43310	1.2061	1.6392
65	298.00	.017429	6.657	267.46	832.1	1099.5	267.67	911.9	1179.6	.43450	1.2035	1.6380
66	299.02	.017439	6.562	268.51	831.2	1099.8	268.72	911.2	1179.9	.43587	1.2009	1.6368
67	300.02	.017449	6.470	269.54	830.4	1100.0	269.75	910.4	1180.2	.43723	1.1983	1.6356
68	301.01	.017458	6.380	270.56	829.6	1100.2	270.77	909.7	1180.5	.43857	1.1958	1.6344
69	301.99	.017468	6.293	271.56	828.8	1100.4	271.78	909.0	1180.8	.43989	1.1933	1.6332
70	302.96	.017478	6.209	272.56	828.1	1100.6	272.79	908.3	1181.0	.44120	1.1909	1.6321
71	303.91	.017487	6.126	273.54	827.3	1100.8	273.77	907.5	1181.3	.44249	1.1884	1.6309
72	304.86	.017496	6.046	274.52	826.5	1101.0	274.75	906.8	1181.6	.44376	1.1860	1.6298
73	305.79	.017506	5.968	275.48	825.8	1101.2	275.72	906.1	1181.9	.44502	1.1837	1.6287
74	306.72	.017515	5.892	276.43	825.0	1101.4	276.67	905.4	1182.1	.44626	1.1814	1.6276
75	307.63	.017524	5.818	277.37	824.3	1101.6	277.61	904.8	1182.4	.44749	1.1790	1.6265
76	308.54	.017534	5.746	278.31	823.5	1101.8	278.55	904.1	1182.6	.44871	1.1768	1.6255
77	309.44	.017543	5.675	279.23	822.8	1102.0	279.48	903.4	1182.9	.44991	1.1745	1.6244
78	310.32	.017552	5.607	280.14	822.1	1102.2	280.40	902.7	1183.1	.45110	1.1723	1.6234
79	311.20	.017561	5.540	281.05	821.3	1102.4	281.30	902.1	1183.4	.45227	1.1701	1.6224
80	312.07	.017570	5.474	281.95	820.6	1102.6	282.21	901.4	1183.6	.45344	1.1679	1.6214
81	312.93	.017578	5.411	282.83	819.9	1102.8	283.10	900.8	1183.9	.45459	1.1658	1.6204
82	313.78	.017587	5.348	283.71	819.2	1102.9	283.98	900.1	1184.1	.45572	1.1637	1.6194
83	314.62	.017596	5.288	284.58	818.5	1103.1	284.85	899.5	1184.3	.45685	1.1616	1.6184
84	315.46	.017605	5.228	285.45	817.8	1103.3	285.72	898.8	1184.5	.45796	1.1595	1.6175
85	316.29	.017613	5.170	286.30	817.1	1103.5	286.58	898.2	1184.8	.45907	1.1574	1.6165
86	317.11	.017622	5.113	287.15	816.5	1103.6	287.43	897.6	1185.0	.46016	1.1554	1.6156
87	317.92	.017630	5.058	287.99	815.8	1103.8	288.27	896.9	1185.2	.46124	1.1534	1.6146
88	318.72	.017639	5.004	288.82	815.1	1104.0	289.11	896.3	1185.4	.46231	1.1514	1.6137
89	319.52	.017647	4.950	289.65	814.5	1104.1	289.94	895.7	1185.6	.46337	1.1494	1.6128
90	320.31	.017655	4.898	290.46	813.8	1104.3	290.76	895.1	1185.9	.46442	1.1475	1.6119
91	321.10	.017664	4.848	291.28	813.2	1104.4	291.57	894.5	1186.1	.46546	1.1456	1.6110
92	321.87	.017672	4.798	292.08	812.5	1104.6	292.38	893.9	1186.3	.46649	1.1436	1.6101
93	322.64	.017680	4.749	292.88	811.9	1104.7	293.18	893.3	1186.5	.46751	1.1418	1.6093
94	323.41	.017688	4.701	293.67	811.2	1104.9	293.98	892.7	1186.7	.46852	1.1399	1.6084
95	324.16	.017696	4.654	294.45	810.6	1105.0	294.76	892.1	1186.9	.46952	1.1380	1.6076
96	324.91	.017705	4.609	295.23	810.0	1105.2	295.55	891.5	1187.1	.47051	1.1362	1.6067
97	325.66	.017713	4.564	296.00	809.3	1105.3	296.32	890.9	1187.3	.47149	1.1344	1.6059
98	326.40	.017721	4.520	296.77	808.7	1105.5	297.09	890.4	1187.4	.47247	1.1326	1.6050
99	327.13	.017729	4.476	297.53	808.1	1105.6	297.85	889.8	1187.6	.47343	1.1308	1.6042
100	327.86	.017736	4.434	298.28	807.5	1105.8	298.61	889.2	1187.8	.47439	1.1290	1.6034
101	328.58	.017744	4.392	299.03	806.9	1105.9	299.36	888.6	1188.0	.47534	1.1273	1.6026
102	329.29	.017752	4.352	299.77	806.3	1106.0	300.11	888.1	1188.2	.47629	1.1255	1.6018
103	330.00	.017760	4.312	300.51	805.7	1106.2	300.85	887.5	1188.4	.47722	1.1238	1.6010
104	330.71	.017768	4.272	301.24	805.1	1106.3	301.58	887.0	1188.5	.47814	1.1221	1.6002
105	331.41	.017775	4.234	301.97	804.5	1106.5	302.31	886.4	1188.7	.47906	1.1204	1.5995
106	332.10	.017783	4.196	302.69	803.9	1106.6	303.04	885.9	1188.9	.47997	1.1187	1.5987
107	332.79	.017791	4.159	303.40	803.3	1106.7	303.75	885.3	1189.1	.48088	1.1171	1.5979
108	333.47	.017798	4.122	304.11	802.7	1106.8	304.47	884.8	1189.2	.48177	1.1154	1.5972
109	334.15	.017806	4.087	304.82	802.2	1107.0	305.18	884.2	1189.4	.48266	1.1138	1.5964
110	334.82	.017813	4.051	305.52	801.6	1107.1	305.88	883.7	1189.6	.48355	1.1122	1.5957
111	335.49	.017821	4.017	306.22	801.0	1107.2	306.58	883.1	1189.7	.48442	1.1106	1.5950
112	336.16	.017828	3.983	306.91	800.4	1107.3	307.28	882.6	1189.9	.48529	1.1090	1.5942
113	336.81	.017836	3.949	307.59	799.9	1107.5	307.97	882.1	1190.0	.48615	1.1074	1.5935
114	337.47	.017843	3.916	308.27	799.3	1107.6	308.65	881.6	1190.2	.48701	1.1058	1.5928

TABLE 2 SATURATION PRESSURES (CONT'D)

Press. Lbf. Sq. In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
115	338.12	.017850	3.884	308.95	798.8	1107.7	309.33	881.0	1190.4	.48786	1.1042	1.5921
116	338.77	.017858	3.852	309.62	798.2	1107.8	310.01	880.5	1190.5	.48870	1.1027	1.5914
117	339.41	.017865	3.821	310.29	797.6	1107.9	310.68	880.0	1190.7	.48954	1.1012	1.5907
118	340.04	.017872	3.790	310.96	797.1	1108.1	311.34	879.5	1190.8	.49037	1.0996	1.5900
119	340.68	.017879	3.760	311.62	796.6	1108.2	312.01	879.0	1191.0	.49119	1.0981	1.5893
120	341.30	.017886	3.730	312.27	796.0	1108.3	312.67	878.5	1191.1	.49201	1.0966	1.5886
121	341.93	.017894	3.701	312.92	795.5	1108.4	313.32	877.9	1191.3	.49282	1.0951	1.5880
122	342.55	.017901	3.672	313.57	794.9	1108.5	313.97	877.4	1191.4	.49363	1.0937	1.5873
123	343.17	.017908	3.644	314.21	794.4	1108.6	314.62	876.9	1191.6	.49443	1.0922	1.5866
124	343.78	.017915	3.616	314.85	793.9	1108.7	315.26	876.4	1191.7	.49523	1.0907	1.5860
125	344.39	.017922	3.588	315.49	793.3	1108.8	315.90	875.9	1191.8	.49602	1.0893	1.5853
126	344.99	.017929	3.561	316.12	792.8	1108.9	316.54	875.4	1192.0	.49680	1.0879	1.5847
127	345.59	.017936	3.535	316.75	792.3	1109.0	317.17	874.9	1192.1	.49758	1.0864	1.5840
128	346.19	.017943	3.508	317.37	791.8	1109.1	317.79	874.5	1192.2	.49836	1.0850	1.5834
129	346.78	.017950	3.482	317.99	791.3	1109.3	318.42	874.0	1192.4	.49913	1.0836	1.5828
130	347.37	.017957	3.457	318.61	790.7	1109.4	319.04	873.5	1192.5	.49989	1.0822	1.5821
131	347.96	.017964	3.432	319.22	790.2	1109.5	319.65	873.0	1192.6	.50065	1.0808	1.5815
132	348.54	.017970	3.407	319.83	789.7	1109.6	320.27	872.5	1192.8	.50141	1.0795	1.5809
133	349.12	.017977	3.383	320.43	789.2	1109.7	320.88	872.0	1192.9	.50216	1.0781	1.5803
134	349.70	.017984	3.359	321.04	788.7	1109.8	321.48	871.6	1193.0	.50290	1.0767	1.5796
135	350.27	.017991	3.335	321.64	788.2	1109.8	322.08	871.1	1193.2	.50364	1.0754	1.5790
136	350.84	.017997	3.312	322.23	787.7	1109.9	322.68	870.6	1193.3	.50438	1.0741	1.5784
137	351.40	.018004	3.289	322.82	787.2	1110.0	323.28	870.1	1193.4	.50511	1.0727	1.5778
138	351.97	.018011	3.266	323.41	786.7	1110.1	323.87	869.7	1193.5	.50583	1.0714	1.5772
139	352.53	.018018	3.244	324.00	786.2	1110.2	324.46	869.2	1193.7	.50655	1.0701	1.5766
140	353.08	.018024	3.221	324.58	785.7	1110.3	325.05	868.7	1193.8	.50727	1.0688	1.5761
141	353.63	.018031	3.200	325.16	785.3	1110.4	325.63	868.3	1193.9	.50799	1.0675	1.5755
142	354.18	.018037	3.178	325.74	784.8	1110.5	326.21	867.8	1194.0	.50870	1.0662	1.5749
143	354.73	.018044	3.157	326.31	784.3	1110.6	326.79	867.3	1194.1	.50940	1.0649	1.5743
144	355.28	.018051	3.136	326.88	783.8	1110.7	327.36	866.9	1194.2	.51010	1.0636	1.5737
145	355.82	.018057	3.115	327.45	783.3	1110.8	327.93	866.4	1194.4	.51079	1.0624	1.5732
146	356.35	.018064	3.095	328.01	782.8	1110.9	328.50	866.0	1194.5	.51149	1.0611	1.5726
147	356.89	.018070	3.075	328.58	782.4	1110.9	329.07	865.5	1194.6	.51218	1.0599	1.5720
148	357.42	.018076	3.055	329.13	781.9	1111.0	329.63	865.1	1194.7	.51286	1.0586	1.5715
149	357.95	.018083	3.036	329.69	781.4	1111.1	330.19	864.6	1194.8	.51354	1.0574	1.5709
150	358.48	.018089	3.016	330.24	781.0	1111.2	330.75	864.2	1194.9	.51422	1.0562	1.5704
152	359.52	.018102	2.978	331.34	780.0	1111.4	331.85	863.3	1195.1	.51556	1.0537	1.5693
154	360.56	.018115	2.941	332.43	779.1	1111.5	332.94	862.4	1195.3	.51689	1.0513	1.5682
156	361.58	.018127	2.905	333.50	778.2	1111.7	334.03	861.5	1195.6	.51820	1.0490	1.5671
158	362.59	.018140	2.870	334.57	777.3	1111.8	335.10	860.7	1195.8	.51949	1.0466	1.5661
160	363.60	.018152	2.836	335.63	776.4	1112.0	336.16	859.8	1196.0	.52078	1.0443	1.5651
162	364.59	.018165	2.802	336.67	775.5	1112.1	337.22	858.9	1196.2	.52205	1.0420	1.5640
164	365.58	.018177	2.770	337.71	774.6	1112.3	338.26	858.1	1196.4	.52331	1.0397	1.5630
166	366.55	.018189	2.738	338.74	773.7	1112.4	339.29	857.2	1196.5	.52455	1.0375	1.5620
168	367.52	.018201	2.707	339.75	772.8	1112.6	340.32	856.4	1196.7	.52578	1.0352	1.5610
170	368.47	.018214	2.676	340.76	772.0	1112.7	341.33	855.6	1196.9	.52700	1.0330	1.5600
172	369.42	.018226	2.646	341.76	771.1	1112.9	342.34	854.7	1197.1	.52821	1.0308	1.5591
174	370.36	.018238	2.617	342.76	770.2	1113.0	343.34	853.9	1197.3	.52940	1.0287	1.5581
176	371.29	.018249	2.589	343.74	769.4	1113.1	344.33	853.1	1197.4	.53059	1.0266	1.5571
178	372.21	.018261	2.561	344.71	768.6	1113.3	345.31	852.3	1197.6	.53176	1.0244	1.5562
180	373.13	.018273	2.533	345.68	767.7	1113.4	346.29	851.5	1197.8	.53292	1.0223	1.5553
182	374.04	.018285	2.507	346.64	766.9	1113.5	347.25	850.7	1197.9	.53407	1.0203	1.5543
184	374.93	.018296	2.480	347.59	766.1	1113.6	348.21	849.9	1198.1	.53521	1.0182	1.5534
186	375.83	.018308	2.455	348.53	765.2	1113.8	349.16	849.1	1198.3	.53634	1.0162	1.5525
188	376.71	.018319	2.430	349.47	764.4	1113.9	350.10	848.3	1198.4	.53746	1.0142	1.5516
190	377.59	.018331	2.405	350.39	763.6	1114.0	351.04	847.5	1198.6	.53857	1.0122	1.5507
192	378.45	.018342	2.381	351.32	762.8	1114.1	351.97	846.7	1198.7	.53967	1.0102	1.5499
194	379.32	.018354	2.357	352.23	762.0	1114.2	352.89	846.0	1198.9	.54076	1.0082	1.5490
196	380.17	.018365	2.334	353.14	761.2	1114.3	353.80	845.2	1199.0	.54184	1.0063	1.5481
198	381.02	.018376	2.312	354.04	760.4	1114.5	354.71	844.4	1199.1	.54291	1.0044	1.5473

