EQL Report No. 19

WATER CONSUMPTION RATES OF SYNTHETIC FUEL INDUSTRIES: A CROSS-REFERENCE GUIDE TO THE OPEN LITERATURE

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MORTON S. ISAACSON

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ABSTRACT

There is a great deal of controversy over how much water synthetic fuel industries will consume. Although this controversy can not be definitively settled until such industries are actually in operation, this report attempts to put it into perspective by summarizing, in an orderly fashion, the water consumption values for synthetic fuel industries found in a major portion of the open literature. Often the values stated in the literature are neither clearly delineated nor substantiated. In many cases they have been borrowed — and reborrowed — from earlier reports. A number of times this has led to seemingly independent reports having actually obtained their values, indirectly, from the same original source (as occurred in a recent, major National Science Foundation study). In addition, the values are often stated in different units in different reports, making comparisons awkward. This survey includes unit-water-requirement values for coal gasification (producing substitute natural gas - SNG), coal liquefaction, and oil-shale processing from over 150 references found in the open literature. These values have all been converted to one common set of units and are presented in this report in easily followed, chronologically arranged information flow charts. This makes it easy to compare values from different reports and to trace the values back to their origins.

The primary conclusion drawn from this survey is that only a handful of key reports have been responsible for most of the water-use values appearing in the open literature. Based on the members of this

subgroup which appear to be most reliable, the following "rule of thumb" is recommended: for water consumption by future synthetic fuel industries a "best guess" estimate is 80 $m^3/10^{12}J$ (of product) and a conservative (high) "best guess" estimate is 110 $m^3/10^{12}J$.

EXECUTIVE SUMMARY

A search of the open literature to find reasonable values for water use by future synthetic fuel developments reveals a confusing array of values. As an example, for the production of substitute natural gas (SNG) by coal gasification some representative values found in the literature are: (1) 0.0865-0.7585 cubic kilometers of water per 10^{18} joules of synthetic fuel product; (2) 300,000 acre-ft/yr for an industry supported by a coal mining rate of 24 million tons per year; and (3) 2-7 x 10^6 gpd for a standard size plant. What is one to make of such numbers? Are they all the same, and if not, which is to be considered most reliable? The purpose of this report is to survey the open literature on water use by the three major synthetic fuel industries (SNG coal gasification, coal liquefaction and oil-shale processing), reducing all water-use values to a common basis so that they can be compared, and tracing them back to their origins to determine which values are likely to be most accurate.

Reason for Survey

The need for such a report as this can be seen by examining the coal-gasification examples cited above in more detail. The 2-7 x 10^6 gpd consumption range is also given in its source report as 7-30 gal/10^6 Btu. In terms of the common basis used in this report, this range is 25-110 $m^3/10^{12}J$ (the volume of water consumed in producing a product with an energy content of $10^{12}J$). This range is from GOLD &

GOLDSTEIN, 1978,* one of a series of reports by Water Purification Associates, Inc. (WPA), Cambridge, Massachusetts. Their water-use values are the result of careful engineering design analyses based on material and energy balances. Water conservation is a major consideration in the designs. Also, assumptions and data sources are clearly stated so that their validity may be checked.

In contrast, the range 0.0865-0.7585 $km^3/10^{18}J$ becomes 87-760 $m^3/10^{12}J$, when converted to the common basis. This is seven times greater than the WPA estimate at the high end. This range is from HARTE & EL GASSEIR, 1978, an article that appeared in Science magazine and was the basis for the water use values used by the National Academy of Sciences in its important CONAES Report (NAT. ACAD. SCI., 1979). Harte and El Gasseir borrowed their range from another National Academy study, EL GASSEIR, 1980. In that report the in-plant coal-gasification water use is based on three similar ranges from three apparently independent references. However, when one traces back to the origins of the water-use values given in those references (chains of three reports, one borrowing from another, in two of the cases and of five reports in the third case) one finds that they all came, ultimately, from the same reference. The ultimate reference, AM. GAS ASSOC., 1971, was a confidential report and is apparently not obtainable. Therefore, it is not possible to check the validity of the water use range given in HARTE & EL GASSEIR, 1978. However, the earliest obtainable report

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* All references are listed alphabetically in the reference section at the end of the report.

to quote the range, U.S. FPC, 1973, states that the high end is for full evaporative cooling using low quality make-up water.

The water use value of 300,000 acre-ft/yr for a coal mining rate of 24 million ton/yr converts into 1500 $m^3/10^{12}J$ in terms of the common basis used in this report. This is fourteen times the high value given in the WPA reports. It, too, comes from an article in Science magazine, BROWN, 1981. In this case the number was only borrowed and reborrowed (without change) twice. The ultimate reference is ROCKY MT. ENV. RES., 1974. That report gives neither explanation nor source for the number. It seems likely that there is a decimal point error in the water-use value, but that can not be ascertained from the information that is given.

Presentation of Survey Data

Because of the complicated way water-use numbers have been transmitted through the literature, and the large number of reports involved (approximately 350 were identified in this survey), it was decided that the best way to present the information is in the form of information flow charts. They are referred to below as cross-reference charts because they allow values in different reports to be easily compared and their origins determined. There are fifteen such charts in this report, five each for SNG coal gasification, coal liquefaction and oil-shale processing.

For each report that was obtained and analyzed for this survey (171 in all), a box appears in the appropriate chart showing the water-use values given in the report and from where the values come. All water-use values presented in the charts have been reduced to the same common units -- the volume of water (in cubic meters) consumed in producing an amount of product with an energy content of 10^{12} joules. A small fragment of one of the charts is presented below in Fig. ES-1. It shows the derivation of the SNG coal-gasification water-use value given in BROWN, 1981—one of the examples used above. The water use of 1500 $m^3/10^{12}$J (in terms of the common basis) was borrowed directly from INGRAM, ET AL., 1980, who borrowed their value directly from ROCKY MT. ENV. RES. 1974. No references are given for the water-use value in ROCKY MT. ENV. RES., 1974. The "N" appearing in the example over the water-use values means that the type of gasification technology is not specified.

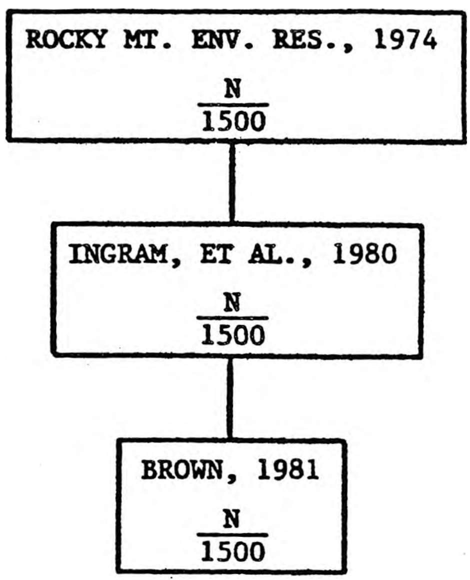

Figure ES-1. Cross-reference chart fragment

In addition to common units, three other major factors enter the analysis of water-use values to form the common basis for comparison. In addition to the water consumed in the fuel conversion processes themselves, synthetic fuel industries will also require water for fuel preparation (e.g., mining) and environmental control (e.g., flue gas scrubbing, spent-shale disposal, and revegetation). Furthermore, if electricity is required to operate an industry, generation of the electricity may also consume water. An industry involved in all aspects of producing its product is referred to below as an integrated industry. Whenever possible (i.e., when sufficient information is supplied in the reports) the water-use values given in the charts are for integrated industries. However, again whenever possible, associated urban use has not been included in the chart values. Associated urban use is defined as the increased water use in a region due to the general population increase (e.g., workers′ families) caused by the synthetic fuel industries. Finally, as part of the common basis, all synthetic fuel plants are considered to be "zero discharge" plants. Once water is used in a plant it can not be returned to its source. For the values given in the cross-reference charts, all of the intake water used in a synthetic fuel industry is considered to be consumed.

Discussion of Survey Results

A total of 331 separate items in the open literature are shown on the cross-reference charts. Of these, 171 were obtained and analyzed. The rest are referenced by those which were analyzed, but not, themselves, obtained. Two main categories of reports were found: (1) originating reports which first introduced water-use values into the open literature, and (2) derived reports which borrowed water-use values from earlier reports with little or no fundamental change in the values. In the sample chart shown in Fig. ES-1, ROCKY MT. ENV. RES., 1974, is an originating report while the other two are derived reports. The originating reports may be further subdivided into three subgroups: (1) developer reports which were written by process or project developers and are, presumably, based on in-house design-analyses; (2) independent engineering design-analysis reports which were written by independent engineering firms and are based on material-and-energy-balance design analyses (the WPA reports mentioned above are examples); and (3) general reports which do not fit into either of the other two classes and do not reveal their technical bases (ROCKY MT. ENV. RES., 1974, is an example). The derived reports may be further subdivided into two subgroups: (1) reports which borrow and restate water use values almost exactly as given in their references, and (2) synthesis reports which borrow water uses for different aspects of an integrated industry (e.g., mining, processing and reclamation) directly from different sources and then combine them.

Because of their more fundamental nature, the rest of this discussion will concentrate on the originating reports. For SNG coal gasification, out of the 100 reports obtained and analyzed, 22 are originating reports; for coal liquefaction, out of the 84 reports obtained and analyzed, 25 are originating reports; and for oil-shale processing, out of the 104 reports obtained and analyzed 27 are originating reports. Some key examples of originating reports (including their water-use values and how many derived reports borrowed from them, either directly or indirectly) are shown separately for the three synthetic fuel industries in Tables ES-1, 2, and 3. Because these few reports are responsible for the water-use values appearing in a majority of the open literature, they can be considered representative of the entire survey.

A few observations on the tables deserve special notice:

(1) The few general reports shown are responsible for approximately one-quarter to one-half of the entire sample of the open literature obtained. However, for the coal processes, the high ends of the water-use ranges given by these key general originating references are poorly founded: in the case of U.S. FPC, 1973, it comes from a confidential report while in the case of DAVIS & WOOD, 1974, no reference is given.

(2) The high ends of the WPA ranges are similar to estimates from process and/or project developers and are based on obtainable technical analyses.

Conclusions and Recommendations

From the foregoing discussion and from an examination of the complete cross-reference charts in chapter 6, it appears that the WPA high-estimate values, derived from careful engineering analyses, are comparable to water-use estimates published by actual process developers. On the other hand, the high ends of the general estimates, especially for coal gasification and coal liquefaction, are poorly founded and do not appear to represent reality, at least not for future

TABLE ES-1

Survey Summary -- SNG Coal Gasification

TOTAL REPORTS OBTAINED = 100
TOTAL DERIVED REPORTS OBTAINED = 78

TYPE OF ORIGINATING REPORT	KEY EXAMPLES	NO. OF DERIVED REPORTS	WATER USE ($m^3/10^{12}J$)
General	U.S. FPC, 1973	25	150-630
Developer	STEARNS-ROGER CORP., 1973	23	130
	BATTELLE COL. LABS, 1973	20	110
Ind. Engin. Analysis	WPA Reports	18	43-110

TABLE ES-2

Survey Summary -- Coal Liquefaction
(Liquid Product)

TOTAL REPORTS OBTAINED = 84
TOTAL DERIVED REPORTS OBTAINED = 59

TYPE OF ORIGINATING REPORT	KEY EXAMPLES	NO. OF DERIVED REPORTS	WATER USE ($m^3/10^{12}J$)
General	DAVIS AND WOOD, 1974	21	100-720
Developer	(R.M.) PARSONS CO., 1973	3	130
	U.S. DOE, 1980a	1	170
Ind. Engin. Analysis	WPA Reports	15	36-79

TABLE ES-3

Survey Summary -- Oil-Shale Processing

(Upgraded Product)

TOTAL REPORTS OBTAINED = 104
TOTAL DERIVED REPORTS OBTAINED = 77

TYPE OF ORIGINATING REPORT	KEY EXAMPLES	NO. OF DERIVED REPORTS	WATER USE ($m^3/10^{12}J$)
General	U.S. DOI, 1974	37	37-120
Developer	COLONY DEVELOP. OP., 1974	18	85-110
	MCKEE & KUNCHAL, 1976	9	63-100
Ind. Engin. Analysis	WPA Reports	13	64-110

use of good quality water in zero-discharge plants. Furthermore, the WPA high estimates consider only high evaporative cooling for coal-conversion processes and highly water consumptive methods of spent-shale disposal for oil-shale conversion processes. Therefore, the WPA high estimates are recommended as reasonably conservative (i.e., slightly overpredicting use) "best guess" estimates. Of course all such estimates are open to some question until actual operating data from commercial installations are available. These "best guess" estimates are shown on the next page in Table ES-4 in both U.S. customary and SI units.

TABLE ES-4

Unit Water Requirements of Synthetic-Fuel Industries,
Conservative "Best Guess" Estimates
(Associated Urban Use Not Included)

INDUSTRY	UNITS: acre-ft/10^{12} Btu	$m^3/10^{12}J$
Coal Gasification (substitute natural gas)	91	110
Coal Liquefaction (liquid product)	68	79
Oil-Shale Processing (upgraded product)	95	110

In addition to <u>conservative</u> best-guess estimates of water consumption by future, commercial synthetic-fuel developments, it is also possible to hazard <u>average</u> best-guess estimates which may not be conservative. From an examination of the WPA reports shown in chapter 6 for <u>all</u> technologies, and <u>intermediate</u> levels of wet cooling, it appears that the best-guess estimates for both SNG coal gasification and oil-shale processing (upgraded product) would be about 80 $m^3/10^{12}J$, while for coal liquefaction (liquid product) it would be about 60 $m^3/10^{12}J$.

Therefore, as a rough "rule of thumb" for water consumption by synthetic-fuel industries, a best-guess estimate is 80 $m^3/10^{12}J$ and a <u>conservative</u> best-guess estimate is 110 $m^3/10^{12}J$.

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Charts of Reported Estimates of Water Consumption
for Integrated Synthetic Fuel Industries
(Author groups denote predominant but not exclusive
author affiliation)

LIST OF UNITS AND CONVERSION FACTORS

acre-ft	=	acre-foot (1 acre-ft = 3.26×10^5 gal = 1.23×10^3 m^3)
acre-ft/Btu	=	acre-foot per British thermal unit (1 acre-ft/Btu = 1.17 m^3/J)
acre-ft/yr	=	acre-foot per year (1 acre-ft/yr = 1.23×10^3 m^3/yr)
bbl	=	barrel, U.S. (oil) (1 bbl = 4.20×10^1 gal = $1.59 \times 10^{-1} m^3$)
Btu	=	British thermal unit (1 Btu = 1.055×10^3 J)
^oC	=	degree Celsius (centigrade)
cfs	=	cubic foot per second (1 cfs = 4.49×10^2 gal/min = 1.70 m^3/min)
cm	=	centimeter (1 cm = 1.00×10^{-2} m)
day	=	day (1 day = 1.44×10^3 min — at 100% stream factor)
^oF	=	degree Fahrenheit (^oC = (5/9)(^oF-32))
gal	=	gallon, U.S. (1 gal = 8.35 lb. H_2O at 50^oF = $3.79 \times 10^{-3} m^3$)
gpm	=	gallon per minute (1 gpm = 1.61 acre-ft/yr = 1.98×10^3 m^3/yr — at 100% stream factor)
J	=	joule
kg	=	kilogram
lb	=	pound, mass (1 lb = 4.54×10^{-1} kg)
m	=	meter
m^3	=	cubic meter
min	=	minute (1 min = 6.00×10^1 sec)
mm	=	millimeter (1 mm = 1.00×10^{-3} m)
quad	=	quadrillion Btu (1 quad = 1.00×10^{15} Btu = 1.055×10^{18} J)
scf	=	standard cubic foot (1 scf = $2.83 \times 10^{-2} m^3$)
ton	=	ton, U.S.(short) (1 ton = 9.07×10^2 kg)
yr	=	year (1 yr = 3.65×10^2 day -- at 100% stream factor)

CHAPTER 1

INTRODUCTION

The survey contained in this report grew out of a study to estimate the effect of energy development in the Upper Colorado River Basin on the reliability of water supply in the lower basin. The results of that study are presented in a separate Environmental Quality Laboratory publication: Isaacson, M.S., Aggregate Water Availability for Energy Development in the Upper Colorado River Basin, Report. No. 20, Environmental Quality Laboratory, California Institute of Technology, Pasadena, California, December 1981. In order to estimate the effect of energy development on water supplies, it was first necessary to estimate the water consumption rate of each type of energy related industry (i.e., the unit water requirement). In reviewing the open literature it quickly became apparent that there is a large controversy over how much water will be used by energy resource development industries. Often the stated water use rates are neither clearly delineated nor substantiated in reports, but are borrowed from earlier reports. Furthermore, the rates are often stated in different units in different reports, making comparisons even more difficult. The objectives of this survey are: (1) to present the water-use numbers given in a major portion of the open literature in terms of a common basis; (2) to trace them back to their origins and (3) to determine which values are likely to be most accurate.

For ease of comparison, the unit water requirements found in this survey for coal gasification, coal liquefaction and oil-shale processing are presented in 15 cross-reference flow charts on pages 45 through 59. The water use numbers presented in these charts are for consumptive use during operation only. They are not meant to include water which is to be returned to the source for further use, nor water used in constructing a processing plant. Furthermore, they are meant to be for completely integrated energy industries. This means they include water use for all process steps starting from the raw resource recovery (e.g., coal mining) and ending with high quality products. For coal gasification the end product is clean, high-Btu substitute (or synthetic) natural gas (SNG, heating value ≈920-1000 Btu/scf ($3.4 - 3.7 \times 10^7 J/m^3$)); for coal liquefaction the end product is primarily clean fuel oil (heating value ≈6.2×10^6 Btu/bbl ($4.1 \times 10^{10} J/m^3$)), although some naphtha may also be produced; for oil-shale processing the end product is a clean liquid hydrocarbon syncrude (heating value ≈5.8×10^6 Btu/bbl ($3.8 \times 10^{10} J/m^3$)) suitable as a feed stock for conventional oil refineries. Also meant to be included are related water uses by off-site utilities such as electricity generation at central stations. Finally, all of the water use numbers given in the charts are presented in the same common units: $m^3/10^{12}J$ (i.e., how many cubic meters of water will be consumed to produce a final product with an energy content of 10^{12} joules).

It must be stressed that all of the water-consumption values given below are for nonexistent industries. The technologies exist in this country, at this time, at the pilot-plant stage at most. Therefore, even the most careful analyses in the literature are subject to question. In addition, errors introduced in converting the numbers to the common units used in this survey may, themselves, exceed ±25%. Therefore, before presenting the results, it is important to clarify what technologies are covered in this survey, to explain enough about the technologies to understand where water is consumed, and to explain the errors, inaccuracies and assumptions involved in reducing all data to the common basis. This is done in Chapters 2-5. Chapter 2 is a general introduction to the synthetic fuel technologies covered by this survey; Chapter 3 contains brief descriptions of the primary process steps involved in each synfuel technology; Chapter 4 explains why and where water is used in the production of synthetic fuels; and Chapter 5 reviews the problems involved in reducing the survey data to the common basis. The cross-reference charts containing the survey results are presented in Chapter 6 along with an explanation of how to interpret the charts. Chapter 7 contains a discussion of the data contained in the charts and Chapter 8 presents some conclusions (including recommended water-use values) that can be drawn from the survey. Detailed discussions of the individual charts, including explanatory information on the stated water-use values, are presented in the Appendix at the end of this report.

CHAPTER 2

ENERGY-DEVELOPMENT INDUSTRY OVERVIEW

For purposes of organizational clarity, an energy recovery or conversion *industry* is defined as the set of *technologies* (i.e. processes) which utilize the same resource base (such as coal or oil shale) to produce similar products (such as electricity or liquid hydrocarbons). Such energy recovery or conversion industries can be separated into two water-use classes: those which use little water per unit of energy (in the output product) and those which use a considerable amount of water. Uranium mining and refining and bulk coal, crude oil and natural gas recovery require relatively little water per unit energy recovered and will not be considered, per se, in this report. On the other hand, electricity generation (both fossil and nuclear), coal gasification, coal liquefaction (including refining to a clean solid), oil-shale processing, tar-sands processing, and transporting coal by slurry pipeline all require considerable quantities of water. Of these, it was decided to concentrate only on synthetic fuel industries with extensive literatures. Therefore, this study concentrates on oil-shale processing, high-Btu (pipeline quality) coal gasification and coal liquefaction. Included in the last category are also processes that produce clean solid fuels via a coal liquefaction step.

As mentioned above, each synthetic-fuel industry encompasses many different technologies. For example, in one report by the National Research Council (see National Academy of Sciences, 1977a) 37 different technologies (i.e., processes) are listed for the production of low- and intermediate-Btu fuel gases from coal. In order to limit the scope of this review, only representative technologies which appear to be subject to commercial development within the next 20 years and for which there is an appreciable history in the open literature are included. Furthermore, when two or more technologies are similar (from a water use standpoint) only one is considered. The specific synthetic fuel technologies included in this survey are listed in Table 2.1. This table should not be construed as a list of technologies recommended by the author, nor does it indicate that other technologies will not be commercially available in 20 years. In addition, many of the reports in the open literature which give water-use numbers do so only on an industry wide basis, without stating what specific technologies are involved. These references have been included in this survey with their water use values clearly labeled as being non-specific as to technology. Finally, although not included in the coal gasification survey, Koppers-Totzek coal gasification references have been included in the coal liquefaction survey. This is because some coal-liquefaction analyses consider designs which include the Koppers-Totzek process for producing reactant gases (such as H_2) needed in the liquefaction process.

TABLE 2.1

Synthetic Fuel Technologies Considered in this Report

COAL GASIFICATION (Hi-Btu, SNG)

Lurgi
Synthane
Hygas
Bigas

COAL LIQUEFACTION (and solid refining)

Synthoil
H-Coal
Solvent Refined Coal (SRC)
Solvent Refined Coal-II (SRC-II)

OIL SHALE PROCESSING

Underground Retorting

Modified In-Situ
True In-Situ

Surface Retorting

TOSCO-II
Paraho-indirect mode
Paraho-direct mode
Union-B
Superior
Lurgi-Ruhrgas

CHAPTER 3

SYNTHETIC FUEL CONVERSION TECHNOLOGIES

The various synthetic fuel technologies, considered in this survey, for converting raw solid hydrocarbon fuels (i.e., coal and oil shale) into clean gaseous, liquid or solid fuels are described in Figure 3.1. The figure summarizes the major process steps involved in each technology. It should be noted that Figure 3.1 is only meant to convey a rough description in order to help understand where water is used in the processes. Many intermediate, bypass and feedback steps are not shown. More complete information on fuel conversion technologies, both those included in this survey and others, can be found in the following references: Dravo Corporation, 1976; Hendrickson, 1975; Hottel and Howard, 1971; Howard-Smith and Werner, 1978; National Academy of Sciences, 1977a and b; Probstein and Gold, 1978; Probstein and Hicks, 1982; Shih, et al., 1979; and White, et al., 1979 a and b.

3.1 Coal Conversion Technologies

All of the coal conversion processes considered in this report have two common objectives: (1) to reduce the ratio of carbon-to-hydrogen in the fuel and (2) to remove impurities--i.e., ash and pollutant precursors, primarily sulfur and nitrogen. The lower the carbon-to-hydrogen ratio, the "lighter" or more "premium" the fuel. Dry, solid coal is primarily carbon with some hydrogen present; liquid hydrocarbons have more hydrogen giving a lower carbon-to-hydrogen

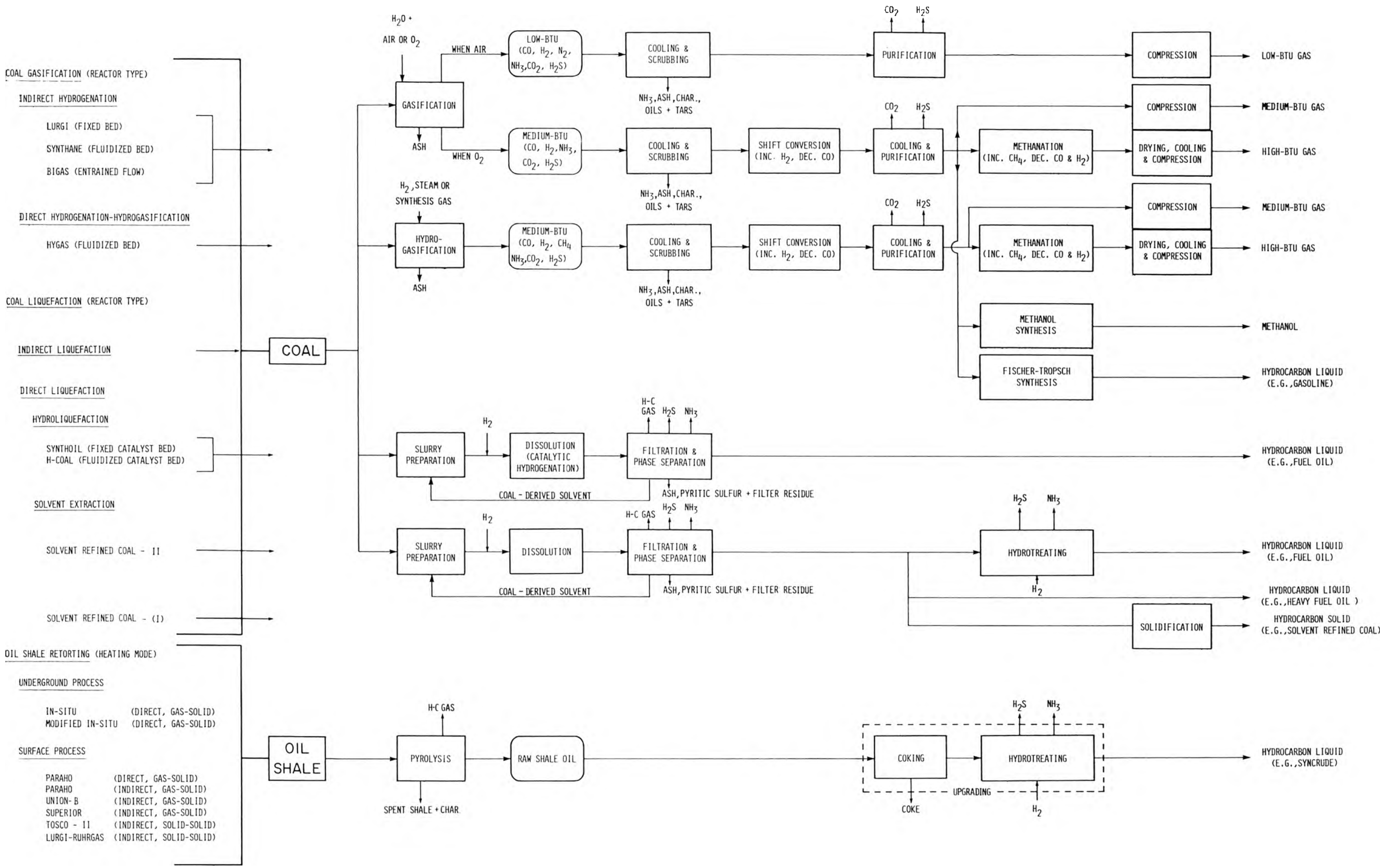


Figure 3.1. Major Process Steps in Synthetic Fuel Technologies (Adapted from Probstein and Gold, 1978).

ratio, while high-Btu substitute natural gas is practically pure methane and has the lowest carbon to hydrogen ratio. In order to decrease the carbon to hydrogen ratio, hydrogen must be added to the fuel's molecular structure. This is known as hydrogenation. All of the coal conversion processes of interest here are hydrogenation processes. They differ primarily in how much or by what method the hydrogen is added.

3.1.1 Coal Gasification (SNG)

High-Btu coal gasification technologies to produce pipeline quality gas (i.e., substitute or synthetic natural gas, SNG) from coal can be divided into "indirect" or "direct" hydrogenation processes. In either case there are roughly six steps in the processes, see Fig. 3.1. In the first step of the indirect hydrogenation technologies, pulverized coal is reacted with oxygen and steam in a gasification reactor to produce a medium-Btu gas containing primarily CO, H_2, CO_2, H_2S and NH_3. Little, if any, methane is formed. Different technologies are distinguished by different types of gasification reactors. In the Lurgi gasifier, motion of the coal bed is controlled by grates, not by the gases passing through the bed. It is called a "fixed bed" or more correctly, a "moving bed" reactor. In the synthane process, the flow of the gases up through the bed supports (or "floats") the coal to form a "fluidized bed" reactor. In the Bigas process, the coal enters the reactor entrained in a gas stream. It is called an "entrained flow" reactor. The Koppers-Totzek gasifier is also an entrained flow reactor.

