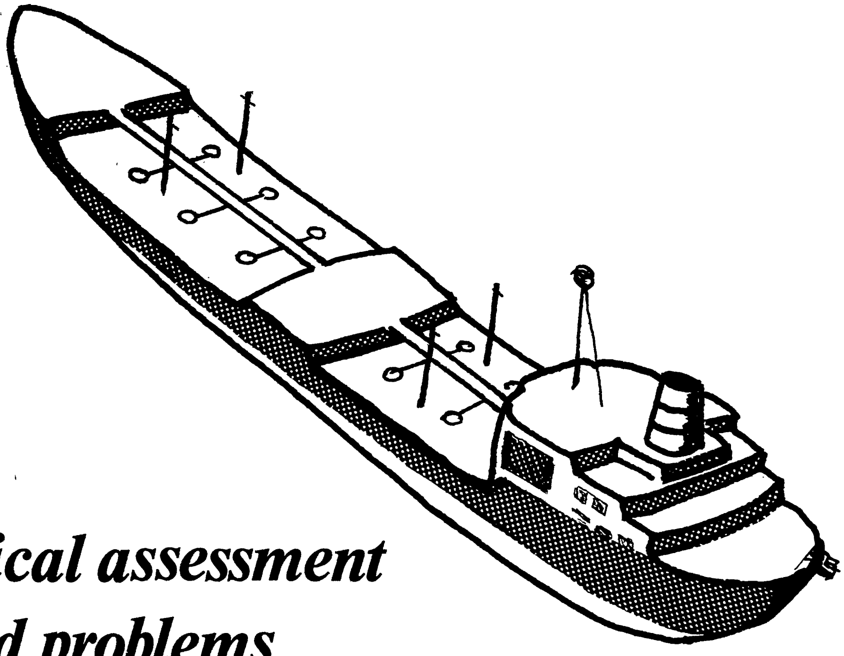
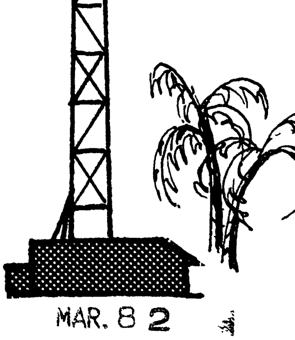
STRATEGIC STOCKPILE IN NATURAL GAS

by M.R.Tek



A proposal for technical assessment of prospects and problems

Department of Chemical Engineering
The University of Michigan
Ann Arbor, Michigan
October, 1977



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NAME AND ADDRESS OF INSTITUTION

The University of Michigan
222 Research Administration Building
Ann Arbor, Michigan 48109

TITLE OF PROPOSED RESEARCH

"Strategic Stockpile of Natural Gas"

DESIRED STARTING DATE

TIME PERIOD FOR WHICH SUPPORT IS REQUESTED

Three Years

Submitted by:

(TEK)

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Title: Professor
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J. F. BRINKERHOFF, VICE PRESIDENT AND
CHIEF FINANCIAL OFFICER

STRATEGIC STOCKPILE IN NATURAL GAS

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STRATEGIC STOCKPILE IN NATURAL GAS

A Proposal to Assess Prospects and Problems in Developing Stockpiled Gas Reserves Toward Energy Independence

By M. R. Tek

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1. EXECUTIVE SUMMARY

A comprehensive engineering research program is proposed to assess the desirability and feasibility of establishing a "strategic stockpile" in natural gas. Not too long ago the United States had the world's largest gas supply. This, along with the climate of free enterprise traditional in our country, led to the development of the world's largest market for natural gas. The two, i.e., the supply and the market were linked with the world's most elaborate pipeline network. It was the combination of these three resources that resulted in a prolific growth record which consumed over 400 trillion cubic feet of natural gas in just 40 years between 1935 and 1975.

Since 1970, however, the reserves leveled and peaked out. Soon after, the declines became painfully apparent. The harsh winter of 1976-77 helped focus the problems of the future into the view of the present. As our dependence on natural gas gets more and more critical and the hour grows late, our supply limited markets must somehow relate to market limited supplies of natural gas around the world. Gas supplies around the globe are indeed plentiful but they are and will remain undeveloped because they will continue to be market limited. Furthermore the gas that is associated with the production of crude oil (our prime energy resource still for a number of years to come) also depends upon markets for proper consumption. In countries which do not practice conservation that gas is flared into the atmosphere contributing both to pollution and waste. It has been reported that in 1974 OPEC countries flared the equivalent of 2.4 million barrels of oil per day into the atmosphere. In countries which practice conservation, rules against flaring such gas causes the production of associated crude oil to be curtailed.

In the United States, we have a unique combination of not only a developed market and pipelines to supply and distribute the gas to it, but also: an environment, safe and ecológical to put the gas in storage.

SO WHY NOT BUILD A STRATEGIC STOCKPILE IN METHANE?

We have in the United States, 132,000 gas wells, some 6,000 plus semi-depleted gas or underground storage reservoirs, 70,000 linear miles of gas gathering lines, 260,000 miles of long distance pipelines and 660,000 miles of low pressure gas distribution networks. These facilities are all operational, mostly paid, and more and more unused. Why not put these available resources to work? If we could pressure up and stock our existing gas reservoirs to conditions which prevailed before, not only our economic well-being would be substantially enhanced but our relationships with our neighbors friend of foe would also ameliorate.

WHERE COULD WE GET THE GAS FROM?

We could get it from Australia, from Saudi Arabia, from Iran, even from distant Siberia. We have the wheat the Soviets so frequently need. They have the largest gas supply that is most unlikely to be developed to full extent.

In many ways; some already underway, others planned or proposed. Some gas is already being imported by special cryogenic tankers in the form of LNG. While the present shipments are small they will undoubtedly increase in the future. The increase is, however, likely to be limited by the present backlog and cost of special tankers. As a major mode of transportation the methane-methanol-methane route has been suggested. This appears not only practical but much favorably competitive to LNG alternative over supply routes in excess of 3,500 miles if the gas can be purchased at the source at a reasonable price. In this scheme methane would be reformed into methanol and methanol would be shipped using regular tankers which are cheaper and available in surplus quantities. Upon arrival to the U.S., the methanol would be used as basic feedstock to be gasified into methane. That step too uses present and commercially established technology. Some methanol could be consumed as liquid fuel.

Other sources of gas for a strategic stockpile may include pipeline gas from Arctic, or Mexico, new gas from the lower 48 and, in the future, SNG from coal.

Where would the methane be stored to build the stockpile? In underground storage in selected gas, oil or water reservoirs. It must be noted that the gas would be stored in none other than where nature had put it in the first place. These storage reservoirs occurring in depths ranging from 2,000 to 7,000 feet are not only safe but environmentally sound and ecologically acceptable.

The establishment of a strategic stockpile in methane would indeed be a bold and innovative concept toward our energy independence. The present proposal would relate to it's technological assessment.

More specifically, the proposed research program would develop technical answers to the following questions.

1. Is a "strategic stockpile" in methane needed?
2. Is it possible?
3. Is it feasible?
4. Is it practical?
5. How big a stockpile?
6. Where stored?
7. How stored?
8. At what rate it can be developed?
9. What would be the economic and financial requirements?
10. What would be the institutional constraints?
11. What would be the lead time to achieve the objectives?

2. INTRODUCTION - BACKGROUND

The economic well-being of the United States depends so critically upon having sufficient energy resources that the status of natural gas reserves must be in the forefront of every long range energy planning effort. Of the 70 Quads we approximately consume each day in energy, about 30 percent comes from natural gas. This is only exceeded by oil which now represents over 46 percent of our total daily energy consumption (1975 figures).

The year of the "destination embargoes" on Arab oil, 1973, was a landmark year to focus public opinion on our dependence to crude oil imports. The recent past winter of 1976-77 is considered to be another landmark year: this one, to focus on our need to develop future supplies in natural gas. The importance and significance of petroleum storage in energy planning has recently been recognized by the Federal Energy Policy and Conservation Act of 1976. Implementation of a National Strategic Petroleum Storage Program was only recently budgeted for FY 1977. While operations for the storage of liquid petroleum products as well as crude oil are currently underway, storage of natural gas imports for stockpiling purposes have not yet been considered. In the United Sates we have the most unique combination of three resources which relate to our presently dwindling indigenous gas reserves. These are:

1. <u>World's largest market in natural gas</u>. This is represented by our gas market mostly in the northeast, unequaled in

the world. The low pressure gas distribution pipeline network, over 660,000 linear miles long, leading to some 43 million individual meters, compressor stations, underground storage facilities constitute the main components of this market. In the U.S., over 60 percent of our homes are heated by natural gas.

2. World's most elaborate long distance pipeline network. Indeed, emanating from the Gulf-Coast and southwest and reaching the markets of west, north and particularly northeast we have over 260,000 miles of long distance pipeline networks. The Figure 1 shows the distribution of natural gas supply areas in the United States and the location of gas storage reservoirs and the Figure 2 shows the pipeline network connecting the supply to market.

3. World's largest gas storage environment. The environment for possible storage of natural gas consists of gas producing fields, depleted oil and gas reservoirs and present underground storage fields. These facilities existing (or presently developed), operational and available include some 132,000 gas wells, 72,000 linear miles long gas gathering networks connected to some 6,000 plus natural gas reservoirs.

The impressive statistics related to the three resources listed above are shown in Figure 3.

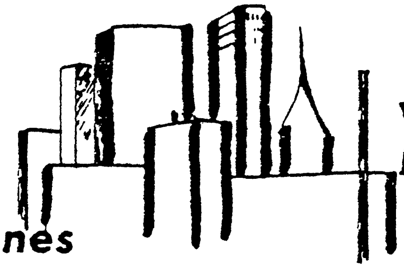
Against the background of the three resources listed above the distribution of gas supplies and gas markets worldwide are depicted in Figure 4. It is noted that among market limited supplies are: U.S.S.R. (Siberia), Iran, then Saudi Arabia, Algeria and northwest shelf of Australia. Opposite these the

Figure 1. Gas Supply Areas and Underground Storage Reservoirs.

Figure 2. Natural Gas Pipeline Network Connecting Supply-Storage Areas to Gas Markets.

Figure 3.

U. S. A.
UNIQUE COMBINATION of 3 RESOURCES



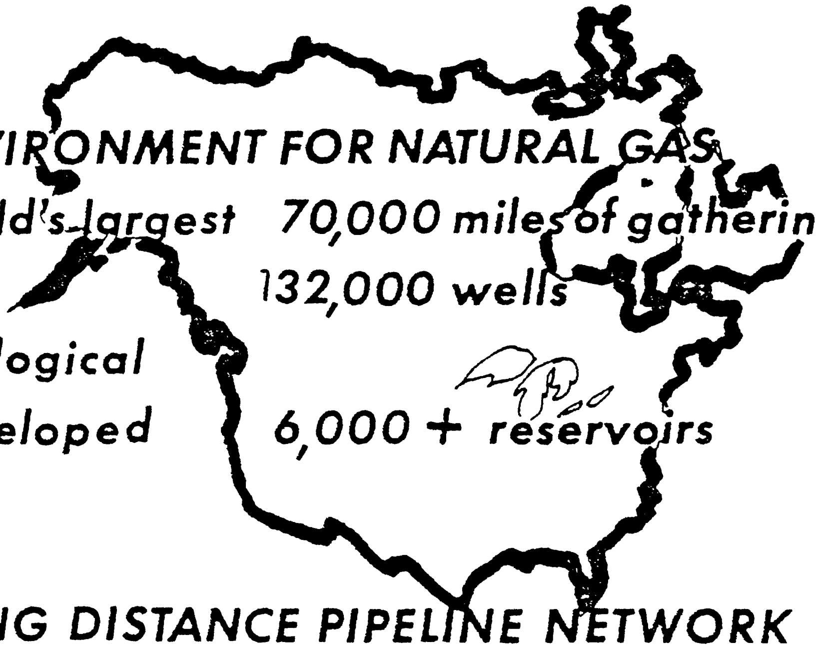
world's largest

MARKET FOR NATURAL GAS

660,000 miles of distribution lines

45,000,000 (res., com.) meters

63 % of homes



2. ENVIRONMENT FOR NATURAL GAS

world's largest	70,000 miles of gathering networks
safe	132,000 wells
ecological	
developed	6,000 + reservoirs

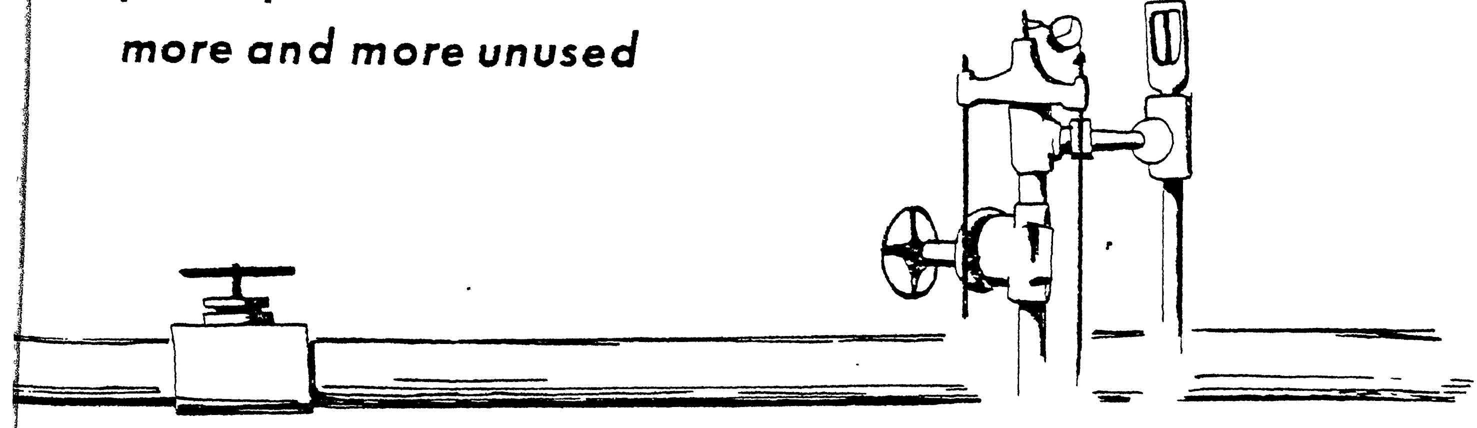
3. LONG DISTANCE PIPELINE NETWORK

world's largest 270,000 miles

operating

paid up

more and more unused



MARKET LIMITED SUPPLIES
VS
SUPPLY LIMITED MARKETS

GLOBAL SUPPLY OF NATURAL GAS

USSR (SIBERIA)
IRAN
SAUDI ARABIA
ALGERIA
NORTHWEST SHELF

ALL
MARKET LIMITE

GLOBAL MARKETS

USA
WESTERN EUROPE
JAPAN

ALL
SUPPLY
LIMITED

Figure 4. Market Limited Supplies Versus Supply Limited Markets.

world's largest gas markets are shown. These are the U.S.A., western Europe and Japan. All three are supply limited.

The present proposal recognizes that natural gas exists in plentiful supply in remote areas of the globe, far from present markets and quite beyond the reach of pipelines. It is generally accepted that world natural gas resources probably exceed those of oil. Outside the U.S. and Canada most of major deep gas prospects are yet to be drilled.

One must also recognize the United States gas reserves were about the largest in the world when they were being developed 30 years ago. While additions to our natural gas reserves no longer exceed the annual consumption, and most our reservoirs are being depleted, there still exists the largest environment, safe and sound, far from the surface and totally ecological for storage of natural gas underground. If it can be shown that natural gas from far away corners of the world such as northwest shelf in Australia, Middle East, the Arctic, Indonesia, even Siberia can be effectively transported to the U.S. and pumped into selected storage reservoirs via existing network of pipelines, it would be possible to build up our gas reserves back to what they represented to the world and our economy about three decades ago. A technological evaluation and assessment of factors involved in such a program to build a strategically meaningful stockpile in gas is the objective of this research proposal.

3. NARRATIVE ON PROPOSED RESEARCH

The basic purpose, as well as specific relevant aspects of the research, proposed will be presented in the following, in logical sequence.

PURPOSE

The purpose of the research work proposed is an overall technological assessment of desirability and feasibility of the prospects of developing a "strategic stockpile" in natural gas. For an appropriate and comprehensive evaluation of the concept "the problems" as well as "the prospects" must be identified. In order to accomplish this and relate it to the methodology proposed the concept will be broken into several logical and sequential aspects and each will be entertained separately:

3.1. DETERMINING THE NEED FOR STOCKPILE

Economic stockpiling is normally accepted as a concept to provide short term solutions to long term problems. On the other hand, economic stockpiling is recognized to aid the long term problem in providing time to study and implement long term solutions. In the field of energy, the long term solutions, involve substitution, conservation, and alternative methods.

In 1976 the Office of Technology Assessment at the request of the House Committee on Science and Technology(1) examined stockpiling as a component of national strategy during peace

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*The numbers in upper script parentheses refer to literature citations given at the end.

time. Their report pointed out that increasing dependence on materials imported from outside did "pose new dangers" to a healthy economy. Obviously the above applies to materials we import for our energy needs.

The Energy Policy and Conservation Act, Public Law 94-163 which was signed into law on December 22, 1975 had listed under one of its purposes:

"To provide for the creation of a strategic petroleum reserve capable of reducing the impact of severe energy supply interruptions."

The winter of 1976-77 provided us the data which showed emphatically how relevant the above quote was. Natural gas is the country's premier fuel. It's the most clean burning of common fuels. It is efficient, transportable, versatile, and most compatible with environment. That is why it occupies a premium place in our primary energy supply distribution as shown by Figure 5. It may be noted from Figure 5 that for instance in 1972 our primary supply of indigenous natural gas exceeded our indigenous crude oil supply on Btu basis. Figure 5 also shows that our residential commercial and industrial markets rely very heavily on natural gas. Also, in 1972 approximately one quarter of our electricity generation was supplied by natural gas.

Unfortunately, in spite of all usage, the consumption of natural gas in all three sectors indicated above clearly peaked out and resumed a downward trend sometime during 1972-1973. This is shown in Figure 6.(3) The Figure 7 shows the natural gas reserves and effective life of current reserves for U.S.

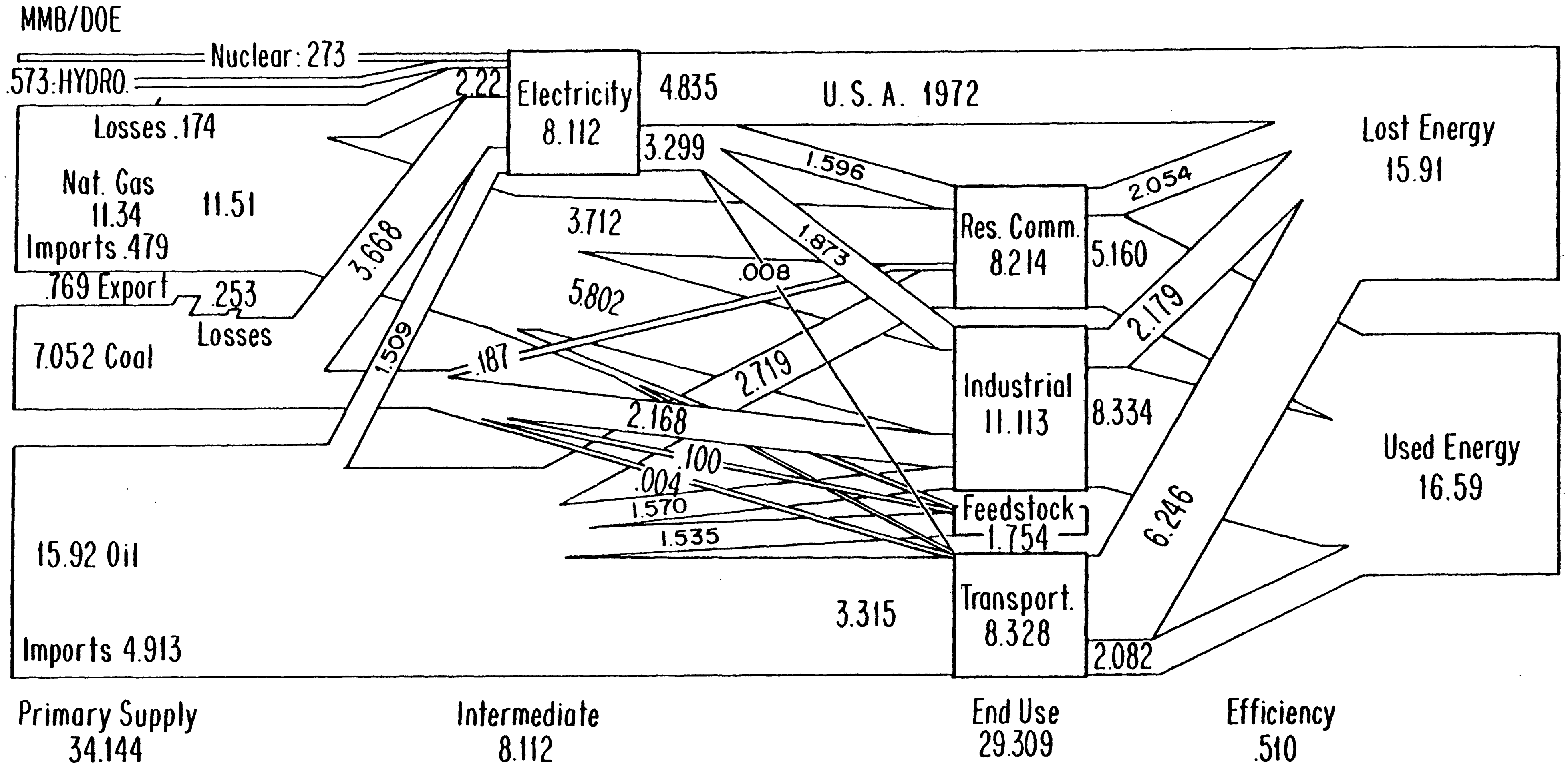


Figure 5. Distribution of Energy Supply and Demand[2] (USA 1972).

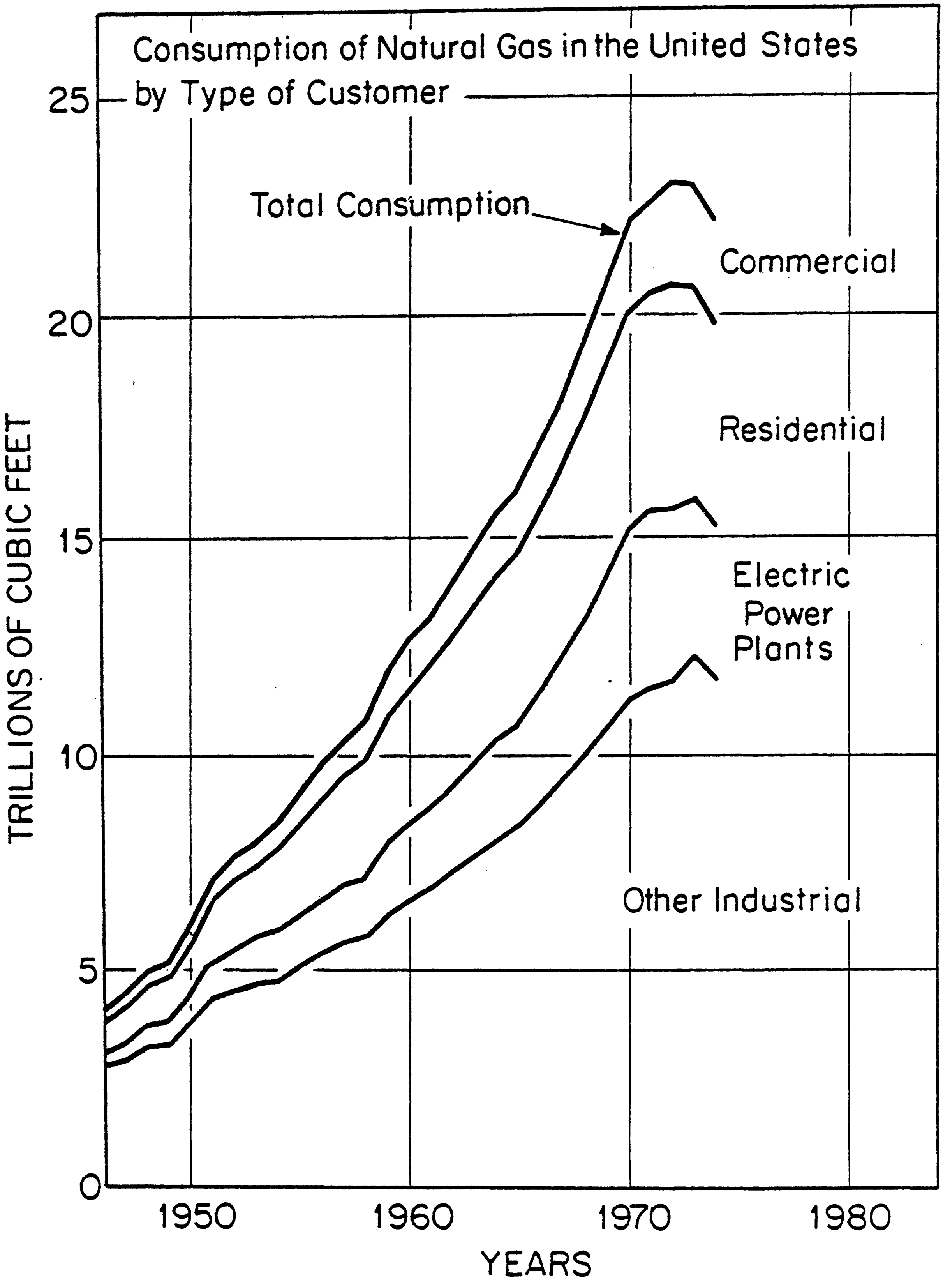


Figure 6. Consumption of Natural Gas in the United States By Type of Customer.

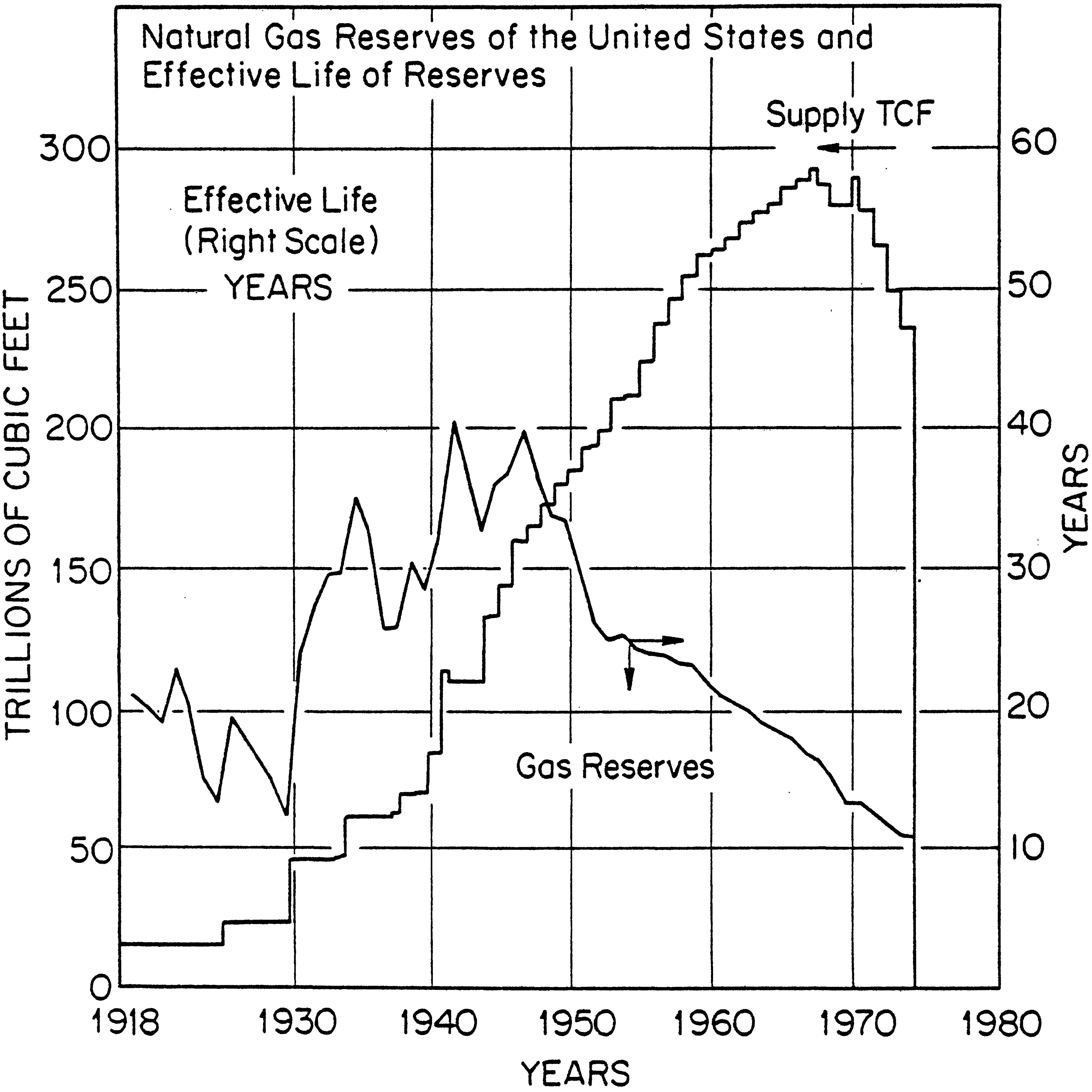


Figure 7. Natural Gas Reserves of the United States and Effective Life of Reserves.

for the period 1918-1974. It can be seen that reserves which steadily increased during the thirties, forties, and fifties have turned around in 1970 and resumed a steady and steep decline during the early 70's. Also on Figure 7, the effective life, which reads from the right hand scale shows the number of years, the current reserves would last at the current rate of consumption if no addition to existing reserves were to occur. That number too, once as high as 40 years has been steadily declining since 1946-47 in spite of then prevailing additions to existing reserves. At the present it is only slightly above ten years.

The Figures 6 and 7 clearly indicate the need for a long range supply of methane if we are to remain economically healthy and if we are to make effective use of our unique resources such as oil and gas wells, reservoirs, pipelines, distribution systems, compression facilities, existing markets.

The relevance of strategic stockpile in natural gas may be justified and analyzed in terms of a "relevance tree", developed by the Office of Technology Assessment(1) as shown in Table I. It may be noted that the question posed at level 1, why stockpile methane? is answered on the basis providing protection against depletion or interruption and on the basis of assuring future supply. These answers given at level 2 are entertained with respect to domestic and foreign supplies on level 3. The levels 4 and 5 further break down and classify possible and probable events which justify establishment of a stockpile.

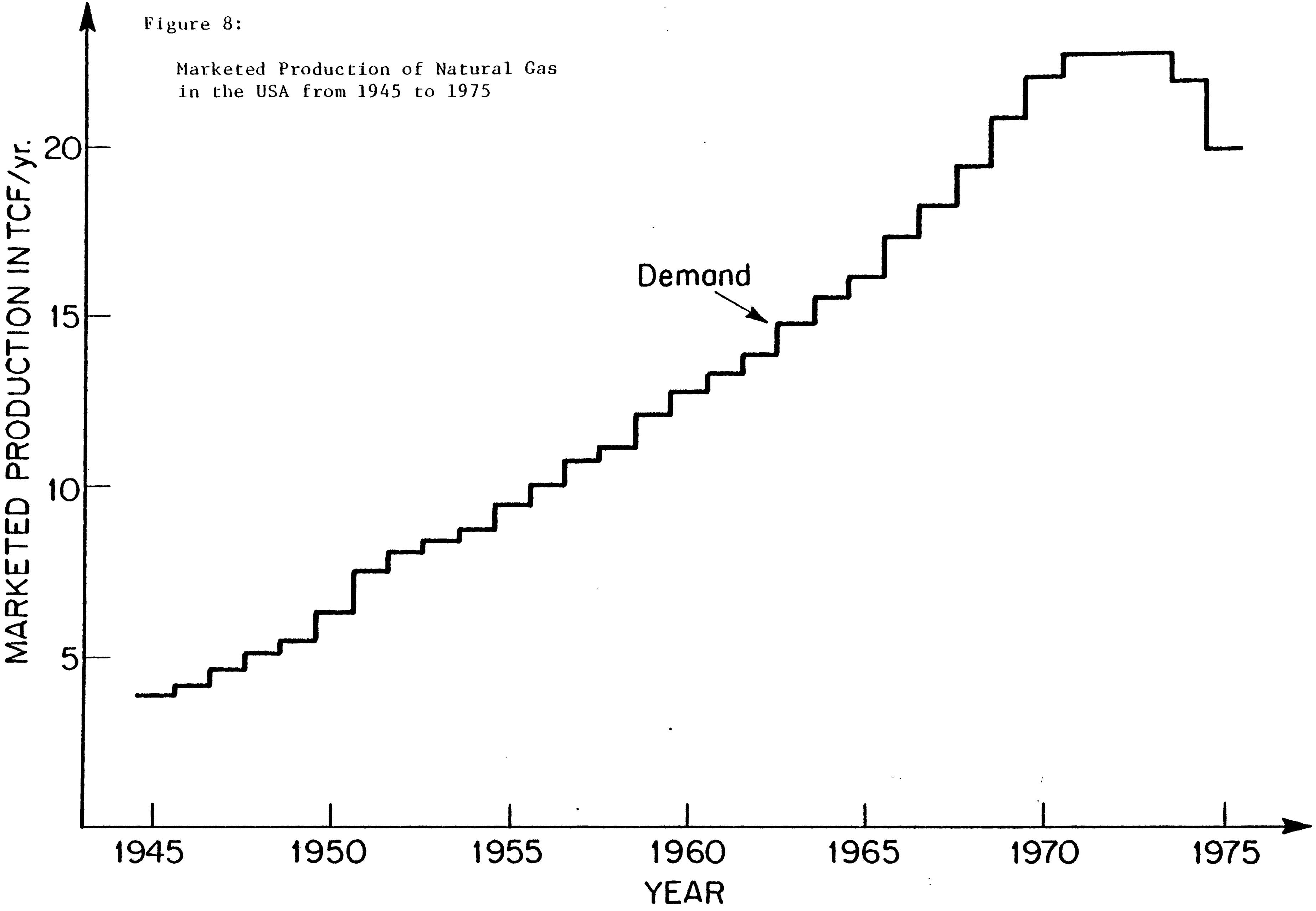
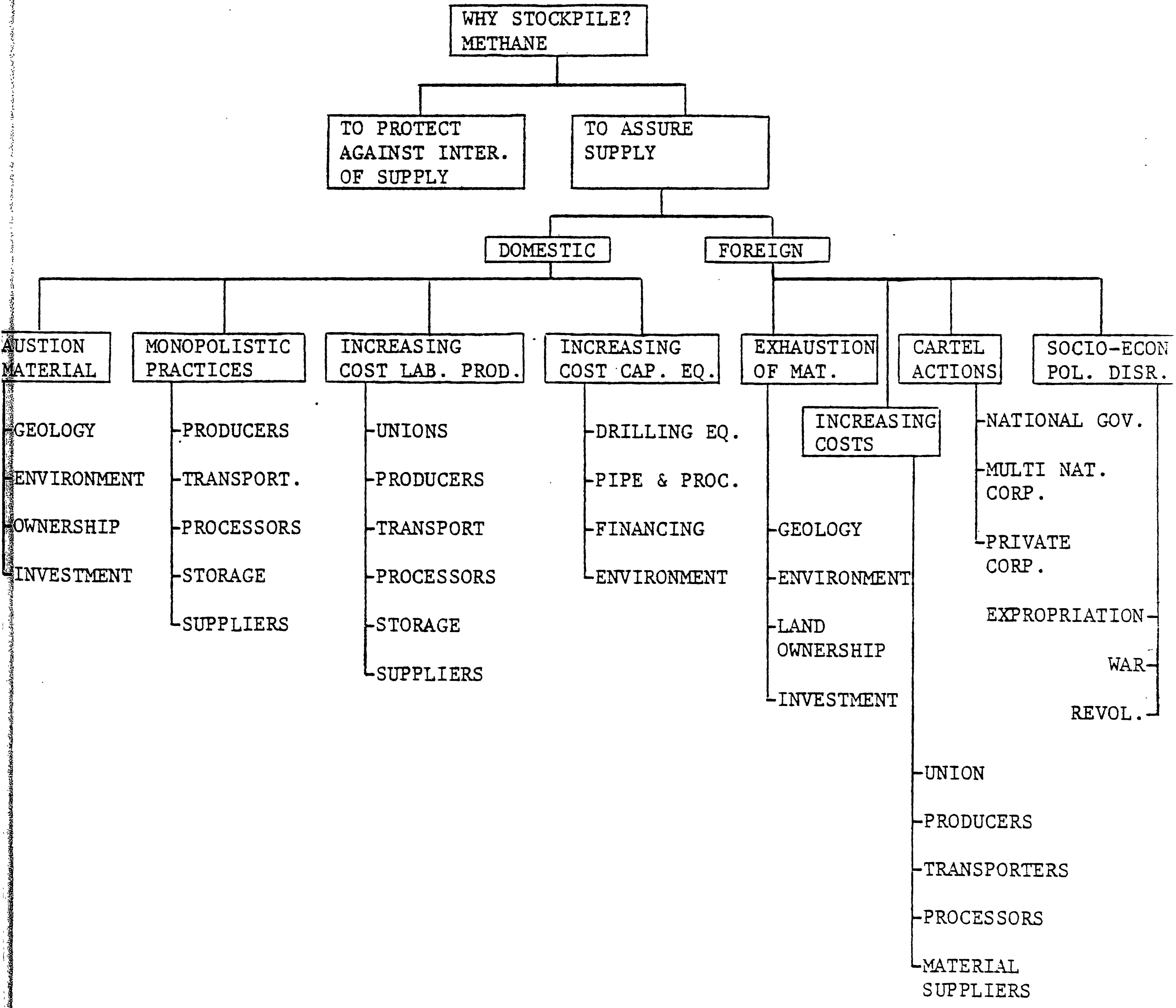


Figure 8:

Marketed Production of Natural Gas in the USA from 1945 to 1975

TABLE I. Relevance Tree Representation of the Need For a Strategic Stockpile in Methane.



3.2. THE SUPPLY VERSUS DEMAND IN NATURAL GAS (PAST-PRESENT-FUTURE)

The Figure 7 shows the natural gas reserves of the United States in historical perspective between the years 1919 and 1974. The bargraph shows the stepwise nature of annual additions to gas reserves representing the increase in supply until the period 1968-1970. As related to Figure 7 showing the supply, the Figure 8 has been plotted from data compiled by the American Gas Association showing the marketed production of natural gas between the years 1945 and 1975. This plot represents the demand. It may be observed that prior to 1970 while the supply (Figure 7) increased at a decreasing rate, the demand (Figure 8) increased at an increasing rate. The reduction shown for the demand curve between 1970 and 1975 simply reflects the curtailments just subsequent to energy crisis of 1972-73. In order to establish meaningful projections from which to forecast future trends, the Figure 9 has been prepared. It depicts three scenarios:

1. No growth, zero percent increase in consumption per year,
2. Two percent increase in consumption per year,
3. Three and one half percent increase in consumption per year.

Of the three, 1. and 3. are offered as bracketing values with the two percent per year as a reasonable restrained growth in gas markets. For each of the 1975-2000 scenarios given above the decline trends of present reserves have been computed.

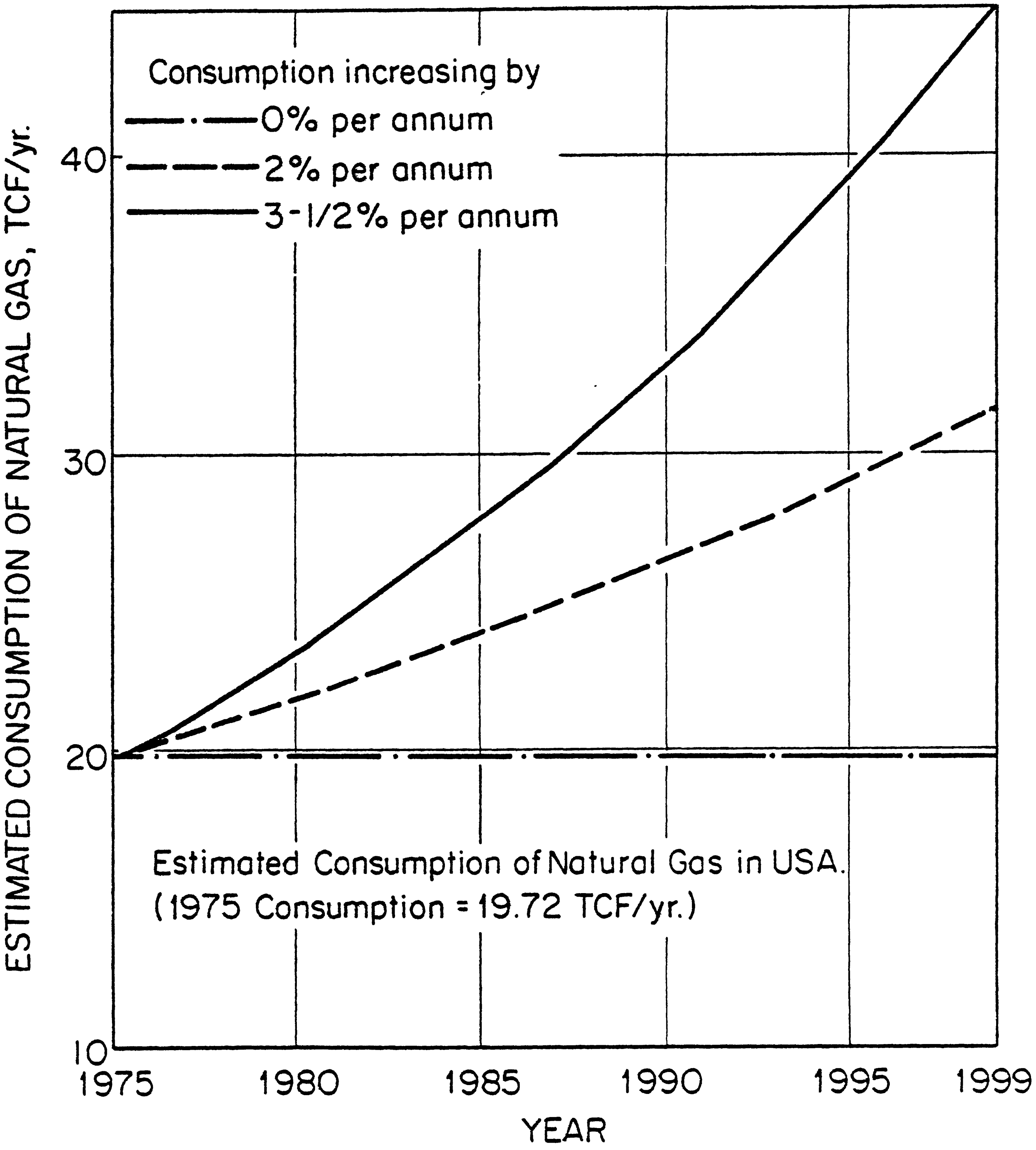


Figure 9. Estimated Consumption of Natural Gas in U.S.A. (1975 Consumption = 19.72 TCF/yr).