TABLE 2 SATURATION PRESSURES (CONT'D)

Press. Lbf. Sq. In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
200	381.86	.018387	2.289	354.9	759.6	1114.6	355.6	843.7	1199.3	.5440	1.0025	1.5464
205	383.94	.018415	2.235	357.1	757.7	1114.8	357.8	841.8	1199.6	.5466	.9978	1.5444
210	385.97	.018443	2.184	359.3	755.8	1115.1	360.0	839.9	1200.0	.5492	.9932	1.5423
215	387.97	.018470	2.135	361.4	753.9	1115.3	362.2	838.1	1200.3	.5517	.9887	1.5403
220	389.94	.018497	2.088	363.5	752.0	1115.5	364.3	836.3	1200.6	.5541	.9842	1.5384
225	391.87	.018523	2.043	365.6	750.2	1115.8	366.3	834.5	1200.8	.5566	.9799	1.5365
230	393.76	.018550	2.000	367.6	748.4	1116.0	368.4	832.7	1201.1	.5589	.9757	1.5346
235	395.63	.018576	1.959	369.6	746.6	1116.2	370.4	831.0	1201.4	.5613	.9715	1.5327
240	397.46	.018602	1.919	371.5	744.8	1116.4	372.4	829.3	1201.6	.5636	.9674	1.5309
245	399.26	.018627	1.881	373.5	743.1	1116.6	374.3	827.5	1201.9	.5658	.9634	1.5292
250	401.04	.018653	1.8448	375.4	741.4	1116.7	376.2	825.8	1202.1	.5680	.9594	1.5274
255	402.79	.018678	1.8097	377.3	739.7	1116.9	378.1	824.2	1202.3	.5702	.9555	1.5257
260	404.51	.018703	1.7758	379.1	738.0	1117.1	380.0	822.5	1202.5	.5723	.9517	1.5240
265	406.20	.018728	1.7432	380.9	736.3	1117.2	381.8	820.9	1202.7	.5744	.9479	1.5224
270	407.87	.018752	1.7117	382.7	734.7	1117.4	383.7	819.2	1202.9	.5765	.9442	1.5208
275	409.52	.018777	1.6813	384.5	733.0	1117.5	385.4	817.6	1203.1	.5786	.9406	1.5192
280	411.15	.018801	1.6520	386.2	731.4	1117.7	387.2	816.0	1203.3	.5806	.9370	1.5176
285	412.75	.018825	1.6237	388.0	729.8	1117.8	389.0	814.5	1203.4	.5826	.9335	1.5160
290	414.33	.018849	1.5963	389.7	728.2	1117.9	390.7	812.9	1203.6	.5845	.9300	1.5145
295	415.89	.018873	1.5698	391.4	726.7	1118.0	392.4	811.3	1203.7	.5864	.9266	1.5130
300	417.43	.018896	1.5442	393.0	725.1	1118.2	394.1	809.8	1203.9	.5883	.9232	1.5115
310	420.45	.018943	1.4953	396.3	722.1	1118.4	397.4	806.8	1204.1	.5921	.9166	1.5086
320	423.39	.018989	1.4493	399.5	719.1	1118.6	400.6	803.8	1204.4	.5957	.9101	1.5058
330	426.27	.019034	1.4061	402.6	716.1	1118.7	403.8	800.8	1204.6	.5992	.9038	1.5031
340	429.07	.019079	1.3653	405.7	713.2	1118.9	406.9	797.9	1204.8	.6027	.8977	1.5004
350	431.82	.019124	1.3267	408.7	710.3	1119.0	409.9	795.0	1204.9	.6060	.8917	1.4978
360	434.50	.019168	1.2903	411.6	707.5	1119.1	412.9	792.2	1205.1	.6093	.8859	1.4952
370	437.13	.019212	1.2557	414.5	704.8	1119.2	415.8	789.4	1205.2	.6125	.8802	1.4927
380	439.70	.019255	1.2229	417.3	702.0	1119.3	418.6	786.7	1205.3	.6157	.8746	1.4903
390	442.23	.019298	1.1916	420.1	699.3	1119.4	421.5	783.9	1205.4	.6188	.8691	1.4879
400	444.70	.019340	1.1620	422.8	696.7	1119.5	424.2	781.2	1205.5	.6218	.8638	1.4856
410	447.12	.019382	1.1337	425.5	694.0	1119.5	426.9	778.6	1205.5	.6247	.8585	1.4833
420	449.50	.019424	1.1067	428.1	691.4	1119.5	429.6	776.0	1205.5	.6276	.8534	1.4810
430	451.84	.019465	1.0809	430.7	688.9	1119.6	432.2	773.3	1205.6	.6305	.8484	1.4788
440	454.14	.019507	1.0562	433.2	686.4	1119.6	434.8	770.8	1205.6	.6333	.8434	1.4767
450	456.39	.019547	1.0326	435.7	683.9	1119.6	437.4	768.2	1205.6	.6360	.8385	1.4746
460	458.61	.019588	1.0100	438.2	681.4	1119.6	439.9	765.7	1205.5	.6387	.8338	1.4725
470	460.79	.019628	.9883	440.6	678.9	1119.6	442.3	763.2	1205.5	.6414	.8291	1.4704
480	462.94	.019668	.9675	443.0	676.5	1119.5	444.8	760.7	1205.5	.6440	.8244	1.4684
490	465.05	.019708	.9475	445.4	674.1	1119.5	447.2	758.2	1205.4	.6465	.8199	1.4664
500	467.13	.019748	.9283	447.7	671.7	1119.4	449.5	755.8	1205.3	.6490	.8154	1.4645
510	469.17	.019787	.9098	450.0	669.4	1119.4	451.9	753.4	1205.2	.6515	.8110	1.4626
520	471.19	.019826	.8920	452.3	667.1	1119.3	454.2	751.0	1205.2	.6540	.8067	1.4607
530	473.18	.019865	.8748	454.5	664.8	1119.3	456.4	748.6	1205.1	.6564	.8024	1.4588
540	475.14	.019904	.8583	456.7	662.5	1119.2	458.7	746.2	1204.9	.6587	.7982	1.4570
550	477.07	.019943	.8423	458.9	660.2	1119.1	460.9	743.9	1204.8	.6611	.7941	1.4551
560	478.97	.019981	.8269	461.0	657.9	1119.0	463.1	741.6	1204.7	.6634	.7900	1.4534
570	480.85	.020020	.8120	463.2	655.7	1118.9	465.3	739.3	1204.5	.6656	.7860	1.4516
580	482.70	.020058	.7976	465.3	653.5	1118.8	467.4	737.0	1204.4	.6679	.7820	1.4499
590	484.53	.020096	.7837	467.4	651.3	1118.7	469.6	734.7	1204.2	.6701	.7780	1.4481
600	486.33	.02013	.7702	469.4	649.1	1118.6	471.7	732.4	1204.1	.6723	.7742	1.4464
620	489.88	.02021	.7445	473.5	644.8	1118.3	475.8	727.9	1203.7	.6766	.7665	1.4431
640	493.33	.02028	.7203	477.4	640.6	1118.0	479.8	723.5	1203.3	.6807	.7591	1.4398
660	496.71	.02036	.6975	481.3	636.4	1117.7	483.8	719.1	1202.9	.6848	.7519	1.4367
680	500.00	.02043	.6761	485.1	632.3	1117.4	487.7	714.8	1202.5	.6888	.7447	1.4335
700	503.23	.02051	.6558	488.9	628.2	1117.0	491.5	710.5	1202.0	.6927	.7378	1.4305
720	506.38	.02058	.6366	492.5	624.1	1116.7	495.3	706.2	1201.5	.6965	.7310	1.4275
740	509.47	.02065	.6184	496.1	620.2	1116.3	499.0	702.0	1201.0	.7002	.7243	1.4246
760	512.49	.02073	.6011	499.7	616.2	1115.9	502.6	697.8	1200.4	.7039	.7178	1.4217
780	515.46	.02080	.5847	503.2	612.3	1115.5	506.2	693.7	1199.9	.7075	.7113	1.4188

TABLE 2 SATURATION PRESSURES (CONT'D)

Press. Lbf. Sq. In. p	Temp. Fahr. t	Specific Volume		Internal Energy			Enthalpy			Entropy		
		Sat. Liquid v _f	Sat. Vapor v _g	Sat. Liquid u _f	Evap. u _{fg}	Sat. Vapor u _g	Sat. Liquid h _f	Evap. h _{fg}	Sat. Vapor h _g	Sat. Liquid s _f	Evap. s _{fg}	Sat. Vapor s _g
800	518.36	.02087	.5691	506.6	608.4	1115.0	509.7	689.6	1199.3	.7110	.7050	1.4160
820	521.21	.02094	.5542	510.0	604.6	1114.6	513.2	685.5	1198.7	.7145	.6988	1.4133
840	524.01	.02101	.5400	513.3	600.8	1114.1	516.6	681.5	1198.0	.7179	.6927	1.4106
860	526.76	.02109	.5264	516.6	597.0	1113.6	519.9	677.5	1197.4	.7212	.6867	1.4080
880	529.46	.02116	.5134	519.8	593.3	1113.1	523.3	673.5	1196.7	.7245	.6808	1.4053
900	532.12	.02123	.5009	523.0	589.6	1112.6	526.6	669.5	1196.0	.7277	.6750	1.4027
920	534.73	.02130	.4890	526.2	585.9	1112.1	529.8	665.6	1195.4	.7309	.6693	1.4002
940	537.29	.02137	.4776	529.3	582.3	1111.6	533.0	661.6	1194.6	.7341	.6636	1.3977
960	539.82	.02145	.4666	532.4	578.7	1111.0	536.2	657.7	1193.9	.7372	.6580	1.3952
980	542.30	.02152	.4561	535.4	575.1	1110.4	539.3	653.9	1193.2	.7402	.6525	1.3927
1000	544.75	.02159	.4459	538.4	571.5	1109.9	542.4	650.0	1192.4	.7432	.6471	1.3903
1050	550.71	.02177	.4222	545.7	562.6	1108.4	550.0	640.4	1190.4	.7505	.6338	1.3844
1100	556.45	.02195	.4005	552.9	553.9	1106.8	557.4	631.0	1188.3	.7576	.6209	1.3786
1150	562.00	.02214	.3806	559.9	545.3	1105.2	564.6	621.6	1186.2	.7645	.6084	1.3729
1200	567.37	.02232	.3623	566.7	536.8	1103.5	571.7	612.3	1183.9	.7712	.5961	1.3673
1250	572.56	.02250	.3454	573.4	528.3	1101.7	578.6	603.0	1181.6	.7778	.5841	1.3619
1300	577.60	.02269	.3297	579.9	519.9	1099.8	585.4	593.8	1179.2	.7841	.5724	1.3565
1350	582.50	.02288	.3152	586.3	511.6	1097.9	592.1	584.6	1176.7	.7903	.5609	1.3513
1400	587.25	.02307	.3016	592.7	503.3	1096.0	598.6	575.5	1174.1	.7964	.5497	1.3461
1450	591.88	.02326	.2888	598.9	495.1	1093.9	605.1	566.3	1171.4	.8024	.5385	1.3409
1500	596.39	.02346	.2769	605.0	486.9	1091.8	611.5	557.2	1168.7	.8082	.5276	1.3359
1550	600.78	.02366	.2657	611.0	478.7	1089.6	617.8	548.1	1165.9	.8140	.5168	1.3308
1600	605.06	.02386	.2552	616.9	470.5	1087.4	624.0	538.9	1162.9	.8196	.5062	1.3258
1650	609.24	.02407	.2452	622.8	462.3	1085.1	630.2	529.8	1159.9	.8252	.4956	1.3208
1700	613.32	.02428	.2358	628.6	454.1	1082.7	636.2	520.6	1156.9	.8307	.4852	1.3159
1750	617.31	.02450	.2268	634.4	445.9	1080.2	642.3	511.4	1153.7	.8361	.4748	1.3109
1800	621.21	.02472	.2183	640.0	437.6	1077.7	648.3	502.1	1150.4	.8414	.4645	1.3060
1850	625.02	.02494	.2102	645.7	429.4	1075.1	654.2	492.8	1147.0	.8467	.4543	1.3010
1900	628.76	.02517	.2025	651.3	421.0	1072.3	660.1	483.4	1143.5	.8519	.4441	1.2961
1950	632.41	.02541	.1952	656.9	412.7	1069.5	666.0	473.9	1140.0	.8571	.4340	1.2911
2000	636.00	.02565	.18813	662.4	404.2	1066.6	671.9	464.4	1136.3	.8623	.4238	1.2861
2050	639.51	.02590	.18139	667.9	395.7	1063.7	677.7	454.7	1132.5	.8674	.4137	1.2811
2100	642.95	.02616	.17491	673.4	387.1	1060.6	683.6	445.0	1128.5	.8725	.4035	1.2760
2150	646.33	.02642	.16869	678.9	378.4	1057.3	689.4	435.1	1124.5	.8775	.3933	1.2709
2200	649.64	.02670	.16270	684.4	369.6	1054.0	695.3	425.0	1120.3	.8826	.3831	1.2657
2250	652.90	.02698	.15692	689.9	360.7	1050.6	701.1	414.8	1115.9	.8876	.3728	1.2604
2300	656.09	.02728	.15133	695.4	351.6	1047.0	707.0	404.4	1111.4	.8927	.3624	1.2551
2350	659.23	.02759	.14592	700.9	342.4	1043.3	712.9	393.8	1106.7	.8977	.3520	1.2497
2400	662.31	.02791	.14067	706.4	332.9	1039.3	718.8	383.0	1101.8	.9028	.3413	1.2441
2450	665.33	.02825	.13556	712.0	323.3	1035.3	724.8	371.9	1096.7	.9079	.3306	1.2385
2500	668.31	.02860	.13059	717.7	313.4	1031.0	730.9	360.5	1091.4	.9131	.3196	1.2327
2550	671.24	.02898	.12574	723.4	303.2	1026.5	737.0	348.8	1085.9	.9183	.3084	1.2267
2600	674.11	.02938	.12099	729.2	292.7	1021.8	743.3	336.7	1080.0	.9236	.2970	1.2205
2650	676.94	.02981	.11632	735.1	281.8	1016.8	749.7	324.2	1073.9	.9289	.2852	1.2141
2700	679.73	.03027	.11172	741.1	270.4	1011.5	756.2	311.1	1067.4	.9345	.2730	1.2075
2750	682.46	.03077	.10717	747.3	258.6	1005.9	763.0	297.4	1060.4	.9401	.2604	1.2005
2800	685.16	.03131	.10264	753.8	246.0	999.8	770.0	283.0	1053.0	.9460	.2472	1.1932
2850	687.81	.03192	.09811	760.5	232.7	993.2	777.3	267.6	1045.0	.9521	.2332	1.1853
2900	690.42	.03260	.09353	767.6	218.4	986.0	785.1	251.1	1036.2	.9586	.2183	1.1769
2950	692.99	.03338	.08887	775.1	202.8	978.0	793.4	233.1	1026.5	.9656	.2022	1.1678
3000	695.52	.03431	.08404	783.4	185.4	968.8	802.5	213.0	1015.5	.9732	.1843	1.1575
3050	698.02	.03546	.07891	792.9	165.3	958.1	812.9	189.8	1002.6	.9819	.1639	1.1458
3100	700.47	.03701	.07322	804.2	140.7	944.8	825.4	161.5	986.8	.9924	.1392	1.1316
3150	702.89	.03944	.06632	819.7	106.8	926.4	842.7	122.4	965.1	1.0070	.1053	1.1123
3200	705.27	.04805	.05444	862.1	25.6	887.7	890.6	29.3	919.9	1.0478	.0252	1.0730
3203.6	705.44	.05053	.05053	872.6	0	872.6	902.5	0	902.5	1.0580	0	1.0580