In direct hydrogenation, also called hydrogasification, the gasifier is charged with hydrogen rather than oxygen. The resulting medium-Btu gas contains an appreciable amount of methane. The Hygas process is a direct hydrogenation process utilizing a fluidized bed hydrogasifier.

In the second step, the medium-Btu gas is cooled and scrubbed. It must be cooled and solids removed from it before entering the third step. Scrubbing also removes the ammonia. The third step is shift conversion. It is applied to only part of the gas stream where it increases the hydrogen concentration and decreases the carbon monoxide concentration. This is necessary in order to have the proper reactant mix for the methanation step which follows. First, however, the gas must again be cooled and acid gases, such as CO_2 and H_2S removed. This "purification" is the fourth step. Acid gas purification is accomplished by dissolving the gases in an organic solvent (as in the Selexol and Rectisol processes) or in an inorganic solvent (as in the Benfield hot potassium carbonate process). The fifth step is methanation in which the CO and H_2 in the gas are reacted over a catalyst to increase the methane concentration to about that of natural gas. The final step in high-Btu gasification is compressing, cooling and drying the product to meet pipeline criteria.

3.1.2 Coal Liquefaction

Coal liquefaction processes are also classified as either direct or indirect, but in a different sense. In indirect liquefaction, synthesis gases produced by coal gasification are reacted over catalysts to form liquid products. Because such processes are not very efficient, they have not been considered in detail in this report. Hydroliquefaction, solvent extraction and pyrolysis are direct liquefaction processes. Because the liquid hydrocarbon yield from coal pyrolysis is low, however, it will not be considered for coal liquefaction in this review.

In both hydroliquefaction and solvent extraction the solid coal is dissolved in a coal derived solvent which transfers "loosely" bound hydrogen atoms to the coal. The primary difference between the two types of processes is that hydroliquefaction processes utilize catalysts in the dissolving process to produce generally more highly hydrogenated products. The Synthoil hydroliquefaction process uses a fixed catalyst-bed reactor while the H-Coal process uses a fluidized catalyst bed reactor. In both hydroliquefaction and solvent extraction, a slurry of pulverized coal and recycled coal-derived solvent is formed and fed, with hydrogen, or a hydrogen containing synthesis gas, into a dissolver. In some technologies, not considered here, the hydrogen is added to the solvent before slurry preparation. The product from the dissolver contains solids, liquids and gases. Ash, pyritic sulfur and undissolved coal are filtered out; byproduct hydrocarbon gases, hydrogen sulfide and ammonia are removed; and part of the product stream is separated out and recycled to the slurry preparation area as solvent.

Typically the output from a direct coal liquefaction technology is a slate of products classified by boiling temperature range. Along with the major products listed below, smaller amounts of fuel gas and naphtha are also produced. In hydroliquefaction technologies, the major products are similar to petroleum crudes (called synthetic crudes or syncrudes) or fuel oils. In solvent extraction technologies, the products generally have higher carbon-to-hydrogen ratios. The major product of the Solvent Refined Coal (SRC or SRC-I) technology has such a high ratio it is a solid at room temperature. The SRC-II technology produces a major product fraction which is similar to a heavy fuel oil as well as a solid product fraction. Hydrotreating (catalytically hydrogenating) the products can decrease the carbon to hydrogen ratios to produce products similar to lighter fuel oils. The sulfur and nitrogen content of the products is also reduced during hydrotreating. The products of coal liquefaction processes have fairly wide boiling ranges and fairly high sulfur and nitrogen contents compared to petroleum and petroleum products. Fractionating the products to produce fractions with narrower boiling ranges and hydrotreating to reduce the carbon-to-hydrogen ratio or remove impurities is called "upgrading." Upgrading also serves to stabilize the products; otherwise, they may change with time. Different coal liquefaction plant designs include different degrees of upgrading.

3.2 Oil-Shale Conversion Technologies

In the case of oil-shale processing, the objectives of improving the carbon-to-hydrogen ratio and removing impurities are similar to those of coal conversion, but the methods are somewhat different. Oil shale is a type of marlstone containing a large amount (20 percent by weight) of a waxy hydrocarbon called kerogen. By heating the shale to approximately $900^{o}F$ ($500^{o}C$) in the absence of oxygen, most of the kerogen is vaporized. This pyrolysis procedure is called oil shale "retorting." The primary product is a condensed hydrocarbon liquid called raw "shale oil". It is usually very viscous and still contains its original load of sulfur and nitrogen. In addition, non-condensible hydrocarbon gases are produced as a byproduct. The shale that remains after retorting is called "spent" shale. Although its weight has been reduced by the removal of the kerogen the volume of the spent shale is actually greater than that of the "raw" shale (by about 15 percent) due to pore expansion. Some carbon char can also be left on the spent shale.

In order to remove contaminants from the raw shale oil and reduce its viscosity (so it can be transported by pipeline), the raw shale oil may be put through an "upgrading" treatment. Typically this would consist of running the heaviest fraction through a coker (which produces solid coke and lighter hydrocarbon liquids) and then hydrotreating all of the liquids to reduce the carbon to hydrogen ratio and remove the sulfur and nitrogen. The resulting product is a synthetic crude (syncrude) able to be handled by normal petroleum refineries. Another way to reduce the viscosity of the raw shale oil, enough to be transportable by pipeline, is by the addition of inexpensive chemicals called pour-point depressants. The product, however, may not be of syncrude quality.

Oil-shale technologies differ primarily in the type of pyrolysis reactor or "retort" used. They are classified on the basis of how the heat used in retorting is supplied and where the retort is located. If the heat is generated external to the retort it is called "indirect" heating. If it is generated internal to the retort (e.g., by burning some of the shale inside the retort by introducing enough air) it is called "direct" heating. Furthermore, these are subdivided on the basis of the heat transfer agent. If the heat carrier is a gas (e.g., combustion products) it is called "gas-solid" heat transfer and if it is a solid (e.g., hot sand) it is a called "solid-solid" heat transfer. Some retorting technologies utilize permanent, reusable reactor vessels constructed above ground. These are called "surface" processes. Other retorting technologies utilize rubblized volumes contained within the shale deposits themselves on a single use basis. These are called "underground" processes.

The two generic underground technologies of interest in this study are true in-situ (or in-situ) and modified in-situ. In true in-situ retorting, a rubblized cavern is created in the shale deposit (e.g., by blasting or high pressure fluid injection). Air, for combustion, and steam, for combustion control, are injected at one end (or top) and the shale is ignited. As the combustion front spreads downstream through the deposit, it retorts the shale ahead of it. Gases and condensed shale oil are collected at the downstream end. The heating is "direct" with gas-solid heat transfer. Modified in-situ retorting is similar, but to create the rubblized cavern, small chambers are first excavated at its bottom to make the rubblizing easier. The raw oil shale removed from the small chambers can also be retorted above ground to increase the overall yield. Shale oil obtained from underground technologies may have a low enough carbon to hydrogen ratio and low enough concentration of sulfur and nitrogen that upgrading will not be necessary.

Of the six surface retorting technologies included in this survey, four use gas-solid heat transfer and two use solid-solid heat transfer. The Paraho processes use gas-solid heat transfer with either direct (internal) or indirect (external) heating of the gas. The crushed shale moves vertically down through the retort while the vaporized kerogen moves upward. The Union-B process is similar to the Paraho-indirect process, but the shale moves up and the gases, vapors and liquids move down. The Superior process also uses indirect gas-solid heating, but the shale bed moves horizontally. In addition, the Superior process is called the Superior Multi-Mineral Process because it can be used to recover nahcolite and dawsonite (two valuable minerals found in some oil-shale deposits) at the same time as shale oil. The TOSCO-II and Lurgi-Ruhrgas processes both employ indirect, solid-solid heating of the raw oil shale. The TOSCO-II process uses marble size (~1cm) ceramic spheres as heat transfer agents while the Lurgi-Ruhrgas process uses sand-grain size (~1mm) pieces of spent shale.

3.3 Auxiliary Processes and Utilities

In addition to the primary conversion process steps reviewed above, each industry also involves utility components as well as pre-process resource preparation and post-process waste and pollution control components. The primary utility needs are for oxygen, hydrogen, water, steam and electricity. Oxygen and hydrogen are process inputs. Steam is a process input and is also used for process heating. Either steam or electricity is used to power the pumps and compressors that run a plant. Water will be dealt with below. Oxygen can be produced by cryogenic air separation which involves compression and cooling. Hydrogen can be produced by gasification of char or reforming some of the gases produced in the process. Steam can be raised by burning the raw resource (if coal), char, byproduct gas, or even the primary product. Electricity can be produced on-site by condensing steam turbines or by gas turbines fired by gaseous products. It can also be purchased from off-site.

Included in pre-process resource preparation is mining, in-situ retort construction, crushing and drying. Included in waste and pollution control is coal-ash and spent shale disposal and sulfur removal from flue and tail gases.

CHAPTER 4

WATER USE IN SYNTHETIC FUEL INDUSTRIES

4.1 General Considerations

When water is taken from a natural water body for use by man it is called "withdrawal" or "diversion". After use, the water may be returned to its source. The difference between the quantity of water withdrawn and that returned is the quantity of water "consumed". Water may be consumed by evaporation, by being included in an output of the process or by having its quality degraded to the extent that its return is considered intolerable pollution. Withdrawal can be much larger than consumption, but for synthetic fuel industries pollution control considerations have fostered a "zero discharge" philosophy. All water used will be consumed. This is especially true for plants located in the arid western United States.

How much water a specific integrated synthetic fuel plant uses is determined by the location of the plant, by the technology involved, and also by conscious design choices by the builder. Location considerations include the temperature and humidity of the climate, the heating value and moisture content of the feed fuel, and the quality of the water supply. These are somewhat outside of the designer′s control, although water could be transported from a different source. The major design choices involve how much internal water recycle or reuse to employ and what types of cooling systems to use.

As will be enumerated below, there are many different kinds of water uses associated with any synthetic fuel plant. Some, such as steam generation, need very pure water. Others, such as ash disposal, can use less pure water. Water recycle involves sequentially using waste water from processes demanding higher quality water in processes accepting lower quality water. In some cases water treatment is applied between sequential uses. The more water recycle used in a plant, the lower the water consumption. However, it can increase the cost of the plant.

All synthetic fuel technologies demand some form of cooling in order to remove waste heat. An "open cycle" or "once through" system uses water to remove the heat. The water is withdrawn from a natural water body, is passed through the plant only once and is then returned to the water body at a slightly higher temperature. Due to environmental considerations, however, most, if not all, synthetic fuel plants will use "closed cycle" cooling. There are three generic types of closed cycle cooling: evaporative or "wet", non-evaporative or "dry", and a combination of the two, "wet/dry" cooling.

In wet cooling, heat is transferred to a stream of recycling cooling water which, in turn, is cooled primarily by the loss of its heat of vaporization when a portion of it is evaporated in a cooling device (e.g., a cooling tower). Of course the evaporated water is lost from the system, so there must be some "make-up" water added. In addition, some liquid water in the form of small droplets (called "drift") is carried away with the vapor. Also, in order to maintain the quality (e.g., the salinity) of the recirculating cooling water, some of it (called "blow-down") must be removed from the system and replaced with higher quality water. Along with evaporation losses, both drift and blow-down must also be replaced by make-up water. The lower the quality of the make-up water, the greater the quantity of blow-down needed and thus the greater the quantity of make-up water needed. In "zero discharge" plants, the blow down must be disposed of and cannot be returned to the water source.

In dry cooling, the heat is removed from the recycling cooling water (or directly from the process stream) by direct transfer to the air in dry cooling towers which act much like automobile radiators. Little if any cooling water is lost in dry cooling. Wet/dry cooling combines the two processes in either series or parallel. The use of dry cooling decreases the plant's water consumption, but can increase the plant's cost.

It is a conscious design choice as to how much wet or dry cooling will be used in each plant process. If no dry cooling is purposely used in a plant it is referred to as "high" or "full wet cooling." If some dry cooling is purposely used it is referred to as "intermediate wet cooling" or "partial air cooling." If the maximum amount of dry cooling economically affordable is used it is referred to as "minimum practical wet cooling."

The specific uses to which water is put in a synthetic fuel industry is summarized in Table 4.1. In the table, the uses have been separated on the basis of where they occur. The primary divisions

TABLE 4.1

Water Uses in Synthetic Fuel Industries

IN-PLANT AND UTILITY USES

<u>Process Inputs</u>

Steam as a reactant
Steam as a source of hydrogen
Steam as a heat transfer medium

<u>Cooling</u>

Condensers for steam turbines (turbines used directly or for electricity generation to power pumps and compressors)
Compressor interstage cooling
Acid gas purification
Product cooling

<u>Fluid Stream Cleaning</u>

Solids removal by scrubbing
Tail gas clean-up
Flue gas desulfurization
Water treatment

<u>Plant service needs</u>

Maintenance
Personal
Fire protection

OFF-SITE USES

<u>Mining and crushing</u>

Dust control
Revegetation

<u>Solid Waste Treatment</u>

Sludge disposal
Ash disposal
Spent shale disposal

ASSOCIATED URBAN USES

are: in-plant, off-site, and in associated urban areas. Associated urban use refers to increased domestic water consumption in urban areas due to population increases caused by nearby synthetic fuel-industry developments. Because of the indirect nature of this water use and because it is not specifically included in most water use estimates in the open literature, it will not usually be included in the water-use numbers presented below. In a few instances, however, it could not be removed from the cited numbers. In these cases its inclusion is clearly indicated on the charts by an asterisk. Very roughly, associated urban use appears to be no more than about 10-20 percent of total consumption (see, e.g., Colorado Department of Natural Resources, 1979, and Harte and El-Gasseir, 1978).

4.2 In-Plant Water Uses

In-plant uses include water consumed as process inputs and water used for cooling and cleaning liquid and gaseous streams. As a process reactant, steam is used directly in many technologies as an input feed to the primary reactor. It can also be used indirectly, as a source of hydrogen in a subsidiary gasifier, which is then used as a feed to the primary reactor or to a hydrotreater. Steam can also be used to heat various process steps. In this case a small amount of "make-up" water is needed to maintain the proper water quality. It should be noted that excess water can actually be produced in oil-shale retorting by the decomposition of the shale-rock matrix.

There are four areas in synthetic fuel plants that present major cooling loads. The largest cooling load occurs in the steam condensers used in conjunction with power turbines. The pumps and compressors which run the plant are powered either directly by condensing steam turbines or indirectly by electricity. Electricity can be generated either on-site or off-site. Even if it is purchased from an off-site utility, nevertheless, somewhere near the synthetic fuel plant there will be an additional cooling load associated with the plant. Therefore, it is considered an in-plant use in this report. Interstage coolers on gas compressors represent another large cooling load. In order to reduce energy consumption, and avoid mechanical damage and the possibility of explosions, gases are compressed in a series of stages with the partially compressed gas cooled between each stage. The third major cooling load is found in the acid gas purification systems. The organic or inorganic solvents used in the systems must be regenerated after use. This consists of boiling the solvents, stripping out the acid gases and then recondensing the solvents. The recondensation is a large cooling load. The last major cooling load is final product cooling and, possibly, dehumidification.

In comparison with cooling, the water consumed directly in cleaning liquid and gas streams is usually smaller, though it can still be significant. Although the flow of water in these systems can be quite large, most is reused with only a small fraction being consumed. What is consumed goes into saturating gases or forming waste sludges. Scrubbing to remove solids and ammonia from process gas streams (including byproduct gas streams) is accomplished by water sprays. Tail gas desulfurization may also use some water. The hydrogen sulfide removed by the acid gas purification processes must be further reduced to an environmentally manageable form. A Claus plant producing elemental sulfur followed by a Stretford tail gas plant is one way to do this. Flue-gas desulfurization systems, such as the lime/limestone scrubbing process, operating on the flue gas streams from boilers and heaters fired by raw feeds, also use considerable amounts of water. In addition, water treatment systems, themselves, consume a small amount of water.

The final category of in-plant water use is general service. This includes general maintenance and equipment cleaning, personal use (such as drinking fountains), and fire protection. With proper care, these can all be minor water uses.

4.3 Off-Site Water Uses

Because the total water consumption by synthetic fuel industries is of interest, water used outside the processing plant for resource extraction and waste residue disposal must also be considered. Although mines and disposal areas may be located adjacent to processing plants, especially in the west, these water uses will be termed "off-site" uses.

There are two operations of interest in raw resource extraction: mining and crushing. The crushing is needed to adjust ore size to that appropriate for the process reactor. In both cases water sprays are used for dust control (e.g., on haul roads). In addition, when strip mining is employed, revegetation will probably be part of the reclamation program following ore removal. Artificial irrigation may be necessary to promote the revegetation.

Waste residues from synthetic fuel plants include waste sludge streams and coal ash or spent shale. Sludge and ash can be disposed of at the mine site with only minor water use. Spent-shale disposal, however, can be a major water consumer. Because of the huge quantity of spent shale involved (approximately 1.5 tons per barrel of oil (8.6 x $10^3 kg/m^3$)), spent-shale disposal is a major operation. Hot spent shales from some retorting technologies may have to be water cooled. Also, spent shales from some retorting technologies "set up" like portland cement when water is added (10-20 percent by weight). Therefore, some disposal schemes call for adding water to surface disposal piles to increase their stability (and decrease their permeability). This can consume a significant amount of water. In addition, irrigation may have to be used to promote the revegetation of spent-shale surface disposal piles.

CHAPTER 5

PREPARATION OF SURVEY DATA

5.1 Sources of Information--the Open Literature

This survey relies entirely on the "open literature." The open literature refers to all articles and reports in the public domain. It does not include personal communications with synthetic fuel plant developers nor does it include reports containing proprietory information not available to the general public. In tracing back through the open literature it became obvious that many references should not, or could not, be included. Common engineering handbooks and references not dealing directly with information relevant to water consumption have been excluded. Also excluded are references relevant only for process steps with very minor water consumption, such as water treatment. Some reports give no references; some give insufficient bibliographic information to locate references; some give only general bibliographies, not specifying which references were consulted for water use information. In the latter case, only the most likely references have been pursued. In many cases, cited references are part of the so called "gray literature" and could not be found. "Gray literature" refers to reports that, while not restricted in distribution, are not part of any established report (publication) series.

5.2 Reduction to Common Basis

The common basis chosen for comparing water use numbers in this survey is the volume of water consumed by an integrated synthetic fuel industry in producing a volume of high grade product which contains a fixed, standard amount of energy. In the metric system, water volume is given in cubic meters, m^3, and energy in joules, J. The fixed, standard amount of product energy used in this survey is 10^{12}J. Therefore, all water use numbers are given in terms of the common unit $m^3/10^{12}$J. To convert to U.S. customary units of acre-ft/10^{12}Btu the water consumption values given below should be multiplied by 0.86. To convert to acre-ft/quad, the water consumption values should be multiplied by 0.86×10^3.

Because integrated industries are being compared, water uses in all phases of the industries, from mining through processing (including off-site utilities) to disposal of waste residues, should be included. However, associated urban use should be excluded. Upgrading should be included when it is necessary to produce a high grade product. The high grade products of interest are shown in Table 5.1.

Unfortunately, in trying to reduce all water use numbers found in the open literature to a common basis, a number of problems arose. These have to do with the types of industries considered in the literature, their products, and various missing pieces of technical information. The following discussion is in general terms. Specific

TABLE 5.1

Synthetic Fuel Industry Products*

Industry	Product	Approximate Heating Value
Coal Gasification	Substitute Natural Gas (SNG)	9.6×10^{2} Btu/scf (3.6×10^{7} J/m^3)
Coal Liquefaction	Fuel Oil	6.2×10^{6} Btu/bbl (4.1×10^{10} J/m^3)
	Solvent Refined Coal (SRC)	
	Liquid	6.2×10^{6} Btu/bbl (4.1×10^{10} J/m^3)
	Solid	3.2×10^{7} Btu/ton (3.7×10^{7} J/kg)
Oil-Shale Processing	Syncrude	5.8×10^{6} Btu/bbl (3.8×10^{10} J/m^3)
	Raw Shale Oil**	6.0×10^{6} Btu/bbl (4.0×10^{10} J/m^3)

*All heating values were inferred from Probstein and Gold, 1978, except for SRC-liquid, the value of which was chosen to be the same as fuel oil as being representative of "oil equivalent."

**Un-upgraded product.

major problems in analyzing specific reports are included in the discussions of the individual charts given in the Appendix.

5.2.1 Integrated Industries

In analyzing the reports, wherever possible, water uses by completely integrated synthetic fuel industries were considered. Many reports, however, do not clarify what phases (e.g., mining, processing or off-site utilities) of an integrated synthetic fuel industry are included in the given water-use numbers. Many other reports give usages for only some phases of an industry. If what is included in a report is not clear or if information on some phases is missing, the water-consumption values have, nevertheless, been used as given. If, however, water consumption values for various phases of an industry are given separately in different parts of the same report volume, but not combined into a net water use number, they have been so combined in this survey.

5.2.2 Water Sources and Waste Streams

There are a number of other factors that complicate the interpretation of given water-use values. In addition to water being brought to a synthetic fuel operation from some external source (e.g., a river or reservoir), it can also come from the feedstock mining operation, either as mine drainage water or surface moisture on the coal or shale. For this survey, mine drainage water used in a synthetic fuel industry has been considered part of the input water requirement. Moisture which enters a process on the surface of the feed stock, however, has been handled as in the source report. If, in the source report, it is subtracted from the water need of the plant, that was also done here. Some processes, such as Lurgi coal gasification and many types of oil-shale retorting, can use the water if properly recovered and treated, while other processes cannot. Not all reports have recognized this fact. Wastewater streams can also cause some uncertainty. Some reports attribute fairly large waste streams to some synfuel plants. Because this review has assumed zero discharge of wastewater back to sources, these waste streams have not been subtracted from the raw intake-water values.

5.2.3 "Stream Factors" or "Plant Factors"

Other problems in the analyses arose because most reports give information in terms of water use rates (e.g., annual water consumption in acre-feet per year (acre-ft/yr)) and fuel production rates (e.g., daily production in barrels per day (bbl/day) for oils or standard cubic feet per day (scf/day) for gases). In order to convert this information to the common basis, two pieces of technical information must be known: (1) the "stream factor" (also called "plant factor" or "load factor") and (2) the product energy content. The stream factor can be loosely defined as the fraction of time (on an annual basis) a plant is "on-line," actually producing its rated product output. Synthetic fuel plants will probably operate at full output 24 hours a day under normal conditions, but will not be operating every day of the year due to equipment or operator malfunction and planned maintenance. They will probably operate between 80 percent and 90 percent of the year. Mines and waste disposal operations may operate closer to 100 percent of the time. When stream factors were needed for the conversion to the common basis, if only the plant stream factor is given it has been used for the entire operation, if none is given a default stream factor of 100 percent has been used.

5.2.4 Product Heating Values

There are a number of problems associated with determining and using the product energy content. Many reports give water usage for "standard size" plants. Usually standard size plants are defined as having product fuel production rates of: 50,000 bbl/day (7,900 m^3/day) for coal liquefaction and oil-shale processing, and 250 million scf/day (7.1 x $10^6 m^3$/day) for coal gasification. Unfortunately the quality (heat content and chemical composition) of the product fuel is often not given. Where this is so, the values stated in Table 5.1 have been used as default values.

5.2.5 Upgrading

For oil-shale processing and coal liquefaction, a further complication arose with respect to upgrading. For oil-shale processing the common basis of this review calls for an upgraded syncrude product. Unfortunately, many reports refer to their products simply as "oil." If it is clear that the product is a raw shale oil, and no heating value is given, it has been assigned a default heating value of 6.0 x 10^6 Btu/bbl (4.0 x 10^{10}J/m^3), otherwise, the default value for syncrude, 5.8 x 10^6 Btu/bbl (3.8 x 10^{10}J/m^3) has been used. This can be further complicated by the fact that some reports actually include water used in upgrading in the total water use, but give plant production in terms of raw shale oil. As the product heating value per unit volume is decreased by upgrading (on the order of 10 - 20%), and the plant output rate is also reduced, this adds an additional uncertainty to the results of the analysis.

Similar problems occurred in analyzing coal liquefaction water consumption values. Some reports include upgrading of coal-derived liquids, some do not, and many do not specify either. In the case of Solvent Refined Coal, the un-upgraded product can even be a solid. Unless product heating values are stated, the default values given in Table 5.1 have been used. For Solvent Refined Coal, the state of the product (solid or liquid) is indicated in the charts, if even that much information is given in a report.

5.2.6 <u>Multiple Products</u>

An additional problem occurred with plants that produce more than one type of fuel product. For example, some coal liquefication plants may also produce high-Btu byproduct gases and some may produce more than one type of liquid product. When the production rate is only given in terms of "barrels equivalent" that number has been used in this analysis with either a given heating value or the default values in Table 5.1. When the primary product quantity is much larger than that of subsidiary products (on the order of 10 times), the subsidiary products have been neglected. If a subsidiary product (of a different state than the primary product) cannot be neglected, it has been included in the analysis and this is indicated on the charts. If two primary products are of the same state and fairly close in production rates, their energy contents have been combined.

5.2.7 Reading and Round-off Errors

Beside the inaccuracies that could have entered the analysis due to incomplete information, there are also possible inaccuracies which have been introduced into the values presented in this report by reading errors and round-off. Reading errors could have been introduced when the data in source reports are presented only in graphical form. Graphs could not always be interpreted precisely. Round-off errors could have been introduced in converting the data given in source reports to the common basis used in this survey. Conversion factors used for this survey are shown in the list of units and conversion factors on page xxi. Because of round-off errors, as well as all the other inaccuracies mentioned above, the results are presented below with no more than two significant figures.

5.2.8 Typographical and Copy Errors

Finally, some of the water consumption values given below are incorrect due to typographical or copy errors in the source reports. A copy error is one in which a water use number (or unit) given in an earlier report is misquoted in a later report. If a typographical or copy error could be detected and corrected by use of information provided in the same published volume, it has been so corrected. Otherwise, it has been used as given--even if it could be detected and corrected by use of information given in a separately published volume. Major errors of these types are explained in the discussions included in the Appendix to this report.

CHAPTER 6

PRESENTATION OF SURVEY RESULTS

6.1 Organization of Charts

The results of this comparative survey of water consumption by synthetic fuel industries are shown below in the form of information flow charts. The charts are divided into three groups (based on industry type) of five charts each. The first group (Charts Nos. 1-5) is for coal gasification; the second group (Charts Nos. 6-10) for coal liquefaction; and the third group (Charts Nos. 11-15) for oil-shale processing. Within each group, individual charts are unified roughly on the basis of the following four author groups: (1) government regulatory and monitoring (oversight) agencies, (2) process and/or project developers, (3) the consulting firm of Water Purification Associates Inc., Cambridge, Massachusetts, and (4) the Science and Public Policy Program of the University of Oklahoma, Norman, Oklahoma. Individual reports are indicated within the charts by boxes (see Figure 6.1 on the next page). The information related to water use contained in the reports is summarized within the boxes. The reports are arranged in the charts chronologically by year, with the oldest reports at the top of the charts. Lines connecting the boxes show the flow of information down from older reports to newer reports.

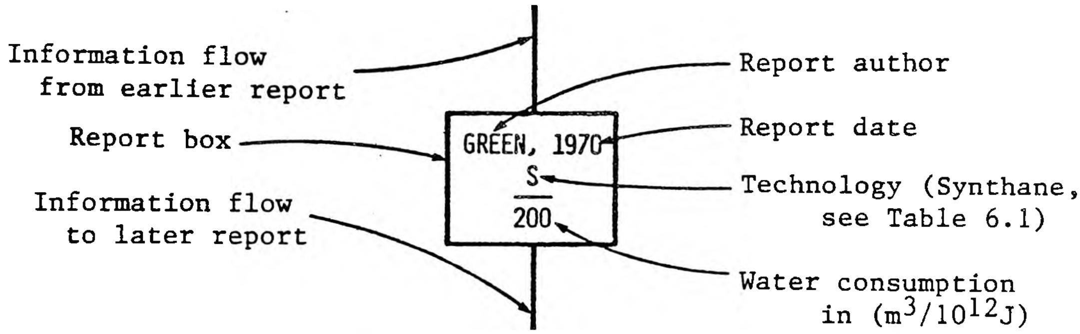


Figure 6.1 Example of Report Box in Charts

6.2 Format of Charts

A symbol key in the form of a self-explanatory example of a hypothetical chart fragment is given in Figure 6.2. Abbreviations used in the charts are defined in Table 6.1. Figure 6.2 and Table 6.1 can be found just before the charts on pages 41 through 43.