In making future projections in supply it becomes important to reliably forecast just when we would totally deplete our present indigenous gas reserves if the gas consumption stayed the same, grew two percent per year or grew three and one half percent per year. In order to do that realistically one has to account for new additions to present reserves which occur every year. These new additions are due to new fields discovered, to extensions of existing fields, to revisions in estimating reserves on account of new data and to new additions of solution gas associated with oil. The latest figure we have on annual additions to our reserves is ten trillion std cubic feet per year.(4) In making future projections we have assumed that +10 TCF addition to reserves will remain the same between 1975 and 1999. The Table II below shows how the remaining reserves for each year have been computed.

Table II. Revision to Indigenous Gas Reserves.

1975 - 1976

(Assumed growth in the market 0%)

1975 reserves = 228.20 TCF

Consumption 1975-76 = 19.72 TCF

Additions to reserves during 1976 = 10.00 TCF

Reserves estimated for 1976 = 228.20-19.72+10.00=218.48 TCF

The procedure shown above has been repeated year by year through 1999 and then again for market growths of two percent and three and one half percent through 1999. The results are given in

Figure 10. They indicate that if the present gas markets were held static (zero percent growth), and, if no more than 10 TCF were added to our reserves each year, and if we continued consuming the natural gas at the observed 1975-76 rate of 19.72 TCF, then our gas reserves would completely run out by about 1998. If on the other hand we allowed the consumption to grow three and one half percent per year and other figures remained the same, then our gas reserves would run out shortly before the year 1990.

3.3. AMOUNT OF GAS NEEDED TO DEVELOP A VIABLE STOCKPILE

The quantity of methane which may be dedicated to a strategic stockpile depends upon many factors, intangible as well as tangible. The value the country is willing to attribute to gas reserves, physical factors which may be controlling the space available for storage, economics of refurbishing old fields, pipelines, regulation, metering, control facilities, must all enter the picture. To determine that amount or the options which may optimize that amount will indeed be some of the objectives of research proposed here.

The total marketed production of natural gas in the U.S. between 1945 and 1975 has been documented to be 407.82 TCF.(5) During 1975 total net production of natural gas in the U.S. amounted to 19.72 TCF. If this annual production rate remained the same, by 1979 the total cumulative consumption for the period 1945-1979 would be 486.7 TCF. On the other hand if the gas markets were able to grow two per annum then the total projected consumption by 1979 would be 490.71 TCF. If the markets grew at

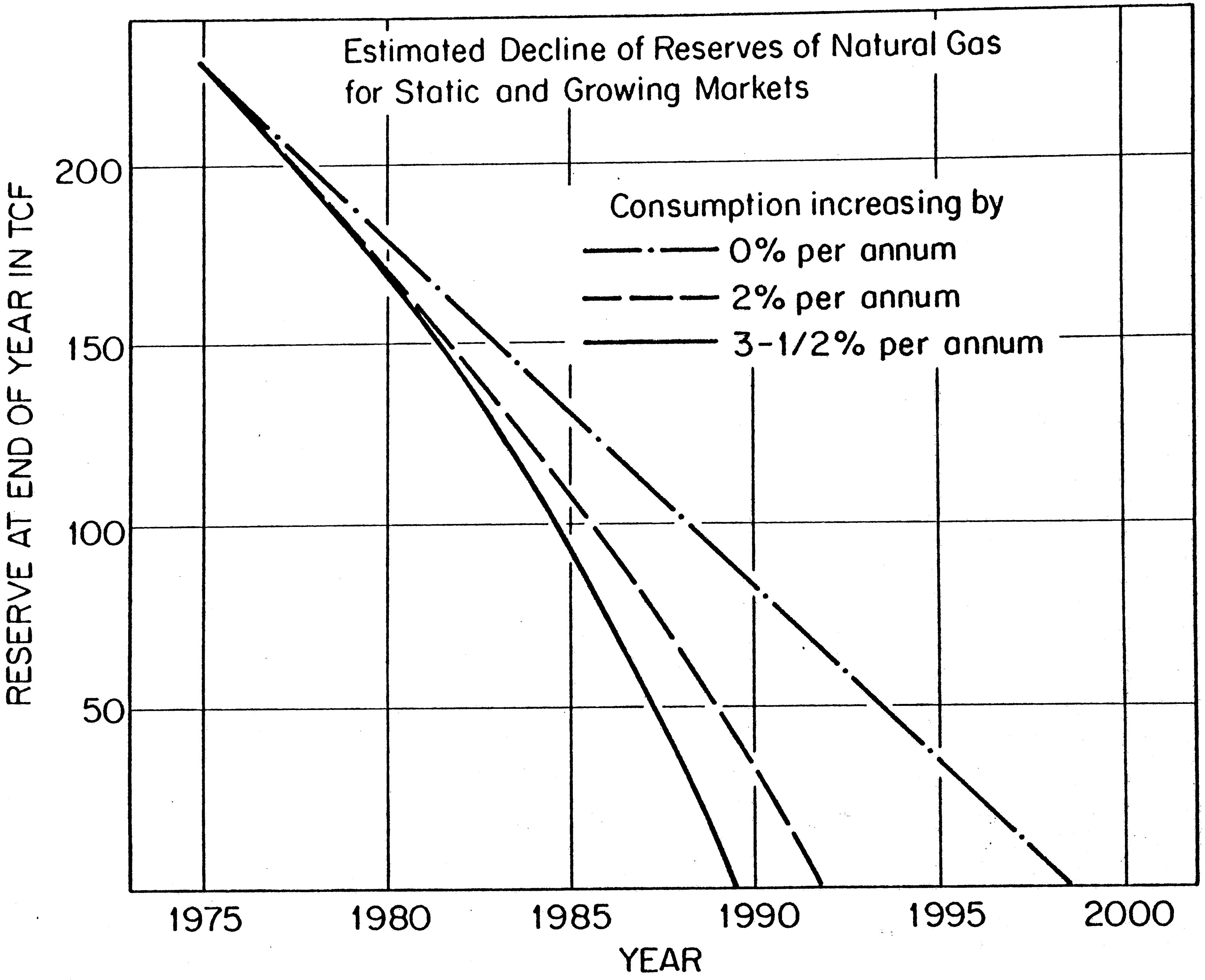


Figure 10. Estimated Decline of Reserves of Natural Gas For Static and Growing Markets.

three and one half percent per year the total cumulative gas for the period 1945-1979 would be 493.84 TCF. The reason for adjusting past production figures through projections around 1979 is that it would appear reasonablé to expect about three years 'lead time' before any strategic stockpile effort can be implemented in the United States. Now, assuming that some methane stockpile will, in principle be developed between 1980 and 1999, the quantity of gas on hand in stockpile by the year 2000 is the next consideration. In preparing this proposal we have proceeded as follows:

We took the figure of gas which will have been cumulatively produced by the end of 1979 and bracketed three premises:

1. Calculate a stockpiling scheme which would meet the condition of having all 100 percent of the gas cumulatively consumed, on hand in stockpile by the year 2000,
2. Calculate a schedule to develop only 20 percent of consumed gas stockpiled by the year 2000, and,
3. Calculate the schedule which would permit having only ten percent of gas cumulatively produced (between 1945 and 1979) on hand by the year 2000.

It must be appreciated that each of the three schedules above will result in annual gas requirement which would not only meet the amount which must be set aside for storage but an existing and currently gas consuming market growing at the compounded rates of zero percent, two percent, and three and one half percent per annum. Again, while this too is part of the proposed assessment, the annual gas requirements for each of the three schedules have been computed for each of the zero, two, and three and one half percent per annum growth markets.

The annual reserves sufficient to meet the growing market and at the same time to build up to a predetermined stockpile are calculated as follows:

Let us say that we want to gradually develop a strategic stockpile equal to 486.7 TCF (Total cumulative production between 1945 and 1979) by the year 2000. We shall further assume that between 1979 and 1999 the annual consumption of gas will remain static at 19.72 TCF per year. Furthermore we shall also assume that each year new additions to existing gas reserves, 10 TCF will remain the same. The 10 TCF figure is obtained from DeGolyer McNaughton statistics(3) and represent new gas found each year in the lower 48 states, new associated gas due to new oil, revision to old reserves.

Under the above conditions each year net amount required to build the 486.7 TCF in 20 years would be 486.7/20 = 24.34 TCF/year. This figure can be incorporated to an annual reserve calculation algorithm as follows:

Reserves as of the end of 1980 = Reserves as of the end of 1979 + 10 TCF new gas + 24.34 TCF addition to stockpile - 19.72 TCF to be consumed during 1979.

Such year by year reserve figures have been calculated for stockpile targets of 100 percent cumulative replacement, 20 percent cumulative replacement and ten percent cumulative replacement and for gas markets subject to growth of zero percent, two percent, and three and one half percent per year.

The results of these calculations are given in the form of various Tables included in the following and the Appendix.

The Table AI gives the marketed production of natural gas in the U.S. for the period 1945-1975. The Table AII gives the estimated proven reserves of natural gas for the same period. The Table AIII gives the annual consumption of natural gas compounded for different market growth rates. The Table AIV shows the expected decline of reserves between 1976 and 1999 due to consumption at zero, two and three and one half percent growth. The Table III gives an annual schedule of natural gas necessary to build-up a stockpile and the annual reserves for a stockpile scheme to replenish the full 100 percent of production between 1945 and 1975.

Table IV is similar to Table III but calculated for the case developing 20 percent of cumulative consumption as a stockpile for the year 2000. The Table V represents the case for developing a stockpile equal to only ten percent of cumulative production (1945-1979). In order to put matters into proper perspective the Figure 7 may be reexamined. It shows the proven gas reserves in U.S. between the years 1945 and 1975. It may be noted that the first true peak occurred during 1967, the harbinger of the declining trend in the lower 48. Subsequently in 1969 a minimum point occurred and uptrend resumed due to discovery of reserves in Alaska's North Slope. Finally during 1969 the down trend resumed once more and steadily held at a nearly constant rate through 1975.

Table III. Amount of Additional Natural Gas Necessary to Build a Stockpile Equal to The Consumption Between 1945 and 1979, and the Corresponding Estimated Reserves After Stockpiling.

Year	At 0% Increase in Consump.		At 2% Increase in Consump.		At 3½% Increase in Consump.	
	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves
1980	24.35 TCF/Year	218.56 TCF	24.54 TCF/Year	198.08	24.69 TCF/Year	193.45
1981	24.35	218.56	24.54	210.41	24.69	203.90
1982	24.34	233.18	24.54	222.30	24.69	213.50
1983	24.35	247.80	24.54	233.74	24.69	222.22
1984	24.35	262.42	24.54	244.71	24.69	230.03
1985	24.35	277.04	24.54	255.21	24.69	236.90
1986	24.35	291.66	24.54	265.23	24.69	242.80
1987	24.35	306.28	24.54	274.76	24.69	247.69
1988	24.34	320.90	24.54	283.79	24.69	251.54
1989	24.34	335.52	24.54	292.31	24.69	254.31
1990	24.34	350.14	24.54	300.31	40.32	271.59
1991	24.34	364.76	24.54	307.78	48.88	296.28
1992	24.34	379.38	28.85	319.02	50.08	390.97
1993	24.34	394.00	42.71	343.56	51.32	345.66
1994	24.34	408.62	43.27	368.10	52.61	370.35
1995	24.34	423.24	43.84	392.64	53.93	395.04
1996	24.34	437.86	44.43	417.18	55.30	419.73
1997	24.34	452.48	45.01	441.72	56.72	444.42
1998	24.34	476.10	45.64	466.26	58.19	469.11
1999	29.42	486.30	46.26	490.80	59.71	493.80

Table IV. Amount of Additional Natural Gas Necessary to Build a Stockpile Equal To 20% of the Consumption Between 1945 and 1979, and the Corresponding Estimated Reserves After Stockpiling.

Year	At 0% Increase in Consump.		At 2% Increase in Consump.		At 3½% Increase in Consump.	
	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves
1980	4.87 TCF/Year	184.47 TCF	4.91 TCF/Year	178.45	4.94 TCF/Year	173.70
1981	4.87	179.62	4.91	171.15	4.94	164.40
1982	4.87	174.77	4.91	163.41	4.94	154.25
1983	4.87	169.92	4.91	155.22	4.94	143.22
1984	4.87	165.07	4.91	146.56	4.94	131.28
1985	4.87	160.22	4.91	137.43	4.94	118.40
1986	4.87	155.37	4.91	127.82	4.94	104.55
1987	4.87	150.52	4.91	117.72	4.94	89.69
1988	4.87	145.67	4.91	107.12	4.94	73.79
1989	4.87	140.82	4.91	96.01	4.94	56.81
1990	4.87	135.97	4.91	84.38	20.57	54.34
1991	4.87	131.12	4.91	72.22	29.13	59.28
1992	4.87	126.27	9.22	63.83	30.33	64.22
1993	4.87	121.42	23.08	68.74	31.57	69.16
1994	4.87	116.57	23.64	73.65	32.86	74.10
1995	4.87	111.72	24.21	78.56	34.18	79.04
1996	4.87	106.87	24.80	83.47	35.55	83.98
1997	4.87	102.02	25.38	88.38	36.97	88.92
1998	4.87	97.17	26.01	93.29	38.44	93.86
1999	9.95	97.40	26.63	98.20	39.96	98.80

Table V. Amount of Additional Natural Gas Necessary to Build a Stockpile Equal To 10% of the Consumption Between 1945 and 1979, and the Corresponding Estimated Reserves After Stockpiling.

Year	At 0% Increase in Consump.		At 2% Increase in Consump.		At 3½% Increase in Consump.	
	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves	Additional Gas Needed	Reserves
1980	2.43 TCF/Year	182.03 TCF	2.45 TCF/Year	175.99	2.47 TCF/Year	171.23
1981	2.43	174.74	2.45	166.23	2.47	159.46
1982	2.43	167.45	2.45	156.03	2.47	146.84
1983	2.43	160.16	2.45	145.38	2.47	133.34
1984	2.43	152.87	2.45	134.26	2.47	118.93
1985	2.43	145.58	2.45	122.67	2.47	103.58
1986	2.43	138.29	2.45	110.60	2.47	87.26
1987	2.43	131.00	2.45	98.04	2.47	69.93
1988	2.43	123.71	2.45	84.98	2.47	51.56
1989	2.43	116.42	2.45	71.41	2.47	32.11
1990	2.43	109.13	2.45	57.32	18.10	27.18
1991	2.43	101.84	2.45	42.70	29.54	29.64
1992	2.43	94.55	6.76	31.84	37.86	32.11
1993	2.43	87.26	20.62	34.30	39.10	34.58
1994	2.43	79.97	21.18	36.75	40.39	37.05
1995	2.43	72.68	21.75	39.20	41.71	39.52
1996	2.43	65.39	22.34	41.65	43.08	41.99
1997	2.43	58.10	22.92	44.10	44.50	44.46
1998	2.43	50.81	23.55	46.55	45.97	46.93
1999	7.51	48.60	24.17	49.00	47.49	49.40

The Figure 11 shows the manner in which the reserves would be built up if, hypothetically, a stockpiling policy of restoring the entire 100 percent cumulative production between 1945 and 1979 was followed between the years 1980 and 2000. It may be noted that again three curves are shown one for each zero, two and three and one half percent per year growth markets. The apparent breakpoint on curves labeled two and three and one half percent correspond to years when the U.S. reserves would run out. The amount of additional gas necessary to build up such a stockpile is given in Figure 12. It can be seen that depending upon the zero, two and three and one half percent growth in national gas consumption, the amount of natural gas needed each year first remains constant then must be abruptly increased to sharply higher rates at specific dates corresponding to indigenous reserves running out. As can be seen from Table III and Figure 12 for a zero growth market the gas needed from additional sources is constant at the level of 24.34 TCF between 1980 and 1998, then jump to 29.42 TCF during 1999. For the same case with three and one half percent growth in the local market, the additional gas required for stockpiling remains first constant at 24.69 TCF per year during the years 1980 and 1989 then increases to 40.32 TCF during 1990 and to 48.88 during 1991 and so on. As expected, the case for two percent increase market is intermediate.

The case for totally replacing by the year 2000 the entire production cumulated between 1935 and 1975 is obviously quite unrealistic because of the staggering economics and engineering

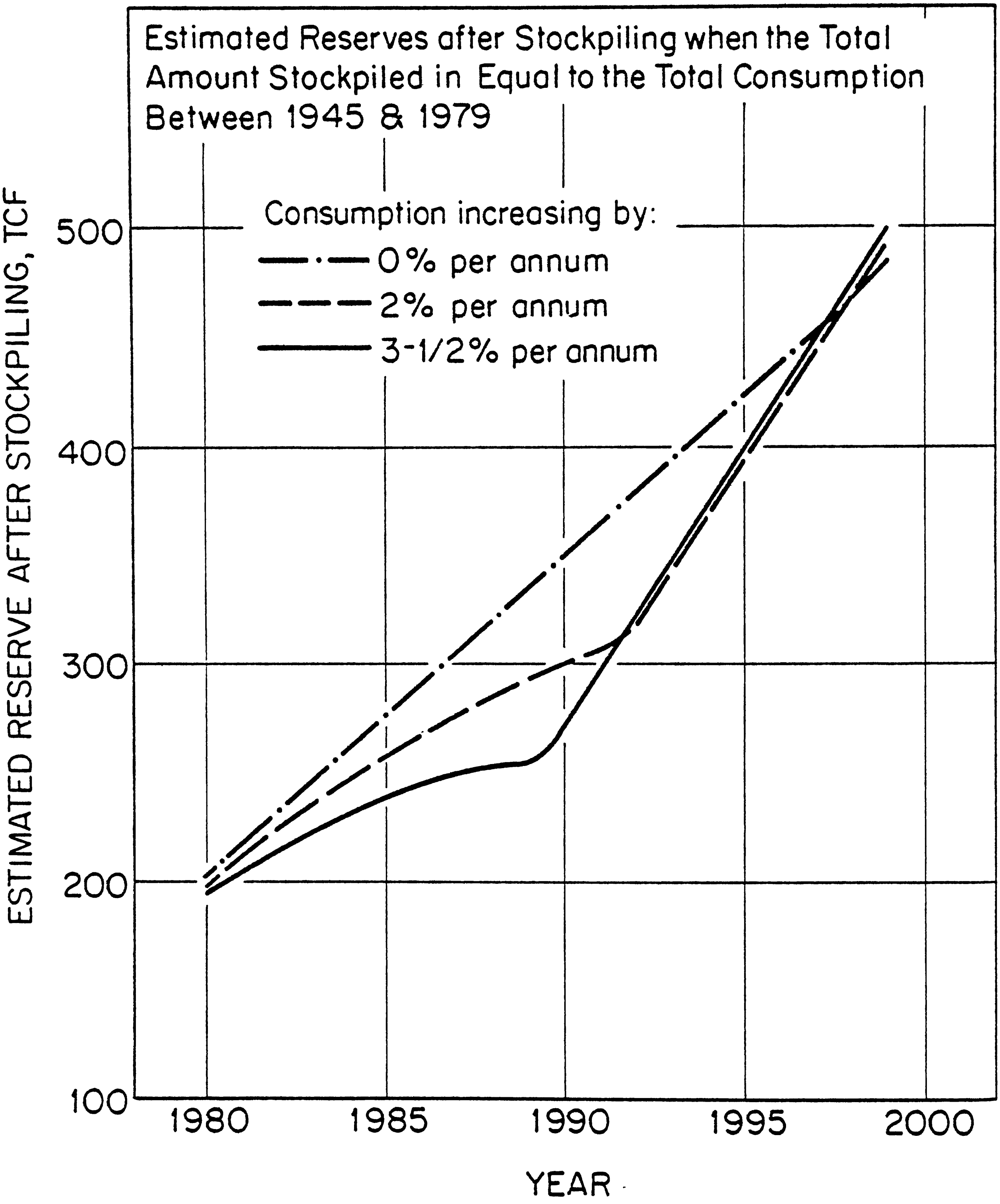


Figure 11. Estimated Reserves After Stockpiling when the Total Amount Stockpiled is Equal to the Total Consumption Between 1945 and 1979.

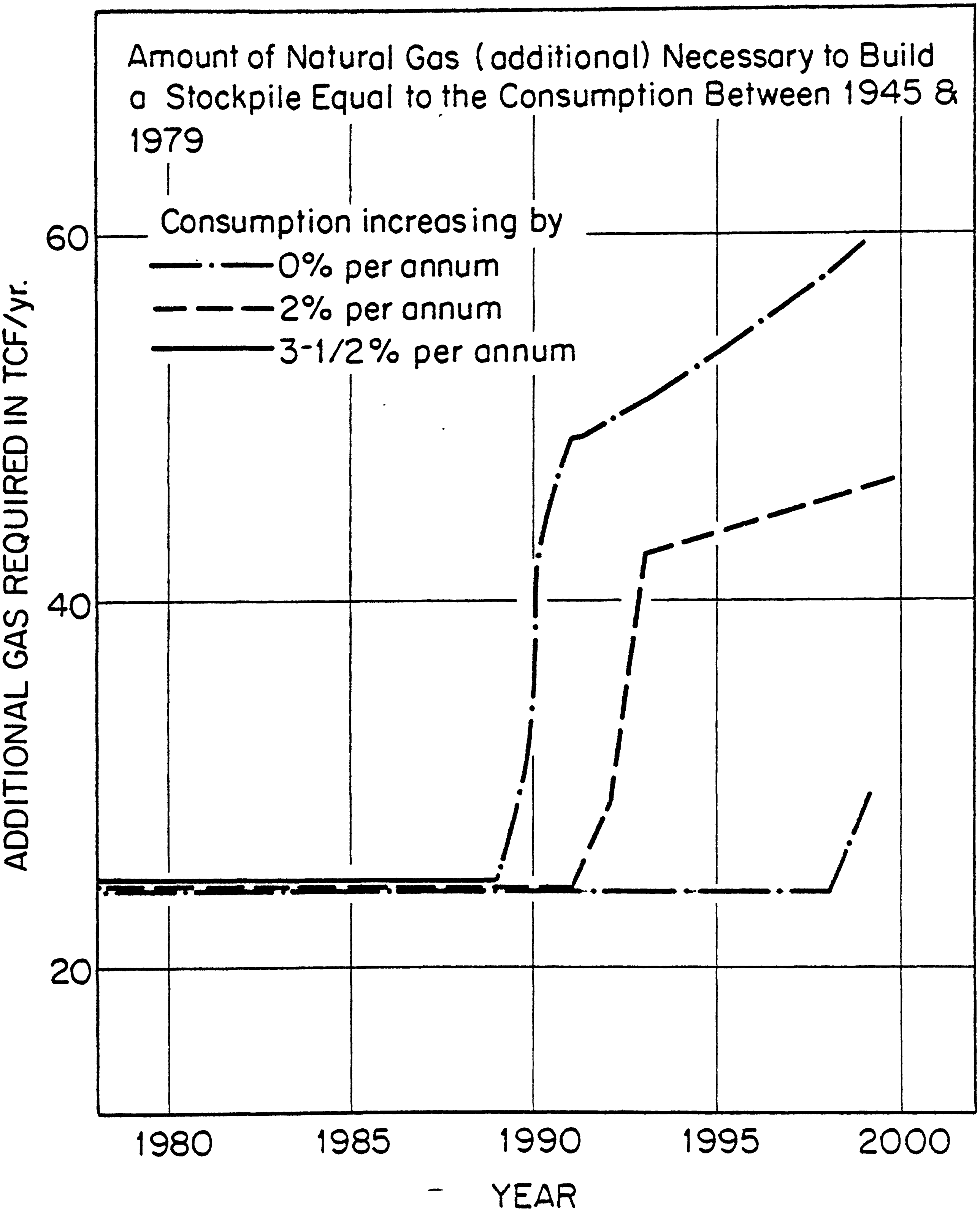


Figure 12. Amount of Natural Gas (additional) Necessary to Build a Stockpile Equal to the Consumption Between 1945 and 1979.

requirements involved. It is however included in these calculations for bracketing purposes. Of the 407 TCF plus consumed between 1935 and 1975 perhaps it is more realistic to expect a stockpile developing 10 to 20 percent of that value. These cases are presented in the following four figures. The Figure 13 shows the time trend in gas reserves which would end up with about 50 TCF in stockpile by the year 2000. The amount of gas (in addition to indigenous production) needed as additional stockpile gas each year is shown in Figure 14. It may be noted that for this particular scenario the additional gas required represent much modest and attainable figures starting constant and at about two and one half trillion cubic feet per year. The quantities are tabulated year to year in Table V. The intermediate case of 20 percent target is given in Table IV and Figures 15 and 16.

In summary, if it is desired to build a strategic stockpile equal to say, 20 percent of gas cumulatively produced between 1945 and 1979, the amount of additional gas needed will range between five and ten trillion cubic feet per year if our consumption is held constant. On the other hand, if the U.S. consumption of gas is allowed to grow at the rate of three and one half percent per year the additional gas which must be available ranges constant at 4.94 TCF per year until 1989 then sharply increases to 20 by 1990 and about 30 TCF per year by 1991 uniformly increasing thereafter to about 49 TCF per year by 1999.

3.3. SOURCES FOR STRATEGIC STOCKPILE

When the market exceeds the supply and has to be curtailed

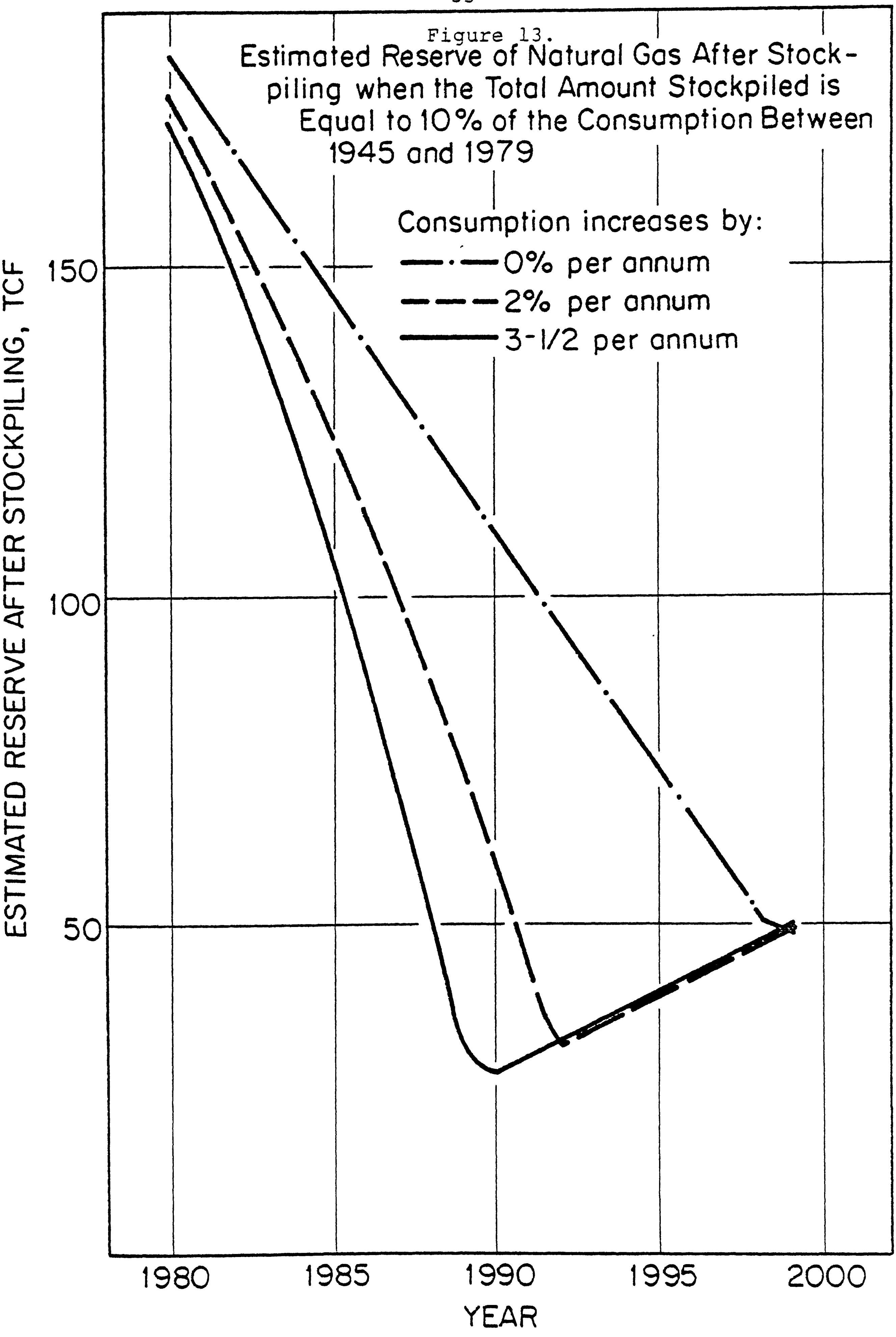


Figure 13.
Estimated Reserve of Natural Gas After Stockpiling when the Total Amount Stockpiled is Equal to 10% of the Consumption Between 1945 and 1979

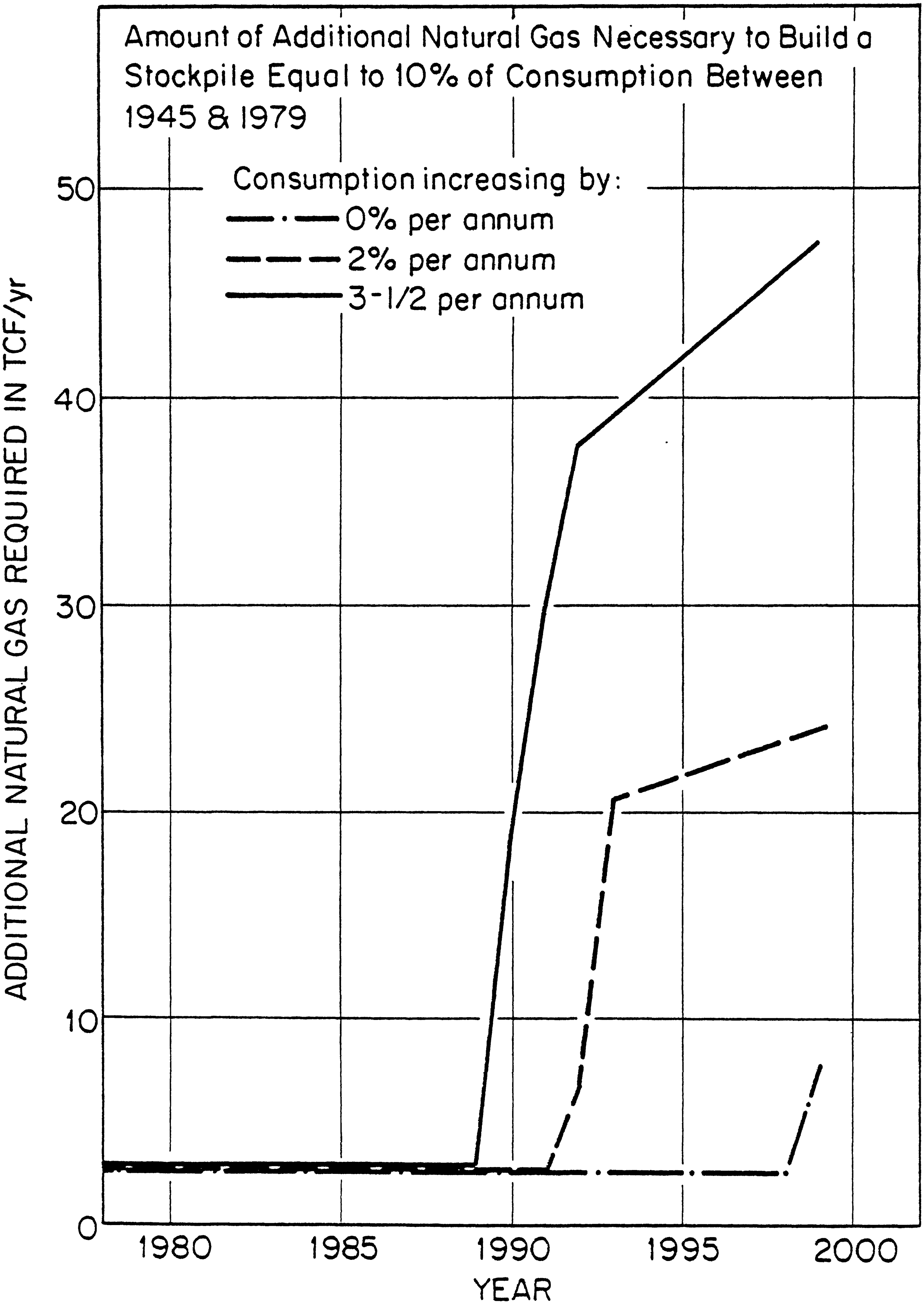


Figure 14. Amount of Additional Natural Gas Necessary to Build a Stockpile Equal to 10% of Consumption Between 1945 and 1979.

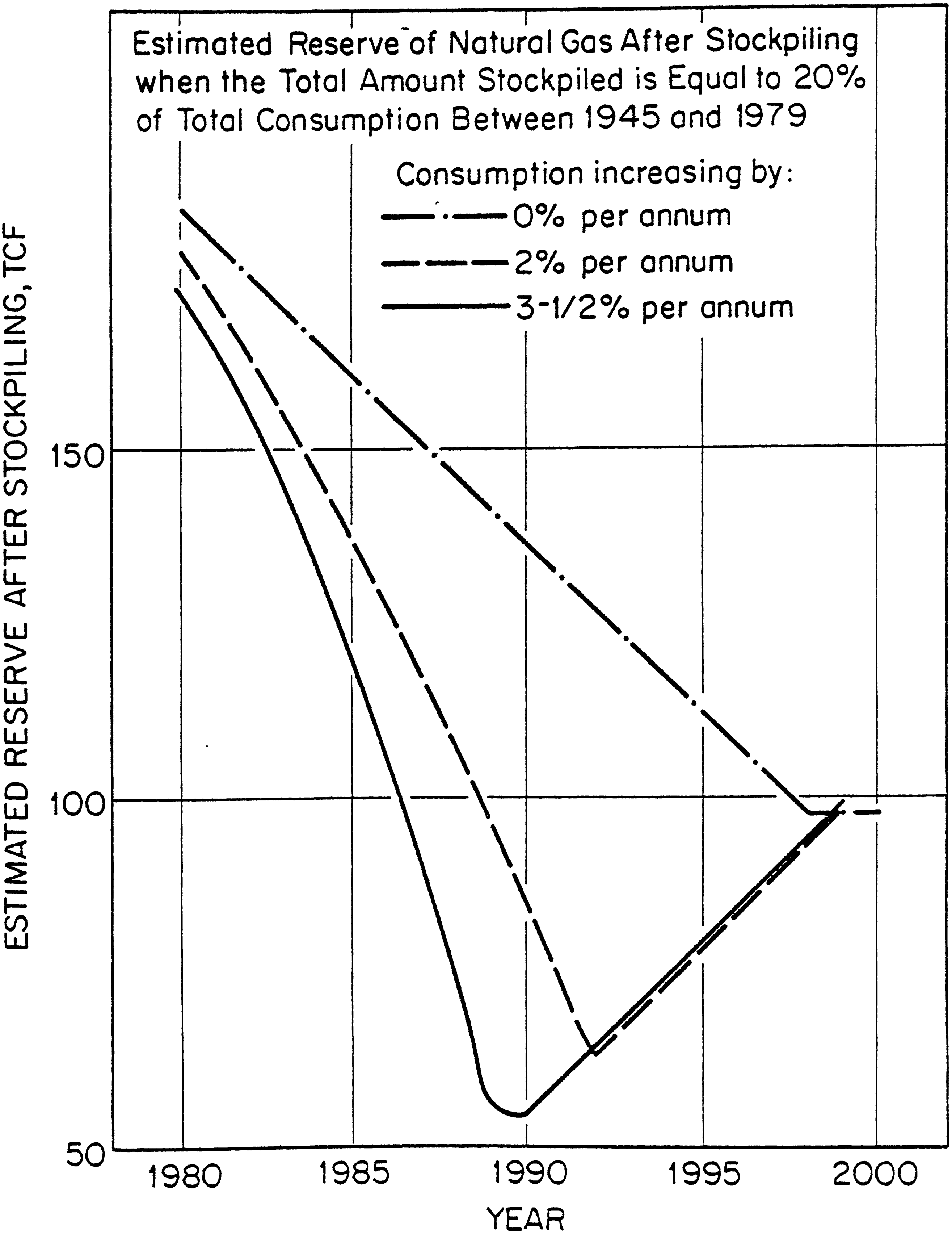


Figure 15. Estimated Reserve of Natural Gas After Stockpiling When the Total Amount Stockpiled is Equal to 20% of Total Consumption Between 1945 and 1979.

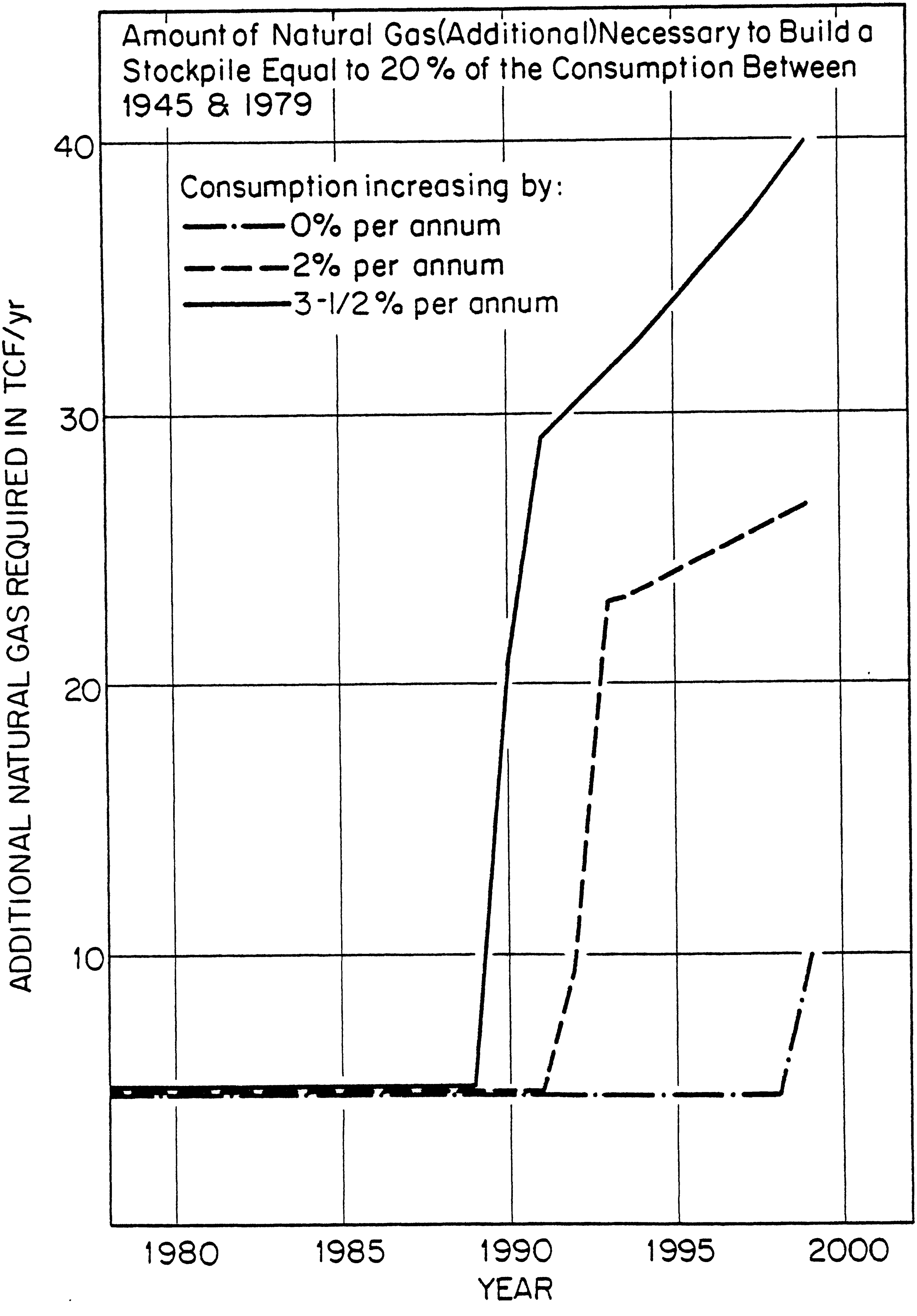


Figure 16. Amount of Additional Natural Gas Necessary to Build a Stockpile Equal to 20% of the Consumption Between 1945 and 1979.

development of any stockpile obviously requires new sources of methane not presently available. As we look into the future, the possible new sources may be classified as short range, intermediate, and, long range. Some accessible by pipelines others not.

1. Short Range Sources

The short range sources for additional gas supply may include new natural gas finds off-shore and continental from the lower 48, additional LNG imports and additional SNG from naphta and coal. All of the above sources may be expected to gradually increase, and, perhaps within the next ten years some gas may become available by pipelines from outside the U.S., from Canada and Mexico.

2. Intermediate Sources

The additional gas which may be available for strategic stockpile may include more LNG imports, gas from Arctic and methane from overseas in the form of methanol. Of these the methane-methanol-methane route appears particularly practical, and hopefully feasible. It will be discussed in some detail in the following.

3. Long Range Sources

If the short range supply occurred the early eighties and the intermediate, during the early nineties, the long range supply must apply to late nineties to figure in the strategic stockpile. This supply would include more methane from overseas in the form of methanol, substantial gas from Arctic (hopefully by pipelines) and substantial gas from coal. The projected capacity for coal gas is estimated to be about 3 TCF per year by 1990 from

176 plants, 141 west of Mississippi and 35 east of Mississippi. Each of these plants would be producing 250 MMcf/D methane.