APPENDIX F
UNITS AND CONVERSION TABLES

This appendix contains tables defining units and conversion among different systems of measurement. The tables are:

- Derived Units of the International System,
- Prefixes for Units in the International System,
- Conversion Factors for the U.S. customary system, metric system, and International System,
- Thermal Conversion Factors, and,
- An Energy Unit Conversion Chart.

Where values appear in the text and tables of this Handbook, English units are generally used. However, because a variety of data sources were used in compiling the Handbook, different units may appear and the conversion charts should be used.

DERIVED UNITS OF THE INTERNATIONAL SYSTEM

Quantity	Name of Unit	Unit Symbol (or abbreviation where differing from basic form)	Unit-expressed in terms of basic or supplementary units*
area	square meter		m^2
volume	cubic meter		m^3
frequency	hertz	Hz	s^{-1}
density	kilogram per cubic meter		kg/m^3
velocity	meter per second		m/s
angular velocity	radian per second		rad/s
acceleration	meter per second squared		m/s^2
angular acceleration	radian per second squared		rad/s^2
volumetric flow rate	cubic meter per second		m^3/s
force	newton	N	$kg \cdot m/s^2$
surface tension	newton per meter, joule per square meter	N/m, J/m ²	kg/s^2
pressure	newton per square meter, pascal	N/m ² , Pa	$kg/m \cdot s^2$
viscosity, dynamic	newton-second per square meter, pascal-second	N $\cdot$ s/m ² , Pa $\cdot$ s	$kg/m \cdot s$
viscosity, kinematic	meter squared per second		m^2/s
work, torque, energy,			
quantity of heat	joule, newton-meter, watt-second	J, N $\cdot$ m, W $\cdot$ s	$kg \cdot m^2/s^2$
power, heat flux	watt, joule per second	W, J/s	$kg \cdot m^2/s^3$
heat flux density	watt per square meter	W/m ²	kg/s^3
volumetric heat release rate	watt per cubic meter	W/m ³	$kg/m \cdot s^3$
heat transfer coefficient	watt per square meter kelvin	W/m ² $\cdot$ K	$kg/s^3 \cdot K$
heat capacity (specific)	joule per kilogram kelvin	J/kg $\cdot$ K	$m^2/s^2 \cdot K$
capacity rate	watt per kelvin	W/K	$kg \cdot m^2/s^3 \cdot K$
thermal conductivity	watt per meter kelvin	W/m $\cdot$ K, J $\cdot$ m/s $\cdot$ m ² $\cdot$ K	$kg \cdot m/s^3 \cdot K$
quantity of electricity	coulomb	C	A $\cdot$ s
electromotive force	volt	V, W/A	$kg \cdot m^2/A \cdot s^3$
electric field strength	volt per meter		V/m
electric resistance	ohm	Ω , V/A	$kg \cdot m^2/A^2 \cdot s^3$
electric conductivity	ampere per volt meter	A/V $\cdot$ m	$A^2 \cdot s^3/kg \cdot m^3$
electric capacitance	farad	F, A $\cdot$ s/V	$A^3 \cdot s^4/kg \cdot m^2$
magnetic flux	weber	Wb, V $\cdot$ s	$kg \cdot m^2/A \cdot s^2$
inductance	henry	H, V $\cdot$ s/A	$kg \cdot m^2/A^2 \cdot s^2$
magnetic permeability	henry per meter	H/m	$kg \cdot m/A^2 \cdot s^2$
magnetic flux density	tesla, weber per square meter	T, Wb/m ²	$kg/A \cdot s^2$
magnetic field strength	ampere per meter		A/m
magnetomotive force	ampere		A
luminous flux	lumen	lm	cd $\cdot$ sr
luminance	candela per square meter		cd/m ²
illumination	lux, lumen per square meter	lx, lm/m ²	cd $\cdot$ m ⁻²

* Supplementary units are: plane angle, radian (rad); solid angle, steradian (sr).

ENERGY UNIT CONVERSION CHART*

BRITISH THERMAL UNITS (Btu)	NATURAL GAS**		KILOWATT HOURS ELECTRICITY (kWhr)	BARRELS OIL (bbl)	SHORT TONS BITUMINOUS COAL (T)
	CF	Therms			
1	-	-	0.000293	-	-
1 M	.001 M	1	0.293	0.00017	0.00004
3.413 M	3.413 M	0.03413	1	0.00059	0.00014
100 M	100	1	29.3	0.017	0.004
1 MM	1 M (1 MCF)	10	293	0.17	0.04
3.41 MM	3.413 M	34.1	1000 (1 M Whr)	0.59	0.14
5.8 MM	5.8 M	58	1.7 M	1	0.23
25 MM	25 M	250	7.325 M	1	
1 MMM	1 MM (1 MMcf)	10 M	293	172	40
3.41 MMM	3.41 MM	34.1	1 MM (1 G) Whr	588	136
1 MMMM	1 MMM (1 Bcf)	10 MM	293 MM	172 M	40 M
5.8 MMMM	5.8 MMM	58 MM	1.7 MMM	1 MM (1MMBbl)	232 M
25 MMMM	25 MMM	250 MM	7.32 MMM	4.31 MM	1 MM
1 MMMMM (QUAD)(Q)	1 TRILLION (1 Tcf)	10 MMM	293 MMM	172 MM	40 MM

*Based on the following nominal fuel heating values: ** Substitute Natural Gas (SNG) and Liquefied Natural Gas (LNG) will have approximately the same heating value.

1 Cubic Foot Natural Gas = 1000 Btu
1 Barrel Crude Oil = 5.8 Million Btu
1 Pound Bituminous Coal = 12,500 Btu
M = 1000 MM = 1,000,000

SI METRIC SYSTEM OF UNITS **

Alphabetical List of Units (Symbols of SI Units given in parenthesis)

To Convert From	To	Multiply By	
abampere	ampere (A)	1.0*	E + 01
abcoulomb	coulomb (C)	1.0*	E + 01
abfarad	farad (F)	1.0*	E + 09
abhenry	henry (H)	1.0*	E - 09
abmho	siemens (S)	1.0*	E + 09
abohm	ohm (Ω)	1.0*	E - 09
abvolt	volt (V)	1.0*	E - 08
acre-foot (U.S. survey) ⁽¹⁾	meter ³ (m ³)	1.233 489	E + 03
acre (U.S. survey) ⁽¹⁾	meter ² (m ²)	4.046 873	E + 03
ampere hour	coulomb (C)	3.6*	E + 03
are	meter ² (m ²)	1.0*	E + 02
angstrom	meter (m)	1.0*	E - 10
astronomical unit ⁽²⁾	meter (m)	1.495 979	E + 11
atmosphere (standard)	pascal (Pa)	1.013 250*	E + 05
atmosphere (technical = 1 kgf/cm ²)	pascal (Pa)	9.806 650*	E + 04
bar	pascal (Pa)	1.0*	E + 05
barn	meter ² (m ²)	1.0*	E - 28
barrel (for petroleum, 42 gal)	meter ³ (m ³)	1.589 873	E - 01
board foot	meter ³ (m ³)	2.359 737	E - 03
British thermal unit (International Table) ⁽³⁾	joule (J)	1.055 056	E + 03
British thermal unit (mean)	joule (J)	1.055 87	E + 03
British thermal unit (thermochemical)	joule (J)	1.054 350	E + 03
British thermal unit (39°F)	joule (J)	1.059 67	E + 03
British thermal unit (59°F)	joule (J)	1.054 80	E + 03
British thermal unit (60°F)	joule (J)	1.054 68	E + 03
Btu (International Table)-ft/(hr-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	1.730 735	E + 00
Btu (thermochemical)-ft/(hr-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	1.729 577	E + 00
Btu (International Table)-in./(hr-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	1.442 279	E - 01
Btu (thermochemical)-in./(hr-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	1.441 314	E - 01
Btu (International Table)-in./(s-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	5.192 204	E + 02
Btu (thermochemical)-in./(s-ft ² -°F) (thermal conductivity)	watt per meter kelvin (W/m·K)	5.188 732	E + 02
Btu (International Table)/hr	watt (W)	2.930 711	E - 01
Btu (thermochemical)/hr	watt (W)	2.928 751	E - 01
Btu (thermochemical)/min	watt (W)	1.757 250	E + 01
Btu (thermochemical)/s	watt (W)	1.054 350	E + 03
Btu (International Table)/ft ²	joule per meter ² (J/m ²)	1.135 653	E + 04
Btu (thermochemical)/ft ²	joule per meter ² (J/m ²)	1.134 893	E + 04

**Source of SI System of Units and Conversion of Units - Society of Petroleum Engineers of AIME

SI METRIC SYSTEM OF UNITS (CONT'D)

To Convert From	To	Multiply By
Btu (thermochemical)/(ft ² -hr)	watt per meter ² (W/m ²)	3.152 481 E + 00
Btu (thermochemical)/(ft ² -min)	watt per meter ² (W/m ²)	1.891 489 E + 02
Btu (thermochemical)/(ft ² -s)	watt per meter ² (W/m ²)	1.134 893 E + 04
Btu (thermochemical)/(in. ² -s)	watt per meter ² (W/m ²)	1.634 246 E + 06
Btu (International Table)/(hr-ft ² -°F) (thermal conductance)	watt per meter ² kelvin (W/m ² -K)	5.678 263 E + 00
Btu (thermochemical)/(hr-ft ² -°F) (thermal conductance)	watt per meter ² kelvin (W/m ² -K)	5.674 466 E + 00
Btu (International Table)/(s-ft ² -°F)	watt per meter ² kelvin (W/m ² -K)	2.044 175 E + 04
Btu (thermochemical)/(s-ft ² -°F)	watt per meter ² kelvin (W/m ² -K)	2.042 808 E + 04
Btu (International Table)/lbm	joule per kilogram (J/kg)	2.326 E + 03
Btu (thermochemical)/lbm	joule per kilogram (J/kg)	2.324 444 E + 03
Btu (International Table)/(lbm-°F) (heat capacity)	joule per kilogram kelvin (J/kg-K)	4.186 8 E + 03
Btu (thermochemical)/(lbm-°F) (heat capacity)	joule per kilogram kelvin (J/kg-K)	4.184 000 E + 03
bushel (U.S.)	meter ³ (m ³)	3.523 907 E - 02
caliber (inch)	meter (m)	2.54 E - 02
calorie (International Table)	joule (J)	4.186 8 E + 00
calorie (mean)	joule (J)	4.190 02 E + 00
calorie (thermochemical)	joule (J)	4.184 E + 00
calorie (15°C)	joule (J)	4.185 80 E + 00
calorie (20°C)	joule (J)	4.181 90 E + 00
calorie (kilogram, International Table)	joule (J)	4.186 8 E + 03
calorie (kilogram, mean)	joule (J)	4.190 02 E + 03
calorie (kilogram, thermochemical)	joule (J)	4.184 E + 03
cal (thermochemical)/cm ²	joule per meter ² (J/m ²)	4.184 E + 04
cal (International Table)/g	joule per kilogram (J/kg)	4.186 E + 03
cal (thermochemical)/g	joule per kilogram (J/kg)	4.184 E + 03
cal (International Table)/(g-°C)	joule per kilogram kelvin (J/kg-K)	4.186 8 E + 03
cal (thermochemical)/(g-°C)	joule per kilogram kelvin (J/kg-K)	4.184 E + 03
cal (thermochemical)/min	watt (W)	6.973 333 E - 02
cal (thermochemical)/s	watt (W)	4.184 E + 00
cal (thermochemical)/(cm ² -min)	watt per meter ² (W/m ²)	6.973 333 E + 02
cal (thermochemical)/(cm ² -s)	watt per meter ² (W/m ²)	4.184 E + 04
cal (thermochemical)/(cm ² -s-°C)	watt per meter kelvin (W/m-K)	4.184 E + 02
capture unit (c.u. = 10 ⁻³ cm ⁻¹)	per meter (m ⁻¹)	1.0 E - 01
carat (metric)	kilogram (kg)	2.0 E - 04
centimeter of mercury (0°C)	pascal (Pa)	1.333 22 E + 03
centimeter of water (4°C)	pascal (Pa)	9.806 38 E + 01
centipoise	pascal second (Pa-s)	1.0 E - 03
centistokes	meter ² per second (m ² /s)	1.0 E - 06
circular mil	meter ² (m ²)	5.067 075 E - 10
clo	kelvin meter ² per watt (K-m ² /W)	2.003 712 E - 01
cup	meter ³ (m ³)	2.365 882 E - 04
curie	becquerel (Bq)	3.7 E + 10
cycle per second	hertz (Hz)	1.0 E + 00
day (mean solar)	second (s)	8.640 000 E + 04
day (sidereal)	second (s)	8.616 409 E + 04
degree (angle)	radian (rad)	1.745 329 E - 02
degree Celsius	kelvin (K)	$T_K = T_C + 273.15$
degree centigrade (see degree Celsius)		
degree Fahrenheit	degree Celsius	$T_C = (T_F - 32)/1.8$
degree Fahrenheit	kelvin (K)	$T_K = (T_F + 459.67)/1.8$
degree Rankine	kelvin (K)	$T_K = T_R/1.8$