Unfortunately it was not possible to develop charts that were completely independent of each other. All of the charts within an industry grouping (i.e., coal gasification, coal liquefaction or oil-shale processing) are really parts of an overall master chart. They are separated into smaller charts primarily for ease of publication. Therefore, there is a small amount of overlap between charts. This connection or continuation between charts is indicated in a chart by a number above or below a report's box (e.g., GREEN & GRAY, 1972 and WHITE, 1975, in Figure 6.2). This number(s) indicates the other chart(s) in which that report also appears.

Normal information flow from earlier to later reports is indicated by a solid line leaving the bottom of a cited reference's box and entering the top of the citing report's box. If the line connecting two boxes is a dashed line this implies the information in the later report probably came from the earlier report, but the connection is not certain (e.g., from GREEN & GRAY, 1972 to GREEN, ET AL., 1974 in Figure 6.2). There are four cases for which a dashed line has been used: (1) incomplete bibliographic information given in the citing report; (2) no specific citations in the citing report, just a separate unreferenced bibliography; (3) no bibliographic information at all given in a report, but the format and content of water-use numbers are exactly the same as those found elsewhere; and (4) the later report is a final version of an unreferenced earlier draft report.

In a few cases, reports cite references actually published chronologically after them. In these cases an arrow head has been placed on the connecting line to show information flow from later to earlier publications (e.g., from GREEN & GRAY, 1972, to GREEN, 1970, in Figure 6.2).

In some cases the line connecting two boxes splits into two or more lines before entering the citing report's box. This means the information was used in more than one place in the citing report. An example of this is mining and reclamation water-use values developed for one technology in a cited reference being applied to several different technologies in a citing report (e.g., from U.S. DOE, 1970, to GREEN, ET AL., 1974, in Figure 6.2).

In a number of cases, besides conference proceedings, two or more complete reports have been published together in one volume. An example of this would be a technical appendix which was originally published separately but later published with the main report. A second example would be written comments submitted by several different parties to a Congressional committee all appearing in the same committee report. In the charts, this is indicated by a large box with cross-hatched borders enclosing the separate report boxes (e.g., BLACK, 1975, and WHITE, 1975, in Figure 6.2). This has not been done in the case of a normal conference proceeding.

The formats of the report boxes have been standardized as much as possible for ease of comparison. The report's author(s) and date are placed at the top of the box (e.g., GREEN, 1970 in Figure 6.2). Personal authors have been used wherever possible. When personal authors could not be determined, the corporate (including government agencies) author designation which most clearly shows the interdependence of reports has been used. Thus, the U.S. Federal Energy Administration is given as the author of Project Independence reports rather than its separate task forces. The abbreviations used for government agencies can be found in Table 6.1. The date given in a box is usually the year of publication, though for conference papers it is sometimes the presentation date. Complete bibliographic information can be found in the Bibliography at the end of this report. Entries are listed alphabetically by the author's last name. It should be noted that the accuracy of bibliographic information can not be guaranteed for cited references which have not been obtained.

Partitions (dotted lines) are used within report boxes to segregate information coming from separate cited references (e.g., GREEN, ET AL., 1974, in Figure 6.2). If information has come from more than one cited reference to only one partition it means that either it is not clear which cited reference provided the information or that information from all of the references was used by the report's author(s) in determining the water consumption value shown in the partition.

In most cases the primary piece of information contained in a box is the water consumption value given by the report, converted to the common units of $m^3/10^{12}J$ (e.g., 200 in GREEN, 1970, in Figure 6.2). If at all possible, total water use for an integrated synthetic fuel industry is given, but associated urban water use is excluded. Numbers that are known to include associated urban use are denoted by asterisks (e.g., S^* in GREEN & GRAY, 1972, in Figure 6.2). For coal using technologies, the numbers given are usually for bituminous and subbituminous feed stocks. When lignite feed stocks have been specified the numbers are enclosed in square brackets (e.g., [150] in GREEN & GRAY, 1972, in Figure 6.2). Water use is given as a function of the type of technology (e.g., Lurgi coal gasification or TOSCO-II oil-shale retorting) and the degree of evaporative (wet) cooling, if that information is given (e.g., full wet cooling or partial air cooling). The technology is specified by an abbreviation over the appropriate water use number(s) (e.g., S for Synthane in GREEN, 1970 in Figure 6.2) and the degree of wet cooling by an abbreviation to the left of the number(s) (e.g., PAC and FWC in GAS CO., 1973, in Figure 6.2). See Table 6.1 for an explanation of the abbreviations.

Often there is a range of numbers given for a single technology and degree of wet cooling (e.g., 200-400 in GAS CO., 1973, in Figure 6.2). The range arises from: (1) site specific environmental variations (such as climate, feed stock quality and moisture content and raw input-water quality); (2) the degree of water recycle involved; and (3) the degree of wet cooling involved, if the degree of wet cooling is not given specifically. Unless otherwise specified in a box, the end points of a range are the extreme values given in a report.

In some boxes, for the same type of technology, two or more different water use numbers (or ranges of numbers) are listed, sometimes, but not always, separated by an "or" (e.g., 250 OR 200 in GREEN, ET AL., 1974, in Figure 6.2). This means that two or more different values (or ranges of values) are given in the same report for what appear to be the same conditions, with no explanation for the differences. Sometimes the differences appear to be due to the water-use numbers being given in two or more different units (e.g., acre-ft/yr and gal/Btu of product). Other times the different numbers appear in different parts of a report and may come from different, unreferenced, sources.

In addition to water consumption values there are only a few other items of information given in the report boxes. A box that is blank, except for bibliographic information, indicates a report that is cited by another report but was not obtained for this survey (e.g., U.S. DOE, 1970 in Figure 6.2). Editorial comments on report availability are enclosed within parentheses (e.g., (CONFIDENTIAL) in RED, 1972, in Figure 6.2). (UNREFERENCED CITATION) means that a reference is cited in the text of a report, but is missing from the reference list--and so could not be obtained. Vague, general references given in a report are enclosed within quotation marks (e.g., from a "SYNTHANE DEVELOPER" as cited by GREEN, ET AL., 1974, in Figure 6.2). In such cases, of course, no author is given in the box.

In some cases, the important information transmitted from one report to another is not total water use, but water uses by some phases of an industry or more basic technical information on a process. In these cases either a short statement describing the relevant information the report contains is given in the report box (e.g., L. (for Lurgi) PROCESS DESCRIPTION in RED, 1971, in Figure 6.2) or a symbol has been placed in the lower right hand corner of the box to indicate what information was transmitted. Even if a cited report was not obtained, there may be a symbol in the lower right hand corner of its box to show what information the citing report attributes to it (e.g., M (for mining or off-site use) in U.S. DOE, 1970, in Figure 6.2). Information about a specific synthetic fuel-conversion process is indicated by the process abbreviation given in Table 6.1.

Information on auxiliary in-plant processes, such as acid gas purification or cooling tower operation, is indicated by a "P" for "process"; and information on off-site processes, such as mining, solid waste disposal and revegetation, is indicated by an "M" for "mining." In one case an "E" has been used to denote information on off-site electric utility water use.

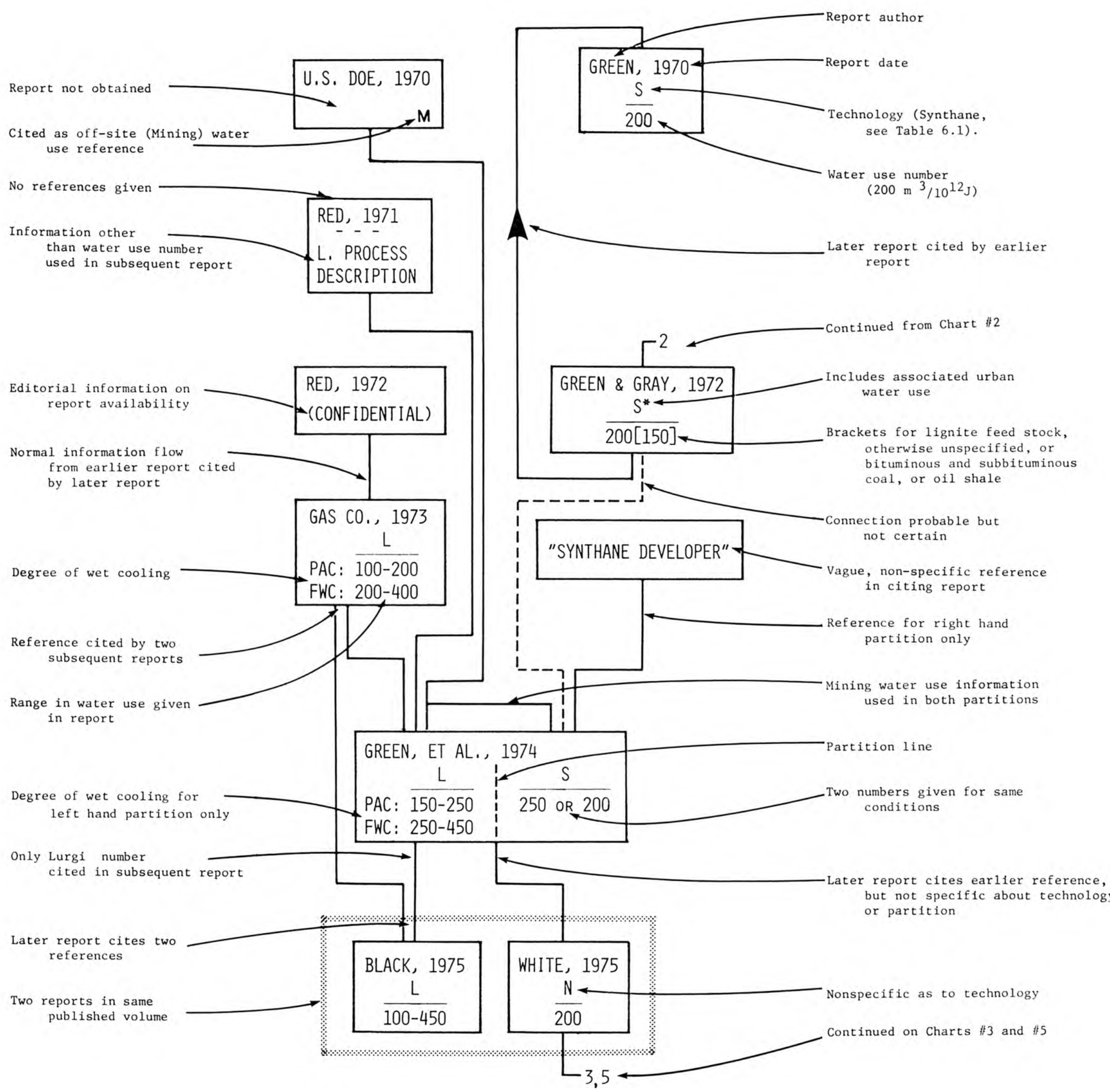


Figure 6.2. Chart Symbol Key (Hypothetical Example).

TABLE 6.1

Abbreviations Used in Charts

SYNTHETIC FUEL TECHNOLOGY

Coal Gasification

B	=	Bigas
C	=	CO_2 acceptor
FLB	=	Fluidized bed reactor
FXB	=	Fixed bed reactor
H	=	Hygas
KT	=	Koppers-Totzek
L	=	Lurgi
N	=	Nonspecific
S	=	Synthane

Coal Liquefaction

CHL	=	Catalytic hydroliquefaction
DIR	=	Direct liquefaction
HC	=	H-Coal
IND	=	Indirect liquefaction
N	=	Nonspecific
PH	=	Pressure hydrogenation
SO	=	Synthoil
SRC	=	Solvent refined coal
SRC-I	=	Solvent refined coal-I
SRC-II	=	Solvent refined coal-II

Oil Shale Processing

DSR	=	Direct surface retorting
ISR	=	Indirect surface retorting
IS	=	In-situ
LR	=	Lurgi-Ruhrgas
MIS	=	Modified in-situ
MIS/LRSR	=	Modified in-situ with Lurgi-Ruhrgas surface retorting
MIS/NSR	=	Modified in-situ with no surface retorting
MIS/SR	=	Modified in-situ with surface retorting
N	=	Nonspecific
PD	=	Paraho direct
PI	=	Paraho indirect
SM	=	Surface mining and surface retorting
SR	=	Surface retorting
SR/MWC	=	Surface retorting using minimum practical wet cooling
SU	=	Superior
T	=	TOSCO-II
TM	=	Technology mix (several technologies in use)
UB	=	Union-B
UM	=	Underground mining and surface retorting

TABLE 6.1

Abbreviations Used in Charts
(continued)

PRODUCT STATE

(g)	=	gaseous (at room temperature)
(hl)	=	hot liquid
(l)	=	liquid (at room temperature)
(s)	=	solid (at room temperature)

DEGREE OF WET COOLING

FWC	=	Full wet cooling
HWC	=	High wet cooling
IWC	=	Intermediate wet cooling
MWC	=	Minimum practical wet cooling
PAC	=	Partial air cooling

ADDITIONAL PROCESS

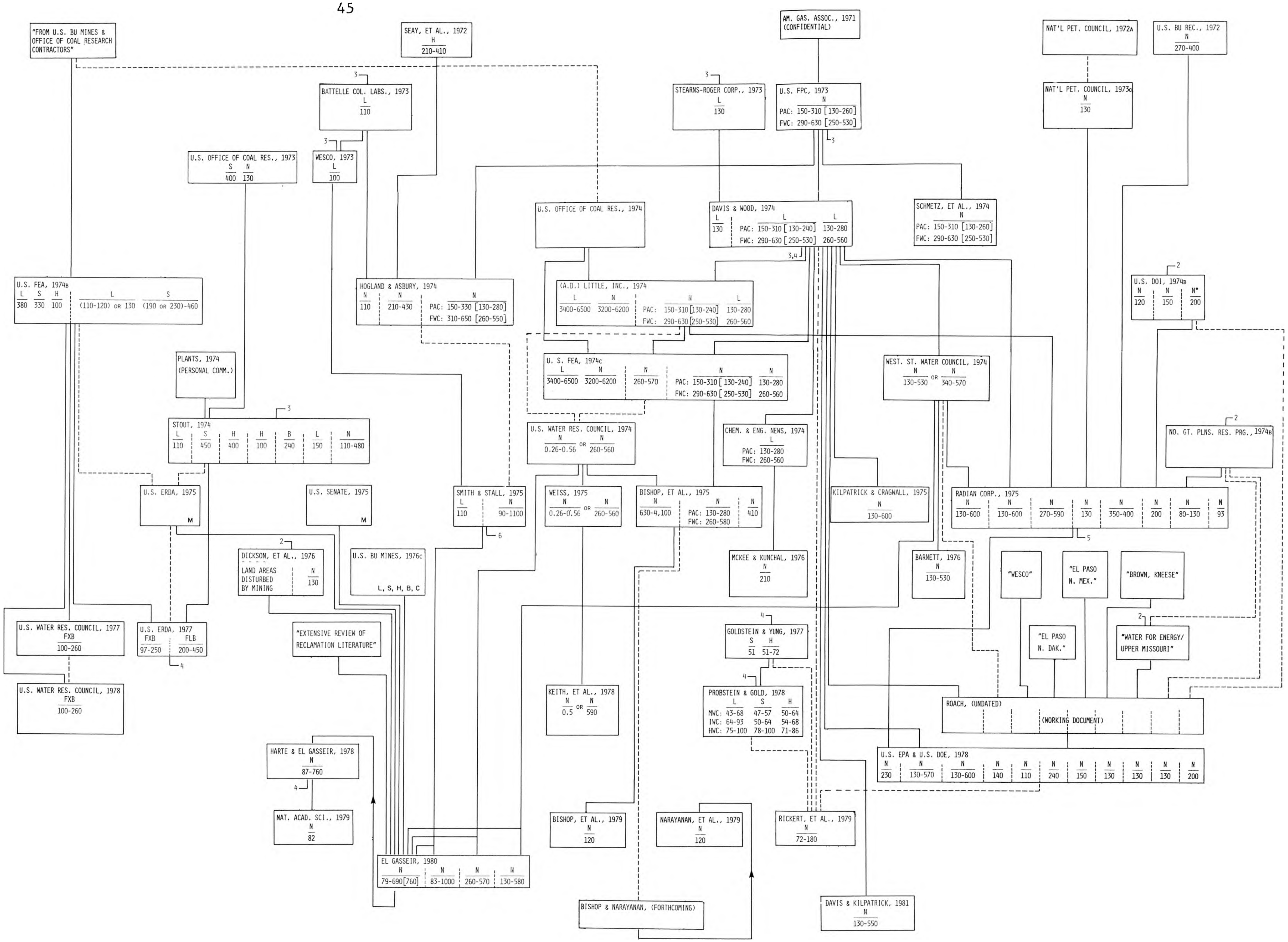
E	=	Off-site electricity production
M	=	Off-site mining, waste disposal or reclamation process
P	=	In-plant auxiliary process

GOVERNMENT AGENCIES (UNITED STATES -- FEDERAL)

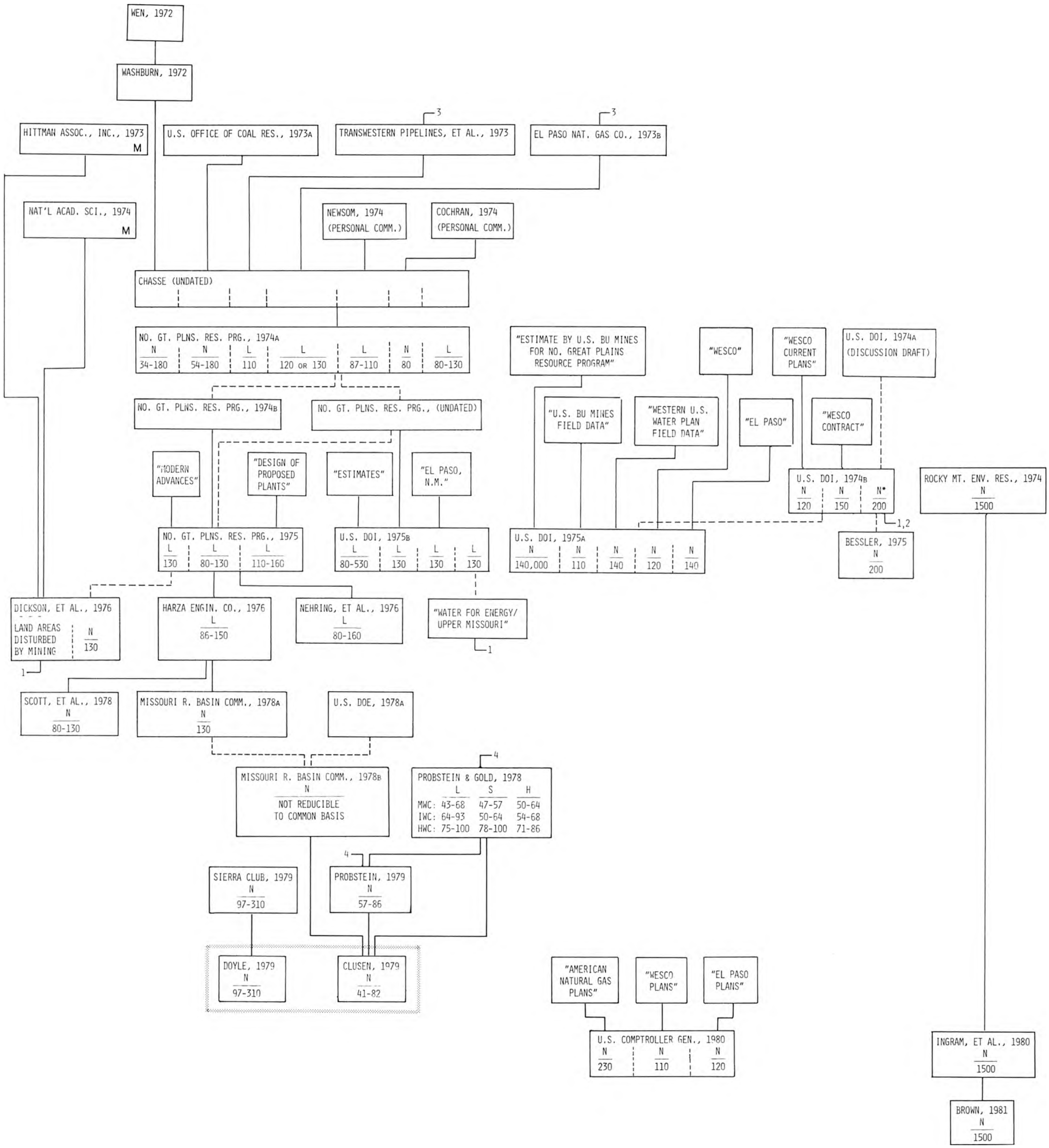
U.S.BLM	=	Bureau of Land Management
U.S. BU MINES	=	Bureau of Mines
U.S. BU REC	=	Bureau of Reclamation
U.S.DOE	=	Department of Energy
U.S.DOI	=	Department of the Interior
U.S.EPA	=	Environmental Protection Agency
U.S.ERDA	=	Energy Research and Development Administration
U.S.FEA	=	Federal Energy Administration
U.S.FPC	=	Federal Power Commission
U.S.GS	=	Geological Survey
U.S.OTA	=	Office of Technology Assessment

6.3 Charts of Reported Estimates of Water Consumption for Integrated Synthetic Fuel Industries

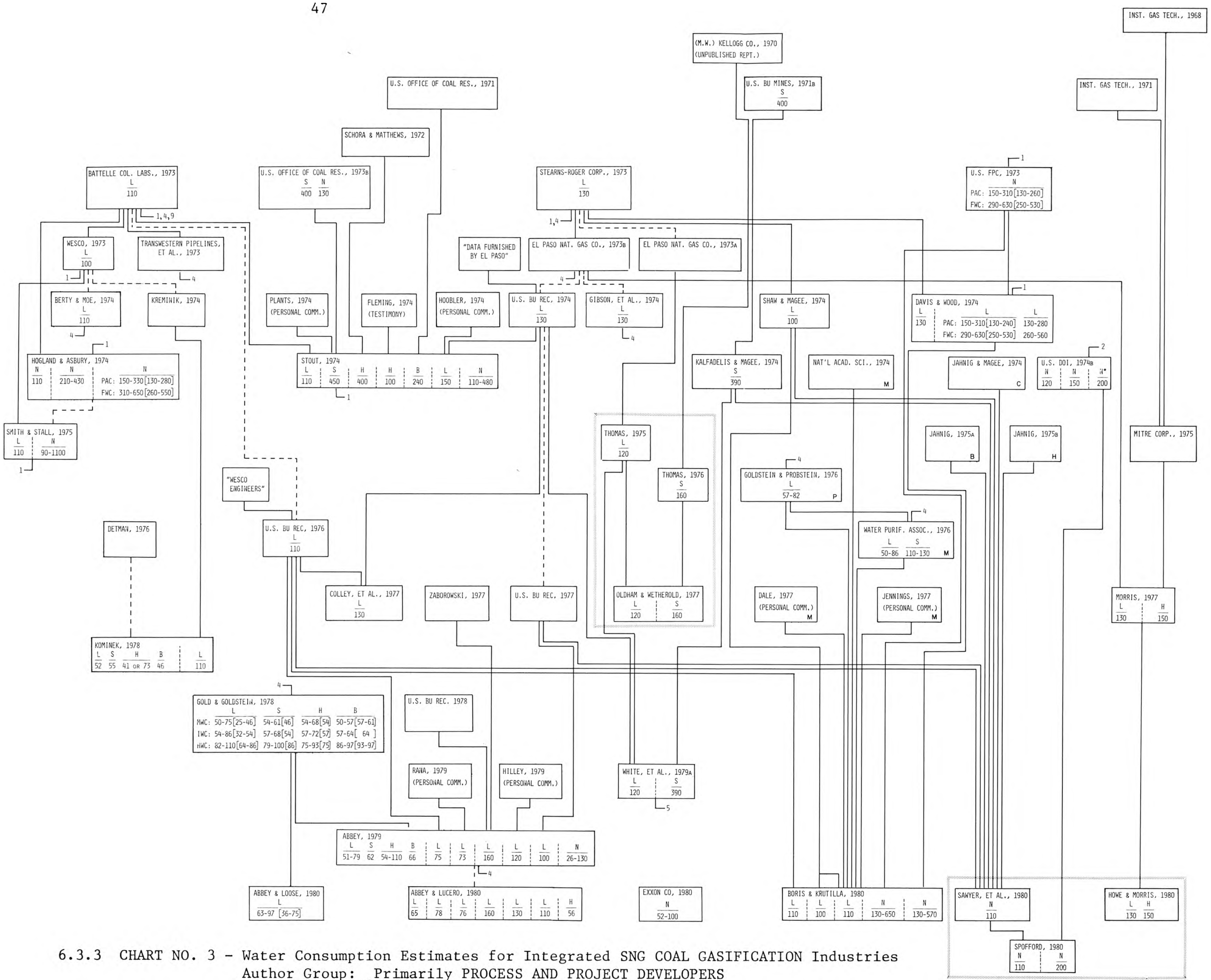
In the following cross-reference charts, author groups denote predominant, but not exclusive, author affiliation. A chart explanation and a symbol key are provided as Fig. 6.2 and Table 6.1 on pages 41 and 42-43 respectively. For detailed discussions of individual charts and the reports contained in them, please see the Appendix.