World Wide Resources of Natural Gas

World's natural gas resources are estimated to be probably larger than those of crude oil. The proved reserves of natural gas are estimated to be 2,250 trillion standard cubic feet. On energy equivalent basis this figures out to be about 60 percent of proved oil reserves. With the exception of North America, the natural gas found in the rest of the world is only incidental to search for or production of crude oil. In those countries people do not search for gas. Throughout the globe there exists many deep prospects for gas yet undrilled. In the U.S. we do look for gas because we have the ready market for it. Currently 27 percent of our energy consumption is supplied by natural gas. In Canada the figure is 21 percent. Western Europe consumes 14 percent of their energy in the form of natural gas.

Presently the gas available at well head in OPEC countries has little if no economic value.

It is flared into the atmosphere in enormous quantities (the equivalent of 2.4 MM barrels of oil per day in 1974.)(6) Plans are being formulated however for limited use, conservation and storage of the natural gas as a future resource even in some of the OPEC countries.

Presently either liquefaction or reforming into methanol then transportation in U.S. is not competitive with current price of energy as controlled by OPEC cartel. In the future however, it may well become so.

The current trends are such that probably in just about two decades the Btu content of proved natural gas reserves will surpass that of remaining oil reserves. The rate at which the gas reserves will be developed are expected to lag behind developments for oil because of engineering, logistic, political and international problems. By the end of the 20th century however, with improved technology and more experience the finding production and transportation of natural gas will be less costly.

The Distribution of Gas Reserves World Wide

The Table VI below compiled from figures given in the CIA Report(6) shows the distribution of natural gas reserves in major areas of the world.

Table VI. Distribution of Proved Gas Reserves.

	Percent	Total (2,250 Trillion cu ft) Trillions SCF
U.S.S.R.	35.4	798
Middle East	25.0	571
U.S.A.	9.5	214
Africa	9.2	207
Western Europe	8.0	180
South America	3.4	76.5
Canada	2.5	56.2
Other Communist Countries	1.6	36.0
	100.0	2250.0

Of the above,the largest reserves are in the U.S.S.R.; nearly 800 trillion cubic feet. The country having the next largest reserve is Iran (330 TCF). The third is the U.S.A. with 214 trillion as of 1977. This is followed by Saudi Arabia with 103 trillion and Algeria with 100 trillion. Table VI shows the countries with the potential of having supply of natural gas for a strategic stockpile from overseas.

Table VI. Overseas Countries with Potential of Gas Supply for a Strategic Stockpile.

Country	Reserves, TCF
U.S.S.R.	798.
Iran	330.
Saudi Arabia	103.
Algeria	100.
Venezuela	40.
Australia	30.-40.

It must be recognized that in the above rank ordered list the first and the last are subject to larger margin of error than the rest because of relative scarcity of data on drilled wells. Most of the Soviet reserves are in extremely remote areas from markets and somewhat at fringes of present technology due to harsh climate and Arctic locations. In addition to the gas reserves directly available from the countries listed above, natural gas, reinjected in oil or condensate reservoirs is fast becoming a universal means for conservation. As the production of oil is vigorously implemented in response to the energy need of the world the reserves in reinjected associated gas may be expected to build up. A summary of natural gas reinjection by free world countries is given in Table VII below.

Table VII. Natural Gas Reinjection Selected Countries (1974)[6]

Country	Rate of Reinjection BCF/Year	Percent of Gross Production
U.S.A.	1,080	5
Venezuela	815	50
Canada	382	11
Saudi Arabia	105	7
Iran	100	6
Chile	121	49
Kuwait	63	13
Algeria	65	19
Libya	71	17
Nigeria	30	3
United Arab Emurates	16	3
Iraq	15	7
Indonesia	15	8

Natural Gas Flared as a Potential Source for Strategic Stockpile

Another potential source for strategic stockpile is natural gas being flared into the atmosphere.

The total amount of natural gas flared in the U.S. cumulatively to date is estimated as 100 TCF.(6) The total amount flared for the world may be three of four times as much. This would be about equivalent to ten percent of producable oil reserves in the world.

As many countries become more and more conservation conscious, no-flare rules are gradually being adopted in many. The total amount of gas flared however still remains a regretfully high figure. For instance during 1974 the total production of natural gas in the world was 57 TCF. Of this, 88 percent, 50 TCF was sold or reinjected, 12 percent, 7 TCF was flared.(6) The Table VIII below shows countries engaged in major flaring.

Table VIII. Percent Distribution of Gas Flared World Wide.

Country	% of World Wide Flared	% of Indigeneous Production
Saudi Arabia	18	79
Iran	14	56
Nigeria	14	96
U.S.S.R.	9	6
U. Arab Emurates	8	84
Venezuela	5	21
China	3	14
Kuwait	3	46
Mexico	3	24
Iraq	2	73
U.S.A.	2	1

It is interesting to note that Saudi Arabia, a major potential supply for a strategic stockpile in this country flares most, 18 percent of the world total and 79 percent of their total production of gas.

3.4. ECONOMICS OF TRANSPORTATION

Obviously one of the most relevant factors involved in assessing a strategic stockpile is the economics of transportation. Because the gas reserves are plentiful, but in remote areas the cost of the particular mode of transportation to the market becomes to the forefront of every engineering economic study.

On overland routes the cost of pipeline transportation of natural gas is about three times that for oil on energy basis. While the cost difference above is quite sharp, the contrast becomes even more spectacular when the transportation of crude oil in VLCC's (Very Large Crude Carrier) are compared with LNG shipments in cryogenic tankers.

The cost of building natural gas pipelines has increased many fold during the last decade. This is due to:

Inflation

High construction costs in build up areas

High construction costs remote areas with harsh environment

High construction costs in offshore lay-barge pipelining.

As an example the total cost of a pipeline laid onshore in rural United States used to be about $1.00 per foot per inch diameter. This figure became 50 percent higher during the early seventies. By comparison the cost of a new gas pipeline from

Arctic Alaska would appear to be about at least ten times higher. An alternative to transportation of gas by pipeline is transportation by tankers. This requires the gas to be turned into liquid form. Liquefied natural gas is shipped by special cryogenic tankers called LNG ships.

Another method of shipment by tankers involves reforming the methane into methanol then transporting it in regular atmospheric pressure, temperature, crude oil tankers, preferably by VLCC's.

The economics of transportation of natural gas to be dedicated for a strategic stockpile to selected delivery ports in the U.S. depend upon the economics of processing plants at either end of the voyage as well. An evaluation of the factors involved in overall cost of the gas to be stockpiled is part of the engineering work that would be undertaken in the proposed study.

It may suffice to point out at the moment that a typical transportation cost for natural gas in the U.S. would be 15¢ per 1,000 miles.

The cost of LNG from Algeria to the east coast of the U.S, has been reported to be about 40¢ per Mcf per 1,000 miles including the conversion at both ends.

The comparative transportation cost figures over distant routes between methane→LNG→Methane and Methane→Methanol→Methane alternatives depend upon many factors including distance, cost of the gas well head, size of project location of the gas field with respect to port in overseas country etc... The published comparisons in this area are speculative. According to figures given by at least one source(6) methanol from Saudi Arabia flared methane purchased at 50¢/Mcf would be slightly competitive with LNG from Iran purchased at $1.05/Mcf well head. In both cases the cost of methane delivered to the U.S. distributors would be slightly under $4.00/Mcf.

In the near term however through improved technology, possible use of VLCC's in methanol route, and utilizing economy of scale the above cost figures may be expected to come down.

The Table IX reproduced from the CIA Report(6) gives some comparative gas costs from various gas supply sources to the U.S. The figures, while admittedly speculative and illustrative, and in some cases incompatible for comparison should provide a reasonable order of magnitude in economic perspective.

3.5. METHANE-METHANOL-METHANE ROUTE AS AN ALTERNATE SUPPLY FOR A STRATEGIC STOCKPILE IN GAS

Methanol, also called methyl alcohol, wood alcohol, or methylated spirits is a colorless, odorless water soluble liquid at room temperature. It's specific gravity is 0.80. It freezes at -144°F and boils at 148°F.

It is totally miscible with water and consequently in case of a spill it is rapidly dispersed. It burns with a clean blue flame, it does not pollute. It can be made of petroleum, oil-shale, wood, from farm or municipal wastes and last but not least, significantly it can be made from natural gas. It does not require specialized, refrigerated, cryogenic tankers for overseas transportation. It can be transported by regular

Table IX. Cost of Natural Gas Delivered to U.S.A.[6]

Mode of Transportation	$/Mcf Well Head Cost	Transportation Cost	Conversion Reconversion Cost	Total Cost To Distributors
1000 mile U.S. Pipeline	.45*	0.15		0.60
Pipeline North Slope to Midwest	1.50**	2.20		3.70
Pt Conversion to LNG, LNG Ship to Pt Conception, Cal. Recon.		.45	.90	3.85
LNG Algeria U.S. East Coast	1.30	.95	.65	2.90
LNG Iran U.S. East Coast	1.05	1.90	1.00	3.95
Methanol Iran U.S. East Coast	0.50	1.10	2.20	3.80

*Average well head price for U.S. gas old and new 1975

**New gas price 1976

atmospheric pressure, normal ambient temperature tankers. Foreign natural gas can indeed be converted to methanol before it is transported to U.S. ports. Until only recently methanol from foreign natural gas was not looked upon as a viable alternative to LNG imports. Because of recent shifts in energy economics and because of recent breakthroughs in methane-methanol technology over the long shipping routes methanol became competitive with LNG. One additional reason which makes methanol route attractive is the cost and backlog problems which continue to affect adversely the LNG alternative.

3.6 VENUE FOR STRATEGIC STOCKPILE-UNDERGROUND STORAGE

Background

Underground storage is the uniquely efficient technique which effectively balances the demands of a variable market with nearly constant supply of energy provided by the pipeline.

The natural gas is simply injected into underground storage reservoirs when market demand falls below the supply available from the pipeline. It is withdrawn from the storage environment to supplement the steady supply from the pipeline when the demand exceeds the pipeline supply.

The fluctuating nature of the demand for natural gas in northern and particularly northeastern markets in residential and commercial end use makes the practice of underground storage not only desirable but an economic necessity for efficient, use of the pipelines. Underground storage permits high load factor utilization of pipeline facilities, effective delivery to market during peak demand, conservation through elimination of flare gas.

Historically, the first recorded use of underground storage technique dates back to 1915 when gas was first stored in a depleted natural gas field in Welland County, (Canada) by Ontario National Fuel Gas Company[7]. This was soon followed by underground storage operations in New York, Kentucky and Pennsylvania between 1915 and 1920. During the decade 1920 to 1930, 6 additional storage projects in 3 different states were developed. A remarkable growth occurred since then resulting in nearly 7 trillion cubic feet of gas now in storage in 386 pools in 26 states. The U.S. market presently consumes about 20 TCF of natural gas per year. This is equivalent to about 10 million barrels of oil per day.

3.6.2. Underground Storage as a Unique Environment for the Strategic Stockpile

The very concept of "underground storage" is almost synonymous to the purpose of developing a stockpile. While the day to day, year to year operation of gas storage reservoir respond to fluctuating market demands, there is no reason why certain underground storage reservoirs should not be earmarked and/or developed as suitable environment for a long range strategic stockpile.

Once the need for a stockpile is accepted and the amount desirable is determined, the question that naturally follows relates to where the gas would be stored?

Underground storage is in practice in some of the Western Eurpoean countries, Russia, Canada and U.S.A. The extent of storage operations in U.S.A. however by far exceeds those of the rest of the world. Consequently the technology and practices developed in the U.S. are the most advanced and supported by ample field data.

The gas is stored in depleted gas, oil or condensate reservoirs. About 20 percent of our storage is in deep water bearing sands called 'aquifers'. While some very marginal storage has been and is being practiced in dissolved or mined cavities, the bulk of underground storage of natural gas takes place in deep subsurface porous environment.

These reservoirs are ecologically sound and environmentally acceptable. After all most of them are where mother nature had stored the fossil fuels over geologic ages i.e. hundreds of millions of years. In addition, the reservoirs are in environments away from populus, safe with respect to explosion, sabotage and other risks.

While they must be evaluated, developed, operated and monitored very carefully, they are basically safe, reliable and economical.

The selection of those suitable in quality and quantity and engineering assessment of their characteristics to match the needs of gas stockpile are some of the major tasks envisaged in this proposal.

Presently Unused Capacities in Reservoir Space

It is important to realize and recognize that the U.S. is not the only country that needs new supplies of natural gas most but is the only country which can effectively, economically and safely develop a long range supply of energy in the form of methane stored underground. It may be suggested that, surely Japan or Western Europe could also use and benefit from such a strategic stockpile as has been proposed. They indeed could, but they do not have to the extent that we do, a place to put the gas in storage nor do they have the associated facilities to convey the gas to the storage fields. The present and near term future extent of unused storage space, pipeline capacity and associated compression, metering, regulation facilities must be quantitatively determined in order to develop economic requirements of a strategic stockpile. This is an area where extensive engineering survey would be undertaken in the proposal research project.

For the purpose of this proposal, the presently available gas reservoir space capabilities may be inferred from a geographic and historical examination of reserves from several states. The Table X shows the estimated recoverable reserves of natural gas in selected states in selected years(5).

Table X. Estimated Proved Recoverable Reserves of Nat. Gas in Selected States in Selected Years, TCF. (Reference: Mineral Yearbook, Bureau of Mines)(5).

*Volumes are reported at a pressure base of 14.65 psia, 60°F

†Volumes are reported at a pressure base of 14.73 psia, 60°F

(Reserves as of Dec. 31, of indicated year)

States	1946*	1951*	1956*	1961*	1966†	1972†	1973†
California	11.13	9.48	8.75	9.10	8.47	5.33	5.20
Alaska	-	-	-	0.93	2.95	31.46	31.64
Kansas	13.68	13.46	17.57	19.19	15.92	11.94	11.72
Louisiana	22.41	29.01	45.05	66.03	83.68	74.97	69.15
New Mexico	5.90	11.59	23.47	14.76	14.75	12.34	12.49
Oklahoma	10.74	11.80	13.78	17.35	20.12	14.49	14.10
Texas	86.36	105.65	112.73	119.84	123.61	95.04	84.94

From figures given in Table X, even if the reservoirs are to be comservatively brought back up to their discovery pressures one can see that there will exist considerable amount of unused storage space still left in most depleted or semi-depleted reservoirs. For instance the reserves in California stood at 5.2 TCF by 1973. The Table X indicates that the gas reserves at 1946 were as high as 11.13 TCF. The difference 11.13 - 5.20 = 5.93 TCF could be, conservatively speaking, at least available for underground storage. The minimum storage capacity available from these states are so calculated as the difference between their peak and latest reserves and given in Table XI below

Table XI Minimum Storage Capability of Selected States

TCF

State	Max Reserve	1973 Reserve	Unused Storage Capability
Alaska	31.64	31.64	-
California	11.13	5.20	5.93
Kansas	19.19	11.72	8.47
Louisiana	83.68	69.15	14.53
New Mexico	14.76	12.49	2.27
Oklahoma	20.12	14.10	6.02
Texas	123.61	84.94	38.67
		Total	95.89

The states shown in Tables X and XI are major gas producing states. It must be remembered that in addition to the above, there exists many northern states which not only have substantial gas production but developed underground storage reserves as well. Michigan, Illinois, Iowa, Pennsylvania, New York, West Virginia are typical examples.

Also in the gas producing states of Table X, if and when certain reservoirs are selected as suitable prospects for a strategic stockpile, the extent to which they may be safely "delta pressured" would further augment the minimum total reserve space of 95.89 TSCF available for a stockpile. The selection of the prospects for strategic stockpile as well as selection of minimum pressure to be programmed for these reservoirs are also part of engineering research proposed. While the figure given above represents additional storage capacity which could ultimately be developed there exists immediately available unused storage capacity of over 1.7 trillion standard cubic feet in existing underground storage reservoirs. The Table XII reproduced from AGA Statistics[7] as of the end of 1976 gives the details of U.S. underground storage reservoirs in all 26 states by kind, content, used and unused capacity. It may be observed that some of the unused capacity highlighted in Table XII is probably also included in unused storage capability developed in Table XI. From a comparison of the above figures it becomes clear that if a strategic stockpile of 40 to 80 trillion cubic feet may be contemplated for development in the next 20 to 25 years the underground pore volume for it is indeed available but must be developed with an appropriate time table while the first 1 to 2 trillion cubic feet of it may be directly developed on existing underground storage fields.

Table XII. STORAGE RESERVOIR DATA AND VOLUME STATISTICS 12/31/76.

	ORIGINAL CONTENT OF RESERVOIR						CAPACITIES OF RESERVOIRS (Volumes in MCF-14.73 psia 60°F)						
							BASE GAS						
State	No. of Reservoirs	Dry Gas	Oil & Gas	Oil	Water	Other	Native	Injected	Total	Working Gas	Unused Capacity	Total Reservoir Capacity	Range Of Rock Pressure (Psig)
Arkansas	5	5	-	-	-	-	23,674,000	0	23,674,000	12,391,257	6,435,743	42,501,000	270
California	9	4	5	-	-	-	163,360,674	56,132,798	219,493,472	192,321,804	85,025,068	496,840,344	650-2800
Colorado	7	6	-	-	-	1 coal	16,668,103	8,328,462	24,996,565	14,024,023	3,578,816	42,599,404	2268-2600
Illinois	31	8	-	1	22	-	10,218,713	471,262,617	481,481,330	229,779,707	284,424,633	995,685,670	1250-2050
Indiana	27	17	-	-	10	-	20,421,704	45,467,893	65,889,597	23,718,610	71,765,860	161,374,067	550-1400
Iowa	9	-	-	-	9	-	0	117,751,259	117,751,259	70,969,599	165,779,142	354,500,000	850-1400
Kansas	17	17	-	-	-	-	22,415,829	49,576,737	71,992,566	47,822,522	9,473,766	129,288,854	1730-1270
Kentucky	23	18	2	-	3	-	77,221,297	18,305,331	95,526,628	79,592,885	29,542,822	204,662,335	450-550
Louisiana	7	6	1	-	-	-	58,698,879	158,913,821	217,612,700	74,444,770	67,000,607	359,058,077	4604-4350
Maryland	1	1	-	-	-	-	32,456,430	9,230,538	41,686,968	14,481,828	8,601,204	64,770,000	3050
Michigan	44	37	2	1	-	4 salt	243,337,385	148,898,354	392,235,739	315,123,401	179,355,609	886,714,749	1900-1888
Minnesota	1	-	-	-	1	-	0	3,000,000	3,000,000	1,365,489	15,634,511	20,000,000	200-400
Mississippi	4	3	-	-	-	1 salt	27,322,873	18,642,911	45,965,784	35,804,347	27,533,509	109,303,640	2115-4000
Missouri	1	-	-	-	1	-	0	11,759,095	11,759,095	15,035,086	18,205,819	45,000,000	-
Montana	5	5	-	-	-	-	29,800,000	31,538,247	61,338,247	110,544,564	41,269,056	213,151,867	300-1600
Nebraska	2	2	-	-	-	-	22,991,776	3,520,181	26,511,957	27,697,964	741,620	54,951,541	1172-1312
New Mexico	2	1	-	-	1	-	11,700,000	6,542,936	18,242,936	16,535,473	346,245	35,124,654	1200-1300
New York	19	18	-	-	1	-	15,524,351	61,945,649	77,470,000	37,322,262	31,660,549	146,452,811	600-2200
Ohio	22	22	-	-	-	-	81,906,620	199,099,438	281,006,058	128,062,706	94,908,636	503,977,400	280-1400
Oklahoma	12	11	1	-	-	-	19,148,310	115,101,915	134,250,225	112,916,378	97,476,517	344,643,120	306-2350
Pennsylvania	68	68	-	-	-	-	28,632,453	304,830,980	333,463,433	214,734,400	208,385,100	756,582,933	100-3600
Texas	18	7	6	5	-	-	74,270,682	17,791,084	92,061,766	105,418,043	133,697,013	331,176,822	300-3500
Utah	2	-	-	-	2	-	0	1,415,544	1,415,544	2,802,729	300,568	4,518,841	1190-1333
Washington	2	-	-	-	2	-	0	16,515,000	16,515,000	8,442,000	2,016,000	26,973,000	315-1600
West Virginia	38	37	1	-	-	-	33,411,877	216,034,525	249,446,402	115,252,442	138,062,766	502,761,610	500-2819
Wyoming	10	9	-	-	1	-	13,498,888	3,138,965	16,637,853	38,879,458	38,531,879	94,049,190	950-1855
TOTALS	386	302	18	7	53	6	1,026,680,844	2,094,744,280	3,121,425,124	2,045,483,747	1,759,753,058	6,926,661,929	

Present Underground Storage Capability

During 1976, the underground storage operations met vital gas supply requirements imposed by the most severe winter in history. The peak day demand from storage turned out to be 35.5 Bcf/D about 5 billion cubic feet more than the year before. Without the storage facilities the effect of cold weather would have been disastrous. Some eastern states experienced extreme hardships in terms of home heating, schools, industries, and employment. They did not have sufficient underground storage.

Because development of a strategic stockpile in natural gas will involve some use of present facilities and much additional storage to be developed the present underground storage facilities are summarized below from the current AGA statistics[7]

Total number of reservoirs: 386 in 26 states

Total storage capability: 6.927 TCF

Recoverable gas from storage: 4.053 TCF

Maximum daily output from storage 1976: 35.5 BCF

Total gas withdrawn from storage during 1976: 2.060 TCF

Estimated capital investment: 2.3 billion dollars

Total compression available: 1.342 million horse power.

The Table A-V in the Appendix II summarized storage facility data and the Table A-VI gives the maximum inventories and daily output during 1976.

The location and distribution of underground storage facilities in the United States are given in Figure 17.

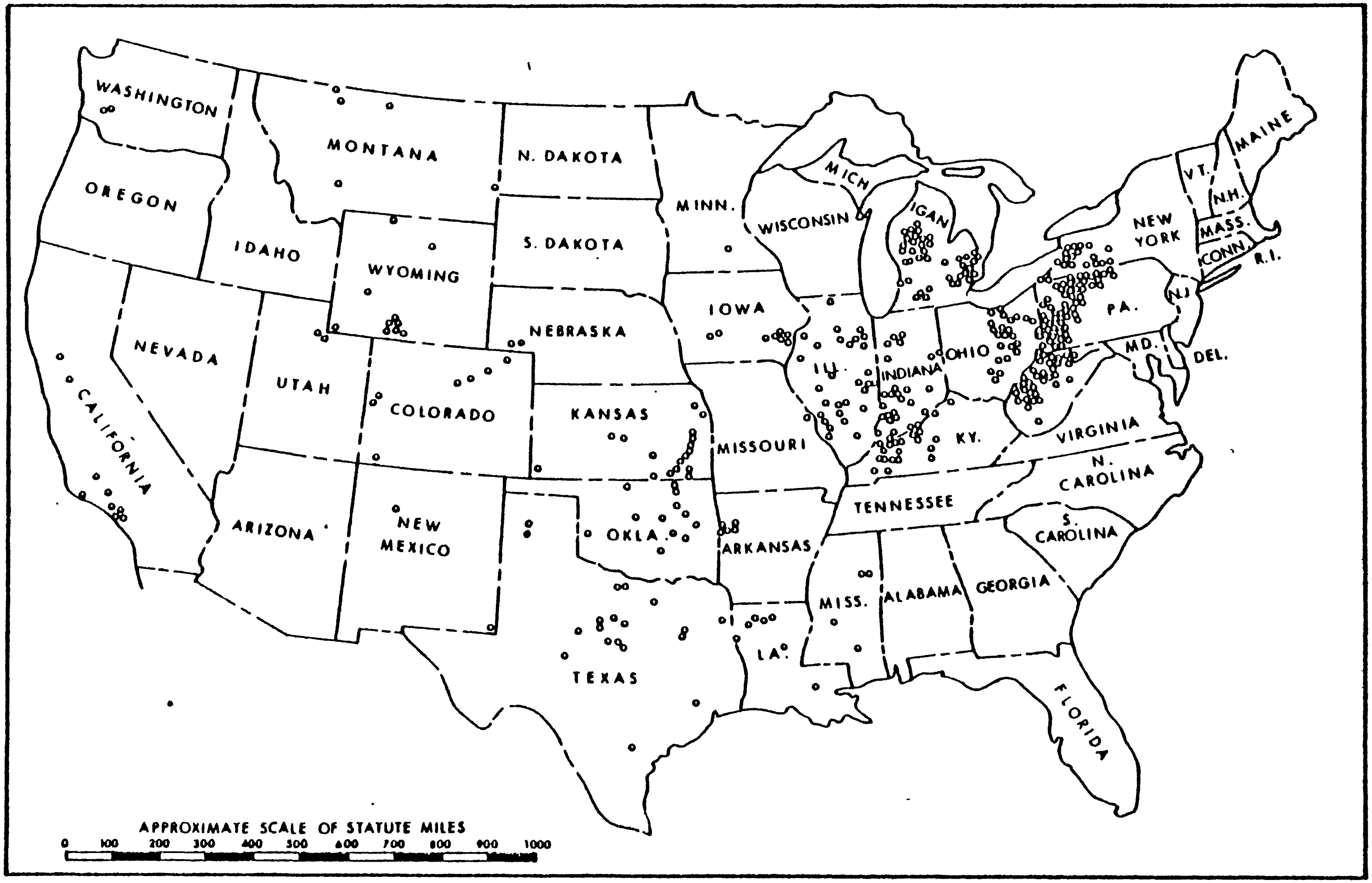


Figure 17. Location of Underground Gas Storage Reservoirs in the United States. 1976.

Aquifer Storage

Almost 80 percent of present underground storage facilities are developed on depleted gas or oil reservoirs. When these are not available near large markets, gas is stored in water bearing subsurface sands called 'Aquifers'. There now exist 52 aquifer storage reservoirs in ten different states. The Table A-VII in the Appendix II gives the present statistics on aquifer storage volumes. The Table A-VIII gives the aquifer storage facilities by states and the Table A-IX shows the recent growth in aquifer storage between the years 1972 and 1976.

3.7. LOGISTICS RELATED TO PROPOSED STOCKPILE

The pipeline capabilities present in our country were discussed earlier. The Figures 1, 2, and 3 relate to impressive statistics which accompany gas gathering systems, long distance transmission pipelines and gas distribution systems near the markets. The locations of present underground storage reservoirs are shown in Figure 17. Against the background of these facilities one must consider the logistics involved for transportation of natural gas from outside sources via pipeline, LNG tankers and/or possibly VLCC or other crude carriers to the United States.

Three distinct geographic areas have already been viewed and selected as LNG tanker terminals. These have been near Los Angeles on the west coast, Boston in the northeast, and Corpus Christi in the southwest. Several pipeline routes from the North Slope in Canada to the United States have been under consideration. So is, also a possible pipeline from Mexico to Texas. If methanol proves possible and feasible via VLCC's suitable port or mooring facilities would have to be thought out in terms of methanol-methane plant siting and existing pipeline networks to carry the stockpile dedicated gas to its prospective underground storage reservoir. Determination of import facility locations, their allocation to certain pipelines leading to particular storage reservoirs and a possible time table for their development would be undertaken in the proposed program. One area of particular interest here would be to study seasonal, monthly and daily gas movements within the existing pipelines to determine whether spare capabilities at certain periods could be scheduled to match the requirements for additional gas to flow to their stockpile destinations. Available versus required compression, need for additional pipelines or added loops to existing pipelines, energy intensiveness of the required stockpile, scheduling and dispatch problems are among areas which appear to be in need of attention.

3.8. ENVIRONMENTAL PROBLEMS AND BENEFITS

If a strategic stockpile is to be developed, due to variety of future sources of gas and the probable magnitude of the project, environmental problems must be carefully identified and assessed. A significant part of the work contemplated in this proposal would be dedicated to evaluate the possible effects, positive or negative, of the strategic stockpile to environment and ecology.

During the preliminary research leading to this proposal it was possible to separate and classify several areas where interaction with environment would occur.

The Figure 18 depicts a comparative view of possible interaction between the proposed strategic stockpile and the environment.

It appears right at the onset that some problems could be identified on global or national scope as well as some benefit which would occur either overseas, in transit, or in the United States. This area in the work proposed would be dealt with in depth and detail which the environment deserves. In the meantime, the highlights which became apparent in our pre-proposal research will be enumerated and briefly discussed below.

The development of a strategic stockpile in natural gas over a number of years would involve environmental interactions at the source of the gas, during its transport to the United States and after its eventual storage in underground reservoirs. These interactions would involve problems requiring special care and meticulously engineered operations in all of the following sequence of events as shown in Figure 18.

1. Exploration for gas in overseas source. This would involve seismic surveys, mapping, gravity magnetic, and other geophysical or geochemical prospecting,
2. Drilling and development of natural gas fields whether on-shore or off-shore,
3. Gathering, separation, dehydration, and field processing of natural gas,
4. Pipelining of natural gas to the port where liquefaction methanol facilities would be sited,
5. Storage, docking, loading facilities at overseas ports,
6. Transportation of the gas to the United States,

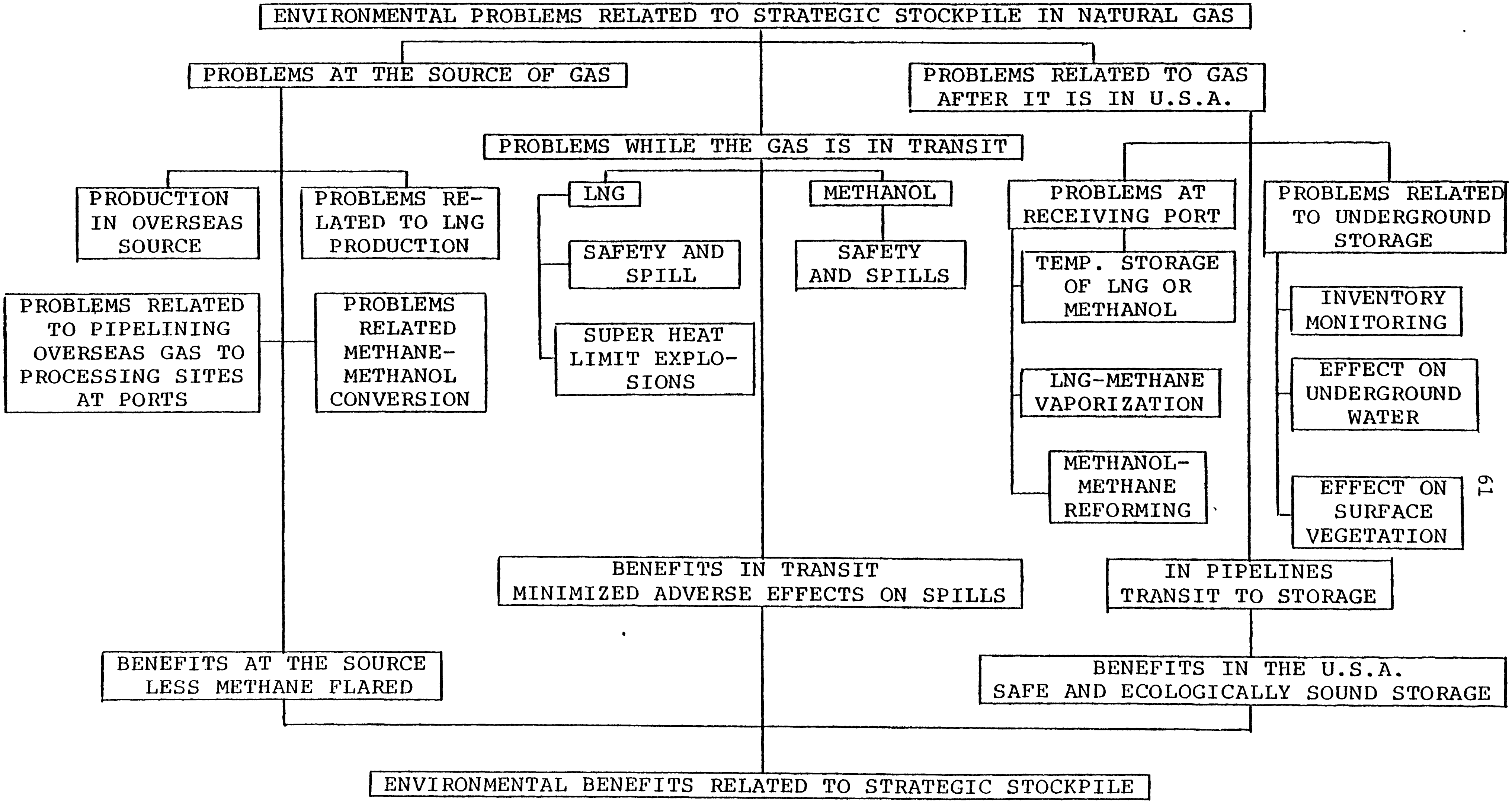


Figure 18. Environmental Problems and Prospects ofStrategic Stockpile in Natural Gas.

    a. Pipeline,
    b. LNG tankers
    c. Methanol carried on VLCC's.

7. Storage, docking, unloading facilities at U.S. port of entry,
8. Gas processing at U.S. port,
    a. LNG to methane vaporization,
    b. Methanol - Methane reconversion,
9. Compression, metering, regulation, pipelining in the United States between the port of entry and underground storage facility,
10. Underground storage operations at selected fields,
    a. Depleted gas reservoirs,
    b. Depleted oil reservoirs,
    c. Selected unused or gas used underground storage reservoirs,
    d. Aquifer storage reservoirs (presently available or to be developed).

At the source of exploration of gas the environmental problems one would encounter with surveying, mapping, geophysical and geochemical prospecting have been assessed and well documented particularly in the United States and lately in the form of environmental impact statements. On the basis of our present knowledge and experience, not only the problems are minimal or manageable but they are presently being meticulously identified and studied. Problems related to drilling and development of overseas gas resources are similar. This area however, involves more severe problems and concerns in terms of safety, ecological damage, blowouts, spills and the like. An area which deserves particular attention would be drilling, production and pipelining from remote regions off-shore, arctic, or antarctic.

In operations involving gathering, separation, dehydration, and field processing, problems overseas would be similar if not the same as those in the United States. These problems have been well documented and are not severe.

In the area of gas gathering, the production of associated gas which would otherwise be flared into the atmosphere would represent a definite benefit to be gained from the development of a strategic stockpile. The amount which would be very significant not only represents an economic gain (direct in terms of gas and indirect in terms of the oil it allows to be produced) but an environmental plus in terms of reducing the atmospheric pollution.

The problems, hazards and risks associated with pipelining of natural gas have been in the limelight of much public scrutiny particularly lately as related to the selection of pipeline routes from the Arctic regions to the United States markets.

The conversion of natural gas into LNG or methanol overseas and reconversion back to methane stateside would involve environmental impacts common to petrochemical operations near large ports. These operations would involve problems and concerns as safety, hazards, real estate requirements, pollution into the atmosphere. The beneficial effects would be in terms of economy, jobs and other related indirect benefits. They would be carefully studied and documented in the proposed research. The same comment also applies to problems, hazards, and other impacts involved while the gas is in transit via tankers.

Problems related to spills and mixing, tanker safety, superheat limit explosions on LNG's, sea worthiness, and stability of VLCC's would be given special consideration in the proposed research.

Finally, the safety and monitoring aspects of the stockpile while in storage, subsurface migration of gas whether in aquifers or depleted fields would be carefully studied documented and reported.

The observation of pressures and inventories in underground storage reservoirs, techniques for minimizing the gas unaccounted for fail-safe protection for long term underground storage are areas interest which would particularly benefit from the proposed study.

3.9. NON-TECHNICAL CONSTRAINTS

Certain aspects of a proposed strategic stockpile must, of necessity, be controlled or limited by factors other than engineering economics. Legal, local, political, institutional constraints may at least be identified as to their effect on possible development of a strategic stockpile. While the proposed assessment would have little impact on these constraints their identification vis-a-vis our energy needs and long range goals would be useful and proper. The assessment study proposed here does not intend to get involved with institutional constraints other than identify areas where they must be reckoned with.

3.10. CONCLUSIONS AND RECOMMENDATIONS FROM PROPOSED ASSESSMENT

It is hoped that the ultimate product and benefit of the assessment study proposed would be a favorable decision for, and deliberate, but prompt, development of a strategic stockpile in the years to come. The information to be developed and documented would be of direct utility to the Department of Energy for their intermediate and long range future planning. Undoubtedly the project report would also be of interest to other users such as gas storage companies, public utilities, major gas producers, other state and governmental authorities.

The conclusions and recommendations to be documented in the form of a final report would be put in terms of direct answers to the following questions.

1. Is "The Strategic Stockpile" needed?
2. Is it physically possible?
3. Is it economically feasible?
4. How big a stockpile?
5. Where to be stored?
6. How to be developed?
7. What would be the recommended rates for development of its various phases?
8. What would be the lead time to achieve the overall objective?

Comprehensive answers to the eight questions posed above would require conclusions on points raised and include recommendations in the form of options to be followed if the stockpile is to be developed.

4. METHODOLOGY

Just about every research, engineering, or technological assessment proposal critically depends on clearly defining "just what would be done" to achieve the objectives of the proposal. The Table XIII below summarizes the various tasks that would be involved in the proposed assessment of a strategic stockpile for methane. These various tasks have been incorporated into an organization chart for the work as shown in Figure 19. It may be noted that the proposal calls for carrying out three major groupings of activities. These three sub-objectives are individually discussed below:

4.1. DETERMINING THE NEED AND SOURCES FOR A STRATEGIC STOCKPILE

This work would commence with the initiation of the project and is estimated to last about one year. This phase will involve careful study of all existing literature and visits with various governmental, industrial and academic agencies to compile data on the precise place of natural gas in country's overall energy posture. The information gathered and documented will involve reserves, consumption trends, markets past, present, and future.

The study will include engineering calculations and operations research type optimizations of gas useage by various markets. Determination of possible sources for a strategic stockpile will too involve data gathering, organizing and updating existing literature, visits with companies and countries.

Table XIII. Specific Areas of Engineering and Research Tasks For Assessment of Strategic Stockpile of Methane.

I. Determining the Need for Stockpile

   1. Historical review - past and present supply of natural gas,
   2. Historical review - past and present demand for natural gas,
   3. Future projections

II. Sources for Strategic Stockpile of Gas

   1. Arctic natural gas from north slope
   2. New gas from off-shore
   3. New gas from lower 48
   4. Manufactured coal gas
   5. LNG imports
   6. Methanol from overseas natural gas

III. Venue for the Stockpile

   1. Present gas producing reservoirs - lower 48
   2. Present underground storage reservoirs
      a. Depleted gas fields
      b. Depleted oil fields
      c. Aquifer storage reservoirs
   3. Other storage prospects - caves, mines underwater

IV. Logistics Related to Stockpile

   1. Present pipelines
   2. Geographic distribution
   3. Available and required compression
   4. Scheduling vis-a-vis present steady state markets
   5. Economics, financing problems, institutional constraints

V. Specific Recommendations and Time-table for the Stockpile

1. Is it needed?
2. Is it possible?
3. Is it feasible?
4. How big a stockpile?
5. Where stored?
6. How stored?
7. The lead time to achieve the objective

Determination of pipeline accessible gas, north slope, Canadian Mexican prospects and new gas offshore lower 48 will be carried out with a view toward reasonable allocations which may be possible for a strategic stockpile.

It is anticipated that some work related to reservoir engineering and geology will be involved in this phase. The study of overseas gas which may be available for a strategic stockpile will include determination of overseas reserves as well as possible conversion to LNG or methanol. While the present technology in cryogenics and methane-methanol conversion is well known and on-going, there exists several areas where engineering research of chemical process engineering nature would help identify and classify the overseas resources of gas as prospects for the proposed strategic stockpile. For instance, feedwater or cooling water requirements at the source would vary depending upon the climate and resources of would be exporting country. In Saudi Arabia or Iran it may be necessary to go to de-salination for fresh water. Possible Siberian gas from the Arctic regions may have entirely different energy intensive problems.

Another instance may be cited for study of scale-up of cryogenic or methane-methanol and LNG-methane as well as methanol-methane conversions. This is an area where scale-up information is quite limited and may be supplemented by laboratory research. A source of two billion cubic feet per day translates into a methanol facility in excess of 60,000 tons per day. The size of presently built or contemplated methanol-plants rarely exceeds

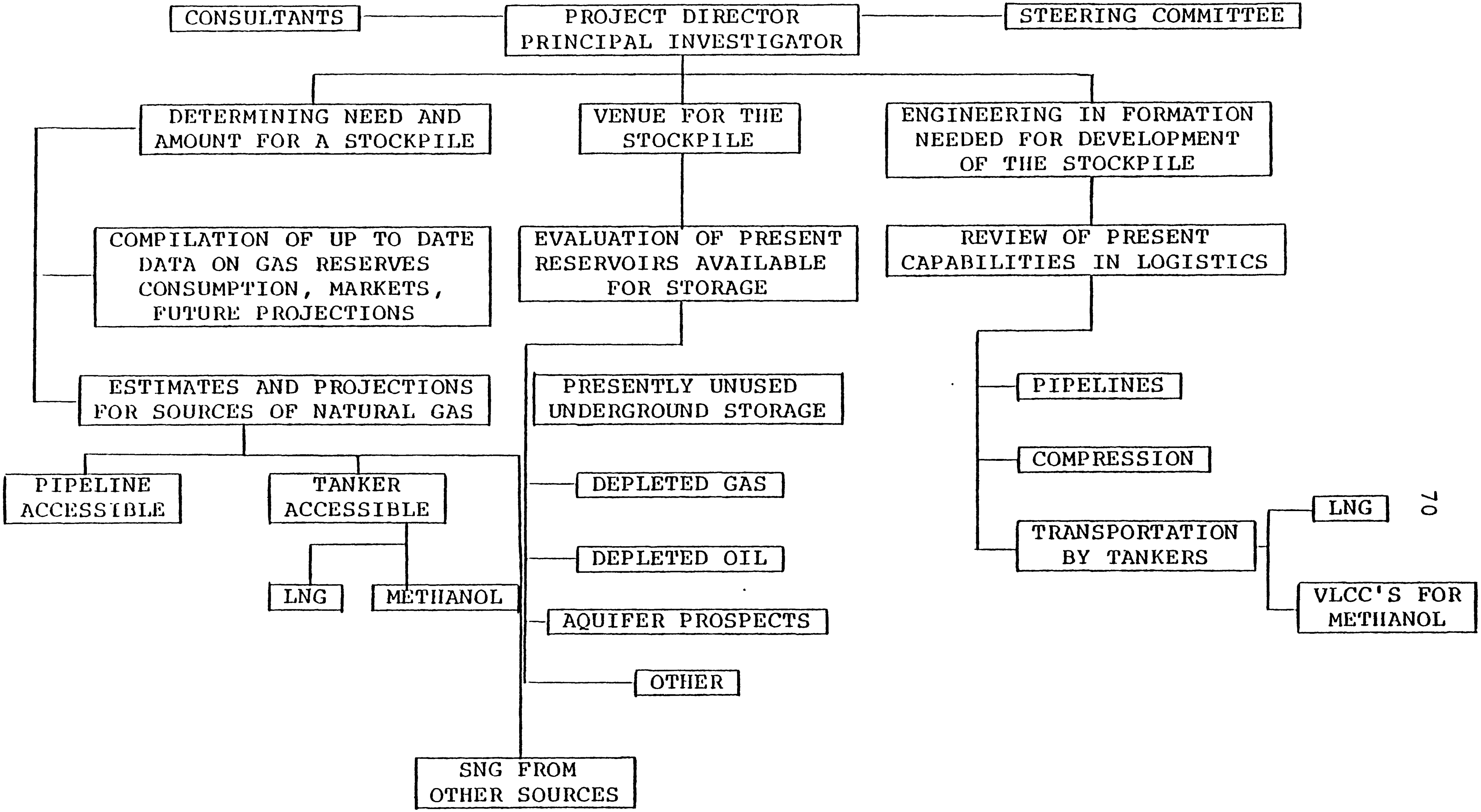


Figure 19. Organization Chart for Assessment Study.