⁽¹⁾Since 1893 the U.S. basis of length measurement has been derived from metric standards. In 1959 a small refinement was made in the definition of the yard to resolve discrepancies both in this country and abroad, which changed its length from 3600.3937 m to 0.9144 m exactly. This resulted in the new value being shorter by two parts in a million. At the same time it was decided that any data in feet derived from and published as a result of geodetic surveys within the U.S. would remain with the old standard (1 ft = 1200.3937 m) until further decision. This foot is named the U.S. survey foot. As a result, all U.S. land measurements in U.S. customary units will relate to the meter by the old standard. All the conversion factors in these tables for units referenced to this footnote are based on the U.S. survey foot, rather than the international foot. Conversion factors for the land measure given below may be determined from the following relationships:

- 1 league = 3 miles (exactly)
- 1 rod = 16 1/2 ft (exactly)
- 1 chain = 66 ft (exactly)
- 1 section = 1 sq mile (exactly)
- 1 township = 36 sq miles (exactly)

⁽²⁾This value conflicts with the value printed in NBS 330.¹ The value requires updating in NBS 330.

⁽³⁾This value was adopted in 1956. Some of the older International Tables use the value 1.055 04 E + 03. The exact conversion factor is 1.055 055 852 62° E + 03.

SI METRIC SYSTEM OF UNITS (CONT'D)

To Convert From	To	Multiply By
°F-hr-ft ² /Btu (International Table) (thermal resistance)	kelvin meter ² per watt (K-m ² /W)	1.781 102 E-01
°F-hr-ft ² /Btu (thermochemical) (thermal resistance)	kelvin meter ² per watt (K-m ² /W)	1.762 250 E-01
denier	kilogram per meter (kg/m)	1.111 111 E-07
dyne	newton (N)	1.0 E-05
dyne-cm	newton meter (N-m)	1.0 E-07
dyne/cm ²	pascal (Pa)	1.0 E-01
electronvolt	joule (J)	1.602 19 E-19
EMU of capacitance	farad (F)	1.0 E+09
EMU of current	ampere (A)	1.0 E+01
EMU of electric potential	volt (V)	1.0 E-08
EMU of inductance	henry (H)	1.0 E-09
EMU of resistance	ohm (Ω)	1.0 E-09
ESU of capacitance	farad (F)	1.112 650 E-12
ESU of current	ampere (A)	3.335 6 E-10
ESU of electric potential	volt (V)	2.997 9 E+02
ESU of inductance	henry (H)	8.987 554 E+11
ESU of resistance	ohm (Ω)	8.987 554 E+11
erg	joule (J)	1.0 E-07
erg/cm ² -s	watt per meter ² (W/m ²)	1.0 E-03
erg/s	watt (W)	1.0 E-07
faraday (based on carbon-12)	coulomb (C)	9.648 70 E+04
faraday (chemical)	coulomb (C)	9.649 57 E+04
faraday (physical)	coulomb (C)	9.652 19 E+04
fathom	meter (m)	1.828 8 E+00
fermi (femtometer)	meter (m)	1.0 E-15
fluid ounce (U.S.)	meter ³ (m ³)	2.957 353 E-05
foot	meter (m)	3.048 E-01
foot (U.S. survey) ⁽¹⁾	meter (m)	3.048 006 E-01
foot of water (39.2°F)	pascal (Pa)	2.988 98 E+03
sq ft	meter ² (m ²)	9.290 304 E-02
ft ² /hr (thermal diffusivity)	meter ² per second (m ² /s)	2.580 640 E-05
ft ² /s	meter ² per second (m ² /s)	9.290 304 E-02
cu ft (volume; section modulus)	meter ³ (m ³)	2.831 685 E-02
ft ³ /min	meter ³ per second (m ³ /s)	4.719 474 E-04
ft ³ /s	meter ³ per second (m ³ /s)	2.831 685 E-02
ft ⁴ (moment of section) ⁽⁴⁾	meter ⁴ (m ⁴)	8.630 975 E-03
ft/hr	meter per second (m/s)	8.466 667 E-05
ft/min	meter per second (m/s)	5.080 E-03
ft/s	meter per second (m/s)	3.048 E-01
ft/s ²	meter per second ² (m/s ²)	3.048 E-01
footcandle	lux (lx)	1.076 391 E+01
footlambert	candela per meter ² (cd/m ²)	3.426 259 E+00
ft-lbf	joule (J)	1.355 818 E+00
ft-lbf/hr	watt (W)	3.766 161 E-04
ft-lbf/min	watt (W)	2.259 697 E-02
ft-lbf/s	watt (W)	1.355 818 E+00
ft-poundal	joule (J)	4.214 011 E-02
free fall, standard (g)	meter per second ² (m/s ²)	9.806 650 E+00
cm/s ²	meter per second ² (m/s ²)	1.0 E-02
gallon (Canadian liquid)	meter ³ (m ³)	4.546 090 E-03
gallon (U.K. liquid)	meter ³ (m ³)	4.546 092 E-03
gallon (U.S. dry)	meter ³ (m ³)	4.404 884 E-03
gallon (U.S. liquid)	meter ³ (m ³)	3.785 412 E-03
gal (U.S. liquid)/day	meter ³ per second (m ³ /s)	4.381 264 E-08
gal (U.S. liquid)/min	meter ³ per second (m ³ /s)	6.309 020 E-05
gal (U.S. liquid)/hp-hr (SFC, specific fuel consumption)	meter ³ per joule (m ³ /J)	1.410 089 E-09
gamma (magnetic field strength)	ampere per meter (A/m)	7.957 747 E-04
gamma (magnetic flux density)	tesla (T)	1.0 E-09
gauss	tesla (T)	1.0 E-04
gilbert	ampere (A)	7.957 747 E-01
gill (U.K.)	meter ³ (m ³)	1.420 654 E-04
gill (U.S.)	meter ³ (m ³)	1.182 941 E-04
grad	degree (angular)	9.0 E-01
grad	radian (rad)	1.570 796 E-02

SI METRIC SYSTEM OF UNITS (CONT'D)

To Convert From	To	Multiply By
grain (1/7000 lbm avoirdupois)	kilogram (kg)	6.479 891 E - 05
grain (lbm avoirdupois/7000)/gal (U.S. liquid)	kilogram per meter ³ (kg/m ³)	1.711 806 E - 02
gram	kilogram (kg)	1.0 E - 03
g/cm ³	kilogram per meter ³ (kg/m ³)	1.0 E + 03
gram-force/cm ²	pascal (Pa)	9.806 650 E + 01
hectare	meter ² (m ²)	1.0 E + 04
horsepower (550 ft-lbf/s)	watt (W)	7.456 999 E + 02
horsepower (boiler)	watt (W)	9.809 50 E + 03
horsepower (electric)	watt (W)	7.460 E + 02
horsepower (metric)	watt (W)	7.354 99 E + 02
horsepower (water)	watt (W)	7.460 43 E + 02
horsepower (U.K.)	watt (W)	7.457 0 E + 02
hour (mean solar)	second (s)	3.600 000 E + 03
hour (sidereal)	second (s)	3.590 170 E + 03
hundredweight (long)	kilogram (kg)	5.080 235 E + 01
hundredweight (short)	kilogram (kg)	4.535 924 E + 01
inch	meter (m)	2.54 E - 02
inch of mercury (32°F)	pascal (Pa)	3.380 38 E + 03
inch of mercury (60°F)	pascal (Pa)	3.376 85 E + 03
inch of water (39.2°F)	pascal (Pa)	2.490 82 E + 02
inch of water (60°F)	pascal (Pa)	2.488 4 E + 02
sq in.	meter ² (m ²)	6.451 6 E - 04
cu in. (volume; section modulus) ⁽⁴⁾	meter ³ (m ³)	1.638 706 E - 05
in. ³ /min	meter ³ per second (m ³ /s)	2.731 177 E - 07
in. ⁴ (moment of section) ⁽⁴⁾	meter ⁴ (m ⁴)	4.162 314 E - 07
in./s	meter per second (m/s)	2.54 E - 02
in./s ²	meter per second ² (m/s ²)	2.54 E - 02
kayser	1 per meter (1/m)	1.0 ^a E + 02
kelvin	degree Celsius	$T_C = T_K - 273.15$
kilocalorie (International Table)	joule (J)	4.186 8 E + 03
kilocalorie (mean)	joule (J)	4.190 02 E + 03
kilocalorie (thermochemical)	joule (J)	4.184 E + 03
kilocalorie (thermochemical)/min	watt (W)	6.973 333 E + 01
kilocalorie (thermochemical)/s	watt (W)	4.184 E + 03
kilogram-force (kgf)	newton (N)	9.806 65 E + 00
kgf-m	newton meter (N-m)	9.806 65 E + 00
kgf-s ² /m (mass)	kilogram (kg)	9.806 65 E + 00
kgf/cm ²	pascal (Pa)	9.806 65 E + 04
kgf/m ²	pascal (Pa)	9.806 65 E + 00
kgf/mm ²	pascal (Pa)	9.806 65 E + 06
km/h	meter per second (m/s)	2.777 778 E - 01
kilopond	newton (N)	9.806 65 E + 00
kilowatthour (kW-hr)	joule (J)	3.6 E + 06
kip (1000 lbf)	newton (N)	4.448 222 E + 03
kip/in. ² (ksi)	pascal (Pa)	6.894 757 E + 06
knot (international)	meter per second (m/s)	5.144 444 E - 01
lambert	candela per meter ² (cd/m ²)	1/π E + 04
lambert	candela per meter ² (cd/m ²)	3.183 099 E + 03
langley	joule per meter ² (J/m ²)	4.184 E + 04
league	meter (m)	(see Footnote 1)
light year	meter (m)	0.460 55 E + 15
liter ^(b)	meter ³ (m ³)	1.0 E - 03
maxwell	weber (Wb)	1.0 E - 08
rho	siemens (S)	1.0 E + 00
microinch	meter (m)	2.54 E - 08
microsecond/foot (μs/ft)	microsecond/meter (μs/m)	3.280 840 E + 00
micron	meter (m)	1.0 E - 06
mil	meter (m)	2.54 E - 05
mile (international)	meter (m)	1.609 344 E + 03
mile (statute)	meter (m)	1.609 3 E + 03
mile (U.S. survey) ⁽¹⁾	meter (m)	1.609 347 E + 03
mile (international nautical)	meter (m)	1.852 E + 03
mile (U.K. nautical)	meter (m)	1.853 184 E + 03
mile (U.S. nautical)	meter (m)	1.852 E + 03

⁽⁴⁾ This sometimes is called the moment of inertia of a plane section about a specified axis.

⁽⁵⁾ The exact conversion factor is 1.638 706 4 E - 05.