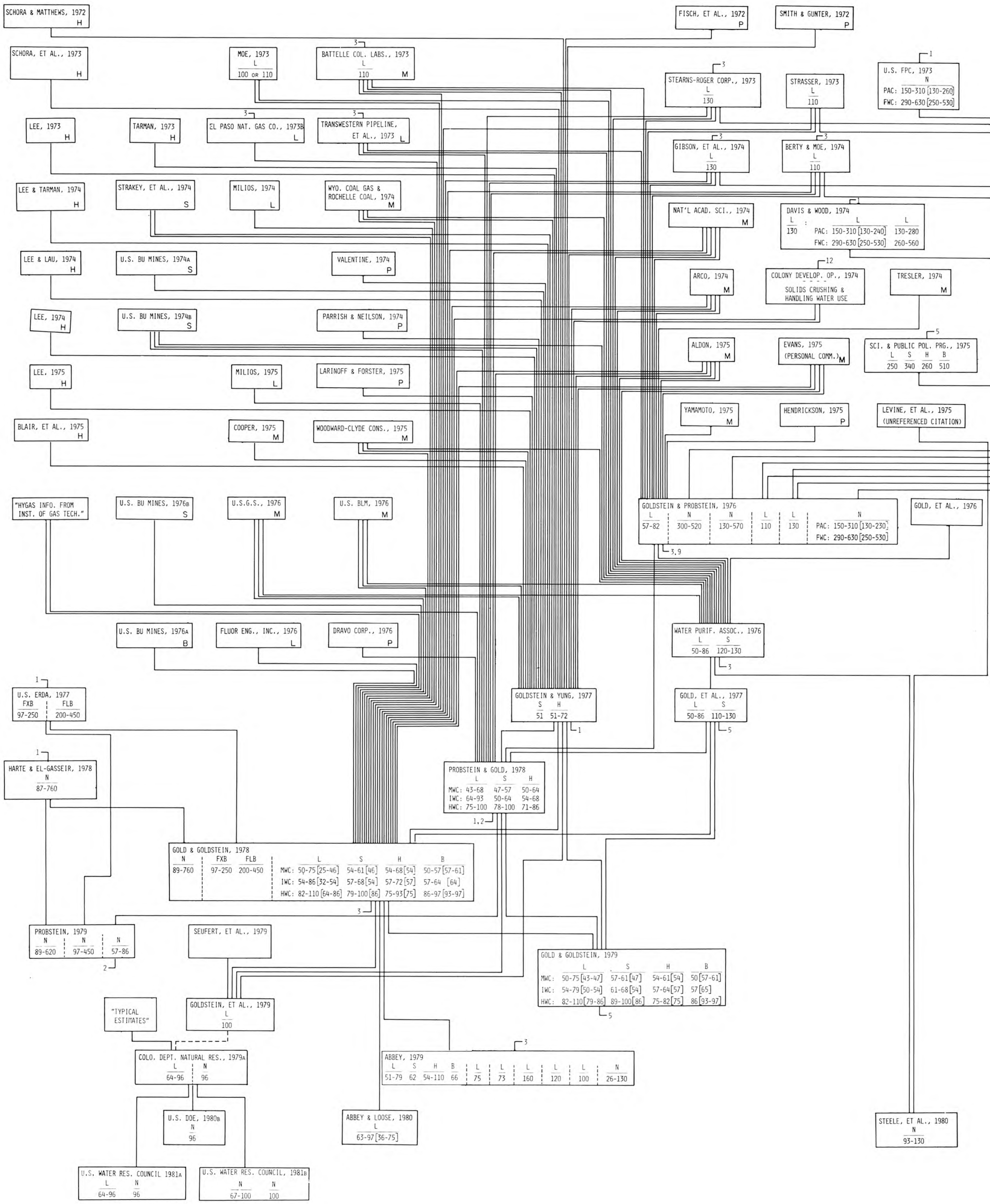
6.3.1 CHART NO. 1 - Water Consumption Estimates for Integrated SNG COAL GASIFICATION Industries
Author Group: Primarily GOVERNMENT OVERSIGHT AGENCIES (NO. 1)
Units: $m^3/10^{12}J$



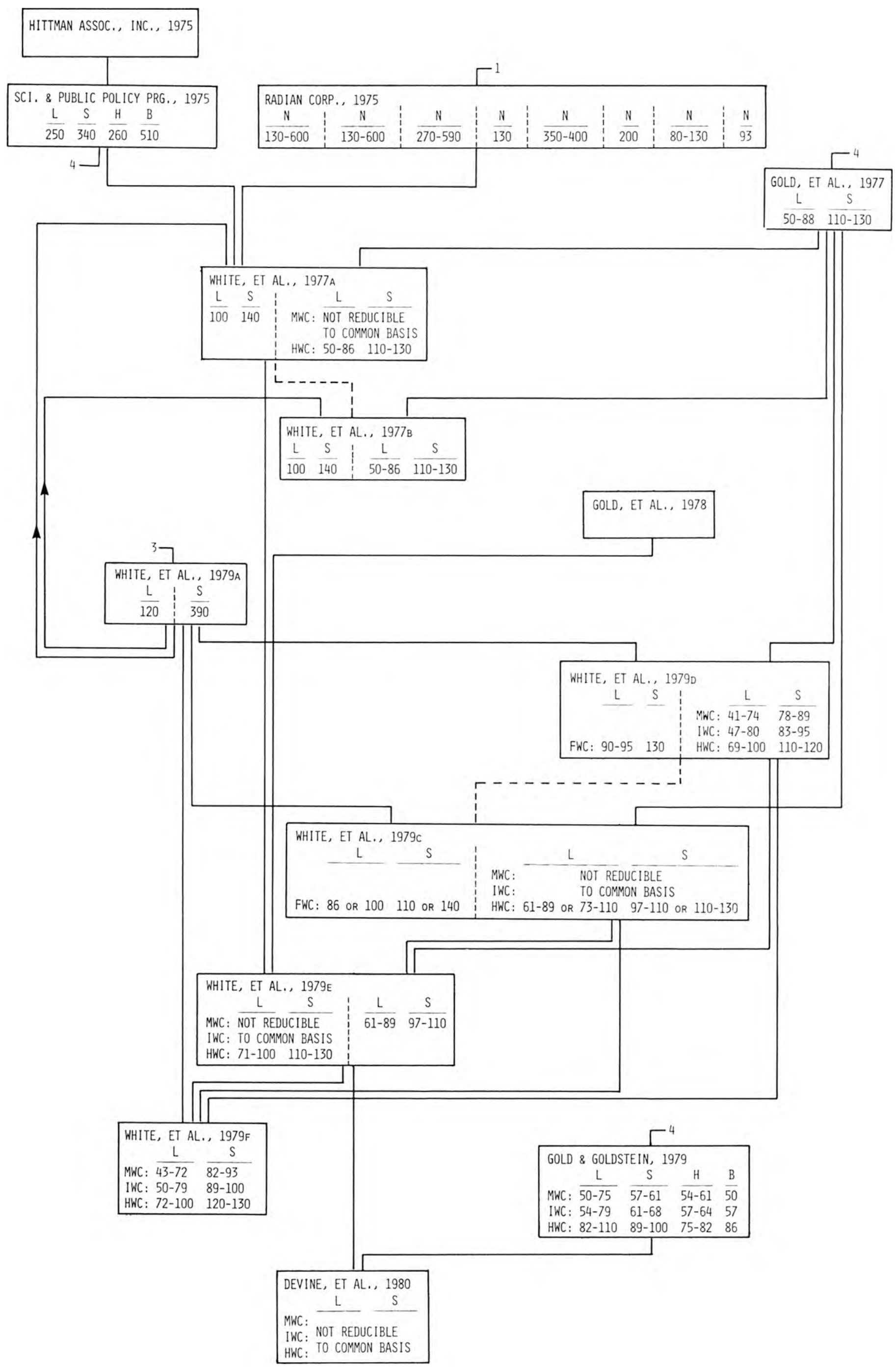
6.3.2 CHART NO. 2 - Water Consumption Estimates for Integrated SNG COAL GASIFICATION Industries
Author Group: Primarily GOVERNMENT OVERSIGHT AGENCIES (NO. 2)
Units: $m^3/10^{12}J$



6.3.3 CHART NO. 3 - Water Consumption Estimates for Integrated SNG COAL GASIFICATION Industries
Author Group: Primarily PROCESS AND PROJECT DEVELOPERS
Units: $m^3/10^{12}J$



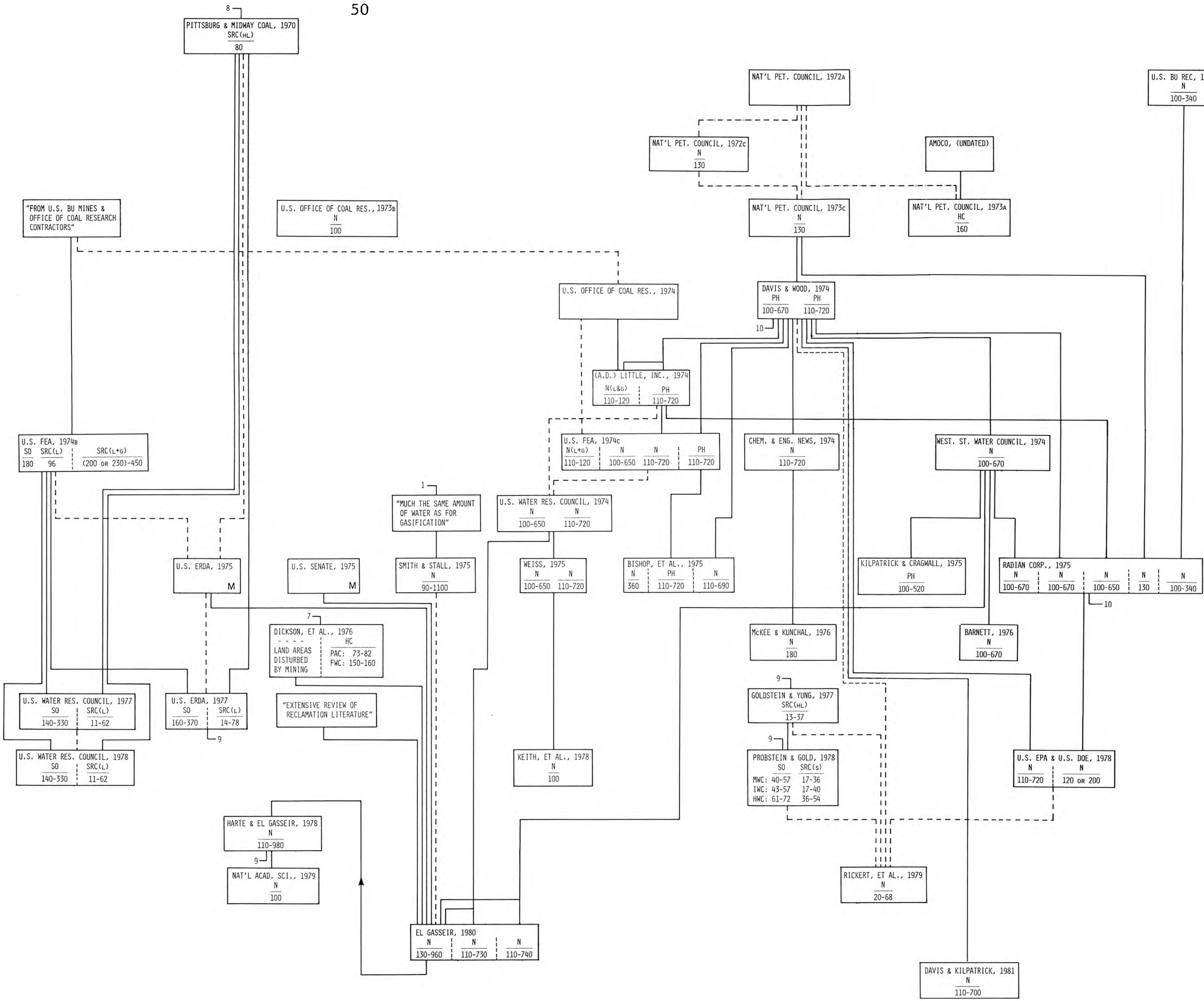
6.3.4 CHART NO. 4 - Water Consumption Estimates for Integrated SNG COAL GASIFICATION Industries
Author Group: Primarily WATER PURIFICATION ASSOCIATES, Cambridge, MA
Units: $m^3/10^{12}J$



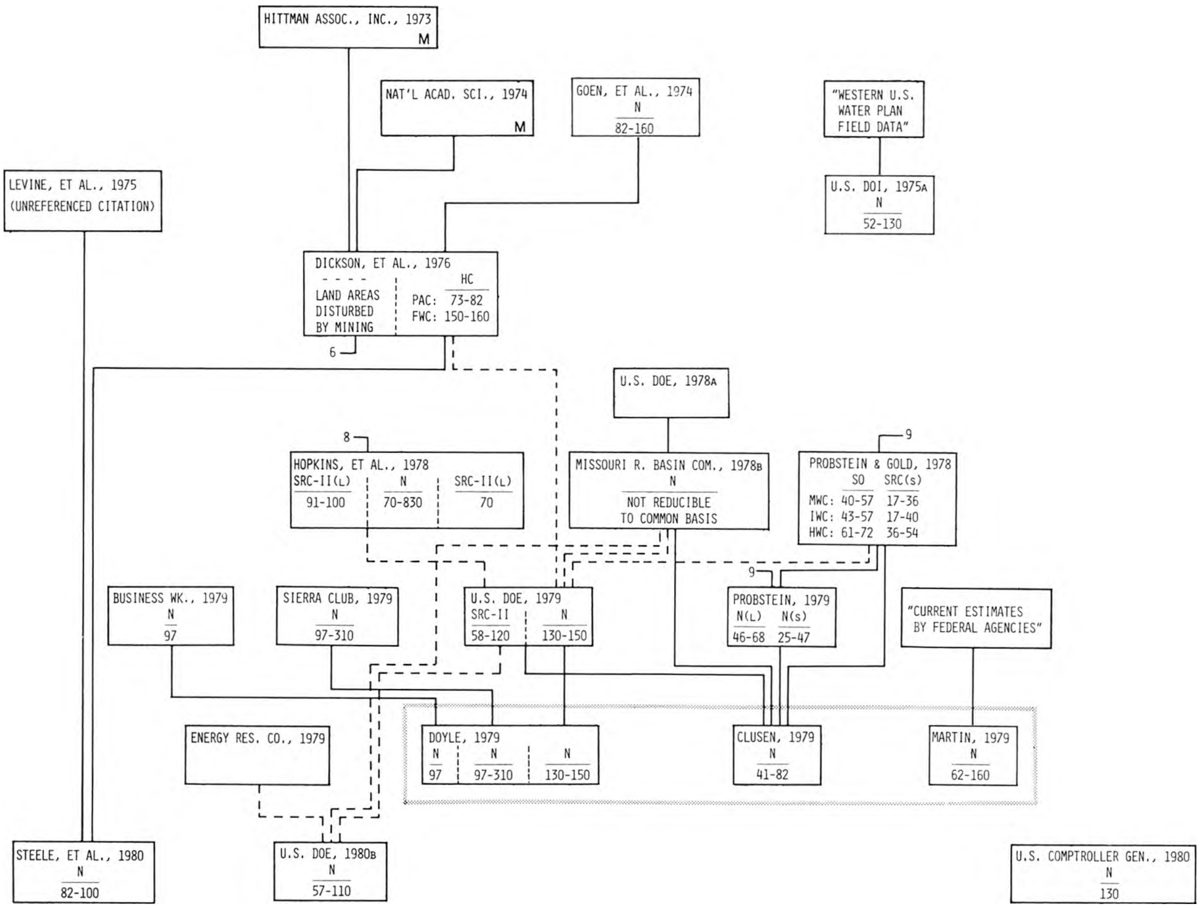
6.3.5 CHART NO. 5 - Water Consumption Estimates for Integrated SNG COAL GASIFICATION Industries

Author Group: SCIENCE AND PUBLIC POLICY PROGRAM, University of Oklahoma, Norman, OK

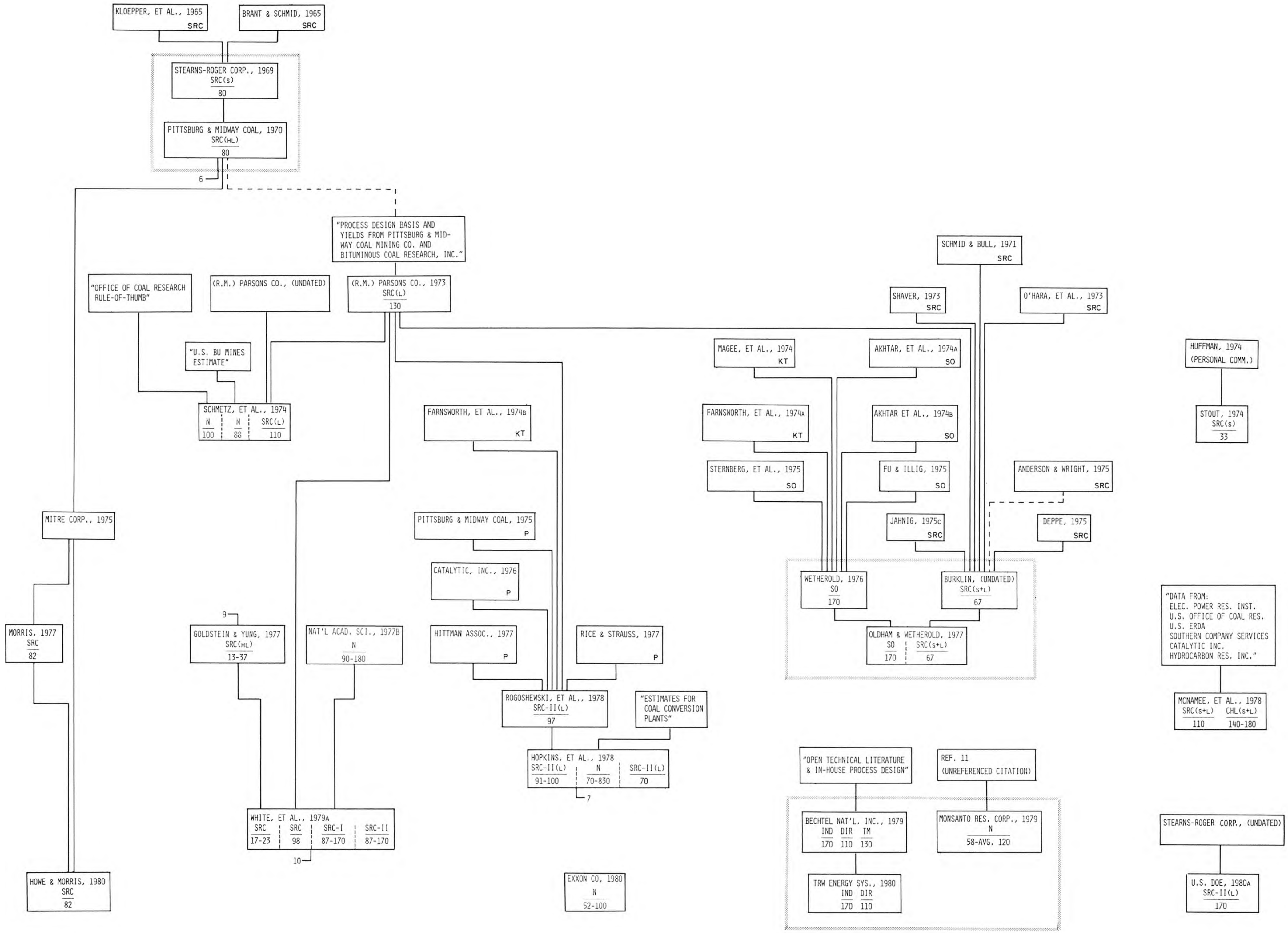
Units: $m^3/10^{12}J$



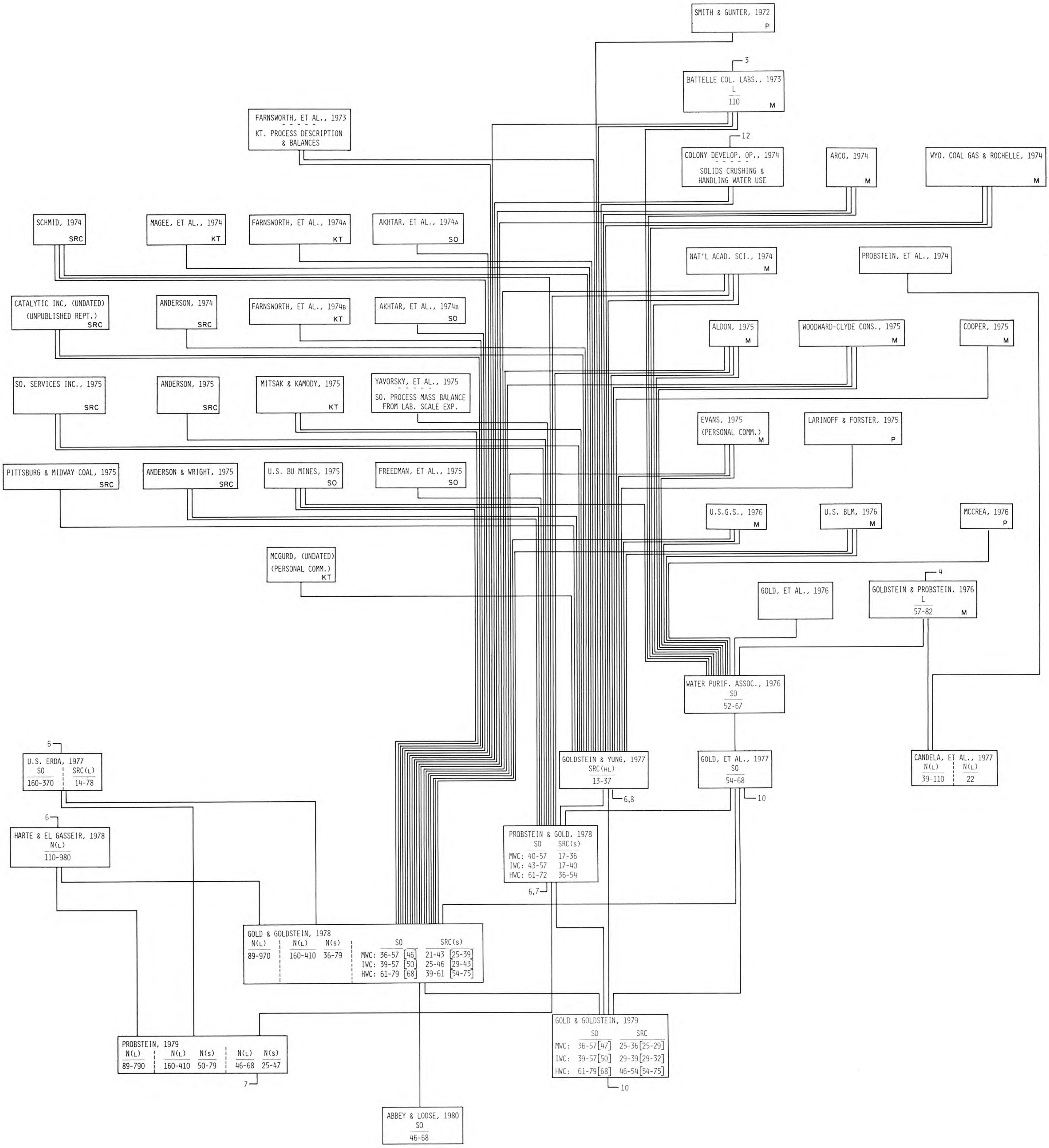
6.3.6 CHART NO. 6 - Water Consumption Estimates for Integrated COAL LIQUEFACTION Industries
Author Group: Primarily GOVERNMENT OVERSIGHT AGENCIES (NO. 1)
Units: $m^3/10^{12}J$



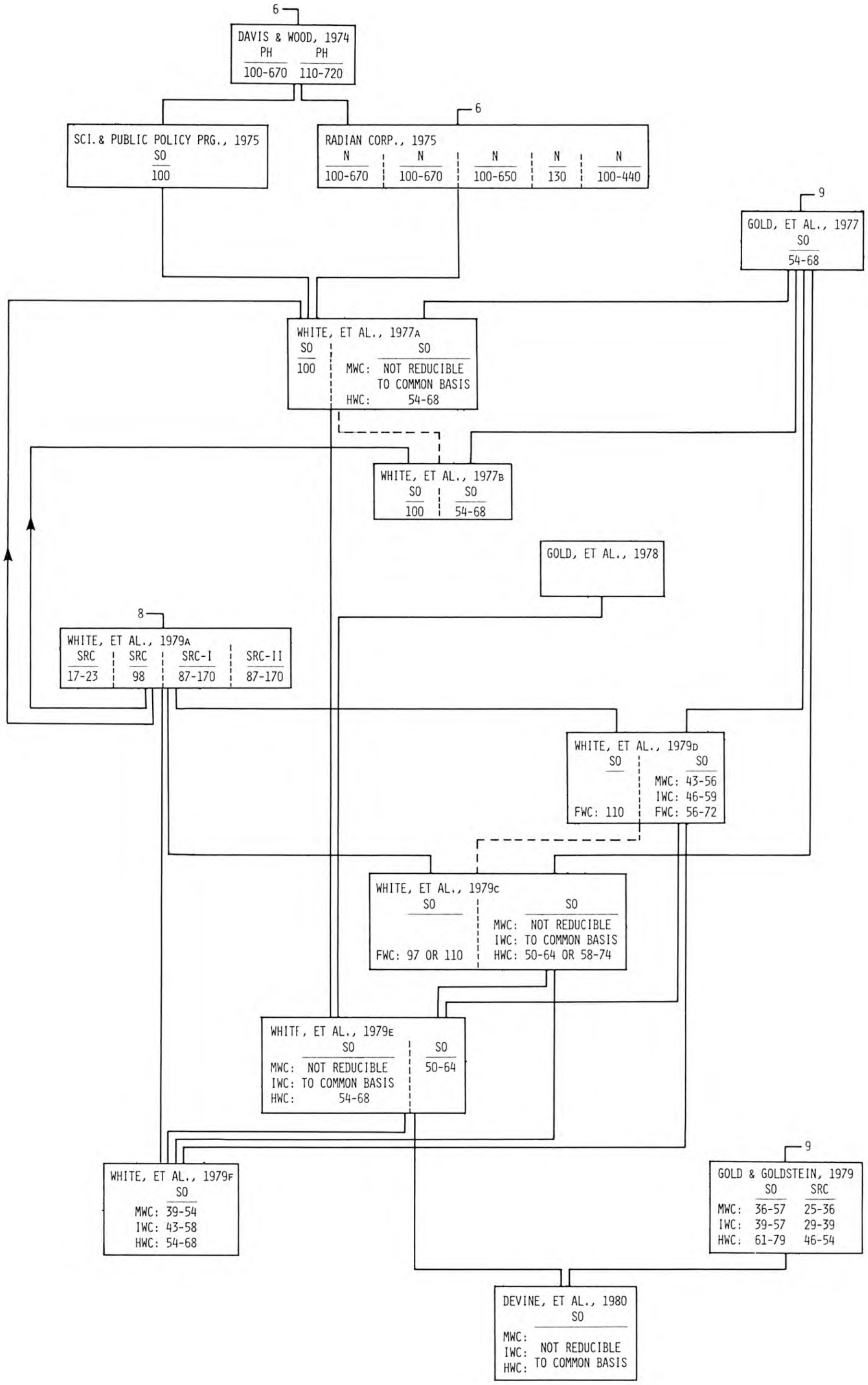
6.3.7 CHART NO. 7 - Water Consumption Estimates for Integrated COAL LIQUEFACTION Industries
Author Group: Primarily GOVERNMENT OVERSIGHT AGENCIES (NO. 2)
Units: $m^3/10^{12}J$



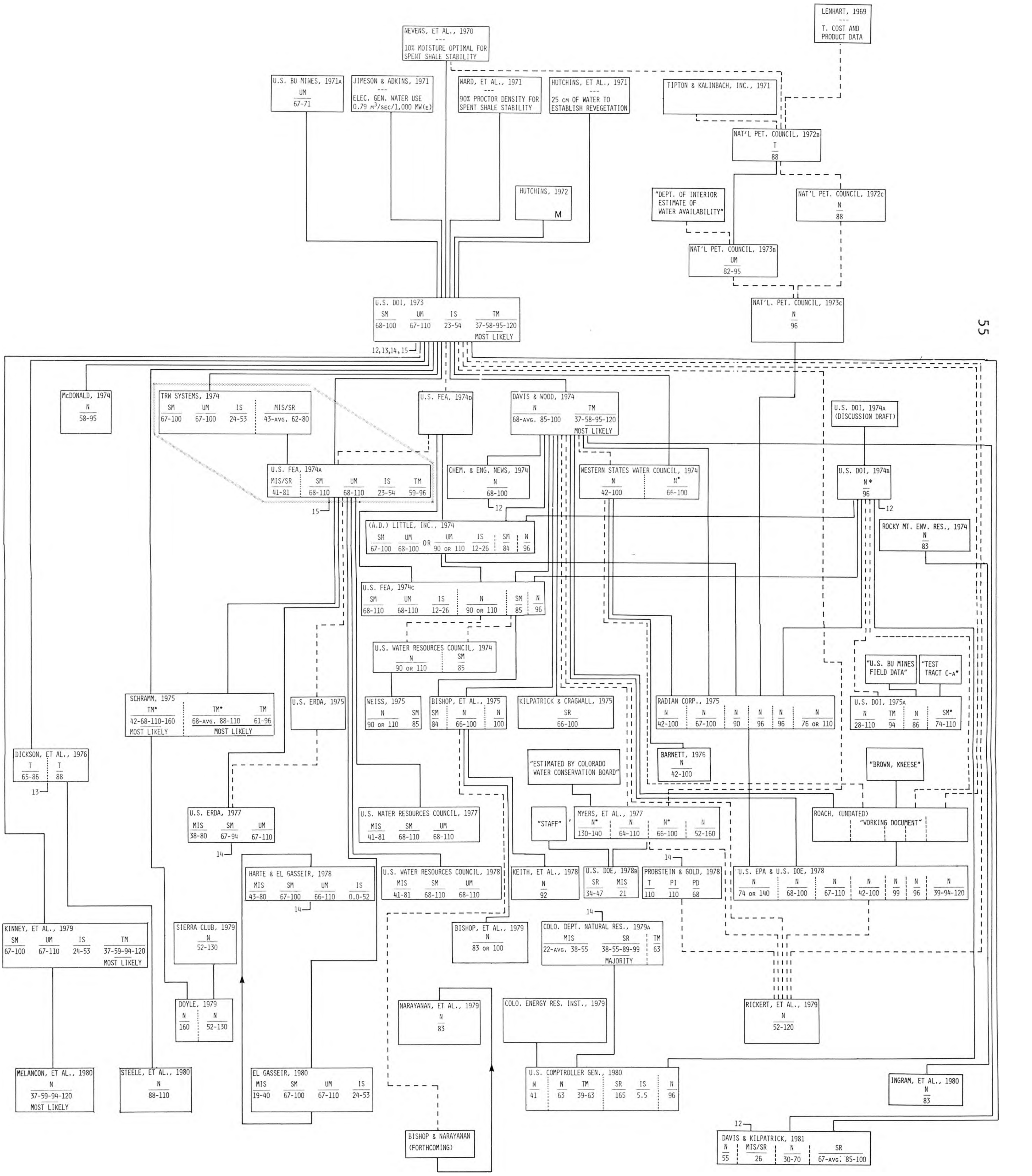
6.3.8 CHART NO. 8 - Water Consumption Estimates for Integrated COAL LIQUEFACTION Industries
Author Group: Primarily PROCESS AND PROJECT DEVELOPERS
Units: $m^3/10^{12}J$