5,000 to 15,000 tons per day. The same comments on process engineering studies would also apply to SNG from other sources such as coal, rubbish, waste, cellulose, etc... It is anticipated that qualitative and quantitative assessment of LNG, SNG and methanol sources for strategic stockpile would involve enough work for at least two chemical engineering Ph.D. candidates. The methodology involved there would be engineering design, laboratory research and possibly computer optimization.

4.2. VENUE FOR THE STRATEGIC STOCKPILE

This task will involve selection of appropriate environment for the underground storage of gas to be stockpiled. This work also estimated to be equal to at least one or two Ph.D. research in chemical engineering, will involve first gathering data on all prospective or available underground storage reservoirs and then screening them as possible media for the strategic stockpile. The methodology here will involve, Geology, Petroleum Engineering, Reservoir Engineering disciplines as well as Chemical Engineering research in flow through porous media. Some laboratory work evaluating cap rocks and measuring threshold pressures and simulation via computer models will be used in determining several geographically distributed prospects for underground storage. The evaluation of depleted gas, depleted oil reservoirs as prospects for underground storage will also involve design work, engineering economics related to gathering systems, pipelines, compression, drilling, plugging recompletion operations.

Study and evaluation of aquifer storage prospects will involve specialized technology in two-phase flow through porous media, geophysical prospecting, logging, drilling, pressure observation. The possibility of using other than conventional media for underground or underwater storage[8] will not be overlooked. An excellent example is northern Michigan where suitable sedimentary environment for conventional underground storage just does not exist. There are many similar ares in northeastern United States which are also devoid of sedimentary basins. In such areas cavern or underwater storage may be more desirable.

Specifically this phase will involve storage engineering work, two-phase flow through porous media as simulated on computers, laboratory measurements and modeling and a large computer data base for documentation and future reference.

4.3. ENGINEERING INFORMATION NEEDED FOR DEVELOPMENT OF STOCKPILE

This phase will relate very closely to sub objective discussed in previous section and will be implemented in sequence following that work.

Once the need for stockpile is determined as several prospective depleted oil, gas or presently unused storage reservoirs are being screened, current capabilities of present pipelines vis-a-vis the development of a strategic stockpile must be studied and documented. The available and/or needed compression also must be determined for future planning. In addition to pipelines, overseas tanker transportation via special cryogenic LNG tankers and/or methanol via VLCC's will be considered for transport schedules say over the next twenty years.

Because it will become necessary to maintain present quasi-steady, or steadily diminishing pipeline operations, and, at the same time, provide for additional gas to flow through the same United States network to predetermined underground storage destinations, the operations must conform to a particular scheduling scheme. Development of a computer model for existing complex pipeline, compression network with enough flexibility to add new loops as loads and markets may grow, and subsequent simulation to provide guidelines for optimized operation will be among partial objectives of this task. The methodology here involve, computational simulation engineering analysis, operations research, linear or dynamic programming.

5. WHY THE PROPOSED ASSESSMENT SHOULD BE CARRIED OUT AT THE UNIVERSITY OF MICHIGAN?

The University of Michigan, in general, and the Chemical Engineering Department, in particular, have been active in the field of energy research and development, particularly over the last several decades. The petroleum option, available within the curricula of Chemical Engineering Department since the days of A. H. White, G. G. Brown, and D. L. Katz has been the source of many distinguished accomplishments by graduate students over the years. These former students are now in responsible positions in energy related industries, universities, and governmental agencies. Many deans from the southwest, directors of research, vice presidents in oil and gas companies are products of petrochemicals option of Chemical Engineering at the University of Michigan.

Undergraduate and graduate courses in petroleum engineering, design courses in petro-chemicals and post graduate seminars in energy continue to attract interest from students in various levels to approach national problems related to energy.

The author of this proposal, Professor M. R. Tek has devoted the last 20 years of his professional career to original research and engineering work in problems of production, pipelining conservation and storage of natural gas. Of his total technical publications 78 papers (11 books, 11 patents) a large number relate to natural gas production and underground storage. He would be the principal investigator and project director. His senior associate, Dr. Donald L. Katz, Professor Emeritus of Chemical Engineering, just retired from teaching but active in research and consulting agreed to participate as consultant to the project. His credentials need little to elaborate.

The University of Michigan is the only place (world wide) where periodic intensive summer courses are regularly offered in underground storage to engineers, scientists, and executives from industry, academia, and government for the last 20 years.

Both Professor Katz and Tek have been active in underground storage research sponsored by the American and Michigan Gas Associations. Between them they had about 16 doctoral programs and several post-doctoral visitors from India, Egypt, Spain, Iran participating in research related to underground storage of natural gas. Notable among their publications and particularly related to the work proposed here are four monographs published by the American Gas Association. These are:

1. "Movement of Underground Water in Contact with Natural Gas," Donald L. Katz, M. Rasin Tek, K. H. Coats, M. L. Katz, S. C. Jones, M. C. Miller, A.G.A., New York, pp. 321, 1963.
2. "New Concepts in Underground Storage of Natural Gas," M. R. Tek and J. O. Wilkes with D. L. Katz and D. A. Saville, B. D. Bhalla, L. G. Sherman, A.G.A., New York, pp. 342, 1966.
3. "Threshold Pressure in Gas Storage," M. A. Ibrahim, M. R. Tek, and D.L. Katz, A.G.A., Arlington, Virginia, pp. 309, 1970.

4. "Retrograde Condensation in Natural Gas Pipelines," D. F. Bergman, M. R. Tek and D. L. Katz, A.G.A., Arlington, Virginia, pp. 498, 1975.

In the above context and related to the background two other principal books must also be cited. These are "Handbook of Natural Gas Engineering"[12] and "Underground Storage of Fluids."[13] Dr. Katz is the principal author of both. Both books are internationally accepted as standards of the profession.

Both Professors Tek and Katz have been and are consultants to more than a dozen public utility, gas storage, oil and gas production companies. The background of University of Michigan professors on energy goes well beyond their involvement in production, pipelining and storage of natural gas. Tek has been on special panels with the Executive Office of the President and State Legislature in Michigan. Dr. Katz is a member of the Academy of Engineering and has been consulting to Federal Government on energy matters from some time. Recently six University of Michigan professors, Tek, Katz, Briggs, Williams, Powers, and Lady participated on a national research effort by EPRI to determine environmentally acceptable use of coal for generation of electric power. Presently there exists a number of energy related projects at the university under the auspices of the National Science Foundation, Michigan Gas Association, NOAA. Currently, Professor Tek leads a team of graduate and doctoral students in a "Sea Grant" research project directed to identify "Problems and Prospects" for oil and gas in the Great Lakes area.

Professor H. Scott Fogler works on matrix acidication and formation treatment with several graduate students in doctoral programs. Professor D. E. Briggs, has a number of research projects in the area of coal gasification, coal liquefaction. Professor G. Brymer Williams has been interested in energy from shale.

Table XIV. Degrees Grant in Chemical Engineering at the University of Michigan.

Year	B.S.	M.S.	Ph.D.	Professional
1973	35	14	7	-
1974	43	20	11	-
1975	52	27	2	1

It is estimated that at least 20 percent of the Ph.D.'s and about 30 percent of the master's recipients receive instruction in energy related areas. Recently, Ph.D. work by Drs. G. Holder in hydrate formation and David Bergman in retrograde condensation may be cited as typical examples.

The University of Michigan's Engineering College has long had a unique position in the area of logistics of energy through various teaching, research, and training programs in underground storage.

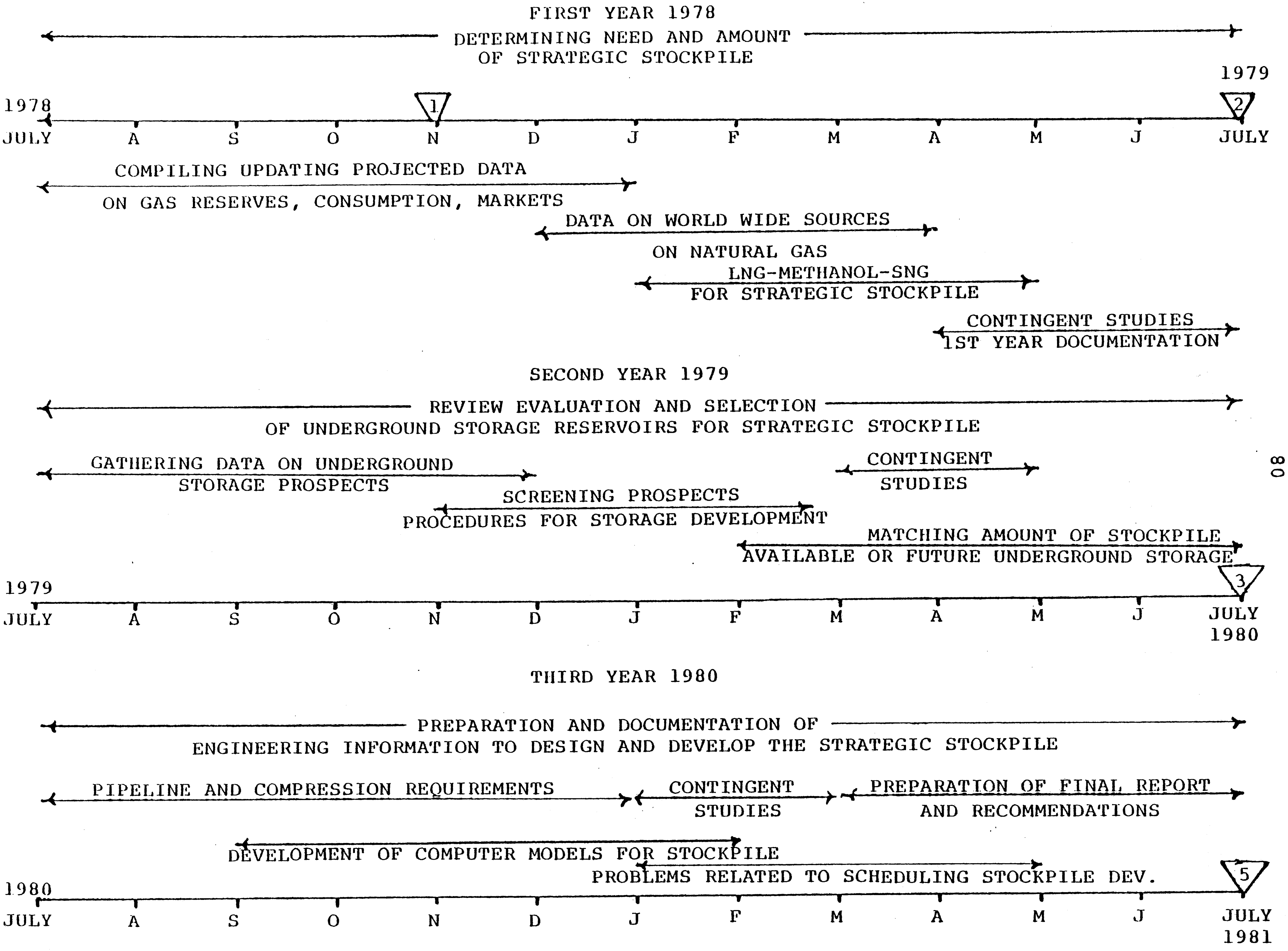
The University of Michigan's Chemical Engineering Department along with the Materials and Metallurgical Department has received gifts totalling six million dollars from two foundations and one individual. As a result, immediate implementation of a new building to provide instruction and laboratory facilities for students in Chemical Engineering is underway. Present facilities in both North and Main Campus also include several modern energy related laboratories and a Computing Center of national renown.

A listing of courses offered in Chemical Engineering is given in the catalog.

6. TIMETABLE FOR THE PROPOSED RESEARCH

The timetable and target dates for the proposed research are presented in graphical sequence in Figure 20. While the university would be prepared to start on the proposed study anytime after January 1, 1978 the timetable is based on the assumption and expectation that the funding will start July 1, 1978. A three year program is proposed which follows in approximate sequence and with some possible minor overlaps the three major tasks indicated on Figure 19.

The first year will be devoted to determining the need for strategic stockpile and the amount possible or feasible for such a project. It is proposed to start with compiling dating and projecting data available on United States reserves consumption, markets. Data on possible natural gas sources world wide will be gathered next. Whether pipeline or tanker accessible these sources will be screened documented and evaluated as possible sources for the strategic stockpile. The first year will also include comparative engineering economics of LNG, SNG, and methanol routes. The second year will be devoted to review and evaluation of present underground storage reservoirs for possible dedication to the strategic stockpile. Several site visits will be undertaken to the field or gas producing company offices and data will be gathered to determine storage capacity, pressures, time schedule, observation procedures. The third year will be devoted to the preparation and documentation of engineering needed to design and develop the strategic stockpile.



<u>TARGET DATES</u> 1 , 2 , 3 , 4 , Major Milestones

This phase will include determining the pipeline and compression needed for a strategic stockpile, to match at least some of the present unused capabilities. Development of a computer model representing the strategic stockpile system and its use for optimization and scheduling studies will be undertaken during the early part of the third year. The last four months of the third year will be devoted to the preparation of the final document which would include conclusions and recommendations.

It may be noted that in order to provide flexibility in scheduling various tasks and to respond to unforeseen needs two months have been set aside each year for contingent studies.

The target dates designated in Figures 20 as 1 , 2 etc. are scheduled as follows:

1 November 1978 - first meeting of the Steering Committee in Ann Arbor, Discussion of immediate future plans

2 July 1979 - meeting of Steering Committee, Report on first year, need and amount of stockpile desired.

3 July 1980 - Need and amount of stockpile desired. (reviewed) Report on selection of reservoirs recommended for a strategic stockpile

4 March 1981 - Need and amount of stockpile desired. (reviewed) Steering Committee, discussion on third year results, outline of proposed manuscript for final documentation

5 July 1981 - Manuscript of project final report to printers. Conclusion of the assessment study.

7. PERSONNEL

7.1. PRINCIPAL INVESTIGATOR-PROJECT DIRECTOR

Professor M. R. Tek, who first conceived the idea of a strategic stockpile during 1975 and who has been working on it since August 1975, is proposed as the Principal Investigator and Project Director. Professor Tek has devoted most of his professional life to production, pipelining, and underground storage of natural gas. He has conducted similar research tasks in the past for the American Gas Association, Michigan Gas Association, EPRI, and others. He has been consultant to a large number of oil and gas companies, public utilities, pipelining storage companies. He has 78 technical publications to his credit including 11 books and 11 patents. His professional resume is included in the Appendix.

7.2. CONSULTANTS

Dr. Donald L. Katz, Professor Emeritus of Chemical Engineering has agreed to serve as consultant and a member of the Steering Committee for the project. Dr. Katz' qualifications need little elaboration. He is probably one of the world's foremost authorities on natural gas. Dr. Tek who prepared this proposal had the good fortune to be closely associated with him for the past twenty years. Dr. Katz' qualifications are also included in the Appendix.

In additional to Professor Katz, J. O. Wilkes agreed to participate as computing consultant and associate investigator during the first two years. During the third year Professor

Wilkes will lead the task force in developing and documenting the engineering information for the development of the stockpile. Professor J. O. Wilkes is a member of the University of Michigan faculty eminently qualified in engineering application of computers, author of several graduate textbooks in numerical analysis. His resume is included in the Appendix.

7.3. STEERING COMMITTEE

It is proposed to form a Steering Committee with Professor Tek, the Principal Investigator, as ex-officio and Dr. D. L. Katz as Chairman. The Energy Department of the Federal Government natural gas pipeline, storage companies, chemical engineering design and construction companies would also be represented. The purpose of the Steering Committee would be to review the progress give advice and guidance on overall conduct of the project.

7.4. TASK LEADERS

It is proposed that the three tasks indicated for the first, second, and third years be specifically assigned to a Task Leader during the first, second, and third years on the project. It is estimated that the project will require on full-time Task Leader each year. The Task Leader for screening storage reservoirs will be someone knowledgeable in storage industry, he will be nominated after the project is funded.

7.5. GRADUATE STUDENT INVESTIGATORS-RESEARCH ASSISTANTS

During the first year three (full-time equivalent) graduate student investigators and four (full-time equivalent) hourly research assistants would be needed. Of the three, it is possible that one or two may elect certain aspects of the assessment project as their doctoral topic. During the second year the graduate student manpower requirements will be approximately the same with two doctoral projects as well. Because the doctoral programs will last more than one year it must be recognized that some overlap will occur in responsibilities between the first and second and between the second and third years. It is estimated that the third year will require two graduate students and two full-time equivalent hourly assistants.

8. BUDGET
FIRST YEAR

SALARIES AND WAGES		
Senior Personnel		
Principal Investigator	9.6 man months	$24,400.00
Faculty Associate	~2.4 man months	6,000.00
Other Personnel		
Professional Task Leader	12 man months	30,000.00
Consultant	10 days	5,000.00
(3) Graduate Research Assistants Tuition and Stipend		28,800.00
(4) Hourly Research Assistants (FTE)		10,400.00
Secretaries		10,000.00
TOTAL SALARIES AND WAGES		$114,600.00
FRINGE BENEFITS		
(charged as direct 16 percent of 60,400.00)		9,650.00
TOTAL SALARIES WAGES AND FRINGE BENEFITS		$124,250.00
PERMANENT EQUIPMENT		
EXPANDABLE SUPPLIES AND EQUIPMENT		1,312.00
TRAVEL		
(20 man trips $500.00/man trip) domestic		10,000.00
4 man trips international		10,000.00
PUBLICATION DOCUMENTATION		2,000.00

OTHER COSTS

computing	$5,000.00
Total direct costs from Salaries and Wages to Other Costs	152,562.00
Indirect costs 75 percent of $124,250.00	93,188.00
TOTAL COSTS	245,750.00

BUDGET
SECOND YEAR

SALARIES AND WAGES		
Senior Personnel		
Principal Investigator	9.6 man months	$24,400.00
Faculty Associate	3.6 man months	9,000.00
Other Personnel		
Professional Task Leader	12 man months	30,000.00
Consultant	10 days	5,000.00
(3) Graduate Research Assistants Tuition and Stipend		28,800.00
(4) Hourly Research Assistant (FTE)		10,400.00
Secretaries		10,000.00
TOTAL SALARIES AND WAGES		$117,600.00
FRINGE BENEFITS		
(charged direct as 16 percent of $63,400.00)		10,120.00
TOTAL SALARIES WAGES AND FRINGE BENEFITS		$127,720.00
PERMANENT EQUIPMENT		
EXPANDABLE SUPPLIES AND EQUIPMENT		1,490.00
TRAVEL (all domestic)		10,000.00
PUBLICATION DOCUMENTATION		2,000.00
OTHER COSTS		
Computing		5,000.00
Total direct costs from Salaries and Wages to Other Costs		146,210.00

Total indirect costs 75 percent of $127,720.00	95,790.00
TOTAL COSTS	$242,000.00

BUDGET
THIRD YEAR

SALARIES AND WAGES		
Senior Personnel		
Principal Investigator	9.6 man months	$24,400.00
Faculty Associate	8 man months	20,000.00
Other Personnel		
Professional Tas Leader (none)		
Consultant	15 days	7,500.00
(2) Graduate Research Assistants		18,200.00
(2) Hourly Research Assistants (FTE)		5,200.00
Secretaries		12,000.00
TOTAL SALARIES AND WAGES		$87,300.00
FRINGE BENEFITS		
(charged as direct 16 percent of $44,400.00)		7,100.00
		$94,400.00
PERMANENT EQUIPMENT		
EXPANDABLE SUPPLIES AND EQUIPMENT		1,800.00
TRAVEL		
(20 man trips) domestic		10,000.00
PUBLICATION DOCUMENTATION		5,000.00

OTHER COSTS

Computing	$5,000.00
Total direct costs	116,200.00
Total indirect costs 75 percent of $94,400.00	70,800.00
TOTAL COSTS	$187,000.00

BUDGET SUMMARY

TOTAL PROPOSED PROJECT COSTS

First Year	$245,750.00
Second Year	$242,000.00
Third Year	$187,000.00
TOTAL	$674,750.00

LITERATURE

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12. "Handbook of Natural Gas Engineering," D. L. Katz, D. Cornell, R. Kobayaski, F. H. Poettmann, J. A. Vary, J. R. Elenbaas, and C. F. Weinang, McGraw Hill Co., Inc., New York, 1959.
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APPENDIX I

PUBLIC DOCUMENTS AND CORRESPONDENCE WITH EXECUTIVE AND LEGISLATIVE LEADERS

EXECUTIVE OFFICE OF THE PRESIDENT
ENERGY POLICY AND PLANNING
WASHINGTON, D.C. 20500

March 31, 1977

Dear Professor Tek:

The President has referred your letter, in which you suggested that a "Strategic Stockpile in Natural Gas" be developed as a measure to help alleviate our Nation's energy shortages, to Mr. James R. Schlesinger, who has asked me to respond on his behalf.

As you are no doubt aware, Mr. Schlesinger is currently formalizing a comprehensive and equitable national energy policy and initiatives and please be assured that your suggestions and comments will receive every consideration as future energy policies are developed for the President.

Your kind offer of assistance and support are most appreciated, and should the opportunity arise we will certainly call upon you.

Sincerely,

Frank R. Pagnotta

Mr. M. R. Tek
Professor of Chemical Engineering
The University of Michigan
Ann Arbor, Michigan 48109

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

July 27, 1977

Mr. M.R. Tek
The University of Michigan
Ann Arbor, MI 48109

Dear Mr. Tek:

The White House has brought your recent correspondence on National energy matters to the attention of the Energy Research and Development Administration.

As you know, the Nation's energy policies are the subject of an ongoing debate in a number of public forums. Your views, and those of several thousand other Americans who have written in recent months, represent a valuable contribution to this debate. We hope you will follow Federal energy actions with interest in the months to come.

Thank you for bringing your thoughts on energy to the attention of the Federal Government.

Sincerely,

Eric H. Willis
Assistant Administrator
for Institutional Relations

ROBERT P. GRIFFIN
MICHIGAN

United States Senate
WASHINGTON, D.C. 20510

February 14, 1977

Professor M. Rasin Tek
University of Michigan
Department of Chemical Engineering
Ann Arbor, Michigan 48105

Dear Professor Tek:

Just a note to thank you for sending me a copy of your article from the Ann Arbor News, as well as my copy of your letter to President Carter.

It was thoughtful of you to take time to provide me with this material. You may be assured that I shall have it in mind as related legislation is considered in the Senate.

With best wishes, I am

Sincerely,

Robert Griffin

Robert P. Griffin
U. S. Senator

RPG:JDl

Congress of the United States
House of Representatives
Washington, D.C. 20515

February 16, 1977

Dr. M. Rasin Tek
Professor of Chemical Engineering
The University of Michigan
Chemical Engineering Department
Ann Arbor, MI 48109

Dear Dr. Tek:

Thank you very much for your recent letter regarding our energy problems and specifically, natural gas.

In reviewing your comments, I found that you have raised some very valid points about our energy supply. Certainly, the idea of of converting methane into methanol is one worth considering.

As a Member of the Science and Technology Committee and the Energy Subcommittee which will be dealing with development of a national energy policy, I am most interested in your ideas. You may be sure that I will keep your comments in mind as my Subcommittee begins work on our energy problems.

I believe that the development of a national energy policy - to both conserve our present sources and develop new sources - is one of the major issues this Congress must address itself to. We can no longer act in a crisis vacuum, we must take steps to develop a long-term energy policy.

I would certainly appreciate any further input you might have on this topic. I look forward to corresponding with you in the future.

With best wishes, I am

Sincerely,

Carl Pursell

Carl D. Pursell
Member of Congress

CDP/ds

THE UNIVERSITY OF MICHIGAN
CHEMICAL ENGINEERING
ANN ARBOR, MICHIGAN 48109

24 January 1977

President Jimmy Carter
White House
Washington, D. C.

Dear President Carter:

This letter is written with the hope that somehow it will receive your attention. In line with your promise to provide us a government close to people and open to suggestions I respectfully wish to point out an opportunity for our country to take a bold step toward energy independence.

If, understandably, this letter cannot reach you, but is read by one of your aides then I sincerely hope it would at least be brought to the attention of Mr. Schlesinger, who has been designated to head up our energy programs.

My suggestion is to take immediate steps to develop a "Strategic Stockpile In Natural Gas." The United States has the most unique combination of three resources unequaled anywhere else in the world. These are:

1. World's largest market for gas,
2. World's largest, safest, ecologically acceptable environment for the gas: depleted oil and gas fields in the lower 48, and,
3. The world's most elaborate pipeline network.

Against the background of the three more and more unused resources above is the fact that world wide most natural gas supplies are market limited while most natural gas markets are supply limited. Accordingly, there are many places in the world, such as Saudi Arabia, Iran, Australia's northwest shelf, Siberia, etc. where the natural gas can be purchased and transported to the United States. Such gas beyond the reach of pipelines is normally liquefied and transported in cryogenic tankers. This route however, is expensive and limited in scope due to unavailability of tankers, in short supply. If, on the other hand, the methane is locally reformed into methanol, then the surplus of crude oil tankers could be used to transport the methanol to the United States.

In areas where large port facilities exist, such as Baltimore, New Orleans, and Los Angeles, the methanol would be turned back into methane. The methane would be pumped via our pipeline network selectively into the underground storage in unused or partially depleted reservoirs. A side benefit of bringing the methanol in the United States would be that part of it could directly be used as liquid fuel in automobiles mixed with gasoline.

During 1945 and 1975 a total of 408 trillion cubic feet of natural gas has been produced and marketed in the United States. With a bold but innovative plan it would be possible to provide not only a modest annual growth in our consumption of natural gas but at the same time, import and store sufficient gas to restore our existing reservoirs to the level of reserves which existed many years ago.

The Congress, through energy and environment act of 1976, has already accepted the need for a strategic stockpile in petroleum. Part of that plan is already underway for imported crude oil. Nothing has been said or done yet for natural gas. Yet natural gas is used in 62 percent of our homes.

The details of the proposed strategic stockpile, where it would come from, how it would be transported, reformed, piped, where it would be stored, economics, financing, lead times, and optimizing have been documented at the University of Michigan by this writer and his graduate students.

Should you be interested, I would be delighted to work with the members of your staff to make our energy dream come true.

Mr. President, congratulations and good luck on your many endeavors.

Respectfully,

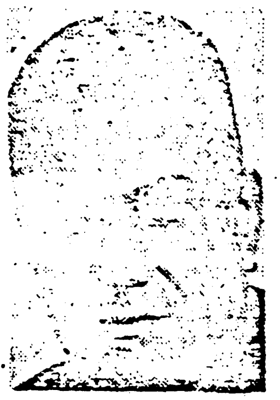
M. R. Tek,
Professor of Chemical Engineering

MRT:sh

8 The Ann Arbor News, Thursday, February 10, 1977

Guest Viewpoint

Build Stockpile In Natural Gas



Dr. M. Rasin Tek

(Editor's note: Dr. M. Rasin Tek is a professor of chemical engineering at the U-M. A native of Istanbul, Dr. Tek worked for Philips Petroleum and for International General Electric before joining the U-M in 1957. One of his areas of expertise is the field of gas storage).

THE UNITED STATES once had the world's largest gas supply. This and the climate of free enterprise in our country led to the development of the world's largest gas market. The two had been connected with the world's most elaborate pipeline network. The combination of these three resources resulted in a prolific growth record which consumed over 400 trillion cubic feet of natural gas between 1935 and 1975.

Since 1970, however, the growth years peaked out and declines became painfully apparent. This harsh winter of 1976-1977 perhaps, marks the climax of our critical dependence on natural gas. Worldwide, gas supplies are plentiful but they remain undeveloped because they are market limited.

In the United States we have a unique combination of not only "a ready to fly" market, and pipelines to supply and distribute the gas to it but also: an environment, safe and ecological to put the gas in storage. So why not build a strategic stockpile in natural gas?

We have 32,000 wells, some 6,000 plus semidepleted gas or underground storage reservoirs, 70,000 miles of gas gathering lines. In addition, we have over 260,000 miles of long distance pipelines and over 660,000 miles of low pressure gas distribution lines being operated under their original design loads. Why not put these unused capacities to work? Where would we get the gas from? We could get it from Australia, from Saudi Arabia, from Iran, even from Siberia. How would we get it to the U.S.A.? In many ways:

1. By (LNG) liquefied natural gas tankers from overseas sources.
2. By making methanol out of methane then shipping the methanol by regular surplus tankers to the U.S., again from overseas sources. Upon arrival the methanol would have to be converted back into methane utilizing present and routine technology.
3. By pipelines from arctic sources.
4. By preplanned over capacity in coal gasification units in due time.

★ ★ ★

WHERE WOULD we store the methane to build the stockpile? In underground storage in selected gas, oil, or other storage fields. It must be emphatically noted that we would put the gas in none other than where nature had put it in the first place.

These reservoirs in depths ranging from 2,000 to 7,000 feet underground, are not only safe, but environmentally and ecologically acceptable.

If we could build our reserves in methane to where they were just before the Second World War, we would not be so vulnerable to winters or embargoes, nor would we be so economically exposed to the ills of unemployment, restrictions or curtailments. Even if we could restore and re-inject only 20 percent of what we used between 1935 and 1975, that would amount to a stockpile which alone would last four years at our current consumption rate. (The last World War we got into lasted four years.)

What is more significant perhaps is that by buying the gas that either will be flared to the atmosphere or would never be produced, we would be doing a favor to our strained environment and we would be aiding our friends, the developing countries.

APPENDIX II

STATISTICAL INFORMATION IN SUPPORT OF STRATEGIC STOCKPILE CALCULATIONS

Table AI. Marketed Production of Natural Gas In the U.S. From 1945 to 1975. (Source: American Gas Association)

Year	Marketed Production (TCF/Year)
1945	3.92
1946	4.03
1947	4.58
1948	5.15
1949	5.42
1950	6.28
1951	7.46
1952	8.01
1953	8.40
1954	8.74
1955	9.41
1956	10.08
1957	10.68
1958	11.03
1959	12.05
1960	12.77
1961	13.24
1962	13.88
1963	14.75
1964	15.46
1965	16.04
1966	17.21
1967	18.17
1968	19.32
1969	20.70
1970	21.92
1971	22.49
1972	22.53
1973	22.65
1974	21.72
1975	19.72

Table AII. Estimated Proven Reserve of Natural Gas At the End of the Year From 1945 to 1975. (Source: American Gas Association)

Year	Reserve At the End of Year (TCF)
1945	144.29
1946	160.58
1947	165.93
1948	173.87
1949	180.38
1950	185.59
1951	193.81
1952	199.72
1953	211.45
1954	211.71
1955	233.70
1956	237.77
1957	246.57
1958	254.14
1959	262.60
1960	263.76
1961	267.73
1962	273.77
1963	277.86
1964	281.25
1965	286.47
1966	289.33
1967	292.91
1968	287.35
1969	275.11
1970	290.75
1971	278.80
1972	266.08
1973	249.95
1974	237.13
1975	228.20

Table AIII. Estimated Consumption of Natural Gas in U.S. At Various Increasing Rates Between 1976 and 1999.

Year	Consumption at 0% Increase Per Year	Consumption at 2% Increase Per Year	Consumption at 3½% Increase Per Year
1976	19.72 TCF/Year	20.11 TCF/Year	20.41 TCF/Year
1977	19.72	20.52	21.12
1978	19.72	20.92	21.86
1979	19.72	21.34	22.63
1980	19.72	21.77	23.42
1981	19.72	22.21	24.24
1982	19.72	22.65	25.09
1983	19.72	23.10	25.97
1984	19.72	23.57	26.88
1985	19.72	24.04	27.82
1986	19.72	24.52	28.79
1987	19.72	25.01	29.80
1988	19.72	25.51	30.84
1989	19.72	26.02	31.92
1990	19.72	26.54	33.04
1991	19.72	27.07	34.19
1992	19.72	27.61	35.39
1993	19.72	28.17	36.63
1994	19.72	28.73	37.92
1995	19.72	29.30	39.24
1996	19.72	29.89	40.71
1997	19.72	30.47	42.03
1998	19.72	31.10	43.50
1999	19.72	31.72	45.02

Table AIV. Expected Estimated Reserve of Natural Gas At Various Rate of Increase in Consumption From 1976 to 1999.

Year	Estimated Reserve If Consumption Increases By		
	0% Per Year	2% Per Year	3½% Per Year
1976	218.48 TCF	218.09 TCF	217.79 TCF
1977	208.76	207.57	206.67
1978	199.04	196.65	194.81
1979	189.32	185.31	182.18
1980	179.60	173.54	168.76
1981	169.88	161.33	154.52
1982	160.16	148.68	139.43
1983	150.44	135.58	123.46
1984	140.72	122.01	106.58
1985	131.00	107.97	88.76
1986	121.28	93.45	69.97
1987	111.56	78.44	50.17
1988	101.84	62.93	29.33
1989	92.12	46.91	7.41
1990	82.40	30.37	-15.63
1991	72.68	13.30	
1992	62.96	-4.31	
1993	53.24		
1994	43.52		
1995	33.80		
1996	24.08		
1997	14.36		
1998	4.64		
1999	-5.08		

Table AV. Storage Facility Data - 12/31/76.

						Number Of Compressor Stations					New Construction	
State	Number Of Companies	Number Of Reservoirs	Input and/or Output	Pressure Control and/or Observation	Total	Input Only	Output Only	Input and Output	Total	Compressor Station Horsepower	Number Of Reservoirs	Est. Ultimate Capacity (MCF)
Arkansas	2	5	21	1	22	4	-	1	5	1,470	-	0
California	2	9	339	41	380	8	-	2	10	85,410	-	0
Colorado	5	7	57	19	76	3	-	3	6	20,495	1	22,278,344
Illinois	9	31	1,076	546	1,622	12	3	13	28	201,775	2	50,000,000
Indiana	7	27	686	222	908	7	2	4	13	18,770	-	0
Iowa	2	9	269	109	378	-	1	3	4	38,500	-	0
Kansas	5	17	667	111	778	1	3	4	8	21,620	-	0
Kentucky	5	23	893	293	1,186	3	2	10	15	34,005	-	0
Louisiana	6	7	132	26	158	2	-	7	9	56,500	-	0
Maryland	1	1	65	5	70	-	-	1	1	11,000	-	0
Michigan	6	44	2,229	477	2,706	4	2	16	22	291,960	4	56,475,902
Minnesota	1	1	14	32	46	-	1	-	1	2,200	-	0
Mississippi	4	4	80	14	94	1	-	3	4	35,800	-	0
Missouri	1	1	50	32	82	-	-	1	1	8,850	-	0
Montana	2	5	111	23	134	-	-	5	5	18,950	-	0
Nebraska	1	2	24	22	46	-	-	2	2	8,950	-	0
New Mexico	2	2	39	7	46	1	1	-	2	5,200	-	0
New York	7	19	874	57	931	4	-	9	13	30,450	1	13,200,000
Ohio	3	22	2,830	273	3,103	3	1	14	18	78,775	-	0
Oklahoma	8	12	176	69	245	3	-	6	9	34,419	-	0
Pennsylvania	15	68	1,573	508	2,081	8	6	37	51	201,710	-	0
Texas	7	18	187	46	233	13	-	3	16	36,085	2	138,500,000
Utah	1	2	4	11	15	2	-	-	2	1,200	-	0
Washington	1	2	25	51	76	-	-	1	1	11,800	1	24,000,000
West Virginia	5	38	1,166	326	1,492	-	-	19	19	78,060	-	0
Wyoming	3	10	23	6	29	4	1	2	7	8,461	-	0
TOTALS	-	386	13,610	3,327	16,937	83	23	166	272	1,342,415	11	304,454,246

Table AVI. Maximum Volumes of Stored Gas and Maximum Day Output - 1976
(All Volumes in MCF - 14.73 psia 60°F)

State	Maximum Volumes Of Stored Gas Exclusive Of Native Gas	Number Of Companies Reporting	Dates For Maximum Volumes Of Stored Gas	Maximum Day Output From Storage	Number Of Companies Reporting	Dates For Maximum Day Output	Percentages Of Peak Day Sendout From Storage	Number Of Companies Reporting
Arkansas	12,416,181	2	11/30-12/31	55,592	2	1/7-1/8	36.0	1
California	261,622,168	2	11/19-12/13	2,862,195	2	1/2-12/19	8.8-34.3	2
Colorado	25,008,717	5	10/31-11/30	429,511	4	1/2-12/7	16.-71.38	4
Illinois	780,991,923	9	2/9-11/27	4,165,175	9	1/7-12/30	19.-723.	6
Indiana	83,753,438	7	3/31-11/21	556,833	6	1/4-11/29	3.39-57.9	6
Iowa	205,511,294	2	11/1-11/15	734,985	2	1/5-12/30	8.48-51.	2
Kansas	120,724,641	5	1/1-11/30	854,463	4	1/7-11/27	5.-21.45	2
Kentucky	201,470,014	5	10/12-12/31	1,035,072	4	1/8-12/21	26.8-57.	2
Louisiana	260,720,226	6	10/15-11/8	1,854,189	4	1/8-12/24	32.14-48.	3
Maryland	62,102,158	1	11/4	313,948	1	1/9	-	0
Michigan	608,993,646	6	6/16-12/31	5,185,817	6	1/4-12/2	27.2-78.3	5
Minnesota	4,997,734	1	11/1	50,423	1	1/7	8.1	1
Mississippi	81,976,179	4	2/12-11/5	1,493,477	4	1/8-12/22	5.13-33.4	3
Missouri	29,295,672	1	1/1	384,649	1	12/30	35.6	1
Montana	135,928,667	2	1/1-10/31	237,097	2	1/5-3/2	39.8-40.9	2
Nebraska	31,577,165	1	12/31	65,052	1	11/28	8.77	1
New Mexico	23,343,590	2	1/1	120,225	2	1/8-11/28	3.-8.	2
New York	125,249,377	7	10/6-11/1	780,730	6	1/15-12/28	9.-100.	5
Ohio	420,661,532	3	10/16-11/1	2,747,702	3	1/9-2/2	30-68.6	3
Oklahoma	269,060,234	8	1/1-10/24	1,378,786	6	1/4-12/10	.00779-48.13	5
Pennsylvania	681,227,964	15	1/1-10/31	5,692,904	11	1/5-12/3	0.5-72.6	6
Texas	193,901,824	7	6/21-12/31	1,034,942	4	1/7-11/16	17.-95.	3
Utah	4,518,841	1	1/1	29,434	1	3/25	6.8	1
Washington	26,973,000	1	11/18	292,760	1	2/5	-	0
West Virginia	414,618,348	5	9/31-11/30	2,942,194	4	1/9-10/30	6.5-70.5	4
Wyoming	47,037,223	3	9/1-12/31	242,599	3	1/6-11/27	20.4-82.3	2
TOTALS	5,113,681,756	-	-	35,540,754	-	-	-	-

Table AVII. Summary of Aquifer Storage Volume Statistics - 1976.
(All volumes in MCF @ 14.73 psia)

State	Number of Companies	Number of Reservoirs	Total Reservoir Capacity 12/31/76	Total Base Gas 12/31/76	Total Working Gas 12/31/76	Stored Gas 12/31/76	Maximum Volume Stored Gas	Maximum Day Output From Storage	Range Of Rock Pressure (Psig)
Illinois	9	22	899,689,970	438,832,735	202,999,754	641,832,489	712,370,593	3,610,369	345-2050
Indiana	5	10	105,122,690	29,985,921	8,869,069	38,854,990	42,645,761	241,434	100-1400
Iowa	2	8	354,500,000	117,751,259	70,969,599	188,720,858	205,511,294	734,985	500-1400
Kentucky	2	4	12,059,012	4,350,000	6,554,297	10,904,297	12,056,302	11,540	310
Minnesota	1	1	20,000,000	3,000,000	1,365,489	4,365,489	4,997,734	50,423	200-400
Missouri	1	1	45,000,000	11,759,095	15,035,086	26,794,181	29,295,672	384,649	--
New Mexico	1	1	9,258,654	3,642,936	5,464,405	9,107,341	9,253,032	19,986	1200
Utah	1	2	4,518,841	1,415,544	2,802,729	4,218,273	4,518,841	29,434	1190-1330
Washington	3	2	26,973,000	16,515,000	8,442,000	24,957,000	26,973,000	292,760	315-1600
Wyoming	1	1	6,941,874	3,138,965	3,315,078	6,454,043	6,941,874	144,285	1855
		52	1,484,064,041	630,391,455	325,817,506	956,208,961	1,054,564,103	5,519,865	

Table AVIII. Aquifer Storage Facility Data 12/31/76.

