ENERGY

Volume II

Non-nuclear Energy Technologies

One of a Three-Volume Set of Lecture Notes
Second Edition

S.S. Penner • L. Icerman

Pergamon Press

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Contents of Volume I, 1981

Contents of Volume III, 1976

PREFACE TO THE FIRST EDITION

Volume II of this series of lecture notes is generally restricted to those aspects of non-nuclear energy technologies dealing with new developments, which promise to bring important modifications to our energy-supply base. Well-developed technologies are not reviewed. Thus, deep understanding of the engineering aspects of coal mining or petroleum recovery by conventional means is not assumed and will not be gained from study of the material contained in this volume. However, it is the authors' expectation that the patient reader will achieve considerable understanding and insight into the nature of developing technologies and will learn to appreciate the enormity of the scientific, technical, economic, and social problems that form a part of any scenario leading to greater U.S. independence from foreign energy supplies.

The authors' personal involvement in some of the newly developing technologies (e.g., fossil-fuel developments, OTEC, the hydrogen economy, geothermal energy generation) is hopefully reflected by comprehensive current coverage of these topics.

We are indebted to the UCSD graduate and undergraduate students who have helped us with the development of these lecture notes by participating in early courses dealing with non-nuclear energy technologies.

In order to assist the reader in the use of this volume, we have reproduced Table 1.2-2 of Volume I on units, conversion factors, and energy consumption. We have also included a set of review problems dealing with energy resources.

The reader should note that reference numbers refer to individual Sections.

La Jolla, CA, June 1975 S. S. Penner

L. Icerman

In the second edition, we have updated much of the text, especially the chapters on fossil fuels, solar energy, and geothermal systems.

La Jolla, CA, March 1984 S. S. Penner

L. Icerman

GLOSSARY OF SYMBOLS

A = ampere

a.c. = alternating current

atm = atmosphere

bbl or B = barrel

Btu = British thermal unit

°C = degrees Celsius

cal = calorie

cm = centimeter

d = day

d.c. = direct current

ev = electron volt

(e) or subscript e = equivalent energy or electrical energy, depending on the context

°F = degrees Fahrenheit

ft = foot

g = gram

gal = gallon

h = hour

hp = horsepower

Hz = Hertz

in. = inch

°K = degrees Kelvin

kcal = kilocalorie = 10^3 calories

kg = kilogram = 10^3 grams

km = kilometer = 10^3 meters

kt = kiloton = 10^3 tons

kV = kilovolt = 10^3 volts

kVA = kilovolt-ampere = 10^3 volt-amperes

kw = kilowatt = 10^3 watts

lb = pound

lbm = pound mass

m = meter

MCM = 10^3 circular mils

mi = mile

min = minute

mph = mile(s) per hour

MVA = megavolt-ampere = 10^6 volt-amperes

Mw = megawatt = 10^6 watts

n = newton

ppm = parts per million

psi = pounds per square inch

psia = pounds per square inch (absolute)

psig = pounds per square inch (gauge)

Q = 10^{18} Btu

rad = radian

rpm = revolutions per minute

sd = standard day or stream day

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sec = second

SCF = standard cubic foot

t = ton = 2,000 pounds

(th) or subscript t = thermal energy

V = volt

w = watt

y = year

UNITS, CONVERSION FACTORS, ENERGY CONSUMPTION*

1 joule = 10^7 erg (= 10^7 dyne-cm) = 6.24 x 10^{12} Mev = 6.24 x 10^9 Bev = 1.0 newton-m = 0.736 ft-lb = 0.24 cal = 0.949 x 10^{-3} Btu = 2.78 x 10^{-4} wh = 3.73 x 10^{-7} hph = 2.78 x 10^{-7} kwh = 2.38 x 10^{-10} ton of TNT equivalent = 1.22 x 10^{-13} of the fusion energy from the deuterium in 1 m^3 of seawater = 1.11 x 10^{-14} g of matter equivalent = 1.22 x 10^{-14} of the fission energy of 1 kg of U-235 equivalent = 6.8 x 10^{-23} of the average daily input of solar energy at the outside of the atmosphere of the earth = 5.8 x 10^{-32} of the daily energy output from the sun.

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1 metric ton of coal $\simeq$ 27.8 x 10^6 Btu (1 metric ton = 1 mt $\simeq$ 2,200 lb)

1 bbl of petroleum $\simeq$ (5.60 to) 5.82 (or more) x 10^6 Btu (1 bbl = 42 gallons)

1 SCF of natural gas $\simeq$ 10^3 Btu

1 cord of wood $\simeq$ 1.95 x 10^7 Btu (1 cord = 128 ft^3)

9,500 Btu (th)/kwh_e at 36% conversion efficiency.

---

1 Q = 10^{18} Btu = 1.05 x 10^{21} joule = 2.93 x 10^{14} kwh(th) = = 1.22 x 10^{10} Mwd(th) = 3.35 x 10^7 Mwy(th) = 1.7 x 10^{11} bbl of petroleum equivalent; 1 y = 8.76 x 10^3h

---

Coal conversion to oil: $\gtrsim$2 bbl/mt ($\gtrsim$ 42% energy-conversion efficiency)

Note: See footnotes to this table on the following page.