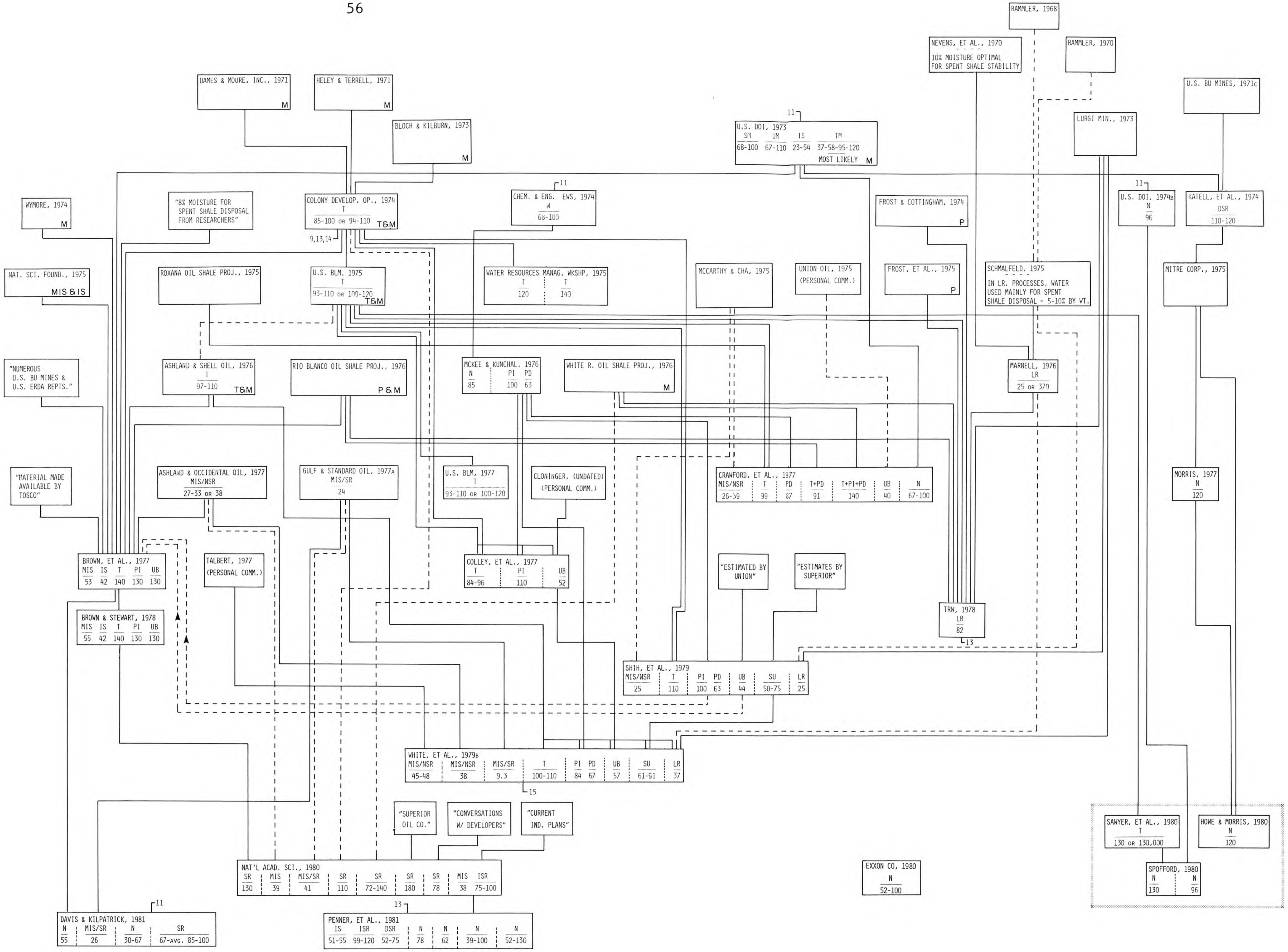
6.3.9 CHART NO. 9 - Water Consumption Estimates for Integrated COAL LIQUEFACTION Industries
Author Group: Primarily WATER PURIFICATION ASSOCIATES, Cambridge, MA
Units: $m^3/10^{12}J$



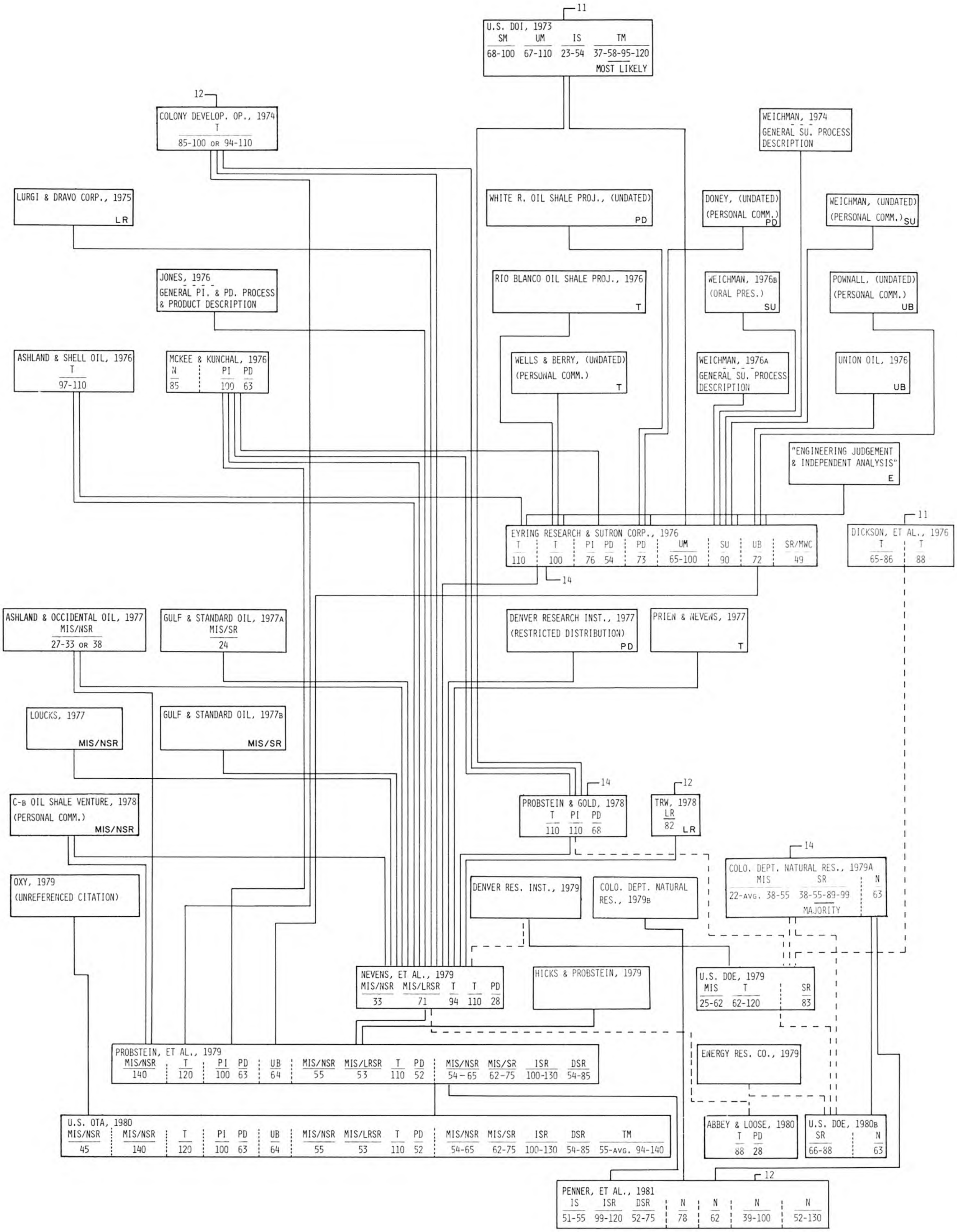
6.3.10 CHART NO. 10 - Water Consumption Estimates for Integrated COAL LIQUEFACTION Industries
Author Group: Primarily SCIENCE AND PUBLIC POLICY PROGRAM, University of Oklahoma, Norman, OK
Units: $m^3/10^{12}J$



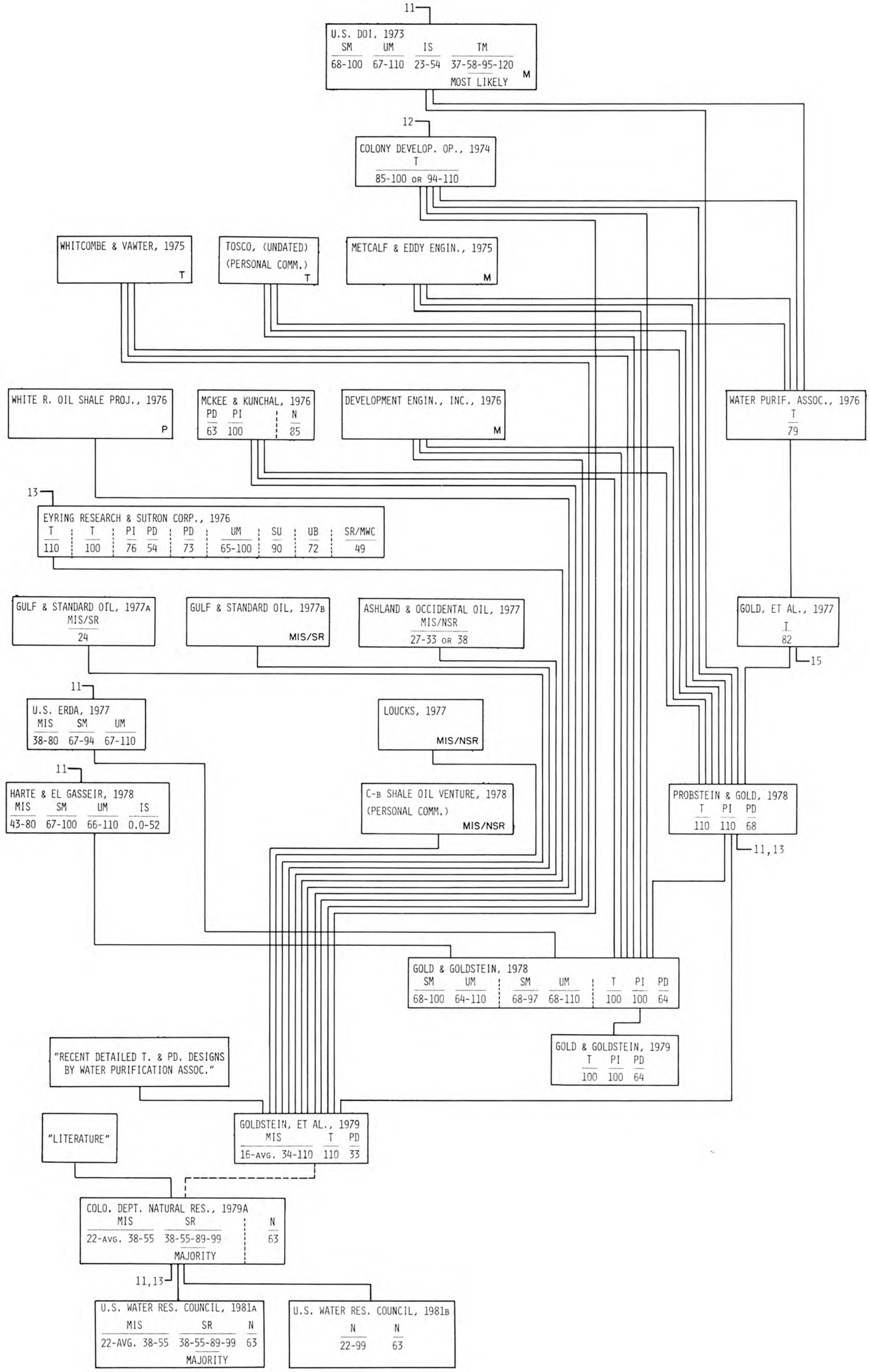
6.3.11 CHART NO. 11 - Water Consumption Estimates for Integrated OIL-SHALE PROCESSING Industries
Author Group: Primarily GOVERNMENT OVERSIGHT AGENCIES
Units: $m^3/10^{12}J$



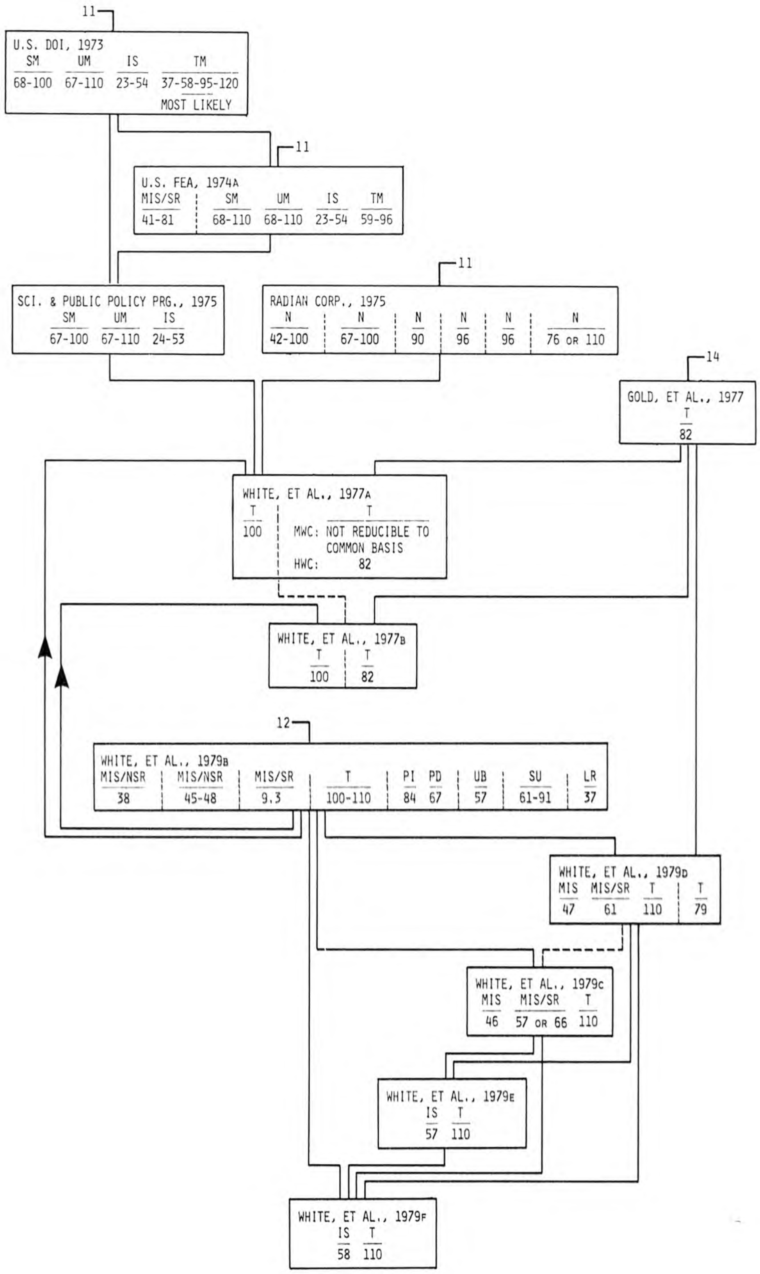
6.3.12 CHART NO. 12 - Water Consumption Estimates for Integrated OIL-SHALE PROCESSING Industries
Author Group: Primarily PROCESS AND PROJECT DEVELOPERS (NO. 1)
Units: $m^3/10^{12}J$



6.3.13 CHART NO. 13 - Water Consumption Estimates for Integrated OIL-SHALE PROCESSING Industries
Author Group: Primarily PROCESS AND PROJECT DEVELOPERS (NO. 2)
Units: $m^3/10^{12}J$



6.3.14 CHART NO. 14 - Water Consumption Estimates for Integrated OIL-SHALE PROCESSING Industries
Author Group: Primarily WATER PURIFICATION ASSOCIATES, Camb., MA
Units: $m^3/10^{12}J$



6.3.15 CHART NO. 15 - Water Consumption Estimates for Integrated OIL-SHALE PROCESSING Industries

Author Group: Primarily SCIENCE AND PUBLIC POLICY PROGRAM, University of Oklahoma, Norman, OK

Units: $m^3/10^{12}J$

CHAPTER 7

DISCUSSION OF SURVEY RESULTS

This chapter contains a discussion of the results of the literature survey on water use by synthetic fuel processes which is summarized in the cross-reference charts of Chapter 6. The discussion emphasizes general statistics on the survey such as the number of reports that were obtained and analyzed for each type of synthetic fuel industry and, of these, how many subsequent reports quoted water use numbers from certain key, earlier reports. Detailed discussions of the individual charts, including explanatory information on specific water-use values, are included in the Appendix to this report.

Although it has not been possible to obtain and analyze every report dealing with water use by synthetic fuel industries that has appeared in the open literature over the last ten years, this survey has attempted to be very extensive and thorough. As an indication of how extensive and thorough it has been, some statistics on it are presented in Table 7.1. In compiling these statistics, care has been exercised to be as accurate as possible. However, due to some ambiguity in the classification of some reports it is possible the numbers may be off by a couple of reports. Reports that appear on more than one chart within an industry grouping have only been counted once.

TABLE 7.1

Summary of Types of Reports Included in Literature Survey

SYNFUEL INDUSTRY	TOTAL REPORTS SHOWN ON CHARTS	REPORTS OBTAINED				REPORTS NOT OBTAINED				
							PROBABLY OBTAINABLE			
		TOTAL	PRIMARY* REFERENCE	SUBSIDIARY** REFERENCE	DERIVED† REPORT	TOTAL	POSSIBLE PRIMARY* REFERENCE	POSSIBLE SUBSIDIARY** REFERENCE	DERIVED† REPORT	PROBABLY NOT OBTAINABLE††
Coal Gasification (SNG)	181	100	19	3	78	81	20	36	9	16
Coal Liquefaction	142	84	20	5	59	58	10	42	1	5
Oil-Shale Processing	155	104	19	8	77	51	16	16	4	15

* Includes reports with no references or sources given for data, process and/or project developer design-analysis reports, and independent engineering design-analysis reports -- usually including material and energy balance information.

** Includes reports supplying data on water requirements for secondary uses (e.g., mining, reclamation, and gas purification) and technical information on processes used as inputs to engineering design analyses.

† Includes reports containing vague references to data sources, reports that borrow water use numbers with little or no alteration, and synthesis reports that borrow water uses intact from different references for different phases of an industry.

†† Includes personal communications, confidential reports, etc.

In Table 7.1, column 2 gives the total number of reports cited in the charts for each of the three synthetic fuel industries. Not all of these reports could be obtained. Those that were not obtained are on the charts because they are cited as references by reports that were obtained. The total number of reports for each synthetic fuel industry that were <u>obtained</u> and analyzed is given in Column 3.

Column 4 gives the "primary references" that were obtained. There are three types of primary references: (1) unreferenced reports that give no explanation or citation for the source of their water-use numbers; (2) process and/or project developer reports that give water use information (presumably based on engineering design analyses); (3) independent engineering design-analysis reports which are based on detailed material and energy balances and usually contain information on the balances.

Column 5 gives the "subsidiary references" that were obtained. There are two types of subsidiary references: (1) reports related to water use for subsidiary off-site (M) and in-plant (P) processes such as mining, reclamation and gas purification; and (2) reports containing technical information on the fuel conversion technologies which provide basic input data for the engineering design analyses.

Column 6 gives the total number of "derived reports" for each synthetic fuel industry that were obtained. There are two types of derived reports: (1) those borrowing water use numbers from references with little or no alteration of the numbers; and (2) synthesis reports which usually combine together water requirements for different aspects of an industry, borrowed from different references. The references may be either specific, cited references or they may be vague references such as "WESCO Current Plans."

Columns 7-10 provide information similar to columns 3-6, but for the reports that were not obtained and analyzed, although they are shown on the charts. In addition, column 11 gives the number of reports that do not appear to be obtainable. These include personal communications, confidential reports, oral presentations and unreferenced citations (where a reference is cited in the text but left out of the reference list).

As can be seen from Table 7.1, if subsidiary references and those not able to be obtained are excluded, approximately 80 percent of the reports listed in the charts were obtained and analyzed. This is approximately 100 reports each for SNG coal gasification and oil-shale processing and 80 reports for coal liquification.

Table 7.2 breaks down the total number of "primary references" that were obtained for each synthetic fuel industry into the three categories explained above. The last column gives the number of the independent engineering design analyses that were performed by the consulting firm of Water Purification Associates (WPA), Inc. of Cambridge, Massachusetts. A listing of the primary references is provided in Table 7.3.

Most of the reports obtainable in the open literature derive their water use numbers directly from other reports. Of those not borrowing directly from other reports, very few contain detailed material and energy balances which allow the reader to understand exactly where the water is used and if the use is reasonable. Of the

TABLE 7.2

Summary of Primary Reports Obtained for Literature Survey

SYNFUEL INDUSTRY	TOTAL NO. PRIMARY REPTS. OBTAINED	REPORTS WITHOUT REFERENCES	DEVELOPER REPORTS	INDEPENDENT ENGINEERING DESIGN-ANALYSIS REPTS.	
				TOTAL	WPA REPTS.*
Coal Gasification (SNG)	19	6	3	10	6
Coal Liquefaction	20	9	2	9	4
Oil-Shale Processing	19	3	9	7	6

*Reports by Water Purification Associates, Inc., Cambridge, Massachusetts.

TABLE 7.3a

Primary Reports Obtained for Literature Survey
(Coal Gasification (SNG))

<u>Reports without References:</u>

SEAY, ET AL., 1972
U.S. BU REC., 1972
SIERRA CLUB, 1973
U.S. OFFICE OF COAL RES., 1973
ROCKY MT. ENV. RES., 1974
EXXON CO., 1980

<u>Developer Reports:</u>

U.S. BU MINES, 1971b
BATTELLE COL. LABS., 1973
STEARNS-ROGER CORP., 1973

<u>Independent Engineering Design Analysis Reports:</u>

KALFADELIS & MAGEE, 1974
SHAW & MAGEE, 1974
THOMAS, 1975
THOMAS, 1976
GOLDSTEIN & PROBSTEIN, 1976*
WATER PURIF. ASSOC., 1976*
GOLDSTEIN & YUNG, 1977*
GOLD & GOLDSTEIN, 1978*
PROBSTEIN & GOLD, 1978*
GOLDSTEIN, ET AL., 1979*

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*Reports by Water Purification Associates, Inc., Cambridge, Massachusetts.

TABLE 7.3b

Primary Reports Obtained for Literature Survey
(Coal Liquefaction)

Reports without References:

U.S. BU REC, 1972
U.S. OFFICE OF COAL RES., 1973
GOEN, ET AL., 1974
NAT'L ACAD. SCI., 1977b
BUSINESS WK., 1979
MONSANTO RES. CORP., 1979
SIERRA CLUB, 1979
EXXON CO., 1980
U.S. COMPTROLLER GEN., 1980

Developer Reports:

STEARNS-ROGER CORP., 1969
(R.M.) PARSONS CO., 1973[†]

Independent Engineering Design Analysis Reports:

BURKLIN, (UNDATED)
WETHEROLD, 1976
MCNAMEE, ET AL., 1978[††]
ROGOSHEWSKI, ET AL., 1978
BECHTEL NAT'L, INC., 1979[††]
WATER PURIF. ASSOC., 1976[*]
GOLDSTEIN & YUNG, 1977[*]
GOLD & GOLDSTEIN, 1978[*]
PROBSTEIN & GOLD, 1978[*]

[*] Reports by Water Purification Associates, Inc., Cambridge, Massachusetts.

[†] May be considered on independent engineering design analysis report.

[††] Probably independent engineering design analysis reports.

TABLE 7.3c

Primary Reports Obtained for Literature Survey
(Oil-Shale Processing)

Reports without References:

ROCKY MT. ENV. RES., 1974
SIERRA CLUB, 1979
EXXON CO., 1980

Developer Reports:

U.S. BU MINES, 1971a
COLONY DEVELOP. OP., 1974
MCCARTHY & CHA, 1975
SCHMALFELD, 1975
ASHLAND & SHELL OIL, 1976
MARNELL, 1976
MCKEE & KUNCHAL, 1976
ASHLAND & OCCIDENTAL OIL, 1977
GULF & STANDARD OIL, 1977a

Independent Engineering Design Analysis Reports:

TRW, 1978
WATER PURIF. ASSOC., 1976*
GOLD & GOLDSTEIN, 1978*
PROBSTEIN & GOLD, 1978*
GOLDSTEIN, ET AL., 1979*
NEVENS, ET AL., 1979*
PROBSTEIN, ET AL., 1979*

*Reports by Water Purification Associates, Inc., Cambridge, Massachusetts.

engineering design analyses based on, and including, material and energy balances, a majority are by Water Purification Associates, Inc.

Table 7.4 is included to provide an indication of how important certain reports have been in influencing the literature. An "originating reference" is considered to be a report in which a water use value, subsequently borrowed by other reports, first appeared in the open literature. It may itself be a derived report, borrowing from a report that is not obtainable (as in the case of U.S. FPC, 1973). Table 7.4 shows the number of derived reports (including synthesis reports) that have borrowed water use values, in substantially unchanged form, either directly or indirectly from certain key originating references. Derived reports which are dependent on vague references such as "WESCO Current Plans" are included. Engineering design analyses that have used data from the originating references are not included. For comparison purposes, the total number of derived reports (including synthesis reports) obtained for each synthetic fuel industry is also shown in the table. Column 4 may total more than Column 2 because some reports borrow numbers from more than one originating reference. It is clear from both Table 7.4 and the structure of some of the cross-reference charts that a few originating references have had a great deal of influence on the literature. The reliability and usefulness of the water-use values given in these originating references are discussed in the following chapter. Further details are given in the Appendix.

TABLE 7.4

Key Originating References

SYNFUEL INDUSTRY	TOTAL NO. OF DERIVED* REPORTS	ORIGINATING REFERENCE**	NUMBER OF DERIVED REPTS.* BORROWING FROM ORIGINATING** REFERENCE
Coal Gasification (SNG)	78	U.S. FPC, 1973	25
		BATTELLE COL. LABS, 1973	20
		STEARNS-ROGER CORP., 1973	23
		WPA Reports†	18††
Coal Liquefaction	59	DAVIS & WOOD, 1974	21
		STEARNS-ROGER CORP., 1969	6
		(R.M.) PARSONS CO., 1973	3
		WPA Reports†	15
Oil-Shale Processing	77	U.S. DOI, 1973	37
		COLONY DEVELOP. OP., 1974	18ξ
		MCKEE & KUNCHAL, 1976	9
		WPA Reports†	13††

* Includes reports containing vague references to data sources, reports that borrow water use numbers with little or no alteration, and synthesis reports that borrow water uses intact from different references for different phases of an industry.

** Reports in which a specific water use number first appeared in the open literature.

† Reports by Water Purification Associates, Inc., Cambridge, Massachusetts.

†† Includes COLO. DEPT. NAT. RES., 1979 and reports derived from it.

ξ Includes ASHLAND & SHELL OIL, 1976 and reports derived from it.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the results of a survey of the open literature for the water-consumption requirements of synthetic fuel industries. For ease of comparison and to facilitate the tracing of the origins of the values, they are presented in a series of cross-reference flow charts in Chapter 6. All of the values presented in the charts have been converted to the common units of $m^3/10^{12}J$ (i.e., the water volume required to produce a product quantity with a total heating value of $10^{12}J$). Associated urban use, when explicitly given, has been excluded from the values. Associated urban use refers to the increase in urban water use caused by the population increase due to the synthetic fuel industries. All other water uses associated with "integrated" synthetic fuel industries, such as those for raw resource recovery (e.g., mining) and environmental control (e.g., spent shale disposal and revegetation), are included in the values given in the charts, when such information has been provided in the references. Because this review assumes zero discharge of wastewater back to sources, all input water streams to an industry are considered to be consumed. Other assumptions involved in the reduction of the data to the common basis are reviewed in Chapter 5. In this chapter the results of the survey will be summarized (Section 8.1) and recommendations for water-use estimates will be presented (Section 8.2).

8.1 Summary of Reported Estimates of Water Consumption by Synthetic Fuel Industries.

As explained in Chapter 7, most of the reports covered in this survey borrowed their water-use values, fairly unchanged, from other reports. As shown in the charts in Chapter 6 and summarized in Table 7.4, just a handfull of originating references (reports in which given water-use values first appeared in the literature) are responsible for a majority of the water-use values quoted in the open literature. Therefore, a good indication of the range of water-use estimates found in the open literature can be obtained by examining the values given in these originating references. This is done in Table 8.1.

Three classes of originating references are represented in Table 8.1: (1) The estimates in the first column are from the reports of Water Purification Associates, Inc. (WPA). They are based on detailed engineering design analyses, including material and energy balances, performed by an independent engineering firm. (2) The estimates in the second column are based on design studies performed by synthetic fuel process and/or project developers. They are usually site specific. (3) The estimates in the third column are from those general originating reference (not themselves belonging to the classes in the first two columns) that have been the most borrowed from in the literature (see Table 7.4).