State	Number of Companies	Number of Reservoirs	Input and/or Output	Pressure Control and/or Observation	Total	Number of Compressor Stations	Compressor Station Horsepower	New Construction Number of Reservoirs	New Construction Estimated Ultimate Capacity (MCF)
Illinois	9	22	761	425	1,186	20	180,755	2	50,000,000
Indiana	5	10	241	124	365	7	12,160	-	0
Iowa	2	8	269	109	378	4	38,500	-	0
Kentucky	2	4	162	67	229	4	20,245	-	0
Minnesota	1	1	14	32	46	1	2,200	-	0
Missouri	1	1	50	32	82	1	8,850	-	0
New Mexico	1	1	4	7	11	1	800	-	0
Utah	1	2	4	11	15	2	1,200	-	0
Washington	3	2	25	51	76	1	11,800	1	24,000,000
Wyoming	1	1	8	4	12	1	3,830	-	0
		52	1,538	862	2,400	42	280,340	3	74,000,000

Table AIX. Comparative Data-Aquifer Storage Statistics, 1972-1976.
(All Volumes in MCF -14.73 psia 60°F)

Description	1972	1973	1974	1975	1976
Number of States	9	10	10	10	10
Number of Companies	22	23	24	24	24
Number of Pools	46	49	51	52	52
Total Number Of Wells	2,028	2,163	2,265	2,321	2,400
Total Number Of Compressor Stations	36	38	41	41	41
Total Horsepower of Compressor Stations	251,355	240,295	266,515	296,050	280,340
Maximum Volume of Stored Gas	768,152,867	842,611,340	898,881,409	973,668,157	1,054,564,103
Total Volume in Storage Reservoirs, 12/31	704,606,275	792,344,504	849,286,078	924,606,959	956,208,961
Input to Storage-Calendar Year	281,600,719	270,672,130	257,573,181	316,827,484	295,374,212
Output from Storage Calendar Year	245,454,955	180,262,190	206,412,221	241,386,809	265,411,166
Total Base Gas	464,100,351	506,216,482	545,942,687	582,550,776	630,391,455
Total Working Gas	240,505,924	286,124,049	303,343,391	342,056,183	325,817,506
Maximum Day Output from Storage	5,004,743	4,566,238	4,679,324	4,767,976	5,519,865
Total Reservoir Capacity	1,277,614,000	1,398,545,225	1,408,115,366	1,458,988,349	1,484,064,041
Number of Pools Under Construction	8	6	8	4	3
Estimated Capacity New Pools	220,000,000	190,000,000	345,000,000	148,500,000	74,000,000

APPENDIX III

PROFESSIONAL BACKGROUND OF PRINCIPAL INVESTIGATOR AND SENIOR FACULTY STAFF PROPOSED.

RESUME

1. Name: M. Rasin Tek — Date: September 1977

   Wife's Name: Margaret Gretchen — Social Security No. 371-30-8770

2. Department: Chem. & Met. Engr. — Citizenship: USA 1959 (N-8066041)

3. Date of Birth: January 6, 1927

4. Present Academic Rank: Professor

   Dates of appointment to various academic ranks at the University of Michigan

   Assistant Professor: September 1957

   Associate Professor: September 1960

   Professor: August 1965

5. Degrees:

   B.S.E. - Mech. University of Michigan - 1948

   M.S.E. - Mech. University of Michigan - 1949

   Ph.D. - Mech. University of Michigan - 1953

6. Appointment fractions during present term

   Academic Budget: 90%

7. Other teaching experience

   University of New South Wales, Sydney, Australia, 1967-1968
   as Visiting Scholar and Senior Fulbright Lecturer

   University of New South Wales Visiting Professor, 1975-1976

8. Full-time industrial experience

   General Electric, 1949-1950, Test Engineer

   Phillips Petroleum Company
   Research Engineer, 1953-1955
   Research Group Leader, 1955-1956
   Research Section Manager, 1956-1957

9. Part-time industrial experience

   Smith, Hinchman and Grylls, Detroit, 1949 (Design)

10. States in which registered:

    Oklahoma

    Michigan

M. Rasin Tek

11. Consulting work in the past five years (* indicates current work)

1. Phillips Petroleum Company
2. Fractionation Research, Inc.
3. Consumers Power Company
4. Columbia Gas System Company
5. Air Products
6. Delavan Inc.
7. Wyandotte Chemical
8. Gas Storage Company of Illinois
9. Chemstrand
10. Texas Eastern Gas Transmission
11. Global Marine Exploration Company
12. Department of Nat'l Development Commonwealth of Australia
13. Department of Mines, Queensland, Australia
14. Australian Gas Light Corp., Sydney, N.S.W. Australia
15. Ansett A and A Airlines, Australia
16. Ransom, Frazenbaker & Ransom (Attys.), Flint, Michigan
17. Dudley Westgarth Property Ltd. Solicitors, Sydney, Australia
18. Marathon Oil Company
19. International Computer Applications Ltd.
20. Goldsmith, Yaker and Goldsmith (Attys.) Detroit, Michigan
21. Interface Systems Inc., Ann Arbor, Michigan
22. Transcontinental Gas Pipeline Corporation
23. Northwest Pipeline Project Consortium
24. Office of Science and Technology,
    Executive Office of the President of the United States
25. Peoples Gas Light and Coke Company, Chicago, Illinois
26. Brown and Wicker, Law Offices, Munroe, Louisiana
27. Optimum Engineering, Menlo Park, California

*28. Michigan Consolidated Gas Company, Detroit, Michigan

29. Electric Power Research Institute
30. AGA-Batelle Memorial Institute, Columbus, Ohio
31. AGA-University of Tulsa Energy Assessment Project

M. Rasin Tek

32. Arcanum Corporation, Ann Arbor, Michigan
33. Vector Incorporated, Ann Arbor, Michigan
34. Citizen's Fuel Gas Corporation, Adrian, Michigan
35. Transco Energy Company, Houston, Texas
36. C.S.I.R.O., Clayton, Monash
37. Abadan Institute of Technology, Abadan, Iran
38. United Nations Return of Technology Program
*39. Turkish Petroleum Company, Ankara, Turkey
*40. Natural Gas Pipeline Company of America

12. Scientific and professional societies of which a member:

AIChE - member
Committee of Joint Symposia
AIME (SPE) - member
ASME - member
ASEE - member

Alpha Xi Sigma
Pi Lambda Upsilon
Sigma XI
Science Research Club, U of M
Amer. Nationals Club, Sydney, Australia
Associate member U.S. Naval Institute

13. Honors and Awards

Authors Assistance Award, Industry Program U of M
Fulbright-Hays Senior Lectureship Award, Australian American Educ. Fnd.
Visiting Professorship, U of New South Wales, 1975-76

14. Committee assignments in department, college and university:

Standing Committee; Faculty & Course Evaluation 1973-
Cooley Essay Contest Committee (College) 1967-70
Scholastic Standing Committee 1970-73
Nominating Committee, Chairman 1970-71
Executive Committee - 1972-1975
Army and Navy ROTC Scholarship Review Board, 1975
University Committee on Military Officer Education Program 1975-79

15. Recent activities during summer periods outside of academic appointments:

Chairman, 1969 U of M Symposium on Threshold Displacement Pressures
Co-Chairman of Session AGA-IGT Symposium on Gas Technology, 1971
Co-Chairman Summer Course on Natural Gas Storage 1955-1971
Co-Director American Gas Association Research
Director, Michigan Gas Association Fellowship Research Program.

16. Other information on professional academic activities:

Dow Chemical Company Graduate Course, 1975
National or International Service: Associate, Commission on Institutions of Higher Education 1974, Full commissioner status 1975-date

M. Rasin Tek

17. Leaves of Absence and Sabbatical leaves while at Michigan:
    - Fall Term 1964 - sabbatical
    - Fall 1967, Winter 1968 - Senior Fulbright Lecturer, Sydney, N.S.W., Australia LWOS
    - Fall 1975, Winter 1976 - sabbatical, Australia

18. Current contracts and grants under your direct supervision:
    - American Gas Association Research Project, 1968-1970
    - Michigan Gas Association Fellowship Research Program, 1957 to present
    - Diffusion of Gases Through Low Permeability Porous Media, NSF, 1968-1970
    - Project PESOS
    - AGA Project, "Prevention and Removal of Condensate from Natural Gas Pipelines"
    - Recovery Prospects from Michigan Reefs, LST, 1975
    - Sea Grant Research on Oil and Gas Under the Great Lakes, 1977

18a. Contract and grant proposals submitted during the year:
    - Michigan Gas Association
    - American Gas Association

19. List doctoral committees for which you were chairman or co-chairman during the past five years:

James Skinner	Diffusion and Mixing in Porous Environment
Thomas Gould	Unsteady State Two-Phase Flow

20. List specific contributions to classroom or laboratory instruction at both undergraduate and graduate levels over the past five years.
    - CM 627 - new course
    - CM 341 - new text
    - CM 341 - laboratory
    - CM 344 - laboratory
    - ChE 527 - new course - content outline and catalog description revised 1973
    - ChE 585 - Revised Graduate Course 1975
    - Energy Environment and Fossil Fuels, University of N.S.W., Australia, 1976

21. Principal publications of last five years

    (see attachment - complete list with cummulatively serialized numbers)

List of Patents of M.R. Tek

1. "Intermittent Lift of Liquid," U.S. Patent No. 2,821,931 issued February 4, 1958.
2. "Oil Recovery by In-Situ Combustion," with J.W. Marx, U.S. Patent No. 2,853,137 issued September 23, 1958.
3. "Water Flooding Method," U.S. Patent No. 2,862,556 issued December 2, 1958.
4. "Cyclone Gas Anchor," with A.F. Bertuzzi, U.S. Patent No. 2,872,985 issued February 10, 1959.
5. "Separation and Recovery of Oil from Oil Sands," with S.J. Marwil, U.S. Patent No. 2,910,424 issued October 27, 1959.
6. "Process for Recovering Hydrocarbons from Underground Formations", With A.F. Bertuzzi, U.S. Patent No. 2,946,382 issued July 26, 1960.
7. "Pipeline Transportation of a Multiple Fluid," U.S. Patent No. 2,958,333 with F.H. Poettmann, issued November 1, 1960.
8. "In-Situ Combustion Process", U.S. Patent No. 3,023,807 issued March 6, 1962.
9. "Hydrocarbon Recovery by Thermal Drive", U.S. Patent No. 3,048,222 issued August 7, 1962.
10. "Production of Heavy Crude Oil by Heating", U.S. Patent No. 3,349,846 issued October 31, 1967.

List of Books and Booklets by M. R. Tek

1. "Third Ann Arbor Industry-Education Symposium on Small Particle Research," University of Michigan, August 1958.

2. "Topics in Multiphase Flow," University of Michigan, 1960.

3. "Underground Storage of Natural Gas," University of Michigan, 1959, 1961, 1963, 1965.

4. "Handbook of Fluid Dynamics," McGraw-Hill, 1960.

5. "Movement of Underground Water in Contact with Natural Gas," American Gas Association Monograph, New York, 1963, 323 pages.

6. "New Concepts in Underground Storage," American Gas Association Monograph, New York, 1966, 342 pages.

1

7. "Production, Conservation, Pipelining, and Storage of Natural Gas," Unisearch Ltd., Sydney, Australia, 1968.

8. "Threshold Pressure in Gas Storage," American Gas Association Monograph, Arlington, Virginia, 1970, 309 pages.

9. "Problem Manual for Rate Operations," University of Michigan, Copyright 1972, 200 pages.

10. "Notes and Problems in Fluid Flow and Heat Transfer," with J. O. Wilkes, Ann Arbor, Michigan, copyright 1974.

11. "Retrograde Condensation in Natural Gas Pipelines," American Gas Association Monograph, with D. Bergman and D. L. Katz, 498 pages, 1976.

Positions Held

Test Engineer, International Electric Company 1949-1950
Research Engineer, Engineering Research Institute, University of Michigan, 1950-1953.
Research Engineer, Phillips Petroleum Company, Bartlesville, Oklahoma, 1953-1956
Research Section Manager, Phillips Petroleum Company, Bartlesville, Oklahoma, 1956-1957
Member of Faculty, University of Michigan, 1957 to date
Assistant Professor of Chemical and Metallurgical Engineering, 1957-1960
Associate Professor of Chemical and Metallurgical Engineering, 1960-1965
Professor of Chemical and Metallurgical Engineering, 1965 to date
Visiting Professor and Senior Fulbright Lecturer, University of New South Wales, Kensington, NSW, Australia, 1967
Consultant to Phillips Petroleum Company, Bartlesville, Oklahoma, 1959 to date
Consultant to Fractionation Research, Inc., 1959 to date
Consultant to Delavan Inc., Air Products Inc., Kaiser Aluminum, Natural Gas Storage Company of Illinois, Global Marine Exploration Company, Consumers Power Company, Texas Eastern Transmissions Company, Columbia Gas System Corporation, Chemstrand, Wyandotte Chemicals, Company, Ransom, Fazenbaker and Ranson, Attys., Flint, General Atomics Company, Australian Gas Light Corporation, Dudley Westgarth Pty. Ltd., Solicitors, Sydney, Department of National Development, Commonwealth of Australia, State Department of Mines, Queensland, others
Invited visiting Professor, University of New South Wales, 1975-1976

Experience in Research and Teaching

The four years spent at Phillips Petroleum Company were devoted to research in problems of crude oil and natural gas production and applications of computers to petroleum production and chemical engineering operations. The work with the University included teaching undergraduate and graduate courses in Fluid Mechanics, Petroleum Production, Heat Transfer, Rate Operations in two departments. Research work at the University included problems in Multiphase Flow, Gas Storage, Gas and Oil Production.

Experience (continued)

Project Director and Principal Investigator, AGA Research Project "New Concepts on Underground Storage"
Associate Director, Michigan Gas Association Fellowship Program
Associate Director, American Gas Association Research Project on "Movement of Water in Contact with Natural Gas"
Co-Chairman of four Intensive Summer Courses in "Storage of Natural Gas," 1959, 1961, 1963, 1965.
Chairman of Intensive Summer Course on "Multiphase Flow" 1960
Author of 52 publications including technical papers, two booklets, one translation, nine U.S. patents, and two books.
Co-author of Handbook of Fluid Dynamics, McGraw Hill
Chairman of 14 doctoral research committees, 1957 to date
Director, Intensive Course in Natural Gas Engineering, University of New South Wales, February 1968.

Business Experience

Member, Board of Directors, Travel Inc., Ann Arbor, Michigan 1962-1966
Member, Board of Directors, Ann Arbor Tennis Club
Vice President, Travel Inc., 1965-1966
Vice President, Racquet Club of Ann Arbor, 1964-1965
Member, Board of Directors, D'Agostino's Associates
Member, Board of Directors, Racquet Club of Ann Arbor
Member, Board of Directors, Barton Hills Maintenance Corp.
Member, Board of Governors, International Center, U of M, 1970
Trustee, Barton Hills Village, 1973-

Publications of M.R. Tek

1. Air Force Technical Report 6067 (with W.W. Hagerty et al), Wright Air Development Center, Wright Field, Ohio, 1953.
2. "The mechanism of Disintegration of Liquid Sheets", (with J.L. York and H.E. Stubbs), ASME Trans. 75, No. 7, 1279-88 (1953), 8 pages, 11 figures.
3. "The Stability of Liquid Free Surfaces," Ph.D. Thesis, The University of Michigan (1953), 93 pages, 8 tables, 36 figures.
4. "Method for Determining the Back-Pressure Behavior of Low Permeability Natural Gas Wells," with F.H. Poettmann and M.L. Grove, Proceedings Research Conference on Flow of Natural Gas from Reservoirs, University of Michigan, June 30-July 1, 1955; also published in AIME, Pet. Tech. Vol. IX, No. 10 (1957); Petroleum Transactions AIME: 210, 302 (1957), 8 pages, 7 figures, 1 table.
5. "Simultaneous Flow of Liquid and Gas through Horizontal Pipe," (with A.F. Bertuzzi and F.H. Poettmann), AIME, Pet. Tech. VIII No. 1; AIME Trans. 207, p. 17 (1956), 8 pages, 9 figures, 6 tables.
6. "3-Inch ID Cyclone Removes Solids from Drilling Fluids," (with W.E. Bergman, C.J. Engle and S.J. Marvill), World Oil: 142 April 5, 1956; 3 pages, 4 figures, 2 tables.
7. "Development of a Generalized Darcy Equation," AIME, Pet. Tech. IX, No. 6, 45-47 (1957); AIME Trans. 210, P. 45 (1957), 3 pages, 1 figure, 1 table.
8. "Co-current Flow of Air, Gas-Oil and Water in a Horizontal Pipe," Invited technical discussion, presented at ASME 1956 Annual Meeting, published in ASME Trans., Vol. 80, 1, p. 256 (1 page), January, 1958.
9. "Intermittent Lift of Liquid," U.S. Patent No. 2,821,931 issued February 4, 1958.
10. "The Flow of Pastes," Transcript of the Third Ann Arbor Industry Education Symposium on Small Particle Research, University of Michigan, August 1958, IP-321, pp. 183-194; 11 pages, 11 figures.
11. "Oil Recovery by In-Situ Combustion," with J.W. Marx, U.S. Patent No. 2,853,137 issued September 23, 1958.
12. "Water Flooding Method," U.S. Patent No. 2,862,556 issued December 2, 1958.
13. "Methods for Predicting Volume Variations of Gas or Oil Reservoirs Associated with Active Water Drive", with H.D. Yoo, D.L. Katz, and R.R. White. Pet. Engr. Vol. 31, No. 10, p. B27; 5 pages, 3 tables, 4 figures, 1959.

14. "Cyclone Gas Anchor," with A.F. Bertuzzi, U.S. Patent No. 2,872,985 issued February 10, 1959.

15. "Engineering applications of Relaxation Procedures by Digital Computation," (with M.E. Radd), AIChE Journal, Vol. 5, No. 1, pp. 111-115 (5 pages, 12 figures, 1 table), March 1959.

16. "Developments in Natural Gas Reservoir Engineering," published in Petroleum Engineer, Vol. 31, No. 3, pp. 1347-1349, March 1959, 3 pp.

17. "Separation and Recovery of Oil from Oil Sands," (with S.J. Marwil), U.S. Patent No. 2,910,424 issued October 27, 1959.

18. "The Effect of Unsteady State Aquifer Motion on the Size of an Adjacent Gas Storage Reservoir," (D.L. Katz and K.H. Coats), Journal of Petroleum Technology and Petroleum Transactions AIME, Vol. 216, pp. 18-22 (1959); 5 pages, 13 figures, 1 table.

19. "Unsteady State Liquid Flow through Porous Media having Elliptic Boundaries," (with K.H. Coats and D.L. Katz). Petroleum Transactions AIME, 216, p. 460 (5 pages, 3 figures, 1 table), 1959.

20. "Method for Predicting the Behavior of Mutually Interfering Gas Storage Reservoirs Adjacent to a Common Aquifer," with K.H. Coats and D.L. Katz, Petroleum Transactions AIME, 216, (1959).

21. "Underground Storage of Natural Gas," with D.L. Katz and K.H. Coats, Booklet on Intensive Course for Scientists and Engineers, University of Michigan, 1959, 1961, 1963, 1965.

22. "Process for Recovering Hydrocarbons from Underground Formations," with A.F. Bertuzzi, U.S. Patent No. 2,946,382 issued July 26, 1960.

23. "Pipeline Transportation of a Multiple Fluid," U.S. Patent No. 2,958,333 with F.H. Poettmann, issued November 1, 1960.

24. "The Calculation of Transient Response Using Analog Computer," with H.D. Yoo and D.T. Greenwood, University of Michigan Industry Program, IP-482, December 1960.

25. "Topics in Multiphase Flow," with J.L. York and A.B. Metzner, Booklet for Intensive Summer Course, University of Michigan, 1960.

26. Book Review, "Handbook of Fluid Dynamics," V.L. Streeter, Editor-in-Chief, McGraw-Hill, 1960.

27. "The Effect of Turbulence on Flow of Natural Gas through Porous Reservoirs," (with D.L. Katz and K.H. Coats), Journal of Petroleum Technology, Vol. 14, No. 7, pp. 799-807, 1962.

28. Chapter on "Two-Phase Flow" in Handbook of Fluid Dynamics (with V. Streeter, Editor-in-Chief), McGraw-Hill, New York; 100 ms pages, 17 figures, 8 tables, 1961.

29. "The Mount Simon Gas Storage Reservoir in the Herscher Field," with W. Rzepczynski, K.H. Coats, and D.L. Katz, Oil and Gas Journ., pp. 86-91, June 19, 1961.

30. "Multiphase Flow of Oil, Natural Gas and Water Through Vertical Pipe," Journal of Petroleum Technology and Transactions of AIME, Oct. 1961.

31. "Study of Gas Reservoirs Subject to Water Drive on Electronic Differential Analyzer," Society of Petroleum Engineers Journal, Vol. 1, Dec. 1961, pp. 287-297.

32. "A Theoretical Study of Pressure Distribution and Fluid Flux in Bounded Stratified Porous Systems with Cross Flow," with Marvin L. Katz, Society of Petroleum Engineers Journal, Vol. 2, March 1962, pp. 68-82.

33. "In-Situ Combustion Process," U.S. Patent No. 3,023,807 issued March 6, 1962.

34. "Hydrocarbon Recovery by Thermal Drive," U.S. Patent No. 3,048,221 issued August 7, 1962.

35. "Evaluation of Scale-up Laws for Two-Phase Flow Through Porous Media," with R.L. Nielsen, Society of Petroleum Engineers Journal, Vol. 3, June 1963, pp. 164-176.

36. "Movement of Underground Water In-Contact with Natural Gas," with Katz et.al., American Gas Association Monograph, New York, 1963, pp. 323.

37. "Developments Recents Dans Le Stockage Souterrain du Gas Naturel," with D.L. Katz, Revue de I'Institut Francais de Petrole et Annales des Combustibles Liquides, Vol. XVIII, No. 11, Nov. 1963.

38. "Unsteady State Gas Liquid Slug Flow Through Vertical Pipe," with J.R. Street, AIChE Journal 11(4), 601-607 (1965).

39. "Dynamics of Bullet Shaped Bubbles Encountered in Gas Liquid Slug Flow," with J.R. Street, AIChE Journal 11(4), 644-650 (1965).

40. "Underground Storage of Natural Gas," with D.L. Katz, booklet on Intensive Summer Course for Scientists and Engineers, University of Michigan, 1965.

41. "Nouveaux Aspects du Stockage Souterrain du Gas," Revue de I'Institut Francais du Petrole et Annales des Combustibles Liquides, Vol. XX, No. 11, 1623-1640, 1965.

42. "Computer Applications for the Petroleum Geologists," with L.N. Briggs and others, Booklet on Intensive Summer Course for Scientists and Engineers, University of Michigan, 1965.

43. "Mechanism of Entrainment formation in Distillation Columns," with D. Nielsen and J.L. York, Proceedings Int. Symp. on Two-Phase Flow, University of Exeter, Exeter, England, 1965.

44. "Pressure Drop and Void Fractions in Horizontal Two-Phase Flow Potassium," with L.R. Smith and R. Balzhiser, AIChE J. 12, No. 1, Jan. 1966.

45. "How Water Displaces Gas from Porous Media," with D.L. Katz, M.W. Legatski, R. Gorring, R.L. Nielsen, The Oil and Gas Journal, Jan. 10, 1966.

46. "New Concepts in Underground Storage of Natural Gas," with J.O. Wilkes and D.L. Katz, American Gas Association Monograph, New York, 1966, 342 pp.

47. "A Numerical Study of Waterflood Performance in a Stratified System with Cross Flow," with F.F. Craig and C. Goddin, Jour. Pet. Tech., p. 765, June 1966.

48. "Effect of Adjacent Expansible Fluids and Caprock Leakage on Build-up and Drawdown Behavior of Wells in an Aquifer," with D.L. Katz and M. Miller, Soc. of Pet. Eng. Journ., p. 431, April 1966.

49. "Production of Heavy Crude Oil by Heating," U.S. Patent No. 3,349,846 issued October 31, 1967.

50. "Production, Conservation, Pipelining and Storage of Natural Gas," with R.J. Enright, intensive course text, Unisearch Ltd., Sydney, 1968 (book).

51. "Threshold Pressure Phenomena in Porous Media," with L.K. Thomas and D.L. Katz, SOE Journal, June 1968.

52. "Recent Developments in Production Storage and Conservation of Natural Gas," The APEA Journal, 1968.

53. "Storage of Natural Gas in Saline Aquifers," with D.L. Katz. Symposium on "Saline Water-A Valuable Resource," Amer. Geophys. Union, Nat. Acad. of Scis., April 24, 1969 (in process of publication).

54. "Threshold Displacement Pressure in Gas Storage," with M.A. Ibrahim and D.L. Katz, Proceedings Transmission Conference A.G.A. Operating Section AGA X29969, paper 69-T-33, T 170, (1969).

55. "Steady and Unsteady State Lifting Performance of Gas Wells Unloading Produced or Accumulated Liquids," with T.L. Gould and D.L. Katz, SPE-2552, 44th Annual Fall Meeting of SPE, Denver, Colorado, 1970.

56. "Steady and Unsteady State Two-Phase Flow Through Vertical Flow Strings," with T.L. Gould, SPE-2804, Second Symposium on Numerical Simulation of Reservoir Performance, Dallas, Texas, Feb. 5-6, 1970.

57. "Report on Threshold Displacement Pressures for Gas Displacing Water from Caprock," with D.L. Katz and M.A. Ibrahim, AGA Gas Transmission Conference, Proceedings Gas Transmission Conference, 1971.

58. "Parametric Pulsing - A New Approach to Increased Gas Field Deliverability," with E.B. Hedges and T.L. Gould, Journal of Petroleum Technology, XXIV, January 1972, pp. 73-84.

59. "Threshold Pressure in Gas Storage", with M.A. Ibrahim and D.L. Katz, American Gas Association Monograph, Arlington, Virginia, 1970, 309 pages.

60. "Digital Simulation of Unsteady State Vertical Two-Phase Flow", T.L. Gould and M.R. Tek, Proceedings of Conference on Natural Gas Research and Technology, Sherman House, Chicago, Illinois, February 28-March 3, 1971.

61. "Diffusion of Fluids through Porous Media with Implications in Petroleum Geology", with G.N. Pandey and D.L. Katz, The American Association of Petroleum Geologists Bulletin V. 58, No. 2, February 1974, p. 291-303, 13 figures, 9 tables.

62. "Studies of Front End Threshold Pressure Measurements", with G.N. Pandey and D.L. Katz, American Gas Association Operating Section Proceedings, 73-T-17, T-112, (1973).

63. Chairman's Summary - Session IV, Natural Gas Fluid Research and Technology, Proceedings of Conference on Natural Gas Technology, AGA, IGT, 1971.

64. "Problem Manual for Rate Operations", The University of Michigan, June, 1972, 200 pages.

65. "Two-Phase Flow Through Vertical, Inclined, or Curved Pipe", with T.L. Gould and D.L. Katz, Journal of Petroleum Technology, August 1974, and Petroleum Transactions AIME, 1974.

66. "Where Reservoir Engineering Stops and Computer Technology Begins", with D.L. Katz, American Gas Association, Operating Section Proceedings, 73-T-15, T-106, (1973).

67. "Evaluation of Coal Conversion Processes to Provide Clean Fuels", Parts I and II, with D.L. Katz, D.E. Briggs, E.R. Lady, J.E. Powers, B. Williams and W.E. Lobo, Final Report Electric Power Research Institute, Palo Alto California, February 28, 1974.

68. "Limiting Performance of Gas Wells Subject to Liquid Production," with D.L. Katz, V. Mallu and R. Rykowski, Paper No. 45C, AIChE 76th National Meeting, Tulsa, Oklahoma (March 10-13, 1974).

69. "M.O.D.E. Measure of Departmental Excellence", with D.V. Ragone, M.J. Sinnott and R.L. Marrone, Engineering Education, Vol. 65, No. 4, January 1975.

70. "Synthetic Gas And Liquid Fuels from Coal", Energy Communications, September 1975.

71. Discussion of "Two-Phase Flow in Oil Wells. Prediction of Pressure Drop," by C. L. Chierici, G. M. Ciucci and G. Schlocchi, Journal of Petroleum

72. "Binary-Gas Diffusion of Methane-Nitrogen through Porous Solids," with Lillian Lung-Yu Chen and Donald L. Katz, *A.I.Ch.E. Journal*, *23*, 3, p. 336-341, 1977.

73. "Prospects for Oil and Gas from Silurean-Niagaran Trend in Michigan," University of Michigan Institute of Science and Technology, 1976 (also in publication review for the Journal of Petroleum Technology, SPE-AIME).

74. Retrograde Condensation in Natural Gas Pipelines, AGA Monograph with D. Bergman, D. L. Katz, 498 pp., 1976.

75. "Perspectives, Problems and Prospects for Energy in the Pacific," Proceedings P.A.Ch.E.C. '77 Meeting, Denver, Colorado, 1977.

76. "Prospects for a Strategic Stockpile in Natural Gas," SPE Paper 6877, Society of Petroleum Engineers Fall Meeting, Denver, Colorado, 1977.

77. "Handling Condensate in Gas Pipelines, *International Pipeline Industry*, *46*, 1, p. 45, January 1977.

BIOGRAPHICAL SKETCH OF

DONALD L. KATZ

Facts: Born near Jackson, Michigan, August 1, 1907
B.S. (Chem. Engr.) 1931; Ph.D. (Chem. Engr.) 1933, The University of Michigan
Research Engineer, Phillips Petroleum Co., Bartlesville, Oklahoma, 1933-36
Member of Faculty, The University of Michigan, 1936-date
Currently, Alfred Holmes White University Professor of Chemical Engineering
Married: L. Maxine Crull, 1932, deceased March 7, 1965
Children: Marvin L., Linda M. (Cantrell)
Married: Elizabeth Harwood Correll, November 26, 1965
Home: 2011 Washtenaw, Ann Arbor, Michigan 48104

The three years spent at the Phillips Petroleum Company in initiating a production research program set the pattern for his research interests: Phase Behavior of Hydrocarbon Systems and Reservoir Engineering. His publications, now numbering 260, were concentrated in the petroleum field, but have included such topics as heat transfer, fluid dynamics, and use of computers in engineering education. He is the author, together with former students, of several books including: Fluid Dynamics and Heat Transfer, The Handbook of Natural Gas Engineering, The Movement of Water in Contact with Natural Gas, The Underground Storage of Fluids, Retrograde Condensation in Natural Gas Pipelines, and Compressed Air Storage.

Dr. Katz is a member of nine professional and technical societies: Am. Chem. Soc., AIChE (Fellow), ASME, AIME, ASEE, AAAS (Fellow), NSPE, ANS (Fellow), and NAE. He served for six years on the Council of the AIChE, serving as president in 1959. He recieved the Hanlon Award from the Natural Gasoline Association of America in 1950. In 1959, he was named Michigan Engineer of the year. In 1961-62, he was a Distinguished Lecturer for the Society of Petroleum Engineers of the AIME, and in 1964, he received the John Franklin Carll Award from the Society. Also in 1964, he received the Founders Award from the AIChE and Distinguished Faculty Acievement Award from the University. In 1966, he was named the Alfred Holmes White University Professor of Chemical Engineering. In 1967, he received the Warren K. Lewis Award, and in 1968, the Walker Award from the American Institute of Chemical Engineers. In 1968, he was elected a member of the National Academy of Engineering. In 1970, he received the Mineral Industry's Education Award of the AIME, and in 1970, he was an honorary member of Phi Lambda Upsilon. In 1971, he was named a Fellow of the American Institute of Chemical Engineers. Also in 1971, the Donald L. Katz Lectureship in Chemical Engineering was established at the University of Michigan. In 1975, he received the E. V. Murphree Award of the Industrial and Engineering Chemistry Division of the American Chemical Society.

In the education field, he served for more than 10 years as Chairman of the Department of Chemical and Metallurgical Engineering at The University of Michigan. Forty-five doctorate students have completed their theses under his supervision. Since 1959, he has directed studies on the use of computers in engineering education supported by the Ford Foundation and NSF. The reports and literature on the project have made a national and international impact on engineering education. In 1963, he spent a semester at the University of Brazil to assist in inaugurating a graduate program.

Dr. Katz has been active as a consulting engineer, serving some 75 companies and governmental organizations during the past 40 years He is an expert in the field of petroleum technology and underground storage of natural gas.

In 1964, Dr. Katz organized a National Academy of Sciences Advisory Committee on Hazardous Materials for the United States Coast Guard and in 1964-65, chaired a subcommittee of ECPD on constitution and rules of procedure. In November 1965, he accepted the chairmanship of a task force in the Tripartite Information Syste He was a member of the CTAB Panel on Automotive Fuels and Air Pollution, 1970-71, and a member of SATCOM, 1968-70. He served as Chairm of the Council (1971-72) of EDUCOM, following a two-year term as Chairman of the Board of Trustees. He was a member of the task forc on an information system of the World Energy Conference, 1970-71. He was a member of the Science Advisory Committee of the U.S. Coast Guard from 1972-75.

In connection with Professor Katz's retirement as Chairman of the Hazardous Materials Committee after eight years of service, RADM W. F. Rea, III, Chief of the Office of Merchant Marine Safety of the U.S. Coast Guard, presented him with the Distinguished Public Service Award on behalf of the Commandant on June 13, 1972.

In his home community, he spent nine years on the Board of Education, three as its president. In 1944-45, he was president of the Ann Arbor Council of Churches and served in many positions, including chairman of the official board and lay leader of the First United Methodist Church in Ann Arbor.

In 1974 he served as a member of the Commerce Technical Advisor Board on Review of Project Independence Blueprint. Also from 1974-75 he was a chairman of NAF/NAS/NRC Committee on Air Quality and Power Plant Emissions.

Recent activities are EPA Technology Assessment and Pollution Control Advisory Committee and ERDA Panel of administrators consultants.

J.O. Wilkes - Curriculum Vitae (1977)

Name: James Oscroft Wilkes

Date of Birth: 24 January, 1932

Social Security Number: 370-44-3514

Wife's Name: Mary Ann

Citizenship: British

Address:
Department of Chemical Engineering
The University of Michigan
Ann Arbor, Michigan 48104 ('Phone (313)-764-2383)

Degrees Held (All in Chemical Engineering)

University of Cambridge: B.A., 1954; M.A., 1960.
University of Michigan: M.S., 1956; Ph.D., 1963.

Positions Held (Full Time)

University of Cambridge, Demonstrator (Assistant Professor) in Chemical Engineering, 1957-1960.
University of Michigan, Department of Chemical Engineering:
Instructor, 1960-63
Assistant Professor, 1963-66
Associate Professor, 1966-70
Professor 1970
Acting Chairman, 1971-72
Chairman, 1972

Part-Time Industrial Experience

Shell Refinery, Stanlow, Cheshire, England, 9 months, supervising Chemical Engineering Practice School, 1957-58-59.
The Dow Chemical Company, Midland, Michigan, 2 months, 1966, performing research into the flow of plastics.

Membership of Scientific and Professional Societies

SPE of AIME, AIChE, Tau Beta Pi, Sigma Xi

Industrial Consultant

The Dow Chemical Company, Midland, Michigan, 1965-72.
Michigan Consolidated Gas Company, 1970-73
Phillips Petroleum Company, 1975
Elastizell Corporation, 1975

Supervision of Ph.D. Students

Chairman or cochairman of 10 doctoral students, 1957-

Sabbatical Leave

For textbook writing and study of polymer rheology, Winter 1970.

Honors and Awards

Associate, Trinity College of Music, London, 1951
Open Scholarship to Emmanuel College, Cambridge, 1951
English-Speaking Union King George VI Memorial Fellow, 1955-56
University of Michigan Class of 1938E Distinguished Service Award, 1966
University of Michigan Distinguished Service Award, 1966
Phi Lambda Upsilon (University of Michigan Chapter) Outstanding Teacher Award, 1967
American Foundrymen's Society, Steel Division, Outstanding Paper Award, 1970

Major University of Michigan Committee Assignments

Department of Chemical Engineering: Chairman, Doctoral Standards Committee, 1970-71
North Campus Planning Committee, 1975-

College of Engineering:
Engineering Curriculum Subcommittee on Core Courses, 1966-67
Engineering Curriculum Committee, 1967-70 (Chairman, 1968-70)
Ad hoc Committee on Computer Engineering, 1970
Computer Graphics Committee, 1974
CICE Program Review Committee, 1976-77

University:
Member, Senate Assembly, 1970-73
Committee on Computer Policies and Utilization, 1967-73, (Chairman, 1970-72)
Senior Scholarships Committee, 1975-
Rackham CICE Program Review Committee, 1976-77

Miscellaneous Professional and Academic Activities

Lecturer, NSF Seminar, "Computers in Engineering Education," University of Houston, 1963 and 1964.

Cochairman, University of Michigan Engineering Two-Week Summer Conference, "Numerical Methods, Optimization Techniques, and Simulation for Engineers," held every year, 1964-77.

Leader of Workshop, "Numerical Solution of Ordinary and Partial Differential Equations," ASEE Annual Meeting, Pullman, Washington, 1966.

Consultant, ARPA Materials Research Conference, LaJolla, 1970; Woods Hole, 1971; Centerville, 1972.

Leader (with B. Carnahan) 1-week Workshop, "Numerical Methods for Chemical Engineering Problems," Chemical Engineering Division of ASEE, Boulder, 1972.

Associate Editor (for the USA), Transactions of the Institute of Chemical Engineers (London), 1973-

Co-chairman (with B. Carnahan) of two-session Symposium, "Numerical Methods in Chemical Engineering," presented at the 78th National AIChE Meeting, Salt Lake City, 19 August, 1974.

Principal Academic Interests

Numerical methods and their application to engineering problems; numerical solution of partial differential equations; flow of polymers; flow through porous media; book writing.

Publications of J.O. Wilkes

Papers

(1) "Two-Phase Flow in Vertical Tubes," (with D.J. Nicklin and J.F. Davidson), *Trans. Instn. Chem. Engrs.* (London), *40*: 61-68, 1962.

(2) "The Measurement of Velocities in Thin Films of Liquid," (with R.M. Nedderman), *Chem. Eng. Sci.*, *17*: 177-187, 1962.

(3) *The Finite Difference Computation of Natural Convection in a Rectangular Enclosure*, Ph.D. Thesis, Univ. of Michigan, 1963.

(4) "A Numerical Study of Waterflood Performance in a Stratified System with Crossflow," (with C.S. Goddin, F.F. Craig, and M.R. Tek), *Journal of Petroleum Technology*, *18*: 765-771, 1966.

(5) "The Finite-Difference Computation of Natural Convection in a Rectangular Enclosure," (with S.W. Churchill), *A.I.Ch.E. Journal*, *12*: 161-166, 1966.

(6) "Discussion of Free-Convection Heat Transfer through Enclosed Vertical Liquid Layers," technical note, *The Trend in Engineerin* Vol. 21, No. 1. p. 17, University of Washington, 1969.

(7) "The Rate of Reaction between Dilute Hydrogen Sulfide and Ozone i Air," (with J.M. Hales and J.L. York), *Atmospheric Environment*, *3*: 657-667, 1969.

(8) "In Defense of the Crank-Nicolson Method," technical note, *A.I.Ch Journal*, *16*: 501, 1970.

(9) "Axisymmetrical Normal Freezing with Convection Above," (with L.C Tien), *Proceedings of the Fourth International Heat Transfer Conference*, Versailles, 1970.

(10) "Numerical Simulation of Solidification. Part I: Low Carbon Steel Casting - "T" Shape," (with R.E. Marrone and R.D. Pehlke), *AFS Cast Metals Research Journal*, *6*:184-187, 1970.

(11) "Numerical Simulation of Solidification. Part II: Low Carbon Steel Casting - "L" Shape," (with R.E. Marrone and R.D. Pehlke), *AFS Cast Metals Research Journal*, *6*: 188-192, 1970.

(12) "Ch.E. Department - Michigan," (with other members of the faculty *Chemical Engineering Education*, *7*, 60-64, 1973.

(13) "Numerical Methods for Chemical Engineering Problems," (with B. Carnahan), *Chemical Engineering Education*, *7*, 80-83, 1973.

Publications of J.O. Wilkes (contd.)

Papers

(14) (with R.E. Marrone and R.D. Pehlke) "Numerical Simulation of Solidification of a Copper-base Alloy Casting--Flanged Barrel Shape," AFS Research Report, 1972 (abstracted in Cast Metals Research Journal, Vol. 8, No. 2, June 1972, p. 94).

(15) (with B. Carnahan) "Simulation of a General Piping and Pumping Network," Computer Programs for Chemical Engineering Education, Vol. 6 (Design), pp. 71-116, CACHE Committee, National Academy of Engineering, Washington, D.C., 1972.

(16) (with J.M. Hales and J.L. York) "The Applications of Ideal Reactors to Studies in Atmospheric Chemistry," Battelle Research Report BWWL01773, UC-11, 37 pp., Richland, Washington, 1973.

(17) (with J.M. Hales and J.L. York) "Some Recent Measurements of H_2S Oxidation Rates and Their Implications to Atmospheric Chemistry," Tellus, Vol. 26, No. 1, 1974, pp. 277-283.

(18) (with T.G. Smith) "Laminar Free-Surface Flow into a Vertical Cylinder," Computers & Fluids, Vol. 3, No. 1. pp. 51-68, 1975.

Publications of J.O. Wilkes (contd)

Books

(1) Applied Numerical Methods, (with B. Carnahan and H.A. Luther), 2 vols, prelim ed., viii + 781 pp., Wiley, New York, 1964.

(2) New Concepts in Underground Storage of Natural Gas, (with M.R. Tek et al.), x + 342 pp., American Gas Association, New York, 196

(3) Introduction to Digital Computing and FORTRAN IV with MTS Applications, (with B. Carnahan), x + 250 pp., published by the autho Ann Arbor, Michigan, 1968.

(4) Introduction to Algorithms and Numerical Methods, (with B. Carnahan), vi + 260 pp., published by the authors, Ann Arbor, Michigan 1969.

(5) Applied Numerical Methods, (with B. Carnahan and H.A. Luther), xvii + 604 pp., Wiley, New York, 1969.

(6) Introduction to Digital Computing and FORTRAN IV with MTS Applications, (with B. Carnahan), x + 342 pp., published by the author Ann Arbor, Michigan, revised edition, 1971.

(7) Digital Computing, FORTRAN-IV, WATFIV, and MTS, (with B. Carnahan published by the authors, Ann Arbor, Michigan, 1972, x + 470 pp.

(8) Digital Computing and Numerical Methods with FORTRAN-IV, WATFOR, and WATFIV Programming, (with B. Carnahan), xi + 477 pp., Wiley, New York, 1973.

(9) Digital Computing, FORTRAN-IV, WATFIV, and MTS, (with B. Carnahan) published by the authors, Ann Arbor, Michigan, 1973, x + 493 pp.

(10) Notes and Problems in FLUID FLOW and HEAT TRANSFER, (with M. Rasin Tek), published by the Department of Chemical Engineering, The University of Michigan, Ann Arbor, Michigan, 1974, vii + 232.

(11) "Simulation of a General Piping and Pumping Network," (with B. Carnahan), Ch. 4, Computer Programs for Chemical Engineering Education: Design, ed. R. Jelinek, Axtec Publishing Company, Austin, Texas, 1974, pp. 71-116.

(12) Digital Computing, FORTRAN-IV, WATFIV, and MTS, (with B. Carnaha published by the authors, Ann Arbor, Michigan, 1976, vi + 500 pp

APPENDIX IV

GRADUATE STUDIES IN CHEMICAL ENGINEERING (1976 - 1977)

CONTENTS

ACADEMIC CALENDAR

The University of Michigan

Fall Term, 1976

Labor Day (Holiday)	Sept. 6, Mon.
Registration	Sept. 8-9, Wed.-Thurs.
Classes begin	Sept. 10, Fri.
Thanksgiving Recess begins (5:00 p.m.)	Nov. 24, Wed.
Classes resume	Nov. 29, Mon.
Classes end	Dec. 13, Mon.
Study Days	Dec. 14-16, Tues.-Thurs.
Examination Period	Dec. 17-18, 20-23, Fri.-Sat, Mon.-Thurs.
Commencement	Dec. 19, Sun.