SI METRIC SYSTEM OF UNITS (CONT'D)

To Convert From	To	Multiply By
sq mile (international)	meter ² (m ²)	2.589 988 E + 06
sq mile (U.S. survey) ⁽¹⁾	meter ² (m ²)	2.589 998 E + 06
mile/hr (international)	meter per second (m/s)	4.470 4 E - 01
mile/hr (international)	kilometer per hour (km/h)	1.609 344 E + 00
mile/min (international)	meter per second (m/s)	2.682 24 E + 01
mile/s (international)	meter per second (m/s)	1.609 344 E + 03
millibar	pascal (Pa)	1.0 E + 02
millimeter of mercury (0°C)	pascal (Pa)	1.333 22 E + 02
minute (angle)	radian (rad)	2.908 882 E - 04
minute (mean solar)	second (s)	6.0 E + 01
minute (sidereal)	second (s)	5.983 617 E + 01
month (mean calendar)	second (s)	2.628 000 E + 06
oersted	ampere per meter (A/m)	7.957 747 E + 01
ohm centimeter	ohm meter (Ω·m)	1.0 E - 02
ohm circular-mil per ft	ohm millimeter ² per meter (Ω·mm ² /m)	1.662 426 E - 03
ounce (avoirdupois)	kilogram (kg)	2.834 952 E - 02
ounce (troy or apothecary)	kilogram (kg)	3.110 348 E - 02
ounce (U.K. fluid)	meter ³ (m ³)	2.841 307 E - 05
ounce (U.S. fluid)	meter ³ (m ³)	2.957 353 E - 05
ounce-force	newton (N)	2.780 139 E - 01
oz·in.	newton meter (N·m)	7.061 552 E - 03
oz (avoirdupois)/gal (U.K. liquid)	kilogram per meter ³ (kg/m ³)	6.236 021 E + 00
oz (avoirdupois)/gal (U.S. liquid)	kilogram per meter ³ (kg/m ³)	7.489 152 E + 00
oz (avoirdupois)/in. ³	kilogram per meter ³ (kg/m ³)	1.729 994 E + 03
oz (avoirdupois)/ft ²	kilogram per meter ² (kg/m ²)	3.051 517 E - 01
oz (avoirdupois)/yd ²	kilogram per meter ² (kg/m ²)	3.390 575 E - 02
parsec ⁽²⁾	meter (m)	3.085 678 E + 16
peck (U.S.)	meter ³ (m ³)	8.809 768 E - 03
pennyweight	kilogram (kg)	1.555 174 E - 03
perm (°C) ⁽⁷⁾	kilogram per pascal second meter ² (kg/Pa·s·m ²)	5.721 35 E - 11
perm (23°C) ⁽⁷⁾	kilogram per pascal second meter ² (kg/Pa·s·m ²)	5.745 25 E - 11
perm-in. (0°C) ⁽⁸⁾	kilogram per pascal second meter (kg/Pa·s·m)	1.453 22 E - 12
perm-in. (23°C) ⁽⁸⁾	kilogram per pascal second meter (kg/Pa·s·m)	1.459 29 E - 12
phot	lumen per meter ² (lm/m ²)	1.0 E + 04
pica (printer's)	meter (m)	4.217 518 E - 03
pint (U.S. dry)	meter ³ (m ³)	5.506 105 E - 04
pint (U.S. liquid)	meter ³ (m ³)	4.731 765 E - 04
point (printer's)	meter (m)	3.514 598 E - 04
poise (absolute viscosity)	pascal second (Pa·s)	1.0 E - 01
pound (lbm avoirdupois) ⁽⁹⁾	kilogram (kg)	4.535 924 E - 01
pound (troy or apothecary)	kilogram (kg)	3.732 417 E - 01
lbm·ft ² (moment of inertia)	kilogram meter ² (kg·m ²)	4.214 011 E - 02
lbm·in. ² (moment of inertia)	kilogram meter ² (kg·m ²)	2.926 397 E - 04
lbm/ft·hr	pascal second (Pa·s)	4.133 789 E - 04
lbm/ft·s	pascal second (Pa·s)	1.488 164 E + 00
lbm/ft ²	kilogram per meter ² (kg/m ²)	4.882 428 E + 00
lbm/ft ³	kilogram per meter ³ (kg/m ³)	1.601 846 E + 01
lbm/gal (U.K. liquid)	kilogram per meter ³ (kg/m ³)	9.977 633 E + 01
lbm/gal (U.S. liquid)	kilogram per meter ³ (kg/m ³)	1.198 264 E + 02
lbm/hr	kilogram per second (kg/s)	1.259 979 E - 04
lbm/(hp·hr)	kilogram per second (kg/s)	1.259 979 E - 04
(SFC, specific fuel consumption)	kilogram per joule (kg/J)	1.689 659 E - 07
lbm/in. ³	kilogram per meter ³ (kg/m ³)	2.767 990 E + 04
lbm/min	kilogram per second (kg/s)	7.559 873 E - 03
lbm/s	kilogram per second (kg/s)	4.535 924 E - 01
lbm/yd ³	kilogram per meter ³ (kg/m ³)	5.932 764 E - 01
poundal	newton (N)	1.382 550 E - 01
poundal/ft ²	pascal (Pa)	1.488 164 E + 00
poundal-s/ft ²	pascal second (Pa·s)	1.488 164 E + 00
pound-force (lbf) ⁽¹⁰⁾	newton (N)	4.448 222 E + 00
lbf·ft ⁽¹¹⁾	newton meter (N·m)	1.355 818 E + 00

SI METRIC SYSTEM OF UNITS (CONT'D)

To Convert From	To	Multiply By
lbf-ft/in. ⁽¹²⁾	newton meter per meter (N-m/m)	5.337 866 E + 01
lbf-in. ⁽¹¹⁾	newton meter (N-m)	1.129 848 E - 01
lbf-in./in. ⁽¹²⁾	newton meter per meter (N-m/m)	4.448 222 E + 00
lbf-s/ft ²	pascal second (Pa-s)	4.788 026 E + 01
lbf/ft	newton per meter (N/m)	1.459 390 E + 01
lbf/ft ²	pascal (Pa)	4.788 026 E + 01
lbf/in.	newton per meter (N/m)	1.751 268 E + 02
lbf/in. ² (psi)	pascal (Pa)	6.894 757 E + 03
lbf/lbm (thrust/weight [mass] ratio)	newton per kilogram (N/kg)	9.806 650 E + 00
quart (U.S. dry)	meter ³ (m ³)	1.101 221 E - 03
quart (U.S. liquid)	meter ³ (m ³)	9.463 529 E - 04
rad (radiation dose absorbed)	gray (Gy)	1.0 E - 02
rhe	1 per pascal second (1/Pa-s)	1.0 E + 01
rod	meter (m)	(see Footnote 1)
roentgen	coulomb per kilogram (C/kg)	2.58 E - 04
second (angle)	radian (rad)	4.848 137 E - 06
second (sidereal)	second (s)	9.972 696 E - 01
section	meter ² (m ²)	(see Footnote 1)
shake	second (s)	1.000 000 E - 08
slug	kilogram (kg)	1.459 390 E + 01
slug/(ft-s)	pascal second (Pa-s)	4.788 026 E + 01
slug/ft ³	kilogram per meter ³ (kg/m ³)	5.153 788 E + 02
statampere	ampere (A)	3.335 640 E - 10
statcoulomb	coulomb (C)	3.335 640 E - 10
statfarad	farad (F)	1.112 650 E - 12
stathenry	henry (H)	8.987 554 E + 11
statmho	siemens (S)	1.112 650 E - 12
statohm	ohm (Ω)	8.987 554 E + 11
statvolt	volt (V)	2.997 925 E + 02
stere	meter ³ (m ³)	1.0 E + 00
stilb	candela per meter ² (cd/m ²)	1.0 E + 04
stokes (kinematic viscosity)	meter ² per second (m ² /s)	1.0 E - 04
tablespoon	meter ³ (m ³)	1.478 676 E - 05
teaspoon	meter ³ (m ³)	4.928 922 E - 06
tex	kilogram per meter (kg/m)	1.0 [*] E - 06
therm	joule (J)	1.055 056 E + 08
ton (assay)	kilogram (kg)	2.916 667 E - 02
ton (long, 2,240 lbm)	kilogram (kg)	1.016 047 E + 03
ton (metric)	kilogram (kg)	1.0 E + 03
ton (nuclear equivalent of TNT)	joule (J)	4.184 E + 09 ⁽¹³⁾
ton (refrigeration)	watt (W)	3.516 000 E + 03
ton (register)	meter ³ (m ³)	2.831 685 E + 00
ton (short, 2000 lbm)	kilogram (kg)	9.071 847 E + 02
ton (long)/yd ³	kilogram per meter ³ (kg/m ³)	1.328 939 E + 03
ton (short)/hr	kilogram per second (kg/s)	2.519 958 E - 01
ton-force (2000 lbf)	newton (N)	8.896 444 E + 03
tonno	kilogram (kg)	1.0 E + 03
torr (mm Hg, 0°C)	pascal (Pa)	1.333 22 E + 02
township	meter ² (m ²)	(see Footnote 1)
unit pole	weber (Wb)	1.256 637 E - 07
watthour (W-hr)	joule (J)	3.60 E + 03
W-s	joule (J)	1.0 E + 00
W/cm ²	watt per meter ² (W/m ²)	1.0 E + 04
W/in. ²	watt per meter ² (W/m ²)	1.550 003 E + 03
yard	meter (m)	9.144 E - 01
yd ²	meter ² (m ²)	8.361 274 E - 01
yd ³	meter ³ (m ³)	7.645 549 E - 01
yd ³ /min	meter ³ per second (m ³ /s)	1.274 258 E - 02
year (calendar)	second (s)	3.153 600 E + 07
year (sidereal)	second (s)	3.155 815 E + 07
year (tropical)	second (s)	3.155 693 E + 07

⁽⁹⁾In 1964 the General Conference on Weights and Measures adopted the name liter as a special name for the cubic decimeter. Prior to this decision the liter differed slightly from the previous value, 1.000 028 dm³, and in expression of precision volume measurement this fact must be kept in mind.

⁽¹⁰⁾Not the same as reservoir "perm."

⁽¹¹⁾Not the same dimensions as "millidarcy-foot."

⁽¹²⁾The exact conversion factor is 4.535 923 7 E - 01.

⁽¹³⁾The exact conversion factor is 4.448 221 615 260 5 E + 00.

⁽¹⁴⁾Torque unit; see text discussion of "Energy, Torque, and Bending Moment."

⁽¹⁵⁾Torque divided by length; see text discussion of "Energy, Torque, and Bending Moment."

⁽¹⁶⁾Defined (not measured) value.

SI METRIC SYSTEM OF UNITS (CONT'D)

TABLES OF RECOMMENDED SI UNITS

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit		
			SPE Preferred	Other Allowable			
SPACE,** TIME							
Length	m	naut mile	km		1.852*	E + 00	
		mile	km		1.609 344*	E + 00	
		chain	m		2.011 68*	E + 01	
		link	m		2.011 68*	E - 01	
		fathom	m		1.828 8*	E + 00	
		m	m		1.0*	E + 00	
		yd	m		9.144*	E - 01	
		ft	m		3.048*	E - 01	
				cm	3.048*	E + 01	
		in.	mm		2.54*	E + 01	
				cm	2.54*	E + 00	
		cm	mm		1.0*	E + 01	
				cm	1.0*	E + 00	
		mm	mm		1.0*	E + 00	
		mil	μm		2.54*	E + 01	
		micron (μ)	μm		1.0*	E + 00	
Length/length	m/m	ft/mi	m/km		1.893 939	E - 01	
Length/volume	m/m ³	ft/U.S. gal	m/m ³		8.051 964	E + 01	
		ft/ft ³	m/m ³		1.076 391	E + 01	
		ft/bbl	m/m ³		1.917 134	E + 00	
Length/temperature	m/K	see "Temperature, Pressure, Vacuum"					
Area	m ²	sq mile	km ²		2.589 988	E + 00	
		section	km ²		2.589 988	E + 00	
				ha	2.589 988	E + 02	
		acre	m ²		4.046 856	E + 03	
				ha	4.046 856	E - 01	
		ha	m ²		1.0*	E + 04	
		sq yd	m ²		8.361 274	E - 01	
		sq ft	m ²		9.290 304*	E - 02	
				cm ²	9.290 304*	E + 02	
		sq in.	mm ²		6.451 6*	E + 02	
				cm ²	6.451 6*	E + 00	
		cm ²	mm ²		1.0*	E + 02	
cm ²	1.0*			E + 00			
mm ²	mm ²		1.0*	E + 00			
Area/volume	m ² /m ³	ft ² /in. ³	m ² /cm ³		5.699 291	E - 03	
Area/mass	m ² /kg	cm ² /g	m ² /kg		1.0*	E - 01	
			m ² /g		1.0*	E - 04	
Volume, capacity	m ³	cubem	km ³		4.168 182	E + 00	
		acre-ft	m ³		1.233 489	E + 03	
				ha·m	1.233 489	E - 01	
		m ³	m ³		1.0*	E + 00	
		cu yd	m ³		7.645 549	E - 01	
		bbl (42 U.S. gal)	m ³		1.589 873	E - 01	
		cu ft	m ³		2.831 685	E - 02	
				L	2.831 685	E + 01	
		U.K. gal	m ³		4.546 092	E - 03	
				L	4.546 092	E + 00	
				dm ³			
				dm ³			

*An asterisk indicates that the conversion factor is exact.

**Conversion factors for length, area, and volume (and related quantities) in Table 2.2 are based on the international foot.