UNITS, CONVERSION FACTORS, ENERGY CONSUMPTION*

Energy consumption estimates:**					
USA	(1970) --	0.07 Q/y	[2×10^8	people, 11.7	kw(th)/p].
	(2000) --	0.16 Q/y	[3×10^8	people, 17.8	kw(th)/p].
	(2020) --	0.3 Q/y	[4×10^8	people, 25	kw(th)/p].
WORLD	(1970) --	0.24 Q/y	[4×10^9	people, 2	kw(th)/p].
	(2000) --	2.1 Q/y	[7×10^9	people, 10	kw(th)/p].
	(2050) --	6 Q/y	[10×10^9	people, 20	kw(th)/p].

*Table abbreviations used: bbl = barrel; Btu = British thermal unit; cal = calorie; d = day; g = gram; h = hour; hp = horsepower; kg = kilogram; kw = kilowatt = 10^3 watt; m = meter; Mw = megawatt = 10^6 watt = 10^3 kw; p = person; SCF = standard cubic foot, corresponding to the gas volume at a pressure of 14.73 psi (= 1 atmosphere) and a temperature of 60°F; w = watt; y = year; the symbol (e) or the subscript e identify electrical energy; the symbol (th) or the subscript t identify thermal energy. The subscript e is also used occasionally in place of the phrase "equivalent energy"; the particular meaning attached to e should generally be clear from the context.

**Representative estimates from various sources; forecasts to the year 2000 and beyond are uncertain by factors of 2 or more.

REVIEW PROBLEMS ON ENERGY RESOURCES

Verify each of the following statements by using the appropriate conversion factors.

1. The 1970 U.S. electrical power-generating capacity was 3.40×10^5 Mw_e.

   (a) Show that the electrical energy generated during 1970, at a 90% average operating capacity, was 3.06×10^5 Mwy_e.

   (b) Assuming a 33.33% average conversion efficiency, show that the primary (total) energy required for electric-power generation was 9.18×10^5 Mwy_e during 1970. Show that this total energy corresponds to 4.70×10^9 $(bbl)_e$ for 1970 or 1.28×10^6 $(bbl/d)_e$ of petroleum.

2. The estimated year 2000 U.S. electrical-power generating capacity is 2×10^6 Mw_e, corresponding to an electrical energy of 1.8×10^6 Mwy_e at an average use rate of 90%, and a primary energy requirement of 5.4×10^6 Mwy_t for the year 2000 or 7.59×10^5 $(bbl/d)_e$.

   (a) The total average continuous input of solar power to the surface of the earth is 18% of the continuous solar power at the outer atmospheric boundary of 5.2×10^{21} Btu/y. Show that the total average yearly input of solar power at the surface of the earth is 9.36×10^{20} Btu/y or $1.61 \times 10^{14} (bbl)_e/y$. Show that this input solar power corresponds to an average power of 4.41×10^{11} $(bbl/d)_e$.

Show that a utilization efficiency of 0.172% of the solar-power input to the surface of the earth would be sufficient to supply the primary power requirements for the U.S. electrical industry in the year 2000.

(b) White has estimated that 8×10^{21} joules = 2.5×10^8 Mwy of hydrothermal energy are available world-wide to a depth of 3 km; 4×10^{22} joules = 1.25×10^9 Mwy are available to a depth of 10 km. The U.S. is believed to have between 5 and 10% of the world's hydrothermal resources.

Assuming that 1% of the world's hydrothermal resources to a depth of 10 km can be exploited at a 25% overall conversion efficiency, show that

$$1.25 \times 10^9 \times 10^{-2} \times 0.25 = 3.13 \times 10^6 \text{ Mwy}_e$$

are available world-wide from this energy reserve.

If we exhaust this hydrothermal reserve at a uniform rate in 50 years, show that the corresponding world-wide electrical power capacity from hydrothermal energy becomes 6.25×10^4 Mw_e. Show that this capacity corresponds to 3.13% of the estimated U.S. electrical-power capacity for the year 2000 or to 2.38×10^7 $(bbl/d)_e$ of primary energy.

(c) The average outward rate of heat flow of geothermal energy from the interior of the earth is 1.25×10^{-6} cal/sec-cm^2 = 39.4 cal/cm^2-y. If the surface area of the earth is 5.1×10^{18} cm^2, show that this average geothermal power corresponds to 2.01×10^{20} cal/y = 7.94×10^{17} Btu/y = 2.66×10^7 Mw. If 1% of this geothermal power could be converted to electrical power with a 25% conversion efficiency, show that

$$2.66 \times 10^7 \times 10^{-2} \times 0.25 = 6.65 \times 10^4 \ Mw_e$$

would be generated. Show that this corresponds to 3.32% of the estimated U.S. year 2000 electrical power-capacity requirement.

(d) The ultimate world capacity for hydroelectric power generation has been estimated to be 2.857×10^6 Mw_e. If the U.S. fraction of this total is 0.0563, show that the ultimate U.S. hydroelectric capacity is 0.161×10^6 Mw_e or 8.05% of the estimated year 2000 U.S. capacity.

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