Winter Term, 1977

Registration	Jan. 5-6, Wed.-Thurs.
Classes begin	Jan. 7, Fri.
Spring Recess (Vacation) begins	Mar. 5, Sat.
Classes resume	Mar. 14, Mon.
Classes end	Apr. 19, Tues.
Study Days	Apr. 20-22, Wed.-Fri.
Examination Period	Apr. 23, 25-29, Sat, Mon.-Fri.
Commencement	Apr. 30, Sat.

Spring-Summer Term, 1977

Registration (Full Term & Spring Half)	May 2-3, Mon.-Tues.
Classes begin	May 4, Wed.
Memorial Day (Holiday)	May 30, Mon.
Classes end (Spring Half Term)	June 21, Tues.
Study Day	June 22, Wed.
Examinations (Spring Half Term)	June 23-24, Thurs.-Fri.
Spring Half Term end	June 24, Fri.
Summer Half Term Registration	June 27-28, Mon.-Tues.
Summer Half Term classes begin	June 29, Wed.
July 4th (Holiday)	July 4, Mon.
Classes end	Aug. 17, Wed.
Study Day	Aug. 18, Thurs.
Examinations (Full & Summer Half Term)	Aug. 19-20, Fri.-Sat.
Full Term and Summer Half Term end	Aug. 20, Sat.
Commencement	Aug. 21, Sun.

THE UNIVERSITY OF MICHIGAN

The University of Michigan is part of the public educational system of the State. The governing body is a Board of Regents, elected by popular vote for terms of eight years, as provided in the State Constitution. The University has grown from a school founded in 1817, and acquired its present name and campus in Ann Arbor in 1837, the year Michigan became a state. Enrollment in 1975-76 was over 35,000 students in Ann Arbor, with several thousand more in University branches at other locations in the State.

The University operates continuously with three terms of equal length. As shown in the Academic Calendar (opposite), the fall term (Term I) begins shortly after Labor Day in early September; the winter term (Term II) begins shortly after New Year's Day; and the spring-summer term (Term III) begins in early May. Summer courses are offered for a full 16 week term, ending in August; others may be taken during two 8-week accelerated sessions, one during May and June, and one during July and August.

Students studying toward the master's, professional or doctor's degree are enrolled in the Horace H. Rackham School of Graduate Studies. Admissions, course enrollment, graduate requirements, and degrees are officially administered by the Dean of the Graduate School and his staff. However, graduate students have most of their university affairs handled at the working level by members of the department teaching staff, organized as a Graduate Committee, and Special Doctoral Committees.

THE DEPARTMENT OF CHEMICAL ENGINEERING

Chemical Engineering was inaugurated at The University of Michigan in 1897 with the appointment of A. H. White as Instructor of Chemical Technology. The following year Michigan offered a course of study leading to the B.S.E. degree in chemical engineering. Professor E. D. Campbell directed the program and the first class graduated in 1903 with five members. The program grew rapidly. In 1914, 33 B.S.E. and 4 Ph.D. degrees were granted. That year the Department of Chemical and Metallurgical Engineering was organized with A. H. White as chairman; for almost 30 years he guided the department to a position of national and international recognition. At his retirement in 1943, there were 20 full-time faculty members and over 300 students in the Department.

Professor G. G. Brown succeeded Professor White and served as chairman until 1951, when he became Dean of the College of Engineering. He was followed by D. L. Katz, who served until 1962, when he asked to be relieved of the duties of chairman. S. W. Churchill then acted as chairman until 1967, when he left The University of Michigan faculty. Thereafter, L. H. Van Vlack served as chairman until early in 1970 when the Department of Chemical and Metallurgical Engineering split into two divisions, which became separate departments in July 1971. Professor Van Vlack continued as chairman of the new Materials and

Metallurgical Engineering Department and R. E. Balzhiser became the first chairman of the Chemical Engineering Division and subsequently chairman of the Chemical Engineering Department. Professor Balzhiser went on leave in the Fall of 1971 to serve in Washington as the Assistant Director of the Office of Science and Technology. Professor J. O. Wilkes became acting chairman in 1971 and chairman in 1972.

The Chemical Engineering Department currently has 19 faculty members and about 250 undergraduate and 70 graduate students.

Since its inception, the Department has awarded over 400 Ph.D. degrees. More than 100 of these degree recipients have taken positions in the academic community. Graduates have been very active in professional societies, such as the A.I.Ch.E. Seven of the last eighteen presidents of the A.I.Ch.E. earned graduate degrees from The University of Michigan, and two past presidents are on the Department's present faculty.

Considerable change has occurred in the department during the past decade. Most significantly, about half of the present faculty have been appointed within that period. Thus, although the department has strong roots in the past, its composition and outlook have kept abreast of the times with research and teaching in rate and transport phenomena, process control and optimization, interdisciplinary work on biological and geological systems, recovery and reuse of natural resources, pollution control and more.

CHEMICAL ENGINEERING GRADUATE STUDIES

Individual graduate programs in Chemical Engineering are administered by the Graduate Committee and its sub-committees. At the Ph.D. level, a special Doctoral committee for each student supervises thesis research and conducts the final Oral Examination.

Graduate Committee

Members: Professors Carnahan (Chairman), Curl, Hand, and Young.

The Graduate Committee administers all policies that concern graduate students. The Committee makes recommendations for admission to the Graduate School, counsels students as to course elections, recommends candidates for the Master's Degree, and supervises all Professional and Doctoral program examinations (except the final oral defense of the thesis).

The graduate programs are flexible enough to satisfy the differing needs of individual students. The major responsibility for planning the specific content of the academic program rests with the student. Each student reviews his record and intended program with a graduate counselor during the registration period for each term, and a course of studies is jointly agreed upon. This course selection is completed before registration or payment of fees (course descriptions are shown on pages 35-38). Students may consult with appropriate members of the Committee at any other time during the term.

During the term in which a student expects to receive a Master's Degree, his graduate record is reviewed by the Graduate Committee; if the record is satisfactory, the Committee then recommends that the M.S.E. degree be granted.

Many students desire to pursue graduate work without specializing while others have an interest in a particular subject or industry. In most areas of specialization the student can take a full doctorate program. At the Master's level, the essential course material in an area of specialization can invariably be completed in a two and one-half term schedule; the Professional Degree program permits additional study in many areas. In addition to departmental courses, a wide selection of courses is available in other departments of the University. Graduate students are encouraged to take as many of these as their schedules and chemical engineering program requirements will allow.

GRADUATE ADMISSION

Admission and financial assistance applications can be obtained by writing to:

Graduate Office
Chemical Engineering Department
The University of Michigan
2020A East Engineering Building
Ann Arbor, Michigan 48104

Applications and supporting credentials should be returned to the above office as early as possible, but no later than July 1 for the fall term. Applicants seeking financial aid should return all forms prior to February 1.

A nonrefundable application fee of fifteen dollars ($15.00) must be submitted with each application for admission to the Graduate School. Admitted students are required to pay a $50.00 advance deposit by May 1, or three weeks from the date on which they receive notification of this fee requirement. This deposit is credited toward the first tuition payment, but is nonrefundable if the student fails to enroll.

ACADEMIC PROGRAMS

The Master's Degree

The master's degree program is intended to extend the student's knowledge and experience in selected areas, to relate the many different aspects of engineering activity in a useful way, and to perfect his ability to apply modern computational and analytical procedures to complex problems.

The program is based upon prior preparation equivalent to the Bachelor's Degree from the University. At least 30 credit hours of graduate coursework must be completed with an average course grade of B or above. At least 21 of the 30 hours must be in the Chemical Engineering program, and two graduate courses must be elected from other departments.

A master's thesis is not required, but research activity may be used to fulfill up to six of the required 30 credit hours by registration in the research course, ChE 695. Such research may be part of an existing program in a specific interest area of a faculty member, or it may be exploratory work preceding more comprehensive research for a doctoral dissertation. In any case, it must be reported each term in written and oral form.

The Chemical Engineering M.S.E. degree requires election of at least one course from each of the following groups (see page 35 for course descriptions):

Kinetics, catalysis, and thermodynamics	ChE 525, 528, 537, 538, 555, 629*
Transport and separations	ChE 526, 527, 529, 547, 625
Design	ChE 857, 585 + 2 hr 698**, 687
Research survey	ChE 595

In addition, the department offers specialized elective groupings as follows:

Applied mathematics and computation	ChE 407, 507, 508, 509
Biochemical engineering	ChE 417, 434, 516
Electrochemical processes	ChE 548, 573
Enviromental engineering	ChE 446, 449
Optimization and control	ChE 566, 588
Polymers	ChE 451, 452, 511, 751

The master's degree is usually completed by a full-time student in two and one-half terms (10 months). Students can earn two master's degrees in different fields, such as chemical engineering and mathematics, or nuclear engineering, or information and control engineering, but the requirements of both programs must be met fully; in such cases, the total number of hours required is the sum of the credit-hour requirements of both degrees. A combined master's degree in chemical engineering and another field can also be established, and usually requires a total of 40 to 45 credit hours of graduate coursework.

* requires ChE 528 or equivalent as a prerequisite
**a design project

The Professional ("Chemical Engineer") Degree

The Professional Degree program provides an opportunity for study beyond the Master's degree in either an area of specialization or a broad range of topics. It leads to the degree of CHEMICAL ENGINEER. The Program requires a minimum of 30 credit hours of work beyond the Master's degree, successful performance on the Qualifying Examination for the Doctoral program (see below), election of a Chemical Engineering seminar course, and at least 6 credit-hours of work on a research, design or development problem, including a written report. A committee of faculty members will supervise the work, approve the report, and conduct a final oral examination.

Other course requirements include at least 24 hours in Chemical Engineering, at least three cognate courses in fields other than mathematics, and at least 9 credit hours in graduate level mathematics study.

The Professional program, in effect, substitutes additional course work and the professional problem for the dissertation required in a doctoral program. It should be attainable in less than two years beyond the M.S.E. degree for a student making normal progress.

The Doctor's Degree

The award of the doctorate in engineering signifies the attainment of knowledge in depth in a specific field, the contribution of original work in that field, and a broad understanding of engineering and associated subject areas.

The doctoral program may be entered either after attainment of the B. S. degree or completion of the M.S.E. degree in Chemical Engineering. Incoming graduate students who have strong research interests and who are seeking the doctorate should enroll directly in the Ph.D. program.

The Doctor's degree requirements include a minimum of 33 hours of graduate coursework beyond the B.S.E., completed with an average course grade of B or better. At least 24 of these 33 hours must be in chemical engineering subjects, including the research survey course (ChE 595), and the doctoral seminar course (ChE 895). Up to six hours of research coursework (ChE 695) may be applied toward the 33 hour total. Additional requirements include a reading competence in one foreign language (normally French, German, or Russian), and a dissertation presenting the results of original and significant research.

Progress toward the degree is measured by a series of two examinations, in addition to the usual academic criteria.

(1) A written Doctoral Qualifying Examination is given early in the Fall and Winter terms. This examination, which must be passed for acceptance into the doctoral program, is based upon undergraduate preparation in chemical engineering fundamentals. The student must take the examination at the first opportunity, and is given two chances to pass the examination.

(2) In the second or third term, a Preliminary Examination consisting of a written and oral defense of a research proposal is given to ascertain the student's ability to assimilate relevant past work and to synthesize a research objective and methodology. Normally, the research proposal would be in an area closely related to the anticipated dissertation research project, although any significant chemical engineering research topic may serve as the basis for the examination. The student is normally allowed one opportunity to pass the examination.

The required coursework is normally taken over a three or four term period, so that the student can begin research work early in his or her program of study. A doctoral dissertation topic may be chosen at any time after passing the Doctoral Qualifying Examination. Once the topic is approved by the departmental staff, a dissertation committee is formed to supervise the student's research work (the research advisor serves as the chairman of the dissertation committee).

When all degree requirements except for those associated with the dissertation research have been completed, the student becomes a candidate for the doctoral degree. Candidacy is usually achieved within two years of entry into the program for a student making normal progress. During the post-candidacy period, students may enroll in advanced-level courses, particularly those covering topics related to the dissertation research (the dissertation committee may require such enrollment, when the course material has significant impact in the area of the dissertation work). Normally, no more than one such course would be elected per term.

A typical pattern of progress toward the doctorate involves:

(1) taking and passing the Doctoral Qualifying Examination during the first semester;
(2) election of 33 hours of coursework over a four-term period (about three courses per term);
(3) election of research coursework (ChE 695) during the first two and one-half terms; this activity should allow the student to begin investigation into the area of the likely dissertation (an early decision concerning the probable area for dissertation research will usually shorten the time required to complete the degree);
(4) passing the Preliminary Examination during the third term (the exam will usually be based on the research accomplishment of the first two and one-half terms and a research proposal for further work);
(5) preparation and acceptance of the dissertation research proposal; this can occur at any time, but will usually happen during the third term for a student entering with a B.S.E. degree;
(6) demonstrating a reading knowledge of one foreign language before the end of the fourth term;
(7) achieving candidacy by the end of the fourth term (i.e., completion of all degree requirements except for the dissertation);
(8) completion of the research work; during this period of one to two years, the student may also take some advanced-level coursework;
(9) preparation of the dissertation;
(10) passing the final oral examination.

The recent restructuring of the doctoral program allows a Ph.D. student to make a very early start on the research work. With normal progress, all degree requirements should be completed within three to four years after the B.S.E. degree.

Students entering the Ph.D. program who have already earned the M.S.E. degree in Chemical Engineering, will normally have satisfied the precandidacy minimum course requirements for the doctorate, with the exception of the research survey course (ChE 595) and the doctoral seminar course (ChE 895), provided that the student's M.S.E. program includes at least 24 credit hours of graduate chemical engineering coursework. Such students must make early decisions regarding their research interests and the dissertation topic.

ChE 695

The principal vehicle for research work by the student during the first year is the research "course", ChE 695, giving an opportunity for a student to work with an individual faculty member on a research topic of mutual interest.

ChE 695 may be elected for one, two, or three hours per term. The student is expected to spend about three hours per week on the project for each credit hour elected. A work plan is arranged at the beginning of the ChE 695 project by agreement between the student and the supervising faculty member. For many M. S. students who elect the research course and for most students in the Ph.D. program, the work plan will involve study over more than one term.

At the end of the planned period for the research (one, two, or two and one-half terms) the student must prepare a written report on his work. An oral examination on the report will be conducted by a committee of three faculty members.

The Doctoral Qualifying Examination

A Doctoral Qualifying Examination (DQE), given early in the Fall and Winter terms, must be passed for acceptance into the doctoral program. This six-hour written examination is based on undergraduate preparation in chemical engineering fundamentals. Students will be examined in subjects such as fluid mechanics, heat transfer, kinetics, mass transfer, separations, stoichiometry, and thermodynamics. The student must take the examination at the first opportunity after entering the degree program (those entering with B.S. degrees not in chemical engineering will normally be excused from this requirement until completion of any undergraduate chemical engineering courses specified by the graduate advisor). The student is allowed two opportunities to pass the examination.

The Preliminary Examination

The Preliminary Examination consists of an oral defense of a written research proposal, and is given to ascertain the student's ability to assimilate relevant past work in an area and to synthesize a research objective and methodology. Any significant chemical engineering research topic may serve as the basis for the examination, which is conducted by a committee of three faculty members, including the Chairman of the Doctoral Standards Committee. The student is normally allowed one opportunity to pass the examination.

In many cases, the research work carried out as a six credit-hour ChE 695 project taken over a two and one-half term period will serve as the basis for the research proposal. In such cases, if the student chooses, the research results can be presented as part of the written report for the preliminary examination. The oral preliminary examination will then cover both the ChE 695 work and the proposal for further work in the same area. In this case, the examination committee makes the final decision on whether the student has (a) passed or failed the preliminary examination, and (b) passed or failed the ChE 695 oral examination.

FEES AND EXPENSES

The tuition per term for full-time (eight hours or more) graduate students is $1,650 for non-residents* and $636 for Michigan residents. A full-time student who is working on his dissertation and has been admitted to Candidacy (in essence, candidacy implies that all requirements for the degree, except for the dissertation, have been met--see the Rackham Graduate School catalog for details) has a special candidacy enrollment, and qualifies for reduced fees of $390 per term.

Living expenses in Ann Arbor, as elsewhere, depend greatly on individual requirements and tastes. Two hundred and fifty dollars a month is near the minimum. The estimated range for unmarried Chemical Engineering graduate students is $260 to $380 per month. The similar range for couples without children is close to $430 to $680 per month.

HOUSING

Most graduate students at The University of Michigan live in apartments, although graduate dormitories are available for single students. The University also operates a married-student housing facility on the North Campus, from which there is excellent free bus service to the Main Campus. For information about housing, please write to:

Housing Information Office
1011 Student Activities Building
The University of Michigan
Ann Arbor, Michigan 48104

In off-campus housing, a single student sharing a furnished apartment can expect to pay between $70 and $130 per month, depending upon the number sharing. Married students can expect to pay from $160 to $190 per month for a one bedroom, unfurnished apartment, up to two to four miles from the campus. Twelve month leases are common, although ten month leases are also available. Housing outside Ann Arbor is generally considerably cheaper, but then one faces additional transportation costs and the problem of parking near the campus. The best time to look for an apartment for the fall term is before July 15, although housing can be found at any time of the year. Additional information about off-campus housing _in Ann Arbor_ may be obtained also from the above address. Copies of the _Michigan Daily_ and the _Ann Arbor News_ also contain long "For Rent" columns.

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*After one year of residence in Michigan, the out-of-state student can apply for reclassification as a Michigan resident (see the Rackham Graduate School Bulletin for criteria).

GRADUATE FINANCIAL ASSISTANCE

Financial assistance for first year students is usually in the form of a fellowship; some first year research assistantships are also available. Applications for financial support are available from the Chemical Engineering Graduate Office. This application and supporting material should be returned as early as possible.

Consideration of applications for assistance for the fall term continues through March. It is sometimes possible to make awards to those applying after February 1, but one's chances are enhanced by early submission of all material. Fellowship offers are transmitted to applicants in mid-March; the recipient has until April 15 to make a final decision on an offer. Support in the form of research assistantships, teaching assistantships, Rackham fellowships, and major loans may be arranged on an individual basis earlier or later in the year, but the financial application should still be submitted as early as possible.

Fellowships are tax-free grants and pay the resident or non-resident tuition plus monthly stipends. Fellowship recipients may supplement their stipends by working on a contract research project with permission from the Graduate Committee.

Graduate student teaching assistants assist the departmental faculty in instruction in laboratory courses and in recitation sections in other undergraduate courses. Appointments are made either for the academic year (eight months) or for a single term, and involve from 10 to 20 hours of effort per week. A "full time" or 100 percent appointment as a graduate student teaching assistant carries a current minimum stipend of $8,224 for the eight-month academic year. However, since most such appointments are for 25 to 50 percent of full time effort, the actual payment is scaled down accordingly. Those appointed to such assistantships carry a reduced course load (the minimum load is six credit hours), and are normally selected from the more advanced graduate students. In all cases, recipients will qualify for resident tuition.

Graduate student research assistants are employed on sponsored research projects which are supervised by departmental faculty members. Most such students work on an hourly basis (a few have salaried appointments) and enroll for a reduced academic program. Salary levels are comparable to those for graduate student teaching assistants. In general, the student research assistant may divide his time as he chooses, depending upon his financial needs and his desire to progress on his academic program. The stipend for a graduate student research assistant who is working on his dissertation research topic may qualify as non-taxable income.

In addition, there is a significant amount of financial support available to both undergraduate and graduate students who assist the faculty in grading papers, preparing problems for assignment in courses, maintaining laboratory equipment and course-related computer programs, etc. These "student assistants" are usually appointed one term at a time; hourly rates vary from $2.65 to $4.25 for graduate students. First year graduate students are eligible for these appointments.

INDUSTRIAL SUPPORT

The Chemical Engineering Department gratefully acknowledges receipt of direct financial aid during the period 1974-1976 from the following organizations:

AIR PRODUCTS COMPANY
AMERICAN GAS ASSOCIATION
AMOCO FOUNDATION, INC.
ATLANTIC RICHFIELD COMPANY
BABCOCK AND WILCOX, INC.
CONTINENTAL OIL COMPANY
DIAMOND SHAMROCK CORPORATION†
DOW CHEMICAL COMPANY
E. I. du PONT de NEMOURS & COMPANY
EL PASO NATURAL GAS COMPANY†
EXXON EDUCATIONAL FOUNDATION
GULF OIL CORPORATION
MARATHON OIL COMPANY†
MICHIGAN GAS ASSOCIATION
MONSANTO COMPANY
NATIONAL SCIENCE FOUNDATION
OLIN CORPORATION†
THE PROCTER AND GAMBLE COMPANY
  (Charmin Paper Products)
THE 3M COMPANY
ROCKEFELLER FOUNDATION
ROCKWELL INTERNATIONAL
SHELL COMPANIES FOUNDATION
STANDARD OIL COMPANY OF CALIFORNIA†
STAUFFER CHEMICAL COMPANY†
TEXACO INCORPORATED
UNIVERSAL OIL PRODUCTS FOUNDATION†

The following organizations have also provided direct financial assistance to the department in previous recent years:

CHEVRON RESEARCH COMPANY
EASTMAN KODAK COMPANY
GENERAL MOTORS CORPORATION
MICHIGAN CONSOLIDATED GAS COMPANY

To the above and to all others who have assisted our department and its students, we offer our thanks.

J. O. Wilkes, Chairman

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† (restricted to undergraduate program)

STUDENT-FACULTY ACTIVITIES AND COLLOQUIA

The faculty believe that acquaintance with the students should extend well beyond the classroom. During the first week of the fall term graduate students and faculty and their spouses or friends get together in the informal atmosphere of the graduate picnic dinner. As virtually all graduate students and faculty attend, this is an excellent opportunity for a new student to meet his fellow students and the departmental staff and faculty.

Although there are no automatic appointments of students to the various departmental faculty committees, graduate students have participated very actively in all review committees concerning the graduate program. The recent major changes in the graduate program requirements and course offerings reflect strong graduate student influence in these committees. Graduate students are welcome and encouraged to attend departmental faculty meetings.

The student chapter of the American Institute of Chemical Engineers (the University of Michigan chapter was founded in 1922 and was the first such student group to be formed in the country) sponsors a weekly luncheon for both students and faculty that features guest speakers or movies on a variety of technical and nontechnical topics.

The department sponsors colloquia at which eminent engineers from both industry and academia discuss their recent research activities. The program for 1975-1976 is shown below.

1975-1976 COLLOGUIM PROGRAM

1. "Design Techniques and the Mechanics of Mass Transfer for Packed Beds. . ."

   Mr. John S. Eckert, P. E.
   The Norton Company

2. "Nonlinear and Transient Effects in Polymer Rheology and Processing"

   Dr. Charles Goldstein
   Whirlpool Corp., Benton Harbor, Michigan

3. "Order - Disorder Transitions in Uniform Colloids"

   Professor I. M. Krieger
   Department of Chemistry
   Case-Western Reserve University

4. "Separation of Solids from Liquefied Coal"

   B. R. Rodgers
   Oak Ridge National Laboratory

5. "The Hemolysis Mystery: Clues to Blood Damage in Shear Flow"

   Professor M. C. Williams
   University of California, Berkeley

6. "Superheated Liquids--A Laboratory Curiosity and an Industrial Curse"

   Professor Robert C. Reid
   Massachusetts Institute of Technology

7. "Catalytic Treatment of Nitric Oxide in the Exhaust. . .Evolution Towards Practical Implementation"

   Dr. Mordecai Shelef
   Research Staff, Ford Motor Company

8. "Ignition and Burning of Solids"

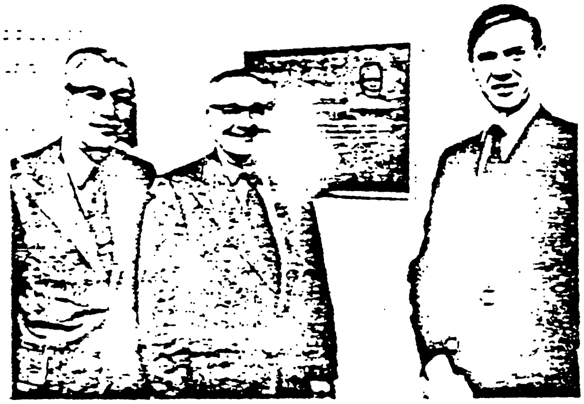
   Professor C. M. Sliepcevich
   University of Oklahoma

   Donald L. Katz Lectureship

9. "Reinforced Polymer Systems--Modeling the Reaction between M_gO and Unsaturated Polyester Resins"

   Professor K. S. Gandhi
   Department of Chemical Engineering
   Indian Institute of Technology, Kanpur

Professor Cedomir M. Sliepcevich (center) of the University of Oklahoma was the 1976 Katz Lecturer. The Katz Lectureship, in honor of Donald A. Katz, A. H. White University Professor (left) is awarded annually to a chemical engineer of outstanding research ability. Department Chairman J. O. Wilkes (right) looks on.



Mr. James Goodwin, a Ph.D. student in the department, is studying the catalytic activity of iron in nitrogen fixation using Mössbauer Spectroscopy.

FACILITIES AND RESEARCH

The following short account summarizes some of the facilities that are available in the Department for research, at both the M. S. and Ph.D. levels, and some of the present activities of students and faculty.

Biochemical Engineering

The Biochemical Engineering Laboratory, supervised by Professors L. L. Kempe, J. S. Schultz and F. G. Bader, includes facilities for biochemical, microbiological, and physiological research such as constant-temperature rooms, walk-in cold room and freezer, sterilization equipment, automatic analyzers, spectrophotometers, refractometers, chromatographs, Coulter Counter, infusion pumps, radioisotope counters, microscopes, and fermentation and continuous culture equipment.

A new laboratory facility, located in the Water Resources Building, was added during the Winter Term of 1975. It is specifically designed for teaching Microbiology for engineers, and is well equipped for studying applied microbiology; three small research labs are also included in the facility.

Osmosis and diffusion in membranes, with respect to defined microporous structures, has been a special interest of Professor Schultz. He is also involved in studies on facilitated diffusion mechanisms in membranes, and oxygen transport in tissue. He is leading a joint project with the Medical School on the thrombogenicity of biomaterials in contact with blood. Prof. Kempe has been concerned with subjects as diverse as lampricide degradation in natural systems, the ecology of the Great Lakes, botulism, and short-time high-temperature food sterilization. Prof. Bader is currently studying microbial and enzyme kinetics and microbial population dynamics.

In cooperation with faculties of the Materials and Metallurgical Engineering Department and the Medical and Dental Schools, Professor J. H. Hand has been studying the development of biomaterials or materials of construction that are compatible with living organisms, including the human body. New, interpenetrating network composites for construction of implantable hip and knee joints are being investigated. Modified acrylic bone cements are also being formulated.

Also, in the "bio" area, Professor R. H. Kadlec has been guiding an extensive program, in cooperation with the School of Natural Resources, on the modeling of a Marsh Ecosystem. The object is to simulate, on the computer, the (unsteady state) interaction of the most important organisms, nutrients, and water in a marsh into which secondarily treated sewage is being introduced. Important parameters for the simulation are being developed cooperatively with students and faculty in the Natural Resources Department from data on an existing marsh in northern Michigan.

Computation and Simulation

The University provides a Central Computing Center for research and instruction using an Amdahl 470V/6 computer (comparable to the IBM 370/168, but with greater speed and capacity), located on the North Campus, and a complete remote batch input/output substation on the Main Campus near the East Engineering Building. The computing system is run by a powerful and user-oriented operating system which processes both batch and timesharing jobs in multiprogramming mode (up to 150 simultaneous users). Teletypewriter-like terminals and keypunches are scattered throughout the Engineering College and University to allow rapid student access to the computing facilities.

A highly interactive modular program for simulating the unsteady-state behavior of chemical processing systems called DYSCO (DYnamic Simulation and COntrol Program) has recently been developed under the direction of Professors Carnahan and Briggs, and is now available for student and industrial use. Professor Carnahan is also directing development of an interactive graphical system for creating process flowsheets, automatic simulation of the steady-state behavior of the system on the University's central computer, and graphical display of the results. DEC 339 processors, as well as College-owned storage tube displays and digital plotters form part of the equipment complement used by the system. The Marsh Ecosystem modeling described above is also heavily dependent upon Computer facilities, as has been the direct-data (analog-digital) reduction work in the liquid dispersions research of Professor R. L. Curl.

A PDP-8I digital computer with an executive system for "real-time" computing is available in the Chemical Engineering Operations Laboratory. Students can connect experiments to the computer through a patchboard to log data and to control experimental apparatus. A real-time computing laboratory involving the PDP-8I minicomputer and new microprocessors is currently being developed under the direction of Prof. Carnahan.

Design

The two computer-aided process analysis efforts described above are, of course, aimed at improving and speeding up the chemical process design process. The graduate process design course makes use of two process design/simulation programs, PACER, a university-developed system, and FLOWTRAN, a full-scale commercial simulator developed by the Monsanto Company.

Education

Educational innovation has always been a trademark of the Department. The Department is involved in the activities of the CACHE (Computer Aids for Chemical Engineering Education) Committee of the National Academy of Engineering through Professors Carnahan and Fogler who are current members of CACHE. A general computer-use course for the whole University is taught by Prof. Carnahan, and a departmental graduate course in numerical methods is based on the widely-used text, Applied Numerical Methods (Wiley, 1969) by Professors Carnahan, Luther (of Texas A&M University) and Wilkes. Professors Carnahan and Wilkes have also written another text, Digital Computing and Numerical Methods (Wiley, 1973), intended for undergraduate students.

Other recent textbooks written by faculty members include Notes and Problems in Fluid Flow and Heat Transfer by Professors Tek and Wilkes (published by the Department, 1974), and Foundations of Thermodynamic Analysis (Aztec Publishing, 1973) by Professors Powers, Sleipcevich (of the University of Oklahoma), and Ewbank (of the University of Oklahoma).

Professor Fogler's new text, The Elements of Chemical Kinetics and Reactor Calculations (Prentice Hall, 1974), uses a programmed learning approach to the subject. He has been a leader in introducing new educational techniques in the Engineering College, including the use of interactive computer graphics for technical instruction and testing.

Polymers

Professor G.S.Y. Yeh links the Chemical Engineering Department, the Materials and Metallurgical Engineering Department, and the Macromolecular Research Institute in the Graduate School, in an extensive program of research and development of polymeric substances. Facilities are available for electron microscopy (both scanning and transmission) infrared spectrometry, high-angle X-ray diffraction, measurements of heat of solution and fusion, dynamic viscosity and light scattering, mechanical testing, dielectric and density measurements. Current research is directed toward understanding processing of transparent semi-crystalline polymers, glassy carbons, structure-property relationships, deformation behavior and effects of radiation on polymers.

Polymer reactions and applications are also under study. Their use in improving boiling heat transfer is being studied by Professor Hand. The kinetics of monomer polymerizations are studied by Professor G. Parravano in a specially designed Ziegler-Natta polymerization facility.

Rate Processes

The triumvirate of momentum, heat and mass transport receive considerable attention in the department.

The rheological properties of solutions of polymers and suspensions of particles are under study by students of Prof. Goddard (now of the Chemical Engineering Department at The University of Southern California). Equipment includes an R-16 Weissenberg Rheogoniometer and other viscometric apparatus. Facilities have been developed to measure rheooptical properties of fluids, such as shearing and spinning birefringence. Rheological properties of molten polymers are also being studied in cooperation with other laboratories. Polymers are also involved in the drag-reduction studies of Professor Hand, mentioned earlier.

Bubble collapse and jet impingement have received detailed study using high-speed cameras available from the Mechanical and Aerospace Departments. Work in this area has been guided by Professor Hammit (Mechanical Engineering) and Professor Williams.

Hydrodynamics and Mass Transfer also interact in studies of ultrasonically induced gas absorption, defoaming and cavitation being guided by Professor Fogler. Professor Fogler also is applying ultrasonics to creating dispersions and affecting the rate of homogeneous and heterogeneous chemical reactions. The Sonochemical Engineering Laboratory is equipped with ultrasonic generators and associated instruments.

Liquid-liquid dispersions have been under study by Professor Curl, using a system that creates a dispersion by stirring and samples the dispersion to determine drop sizes and the concentration of a tracer. The system is unique in providing an automated data gathering mode that measures individual drop size and concentration at a high rate, and records the data on analog tape for subsequent computer processing after digitizing.

Mass transfer and chemical reactions interact in a variety of studies. Professor Schultz has been studying diffusion with reaction in membranes, with particular application to biological systems. Similar simultaneous diffusion and reaction processes lead to regime-transition phenomena in the precipitation and dissolution of calcite in carbonic acid, under study by Professor Curl, while the dissolution of various porous media, rocks in particular, with acids (related to the acidization of petroleum oil wells) is involved in a project under the guidance of Professor Fogler.

Professor F. M. Donahue, an electrochemical engineer, has been looking into a variety of coupled transport systems involving electrochemical kinetics. This pertains to both transport at electrodes and electrochemical reactors.

Mass and heat transfer studies have involved systems as diverse as evaporating droplets containing solutes (being guided by Professors Briggs and Kempe) to the dissolution of iron into molten iron-carbon alloys (under Professor R. Pehlke, Chairman of the Materials and Metallurgical Engineering Department).

Professor Young has developed extensive facilities for heat transfer studies in two-phase boiling, steam condensing on tubes of various compositions and geometries, and falling film boiling and condensing of steam.

Professors Wilkes and Pehlke (of the Materials and Metallurgical Engineering Department) have recently initiated finite element method simulation studies of the continuous plasma arc remelting process for enhancing the properties of high alloy steels.

Reactions and Reactors

The Ziegler-Natta polymerization facility has already been mentioned. Professor Parravano also has organized a catalyst characterization facility, with equipment for surface area measurement and a magnetic balance for determining the magnetic susceptibility and oxidation states of catalysts. College facilities such as the electron microprobe and scanning electron microscope are also available for detailed surface analysis. A Mössbauer spectrometer allows detailed chemical, structural and compositional analysis of a variety of solid materials, especially iron and iron compounds used as catalysts.

A high-pressure Hasteloy B two-phase reactor is available for use in the acidization laboratory. This reactor is currently being used in a study of the kinetics of HF/HCl acid mixtures with clays, under the direction of Professor Fogler.

Equipment is also available for the use of radioactive isotopes, including isotope-ratio mass spectrometer, liquid scintillation counting apparatus, ionization chamber, Geiger counters, etc. The above have been used by Professor Parravano and his students on studies of the kinetics of heterogeneous catalytic reactions, reaction selectivities, sintering of supported catalysts, and other topics.

Other reactor studies include a packed-bed photoreactor study, guided by Professors Carnahan and Kadlec; electrochemical reactor studies under Professor Donahue; supported and encapsulated enzyme reactors, by Professor Schultz and co-workers; and unsteady-state optimization of a tubular reactor, representing an interest in functional optimization that has led to several related studies under Professor Kadlec.

Natural Resources

The fuel shortage, or rather the shortage of high-grade (especially low sulfur) fuels, of natural gas, and of untainted water, has stimulated the interest of department faculty and students in the recovery and re-use of various natural resources. Several studies are underway in this area.

Professor Briggs has begun a study of the separation of asphaltenes and inorganic solids from extract produced in the dissolution and liquefaction of coal. A study of the physical and chemical characteristics of lignite is also being initiated.

Professors Katz and Tek are very active in reservoir engineering research, including two-phase flow in wells and pipelines, caprock properties, underground storage of gas and oil, and other subjects related to fuel recovery and conservation.

Water resources are also of particular importance today. The subject is treated in a course, The Chemical Engineering of Water, coordinated by Professor Kempe, and water treatment and conservation are also the subjects of the Marsh Ecosystem studies of Professor Kadlec, already described, and the Great Lakes studies of Professor Kempe. The underground flow of water in limestone terrains has been a continuing study area of Professor Curl.

Separations

Professor Powers has, in the past, pursued studies of advanced separation methods, including adsorption, continuous crystallization, thermal diffusion, and ion-ion competition in liquid-liquid ion-exchange, involved in the separation of transition metals.

Rather different is a study under Professor Kadlec on improving flash separation by the unsteady or cyclic operation of a vapor-liquid separator. This takes advantage of transport nonlinearities under transient conditions to improve certain separations. Advanced functional optimization theory is also involved.

Still another type of separation is being studied in cooperation with the Department of Anthropology, under the direction of Professor Curl. Methods are being developed for the separation of carbonized plant remains (seeds, nuts, charcoal, etc.) on the basis of their physical properties.

Moderately large-scale separations apparatus is available in the Unit Operations Laboratory on North Campus which is used primarily as an undergraduate instruction facility. A Swenson long-tube vertical evaporator (20-ft tubes), an 18-inch fractionating tower with complete instrumentation for control and data acquisition, an ion-exchange column, and equipment for experiments in heat transfer, reactor behavior, filtering, etc., are all available.

Thermodynamics

The thermodynamics and phase behavior of hydrocarbon systems may be studied with the equipment that is available for purification of compounds by precision distillation, determination of vapor-liquid equilibrium to 2000 psi and 500°F, measurement of gas-adsorbent equilibrium at near-ambient conditions, and on-stream analysis of samples by chromatographs and sensors.

A precision calorimetric facility has been developed under the direction of Professor Powers. Thermodynamic properties, including heat capacity, isothermal throttling coefficient, and heats of vaporization have been measured with great precision in the vicinity of the critical point. Heats of mixing of binary and ternary gaseous mixtures at elevated pressures have been determined in a companion facility.

Refrigerants have also been studied recently in a laboratory equipped for PVT, vapor pressure, liquid density and heat capacity measurements. This work was supervised by Professor J. J. Martin, who is developing better correlating equations for thermodynamic properties, such as equations of state.

Professors Hand, Katz and students have been engaged in studies on the phase behavior of hydrocarbon hydrates that exist in large quantities on the continental shelf and in Alaskan oil reservoirs and in vapor-liquid equilibria in pipeline natural gas consensate systems.

FACULTY INTERESTS

Applied Mathematics

B. Carnahan
R. L. Curl
R. H. Kadlec
J. J. Martin
J. O. Wilkes

Biochemical Engineering

F. G. Bader
J. H. Hand
R. H. Kadlec
L. L. Kempe
J. S. Schultz

Chemical Kinetics, Catalysis and Reactors

F. G. Bader
D. E. Briggs
R. L. Curl
F. M. Donahue
H. S. Fogler
R. H. Kadlec
G. Parravano
J. S. Schultz

Electrochemical Engineering

F. M. Donahue
J. J. Martin
G. Parravano

Energy and Related Topics

D. E. Briggs
R. L. Curl
D. L. Katz
J. E. Powers
M. R. Tek
R. B. Williams

Fluid Mechanics

R. L. Curl
H. S. Fogler
J. H. Hand
D. L. Katz
M. R. Tek
J. O. Wilkes
E. H. Young

Heat Transfer

D. E. Briggs
J. H. Hand
E. H. Young
J. O. Wilkes

Mass Transfer

R. L. Curl
F. M. Donahue
H. S. Fogler
J. S. Schultz

Materials

F. M. Donahue
J. H. Hand
G. Parravano
M. J. Sinnott
G.S.Y. Yeh
E. H. Young

Modeling and Simulation

F. G. Bader
B. Carnahan
R. L. Curl
H. S. Fogler
R. H. Kadlec
J. O. Wilkes

Petroleum and Coal Technology

D. E. Briggs
H. S. Fogler
D. L. Katz
M. R. Tek
J. E. Powers
G. B. Williams

Polymers

J. H. Hand
G. Parravano
G.S.Y. Yeh

Process Dynamics and Control

B. Carnahan
R. L. Curl
R. H. Kadlec
G. B. Williams

Process and Equipment Design

D. E. Briggs
B. Carnahan
R. L. Curl
R. H. Kadlec
D. L. Katz
L. L. Kempe
G. B. Williams
E. H. Young

Rheology

D. E. Briggs
J. H. Hand

Two-Phase & Particulate Systems

R. L. Curl
J. H. Hand
D. L. Katz
M. R. Tek
J. O. Wilkes

Separation Processes

D. E. Briggs
R. L. Curl
R. H. Kadlec
J. E. Powers
M. R. Tek
G. B. Williams

Thermodynamics

R. L. Curl
J. H. Hand
D. L. Katz
J. J. Martin
J. E. Powers
M. J. Sinnott
G. B. Williams

Chemical Engineering Faculty

BADER, FREDRIC G., Du Pont Assistant Professor;

B. S., University of Michigan, 1969,
Ph.D., University of Minnesota, 1974.

Interests:

Microbial population dynamics, continuous stirred tank reactor analysis, fermentations, water pollution, food technology.

Selected Publications:

"Comments on Microbial Growth Rate," (with J. S. Meyer, A. G. Fredrickson, and H. M. Tsuchiya), Biotech. Bioeng., 17, 279-283 (1975).

"Dynamics of an Algal-Protozoan Grazing Interaction," (with A. G. Fredrickson and H. M. Tsuchiya), in Modeling Biochemical Processes in Aquatic Ecosystems, edited by R. P. Canale, Ann Arbor Science, 1976.

"Grazing of Ciliates on Blue-Green Algae: Effects of Ciliate Encystment and Related Phenomena," (with A. G. Fredrickson and H. M. Tsuchiya), Biotech. Bioeng., 18, 311-332 (1976).

"Grazing of Ciliates on Blue-Green Algae: Effects of Light Shock on the Grazing Relation and on Algal Populations," (with A. G. Fredrickson and H. M. Tsuchiya), Biotech. Bioeng., 18, 333-348 (1976).

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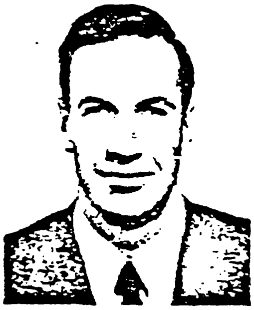

BRIGGS, DALE E., Associate Professor;

B. S., University of Louisville, 1953;
M. S., University of Michigan, 1958;
Ph.D., University of Michigan, 1968.

Interests:

Separations processes, air pollution control, coal gasification and liquefaction.

Selected Publications:

"Convection Heat Transfer and Pressure Drop of Air Flowing Across Triangular Pitch Banks of Finned Tubes," (with E. H. Young), Chem. Eng. Prog. Symp. Series, 59, No. 51 (1963).