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit			
			SPE Preferred	Other Allowable				
SPACE,** TIME								
Volume, capacity	m ³	U.S. gal	m ³		3.785 412	E - 03		
			dm ³	L	3.785 412	E + 00		
		liter	dm ³	L	1.0*	E + 00		
		U.K. qt	dm ³	L	1.136 523	E + 00		
		U.S. qt	dm ³	L	9.463 529	E - 01		
		U.S. pt	dm ³	L	4.731 765	E - 01		
		U.K. fl oz	cm ³		2.841 308	E + 01		
		U.S. fl oz	cm ³		2.957 353	E + 01		
		cu in.	cm ³		1.638 706	E + 01		
Volume/length (linear displacement)	m ³ /m	mL	cm ³		1.0*	E + 00		
		bbl/in.	m ³ /m		6.259 342	E + 00		
		bbl/ft	m ³ /m		5.216 119	E - 01		
		ft ³ /ft	m ³ /m		9.290 304*	E - 02		
		U.S. gal/ft	m ³ /m		1.241 933	E - 02		
		dm ³ /m	L/m	1.241 933	E + 01			
Volume/mass	m ³ /kg	see "Density, Specific Volume, Concentration, Dosage"						
Plane angle	rad	rad	rad		1.0*	E + 00		
		deg (°)	rad		1.745 329	E - 02		
				°	1.0*	E + 00		
		min (')	rad		2.908 882	E - 04		
				'	1.0*	E + 00		
Solid angle	sr	sec (")	rad		4.848 137	E - 06		
				"	1.0*	E + 00		
Solid angle	sr	sr	sr		1.0*	E + 00		
Time	s	million years (MY)	Ma		1.0*	E + 00		
		yr	a		1.0*	E + 00		
		wk	d		7.0*	E + 00		
		d	d		1.0*	E + 00		
		hr	h		1.0*	E + 00		
				min	6.0*	E + 01		
		min	s		6.0*	E + 01		
				h	1.666 667	E - 02		
				min	1.0*	E + 00		
		s	s		1.0*	E + 00		
millimicrosecond	ns		1.0*	E + 00				
MASS, AMOUNT OF SUBSTANCE								
Mass	kg	U.K. ton (long ton)	Mg	t	1.010 047	E + 00		
		U.S. ton (short ton)	Mg	t	9.071 847	E - 01		
		U.K. ton	kg		5.080 235	E + 01		
		U.S. cwt	kg		4.535 924	E + 01		
		kg	kg		1.0*	E + 00		
		lbm	kg		4.535 924	E - 01		
		oz (troy)	g		3.110 348	E + 01		
		oz (av)	g		2.834 952	E + 01		
		g	g		1.0*	E + 00		
		grain	mg		6.479 891	E + 01		
		mg	mg		1.0*	E + 00		
		g	g		1.0*	E + 00		
		Mass/length	kg/m	see "Mechanics"				
		Mass/area	kg/m ²	see "Mechanics"				

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit		
			SPE Preferred	Other Allowable			
Mass/volume	kg/m ³	see "Density, Specific Volume, Concentration, Dosage"					
Mass/mass	kg/kg	see "Density, Specific Volume, Concentration, Dosage"					
Amount of substance	mol	lbm mol	kmol		4.535 924	E - 01	
		g mol	kmol		1.0*	E - 03	
		std m ³ (0°C, 1 atm)	kmol		4.461 58	E - 02	
		std m ³ (15°C, 1 atm)	kmol		4.229 32	E - 02	
		std ft ³ (60°F, 1 atm)	kmol		1.195 3	E - 03	
CALORIFIC VALUE, HEAT, ENTROPY, HEAT CAPACITY							
Calorific value (mass basis)	J/kg	Btu/lbm	MJ/kg		2.326	E - 03	
			kJ/kg	J/g	2.326	E + 00	
				kW-h/kg	6.461 112	E - 04	
		cal/g	kJ/kg	J/g	4.184*	E + 00	
		cal/lbm	J/kg		9.224 141	E + 00	
Calorific value (mole basis)	J/mol	kcal/g mol	kJ/kmol		4.184*	E + 03	
		Btu/lbm mol	MJ/kmol		2.326	E - 03	
			kJ/kmol		2.326	E + 00	
Calorific value (volume basis — solids and liquids)	J/m ³	therm/U.K. gal	MJ/m ³	kJ/dm ³	2.320 80	E + 04	
			kJ/m ³		2.320 80	E + 07	
				kW-h/dm ³	6.446 660	E + 00	
		Btu/U.S. gal	MJ/m ³	kJ/dm ³	2.787 163	E - 01	
			kJ/m ³		2.787 163	E + 02	
				kW-h/m ³	7.742 119	E - 02	
		Btu/U.K. gal	MJ/m ³	kJ/dm ³	2.320 8	E - 01	
			kJ/m ³		2.320 8	E + 02	
				kW-h/m ³	6.446 660	E - 02	
		Btu/ft ³	MJ/m ³	kJ/dm ³	3.725 895	E - 02	
			kJ/m ³		3.725 895	E + 01	
				kW-h/m ³	1.034 971	E - 02	
		kcal/m ³	MJ/m ³	kJ/dm ³	4.184*	E - 03	
			kJ/m ³		4.184*	E + 00	
Calorific value (volume basis — gases)	J/m ³	cal/mL	MJ/m ³		4.184*	E + 00	
		ft-lbf/U.S. gal	kJ/m ³		3.581 692	E - 01	
		cal/mL	kJ/m ³	J/dm ³	4.184*	E + 03	
		kcal/m ³	kJ/m ³	J/dm ³	4.184*	E + 00	
		Btu/ft ³	kJ/m ³	J/dm ³	3.725 895	E + 01	
			kW-h/m ³	1.034 971	E - 02		
Specific entropy	J/kg·K	Btu/(lbm·°R)	kJ/(kg·K)	J/g·K	4.186 8*	E + 00	
		cal/(g·°K)	kJ/(kg·K)	J/g·K	4.184*	E + 00	
		kcal/(kg·°C)	kJ/(kg·K)	J/g·K	4.184*	E + 00	
Specific heat capacity (mass basis)	J/kg·K	kW-hr/(kg·°C)	kJ/(kg·K)	J/g·K	3.6*	E + 03	
		Btu/(lbm·°F)	kJ/(kg·K)	J/g·K	4.186 8*	E + 00	
		kcal/(kg·°C)	kJ/(kg·K)	J/g·K	4.184*	E + 00	
Molar heat capacity	J/mol·K	Btu/(lbm mol·°F)	kJ/(kmol·K)		4.186 8*	E + 00	
		cal/(g mol·°C)	kJ/(kmol·K)		4.184*	E - 00	
TEMPERATURE, PRESSURE, VACUUM							
Temperature (absolute)	K	°R	K		5/9		
		°K	K		1.0*	E + 00	
Temperature (traditional)	K	°F	°C		(°F - 32)/1.8		
		°C	°C		1.0*	E + 00	
Temperature (difference)	K	°F	°C		5/9	E + 00	
		°C	°C		1.0*	E + 00	
Temperature/length (geothermal gradient)	K/m	°F/100 ft	mK/m		1.822 689	E + 01	

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit	
			SPE Preferred	Other Allowable		
TEMPERATURE, PRESSURE, VACUUM						
Length/temperature (geothermal step)	m/K	ft/°F	m/K		5.486 4°	E - 01
Pressure	Pa	atm (760mm Hg at 0°C or 14.696 (lbf/in. ²)	MPa		1.013 25°	E - 01
			kPa		1.013 25°	E + 02
				bar	1.013 25°	E + 00
		bar	MPa		1.0°	E - 01
			kPa		1.0°	E + 02
				bar	1.0°	E + 00
		at (technical atm., kgf/cm ²)	MPa		9.806 65°	E - 02
			kPa		9.806 65°	E + 01
	bar		9.806 65°	E - 01		
Pressure	Pa	lbf/in. ² (psi)	MPa		6.894 757	E - 03
			kPa		6.894 757	E + 00
				bar	6.894 757	E - 02
		in. Hg (32°F)	kPa		3.386 38	E + 00
		in. Hg (60°F)	kPa		3.376 85	E + 00
		in. H ₂ O (39.2°F)	kPa		2.490 82	E - 01
		in. H ₂ O (60°F)	kPa		2.488 4	E - 01
		mm Hg (0°C) = torr	kPa		1.333 224	E - 01
		cm H ₂ O (4°C)	kPa		9.806 38	E - 02
		lbf/ft ² (psf)	kPa		4.788 026	E - 02
		μm Hg (0°C)	Pa		1.333 224	E - 01
		μbar	Pa		1.0°	E - 01
		dyne/cm ²	Pa		1.0°	E - 01
		Vacuum, draft	Pa	in. Hg (60°F)	kPa	
in. H ₂ O (39.2°F)	kPa				2.490 82	E - 01
in. H ₂ O (60°F)	kPa				2.488 4	E - 01
mm Hg (0°C) = torr	kPa				1.333 224	E - 01
cm H ₂ O (4°C)	kPa				9.806 38	E - 02
Liquid head	m	ft	m		3.048°	E - 01
		in.	mm		2.54°	E + 01
				cm	2.54°	E + 00
Pressure drop/length	Pa/m	psi/ft	kPa/m		2.262 059	E + 01
		psi/100 ft	kPa/m		2.262 059	E - 01
DENSITY, SPECIFIC VOLUME, CONCENTRATION, DOSAGE						
Density (gases)	kg/m ³	lbm/ft ³	kg/m ³		1.601 846	E + 01
			g/m ³		1.601 846	E + 04
Density (liquids)	kg/m ³	lbm/U.S. gal	kg/m ³		1.198 264	E + 02
				g/cm ³	1.198 264	E - 01
		lbm/U.K. gal	kg/m ³		9.977 633	E + 01
				kg/dm ³	9.977 633	E - 02
		lbm/ft ³	kg/m ³		1.601 846	E + 01
				g/cm ³	1.601 846	E - 02
		g/cm ³	kg/m ³		1.0°	E + 03
				kg/dm ³	1.0°	E + 00
		°API	g/cm ³		141.5/(131.5 + °API)	
Density (solids)	kg/m ³	lbm/ft ³	kg/m ³		1.601 846	E + 01
Specific volume (gases)	m ³ /kg	ft ³ /lbm	m ³ /kg		6.242 796	E - 02
			m ³ /g		6.242 796	E - 05
Specific volume (liquids)	m ³ /kg	ft ³ /lbm	dm ³ /kg		6.242 796	E + 01
		U.K. gal/lbm	dm ³ /kg	cm ³ /g	1.002 242	E + 01
		U.S. gal/lbm	dm ³ /kg	cm ³ /g	8.345 404	E + 00

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit			
			SPE Preferred	Other Allowable				
DENSITY, SPECIFIC VOLUME, CONCENTRATION, DOSAGE								
Specific volume (mole basis)	m³/mol	L/g mol	m³/kmol		1.0*	E + 00 ¹³		
		ft³/lbm mol	m³/kmol		6.242 796	E - 02 ¹³		
Specific volume (clay yield)	m³/kg	bbl/U.S. ton	m³/t		1.752 535	E - 01		
		bbl/U.K. ton	m³/t		1.564 763	E - 01		
Yield (shale distillation)	m³/kg	bbl/U.S. ton	dm³/t	L/t	1.752 535	E + 02		
		bbl/U.K. ton	dm³/t	L/t	1.564 763	E + 02		
		U.S. gal/U.S. ton	dm³/t	L/t	4.172 702	E + 00		
		U.S. gal/U.K. ton	dm³/t	L/t	3.725 627	E + 00		
Concentration (mass/mass)	kg/kg	wt %	kg/kg		1.0*	E - 02		
			g/kg		1.0*	E + 01		
		wt ppm	mg/kg		1.0*	E + 00		
Concentration (mass/volume)	kg/m³	lbm/bbl	kg/m³	g/dm³	2.853 010	E + 00		
		g/U.S. gal	kg/m³		2.641 720	E - 01		
		g/U.K. gal	kg/m³	g/L	2.199 692	E - 01		
Concentration (mass/volume)	kg/m³	lbm/1000 U.S. gal	g/m³	mg/dm³	1.198 264	E + 02		
		lbm/1000 U.K. gal	g/m³	mg/dm³	9.977 633	E + 01		
		grains/U.S. gal	g/m³	mg/dm³	1.711 806	E + 01		
		grains/ft³	mg/m³		2.288 352	E + 03		
		lbm/1000 bbl	g/m³	mg/dm³	2.853 010	E + 00		
		mg/U.S. gal	g/m³	mg/dm³	2.641 720	E - 01		
		grains/100 ft³	mg/m³		2.288 352	E + 01		
		Concentration (volume/volume)	m³/m³	bbl/bbl	m³/m³		1.0*	E + 00
				ft³/ft³	m³/m³		1.0*	E + 00
bbl/acre-ft	m³/m³				1.288 923	E - 04		
				m³/ha-m	1.288 923	E + 00		
vol %	m³/m³				1.0*	E - 02		
U.K. gal/ft³	dm³/m³			L/m³	1.605 437	E + 02		
U.S. gal/ft³	dm³/m³			L/m³	1.336 806	E + 02		
mL/U.S. gal	dm³/m³			L/m³	2.641 720	E - 01		
mL/U.K. gal	dm³/m³			L/m³	2.199 692	E - 01		
vol ppm	cm³/m³				1.0*	E + 00		
	dm³/m³	L/m³	1.0*	E - 03				
		U.K. gal/1000 bbl	cm³/m³		2.859 406	E + 01		
		U.S. gal/1000 bbl	cm³/m³		2.380 952	E + 01		
		U.K. pt/1000 bbl	cm³/m³		3.574 253	E + 00		
		lbm mol/U.S. gal	kmol/m³		1.198 264	E + 02		
		lbm mol/U.K. gal	kmol/m³		9.977 633	E + 01		
Concentration (mole/volume)	mol/m³	lbm mol/ft³	kmol/m³		1.601 846	E + 01		
		std ft³ (60°F, 1 atm)/bbl	kmol/m³		7.518 18	E - 03		
		Concentration (volume/mole)	m³/mol	U.S. gal/1000 std ft³ (60°F/60°F)	dm³/kmol	L/kmol	3.166 93	E + 00
bbl/million std ft³ (60°F/60°F)	dm³/kmol			L/kmol	1.330 11	E - 01		
FACILITY THROUGHPUT, CAPACITY								
Throughput (mass basis)	kg/s	million lbm/yr	t/a	Mg/a	4.535 924	E + 02		
		U.K. ton/yr	t/a	Mg/a	1.016 047	E + 00		
		U.S. ton/yr	t/a	Mg/a	9.071 847	E - 01		
		U.K. ton/D	t/d	Mg/d	1.016 047	E + 00		
				t/h, Mg/h	4.233 529	E - 02		

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit	Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit		
		SPE Preferred	Other Allowable			
FACILITY THROUGHPUT, CAPACITY						
Throughput (volume basis)	m ³ /s	U.S. ton/D	t/d	9.071 847	E - 01	
			t/h, Mg/h	3.779 936	E - 02	
		U.K. ton/hr	t/h	1.016 047	E + 00	
		U.S. ton/hr	t/h	9.071 847	E - 01	
		lbm/hr	kg/h	4.535 924	E - 01	
		bbl/D	t/a	5.803 036	E + 01	
			m ³ /d	1.589 873	E - 01	
			m ³ /h	6.624 471	E - 03	
		ft ³ /D	m ³ /h	1.179 869	E - 03	
			m ³ /d	2.831 685	E - 02	
		bbl/hr	m ³ /h	1.589 873	E - 01	
		ft ³ /h	m ³ /h	2.831 685	E - 02	
		U.K. gal/hr	m ³ /h	4.546 092	E - 03	
			L/s	1.262 803	E - 03	
		U.S. gal/hr	m ³ /h	3.785 412	E - 03	
			L/s	1.051 503	E - 03	
			U.K. gal/min	m ³ /h	2.727 655	E - 01
				L/s	7.576 819	E - 02
	U.S. gal/min	m ³ /h	2.271 247	E - 01		
		L/s	6.309 020	E - 02		
Throughput (mole basis)	mol/s	lbm mol/hr	kmol/h	4.535 924	E - 01	
			kmol/s	1.259 979	E - 04	