The WPA numbers in Table 8.1 represent the extremes of the ranges found in the major WPA reports. They were developed for fully integrated industries producing upgraded products on a site-specific

TABLE 8.1

Estimates of Unit Water Requirements of Synthetic Fuel Industries
Summary of Originating Reports in Literature Survey
(Associated Urban Use is Excluded)

UNITS: $m^3/10^{12}J$

SYNFUEL INDUSTRY	WPA REPORTS		DEVELOPER REPORTS		GENERAL REPORTS	
	Reference	Estimate	Reference	Estimate	Reference	Estimate
Coal Gasification* (SNG)	PROBSTEIN & GOLD, 1978 GOLD & GOLDSTEIN, 1979	43-110	BATTELLE COL. LABS., 1973 STEARNS-ROGER CORP., 1973	110 130	U.S. FPC, 1973	150-630
Coal Liquefaction*	GOLD & GOLDSTEIN, 1979	36-79	(R.M.) PARSONS CO., 1973† U.S. DOE, 1980a	130 170	DAVIS & WOOD, 1974	100-720
Oil-Shale Processing	GOLD & GOLDSTEIN, 1979 PROBSTEIN & GOLD, 1978	64-110	COLONY DEVELOP. OP., 1974 MCKEE & KUNCHAL, 1976	85-110 63&100**	U.S. DOI, 1974	37-120

* For bituminous and subbituminous coals.

** Low number for Paraho-direct retorting, high number for Paraho-indirect retorting.

† May be considered an independent engineering analysis rather than a developer report.

basis. In most cases all water uses have been included except associated urban use.

The low end of the WPA range for coal-gasification water use is for a Lurgi plant using the maximum amount of dry cooling that is economically justifiable. The plant location is <u>outside</u> of the hot, arid southwest. For the Four-Corners region this number (still using the maximum amount of dry cooling that is economically justifiable) could be as much as 60 percent higher. The high end of the range is for a Lurgi plant not purposely using dry cooling (i.e., using high wet cooling), located in the Four-Corners region. Siting information for the coal liquefaction plants analyzed by WPA to give their coal liquefaction water-use range is similar to that for coal gasification. The plants considered are synthoil plants. For oil-shale processing, the low end of the WPA water-use range is for Paraho-direct surface retorting at Rifle, Colorado. It is possible this value is based on the total energy output of the plant, including by-products. If so, this value would be 68 $m^3/10^{12}J$ if it were based on the energy content of the syncrude product only. The high end of the water use range for oil-shale processing is for TOSCO-II or Paraho-indirect surface retorting, also at Rifle Colorado. It appears that the TOSCO-II value does not include the water used to produce the electricity consumed in the plant. However, a later WPA report, Goldstein, et al., 1979, gives virtually the same water use including electricity generation (though possibly less water for revegetation). The range in oil-shale processing water use is primarily due to different spent-shale disposal practices. All of the oil-shale processing plants are credited as using intermediate levels of evaporative cooling.

The developers' estimates of water consumption for SNG coal gasification come from site specific development plans for the Four-Corners region. The Wesco plant is described in Battelle Col. Labs., 1973, and the El Paso plant in Stearns-Rogers Corp., 1973. The primary differences appear to be that the El Paso design calls for on-site generation to cover <u>all</u> electrical needs and uses fresh river water for mine dust control.

The developers' estimates for coal liquefaction are for SRC-II plants producing liquid products at room temperature. Both reports consider only high wet cooling at eastern sites. In the Parson's design, one-third of the raw intake water (used in deriving the value shown in Table 8.1) is returned to the source. The DOE report states the water use as "consumption." Neither report includes water use at the mine, but the Parsons' report does include on-site electricity generation. Properly speaking, neither report is a developer report since they were both written by or for the government. However, the DOE report was derived directly from a developer's report and the Parsons' report relied on data supplied by a developer.

The developers' estimates for oil-shale processing water use are for surface retorting projects located near Rifle, Colorado. Colony Develop. Op., 1974, describes a proposed TOSCO-II retorting operation while McKee & Kunchal, 1976, describes proposed Paraho retorting operations. The lower value from McKee & Kunchal, 1976, is for Paraho-direct retorting and the higher for Paraho-indirect retorting.

Electricity needs are not included in the Colony report but are in the McKee and Kunchal report.

The "general estimate" for SNG coal-gasification water use comes from U.S. FPC, 1973. That report cites as its data source a <u>confidential</u> American Gas Association study (Am. Gas Assoc., 1971). Thus a technical analysis to substantiate this range (the high end of which is approximately five times greater than the high WPA estimate) is not available in the open literature. The U.S. FPC report, however, does state that the high end of the range is for full evaporative cooling using low quality make-up water (the make-up rate being 7 percent of the cooling water circulation rate). It also states that the number includes process, cooling, and power generation needs, as well as blowdown.

The "general estimate" for coal liquefaction comes from Davis & Wood, 1974, a U.S. Geological Survey report. The low end of the range given in that report comes from a 1973 National Petroleum Council report (Nat'l Pet. Council, 1973c), but <u>no</u> reference or explanation is given for the high end of the range, which is an order of magnitude greater than the WPA high estimate.

The "general estimate" for oil-shale processing comes from U.S. DOI, 1973, the U.S. Department of Interior's Environmental Impact Statement for the Prototype Oil Shale Leasing Program. This appears to be a synthesis report. In it, mining, retorting, and upgrading information come from U.S. Bureau Mines, 1971a. This is a developer report based on the U.S. Bureau of Mines' Combustion retort process. It does not give a detailed breakdown of water use, but does specify the equipment involved. In U.S. DOI, 1973, water use for electricity generation, spent-shale disposal and revegetation come from separate, primarily technical, reports.

From the foregoing discussion and from an examination of the cross-reference charts in Chapter 6, it appears that the WPA high-estimate values, derived from careful engineering analyses, are comparable to water-use estimates published by actual process developers. On the other hand, the high ends of the general estimates, especially for coal gasification and coal liquefaction, are poorly founded and do not appear to represent reality, at least not for future use of good-quality water in zero-discharge plants.

8.2 Recommended Estimates of Water Consumption by Synthetic Fuel Industries

Based on the extensive survey of the open literature reviewed in this report, it was decided to rely on the studies of Water Purification Associates, Inc. (WPA), Cambridge, Massachusetts, for estimates of water consumption by synthetic fuel industries. The WPA reports comprise the majority of the "independent" engineering design analyses of synthetic fuel plants. In addition, they have given special attention to careful use of water. Although many of the inputs to their analyses have come from process and/or project developers and additional assumptions also had to be made, these inputs and assumptions have been clearly indicated and given critical examination. Although it is impossible to predict exactly what the water requirements will be of the nonexistent synthetic fuel industries, the WPA value should serve as reasonable estimates until actual operating data from commercial installations are available.

The high ends of the WPA ranges shown in Table 8.1 are considered here to be <u>conservative</u> "best guesses" for estimating purposes. These values are 110 $m^3/10^{12}J$ for SNG coal gasification and oil-shale processing (producing an upgraded product) and 79 $m^3/10^{12}J$ for coal liquefaction (producing a liquid product at room temperature). These are considered conservative in the sense of erring on the side of overpredicting water use. This is because, for the coal conversion industries, only high evaporative cooling is considered. Because of the "zero discharge" nature of plants now being built in the arid west, industry is becoming very sensitive to the costs incurred from having to dispose of large quantities of cooling-tower blowdown (Abbey & Lucero, 1980, and Lihach, 1981). This should encourage high rates of in-plant recycle and use of partial air cooling. Furthermore, the WPA estimates are for plants located in the hottest, dryest part of the country. The estimates are for bituminous and subbituminous coal feeds. For lignite feeds, the estimates are lower. For the oil-shale conversion processes, only surface retorting methods involving highly water-consumptive methods of spent-shale disposal and reclamation are considered.

The low ends of the WPA ranges shown in Table 8.1 are considered here to be minimum probable requirements. These values are 43 $m^3/10^{12}J$ for SNG coal gasification, 35 $m^3/10^{12}J$ for coal liquefaction (producing a liquid product at room temperature), and 54 $m^3 10^{12}J$ for oil-shale processing (producing an upgraded product). For the coal conversion processes, high degrees of partial air cooling are employed and the estimates are for plants located <u>outside</u> of the hottest, dryest part of the country. The estimates are for bituminous and subbituminous coal feeds. For lignite feeds, the SNG estimate might be about 40 percent lower. For oil-shale processing, only direct surface retorting, combined with on-site upgrading are considered. It is possible the oil-shale processing water use could be reduced by about 50% if the product is not upgraded on site, or if modified (or true) in-situ retorting prove to be economically and environmentally sound (Goldstein, et al., 1979).

From the WPA data in the cross-reference charts of Chapter 6, it is also possible to hazard "best guesses" for water consumption by synthetic-fuel developments in the 21st century. The following estimates are made under two general assumptions: (1) that "zero discharge" of wastewater is the rule and (2) that use of wet/dry cooling on stream-turbine condensers is standard practice. From an examination of the WPA charts in Chapter 6 for <u>all</u> technologies and <u>intermediate</u> levels of wet cooling, it appears that a best guess for both SNG coal gasification and oil-shale processing (upgraded product) might be about 80 $m^3/10^{12}J$, while for coal liquefaction (liquid product) it would be about 60 $m^3/10^{12}J$. The high end of the ranges for bituminous and subbituminous coals are considered because these are for sites in the hot, arid southwest.

Therefore, as a "rule of thumb" for water consumption by future synthetic fuel industries, a best guess would be about 80 $m^3/10^{12}J$ and a <u>conservative</u> best guess would be about 110 $m^3/10^{12}J$.

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APPENDIX

DETAILED DISCUSSIONS OF INDIVIDUAL CHARTS

The results of the literature survey for water consumption rates of synthetic fuel industries summarized in the charts presented in Chapter 6 are discussed in some detail in this appendix. Each chart is discussed individually. The primary purposes are to highlight the ultimate sources where the most quoted water use values originated and to determine what is included in the values (e.g., what phases of an industry) and what the values are based on. The transmission of the values through the literature is traced with emphasis on reports that formed key nexus and on inconsistencies (errors?) in the transmission of data.

A-1 Chart No. 1 - Coal Gasification (SNG) - Government Oversight Agencies (No. 1)

There are two primary (though connected) families of reports shown in Chart No. 1: reports related to the Project Independence report U.S. FEA, 1974b, and reports related to U.S. FPC, 1973. The primary sources for the water-use values found in U.S. FEA, 1974b, are general and vague in nature. The primary reference for U.S. FPC, 1973, is AM. GAS ASSOC., 1971. Unfortunately, this key reference is cited as a confidential report and is, apparently, not available in the open literature. Written requests to the American Gas Association for it were unsuccessful. Therefore, there is no way to determine the actual origin of these numbers.

DAVIS & WOOD, 1974, appears to be a key nexus in the transmission of information from U.S. FPC, 1973, to the rest of the literature. The reason for two different sets of water-use values appearing in the box labeled DAVIS & WOOD, 1974, both apparently derived from U.S. FPC, 1973, is because Davis and Wood not only borrowed water-use rates in units of gallons per minute directly from U.S. FPC, 1973, but also converted the rates to unit of gallons/10^6Btu. It appears that, in the conversion, Davis and Wood assumed that the plant capacity, given as 250 billion Btu per day (250 million scf per day), was per calendar day rather than per stream day as implied in U.S. FPC, 1973. Since this ambiguity has been passed on in the literature, both sets of values are given in the chart. Davis and Wood also indicate these values are for Lurgi technology, but the type of technology related to water use does not appear to be specified in U.S. FPC, 1973. Both DAVIS & WOOD, 1974, and U.S. FPC, 1973, agree, however, that the ranges in water-use values for both partial air cooling ("PAC") and full wet cooling ("FWC") are due to the quality of the make-up water. The high end is for low quality make-up water, requiring a make-up rate which is 7% of the recirculation rate. The low end is for higher quality make-up water, requiring a make-up rate which is only 3% of the recirculation rate. Furthermore, U.S. FPC, 1973, also states that both cooling and process water needs (including electric power generation) are considered and that blow-down has <u>not</u> been subtracted from the water needs (therefore, "zero discharge" plants). However, mine-related off-site uses, such as reclamation, are not mentioned.

To show how AM. GAS ASSOC., 1971, is the ultimate reference for many reports and how DAVIS & WOOD, 1974, is the key nexus for the transmission of the information, and also to illustrate how the charts may be used, it is instructive to trace through the derivation of the water-use value for coal gasification that appears in NAT. ACAD. SCI., 1979 (the CONAES Report). This value of 82 $m^3/10^{12}J$, for a nonspecific technology, comes from the low end of the range given in HARTE & EL GASSEIR, 1978, 87-760 $m^3/10^{12}J$. The low end was chosen "since engineering practice will tend to improve." This is the only indication of the extent of recycle or degree of air cooling. The discrepancy in the values between 82 $m^3/10^{12}J$ and 87 $m^3/10^{12}J$ is probably due to rounding of the value given in NAT. ACAD. SCI., 1979. The range stated in HARTE & EL GASSEIR, 1978, was borrowed from EL GASSEIR, 1980, which was not published until two years after HARTE & EL GASSEIR, 1978. The high-end value in HARTE & EL GASSEIR, 1978, may be for lignite conversion as shown by the square brackets in EL GASSEIR, 1980. Unbracketed numbers are for bituminous, subbituminous or unstated types of coal. El Gasseir's water-use range comes from adding off-site uses (viz., mining and reclamation) to a range for in-plant water uses derived from three apparently independent estimates. (The values given in a fourth reference, actually a series of reports, U.S. BU MINES, 1976c, are said to all fall within those ranges, thus "confirming them.")

The left most of the three borrowed estimates, 83-1000 $m^3/10^{12}J$, was borrowed from SMITH & STALL, 1975. No reference for the high end of the water-use range given in SMITH & STALL, 1975, is cited directly, although a bibliography is provided. HOGLAND & ASBURY, 1974, contains the highest water-use value of any reference listed in the "Coal Conversion" section of Smith and Stall's bibliography. This is why a dashed line is used in the chart to indicate some uncertainty in the citation. No explanation is offered for the high end of the range in SMITH & STALL, 1975. It is nearly double the high end in HOGLAND & ASBURY, 1974. The high-end ranges given in HOGLAND & ASBURY, 1974, come from U.S. FPC, 1973, and thus, ultimately, from AM. GAS ASSOC., 1971. The slight discrepancy in values is due to the conversion in the present report to the common basis. In U.S. FPC, 1973, plant output is given in terms of product energy content. In HOGLAND & ASBURY, 1974, however, it is given in terms of product volume with no heating value given, thereby necessitating the use of the default heating value.

Now considering the middle estimate in EL GASSEIR, 1980, 260-570 $m^3/10^{12}J$, this range was borrowed from U.S. WATER RES. COUNCIL, 1974. That report was part of the Project Independence family of reports. The reason for two ranges appearing in the box for U.S. WATER RES. COUNCIL, 1974, 0.26-0.56 $m^3/10^{12}J$ or 260-560 $m^3/10^{12}J$, is that two ranges in different units are given in the same table in the report. In one case, "MSCF" is designated (in a footnote to the table) as meaning million standard cubic feet. It probably should be thousand standard cubic feet. No reference is given for the table, but it is identical (without the "MSCF" footnote) to a table that appears in another Project Independence report, U.S. FEA, 1974c. Therefore dashed lines have been used in the chart to show the probable connections. The table in U.S. FEA, 1974c, cites (A.D.) LITTLE, INC., 1974, as its reference. The A.D. Little report cites DAVIS & WOOD, 1974, as its reference, and thus the trail again leads back to AM. GAS ASSOC., 1971.

Finally considering the right-hand member of the three borrowed estimates, 130-580 $m^3/10^{12}J$, the cited reference is WEST. ST. WATER COUNCIL, 1974. This reference gives two different ranges for water use in coal gasification in two different tables (in different units) on the same page. No reason for the differences is given. Therefore two separate ranges are given in the chart box. WEST. ST. WATER COUNCIL, 1974, cites as its general reference DAVIS & WOOD, 1974. Therefore, the trail leads back once again to AM. GAS ASSOC., 1971.

Therefore, the high ends of all three apparently independent ranges used in EL GASSEIR, 1980, come from the same ultimate source, AM. GAS ASSOC., 1971 -- and that source is unobtainable. What is known is that the high-end values are claimed to be based on full wet cooling using very poor quality make-up water, blow-down is included in the water needs and off-site uses are not included (although electric power generation needs are). In addition, the high-end value borrowed by HARTE & EL GASSEIR, 1978, is probably for industries using lignite feed stocks.

The <u>low</u>-end value adopted by EL GASSEIR, 1980, comes from three sources: the same, unavailable ultimate reference as the high-end value and also design plans for the Wesco and El Paso coal gasification plants. These design plans will be discussed below in Section A-3.

Considering some of the other reports summarized in Chart No. 1, U.S. BU REC., 1972, cites no reference for its water-use values and gives no basis nor explanations for them. The same situation pertains to NAT´L PET. CONCIL, 1973c. NAT´L PET. COUNCIL, 1972a may have been the source, but it is no longer available from the National Petroleum Council and may never have been available. The values given in SEAY, ET AL., 1972, are for the Hygas process using electrothermal production of H_2, thus necessitating a large amount of electric power production. The range is for absolute minimum water consumption to what it would be with partial air cooling. Off-site uses are not mentioned and neither is a reference for the numbers.

The numbers given for RADIAN CORP., 1975, were obtained for this survey from a poor copy of a hard-to-read table and may contain reading errors. Besides references, no other explanatory information on the numbers is given in the report. The range of values given in RICKERT, ET AL., 1979, is not explained and neither a basis nor a direct reference is given. The references shown in Chart No. 1 are the most likely ones listed in the report´s bibliography. The values had to be read from a bar graph and thus the values given in the chart may be inaccurate. The very high range of 630-4,100 $m^3/10^{12}J$ given in BISHOP, ET AL., 1975, appears to be due to a copy error in borrowing from its source. The coal <u>liquefaction</u> numbers given in U.S. WATER RES. COUNCIL, 1974, were borrowed instead of the gasification numbers.

The Project Independence family of reports is very confusing. The very high water-use values given in the left-hand partitions of U.S. FEA, 1974c, and (A.D.) LITTLE, INC., 1974, are from identical tables. Off-site water use is not included in the tables. The ranges are due to use of partial air cooling (reducing cooling water use approximately 50%) and use of the moisture on the feed coal (water recovered in the mining operation). It is possible that the table gives the cooling water recirculation rate rather than the make-up rate, but the recirculation rate should not be reduced 50% by use of partial air cooling. U.S. FEA, 1974b, is even more difficult to decipher. In this box the partition line separates values found in different parts of the report. In the right-hand partition, off-site water uses do not appear to be included although electric power production is. The Lurgi value ("L") includes a 50% reduction in water use due to partial air cooling. The range for synthane ("S") is also due to a 50% reduction due to use of partial air cooling and the use of the moisture on the feed coal. No explanations are made for the numbers in the left-hand partition. The ranges given in U.S. WATER RES. COUNCIL, 1977 and 1978, and U.S. ERDA, 1977, are due in part to assuming a 50% reduction in water use due to water recycling, and in part by using the water contained in the input coal.

A-2 Chart No. 2 - Coal Gasification (SNG) - Government Oversight Agencies (No. 2)

The two primary families in this chart consist of the reports of the Northern Great Plains Resources Program (NGPRP) and the "Water for Energy" studies of the Department of the Interior's Denver Management Team. Not all of the earlier NGPRP reports cited in later reports were obtained, so there is some question as to the structure of the chart (see dashed lines on chart). The range of water consumption values recommended in NO. GT. PLNS. RES. PRG., 1974a, 80-130 $m^3/10^{12}J$, appears to have been borrowed by many subsequent reports. The high end of this range appears to be based on the El Paso, New Mexico, gasification-plant design, EL PASO NAT. GAS CO., 1973b. This design entails extensive use of internal water recycle and partial air cooling (see Section A-3). The dual values shown in the El Paso partition of NO. GT. PLNS. RES. PRG., 1974a, are because the water-use rates are given in terms of both gal/min and acre-ft/yr. It is not apparent why the converted numbers do not match.

The low end of the recommended range given in NO. GT. PLNS. RES. PRG., 1974a, may have come from two sources, both are personal communications. NEWSOM, 1974, projects the benefits of improved water treatment and the resulting increased rate of internal recycle. COCHRAN, 1974, projects the benefits of the improved efficiency due to second generation technologies. A few values from U.S. FPC, 1973, are also mentioned in passing in NO. GT. PLNS. RES. PRG., 1974a, but are not shown in its chart box.

Although NO. GT. PLNS. RES. PRG., 1975, cites no references directly for its water use numbers, it does claim NO. GT. PLNS. RES. PRG., 1974b, as a general reference. A single, high value from U.S. FPC, 1973, is also given, but is said to include significant wastewater discharge. The numbers which have been passed along are the same as those given in NO. GT. PLNS. RES. PRG., 1974a. The El Paso value appears to form the basis of their "best estimate," 9,500 acre-ft/yr, which converts to 130 $m^3/10^{12}J$. Their numbers are stated to be for Lurgi technology and to be for "zero discharge" plants.

They appear to be for in-plant uses only. The high end of the higher range given in this report (160 $m^3/10^{12}J$, given as 12,000 acre-ft/yr) corresponds to the highest numbers given in NO. GT. PLNS. RES. PRG., 1974a. In that report, however, a plant factor of 90% is given, whereas in this report no plant factor is stated. Thus the difference between 160 and 180 $m^3/10^{12}J$.

The water use value given in DICKSON, ET AL., 1976, is the "best estimate" given in NO. GT. PLNS. RES. PRG., 1975, 130 $m^3/10^{12}J$ (9,500 acre-ft/yr). The consumptive use range given in NEHRING, ET AL., 1976, appears to be from a combination of both ranges given in NO. GT. PLNS. RES. PRG., 1975. No specific information besides technology is given. The water use range given in HARZA ENGIN. CO., 1976, is based on the low range of NO. GT. PLNS. RES. PRG., 1975, but with off-site mining and reclamation water use added. No reference is given for the mine-use values. The high end of the range is said to be for normal water usage while the low end involves partial air cooling. As shown in Chart No. 2 and described above, this explanation appears to be wrong. The water use range in SCOTT, ET AL., comes from HARZA ENGIN. CO., 1976, without the off-site water use addition. Again, 130 $m^3/10^{12}J$ is given for "normal process" and 80 $m^3/10^{12}J$ for "partial air cooling."

The MISSOURI R. BASIN COMM., 1978a, report refers to HARZA ENGIN., CO. 1976, as a general reference. The water use value of 130 $m^3/10^{12}J$ comes from a table giving total product produced and water used in each subarea. No explanations are given. Unfortunately, in MISSOURI R. BASIN COMM., 1978b, subarea totals could not be manipulated into a unique relationship between water use and product quantity. Also, although specific plant usage is given, specific plant size is not. Thus its water-use value(s) could not be reduced to the common basis. U.S. DOE, 1978a, has been superseded and a copy could not easily be obtained for this study.

The water use range given in CLUSEN, 1979, is an average for both coal gasification and coal liquefaction taken together. The 82 $m^3/10^{12}J$ value appears to be derived from the Missouri River Basin Commission studies. The 41 $m^3/10^{12}J$ value is a reduction of 50% based on a comment in the report (following the statement leading to the 82 $m^3/10^{12}J$ value) that the Probstein studies have shown water use can be reduced up to 50% by use of partial air cooling. This may be misleading because the 82 $m^3/10^{12}J$ value already includes reductions due to use of partial air cooling. No other information is given. The report SIERRA CLUB, 1979, gives neither a basis nor an explanation for its range and cites no references.

Now considering the other major family in this chart, the Department of Interior's "Water for Energy" studies, U.S. DOI, 1974b, gives no explicit references, but does mention a discussion draft, U.S. DOI, 1974a. Unfortunately, that report could not be located for this survey. Two of the water-use numbers in U.S. DOI, 1974b, are referenced vaguely to the Wesco plant. The 200 $m^3/10^{12}J$ value is unreferenced but is said to include associated urban use. BESSLER, 1975, and U.S. EPA & U.S. DOE, 1978 (Chart No. 1), do not cite U.S. DOI, 1974b, explicitly as the source of their water-use numbers, but do imply it is. None of the derived reports, including RADIAN CORP, 1975 (Chart No. 1), and SPOFFORD, 1980, (Chart No. 3) mention that the value includes associated urban use.

U.S. DOI, 1975a, mentions U.S. DOI, 1974b, only as a general reference. It gives no explicit references tied to specific numbers. The extraordinarily high value of 140,000 $m^3/10^{12}J$ arises from interpreting "MCFD" according to standard American usage as <u>thousand</u> cubic feet per day. If the "M" should be read as "million," and there is no indication of this, the value would be 140 $m^3/10^{12}J$. The range in the middle partition is due to the amount of dry cooling involved. A very low value of 900 Btu/scf is given in the report as the heating value of the product. If the more reasonable value of 960 Btu/scf were used, the "El Paso" value would become 130 $m^3/10^{12}J$.

The recommended water-use value given in U.S. DOI, 1975b, 130 $m^3/10^{12}J$, which is attributed to NO. GT. PLNS. RES. PRG., (UNDATED), cited as an interim report, derives from a water use of 9,500 acre-ft/yr, which is the value given for the El Paso plant in NO. GT. PLNS. RES. PRG., 1974a -- probably the original reference for the NGPRP family.

Finally, the extremely high water-use value given in ROCKY MT. ENV. RES., 1974, 1500 $m^3/10^{12}J$, comes from reducing its water-use rate (300,000 acre-ft/yr) given as a function of coal-mining rate (24 million tons per year) to the common basis using the coal-mining rate given for the El Paso plant in U.S. BU REC., 1974 (9.38 million tons per year to produce 288 million scfd). Neither a basis nor a reference for the water-use value appearing in ROCKY MT. ENV. RES., 1974, is given.

Therefore, excluding the Probstein reports which will be considered in Section A-4, the low end of the most popular water use range found in this chart, 80 $m^3/10^{12}J$, is ultimately based on personal correspondence concerning second generation technologies, while the high end, 130 $m^3/10^{12}J$, is ultimately based on the El Paso Natural Gas Co. design plans.

A-3 <u>Chart No. 3 - Coal Gasification (SNG) - Process and Project Developers</u>

The two primary families of reports shown in Chart No. 3 are those related to the Wesco and El Paso coal gasification plants. These plants were slated for construction in the four corners region of the Upper Colorado River Basin. The ultimate references are BATTELLE COL. LABS., 1973, and STEARNS-ROGER CORP., 1973, respectively. These are environmental reports written on behalf of the plants' sponsors and submitted to the Federal Power Commission as part of their permit applications. They were based on the design plans of the plants. Detailed information on plant designs and material balances are given, but no references are cited. In addition to process inputs and process cooling, the Wesco design given in BATTELLE COL. LABS., 1973, includes water use for <u>part</u> of the plant's power needs (on-site condensing steam turbines) and for off-site mine use. This latter use entails using recycled plant wastewater streams. Revegetation water use does not appear to be included. The El Paso design given in STEARNS-ROGER CORP., 1973, includes water use for <u>all</u> power needs (fuel-gas turbines and steam turbines) and, apparently, uses river water directly for all off-site mine uses. Both designs involve extensive use of partial air cooling and water recycle.

Considering some of the other originating reports shown in the chart, U.S. OFFICE OF COAL RES., 1973b, gives no indication of the details of water use nor any references for its synthane ("S") and non-specific ("N") water-use values. U.S. BU MINES, 1971b, includes electric power needs for the Synthane process but does not include off-site water uses. A detailed list of equipment is included, but material and energy balances are not given. The plant is cited in the Ohio Valley and, apparently, uses full wet cooling. (M.W.) KELLOGG CO., 1970, is cited as a confidential report by THOMAS, 1976, which includes a material-and-energy balance engineering design analysis. Full wet cooling of steam condensors is employed, but with fairly extensive water recycle intended for a "zero discharge" plant. Water for electric power needs is included, but not for mine uses. Similar considerations hold for the Lurgi water use given in THOMAS, 1975.

SHAW & MAGEE, 1974, and KALFADELIS & MAGEE, 1974, are also based on material-and-energy-balance engineering analyses of in-plant uses only. The analyses are based primarily on the indicated references, but in the Lurgi case, it was an earlier version of the design than that given in STEARNS-ROGER, 1973.