"An Optimization Technique for the Discrete Value Problem-Heat Exchangers," (with L. B. Evans), Chem. Eng. Prog. Symp. Series, 60, No. 50 (1964).

"Bond Resistance of Bimetallic Finned Tubes," (with E. H. Young), Chem. Engr. Progr., 61, No. 7 (1965).

"The Condensing of Low Pressure Steam on Vertical Rows of Horizontal Copper and Titanium Tubes," (with E. H. Young), AIChE Journal, 12, No. 1, 31-35 (1966).

"Pressure Drop of Air Flowing Across Triangular Pitch Banks of Finned Tubes," (with K. K. Robinson) Chem. Eng. Prog. Symp. Series, 62, No. 64 (1966).

CARNAHAN, BRICE, Professor;

B. S., Case, 1955;
M. S., Case, 1957;
Ph.D., University of Michigan, 1964.

Interests:

Digital computation, numerical mathematics, optimization, simulation, engineering and medical applications of digital computers.

Selected Publications:

Applied Numerical Methods, (with J. O. Wilkes and H. A. Luther), J. Wiley and Sons, New York, 604p (1969).

Digital Computing and Numerical Methods, (with J. O. Wilkes), J. Wiley and Sons, New York, 486p (1973).

"A Model of the Renal Cortex and Medulla," (with J. A. Jacquez and P. H. Abbrecht), Math. Biosci., 1, No. 1, 227-261 (1967).

"Simulation of General Piping and Pumping Networks," (with J. O. Wilkes), Computer Programs for Chemical Engineering Education - Design, R. Jelinek, ed., 71-116, Aztec Publishing Co., Austin, Texas (1974).

"DYSCO: An Interactive Executive Program for Dynamic Simulation and Control of Chemical Processes," (with L. A. Lopez and D. E. Briggs), to appear in Computers in Chemical Engineering.

* * * * *

CURL, RANE L., Professor;

S. B., M.I.T., 1951;
Sc.D., M.I.T., 1955.

Interests:

Mass transfer with reaction, liquid dispersion dynamics, mixing, particulate systems, statistical applications, geological transport and rate phenomena.

Selected Publications:

"Minimum Diameter Stalagmites," Bull. Nat. Speleo. Soc., 35, 1 (1973).

"A Pologonal Approximation for Unsteady State Diffusion of Oxygen into Hemoglobin Solutions," (with J. S. Schultz), Advances in Experimental Medicine and Biology, 37B, Plenum Press, New York (1973).

"Experimental and Theoretical Studies of Dissolution Roughness," (with P. N. Blumberg), J. Fluid Mech., 65, 735 (1974).

"Chemical Equilibrium Conversion and Composition with Five Components," Hewlett Packard HP-65 User's Library, Program No. 01302A (1975).

"Breakage and Coalescence Processes in an Agitated Dispersion, Part 2, Experimental Results," (with S. L. Ross and F. H. Verhoff), submitted for publication.

DONAHUE, FRANCIS M., Associate Professor;

B. A., LaSalle, 1956;
Ph.D., University of California, Los Angeles, 1965.

Interests:

Fundamental and applied electrochemical engineering; simulation of electrochemical reactors, mechanisms of metallic dissolution and deposition processes, electroless plating, mechanisms of corrosion reactions, and unsteady-state electrode processes.

Selected Publications:

"Technique for Continuous Measurement of Electroless Plating Rates," (with C. U. Yu and F. L. Shippey), Plating, 59, 762 (1972).

"Corrosion and Corrosion Control", chapter in Physicochemical Processes for Water and Wastewater Treatment, W. J. Weber, Jr., ed., 457-501, Wiley-Interscience, New York (1972).

"Mechanismus der chemischen Metallabscheidung," Oberfläche - Surface, 13, 301 (1972).

"Kinetics of Electroless Copper Plating. I. Empirical Rate Law," (with F. L. Shippey), Plating, 60, 43 (1973).

"Kinetics of Electroless Copper Plating. II. Mixed Potential Analysis," (with F. L. Shippey), Plating, 60, 135 (1973).

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FOGLER, H. SCOTT, Professor;

B. S., University of Illinois, 1962;
M. S., University of Colorado, 1963;
Ph.D., University of Colorado, 1965.

Interests:

Kinetics and mechanisms of solid-liquid reactions, reaction engineering, modeling of the dissolution of porous media, sonochemical reactions, ultrasonics, ionic adsorption at interfaces, tertiary oil recovery, shale oil

Selected Publications:

The Elements of Chemical Kinetics and Reactor Calculations, Prentice Hall Series in Chemical Engineering, Englewood Cliffs, 495p (1974).

Acidization II, "The Dissolution of Calcite in HCl," Chem. Eng. Sci., 30, p. 825 (1975).

Acidization III, "The Kinetics of the Dissolution by Sodium and Potassium Feldspar in HF/HCl Acid Mixtures," Chem. Eng. Sci., 30, p. 1325 (1975); Acidization IV, "Experimental Correlations and Techniques for the Acidization of Sandstone Cores," ibid, 31 p. 373 (1976).

"Second Order Sonochemical Phenomena - Extension of Previous Work and Applications to Industrial Processing," Chem. Eng. J., 8, p. 165 (1975).

Acidization V, "On the Movement of Permeability and Reaction Fronts in Porous Media," Chem. Eng. Sci., 31, p. 831 (1976).

HAND, JAMES H., Dupont Associate Professor;

B. S., Newark College of Engineering, 1966;
Ph.D., University of California, Berkeley, 1971.

Interests:

Polymer applications, biomaterials, hydrates in subsurface environments, applied statistical mechanics.

Selected Publications:

"Denuding Hydrocarbons of Natural Gas Constituents by Hydrate Formation," (with D. L. Katz, V. K. Verma, and G. D. Holder), *J. Pet. Tech.*, (Feb. 1975).

"Gas Hydrates from Liquid Hydrocarbon (Methane-Ethane-Propane) Systems," (with D. L. Katz and V. K. Verma), preprints of the joint AIChE-VIG meeting, Munich, Sept. 1974.

"Review of Gas Hydrates with Implications for Ocean Sediments," (with D. L. Katz and V. K. Verma), *Marine Sci.*, *3*, 179 (1974).

"Wall Layer Effects in Drag Reduction," (with M. C. Williams), *Chem. Eng. Sci.*, *28*, 63 (1973).

"Hydrate Formation in Subsurface Environments," (with G. D. Holder and D. L. Katz), *Amer. Assoc. Pet. Geol. Bull.*, *60*, 981 (1976).

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KADLEC, ROBERT H., Professor;

B. S., University of Wisconsin, 1958;
M. S., University of Michigan, 1959;
Ph.D., University of Michigan, 1962.

Interests:

Process dynamics, cyclic processes, functional optimization, simulation, ecosystem modelling, deterministic modelling, applied mathematics, reactors, biological waste treatment, omission control reactors.

Selected Publications:

"Optimal Operation of a Tubular Chemical Reactor," (with M. R. Newberger), *AIChE Journal*, *17*, No. 6, 1381-1387 (1971).

"The Optimal Control of a Periodic Adsorber - Part I: Experiment, Part II: Theory," (with D. E. Kowler), *AIChE Journal*, *18*, No. 6, 1207-1219 (1972).

"Chlorination of Sulfur Dioxide in a Plasma Arc Photochemical Reactor: Part I - Reactor Performance; Part II - Chlorination of Sulfur Dioxide," (with G. J. Quarderer), *AIChE Journal*, *20*, No. 1, 141-154 (1974).

"Limiting Factors on Steady-State Thermal Reactor Performance," International Automotive Engineering Congress, Detroit, Mich., Jan. 8-12, 1973.

"Surface Hydrology of Peatlands," National Symposium on Freshwater Wetlands and Sewage Effluent Disposal, Ann Arbor, Mich., May 1976.

MARTIN, JOSEPH J., Professor;

B. S., Iowa State, 1939;
M. S., University of Rochester, 1944;
D.Sc., Carnegie, 1948;
D.Sc. Hon., University of Nebraska, 1971.

Interests:

Measurement and correlation of thermodynamic properties, applications of mathematical tools to chemical engineering problems, radiation processes, and fluid mechanical problems.

Selected Publications:

"Thermodynamic Properties of Refrigerant 502," (with Ralph C. Downing), *ASHRAE Transactions*, *IV*, 1.1-10 (1970).

"Pressure-Volume-Temperature Behavior of CF_4 Using a Variable-Volume Cell of Bellows Design," (with R. K. Bhada), *AIChE Journal*, *17*, No. 3, 683 (1971).

"The Symmetrical Fundamental Property Relation of Thermodynamics," *Ingr. Technik*, *44*, 249 (1972).

"Expansion and Contraction Losses in Fluid Flow," *Chem. Eng. Ed.*, *8*, No. 3, 138 (1974).

"Development of High Precision Equations of State for Wide Ranges of Density Utilizing a Minimum of Input Information: Example - Argon," (with T. G. Stanford), AIChE Sym. No. 140, Vol. 70, 1-13 (1974).

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PARRAVANO, GUISEPPE, Professor;

B. S. (Eng.), University of Rome, 1937;
Ph.D. (E.E.), University of Rome, 1940;
Ph.D. (Chem.), University of Rome, 1942.

Interests:

Kinetics of heterogeneous catalytic reactions, catalytic activity, selectivity and solid-state catalyst and surface properties; electro-initiated polymerization, reactions, kinetics, and polymer structure; applications of Mössbauer spectroscopy to heterogeneous catalysis; studies on the sintering of supported platinum catalysts.

Selected Publications:

"Alkyl Transfer Steps in the Catalytic Alkylation of Benzene, Toluene, and Cyclohexane," *J. Catalysis*, *24*, 233 (1972).

"Electrochemical Polymerization," chapter in *Organic Electrochemistry*, M. M. Brazier, ed., M. M. Kakker, New York (1973).

"A Note on a Statistical Mechanical Treatment of Activation-Limited Surface Diffusion," (with J. D. Goddard), *Reaction Kinetics and Catalysis Letters*, *1*, 57 (1974).

"A Mössbauer Study of Complexes between Iron Salts and Poly(4 Vinylpyridine)," (with N. Burriesci), in Proceedings of Fifth Mössbauer Conference, Krackow, 1975.

"Chemical Reactivity of Supported Gold. III. Atomic Binding and Coordination of Gold by Extended X-Ray Absorption Fine Structure Spectroscopy," (with F. W. Lytle and I. W. Bassi), *Journal of Catalysis*, June 1976.

KATZ, DONALD L., A. H. White University Professor of Chemical Engineering;

B. S., University of Michigan, 1931;
M. S., University of Michigan, 1932;
Ph.D., University of Michigan, 1933.

Interests:

Phase behavior of hydrocarbons, retrograde condensation in pipelines, gas hydrates from liquid phases, conversion of coal to clean fuel.

Selected Publications:

"Diffusion of Fluids through Porous Media Applied to the Earth," (with G. N. Pandey and M. R. Tek), Bull. Amer. Assn. of Pet. Tech., (Feb. 1974).

"Utility Gas from Coal: Need for Underground Storage," (with M. W. Britton and G. D. Holder), Proc. AGA Transmission Conference, Kansas City, May 20-21, 1974.

"Denuding Hydrocarbon Liquids of Natural Gas Constituents by Hydrate Formation," (with V. K. Verma, J. H. Hand, and G. D. Holder), J. Pet. Tech., (Feb. 1975).

"Retrograde Condensation in Natural Gas Pipelines," (with D. F. Bergman and M. R. Tek), AGA Monograph (1975).

Compressed Air Storage for Electric Power Generation, (with E. R. Lady), Ulrich's Books, Inc. (1976).

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KEMPE, LLOYD L., Professor;

B. S. (Ch.E.), University of Minnesota, 1932;
M. S. (Pub. Health Eng.), University of Minnesota, 1937;
Ph.D. (Ch.E.), University of Minnesota, 1948.

Interests:

Pollution problems, particularly of the Great Lakes; high temperature - short time sterilization of foods.

Selected Publications:

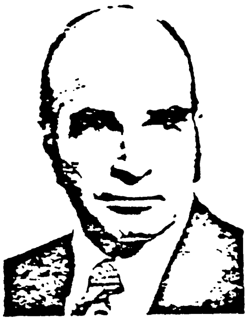
"Characteristics of Various Types of Clostridium Botulinum that Lead to Different Food Processing and Handling Requirements," J. Assn. Food and Drug Officials of U. S., 28, No. 4, 199-206 (1964).

"The Separation of Bacteria by Adsorption onto Ion-exchange Resins: Resolution of Binary Mixtures," (with S. L. Daniels), Chemical Engineering in Medicine and Biology, D. Hershey, ed., 391-415, Plenum Press, New York (1967).

"Kinetics of the Conversion of Glucose to Gluconic Acid by Pseudomonas Ovalis," (with D. N. Bull), Biotech. and Bioeng., 12, No. 2, 273-290 (1970).

"High Temperature - Short Time (HTST) Processing of Suspensions Containing Bacterial Spores," (with R. A. Jacobs and N. A. Milone), J. Food Sci., 38, No. 3, 168-172 (1973).

"Sediment Phosphorous Translocation through Anaerobic Dissolution and Gas-Lift," (with W. B. Woods and J. F. Carr), Proc. AIChE/EPA 2nd Nat. Conf. on Water Use, May 4-8, 1975, (in press).



POWERS, JOHN E., Professor;

B. S., University of Michigan, 1951;
Ph.D., University of California, Berkeley, 1954.

Interests:

Separation processes, experimental determination of thermodynamic properties, and thermonuclear production of hydrogen from water.

Selected Publications:

Foundations of Thermodynamic Analysis, (with C. M. Sliepcevich and W. J. Ewbank), Stirling-Swift Publishing Co., Austin (1974).

"Crystallization from the Melt," Chemical Engineers' Handbook, 17-8, McGraw Hill, New York (1973).

"Separation in a Thermoelectrogravitational Electrophoresis Column without Reservoirs," (with O. K. Crosser and R. K. Prabhudesai), Part I: "Theoretical Development of the Transport Equation," AIChE Journal, 19, 38 (1973); Part II: "Steady State Operation of a Continuous Flow Column: Theory and Experiment," AIChE Journal, 19, 46 (1973); Part III: "Transient Behavior of a Batch Column," AIChE Journal, 19, 52 (1973).

"Cryogenic Thermal Properties from the U. of Michigan Fluids Laboratory," Advances in Cryogenic Eng. (K. D. Timmerhaus, ed.), 18, 234, Plenum Press, New York (1973).

"Smoothing Thermodynamic Data Based on Equality of Second Derivatives," (with T. Miyazaki and A. W. Furtado), Proceedings of the First Int. Conf. on Calorimetry and Thermodynamics, 617, Polish Scientific Publishers, Warsaw (1969).

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SCHULTZ, JEROME S., Professor;

B. S. (Ch.E.), Columbia University, 1954;
M. S. (Ch.E.), Columbia University, 1956;
Ph.D. (Biochem), University of Wisconsin, 1958.

Interests:

Mechanisms of membrane transport; hindered diffusion in pores, coupled diffusion and chemical reaction in membranes, enzyme reactors, artificial organs, oxygen transport in blood and tissues, dynamics of thrombus formation, biomaterials; cooperative research with Medical School.

Selected Publications:

"Hindrance of Solute Diffusion within Membranes as Measured with Microporous Membranes of Known Pore Geometry," (with R. E. Beck), Biochimica and Biophysica Acta, 255, 273-303 (1972).

"Effectiveness Factor Calculations for Immobilized Enzyme Catalysts," (with D. J. Fink and T. Y. Na), Biotechnol. and Bioeng., 15, 879-888 (1973).

"The Permeability of Gases through Reacting Solutions: The Carbon Dioxide-bicarbonate Membrane System," (with S. R. Suchdeo), Chem. Eng. Sci., 29, 13-23 (1974).

"Facilitated Transport via Carrier-Mediated Diffusion in Membranes: Part I - Mechanistic Aspects, Experimental Systems, and Characteristic Regimes," (with J. D. Goddard and S. R. Suchdeo), AIChE Journal (review), 20, 417-445 (1974), and "Part II - Mathematical Aspects and Analyses," ibid, 20, 625-645 (1974).

"Kinetics of Thrombus Formation (with J. D. Goddard, J. Penner, M.D., S. M. Lindenauer, M.D., A. Ciarkowski), Amer. Soc. Artificial Organs, 22, 269-277 (1976).

SINNOTT, MAURICE J., Professor and Associate Dean of the College of Engineering;

B. S. (Ch.E.), University of Michigan, 1938;
M. S. (Ch.E.), University of Michigan, 1941;
Ph.D. (Met. Eng.), University of Michigan, 1946.

Interests:

Physical metallurgy and materials, physical properties of fluids.

Selected Publications:

"Evaluation of Abrasive Wear," (with J. Muscara), Met. Eng. Quart., 12, No. 2, 21-32 (1972).

Computer Applications in Metallurgical Engineering, (editor with R. D. Pehlke), American Society for Metals, Cleveland, 119p (1964).

"Quantitative Metallography of Particles with Polyhedral Shapes," (with E. J. Myers), Computer Applications in Metallurgical Engineering, (M. J. Sinnott and R. D. Pehlke, ed.), American Society for Metals, Cleveland (1964).

"Solid State Science", La Scuola in Azioni, 9, 153 (1963).

"High Temperature Phase Equilibria in the C-O-U System," (with J. R. Piazza), J. Chem. and Eng. Data, 7, 451 (1962).

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TEK, M. RASIN, Professor;

B. S. (M.E.), University of Michigan, 1948;
M. S. (M.E.), University of Michigan, 1949;
Ph.D. (M.E.), University of Michigan, 1953.

Interests:

Production, pipelining, storage and conservation of natural gas and crude oil, multi-phase flow, underground storage, logistics of energy supply. Slurry pipelines for coal and ash.

Selected Publications:

Discussion of "Two-Phase Flow in Oil Wells. Prediction of Pressure Drops," (with C. L. Chierici, G. M. Ciucci and G. Schlocchi), Journal of Petroleum Technology, August 1974.

"Binary-Gas Diffusion of Methane-Nitrogen through Porous Solids," (with Lillian Lung-Yu Chen and Donald L. Katz), accepted for publication in AIChE Journal.

"Prospects for Oil and Gas from Silurean-Niagaran Trend in Michigan," University of Michigan Institute of Science and Technology, 1976 (also in publication review for the Journal of Petroleum Technology, SPE-AIME).

Retrograde Condensation in Natural Gas Pipelines, AGA Monograph (with D. Bergman, D. L. Katz, 498 pp., 1976.

"Perspectives, Problems and Prospects for Energy in the Pacific," paper submitted to P.A.Ch.E.C. '77 Meeting, Denver, Colorado.

WILKES, JAMES O., Professor and Department Chairman;

B. A., University of Cambridge, England, 1954;
M. S., (Ch.E.) University of Michigan, 1956;
M. A., University of Cambridge, England, 1960;
Ph.D., University of Michigan, 1963.

Interests:

Applied numerical methods, two-phase flow, underground storage of gas, flow of polymers.

Selected Publications:

Applied Numerical Methods, (with B. Carnahan and H. A. Luther), J. Wiley and Sons, New York, 604p (1969).

"Numerical Methods for Chemical Engineering Problems," (with B. Carnahan), Chem. Eng. Ed., 7, 80-83 (1973).

Digital Computing and Numerical Methods, (with B. Carnahan), J. Wiley and Sons, New York, 486p (1973).

"Some Recent Measurements of H_2S Oxidation and Their Implications to Atmospheric Chemistry," (with J. M. Hales and J. L. York), Tellus, 26, 277-283 (1974).

"Laminar Free-Surface Flow into a Vertical Cylinder," (with T. G. Smith), Computers and Fluids, 3, 51-68 (1975).

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WILLIAMS, G. BRYMER, Professor;

B. S. (Eng.) University of Michigan, 1936;
Ph.D. University of Michigan, 1949.

Interests:

Development, design and computer control of chemical processes; Natural resource utilization including coal, oil shale and mineral beneficiation.

Selected Publications:

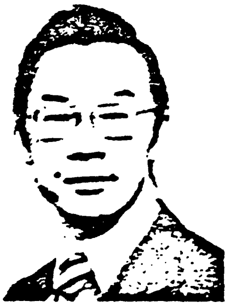
"Adsorption of Nitrogen-Methane on Molecular Sieves," (with P. B. Lederman), AIChE Journal, 10, 30 (1964).

"Solubility of Carbon Dioxide in Various Solvents," (with J. W. Begley and H. Maget), J. Chem. Eng. Data, 10, 4-8 (1965).

"Vapor-Liquid Equilibrium in Hydrogen-Hexane-Benzane Cyclohexane Systems," (with A. J. Brainard), AIChE Journal, 13, 60-70, (1967).

"Vapor-Liquid Equilibrium in Methane-Pentanes," (with N. W. Prodany), J. Chem. Eng. Data (1971).

"The Man-Made World", The Engineering Concepts Curriculum Project. Participant. Vols. I-IV, McGraw Hill, New York, (1968).



YEH, GREGORY S. Y., Professor;

B. S., Holy Cross, 1957;
M. S., Cornell, 1960;
Ph.D., Case, 1966.

Interests:

Polymers.

Selected Publications:

"Strain-Induced Crystallization of Natural Rubber. Part I: Electron Microscopy on Uncrosslinked Thin Films," (with D. Luch), J. Appl. Phys, 43, 4326 (1972); "Part II: x-ray on Bulk Crosslinked Vulcanates," (with D. Luch), J. Polymer Sci. (Physics), A2, 467 (1973).

"Morphology of Amorphous Polymers," J. Crit. Rev. Solid State Sci., 1, 173 (1972).

"On the Macroscopic Yield Behavior of Polymers," (with R. S. Raghava and R. M. Caddell), J. Mat. Sci., 8, 225 (1973).

"Origin of Impact Strength in Polycarbonate. Part I: Effect of Crystallization and Residual Solvent," (with M. G. Wyzgosky), Int. J. Polymeric Matls., 3, 133 (1974).

"Mechanisms of Yielding and Cold Flow," (with T. E. Brady), J. Macromol. Sci. (Physics), B9, 659 (1974).

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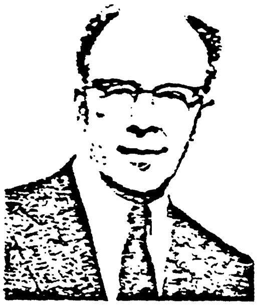
YOUNG, EDWIN H., Professor;

B. S. (Ch.E.), University of Detroit, 1942;
M. S. (Ch.E.), University of Michigan, 1949;
M. S. (Met. Eng.), University of Michigan, 1952.



Interests:

Process heat transfer, process equipment design, process plant design, and process equipment failure analysis.

Selected Publications:

"Investigation of Steam Condensing on Vertical Rows of Horizontal Corrugated and Plain Tubes," (with James G. Withers), Symposium on Enhanced Tubes for Desalination Plants, Office of Saline Water, U.S. Dept. of the Interior, Superintendent of Documents, U.S. Government Printing Office, Washington, D. C., 117-151 (1970).

"Simulated Performance of Refrigerant-22 Boiling Inside of Tubes in a Four Tube Pass Shell and Tube Heat Exchanger," (with John F. Pearson), Chemical Engineering Progress Symposium Series No. 102, 66, 164-173 (1970).

"Steam Condensing on Vertical Rows of Horizontal Corrugated and Plain Tubes," (with James G. Withers), Industrial & Engineering Chemistry Process Design and Development, 10, No. 1, 19-30 (1971).

"Heat Transfer to Boiling Refrigerants Flowing inside a Plain Copper Tube," (with Byung-Woo Rhee), AIChE Symposium Series No. 138, 70, 64-70 (1974).

"Direct Contact Heat Transfer of a Concurrent Oil-Water System," (with G. T. S. Chen and J. L. York), AIChE Symposium Series No. 138, 70, 144-153 (1974).

EMERITUS

TOWNSEND, RICHARD E., Associate Professor

Certificate, Pratt University, 1917;
B. S. (Ch.E.), University of Michigan, 1924;
M. S. (Ch.E.), University of Michigan, 1925.

Prof. E. H. Young (center) is discussing a corrugated tube with doctoral students William B. Lampert (left) and Byung Woo Rhee (right), for studying in-tube boiling.

Members of the Chemical Engineering Gaming Society are fortifying themselves for one of the frequent graduate student/faculty duplicate bridge matches. (L to R): Profs. Kadlec and Wilkes, Kasper Lund, Prof. Hand, William Talbott, Robert Griffiths, Peter Parker, and Prof. Carnahan.

RECENT MASTERS DEGREES

Since 1972	School Granting B. S. Degree
Addington, David Vern	Purdue University
Altemos, Edward A.	State University of New York, Maritime College
Anderson, Paul A.	The University of Michigan
Bagrodia, Vijay	Banaras Hindu University, India
Berger, Charles R.	The University of Michigan
Bernstein, William Allan	The University of Michigan
Bichel, Richard Paul	The University of Michigan
Bose, Arindam	Indian Institute of Technology, Kanpur
Brenner, Merrill Scott	Stanford University
Britton, Michael	The University of Michigan
Broad, Walter	The University of Michigan
Brush, Jay	The University of Michigan
Bujanda, Carlos Eduardo	Universidad Central de Venezuela
Chari, Vinod	Nagpur University, India
Cohen, Harvey A.	Carnegie-Mellon Institute
Cunningham, John R.	The University of Michigan
Emmert, Robert W.	University of Cincinnati
Ericson, Franklyn	Michigan Technological University
Farrant, Leslie A.	University of New South Wales
Flessner, Michael Franci	U. S. Coast Guard Academy
Forreger, Joseph H.	University of Wisconsin
Franklin, Howard	McGill University, Canada
Giacaman, Gloria	University of the North, Chile
Gibson, Larry Harold	U. S. Coast Guard Academy
Gray, Charles L.	University of Mississippi
Griffin, Steve James	The University of Michigan
Griffis, Carl H.	The University of Michigan
Hammer, David E.	The University of Michigan
Hanson, Linda Joan	Michigan State University
Hanzevack, Karen M.	Northwestern University
Harmon, Stephen P.	University of Cincinnati
Harrer, Robert D.	Purdue University
Harrington, Mark Thomas	The University of Michigan
Heetderks, James Paul	The University of Michigan
Ho, Benedict Sou-Yan	Iowa State University
Hoang, Ngocloan Thi	University of Southern Illinois
Hoffmann, Donald J.	The University of Michigan
Holder, Gerald D.	The University of Michigan
Holloway, Daniel William	The University of Michigan
Hruska, Louis William	The University of Michigan
Huxtable, William Paul	Kalamazoo College
Jannarone, Richard	Princeton University
Johnson, Philip	The University of Michigan
Judzis, Arnis	Cornell University
Judzis, Arvids, Jr.	Cornell University
Kant, Ravi	Indian Institute of Technology, Kharagpur
King, James V. B.	University of Wisconsin
Kline, William	University of Cincinnati
Kucharski, William A.	U. S. Coast Guard Academy
Kwan, Adriana	The University of Michigan
Lambert, John	The University of Michigan
Leemhuis, Ronald P.	Massachusetts Institute of Technology
Leung, Cheung Kwok	University of Illinois, Urbana
Leyshon, David	Lehigh University
Li, Ming Kung	University of Wisconsin
Lo, Bernard Kin-Keung	The University of Michigan
MacFarlane, Kenneth	The University of Michigan
McCollough, George T.	The University of Michigan
Mallu, Vernon J.	The University of Michigan
Mensinger, Michael C.	The University of Michigan
Mihalik, Daniel	The University of Toledo
Miller, Dennis Paul	Purdue University
Mitasik, Charles F.	The University of Michigan
Mohr, David	Purdue University
Motazedi, Mercede	Tehran Polytechnic University, Iran
Nagar, Hari W.	University of Missouri
Ny, Len Foon	University of Wisconsin

Offley, Ronald D.	The University of Michigan
Oscarson, John L.	Brigham Young University
Piedrahita, Oscar	University of Antioquia, Columbia
Ploeger, James P.	The University of Michigan
Rajkhowa, Preetam	Banaras Hindu University, India
Raymond, James E.	Michigan State University
Roberge, Raymond	Worcester Polytechnic Institute
Roig, Francisco	Universidad de Puerto Rico
Ross, Donald A.	The University of Michigan
Salo, Kenneth William	University of Minnesota
Sanz, Ramon	Universidad Iberoamericana, Mexico
Schmidt, Peter C.	The University of Michigan
Schoettle, Ekkehard	The University of Michigan
Schweickart, John	The University of Michigan
Sigmund, Paul	Lehigh University
Stirling, J. Andrew	University of Utah
Stuewer, Lester A.	University of Texas
Sze, Mason	Illinois Institute of Technology
Talbott, William H.	University of Cincinnati
Tanner, Ronald Wallace	State University of New York, Maritime College
Taylor, Michael	U. S. Coast Guard Academy
Thompson, Gregory	University of Illinois
Toomajian, Martin Albert	Cornell University
Trainor, Robert Hamlin	U. S. Coast Guard Academy
Triyanond, Prakit	The University of Michigan
Uppal, Jai	Banaras Hindu University, India
Valentine, Richard L.	The University of Michigan
Valle, Antonio	Universidad de Puerto Rico
Vitale, Alexander J.	University of Cincinnati
Weisser, Frank M.	University of Texas
Wong, George W. W.	University of Wisconsin
Wound, Fu Yii	Taiwan Cheng Kung University
Wyhs, Neal Alan	San Jose State College, California

RECENT PH.D. DEGREES

Name	Advisor	Thesis Title
Bergman, David F.	Katz	Predicting the Phase Behavior of Natural Gas in Pipelines
Bhirud, Vasant L.	Martin	Physical Properties and Intermolecular Potential Functions of Chlorodifluoromethane, Chloropentafluoroethane and their Mixture of Composition: Chlorodifluoromethane, 48.8WT.% and Chloropentafluoroethane, 51.2WT.%
Chan, Lilan Y.	Goddard & Wilkes	Experimental Observations and Numerical Simulation of the Weissenberg Climbing Effect
Chen, George T. S.	Young	Direct Contact Heat Transfer of a Co-current Oil Water System
Chen, Lillian Chou	Katz	Binary Gas Diffusion of Methane-Nitrogen through Porous Solids
Duffy, John P.	Kadlec	The Behavior of the Dispersed Phase in Liquid-liquid Co-current Flow through a Packed Bed
Farrant, Leslie A.	Powers	Computer-Aided Design of Liquid Ion-Exchange Processes, Competing Extraction of Iron III and Copper II by Tri-Iso-Octylamine and by Di-(2-Ethylhexyl)-Phosphoric Acid
Fink, David J.	Schultz	The Kinetics of Enzymes Immobilized in Semi-Permeable Microcapsules

Furtado, Andre W.	Powers	The Measurement and Prediction of Thermal Properties for Selected Mixtures of Methane, Ethane, and Propane
Gould, Thomas L.	Tek	Vertical Two-Phase Flow in Oil and Gas Wells
Joseph, Larry M.	Kadlec	The Cyclic Operation of a Vapor-Liquid Separator
Khanna, Vijay Kumar	Powers	The Experimental Determination and Prediction of Excess Enthalpies for the System CH_4-N_2-H_2
Kim, Kwan Young	Powers	Calorimetric Studies on Argon and Hexafluoroethane and a Generalized Correlation Maxima in Isobaric Heat Capacity
Kim, Yeong-U	Pehlke	Mass and Heat Transfer during Dissolution of a Solid Cylinder of an Iron-Carbon Alloy into a Liquid Iron-Carbon Alloy
Lopez, Luis Alfonso	Carnahan & Briggs	DYSCO: An Interactive Executive Program for Dynamic Simulation and Control of Chemical Processes
Lund, Kasper	Fogler	On the Acidization of Sandstone
Mann, Gamdur S.	Van Vlack	Subscale Formation in Iron-Base Alloys with Group VI B Elements
Miyazaki, Takaya	Powers	Design, Development and Evaluation of a High Accuracy Recycle Flow Multipurpose Calorimeter
Oltrogge, R. David	Kadlec	Gas Fluidized Beds of Fine Particles
Parker, Peter E.	Kadlec	A Dynamic Ecosystem Simulator
Rhee, Byung Woo	Young	Heat Transfer to Boiling Refrigerants R-12 and R-22 Flowing Inside a Plain Copper Tube
Ross, Seymour	Curl	Measurements and Models of the Dispersed Phase Mixing Process
Schorle, Bernard J.	Bigelow	Nucleation of Calcium Sulfate in Drops of Aqueous Solution
Singh, Surrendra P.	Carnahan	AGPSS: A Graphical Process Simulation System
Sondreal, Everett	Kadlec	Models for Thermal Exhaust Reactors: Limits on Performance Posed by Mixing and Thermal Quenching
Stover, Dennis E.	Donahue	Electrochemical Reactor Design and Kinetics: The Copper Electro-Refining Cell
Suchdeo, Shyam	Schultz	Facilitated Transport of Carbon Dioxide Across Liquid Membranes Containing Bicarbonate Ion and Catalyst Carbonic Anhydrase
Timm, Edward E.	Williams & Hammitt	An Experimental Photographic Investigation of Vapor Bubble Collapse and Liquid Jet Impingement
Verma, Vigender K.	Hand & Katz	Hydrate Formation from Liquid Hydrocarbon Water Systems
Woods, William B. Jr.	Kempe	Nutrient Translocation from Lake Sediment to Overlying Water by Gas-Lift

DESCRIPTION OF GRADUATE COURSES

CHEMICAL ENGINEERING

(Consult the College of Engineering Catalog for descriptions of the undergraduate program and its courses, which are marked with an asterisk.)

230* Thermodynamics I.

330* Thermodynamics II.

341* Rate Processes I.

342* Rate Processes II.

343* Separation Processes.

360* Chemical Engineering Laboratory I.

407 Mathematical Modeling in Chemical Engineering. (3)[†] (I)[††]
Prerequisite: Math. 216 and ChE 342.
Analysis and mathematical modeling of chemical engineering systems. Formulation of models in terms of algebraic, integral, differential, and some partial-differential equations. Solution methods for ordinary differential equations, and the Laplace transform.

417 Biochemical Technology. (3) (II)
Prerequisite: Organic Chemistry.
Concepts necessary in the adaptation of biological and biochemical principles to industrial processes and technology of the biochemical engineering industries. Lectures, problems, and library study will be used to develop the ideas presented.

434 Microbiology for Engineers. (3) (I)
Prerequisite: Chem. 225.
Principles and techniques of microbiology with an introduction to their application in the several fields of engineering. Lectures and laboratory.

444* (Mat.-Met. Eng. 444). Properties of Gases, Liquids, Solids, and Surfaces. (3)

446 Chemical Engineering of Water. (3) (I)
Prerequisite: Chem. 225 and ChE 342 or ChE 340.
Development and modification of chemical and metallurgical processes and plant designs as indicated by raw water and effluent disposal requirements.

449 Air Pollution Control. (3) (II)
Prerequisite: ChE 340 or 342 or M.E. 471.
Sources of air pollution are identified. Principles and techniques are discussed to eliminate or control gaseous and particulate pollutants to within required legal limits.

451 Introduction to Polymers. (4) (I)
Prerequisite: Junior standing in engineering or science.
Preparation, properties, and utilization of polymeric materials. Lectures, recitation, and laboratory.

452 Applied Polymer Processing. (3) (II)
Prerequisite: None
Theory and practice of polymer melt processing. Non-Newtonian flow; extrusion, injection and molding operations, fiber, film, and rubber processing; kinetics of solidification; mechanical orientation; product characterization; structure-property relations.

460* Chemical Engineering Laboratory II.

485* Biochemical Engineering Process Design.

486* Engineering Materials in Design.

487* Principles of Chemical Engineering Design.

488* Practice of Chemical Engineering Design.

[†] Indicates credit hours.

[††] Indicates term in which course is normally taught (I=fall, II=winter). Courses which are taught biannually are marked with b. Those taught when student interest warrants are marked with c. Normally, one or two courses are offered in term IIIa.

490* Directed Study, Research and Special Problems.

507 Mathematical Modeling in Chemical Engineering II. (3) (J)
Prerequisite: ChE 407.
Development of mathematical models for chemical engineering systems in terms of partial differential equations, difference equations and population balances. Separation of variables and related boundary-value problems, similarity solutions, and dimensional analysis, orthogonal functions, Fourier series and integrals and Laplace transform methods.

508 Numerical Methods in Chemical Engineering. (3) (I)
Prerequisite: Engineering 132.
Numerical approximation: interpolating, least squares, and Chebyshev polynomials; spline functions. Numerical integration and differentiation. Single and simultaneous linear and nonlinear equations. Ordinary and partial differential equations. Implementation of numerical methods on the digital computer. Applications to problems in fluid mechanics, heat transfer, reaction engineering and related areas.

509 Statistical Analysis of Engineering Experiments. (3) (3)
Prerequisite: None.
The use of statistical methods in analyzing and interpreting experimental data and in planning experimental programs. Probability, distributions, parameter estimation, tests of hypotheses, control charts, regression and introduction to analysis of variance.

511 Polymer Processes and Characterization. (3) (J)
Prerequisite: a course in physical chemistry and a course in organic chemistry.
Polymerization kinetics and polymer properties. Kinetics of free radical, ionic, condensation, stereo-specific polymerization and copolymerizations. Emulsion, solution, suspension, slurry, solid state, melt polymerizations. Rate equations for reaction mechanism and process design. Methods of molecular weight characterization and fractionation. Control equations for molecular weight distribution.

516 Dynamics of Biochemical Systems. (3) (I)
Prerequisite: a course in physical chemistry and a course in biology.
Colloidal phenomena in biological systems, mechanisms of transport through membranes, physical chemical properties of biological materials, kinetics of growth processes, enzyme catalysis, natural control mechanisms, engineering applications of biochemical phenomena.

525 Catalysis, Kinetics, and Research Reactors. (3) (I)
Prerequisite: two physical chemistry courses.
The course covers topics in heterogeneous catalytic reactions and research reactor kinetics. It emphasizes basic principles of heterogeneous catalysis, surface effects, reaction kinetics, and design of research reactors.

526 Heat Transfer. (3) (J)
Prerequisite: ChE 341.
Principles of conduction, convection, and radiation. Application to processes in the chemical and petroleum industries. Selected topics such as heat transfer effects in two-phase flow, condensation of multicomponent vapors, extended surfaces, and radiation from gases and flames.

527 Fluid Flow. (3) (I)
Prerequisite: ChE 341.
Applications of fluid dynamics to chemical engineering systems. Theory and practice of laminar and turbulent flow of Newtonian and non-Newtonian fluids in conduits and other equipment. Introduction to the dynamics of suspended particles, drops, bubbles, foams and froth. Selected topics relevant to other engineering disciplines.

528 Chemical Reactor Engineering. (3) (II)
Prerequisite: ChE 342.
Analysis of kinetic, thermal, diffusive, and flow factors on reactor performance. Topics include batch, plug flow, backmix reactors, empirical rate expressions, residence time analysis, catalytic reactions, stability, and optimization.

529 Mass Transfer. (2) (3)
Prerequisite: ChE 342.
Formulation of diffusional mass balances; diffusion in solids, liquids and gases; Fick's first and second laws, convective mass transfer, modeling of mass transfer systems.

APPENDIX V

SPE PAPER 6877 PROSPECTS FOR A STRATEGIC STOCKPILE IN NATURAL GAS, M. R. TEK, DENVER 12 OCTOBER 1977

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PROSPECTS FOR A STRATEGIC STOCKPILE IN NATURAL GAS

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This paper was presented at the 52nd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in Denver, Colorado, Oct 9-12, 1977. The material is subject to correction by the author. Permission to copy is restricted to an abstract of not more than 300 words. Write: 6200 N. Central Expy, Dallas, Texas 75206.

ABSTRACT

The need for a "Strategic Stockpile in Natural Gas" so vividly demonstrated by the harsh winter of 1976 is examined to identify 'prospects' as well as 'problems' the development of such a stockpile would entail. World wide distribution of "market limited supplies" as contrasted with "supply limited markets" suggests that the U.S. is the only country having the unique combination of three natural gas related resources. These are:

1. World's largest market for natural gas;
2. World's most elaborate existing pipeline network;
3. World's largest number of existing gas reservoirs already connected to markets.

Having all the three resources, all developed, mostly paid up, and more and more unused, the paper, treats the inescapable conclusion that long range solution of present gas shortage may be possible through a long range development of a stockpile of gas imported from overseas.

The main source for the suggested stockpile is identified as natural gas transported to the U.S. following "Methane-Methanol-Methane" route using standard and surplus crude oil tankers.

Prospects and problems related to production overseas, methane-methanol reforming, transport in comparison to LNG, U.S. based plants and technology to gasify methanol into methane are reviewed in reasonable detail.

Other possible or probable sources for the strategic stockpile such as new gas from arctic or lower 48, LNG imports (presently underway), SNG from coal are also entertained as well as a review of pipeline, compression and underground storage capabilities.

INTRODUCTION

The United States once possessed the world's largest gas supply. This, along with the traditional climate of free enterprise led to the development of the world's largest market. The two, the supply and the market were connected with the world's most elaborate pipeline network. Due to the unique combination of these three resources a prolific growth industry resulted which consumed over 400 trillion cubic feet of natural gas between the years 1935 and 1975. However, the reserves leveled and appear to peak out. The discovery of oil and gas in the 'north slope' brought a brief sign of encouragement but the declines painfully resumed and appeared to persist thereafter. The harsh winter of 1976-77 helped focus the problems of the future into the view of the present. As our dependence on natural gas gets more and more critical and the hour grows late, our supply limited market must have access to market limited supplies around the world. Furthermore, the solution gas associated with the production of crude oil (our prime energy resource still for a number of years to come) also depends upon gas markets for proper consumption. In countries which do not practice conservation, the gas is flared into the atmosphere contributing both to pollution and waste. In countries where conservation is practiced through 'no flare' rule, scarcity of local markets for gas curtails the production of oil so much in need.

In the United States, we are fortunate to have a unique combination of not only a developed market and pipelines to supply and distribute the gas to it, but, at the same time, an environment, safe and ecological to put the gas in storage.

SO WHY NOT BUILD A STRATEGIC STOCKPILE IN METHANE?

We have over 32,000 gas wells, some 6,000 plus existing gas or storage reservoirs, over 70,000 linear miles of gas gathering lines 260,000 miles of long distance pipelines and 660,000 miles gas distribution networks. We have over 45 million meters. Over 60 percent of our homes are heated by natural gas. These facilities shown schematically in Figure 1 are all operational, mostly paid and more and more unused. Why not use these resources more effectively? If we could pressure up and restock our existing reservoirs to conditions which prevailed before our overall economic well-being would be vastly improved.