FLOW RATE					
Pipeline capacity	m ³ /m	bbl/mile	m ³ /km	9.879 013	E - 02
Flow rate (mass basis)	kg/s	U.K. ton/min	kg/s	1.693 412	E + 01
		U.S. ton/min	kg/s	1.511 974	E + 01
		U.K. ton/hr	kg/s	2.822 353	E - 01
		U.S. ton/hr	kg/s	2.519 958	E - 01
		U.K. ton/D	kg/s	1.175 980	E - 02
		U.S. ton/D	kg/s	1.049 982	E - 02
		million lbm/yr	kg/s	5.249 912	E + 00
		U.K. ton/yr	kg/s	3.221 864	E - 05
		U.S. ton/yr	kg/s	2.876 664	E - 05
		lbm/s	kg/s	4.535 924	E - 01
		lbm/min	kg/s	7.559 873	E - 03
		lbm/hr	kg/s	1.259 979	E - 04
Flow rate (volume basis)	m ³ /s	bbl/D	m ³ /d	1.589 873	E - 01
			L/s	1.840 131	E - 03
		ft ³ /D	m ³ /d	2.831 685	E - 02
			L/s	3.277 413	E - 04
		bbl/hr	m ³ /s	4.416 314	E - 05
			L/s	4.416 314	E - 02
		ft ³ /hr	m ³ /s	7.865 791	E - 06
			L/s	7.865 791	E - 03
		U.K. gal/hr	dm ³ /s	1.262 803	E - 03
		U.S. gal/hr	dm ³ /s	1.051 503	E - 03
		U.K. gal/min	dm ³ /s	7.576 820	E - 02
		U.S. gal/min	dm ³ /s	6.309 020	E - 02
		ft ³ /min	dm ³ /s	4.719 474	E - 01
		ft ³ /s	dm ³ /s	2.831 685	E + 01

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit	
			SPE Preferred	Other Allowable		
Flow rate (mole basis)	mol/s	lbm mol/s	kmol/s		4.535 924	E - 01
		lbm mol/hr	kmol/s		1.259 979	E - 04
		million scf/D	kmol/s		1.383 449	E - 02
Flow rate/length (mass basis)	kg/s-m	lbm/(s-ft)	kg/(s-m)		1.488 164	E + 00
		lbm/(hr-ft)	kg/(s-m)		4.133 789	E - 04
Flow rate/length (volume basis)	m³/s	U.K. gal/(min-ft)	m³/s	m³/(s-m)	2.485 833	E - 04
		U.S. gal/(min-ft)	m³/s	m³/(s-m)	2.069 888	E - 04
		U.K. gal/(hr-in.)	m³/s	m³/(s-m)	4.971 667	E - 05
		U.S. gal/(hr-in.)	m³/s	m³/(s-m)	4.139 776	E - 05
		U.K. gal/(hr-ft)	m³/s	m³/(s-m)	4.143 055	E - 06
		U.S. gal/(hr-ft)	m³/s	m³/(s-m)	3.449 814	E - 06
Flow rate/area (mass basis)	kg/s-m²	lbm/(s-ft²)	kg/s-m²		4.882 428	E + 00
		lbm/(hr-ft²)	kg/s-m²		1.356 230	E - 03
Flow rate/area (volume basis)	m/s	ft³/(s-ft²)	m/s	m³(s-m²)	3.048*	E - 01
		ft³/(min-ft²)	m/s	m³/(s-m²)	5.08*	E - 03
		U.K. gal/(hr-in.²)	m/s	m³/(s-m²)	1.957 349	E - 03
		U.S. gal/(hr-in.²)	m/s	m³/(s-m²)	1.629 833	E - 03
		U.K. gal/(min-ft²)	m/s	m³/(s-m²)	8.155 621	E - 04
		U.S. gal/(min-ft²)	m/s	m³/(s-m²)	6.790 972	E - 04
		U.K. gal/(hr-ft²)	m/s	m³/(s-m²)	1.359 270	E - 05
		U.S. gal/(hr-ft²)	m/s	m³/(s-m²)	1.131 829	E - 05
Flow rate/ pressure drop (productivity index)	m³/s-Pa	bbl/(D-psi)	m³/(d-kPa)		2.305 916	E - 02

ENERGY, WORK, POWER

Energy, work	J	quad	MJ		1.055 056	E + 12
			TJ		1.055 056	E + 06
			EJ		1.055 056	E + 00
		therm		MW-h	2.930 711	E + 08
				GW-h	2.930 711	E + 05
				TW-h	2.930 711	E + 02
			MJ		1.055 056	E + 02
			kJ		1.055 056	E + 05
				kW-h	2.930 711	E + 01
		U.S. tonf-mile	MJ		1.431 744	E + 01
		hp-hr	MJ		2.684 520	E + 00
			kJ		2.684 520	E + 03
				kW-h	7.456 999	E - 01
		ch-hr or CV-hr	MJ		2.647 796	E + 00
			kJ		2.647 796	E + 03
				kW-h	7.354 99	E - 01
		kW-hr	MJ		3.6*	E + 00
			kJ		3.6*	E + 03
		Chu	kJ		1.899 101	E + 00
				kW-h	5.275 280	E - 04
		Btu	kJ		1.055 056	E + 00
				kW-h	2.930 711	E - 04
		kcal	kJ		4.184*	E + 00
		cal	kJ		4.184*	E - 03
		ft-lbf	kJ		1.355 818	E - 03
		lbf-ft	kJ		1.355 818	E - 03
		J	kJ		1.0*	E - 03
		lbf-ft²/s²	kJ		4.214 011	E - 05
		erg	J		1.0*	E - 07

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit	Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit		
		SPE Preferred	Other Allowable			
ENERGY, WORK, POWER						
Impact energy	J	kgf-m	J	9.806 650*	E + 00	
		lbf-ft	J	1.355 818	E + 00	
Work/length	J/m	U.S. tonf-mile/ft	MJ/m	4.697 322	E + 01	
Surface energy	J/m ²	erg/cm ²	mJ/m ²	1.0*	E + 00	
Specific impact energy	J/m ²	kgf-m/cm ²	J/cm ²	9.806 650*	E - 00	
		lbf-ft/in. ²	J/cm ²	2.101 522	E - 01	
Power	W	quad/yr	MJ/a	1.055 056	E + 12	
			TJ/a	1.055 056	E + 06	
			EJ/a	1.055 056	E + 00	
		erg/a	TW	3.170 979	E - 27	
			GW	3.170 979	E - 24	
		million Btu/hr	MW	2.930 711	E - 01	
		ton of refrigeration	kW	3.516 853	E + 00	
		Btu/s	kW	1.055 056	E + 00	
		kW	kW	1.0*	E + 00	
		hydraulic horse-power — hhp	kW	7.460 43	E - 01	
		hp (electric)	kW	7.46*	E - 01	
		hp (550 ft-lbf/s)	kW	7.456 999	E - 01	
		ch or CV	kW	7.354 99	E - 01	
		Btu/min	kW	1.758 427	E - 02	
		ft-lbf/s	kW	1.355 818	E - 03	
		kcal/hr	W	1.162 222	E + 00	
		Btu/hr	W	2.930 711	E - 01	
		ft-lbf/min	W	2.259 697	E - 02	
Power/area	W/m ²	Btu/s-ft ²	kW/m ²	1.135 653	E + 01	
		cal/hr-cm ²	kW/m ²	1.162 222	E - 02	
		Btu/hr-ft ²	kW/m ²	3.154 591	E - 03	
Heat flow unit — hfu (geothermics)		μcal/s-cm ²	mW/m ²	4.184*	E + 01	
Heat release rate, mixing power	W/m ³	hp/ft ³	kW/m ³	2.633 414	E + 01	
		cal/hr-cm ³	kW/m ³	1.162 222	E + 00	
		Btu/s-ft ³	kW/m ³	3.725 895	E + 01	
		Btu/hr-ft ³	kW/m ³	1.034 971	E - 02	
Heat generation unit — hgu (radioactive rocks)		cal/(s-cm ³)	μW/m ³	4.184*	E + 12	
Cooling duty (machinery)	W/W	Btu/(bhp-hr)	W/kW	3.930 148	E - 01	
Specific fuel consumption (mass basis)	kg/J	lbm/(hp-hr)	mg/J	1.689 659	E - 01	
			kg/MJ kg/kW-h	6.092 774	E - 01	
Specific fuel consumption (volume basis)	m ³ /J	m ³ /(kW-hr)	dm ³ /MJ	2.777 778	E + 02	
			mm ³ /J dm ³ /kW-h	1.0*	E + 03	
		U.S. gal/(hp-hr)	dm ³ /MJ	1.410 089	E + 00	
			mm ³ /J dm ³ /kW-h	5.076 321	E + 00	
Fuel consumption (automotive)	m ³ /m	U.K. pt/(hp-hr)	dm ³ /MJ	2.116 809	E - 01	
			mm ³ /J dm ³ /kW-h	7.620 512	E - 01	
		U.K. gal/mile	dm ³ /100 km	L/100 km	2.824 811	E + 02
		U.S. gal/mile	dm ³ /100 km	L/100 km	2.352 146	E + 02
		mile/U.S. gal	km/dm ³	km/L	4.251 437	E - 01
		mile/U.K. gal	km/dm ³	km/L	3.540 060	E - 01

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit	
			SPE Preferred	Other Allowable		
MECHANICS						
Velocity (linear), speed	m/s	knot	km/h		1.852*	E + 00
		mile/hr	km/h		1.609 344*	E + 00
		m/s	m/s		1.0*	E + 00
		ft/s	m/s		3.048*	E - 01
				cm/s	3.048*	E + 01
				m/ms	3.048*	E - 04
		ft/min	m/s		5.08*	E - 03
				cm/s	5.08*	E - 01
		ft/hr	mm/s		8.466 667	E - 02
				cm/s	8.466 667	E - 03
		ft/D	mm/s		3.527 778	E - 03
				m/d	3.048*	E - 01
		in./s	mm/s		2.54*	E + 01
				cm/s	2.54*	E + 00
		in./min	mm/s		4.233 333	E - 01
				cm/s	4.233 333	E - 02
Velocity (angular)	rad/s	rev/min	rad/s		1.047 198	E - 01
		rev/s	rad/s		6.283 185	E + 00
		degree/min	rad/s		2.908 882	E - 04
Reciprocal velocity	s/m	s/ft	s/m		3.280 840	E + 00
Corrosion rate	m/s	in./yr (ipy)	mm/a		2.54*	E + 01
		mil/yr	mm/a		2.54*	E - 02
Rotational frequency	rev/s	rev/s	rev/s		1.0*	E + 00
		rev/min	rev/s		1.666 667	E - 02
		rev/min	rad/s		1.047 198	E - 01
Acceleration (linear)	m/s ²	ft/s ²	m/s ²		3.048*	E - 01
				cm/s ²	3.048*	E + 01
		gal(cm/s ²)	m/s ²		1.0*	E - 02
Acceleration (rotational)	rad/s ²	rad/s ²	rad/s ²		1.0*	E + 00
		rpm/s	rad/s ²		1.047 198	E - 01
Momentum	kg-m/s	lbm-ft/s	kg-m/s		1.382 550	E - 01
Force	N	U.K. tonf	kN		9.964 016	E + 00
		U.S. tonf	kN		8.896 443	E + 00
		kgf (kp)	N		9.806 650*	E + 00
		lbf	N		4.448 222	E + 00
		N	N		1.0*	E + 00
		pdl	mN		1.382 550	E + 02
		dyne	mN		1.0*	E - 02
Bending moment, torque	N-m	U.S. tonf-ft	kN-m		2.711 636	E + 00
		kgf-m	N-m		9.806 650*	E + 00
		lbf-ft	N-m		1.355 818	E + 00
		lbf-in.	N-m		1.129 848	E - 01
		pdl-ft	N-m		4.214 011	E - 02
Bending moment/length	N-m/m	(lbf-ft)/in.	(N-m)/m		5.337 866	E + 01
		(kgf-m)/m	(N-m)/m		9.806 650*	E + 00
		(lbf-in.)/in.	(N-m)/m		4.448 222	E + 00
Elastic moduli (Young's, Shear bulk)	Pa	lbf/in. ²	GPa		6.894 757	E - 06
Moment of inertia	kg-m ²	lbm-ft ²	kg-m ²		4.214 011	E - 02
Moment of section	m ⁴	in. ⁴	cm ⁴		4.162 314	E + 01
Section modulus	m ³	cu in.	cm ³		1.638 706	E + 01
		cu ft	cm ³		1 638 706	E + 04