The Synthane value given in STOUT, 1974, includes water for mine use but none for electric power generation. Water recycle and partial air cooling are not considered. The larger Hygas ("H") water use, 400 $m^3/10^{12}J$, does not include mine or electric-power related water use, nor is water recycle considered. There is also a large quantity (approximately 20% of make-up rate) of wastewater discharged.

The water-use values derivable from MORRIS, 1977, appear to be for mine-mouth sites, but it is not clear what uses are included. Nor is it stated what water uses are considered in HOWE & MORRIS, 1980. SAWYER, ET AL., 1980, "combined the technical alternatives into one representative process," but they do not explain this in detail. They do state, however, that the number includes mining, fuel preparation, transportation and processing water needs. BORIS & KRUTILLA, 1980, adopted the Wesco in-plant water use information to a Montana site and added appropriate off-site uses for that region. Their analysis, however, was not a true material-and-energy-balance engineering analysis.

The Wesco and El Paso values given in ABBEY, 1979, appear to be the total water-use values given in the indicated source reports with off-site uses subtracted. If this is so, there is a problem with the Wesco value since, in that case, water for mine use comes from recycled plant effluents.

The values in the chart for ABBEY & LUCERO, 1980, are slightly different from those in ABBEY, 1979, its source report, since the default heating value of 960 Btu/scf had to be used in analyzing the later report. In the earlier report a heating value of approximately 1000 Btu/scf is given. The ranges in water use given in partitions which cite GOLD & GOLDSTEIN, 1978, are due to varying degrees of partial air cooling and to site specific factors, primarily the amount of moisture in the feed coal. The data are primarily from western sites and come from analyses of designs involving extensive internal water recycle.

The EXXON CO., 1980, values are given without explanation as general limits for all types of synthetic-fuel processes.

A-4 Chart No. 4 - Coal Gasification (SNG)-Water Purification Associates, Cambridge, MA

This chart is organized around the family of reports written by Water Purification Associates, Inc. (WPA), a consulting firm located in Cambridge, Massachusetts. The water consumption values are based on detailed material-and-energy-balance engineering design evaluations, which are included in many of the reports. The designs are site specific and are for fully integrated (including mining, reclamation and electric power production) "zero discharge" plants. Furthermore, the designs involve extensive internal water recycling and various, specified degrees of wet cooling.

Unlike the majority of reports in other charts, the WPA water-use values are not borrowed directly from the references, but the references (usually first hand from process developers) are used as the basis of the engineering analysis. Therefore many references feed into single partitions in the WPA reports. The exceptions to this are when numbers are borrowed by later WPA reports from earlier WPA reports or when numbers are borrowed from other reports for comparative purposes.

The WPA reports dating from 1977 or earlier are site specific for a limited number of western sites only; and all but one report consider only high levels of wet cooling. The exception was GOLDSTEIN

& YUNG, 1977, which considers <u>only</u> partial air cooling. The later WPA reports are for site specific analyses at many sites, including the eastern United States, and consider several levels of partial air cooling at each site.

In the case of COLO. DEPT. NATURAL RES., 1979a, WPA worked on water treatment for the study, but the source of the water-use numbers is given only vaguely as "typical water consumption estimates." In addition, although not shown in the chart, water-use projections for the Wesco and El Paso plants (four corners region) are noted in a footnote.

The only explanatory information for the water-use values given in STEELE, ET AL., 1980, is that they are for plants in "areas of limited water supply." In addition to the WPA report, they also cite LEVINE, ET AL., 1975, as a reference, but do not include it in their bibliography. Thus, it could not be obtained for this study.

The Abbey reports are reviewed in Section A-3.

A-5 <u>Chart No. 5 - Coal Gasification (SNG) - Science and Public Policy Program, Univ. of Oklahoma, Norman, Ok.</u>

The unifying factor in this chart is the series of reports published by the Science and Public Policy Program of the University of Oklahoma, Norman, Oklahoma. This is the <u>Energy from the West</u> series which was under the direction of I.L. White. The later "Impact and Policy Analysis" reports of the series (WHITE, ET AL., 1979c-1979f) rely primarily on water-use values derived from the reports of Water Purification Associates, Cambridge, Massachusetts (WPA), see Section A-4. Earlier reports in the series, e.g. WHITE, ET AL., 1979a, also depend on early process and/or project developer reports (see Chart No. 3) and on reports in the general open literature.

Off-site, mine-related water uses are included in the numbers coming from the WPA reports, but not in other numbers. Nothing is said about off-site electric power production. The only explanatory information given in SCI & PUBLIC POLICY PRG., 1975, is that the water-use values are for northwestern coals.

Many of the water-use values given in many of the reports of this series (e.g. WHITE, ET AL., 1979c and e, and DEVINE, ET AL., 1980) could not be reduced to the common basis. This is because they are given as reductions in water use when partial air cooling is used instead of full wet cooling. Unfortunately, the reductions are stated in such a manner that unambiguous values can not be obtained (e.g. as ranges of percent reductions of a given water use range, it not being clear how the range in reductions relates to the range in values -- i.e. high end of reduction range times high end of value range or times low end of value range). There are also numerous inconsistencies within reports in the use of plant factors. In addition, there are unexplained inconsistencies between water-use values in the reports of this series and in their cited references.

A-6 Chart No. 6 - Coal Liquefaction - Government Oversight Agencies (No. 1).

Before reviewing the coal liquefaction charts, it is important to note that many of the reports giving water-consumption requirements of coal-liquefaction industries do not clearly state what form the products are in or even what exactly the products are. This is especially true for Solvent Refined Coal (SRC) plants. For such plants it is often not stated (and not clear) whether the product is a hot liquid, a room temperature liquid or a solid; or whether or not an upgrading step has been included. Solidification requires cooling and upgrading may require hydrogen production as well as cooling.

Chart No. 6, for coal liquefaction, is very similar to Chart No. 1, for coal gasification, in both structure and the reports included. In this case there are only a few well documented originating reports. PITTSBURG & MIDWAY COAL, 1970, is based on engineering design reports. Its origin is shown in Chart No. 8. The dual ranges in DAVIS & WOOD, 1974, arise from the water consumption being stated in different units in different places in the report: 0.2-1.3 acre-ft/yr per bpd oil output and 31-200 gal/10^6Btu. To convert to the common basis of this report, the default assumptions for plant factor and product heating value had to be used for the acre-ft/yr values. The low ends of the ranges given in DAVIS & WOOD, 1974, come from NAT´L PET. COUNCIL, 1973c. The discrepancy is probably due to rounding in DAVIS & WOOD, 1974. No reference is given for the high ends of the ranges and no indication is given for the basis of the ranges either. The report recommends the low end as a "best guess."

NAT´L PET. COUNCIL, 1973c, provides no information on the basis or origin of its water-use value. It may come from NAT´L PET. COUNCIL, 1972c, which also provides no information on the origin of its number, but does state that "use could be reduced" from it. U.S. BU REC., 1972, provides no information on the origin or basis of its number except that it is for the Upper Missouri River Basin. U.S.

OFFICE OF COAL RES., 1973b, also provides no information on the origin or basis of its water-use value.

As in the coal gasification case, the number used for in-plant water needs in the National Academy of Sciences' CONAES study (NAT'L ACAD. SCI., 1979) comes, ultimately, from a single reference: NAT'L PET. COUNCIL, 1973c. The two seemingly independent ranges quoted in EL GASSEIR, 1980, both come from DAVIS & WOOD, 1974. The range in the middle partition was transmitted through the chain of reports: U.S. WATER RES. COUNCIL, 1974, from U.S. FEA, 1974c, from (A.D.) LITTLE, 1974, from DAVIS & WOOD, 1974. The range in the right-hand partition comes from WEST. ST. WATER COUNCIL, 1974, from DAVIS & WOOD, 1974. The low end of the range in DAVIS & WOOD, 1974, is from NAT'L PET. COUNCIL, 1973c, which gives neither basis nor reference for the value. No reference is given for the high end of the range in DAVIS & WOOD, 1974.

Considering some of the other reports which borrowed from DAVIS & WOOD, 1974, the right-hand partition in (A.D.) LITTLE, INC., 1974, is derived directly from DAVIS & WOOD, 1974. The left-hand partition is from a table which purportedly includes cooling-water use from DAVIS & WOOD, 1974. Evidently, process-water use comes from U.S. OFFICE OF COAL RES., 1974.

In KILPATRICK & CRAGWALL, 1975, the discrepancy at the high end of the range between it and its reference is not explained, though it appears to come from rounding. The range, itself, is attributed to "widely differing processes" used for pressure hydrogenation. The values shown in the box for RADIAN CORP., 1975, come from a very hard to read microfiche. The report gives references for the values, but no other information. The 120 $m^3/10^{12}J$ value in U.S. EPA & U.S. DOE, 1978, is attributed directly to RADIAN CORP., 1975. It is for a liquid product to be used for electricity production. The 200 $m^3/10^{12}J$ value is derived from RADIAN CORP., 1975, and is for a refined or upgraded product. RICKERT, ET AL., 1979, gives no basis for its range and cites no references directly for it. The indicated references are some of those listed in its bibliography.

The other major family in this chart consists of reports that borrowed water-use values from the Project Independence report U.S. FEA, 1974b. The water-use range in the right-hand partition of this report is due to use of partial air cooling and of water contained in the feed coal. No off-site uses are considered. No explanatory information is given for the values in the left-hand partition. In both partitions of U.S. WATER RES. COUNCIL, 1977 (and 1978), the range is due to a 50% reduction resulting from water recycle coupled with use of the moisture in the feed coal. This is also the explanation of the ranges in U.S. ERDA, 1977. The "SRC" values are given for a "liquid product", while the product discussed in their source reference, PITTSBURG & MIDWAY COAL, 1970, is a hot liquid.

A-7 Chart No. 7 - Coal Liquefaction - Government Oversight Agencies (No. 2)

Chart No. 7, for coal liquefaction, is similar to Chart No. 2, for coal gasification, in structure and the reports included, except for the lack of the Northern Great Plains Resource Program family.

Coal liquefaction was not considered by the Northern Great Plains Resource Program.

Considering individual reports in Chart No. 7, the range of water-use values given in U.S. DOI, 1975a, is attributed to reductions due to use of dry cooling. No other explanatory information of the numbers is given. The range of values in GOEN, ET AL., 1974, is from use of partial air cooling and internal water recycle. The H-coal process is referred to in the report, but not in conjunction with water use. No references for the water-use numbers are cited directly. The only explanatory information given in DICKSON, ET AL., 1976, is that the partial air cooling values also include reductions due to internal water recycle, while the full wet cooling values do not. The only explanatory information given in STEELE, ET AL., 1980, is that their water-use values are for a "surface retorting facility." Since the numbers given are the same as for oil-shale processing, there may be a copy error present in their report. In addition to DICKSON, ET AL., 1976, they also cite LEVINE, ET AL., 1975, in the text as a reference, but do not include it in their bibliography. Thus, it could not be obtained for this study. U.S. DOE, 1978a, has been superseded, and a copy of this earlier report could not be readily obtained. The MISSOURI R. BASIN COM., 1978b, water-use values are given for individual plants of unstated capacity and so could not be converted to the common units.

In U.S. DOE, 1979, the water-use value appearing in the left-hand partition is given with no explanatory information. The value in the right-hand partition is said to include cooling, process, mining, reclamation and steam-generation water needs. The indicated references are listed in the table in which the values appear, but are not connected to specific numbers in the table. The value in the right-hand partition of DOYLE, 1979, is said to include cooling, process, mining, reclamation and steam-generation water needs. No explanatory information is given for the numbers in the other two partitions. They may, in fact, be for both coal liquefaction and gasification. Neither BUSINESS WK., 1979, nor SIERRA CLUB, 1979, give any details--including references. The water use values given in U.S. DOE, 1980b, include mining use as well as in-plant uses, but the type of plant is specified only as "coal conversion" with a product in "barrels per day equivalent". The indicated references are mentioned in the report, but are not tied directly to the water-use values.

As mentioned in Section A-2, the range given in CLUSEN, 1979, is an average for both gasification and liquefaction plants. The lower end of the range is based on a comment in CLUSEN, 1979, attributed to the Probstein reports, that water usage in some plants could be reduced by over 50%. The high end appears to have originated in reports related to coal gasification and, curiously enough, already contains a reduction of about 50% (see Section A-2 and Chart No. 2). The water-use range given in MARTIN, 1979, is for a plant located in the northern great plains and includes mining and reclamation as well as in-plant uses. The range is said to be due mostly to differences in processes and cooling requirements. Finally, the water use given in U.S. COMPTROLLER GEN., 1980, is for a plant located in the Yellowstone Basin, but no other information is given. The value appears in an appendix to the report containing written comments on the report submitted by the Department of the Interior.

A-8 Chart No. 8 - Coal Liquefaction - Process and Project Developers

Chart No. 8 provides a good example of the difficulties involved in reducing coal liquefaction (especially SRC) water-use numbers to the common basis. The product described in PITTSBURG & MIDWAY COAL, 1970, appears to be a hot liquid that would be a solid at room temperature. Solidification water consumption is not mentioned. None of the reports quoting a water use directly from PITTSBURG & MIDWAY COAL, 1970, list the product as a hot liquid. These reports are: U.S. WATER RES. COUNCIL, 1977 and 1978, and U.S. ERDA, 1977 (Chart No. 6); and MORRIS, 1977, and HOWE & MORRIS, 1980 (this chart). MORRIS, 1977, states it is for a mine-mouth site, but gives no other explanatory information.

PITTSBURG & MIDWAY COAL, 1970, took its data from STEARNS-ROGER CORP., 1969, contained in the same volume as an appendix. The Stearns-Roger Corp. report summarizes a conceptual design study for a midwestern site and gives detailed energy and material balance information. Water use for electric power needs is included, but off-site mine-related water needs are not. The product, unlike that in the Pittsburg and Midway Coal report, is stated to be solid.

Considering (R.M.) PARSONS CO., 1973, and the subsequent reports citing it, the primary output product given in the Parsons´ report are room temperature liquids (mostly light and heavy boiler fuels and some naphtha). The report includes a detailed design description including equipment lists and energy and material balances. The plant uses a Bi-gas gasifier. Water use for electric power needs is included, but off-site mine-related uses are not. It is a site specific analysis for the midwest, involving high wet cooling and a low level of water recycle. Approximately one-third of the raw intake water is returned to its source. The value in the chart is based on the raw intake-water value.

The value given in the right-hand partition of SCHMETZ, ET AL., 1974, is attributed directly to (R.M.) PARSONS, 1973, but potable water use, included in the Parsons report, is not included here and no heating value for the product is given. The default heating value of 6.2×10^6 Btu/bbl, which had to be used to reduce the water use to the common basis, is slightly higher than the value derivable from the Parsons' report, 5.8×10^6 Btu/bbl. The product is said to be a room temperature liquid and no off-site water uses are considered. For the other two partitions, no explanatory information is given.

The second from the left partition in WHITE, ET AL., 1979a, is referenced as being derived directly from (R.M.) PARSONS CO., 1973, but there may be a discrepancy in plant inputs and outputs. The plant referred to in the White, et al., report produces 100,000 bpd "on a Btu basis" for an input of 30,000 t/d of coal. The plant described in the Parsons' report, scaled up to a 30,000 t/d coal feed, would only produce 75,000 bpd of liquid fuel products (plus its internally consumed plant fuel). To reduce the White, et al., number to the common units, the 100,000 bpd value had to be used along with the default heating value. White, et al., state this number represents a "conventional level of water recycle and re-use." Off-site uses are apparently not included. In contrast, they claim the number in the left most partition represents minimum consumption in which maximum recycle and re-use is employed. Since "dust control" is included, off-site uses may be included in this partition. No explanatory information is given for the number quoted from NAT´L ACAD. SCI., 1977b, and that report, itself, offers neither explanatory information nor references.

The ROGOSHEWSKI, ET AL., 1978, report presents the results of an engineering analysis. A material balance is included, but not an energy balance. The analysis is for a southern Illinois site and assumes use of a Koppers-Totzek gasifier rather than a Bi-gas gasifier as in (R.M.) PARSONS CO., 1973. Water needs for electric power and mine use are not considered. Considering the left-hand partition in HOPKINS, ET AL., 1978, the only clear explanatory information is that the low end of the range corresponds to the case where process water is recirculated while the high end is for a once through system. No explanatory information is given for the middle partition and the numbers may, in fact, have been derived for coal gasification. The authors took the lower end as their recommended value for coal liquefaction.

Both WETHEROLD, 1976, and BURKLIN, (UNDATED), are summaries of engineering analyses based on material and energy balances. Detailed material balances are presented. Water to provide the required electric power is included, but mine use is not. The products in the Burklin report are both solids and liquids at room temperature.

Little explanatory information is provided in STOUT, 1974, but it appears electric power needs and off-site uses are not included. The water-use values given in MCNAMEE, ET AL., 1978, result from engineering-design feasibility studies. The results are site specific for southern Illinois and include water needs for electricity but not for mining. Approximately one-third of the raw intake water is returned to the source. The range in the "CHL" data is due to differences in product slates. The low water-use end is for a production of about twice as much solid as liquid products. The high end is for production of slightly more liquid than solid products. U.S. DOE, 1980a, summarizes the results of an environmental impact investigation based on design reports, but does not, itself, give details of the design analysis. It is for an eastern site and water needs for electric power generation are not included.

The water-use numbers given in BECHTEL NAT'L INC., 1979, are the results of an in-house analysis. Electric power generation is considered. For the "TM" value, mine use may be included, but probably not for the other values. The values given in MONSANTO RES. CORP., 1979, appear to be from outside estimates. A reference number is given only for the low end of the range, but the reference is not included in the reference list. Mine use is probably not included. The EXXON CO., 1980, values are given without explanations as general limits for all types of synthetic fuel processes.

A-9 Chart No. 9 - Coal Liquefaction - Water Purification Associates, Cambridge, MA.

This chart, for coal liquefaction, is very similar in structure to Chart No. 4, for coal gasification. Both are based on the reports of Water Purification Associates of Cambridge, Massachusetts. Comments on individual Water Purification Associates reports are also similar. CANDELA, 1977, did not appear in Chart No. 4, and needs some explanation. The high end of the water use given in the left-hand partition comes from PROBSTEIN, ET AL., 1974, and is for a Synthoil plant using high wet cooling. All water uses are included. The low end of the range is derived from the high end by reducing water use for mining, dust control, utilities, process and miscellaneous losses to the minimum value predicted for them in GOLDSTEIN & PROBSTEIN, 1976 for Lurgi coal gasification at a western site. High wet cooling is still employed. The value given in the right-hand partition is the estimate of Candela, et al., for minimum water consumption when extreme dry cooling is employed.

A-10 Chart No. 10 - Coal Liquefaction - Science and Public Policy Program, Univ. of Oklahoma, Norman, Ok.

This chart, for coal liquefaction, is very similar in structure to Chart No. 5, for coal gasification. Both are based on the reports of the Science and Public Policy Program of the University of Oklahoma, Norman, Oklahoma. The general comments made in Section A-5 are also applicable to this chart.

A-11 Chart No. 11 - Oil-Shale Processing - Government Oversight Agencies

This first chart in the oil-shale processing group, Chart No. 11, includes most reports covered by the first two charts in the coal gasification group (Charts No. 1 and 2) and coal liquefaction group (Charts No. 6 and 7). It is organized around the Final Environmental Statement for the Prototype Oil Shale Leasing Program, U.S. DOI, 1973. Almost every report in it contains water use numbers derived directly or indirectly from this report. Many times numbers were borrowed from seemingly independent sources, but when carefully traced to their origins, it turns out that all ultimately originated in this report. The following are two examples: (1) The numbers in the three partitions in U.S. FEA, 1974c, all come from U.S. DOI, 1973: in one case through U.S. FEA, 1974d; in the second case through (A.D.) LITTLE INC., 1974, and U.S. FEA, 1974d; in the third case through DAVIS & WOOD, 1974. (2) The numbers in the two derived partitions in BISHOP, ET AL., 1975, both come from U.S. DOI, 1973: through U.S. FEA, 1974c, and DAVIS & WOOD, 1974, in one case; and directly through DAVIS & WOOD, 1974, in the second case.

Before discussing, in detail, the family of reports related to U.S. DOI, 1973, the other reports in the chart not (knowingly) directly tied to it will be discussed. References for the water-use number given in NAT'L PET. COUNCIL, 1972b, are not cited specifically, but the indicated references are mentioned in the report. Mining, retorting and upgrading are stated to be included, but electric power generation, spent-shale disposal and reclamation are not mentioned.

All of the above water uses are included in the range given in NAT´L PET. COUNCIL, 1973b, though possibly not reclamation. The range is due to recycle of blowdown to spent-shale disposal. The plant is said to use maximum air cooling. The same uses are included in NAT´L PET. COUNCIL, 1973c, although the breakdown is not exactly the same. No specific reference is given, although the numbers are credited to the "Oil Shale Task Group."

No explanatory information is given in U.S. DOI, 1974b, except that associated urban use is included. In U.S. DOI, 1975a, no specific references are cited directly, but U.S. DOI, 1974b, is given as a general reference. U.S. DOI, 1973, is also mentioned but not in conjunction with water use. In addition to the values given in the chart for U.S. DOI, 1975a, a water-use of 85 $m^3/10^{12}J$ is derivable from "Field Data: Western U.S. Water Plan." No explanatory information besides that present in the chart is given. No explanatory information is given in U.S. COMPTROLLER GEN., 1980, either. The information in the partition second from the right-hand end is from the U.S. Department of the Interior´s comment on the report, contained in an appendix. COL. ENERGY RES. INST., 1979, is given as a citation in the text, but is not contained in the reference list.

No explanatory information and no references are given in ROCKY MT. ENV. RES., 1974. INGRAM, ET AL, 1980, derived from ROCKY MT. ENV. RES., 1974, also contains no explanatory information.

Now turning to the primary report in the chart, U.S. DOI, 1973, it gives water use for oil-shale processing by surface retorting (supplied by surface mining ("SM") and underground mining ("UM")), true in situ retorting ("IS") and a technology mix ("TM"). The last category represents a large scale, commercial industry. Detailed material and energy balances are not given, but water use is broken down according to mining, retorting, upgrading, spent-shale disposal, revegetation, electric power production and sanitary use. Reasons for the ranges in estimates are given in general terms only. The shale grade is not given in the water-use section but is given as 30 gal/t in the land-use section. Data for water use in mining, retorting and upgrading come from U.S. BU MINES, 1971a. That report gives a detailed list of the equipment involved, but does not contain or reference detailed material or energy balances. Water use is not categorized, except for the fact that upgrading requires about ten times as much water consumption as the actual retorting. In U.S. BU MINES, 1971a, underground mining of 30-35 gal/t shale and surface retorting using the Bureau of Mines gas combustion retort are considered. The range in water use results from the range in shale grade. U.S. DOI, 1973, relies on other, primarily technical reports, for determining water use for electric power generation, spent-shale disposal and revegetation. The latter two uses could account for up to 40% of the water use and were not considered to be well established. Associated urban water use is also given, but it has been left out of the charts. Also not shown in the chart are some estimates of water use from very early reports, cited only for comparative purposes.

Some reports have quoted U.S. DOI, 1973, directly, but many others have quoted its numbers indirectly through the Project Independence report, U.S. FEA, 1974a, or through the U.S. Geological Survey report, DAVIS & WOOD, 1974. Considering DAVIS & WOOD, 1974, first, the breakdown of water use is the same as that given in U.S. DOI, 1973. The nonspecific ("N") entry is the same as the surface mine ("SM") entry in U.S. DOI, 1973, but this is not stated in DAVIS & WOOD, 1974. No reasons for the ranges in estimates are given; and no shale grade is indicated.

Of the reports quoting DAVIS & WOOD, 1974, CHEM. & ENG. NEWS, 1974, and KILPATRICK & CRAGWALL, 1975, give no explanatory information beside spent-shale disposal being the largest use. The left-hand partition in WESTERN STATES WATER COUNCIL, 1974, comes from an unreferenced table, but DAVIS & WOOD, 1974, is given as a general reference for the report, hence the dashed line. Little explanatory information is given, but the following water uses are mentioned: retorting, upgrading, spent-shale disposal, revegetation and sanitary. The value in the right-hand partition is attributed directly to U.S. DOI, 1973, but is said to include associated urban use. RADIAN CORP., 1975, gives no explanatory information. U.S. EPA & U.S. DOE, 1978, also gives no explanatory information except for the left-hand partition in which the higher number is said to include surface mining, retorting and upgrading. The upgrading is to be done off-site in the midwest. The two numbers in that partition were given in different places in the report with no explanation for the lower number or how either number was derived. The values attributed to

ROACH, (UNDATED), are all from a single table in U.S. EPA & U.S. DOE, 1978, which gave ROACH, (UNDATED), as its source. Each entry in the table had a vaguely stated reference which is why dashed lines appear in the chart.

Water use was neither explained nor broken down in MYRES, ET AL., 1977, but associated urban use appears to be included in the first and third partitions. The number given in the second partition from the left is from a very hard to read graph. The range in the right-hand partition appears to be their rounded rule of thumb. References are given only vaguely. In U.S. DOE, 1978b, water is said to be used for "shale processing" and "oil refining." Oil-refining water use is said to be reducible through recycle, but it is not clear if this is the cause of the range. It is possible that spent-shale disposal is not included. How the numbers were derived is not stated.

No explanatory information and no direct references are given in RICKERT, ET AL., 1979. The references indicated in the chart are listed in the bibliography. In DAVIS & KILPATRICK, 1981, the range appearing in the second from the right partition is from a very hard to read graph and so may not have been accurately converted to the common basis. The range given under "SR" is the same as that given under "SM" in U.S. DOI, 1973, but given here without a breakdown of water use, except that almost one-half of the use is for spent-shale disposal and 10% for electric power production.

Now considering U.S. FEA, 1974a, and the reports that have borrowed water-use value from it, U.S. FEA, 1974a, takes its water use values for all technologies except modified in situ ("MIS") directly from U.S. DOI, 1973. Water use is broken down as in U.S. DOI, 1973, with the comment that spent shale is wetted to 20% moisture content for disposal. No explanations for the ranges in estimates are given. No indication of shale grade is indicated in the water use section, but a grade of 30 gal/t is mentioned in the economics section. The "MIS" range comes from TRW SYSTEMS, 1974, which is an appendix to U.S. FEA, 1974a. In TRW SYSTEMS, 1974, The "MIS" numbers (including surface retorting of the mined raw shale, "MIS/SR") are derived from values given in U.S. DOI, 1973. Upgrading, electric power, and sanitary water uses are considered proportional to the amount of oil produced. Other water uses were considered proportional to the amount of raw shale retorted above ground (at 80% retorted below ground (in situ) and 20% retorted above ground). Even though the only reference cited specifically in the water-use section is U.S. DOI, 1973, a shale grade of 30 gal/t is given for "UM" and "SM", 22 gal/t for "IS" and 18 gal/t for "MIS". Most of the other references in the reference list are personal communications or internal documents, but even these are not cited directly in the water use section.

The water-use values given in SCHRAMM, 1975, were borrowed from U.S. FEA, 1974a, as well as directly from U.S. DOI, 1973. It is possible the citations to the two references are switched in the report. All the use categories listed in U.S. DOI, 1973, are mentioned here, too. Associated urban use is included in some of the values. DOYLE, 1979, borrowed the value of 160 $m^3/10^{12}J$ from SCHRAMM, 1975, stating it includes mining, processing and power-production water needs, but not stating that it includes associated urban use, too. The values in the right-hand partition in DOYLE, 1979, are from SIERRA CLUB, 1979, which gives neither an explanation nor a reference for the numbers. DOYLE, 1979, states that the numbers include cleaning, processing and cooling water use.

U.S. WATER RES. COUNCIL, 1977 and 1978, and U.S. ERDA, 1977, all list water uses categorized as in U.S. FEA, 1974a, and mention that the spent shale is to be moisturized to 20% water content.

EL GASSEIR, 1980, categorizes the water uses in the same manner as its sole reference, U.S. FEA, 1974a. No explanation for the ranges in values is given, and no shale grade is tied specifically to the water use numbers. The range for "MIS" is low by a factor of two due to a copy error from the reference where the plant size is listed as 50,000 bpd rather than 100,000 bpd as in EL GASSEIR, 1980. HARTE & EL GASSEIR, 1978, break down water use into mining, conversion and reclamation (including spent-shale disposal) categories. Power production is not mentioned, and neither are any reasons for the ranges, except, possibly, for the reclamation use. The discrepancy in the lower end of the range for "IS" is not explained, but the copy error in EL GASSEIR, 1980, for "MIS" appears to have been corrected.