Where could we get the gas from? We could get it from far away overseas resources where market limited supply exists: Saudi Arabia, Iran, West Irian, Australia, even Siberia, other areas.

References and illustrations at end of paper

How would the gas be transported to the U.S.? Some gas is already being imported by special cryogenic tankers in the form of L.N.G. While the present shipments are small they do have a potential for a limited increase in quantity in the future. The increase is however likely to be limited due to present backlog and cost of special tankers. An alternate mode of transportation had been under consideration recently in the form of methanol. Under this scheme, methane would be reformed into methanol near the point of supply then shipped to the U.S. by standard petroleum tankers much more economical and abundant, surplus supply. Once the methanol is discharged in a U.S. port then it would be used as feedstock for gasification into methane. The methane would be pipelined into selected underground storage areas using the existing facilities such as pipelines, compressors, gathering and distribution networks. The scheme appears not only practical but favorably competitive to LNG alternative over supply routes in excess of 3,500 miles or more depending upon the price.

Other sources of gas for a strategic stockpile may include pipeline gas from the arctic, new natural and associated gas from the lower 48 and, in the future SNG from coal and wastes.

Where would the gas be stored to build a stockpile? In underground storage in selected gas oil or water reservoirs. The scheme must be environmentally acceptable and ecologically sound because essentially that is where nature has accumulated and stored the gas in the first place.

The idea of developing a strategic stockpile may be regarded as a bold and innovative concept toward our energy independence. The technological assessment and identification of problems and prospects it entails are the objectives of this paper.

It is hoped that research and engineering directed into future will provide the answers to the following questions:

1. Is a strategic stockpile in methane needed?
2. Is it possible?
3. Is it feasible?
4. Is it practical?
5. How big a stockpile?
6. Where stored?
7. At what rate can it be developed?
8. What problems could it create on institutional, environmental, legal, economic, and financial grounds?
9. What would be a reasonable 'lead-time' to achieve the objectives?

THE NEED FOR STOCKPILE IN NATURAL GAS

The importance and significance of petroleum storage in energy planning has recently been recognized by the Federal Energy Policy and Conservation Act of 1976. As a result a National Strategic Petroleum Storage Program was budgeted for FY 1977. While operations involving storage of liquid petroleum and petroleum products are currently underway, assessment of stockpiling methane remains a problem in need of analysis and solution.

Economic stockpiling of any commodity is normally accepted as a concept to provide short term solutions to long term problems. In the field of energy, the long term solutions involve substitution, conservation, and alternative methods. Natural gas is our country's premier fuel. It is clean burning, powerful, efficient, transportable and versatile. As shown in Figure 2, it occupies a premium place in the distribution of our primary energy sources.(1)* It may be noted from the Figure 2 that in 1972, for instance, our primary supply of indigenous natural gas exceeded our indigenous crude oil supply on Btu basis. As shown in Figure 2 our Residential, Commercial, and Industrial markets rely very heavily on natural gas. Also, in 1972 approximately one quarter of our electricity generation was supplied by natural gas.

The Figure 3 shows the natural gas reserves and effective life of current reserves for the U.S. for the period 1918-1974.(2) It can be seen that reserves which steadily increased during the thirties, forties and fifties have turned around 1970 and resumed a steady and steep decline during early 70's. Also on Figure 3, the effective life, which reads from the right scale shows the number of years, the current reserves would last at the current rate of consumption if no addition to existing reserves were to occur. That number too, once as high as 40 years has been steadily declining since 1946-47 in spite of then prevailing additions to existing reserves. At the present it is only slightly above 10 years.

The Figures 2 and 3 clearly indicate the need for a long range supply of methane if we are to remain economically healthy and if we are to make effective use of our unique resources such as oil and gas wells, reservoirs, pipelines, distribution systems, compression facilities, existing markets.

The relevance of strategic stockpile in natural gas may be justified and analyzed in terms of a "Relevance Tree", developed by the Office of Technology Assessment(3) as shown in Table I. It may be noted that the question posed at level 1, why stockpile methane is answered on the basis of providing protection against depletion or interruption and on the basis of assuring future supply. These answers given at level 2 are entertained with respect to domestic and foreign supply on level 3. The levels 4 and 5 further break down and classify possible and probable events which justify establishment of a stockpile.

SUPPLY VERSUS DEMAND (PAST-PRESENT-FUTURE)

The Figure 3 shows the natural gas reserves in the United States in historical perspective between the years 1919 and 1974. The Barrgraph depicts the stepwise nature to the additions to gas reserves representing increase in supply until the period 1968-1970. Along with the supply, the annual consumption or demand also increased stepwise until the early seventies. It has been also observed that prior to 1970 while the supply increased at a decreasing rate, the demand increased at an increasing rate. The reduction in consumption which occurred between 1970 and 1975 reflect curtailments just subsequent and related to energy crisis of 1972-73.

In order to forecast the future relationship between the supply and the demand the Figure 4 has been prepared. It is based on 3 growth scenarios:

1. No growth, 0 percent increase in consumption per year
2. 2 percent increase in consumption per year
3. 3½ percent increase in consumption per year

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*Numbers in upper script parentheses refer to references given at the end.

In making future projections in supply it becomes important to reliably forecast just when we would totally deplete our present indigenous gas reserves if the gas markets and usage stayed the same, grew 2 percent per year or grew 3½ percent per year. In order to do that realistically one has to account for new additions to present reserves which occur every year. These new additions are usually due to new fields discovered, due to extensions of existing reserves on account of new data and new additions of solution gas associated with oil. The latest figure we have on annual additions to our reserves is 10 trillion std cubic feet.(4) In making future projections we have assumed that +10 TCF addition to reserves will remain the same between 1975 and 1999. The Table II shows how the remaining reserves for each year have been computed.

The procedure shown in Table II has been repeated year by year through 1999 and then again for market growths of 2 percent and 3½ percent through 1999. The results are given in Figure 4. They indicate that if the present gas markets were held static (0 percent growth) and if we added no more than 10 TCF to our reserves each year and if we continued consuming the natural gas at the observed 1975-76 rate of 19.72 TCF, then our gas reserves would completely run out by about 1998. If on the other hand we allowed the consumption to grow 3½ percent per year and other figures remained the same, then our gas reserves would run out shortly before the year 1990.

AMOUNT OF GAS NEEDED TO DEVELOP A VIABLE STOCKPILE

The quantity of methane which may be dedicated to a strategic stockpile depends upon many factors, intangible as well as tangible. The value the country is willing to attribute to gas reserves, physical factors which may be controlling available room for storage, economics of refurbishing old fields, pipelines, regulation, metering, control facilities, must all enter the picture.

The total marketed production of natural gas in the U.S. between 1945 and 1975 has been documented to be 407.82 TCF.(4) During 1975 total net production of natural gas in the U.S. amounted to 19.72 TCF. If this annual production quantity remained the same, by 1979 the total cumulative consumption for the period 1945-1979 would be 486.7 TCF. On the other hand if the gas markets were able to grow 2 percent per annum then the total projected consumption by 1979 would be 490.71 TCF. If the markets grew at 3½ percent per year the total cumulation gas for the period 1945-1979 would be 493.84 TCF. The reason for adjusting past production figures through projections around 1979 is that it would appear reasonable to expect about 3 years 'lead time' before any strategic stockpile effort can be implemented in the U.S. Now assuming that some methane stockpile will, in principle be developed between 1980 and 1999, the quantity of gas on hand in stockpile by the year 2000 is the next consideration.

Using the total amount of gas which will have been cumulatively produced by the end of 1979, three premises have been bracketed:

1. Calculate a stockpiling scheme which would meet the condition of having <u>all</u> 100 percent of the gas cumulatively consumed on hand in stockpile by the year 2000,
2. Calculate a schedule to develop only 20 percent of consumed gas on hand by the year 2000, and,
3. Calculate the schedule which would permit having on hand only 10 percent of gas cumulatively produced (between 1945 and 1979) on hand by the year 2000.

It must be appreciated that each of the three schedules above will result in annual gas requirement which would not only meet the amount which must be set aside for storage but an existing and currently gas consuming market growing at the compounded rates of 0 percent, 2 percent, and 3½ percent per annum.

The annual gas requirements for each of the three schedules have been computed for each of the 0, 2, and 3½ percent per annum growth markets.

The annual reserves sufficient to meet the growing market and at the same time to build up to a predetermined stockpile are calculated as follows:

Let us say that we want to gradually develop a strategic stockpile equal to 486.7 TCF (total cumulative production between 1945 and 1979) by the year 2000. We shall further assume that between 1979 and 1999 the annual consumption of gas will remain static at 19.72 TCF. Furthermore we shall also assume that each year new additions to existing gas reserves, 10 TCF* will remain the same. The 10 TCF figure is obtained from DeGolyer McNaughton statistics(2) and represent new gas found each year in lower 48, new associated gas due to new oil, revision to old reserves.

Under the above conditions each year net amount required to build the 486.7 TCF in 20 years would be 486.7/20 = 24.34 TCF/year. This figure can be incorporated to an annual reserve calculation algorithm as follows:

Reserves as of the end of 1980 = Reserves as of the end of 1979 + 10 TCF new gas + 24.34 TCF addition to stockpile - 19.72 TCF to be consumed during 1979. Such year by year reserve figures have been calculated for 20% cumulative replacement and 10% cumulative replacement and for gas markets subject to growth of 0 percent, 2 percent, and 3½ percent per year.

The Figure 6 shows the manner in which the reserves would be built up if, hypothetically, a stockpiling policy of the entire 100 percent cumulative production between 1945 and 1979 was followed between the years 1980 and 2000. It may be noted that again 3 curves are shown one for each 0, 2, and 3½ percent per year growth markets. The apparent breakpoint on curves labeled 2 and 3½ percent correspond to years when the U.S. reserves would run out. The amount of additional gas necessary to build up such a stockpile is given in Figure 7. It can be seen that depending upon the 0, 2, and 3½ percent growth in national gas consumption the amount of natural gas needed each year first remains constant then must be abruptly increased to sharply higher rates at specific dates corresponding to indigenous reserves running out. The gas needed from additional sources is constant at the level of 24.34 TCF between 1980 and 1998, then jump to 29.42 TCF during 1999. For the same case with 3½ percent growth in the local market, the additional gas required for stockpiling remains first constant at 24.69 TCF per year during the years 1980 and 1989 then increases to 40.32 TCF during 1990 and to 48.88 during 1991 and so on. As expected, the case for 2 percent increase market is intermediate.

The case for totally replacing by the year 2000 the entire production cumulated between 1935 and 1979 is obviously quite unrealistic because of the staggering economic and engineering requirements involved. It is however included in these calculations only for bracketing purposes. Of the 407 TCF plus consumed between 1935 and 1975 perhaps it is more realistic to expect a stockpile developing 10 to 20 percent of that value.

These cases are presented in the following 4 figures. The Figure 8 shows the time trend in gas reserves which would end up with about 50 TCF in stockpile by the year 2000. The amount of gas (in addition to indegenous production) needed as additional stockpile gas each year is shown in Figure 9. It may be noted that for this particular scenario the additional gas required represent much modest and attainable figures starting constant at about 2½ trillion cubic feet per year.

The intermediate case of 20 percent target is given in Figures 10 and 11. In summary, if it is desired to build a strategic stockpile equal to say, 20 percent of gas cumulatively produced between 1945 and 1979, the amount of additional gas needed will range between 5 and 10 trillion cubic feet/year if our consumption is held constant. On the other hand if the U.S. consumption of gas is allowed to grow at the rate of 3½ percent per year the additional gas which must be available ranges constant at 4.94 TCF per year until 1989 then sharply increases to 20 by 1990 and about 30 TCF/year by 1991 uniformly increasing thereafter to about 40 TCF/year by 1999.

SOURCES FOR STRATEGIC STOCKPILE

When the market exceeds the supply and has to be curtailed, development of any stockpile obviously requires new sources of methane not presently available. As we look into the future, the possible new sources may be classified as short range intermediate and long range.

1. Short Range Sources

The short range sources for additional gas supply may include new natural gas to be found offshore and in continental lower 48, additional LNG imports and additional SNG from naphta and coal. All of the above sources may be expected to gradually increase and perhaps within the next ten years some gas may become available by pipelines from outside the U.S.

2. Intermediate Sources

The additional gas which may be available for strategic stockpile may include more LNG imports, gas from Arctic and methane from overseas in the form of methanol. Of these the methane-methanol-methane route appears particularly practical, and hopefully feasible.

3. Long Range Sources

If the short range supply covered the early eighties and the intermediate, the early nineties the long range supply must apply to the late nineties to figure in the strategic stockpile. This supply would include more methane from overseas in the form of methanol, substantial gas from arctic (hopefully by pipelines) and substantial gas from coal and wastes.

METHANE-METHANOL-METHANE ALTERNATIVE VERSUS LNG

Methanol, also called methyl alcohol, wood alcohol or methylated spirits is a colorless odorless water soluble liquid at room temperature. It's specific gravity is 0.80. It freezes at -144°F and boils at 148°F.

It is totally miscible with water and consequently in case of a spill it is rapidly dispersed. It burns with a clean blue flame, it does not pollute. It can be made from petroleum, shale oils, wood, from farm or municipal wastes and last but not least, significantly, it can be made from natural gas. It does not require specialized, refrigerated, cryogenic tankers for overseas transportation. It can be transported by regular atmospheric pressure, normal ambient temperature tankers.

Foreign natural gas can indeed be converted to methanol before it is transported to U.S. ports. Until only recently methanol from foreign natural gas was not looked upon as a viable alternative to LNG imports. Because of recent shifts in energy economics and because of recent breakthroughs in methane-methanol technology over the long shipping routes methanol became competitive with LNG. One additional reason which makes methanol route attractive is the cost and backlog problems which continue to affect adversely the LNG tanker schedules.

The conversion of methane into methanol(5)(6) is present day technology, currently available, viable, economical. There are two prominently commercialized processes: Lurgi and ICI. The chemistry, kinetics, equilibrium of both conversions methane into methanol and of methanol back into methane are also well known and present the basis for current day technologies.

A comparison between the two alternatives: natural gas in U.S. pipelines and storage from methanol-LNG-vaporization plant route and methane-methanol-methane route is involved and depends upon many engineering economic and geographic factors.(6) There has been papers supporting one or the other. Certain facts however became well accepted as a result of current interest on the subject:

Methane-methanol reforming is, in general, expensive and thermally inefficient. The cost of overseas methanol plants are at least twice of LNG plants. The LNG plant on the other hand must nearly always be sited on a port because it is prohibitively expensive to pipeline LNG from an inland liquefaction facility to port. The cost of shipping methanol is much cheaper and less distance intensive than LNG. In making comparisons, to the cost of LNG plant one must add the cost of natural gas pipeline to liquefaction site if the overseas gas field is inland. As the price of energy goes up, a much higher fraction of the delivered Btu cost becomes that of raw material at source. As the question of which alternative, LNG or methanol route is superior on engineering, economic, geographic or institutional grounds is not likely to be decided or resolved in generalities, it is fair to accept that a stockpile in natural gas will probably need both as soon and as much as possible. It now appears entirely possible that gas from Nigeria, Algeria, Caribbean, North Slope may be better prospects for LNG route while the gas from the Persian Gulf, Saudi, Australia, Siberia may be more suited to methanol route.

While a detailed comparison is clearly beyond the intent of this paper in order to fix orders of magnitude it may be appropriate to note that 35,380 std cubic feet of natural gas will yield 1 ton of methanol which in turn in U.S. will yield about 17,867 std cubic feet of SNG. This gives methane-methanol-methane route 50 to 75 percent overall thermal efficiency which compares with 80 to 85 percent for LNG route.

VENUE FOR STRATEGIC STOCKPILE

The first recorded use of underground storage dates back to 1915 where gas was first stored in a depleted natural gas field in Welland County, Ontario by National Fuel Gas Company.(7) A remarkable growth occurred since then resulting nearly in 7 trillion cubic feet of gas now in storage in 386 pools in 26 states.

Underground storage permits high load factor utilization of pipeline facilities, effective delivery to market, conservation through elimination of flare gas. The gas is stored in depleted gas oil or condensate reservoirs, in aquifers, and, in few cases, salt cavities.

If a strategic stockpile in natural gas is to be developed there exists four major areas of venue which may be selected for storage. These are:

1. Depleted gas reservoirs,
2. Depleted oil reservoirs,
3. Present underground storage reservoirs which includes aquifers,
4. Other environment for storing gas such as mines, caves, salt cavities, under water, etc.

The Table III shows the estimated proven reserves of natural gas between the years 1946 and 1973 for those states having most of the gas reserves in 'Lower 48'. Unused storage capacity for various states can be determined from the various declines which occurred over the years. Unused capacity in both depleted and storage reservoirs as well as pipeline compression facilities appears to be one of the major considerations in favor of developing a strategic stockpile.

Selection, reconditioning, testing, and evaluating of the prospective reservoirs appears to be a major task in need of a comprehensive technological assessment.

PROSPECTS AND PROBLEMS

The desirability of building up our natural gas reserves through judicious stockpiling is accepted by all preoccupied with the future of our energy supply. Prospects of healthy and growing economy, clean air, high standard and good quality living would be enhanced if significant quantities of natural or synthetic gas is stockpiled. The development of such a stockpile however will present enormous problems in economic, engineering, environmental and institutional areas. While the technical problems will certainly be challenging they may not be critical or controlling toward the achievement of stockpile objectives. The overall 'lead time' for such a stockpile depends upon economics, financing, scheduling problems, institutional constraints, and other social and political factors.

CONCLUSIONS

The present paper is the result of an energy seminar study at the University of Michigan conducted during 1976. It has recently been put in the form of a proposal to our federal energy agencies for assessment of a strategic stockpile.

Obviously, many questions have been raised the answers to which must await further engineering research. Some conclusions however may be reached at present on the basis of our energy picture as it appears today:

1. A strategic stockpile is not only desireable but critically needed for the overall energy requirements of our country,
2. Such a stockpile is possible,
3. Some stockpile is feasible,
4. How big a stockpile? where to store, how to store, the lead time, other problems must be further but conclusively investigated.

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TABLE I. Relevance Tree Representation of the Need For a Strategic Stockpile in Methane.

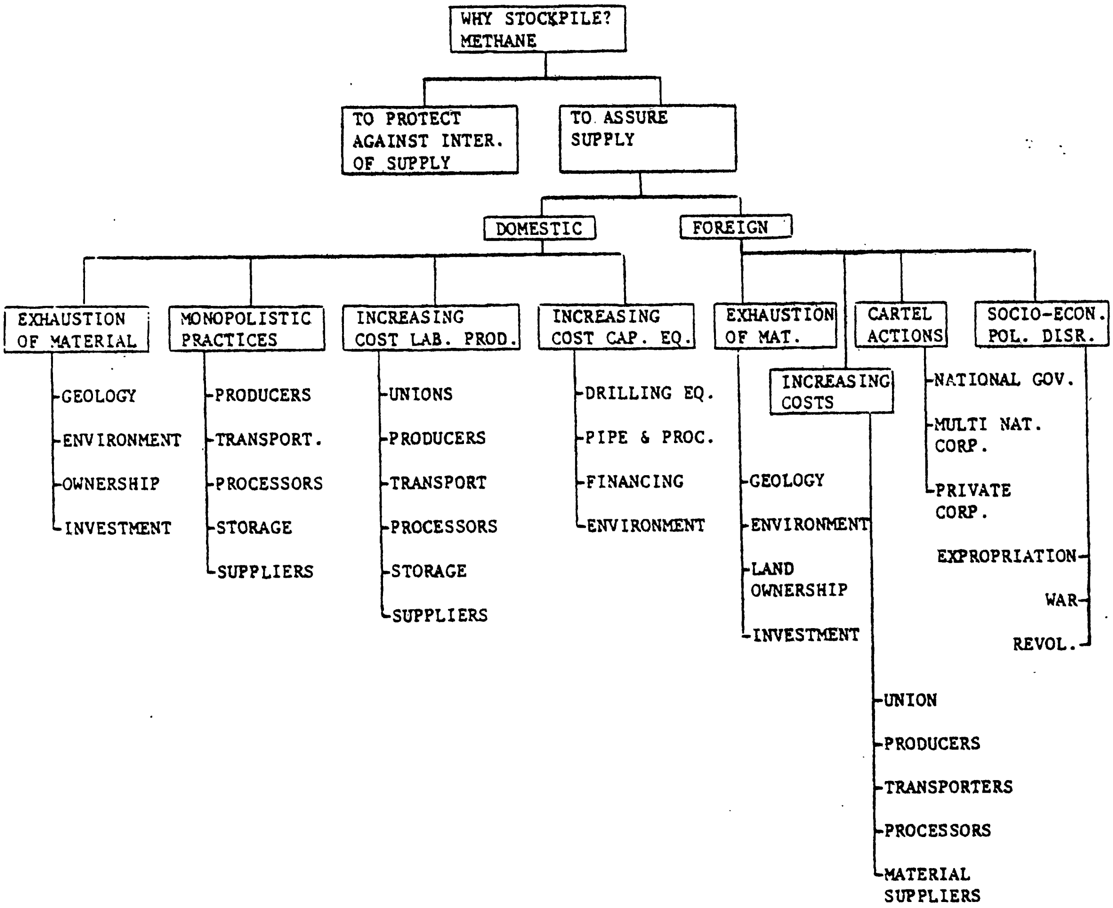

TABLE II. Revision to Indigenous Gas Reserves 1975 - 1976.

(Assumed growth in the market 0%)

1975 Reserves = 228.20 TCF

Consumption 1975-76 = 19.72 TCF

Additions to Reserves during 1976 = 10.00 TCF

Reserves Estimated for 1976 = 228.20 - 19.72 + 10.00 = 218.48 TCF

TABLE III. Estimated Proved Recoverable Researves of Natural Gas in U.S. in Selected Year in TSCF (Reference = Mineral Yearbook, Bureau of Mines).

* Volumes are reported at a pressure base of 14.65 psia, 60°F

\+ Volumes are reported at a pressure base of 14.73 psia, 60°F

STATES	Reserves of Natural Gas In U.S. In The Year (as of Dec. 31) In TSCF						
	1946*	1951*	1956*	1961*	1966+	1972+	1973+
California	11.13	9.48	8.75	9.10	8.47	5.33	5.20
Alaska	--	--	--	0.93	2.95	31.46	31.64
Kansas	13.68	13.46	17.57	10.10	15.92	11.94	11.72
Louisiana	22.41	29.01	45.05	66.03	83.68	74.97	69.15
New Mexico	5.90	11.59	23.47	14.76	14.75	12.34	12.49
Oklahoma	10.74	11.80	13.78	17.35	20.12	14.49	14.10
Texas	86.36	105.65	112.73	119.84	123.61	95.04	84.94

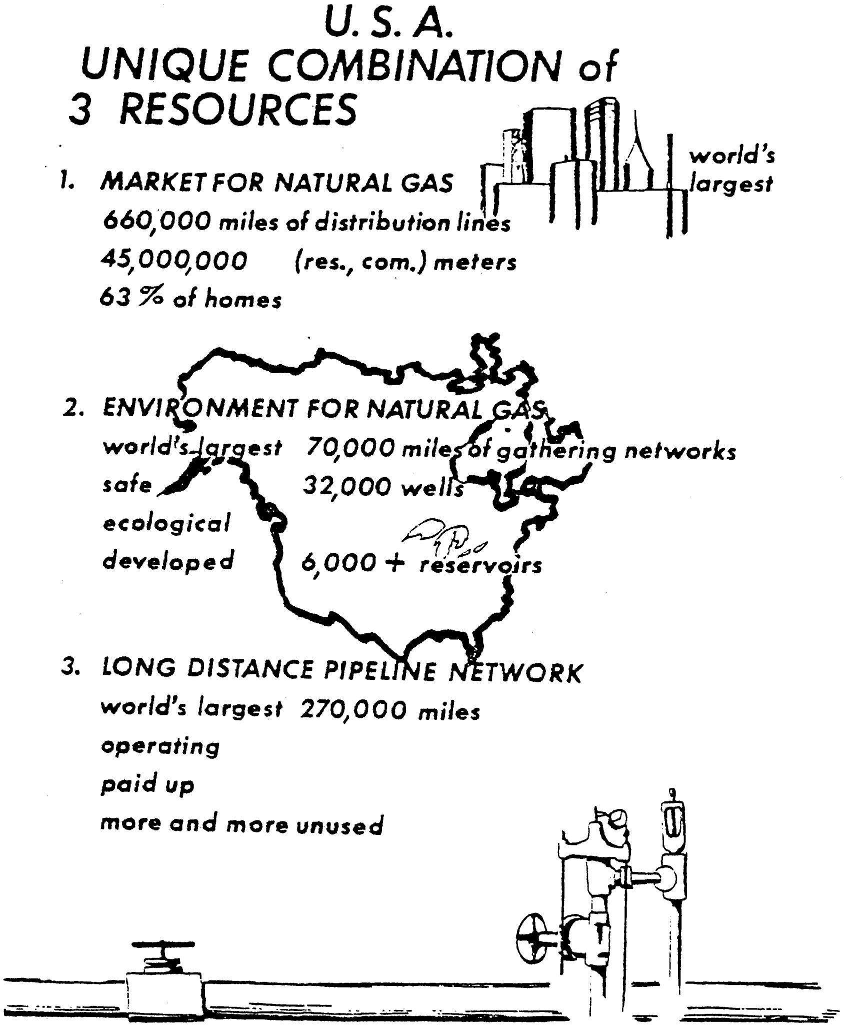

FIG. 1 - U.S.A. UNIQUE COMBINATION OF THREE RESOURCES.

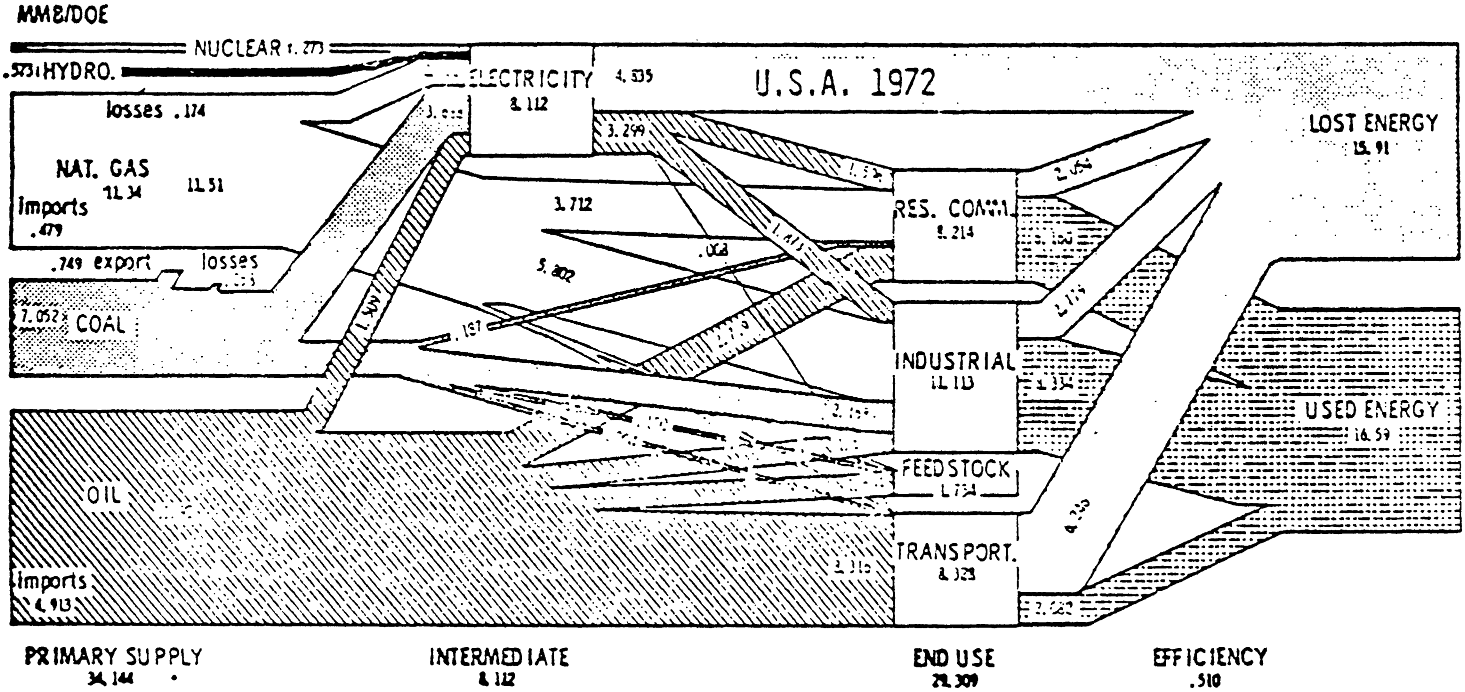

Fig. 2 - Distribution of energy supply and demand (U.S.A. 1972).

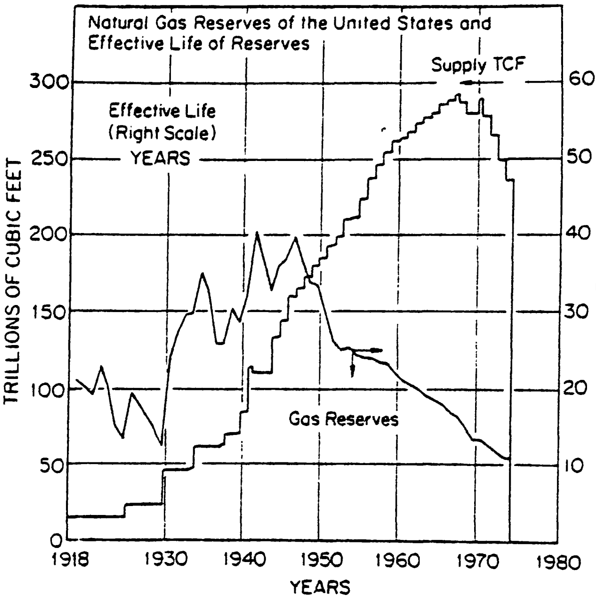

Fig. 3 - Natural gas reserves of the United States and effective life of reserves.[2]

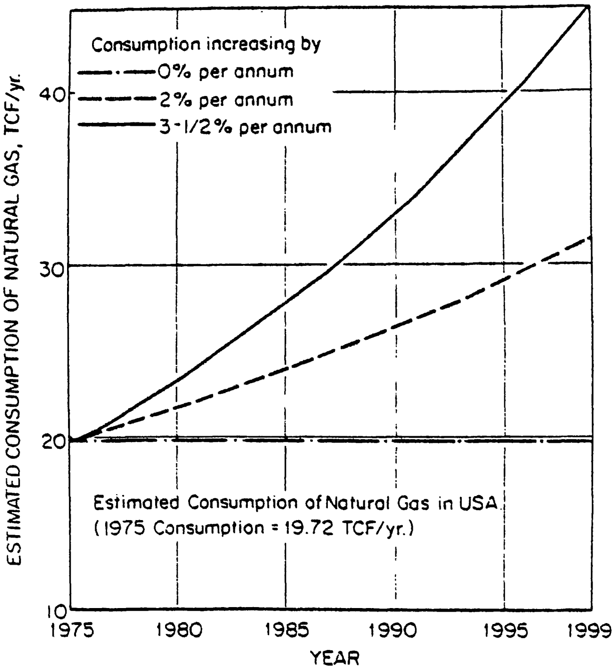

Fig. 4 - Estimated consumption of natural gas in U.S.A.

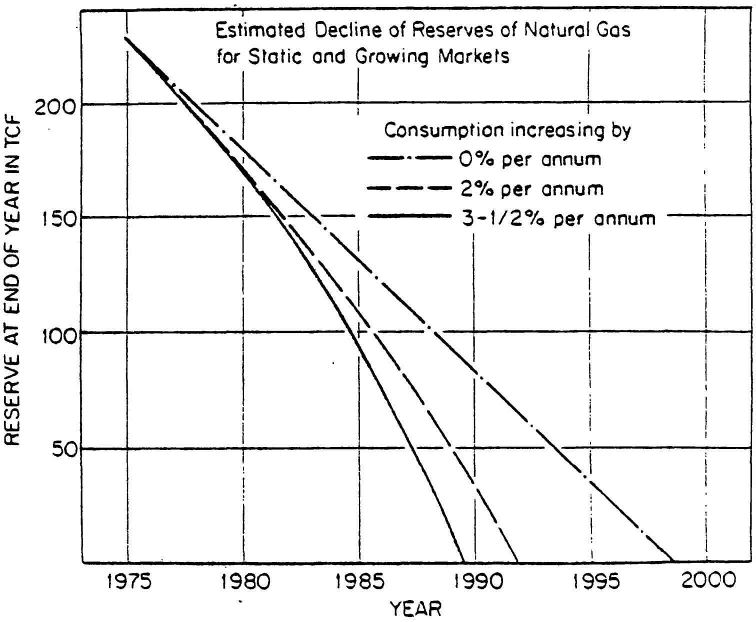

Fig. 5 - Estimated decline of reserves of natural gas for static and growing markets.

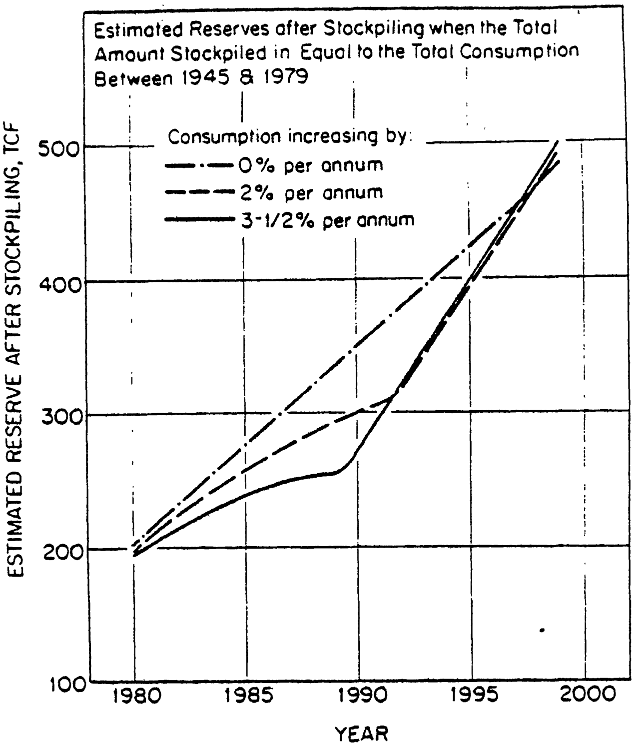

Fig. 6 - Estimated reserves after stockpiling when the total amount stockpiled is equal to the total consumption between 1945 and 1979.

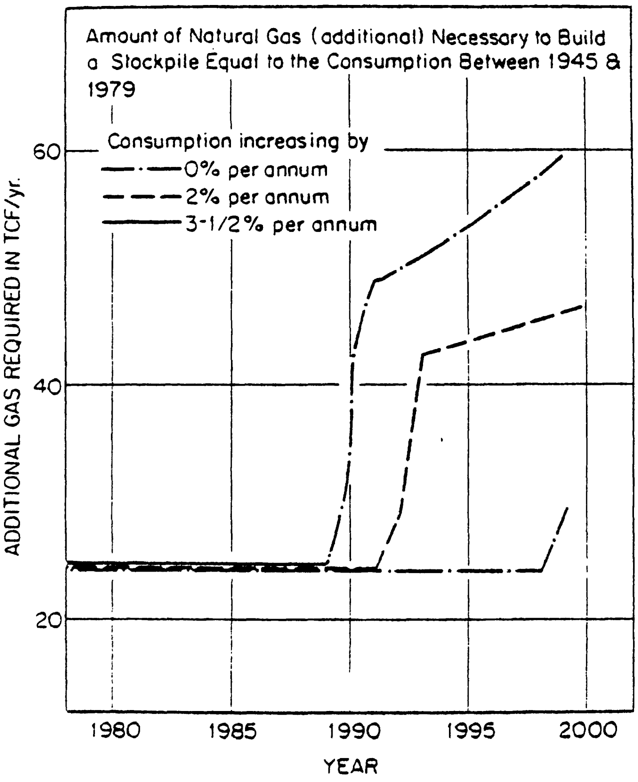

Fig. 7 - Amount of natural gas (additional) necessary to build a stockpile equal to the consumption between 1945 and 1979.

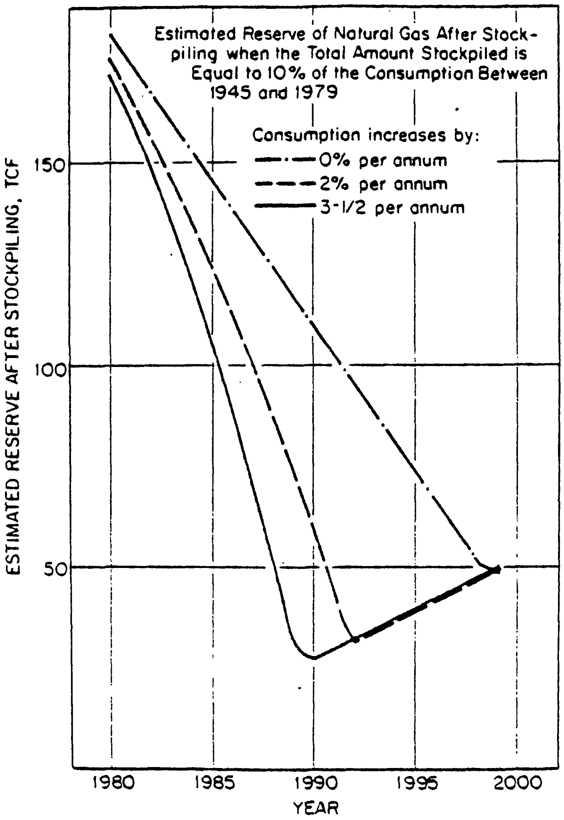

Fig. 8 - Estimated reserves after stockpiling when the total amount stockpiled is equal to 10% of total consumption between 1945 and 1979.

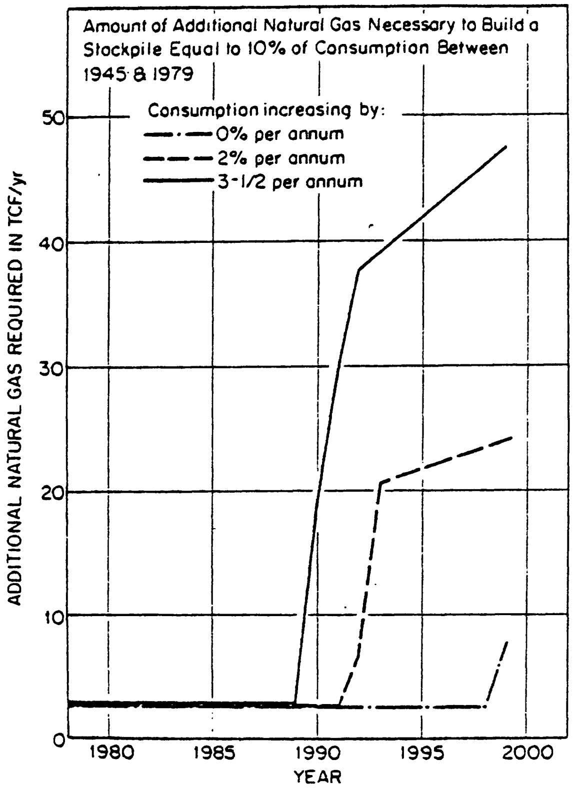

Fig. 9 - Amount of natural gas necessary to build a stockpile equal to 10% of consumption between 1945 and 1979.

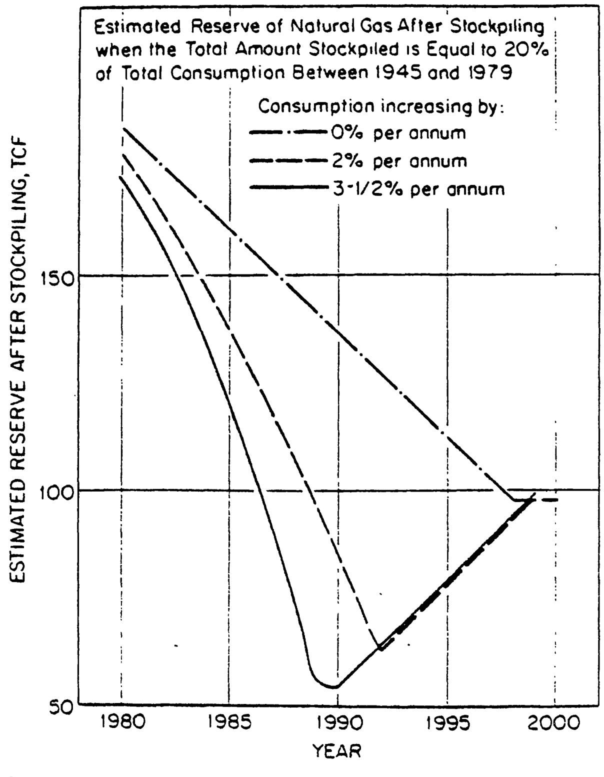

Fig. 10 - Estimated reserves of natural gas after stockpiling when the total amount stockpiled is equal to 20% of total consumption between 1945 and 1979.

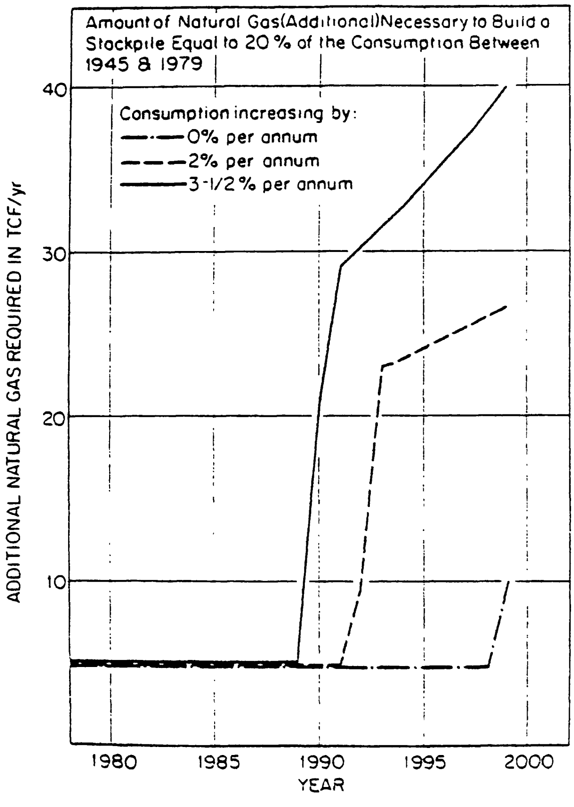

Fig. 11 - Amount of natural gas necessary to build a stockpile equal to 20% of the consumption between 1945 and 1979.