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit	
			SPE Preferred	Other Allowable		
MECHANICS						
				mm ³ m ³	2.831 685 2.831 685	E + 04 E - 02
Stress	Pa	U.S. tonf/in. ²	MPa	N/mm ²	1.378 951	E + 01
		kgf/mm ²	MPa	N/mm ²	9.806 650*	E + 00
		U.S. tonf/ft ²	MPa	N/mm ²	9.576 052	E - 02
		lbf/in. ² (psi)	MPa	N/mm ²	6.894 757	E - 03
		lbf/ft ² (psf)	kPa		4.788 026	E - 02
		dyne/cm ²	Pa		1.0*	E - 01
Yield point, gel strength (drilling fluid)		lbf/100 ft ²	Pa		4.788 026	E - 01
Mass/length	kg/m	lbm/ft	kg/m		1.488 164	E + 00
Mass/area structural loading, bearing capacity (mass basis)	kg/m ²	U.S. ton/ft ²	Mg/m ²		9.764 855	E + 00
		lbm/ft ²	kg/m ²		4.882 428	E + 00
Coefficient of thermal expansion	m/(m·K)	in./(in.·°F)	mm/(mm·K)		5.555 556	E - 01
TRANSPORT PROPERTIES						
Diffusivity	m ² /s	ft ² /s	mm ² /s		9.290 304*	E + 04
		cm ² /s	mm ² /s		1.0*	E + 02
		ft ² /hr	mm ² /s		2.580 64*	E + 01
Thermal resistance	K·m ² /W	(°C·m ² ·hr)/kcal	(K·m ²)/kW		8.604 208	E + 02
		(°F·ft ² ·hr)/Btu	(K·m ²)/kW		1.761 102	E + 02
Heat flux	W/m ²	Btu/(hr·ft ²)	kW/m ²		3.154 591	E - 03
Thermal conductivity	W/m·K	(cal/s·cm ² ·°C)/cm	W/(m·K)		4.184*	E + 02
		Btu/(hr·ft ² ·°F/ft)	W/(m·K)		1.730 735	E + 00
				kJ·m/(h·m ² ·K)	6.230 646	E + 00
		kcal/(hr·m ² ·°C/m)	W/(m·K)		1.162 222	E + 00
		Btu/(hr·ft ² ·°F/in.)	W/(m·K)		1.442 279	E - 01
		cal/(hr·cm ² ·°C/cm)	W/(m·K)		1.162 222	E - 01
Heat transfer coefficient	W/m ² ·K	cal/(s·cm ² ·°C)	kW/(m ² ·K)		4.184*	E + 01
		Btu/(s·ft ² ·°F)	kW/(m ² ·K)		2.044 175	E + 01
		cal/(hr·cm ² ·°C)	kW/(m ² ·K)		1.162 222	E - 02
		Btu/(hr·ft ² ·°F)	kW/(m ² ·K)		5.678 263	E - 03
				kJ/(h·m ² ·K)	2.044 175	E + 01
		Btu/(hr·ft ² ·°R)	kW/(m ² ·K)		5.678 263	E - 03
Volumetric heat transfer coefficient	W/m ³ ·K	kcal/(hr·m ² ·°C)	kW/(m ² ·K)		1.162 222	E - 03
		Btu/(s·ft ² ·°F)	kW/(m ³ ·K)		6.706 611	E + 01
		Btu/(hr·ft ³ ·°F)	kW/(m ³ ·K)		1.862 947	E - 02
Surface tension	N/m	dyne/cm	mN/m		1.0*	E + 00
Viscosity (dynamic)	Pa·s	(lbf·s)/in. ²	Pa·s	(N·s)/m ²	6.894 757	E + 03
		(lbf·s)/ft ²	Pa·s	(N·s)/m ²	4.788 026	E + 01
		(kgf·s)/m ²	Pa·s	(N·s)/m ²	9.806 650*	E + 00
		lbm/(ft·s)	Pa·s	(N·s)/m ²	1.488 164	E + 00
		(dyne·s)/cm ²	Pa·s	(N·s)/m ²	1.0*	E - 01
		cp	Pa·s	(N·s)/m ²	1.0*	E - 03
		lbm/(ft·hr)	Pa·s	(N·s)/m ²	4.133 789	E - 04
Viscosity (kinematic)	m ² /s	ft ² /s	mm ² /s		9.290 304*	E + 04
		in. ² /s	mm ² /s		6.451 6*	E + 02

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit
			SPE Preferred	Other Allowable	
TRANSPORT PROPERTIES					
		m ² /hr	mm ² /s	2.777 778	E + 02
		cm ² /s	mm ² /s	1.0*	E + 02
		ft ² /hr	mm ² /s	2.580 64*	E + 01
		cSt	mm ² /s	1.0*	E + 00
Permeability	m ²	darcy	μm ²	9.869 233	E - 01
		millidarcy	μm ²	9.869 233	E - 04
			10 ⁻³ μm ²	9.869 233	E - 01
ELECTRICITY, MAGNETISM					
Admittance	S	S	S	1.0*	E + 00
Capacitance	F	μF	μF	1.0*	E + 00
Capacity, storage battery	C	A-hr	kC	3.6*	E + 00
Charge density	C/m ³	C/mm ³	C/mm ³	1.0*	E + 00
Conductance	S	S	S	1.0*	E + 00
		℧ (mho)	S	1.0*	E + 00
Conductivity	S/m	S/m	S/m	1.0*	E + 00
		℧ /m	S/m	1.0*	E + 00
		m℧ /m	mS/m	1.0*	E + 00
Current density	A/m ²	A/mm ²	A/mm ²	1.0*	E + 00
Displacement	C/m ²	C/cm ²	C/cm ²	1.0*	E + 00
Electric charge	C	C	C	1.0*	E + 00
Electric current	A	A	A	1.0*	E + 00
Electric dipole moment	C·m	C·m	C·m	1.0*	E + 00
Electric field strength	V/m	V/m	V/m	1.0*	E + 00
Electric flux	C	C	C	1.0*	E + 00
Electric polarization	C/m ²	C/cm ²	C/cm ²	1.0*	E + 00
Electric potential	V	V	V	1.0*	E + 00
		mV	mV	1.0*	E + 00
Electromagnetic moment	A·m ²	A·m ²	A·m ²	1.0*	E + 00
Electromotive force	V	V	V	1.0*	E + 00
Flux of displacement	C	C	C	1.0*	E + 00
Frequency	Hz	cycles/s	Hz	1.0*	E + 00
Impedance	Ω	Ω	Ω	1.0*	E + 00
Interval transit time	s/m	μs/ft	μs/m	3.280 840	E + 00
Linear current density	A/m	A/mm	A/mm	1.0*	E + 00
Magnetic dipole moment	Wb·m	Wb·m	Wb·m	1.0*	E + 00
Magnetic field strength	A/m	A/mm	A/mm	1.0*	E + 00
		oersted	A/m	7.957 747	E + 01
		gamma	A/m	7.957 747	E - 04
Magnetic flux	Wb	mWb	mWb	1.0*	E + 00
Magnetic flux density	T	mT	mT	1.0*	E + 00
		gauss	T	1.0*	E - 04
Magnetic induction	T	mT	mT	1.0*	E + 00
Magnetic moment	A·m ²	A·m ²	A·m ²	1.0*	E + 00
Magnetic polarization	T	mT	mT	1.0*	E + 00

SI METRIC SYSTEM OF UNITS (CONT'D)

SOME ADDITIONAL APPLICATION STANDARDS

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit	
			SPE Preferred	Other Allowable		
Capillary pressure	Pa	ft (fluid)	m (fluid)		3.048*	E-01
Compressibility of reservoir fluid	Pa ⁻¹	psi ⁻¹	Pa ⁻¹		1.450 377	E-04
				kPa ⁻¹	1.450 377	E-01
Corrosion allowance	m	in.	mm		2.54*	E+01
Corrosion rate	m/s	mil/yr (mpy)	mm/a		2.54*	E-02
Differential orifice pressure	Pa	in. H ₂ O (at 60°F)	kPa		2.488 4	E-01
				cm H ₂ O	2.54*	E+00
Gas-oil ratio	m ³ /m ³	scf/bbl	"standard" m ³ /m ³		1.801 175	E-01
Gas rate	m ³ /s	scf/D	"standard" m ³ /d		2.063 640	E-02
Geologic time	s	yr	Ma			
Head (fluid mechanics)	m	ft	m		3.048*	E-01
				cm	3.048*	E+01
Heat exchange rate	W	Btu/hr	kW		2.930 711	E-04
				kJ/h	1.055 056	E+00
Mobility	m ² /Pa·s	d/cp	μm ² /mPa·s		9.869 233	E-01
				μm ² /Pa·s	9.869 233	E+02
Net pay thickness	m	ft	m		3.048*	E-01
Oil rate	m ³ /s	bbl/D	m ³ /d		1.589 873	E-01
		short ton/yr	Mg/a	t/a	9.071 847	E-01
Particle size	m	micron	μm		1	
Permeability-thickness	m ³	md-ft	md·m	μm ² ·m	3.008 142	E-04
Pipe diameter (actual)	m	in.	cm		2.54*	E+00
				mm	2.54*	E+01
Pressure buildup per cycle	Pa	psi	kPa		6.894 757	E+00
Productivity index	m ³ /Pa·s	bbl/(psi·D)	m ³ /(kPa·d)		2.305 916	E-02
Pumping rate	m ³ /s	U.S. gal/min	m ³ /h		2.271 247	E-01
				L/s	0.309 020	E-02
Revolutions per minute	rad/s	rpm	rad/s		1.047 198	E-01
				rad/m	6.283 185	E+00
Recovery/unit volume (oil)	m ³ /m ³	bbl/(acre-ft)	m ³ /m ³		1.288 931	E-04
				m ³ /ha·m	1.288 931	E+00
Reservoir area	m ²	sq mile	km ²		2.589 988	E+00
		acre		ha	4.046 856	E-01
Reservoir volume	m ³	acre-ft	m ³		1.233 482	E+03
				ha·m	1.233 482	E-01
Specific productivity index	m ³ /Pa·s·m	bbl/(D·psi·ft)	m ³ /(kPa·d·m)		7.565 341	E-02
Surface or interfacial tension in reservoir capillaries	N/m	dyne/cm	mN/m		1.0*	E+00
Torque	N·m	lbf-ft	N·m		1.355 818	E+00
Velocity (fluid flow)	m/s	ft/s	m/s		3.048*	E-01
Vessel diameter	m	1-100 cm	cm		2.54*	E+00
		above 100 cm	m		3.048*	E-01

*An asterisk indicates the conversion factor is exact.

**See Notes 1-3 on page 1598.

SI METRIC SYSTEM OF UNITS (CONT'D)

Quantity and SI Unit		Customary Unit	Metric Unit		Conversion Factor* Multiply Customary Unit by Factor to Get Metric Unit
			SPE Preferred	Other Allowable	
ELECTRICITY, MAGNETISM					
Magnetic potential difference	A	A	A		1.0* E + 00
Magnetic vector potential	Wb/m	Wb/mm	Wb/mm		1
Magnetization	A/m	A/mm	A/mm		1
Modulus of admittance	S	S	S		1
Modulus of impedance	Ω	Ω	Ω		1
Mutual inductance	H	H	H		1
Permeability	H/m	μH/m	μH/m		1
Permeance	H	H	H		1
Permittivity	F/m	μF/m	μF/m		1
Potential difference	V	V	V		1
Quantity of electricity	C	C	C		1
Reactance	Ω	Ω	Ω		1
Reluctance	H ⁻¹	H ⁻¹	H ⁻¹		1
Resistance	Ω	Ω	Ω		1
Resistivity	Ω·m	Ω·cm	Ω·cm		1
		Ω·m	Ω·m		1
Self inductance	H	mH	mH		1
Surface density of charge	C/m ²	mC/m ²	mC/m ²		1
Susceptance	S	S	S		1
Volume density of charge	C/m ³	C/mm ³	C/mm ³		1
ACOUSTICS, LIGHT, RADIATION					
Absorbed dose	Gy	rad	Gy		1.0* E - 02
Acoustical energy	J	J	J		1
Acoustical intensity	W/m ²	W/cm ²	W/m ²		1.0* E + 04
Acoustical power	W	W	W		1
Sound pressure	N/m ²	N/m ²	N/m ²		1
Illuminance	lx	footcandle	lx		1.076 391 E + 01
Illumination	lx	footcandle	lx		1.076 391 E + 01
Irradiance	W/m ²	W/m ²	W/m ²		1
Light exposure	lx·s	footcandle·s	lx·s		1.076 391 E + 01
Luminance	cd/m ²	cd/m ²	cd/m ²		1
Luminous efficacy	lm/W	lm/W	lm/W		1
Luminous exitance	lm/m ²	lm/m ²	lm/m ²		1
Luminous flux	lm	lm	lm		1
Luminous intensity	cd	cd	cd		1
Quantity of light	lm·s	talbot	lm·s		1.0* E + 00
Radiance	W/(m ² ·sr)	W/(m ² ·sr)	W/(m ² ·sr)		1
Radiant energy	J	J	J		1
Radiant flux	W	W	W		1
Radiant intensity	W/sr	W/sr	W/sr		1
Radiant power	W	W	W		1
Wave length	m	Å	nm		1.0* E - 01
Capture unit	m ⁻¹	10 ⁻³ cm ⁻¹	m ⁻¹		1.0* E + 01
			10 ⁻³ cm ⁻¹		1
		m ⁻¹	m ⁻¹		1
Radioactivity		curie	Bq		3.7* E + 10

Values of gas constant R in various units

Units	R
atm, cc/g mole, $^{\circ}\text{K}$	82.06
atm, liter/g-mole, $^{\circ}\text{K}$	0.08206
BTU/lb-mole, $^{\circ}\text{R}$	1.987
psia, cu ft/lb-mole, $^{\circ}\text{R}$	10.73
lb/sq ft abs, cu ft/lb-mole, $^{\circ}\text{K}$	1544
atm, cu ft/lb-mole, $^{\circ}\text{R}$	0.730
kwh/lb-mole, $^{\circ}\text{K}$	0.001049
hp-hr/lb-mole, $^{\circ}\text{K}$	0.000780
atm, cu ft/lb-mole, $^{\circ}\text{K}$	1.3145
mm Hg, liters/g-mole, $^{\circ}\text{K}$	62.37
in, Hg, cu ft/lb-mole, $^{\circ}\text{R}$	21.85
cal/g-mole, $^{\circ}\text{K}$	1.987
atm, cu ft/lb-mole, $^{\circ}\text{K}$	1.314