The next category of reports to be considered are those that have borrowed water-use numbers from both Project Independence reports and DAVIS & WOOD, 1974, even though these reports contain numbers which are ultimately from the same source. In (A.D.) LITTLE, 1974, water uses given in Table I-11 (from U.S. FEA, 1974d) are broken down according to the same categories as in U.S. DOI 1973, with the same usage in each category. There are a number of inconsistencies, however: (1) Water uses for upgrading are missing from the breakdowns, but included in the "totals." (2) There is a typo in the low-end subtotal (excluding associated urban use) for "UM" which can be corrected by considering the total including associated urban use. (3) In addition to water use being given in units of acre-ft/yr it is also given as "process water (consump) use coefficient" in units of gal/10^6Btu and gal/bbl. This is the reason for the multiple entries for "UM" in the chart. The two values for this "use coefficient" could be reconciled by assuming an unreasonably low heating value of 4.8 x 10^6Btu/bbl. The "SM" and "IS" entries also have "use coefficients," but they are not shown in the chart. (4) The "IS" water use is off by a factor of two from the value given in its reference since a plant size of 50,000 bpd is specified in U.S. DOI, 1973, but here it is given as 100,000 bpd. Interestingly, it appears the "IS" "use coefficient" is based on a plant size of 50,000 bpd. The grade of the raw oil shale is not stated in (A.D.) LITTLE, 1974.

U.S. FEA, 1974c, contains a Table I-11 identical to Table I-11 in (A.D.) LITTLE, 1974, and attributed to the same source. Numbers from this table are shown in the left-hand partition of U.S. FEA, 1974c, although the "process water (consump) use coefficients" have been left out of the chart this time. Comments on it are the same as for the A.D. Little report. The cited reference is U.S. FEA, 1974d. Values in the second from the left partition were apparently adopted from the "use coefficients" in (A.D.) LITTLE, 1974.

In BISHOP, ET AL., 1975, the water-use value shown in the left-hand partition is broken down into different use categories as in U.S.

FEA, 1974c, from DAVIS & WOOD, 1974. The range given in the middle partition was quoted directly from DAVIS & WOOD, 1974, without explanatory information. The value in the right-hand partition is their conservative guess. No explanatory information is given in KEITH, ET AL., 1978, NARAYANAN, ET AL., 1979, or BISHOP, ET AL., 1979. In this last report water use is given in two separate places in different units.

DICKSON, ET AL., 1976, cites U.S. DOI, 1973, directly as its reference. The high end of the range is probably from the average use for "SM" in U.S. DOI, 1973. The low end is derived by assuming none of the cooling tower make-up is raw intake water (i.e. all of it is recycled water). Mining, retorting, upgrading, spent-shale disposal and electric power water needs are included. No explanation is given in STEELE, ET AL., 1980, for the apparent discrepancy with its reference. Both KINNEY, ET AL., 1979, and MELANCON, ET AL., 1980, categorize their water uses as in U.S. DOI, 1973.

A-12 Chart No. 12 - Oil-Shale Processing - Process and Project Developers (No. 1)

This and the following chart are organized around reports written by oil-shale conversion process researchers, developers and users. Broadly speaking there are three classes of reports in the charts: (1) those written by process developers describing a particular oil-shale conversion process, (2) those written by process users describing a particular oil-shale development project, and (3) those written by third parties summarizing the information contained in reports in the first two categories. In many cases, reports of the third kind summarize several different processes or projects. The following discussion considers the reports in Chart No. 12 in the order mentioned above.

The different retorting processes considered in this chart are Bureau of Mines, TOSCO-II, Paraho indirect and direct, Union-B, Superior multimineral, Lurgi-Ruhrgas, modified in situ, and true in situ. The Bureau of Mines retort is the conversion method actually considered in U.S. DOI, 1973. It no longer seems to be of commercial interest, having been superseded by the Paraho-direct process. In this chart it is represented by KATELL, ET AL., 1974 which contains a general process description and financial breakdown. The water use apparently includes mining, retorting, upgrading, spent-shale disposal and electric power production. The shale grade is given as 30 gal/t. U.S. DOI, 1973, was a reference for spent-shale disposal and retort-gas clean-up information, which may be responsible for the range in the estimates. No explanatory information is given in MORRIS, 1977, or HOWE & MORRIS, 1980, which indirectly cite KATELL, ET AL., 1974.

The main reference for the TOSCO-II process is COLONY DEVELOP. OP., 1974. This is an environmental report on the Colony Development Operation and, as such, is also a project development report as well as a process development report. It is the most definitive and most often cited reference for the TOSCO-II process. Water use is detailed, including a breakdown of steam use, but no references are cited for process use. The references shown in the chart are given for spent-shale disposal and revegetation. The water use includes mining, retorting, upgrading, spent-shale disposal, revegetation and sanitary use. Electric power production is not included. About one quarter of the water use is for spent-shale disposal to produce a 12% moisture content in the disposal piles. The range in values is due to increasing water use for revegetation as the waste piles increase in size. The dual range is because the water use range of 10-12 cfs given on page 145 could not be reconciled with the range of 4970-5600 gpm given in Fig. 37. The shale grade is given as 35 gal/t.

WATER RESOURCES MANAG. WKSHP., 1975, uses the numbers given in COLONY DEVELOP. OP., 1974, but adds water use for electric power production. The left-hand partition is for a raw shale grade of 35 gal/t as in the Colony report. The right-hand partition is for a raw shale grade of 30 gal/t. Shale grade can be important; however, in their analysis for the right-hand partition they apparently did not subtract water produced in the retort and used the crude shale-oil output rate as the syncrude output rate.

U.S. BLM, 1975 and 1977, are the draft and Final Environmental Impact Statements on the Colony Development Operation. They claim to come from COLONY DEVELOP. OP., 1974, but the discrepancy in water use is not explained. There are numerous inconsistencies in the water flow diagrams. As in the Colony report, all water uses except electric power production are considered. Again, the dual ranges are due to irreconcilable differences between values given in the texts and in the water flow diagrams.

SAWYER, ET AL., 1980, cites U.S. BLM, 1975, as its reference. The discrepancy is due to a heating value of 4.8×10^6 Btu/bbl being given in SAWYER, ET AL., 1980. If 5.8×10^6 Btu/bbl is used instead, the value matches the 110 $m^3/10^{12}J$ value in U.S. BLM, 1975. The dual entry given for this report is due to an apparent decimal point misplacement in Table 11 of the report compared to the value given in the text on page 118. The only explanatory information given in the report is that full wet cooling is used and that much of the water goes to spent-shale disposal. ASHLAND & SHELL OIL, 1976, is another report containing water-use information apparently derived from U.S. BLM, 1975. Unfortunately the entire report was not obtained for this study, although its water use diagram was. It is identical to the diagram given in U.S. BLM, 1975, except for a minor correction.

The main reference for the Paraho processes is MCKEE & KUNCHAL, 1976. This report gives a semi-detailed breakdown of water use as well as a semi-detailed energy balance. No references are given for the information. All water uses are considered, including upgrading and power generation. In spent-shale disposal, most of the water is used for dust control and revegetation. For the Paraho-direct process, about 25% of the water consumed ends up in spent-shale disposal while for the Paraho-indirect process it is closer to 45%. The shale grade is given as 30 gal/t.

For the Union-B and Superior-multimineral processes no authoritative references could be obtained for this study. They appear to be rather poorly documented on a first hand basis in the open literature. More will be said about them in the discussion of summarizing reports below.

The main reports for the Lurgi-Ruhrgas process appear to be foreign reports which have been difficult to obtain. These are

RAMMLER, 1968 and 1970, and LURGI MIN., 1973. However, two domestic reports do help to clarify the water use. According to MARNELL, 1976, the primary water requirements for the process are for flue gas conditioning and for moisturizing the spent shale to 5%. Mining, upgrading and power production water needs do not seem to be included. The dual entry in the report box in the chart is because a large, undefined "chilled water" requirement is listed under the "consumption" heading in Table 9 of the report. This could be a recirculation rate. The lower number of 25 $m^3/10^{12}J$ does not include this requirement. TRW, 1978, is a report of an engineering analysis of the process and includes information on material and energy balances. It depends on MARNELL, 1976, and LURGI MIN., 1973, for process inputs, but adds mining and upgrading water use to bring the output product quality up to that of a synthetic crude. No electric power or revegetation water needs are included. Spent shale is said to be moisturized to 10% and the raw shale grade is given as 35.5 gal/t.

The main reports for the modified in situ process, developed by Occidental Petroleum, appear to be MCCARTHY & CHA, 1975, and ASHLAND & OCCIDENTAL OIL, 1977. The McCarthy and Cha paper (actually a later paper by McCarthy, Cha, Bartel and Burton which is believed to contain the same information) contains process and product descriptions. Shale-oil upgrading is not included. Electricity is produced on-site by gas turbine generators. The only water use considered important is in the mining operation and most of that is to be provided by water generated in the retorting. No surface retorting is involved.

ASHLAND & OCCIDENTAL OIL, 1977, also considers modified in situ retorting with no surface retorting. A crude water use diagram is included. The process includes mining, raw shale disposal and on-site electric power production in addition to retorting. In the text, water use is given as 2500 gpm, with most of this being made up from mine dewatering. However, from the water use diagram, it appears this number includes "returned condensate." The lower range is for the returned condensate removed. The reason for there being a range is not explained. No references are given.

ASHLAND & OCCIDENTAL OIL, 1977, is one of a series of reports (ROXANA OIL SHALE PROJ., 1975; ASHLAND & SHELL OIL, 1976; ASHLAND & OCCIDENTAL OIL, 1977; and TALBERT, 1977) dealing with oil shale development on federal oil shale lease tract C-b. At first, TOSCO-II technology was to be used, but after Occidental bought out Shell, the retorting technology was switched to the Occidental in situ method.

RIO BLANCO OIL SHALE PROJ., 1976 and GULF & STANDARD OIL, 1977a, are reports dealing with the Rio Blanco Oil Shale Project on federal oil shale lease tract C-a. This project, too, started with only surface retorting technology and then switched to "MIS" technology. In this case, however, the mined raw shale from the "MIS" retort is to be retorted above ground, using TOSCO-II retorting. The water-use value shown in the chart, 24 $m^3/10^{12}J$, includes all water coming from outside the retort. Their claimed ground water use is 15 $m^3/10^{12}J$; while including the undefined "MIS retort water" the total usage would be 40 $m^3/10^{12}J$. Electric power production water use is not included.

WHITE R. OIL SHALE PROJ., 1976, is a report related to development on federal oil shale lease tracts U-a and U-b. It was not obtained for this study.

This discussion now turns to reports, written by others, that summarize information provided by process or project developers. In COLLEY, ET AL., 1977, water use for mining is given separately (derived from COLONY DEVELOP. OP., 1974) and has been added to the process uses of all three technologies to result in the numbers given in the chart. In the reference for the "PI" water use, MCKEE & KUNCHAL, 1976, water for mine use comes from recycle of process wastewater so that adding mine usage, though implied by COLLEY, ET AL, 1977, may not be correct. Both the TOSCO-II ("T") and Paraho-indirect ("PI") numbers include water use for upgrading and spent-shale disposal. The "T" value is for a raw shale grade of 35 gal/t; the "PI" value for a grade of 30 gal/t. The Union-B ("UB") water use is said to include retorting, cooling, gas treatment, deashing, scrubbing, and processed shale moisturizing and disposal. Upgrading and revegetation do not appear to be included. The raw shale grade is given as 34 gal/t.

In CRAWFORD, ET AL., 1977, the water-use values in all but the right-hand partition come from specific project developers. Information on the development plans is given in other sections of the report, so there is some uncertainty as to their relationship to water use. References are not connected to individual water use numbers. Uncertainty as to reference is indicated in the chart by dashed lines. All of the water use values include spent-shale disposal, but it is not clear if this includes revegetation. The "MIS/NSR" number includes mining and electric power production water use, but not upgrading. The "T" number includes mining and upgrading, but not electric power production. The "PD" number includes mining, but not electric power production. The "T + PD" number includes mining and upgrading, but not electric power production. The T + PD + PI number includes mining and upgrading, but the inclusion of water used for electric power production is uncertain. The "UB" number includes mining, but not upgrading or electric power production.

In SHIH, ET AL., 1979, the "MIS/NSR" water-use number is given without a reference; the indicated reference is cited elsewhere in the report. The number is for the Occidental MIS process applied to 15 gal/t grade shale. Electric power production is included, but not upgrading. Water consumption is said to be the same as wastewater production. The "T" water use is given without a breakdown as to where used but probably includes all uses except electric power production. The shale grade is not stated. The "PI" and "PD" water uses are given with the same breakdown as given in MCKEE & KUNCHAL, 1976. The shale grade is given as 30 gal/t. The "UB" water use is poorly referenced. It appears to include moisturizing the spent-shale to 19%-20% water content, but not electric power production or upgrading. Mining use may be included. The "SU" water use is also poorly referenced. It is for a multimineral process in which nacalite and dawsonite are recovered along with the shale oil. In converting the water use to the common basis of the charts, all water use has been accredited to the oil production. It appears that three-quarters of the water that is consumed is used for slurry backfilling of the mine with spent shale. Cooling appears to be done by once-through use of highly saline ground water and is not counted towards water consumption. The "LR" water use is mainly for air pollution control and spent-shale disposal (10-12% moisture content in the spent shale). Upgrading, mining, gas treatment, and electric power production are not included.

In WHITE, ET AL., 1979b, the water-use value for "MIS/SR" is for "make up water." If "retort water and residual ground water inflow" is added the water use would be about 25 $m^3/10^{12}J$. For the "T", "PI", "PD", "UB", "SU", and "LR" entries in the chart, mining water use from ASHLAND & SHELL OIL, 1976 (given elsewhere in WHITE, ET AL., 1979b) was added to the other water uses given in WHITE, ET AL., 1979b, which were adopted from the indicated references. Water use breakdowns are given for "T", "PI" and "PD". A shale grade of 30 gal/t is given for the Paraho processes. No shale grades are given for the other processes. The inconsistencies with their reference for the Paraho water use numbers may be due to the use of the TOSCO mining value, but it might also be due to their giving plant outputs which are actually for raw shale oil even though upgrading water use has been included. The "UB" water use includes retorting, cooling, gas treatment, deashing, scrubbing, spent shale moisturizing and disposal. Upgrading is not included. No explanatory information is given for the "SU" water use. The "LR" water use is said to exclude gas treatment and upgrading.

BROWN, ET AL., 1977, is a synthesis report of engineering estimates. It puts together water-use rates for different aspects of an industry (e.g., retorting, mining, upgrading, etc.) from different sources. All major water uses are included: mining, retorting, electric power production, spent-shale disposal and revegetation. Even though upgrading is included, it is only mild upgrading consisting of visbreaking without hydrotreating or coking. The spent-shale is disposed of with a low water content of 8% moisture, but substantial irrigation for revegetation is used, 8 ft of applied water. Wet venturi scrubbing is probably included for air pollution control and a steam cycle is used for electric power production. For "MIS" and "IS" water use, on site power generation is included, but surface retorting of raw shale is not considered. Mine-water inflow has not been subtracted from the water need. A shale grade of 35 gal/t is given for the "T" process, but no grade is stated for the others. Simplified water-flow diagrams for all of the processes are included. Water use for slurry backfill of spent shale to the mines is also given in the report, but is not included in the chart. For the Paraho and Union processes, an apparently earlier version ("Supplement to Fifth Quarterly Report," September 1976) of SHIH, ET AL., 1979, is given as a reference. That is the reason for the dashed lines.

In NAT´L ACAD. SCI., 1980, explanatory information is offered only for the left-hand partition. In addition to process use, power generation, spent-shale disposal and reclamation are said to be included. Mining and upgrading are not mentioned. The other water-use values are presented in the report without explanation and with only vague references to project developers. The indicated references are listed in the report's bibliography without direct citation.

The EXXON CO., USA, 1980, values are given without explanation as general limits for all types of synthetic fuel processes.

A-13 Chart No. 13-Oil-Shale Processing - Process and Project Developers (No. 2)

The organization of this chart is quite similar to that of Chart No. 12. In both cases the originating reports are by process and/or project developers. The data from these reports are summarized, synthesized and analyzed in subsequent reports by third parties. Many of the same originating reports by process and project developers occur in both charts. In this chart these reports are not shown as continuing from Chart No. 12 unless the information in them is traceable to even earlier reports shown in that chart.

Considering private process and project developers first, the TOSCO-II process is primarily represented by COLONY DEVELOP OP., 1974. The Paraho processes are mainly represented by MCKEE & KUNCHAL, 1976, and JONES, 1976. The latter is a general description of the two Paraho processes and their products. Information on the Superior multimineral process is derived from four sources, all by the same author: WEICHMAN, 1974, (undated), 1976a and 1976b. They are all either general process descriptions or are not generally available. Information on the Union-B process is derived from POWNALL (undated), and UNION OIL, 1976, also not generally available. The Lurgi-Ruhrgas process is represented by LURGI & DRAVO CORP. 1975, and TRW, 1978.

Derivation of the information in the latter report is shown in chart No. 12.

Now considering the federal oil shale lease tract developers, tract C-a is represented by RIO BLANCO OIL SHALE PROJ., 1976, WELLS & BERRY, (undated), and GULF & STANDARD OIL, 1977 a and b. The first two reports deal with the TOSCO-II process, primarily, while the latter two reports concentrate on "MIS" oil shale retorting. Tract C-b is represented by ASHLAND & SHELL OIL, 1976 (TOSCO-II technology), and ASHLAND & OCCIDENTAL OIL, 1977, LOUCKS, 1977, C-b OIL SHALE VENTURE, 1978, and OXY, 1979 ("MIS" retorting). Tracts U-a and U-b are represented by WHITE R. OIL SHALE PROJ., (undated), and DONEY, (undated).

Now considering the derived reports, there are two main families: EYRING RESEARCH & SUTRON CORP., 1976, and NEVENS, ET AL., 1979. The former report summarizes and adapts the water use numbers given by developers. A breakdown for the water use is given. The latter report summarizes the results of detailed, independent engineering analyses and includes energy and material balances. It appears that the analyses given in NEVENS, ET AL., 1979, were performed by Water Purification Associates, Inc., which ties this chart to Chart No. 14.

In reducing the water-consumption values given in EYRING RESEARCH & SUTRON CORP., 1976, to the common basis used in this report, an uncertainty arose over the nature of the product. Not all of the references have included upgrading and the Eyring and Sutron report refers to the product as both "synthetic crude" and "crude shale oil." In the case of the Paraho values coming from MCKEE & KUNCHAL, 1976, it appears that the output rate given in the Eyring and Sutron report is that of the raw shale oil (i.e., before upgrading), while upgrading water use is included. The uncertainty is increased because it appears that a stream factor of about 90 percent may have been used in the report. In reducing the data here, it was assumed that in all cases the product is a raw shale oil (not upgraded) with a heating value of 6.0×10^6 btu/bbl.

Considering individual partitions within EYRING RESEARCH & SUTRON CORP., 1976, the water use given in the second partition from the left is for a combination of TOSCO-II retorting and gas combustion retorting. The raw shale (with a grade of 23 gal/t) is to be surface mined and the spent shale is to contain 13 percent moisture. The water use in the next partition, coming from MCKEE & KUNCHAL, 1976, already includes an estimate of the water need for power generation. Although the next partition is labeled "PD", only 71 percent of the retorting is by "PD", while 14 percent is by "PI" and 15 percent by "T". The spent shale is to contain 9 percent moisture and little water is to be used for electricity production since fuel gas is to be burned. In the "SU" process, the spent shale is to be moisturized to 22 percent for slurry backfilling and no upgrading is to be included. In the UB process, the spent shale is moisturized to 19 percent and revegetation and upgrading are included. The raw shale grade is 34 gal/t. The "SM" value is given for comparative purposes and the "SR/MWC" is their best guess of a minimum water requirement for surface retorting employing minimum wet cooling.

The most important subsequent reports included in the NEVENS, ET AL., 1979, family are DENVER RES. INST., 1979 (which is probably a draft version of the Nevens report), PROBSTEIN, ET AL., 1979 (which is an update and modification of the Nevens report), and U.S. OTA, 1980 (which quotes directly from the Probstein report). The water use values result from critical, independent technical analyses of designs supplied by the developers. Energy and material balances are given in NEVENS, ET AL., 1979. The following are some specific comments on individual water-consumption values given in NEVENS, ET AL., 1979: (1) The "MIS/NSR" value does not include upgrading, but does include electric power production by gas turbines. Background on the process comes from Occidental reports. (2) The "MIS/LRSR" value does not include upgrading, but does include slurry backfill from the surface retort back to the "MIS" retort. Power production is included. (3) The "T" values include an average amount of water for revegetation over the plant life time, unlike what is done in COLONY DEVELOP OP., 1974. As in the Colony report, upgrading is included and power production is not. The higher "T" value is for use of wet scrubbers for flue-gas particulate control as in the Colony report; the lower "T" value is for use of a bag house and electrastatic precipitators. (4) The "PD" value does not include upgrading and includes electric power production by gas turbines; both of which are different than in MCKEE & KUNCHALL, 1976.

The differences in the water-use values appearing in PROBSTEIN, ET AL., 1979, from those given in NEVENS, ET AL., 1979, are due to (1) the "MIS/NSR" value including upgrading, (2) the "MIS/LRSR" value including upgrading and surface disposal of spent shale rather than slurry backfilling; (3) the "T" value including power production in addition to dry methods of flue-gas particulate control; and (4) the "PD" value including upgrading.

The ranges in water consumption that appear in the right-hand partition of PROBSTEIN, ET AL., 1979, are primarily due to the effects of varying the grade of the raw feed shale. The lower the grade the higher the water use. The raw shale grades considered are: "MIS/NSR": 23-27 gal/t, "MIS/SR": 23-25 gal/t, "ISR": 32-35 gal/t, and "DSR": 29-32 gal/t.

Briefly considering some of the other derived reports in this chart, in U.S. DOE, 1979, the values in the left-hand partition are given with no further explanatory information. The value in the right-hand partition is said to include water use for cooling, process, dust control, reclamation and steam generation. No citation is connected directly to the value, but the indicated references are mentioned in various parts of the text. U.S. DOE, 1980b, is an update of U.S. DOE, 1979. The value in the right-hand partition comes from an appendix to the report that is an executive summary of COLO. DEPT. NATURAL RES, 1979a. The range in the left-hand partition does not include "support facilities," i.e., mine use. It is also stated that the high end of the range could be reduced by 50 percent through improvements in process use and by increased use of dry cooling.

The values in ABBEY & LOOSE, 1980, are given with little explanation other than that the "T" number is an upper bound and that the "PD" number is an intermediate estimate. The reference is cited as "Denver Research Institute, 1979," which does not appear in the reference list.

The water use values given in PENNER, ET AL., 1981, are all for processes which include upgrading. The numbers from PROBSTEIN, ET AL., 1979, are given with a breakdown into use categories. The number from COLO. DEPT. NATURAL RES., 1979a, does not include electric power production. No other specific comments are given, but it is stated that all of the source reports use the same basic data from site-specific development plans. It is also stated that the biggest uncertainty involves spent-shale disposal and, especially, the revegetation water requirement.

A-14 Chart No. 14 - Oil-Shale Processing - Water Purification Associates, Cambridge, MA

This chart summarizes primarily the reports of Water Purification Associates (WPA), Inc. As mentioned in the discussion of Chart No. 13, NEVENS, ET AL., 1979, and its descendents also appear to belong in this family. The WPA reports contain summaries of detailed conceptual design studies. Often information on energy and material balances are included. The conceptual designs are for almost completely integrated industries. Water requirements for mining, fuel preparation, retorting, upgrading, waste disposal and reclamation are usually all considered. There are some exceptions, however. In all reports but GOLDSTEIN, ET AL., 1979, water needs for electric power production are not included in the TOSCO-II ("T") numbers. Power production needs are included in the Paraho ("P") numbers. It is possible, though not stated, that the designs summarized in GOLDSTEIN, ET AL., 1979, are the same as those summarized in NEVENS, ET AL., 1979, in Chart No. 13. If so, then its TOSCO-II water-use value includes power production. On the other hand, if this is so, the number does not include a maximum water requirement for revegetation, but only an average over the plant's lifetime.

The major water-consumption differences between the TOSCO-II and Paraho plants have to do with spent shale disposal. The TOSCO-II ("T") design uses a large amount of water for moisturizing the spent shale to 13-14% by weight (so it will set up like a weak Portland cement), but only a moderate amount for revegetation. The Paraho indirect ("PI") design uses a much smaller amount of water for moisturizing the spent shale (placing it in an imperviously lined containment--the so called "bath tub" method), but a large amount for revegetation of the carbon coated surface layers. The Paraho direct ("PD") design uses a small amount of water for moisturizing and also needs only a small amount for revegetation. In all of the WPA reports, the grade of the raw shale considered for the TOSCO-II process is 35 gal/t while for the Paraho processes it is 30 gal/t.

The water use breakdown is very similar in PROBSTEIN & GOLD, 1978, and GOLD & GOLDSTEIN, 1978 (and 1979). The slight differences in water-use values shown in the chart appear to arise from the normalization of the water use-values on a per-unit-energy basis in the WPA reports. In PROBSTEIN & GOLD, 1978, only the heating value of the syncrude product is used. In GOLD & GOLDSTEIN, 1978 and 1979, the heating value of the syncrude is combined with the heating value of the byproducts.

The water use breakdown is quite different between WATER PURIF. ASSOC., 1976 (and GOLD, ET AL., 1977) and PROBSTEIN & GOLD, 1978. In the earlier reports more water is consumed in upgrading, while in the Probstein and Gold report more is consumed in dust control, cooling, spent-shale moisturizing and revegetation.

The difference in the "PD" value in GOLDSTEIN, ET AL., 1979, from the other "PD" numbers on the chart appears to be primarily due to two causes: (1) the product is a pumpable crude shale oil and not an upgraded syncrude as in the other cases; (2) the byproduct fuel gas is not compressed before purification, as in the other designs, but before the turbine so the sensible heat in the gas can be used and a large cooling load associated with cooling the compressed gas can be avoided.

Considering the modified in situ ("MIS") water-use range in GOLDSTEIN, ET AL., 1979, the low end is derived from Rio Blanco Oil Shale (Tract C-a) plans (using open cycle gas turbines for power generation) and the high end is from Occidental Oil Shale (Tract C-b) plans (using combined cycle power generation). The average value is WPA's own plan using the same rate of steam injection into the retort as Occidental, but much less water for irrigation than Occidental. It also calls for combined cycle power generation, but consumes much less water than the Occidental plan by compressing the fuel gas after purification, just upstream of the turbines. In all of the "MIS" cases, upgrading is not considered and the water-use values do not include the contribution of "MIS" retort water or water of combustion (i.e., they have been subtracted from the water requirement). The cases are site specific for sites with excess mine-drainage water.

Considering COLO. DEPT. NATURAL RES., 1979a, WPA did work on water treatment costs for the study, but the source of their water consumption values is given only vaguely as "literature estimates." Little specific explanation is given for the ranges, but it is stated that the "MIS" range is lower than the "SR" range due to a lack of water requirements for spent-shale disposal and revegetation. The 63 $m^3/10^{12}J$ value is their arbitrarily chosen working assumption, considered reasonably conservative by them even for surface retorting because they believe on-site upgrading will not be necessary with the use of additive pour point depressants.

Of the two Water Resources Council reports, U.S. WATER RES. COUNCIL, 1981a, is almost a direct copy of COLO. DEPT. NATURAL RES., 1979a, while U.S. WATER RES. COUNCIL, 1981b, is a condensation of it.

A-15 Chart No. 15 - Oil-Shale Processing - Science and Public Policy Program, Univ. of Oklahoma, Norman, Ok.

This chart is centered around the "Energy from the West" reports of the University of Oklahoma's Science and Public Policy Program. It is similar in structure to Charts Nos. 5 and 10, but in this case the "Impact Reports" do not appear to depend on water-consumption values developed by Water Purification Associates, Inc. Instead they depend on WHITE, ET AL., 1979b, the values in which are derived more directly from process and/or project developers, see Chart No. 12.

Considering individual reports, in WHITE, ET AL., 1979d, rough breakdowns of water-use are given. However, no apparent reason is given for the inconsistency in the "MIS/SR" water-use value between this report and its source, WHITE, ET AL., 1979b. In that report the $9.3\ m^3/10^{12}J$ comes from considering the "make up" water only. If "retort water and residual groundwater" are also included, the water-use is $25\ m^3/10^{12}J$. How it climbs to $61\ m^3/10^{12}J$ in WHITE, ET AL., 1979d, is not explained.

In WHITE, ET AL., 1979c, the listing of two water-use values under "MIS/SR" is due to confusion in their Table 3-12 over plant factors and product heating values. Finally, in WHITE, ET AL., 1979e and 1979f, what they call in situ ("IS") is probably modified in situ ("MIS") retorting.