Potential CTR Requirements for Helium Up to the Year 2020

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August 28, 1973

UWFDM-83

FUSION TECHNOLOGY INSTITUTE

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INTRODUCTION

It must certainly be apparent to everyone that we are in the midst of many crises; energy, food, and materials resources to name just a few. Our attempts to solve the energy crisis have taken many forms such as more efficient utilization of our present fossil fuels, development of fission reactors and research into more advanced sources of energy.

One of the most promising future methods for generating electricity is that of controlled thermonuclear fusion. It certainly will solve our long term fuel problems as we have enough deuterium and lithium (the basic fuels for a D-T fusion reactor) to supply the present electrical needs of the entire world for over 10,000 years. However, we must carefully study the non-fuel materials requirements that would stem from the development of controlled thermonuclear reactors (CTR's) lest we induce a crisis in resources in our attempt to solve the crisis in energy.

Close examination of CTR technology reveals that if we are to capitalize on its potential for high thermal efficiencies, there will be large requirements for relatively scarce refractory metals such as V, Nb, or Mo. This situation can only be somewhat relieved by the use of lower temperature iron based alloys if future shortages of Cr, Ni, or Mn arise. Another important consideration in determining potential resource problems is the plasma confinement approach which will prove to be most economical for CTR's; inertial or magnetic. If the latter route proves most promising (as it appears today) then, for reasons of economics, the magnets required for CTR's must be superconducting. Such a system again places large demands on the refractory metals Nb or V because their alloys (Nb-Ti, Nb_3Sn, V_3Ga) are currently the best superconductors from an engineering standpoint.

Another, perhaps equally serious, requirement of CTR's which use superconducting magnets is the need for large amounts of helium. It has been known for some time that the readily accessible helium supplies of the world are rapidly being wasted into the atmosphere and, ultimately into space. There is a real question of whether there will be any helium available to supply the CTR's of the future and even if there is enough helium, how long it will last.

The object of this paper is to examine how much helium would be required by the development of fusion power if the magnetic confinement schemes prove to be the most efficient. This demand will be compared to our present and projected reserves. Such an assessment is at best highly speculative, based on our knowledge of the CTR technology of today and without the benefit of future scientific breakthroughs in superconductor technology. Nonetheless, we must make such assessments today if for no other reason than to clearly identify problems which can hopefully be solved at some later date.

Question: What are our present sources of helium?

Helium is the product of radioactive decay of uranium and thorium isotopes. After a long series of radioactive events these elements produce isotopes of lead and many helium atoms as shown below.

$$U^{238} \rightarrow 8He + Pb^{206}$$
$$U^{235} \rightarrow 7He + Pb^{207}$$
$$Th^{232} \rightarrow 6He + Pb^{208}$$

The helium atoms diffuse out of the rocks containing U and Th and are often collected in large pockets of natural gas. However, not all natural gas contains helium and only that gas which contains helium in concentrations of >0.3% can be economically processed at the present time.

Practically all of the known helium reserves in the world are in the U.S.[1] Furthermore, over 98% of the U.S. reserves are in the Panhandle fields of Texas, Oklahoma, and Kansas. The total amount of helium available from U.S. sources has been estimated by Lipper[2] in 1970 and the information is summarized in Table I.

Table I

Total U. S. Resources of Helium[2]

	Billion Cubic Feet at 16°C and 760 Torr
Proven	250
Probable	155
Possible	220
Speculative	310
Total	935

D. Evans[3], the Director of the Potential Gas Agency, Mineral Resources Institute, Colorado School of Mines, has also described the U.S. helium supply picutre as of June 1973. The results are summarized in Table II.

Table II

Anticipated U.S. Resources of Helium[3]

% Helium	Billion Cubic Feet at 16°C and 760 Torr	
0.006 to 0.007	58.4	
0.024	95.3	
0.090 -0.091	13.9	
0.094	169	
0.106	77.4	
0.240	161.6	
>0.3 as of 1968	165.3	Proved
>0.3 as of 1968	24.6	Probable
Total	765.5	

Finally, it should be noted that the helium concentration in the atmosphere is constant at 5.24 parts per million.[4] It therefore has been calculated that the total quantity in the atmosphere is ~720,000 billion cubic feet.

It must be quickly pointed out that the cost of obtaining helium from sources with low concentrations is quite high. Laverick's[5] estimate of the procurement costs of helium are given in Table III.

Table III

Price of Helium from Natural Gas

Helium Concentration	$/Thousand Standard Cubic Ft. (Mscf)
0.3%	13
0.1	72
0.006	500-700
<0.0006(atmosphere)	1000-3000

Using the data from Tables II and III, one can estimate that the U.S. has ~600 billion cubic feet of helium at prices ranging from $13 to ~$100 per thousand cubic feet in 1973 dollars.

Question: How Much energy does it require to extract helium from the atmosphere?

There are two possibilities that must be considered; the energy required to extract helium directly from the air with oxygen and nitrogen as the main by-products, or the energy required to extract helium from the exhaust streams of liquid oxygen plants.

It has been estimated that the U.S. production of liquid oxygen is $\sim 10^5$ tons per day and $\sim 10^3$ tons per day of liquid nitrogen. If one were to use the exhaust from the liquid oxygen plants then such a stream would contain almost ~165 million scf of helium per year. We shall see later that this number is only a factor of 3-4 lower than our present consumption rate and future expansion of the liquid oxygen industry, mainly for steel production, may overcome this difference.

The energy required to produce one scf of helium gas at 220°K from air at 300°K has been calculated by I. Sviatoslavsky to be ~400 kw-hr (see Appendix A). However if the output of the liquid oxygen plants can be used, the incremental energy cost to produce one scf of helium gas at 20°K is 2.41 kw-hr. (see Appendix B)

It is presumed that Laverick's[5] estimates in Table III for ~$3000/1000 scf of helium from the atmosphere are based largely on electricity at a cost of ~10 mills/kw-hr with credits for selling oxygen and nitrogen. On the other hand if the demands for helium do not exceed that amount already being handled by liquid oxygen plants, then the cost of helium extraction could drop by a factor of ~100 from the $3000/1000 scf figure. This possibility needs further study, in addition to what effects large amounts of cheap oxygen might have on the steel industry if we had to pursue the more expensive extraction method. The effects of large nitrogen production should also be investigated.

We are now in a position to estimate how much helium could be produced from the electricity available from a 1000 MWe electric plant running an air 80% plant factor. If the helium comes from air at 300°K it is calculated that our reference plant could provide the energy for 17.5 million scf of helium per year. On the other hand if the exhaust stream from liquid oxygen plants could be used, approximately 2.9 billion cubic feet of helium could be produced per year.

Question: What is the present helium consumption rate and what is it being used for?

In order to understand our present situation, it is worthwhile to look at our past history. Figure 1 shows the helium sales in the U.S. from 1920 through 1972.[6] The large increase in sales during 1940-1946 was related to the use of helium in lighter-than-air craft. In the early 1950's, a large demand for helium came from NASA where it was used as a presurizing media in rockets. The drop in sales from 1966-1970 reflected the reduced requirements of the space program and in 1972, 601 million cubic feet were sold.

A summary of some of the uses for helium is given in Table IV for the years 1969 and 1970. Figures are also included for the amount of helium which was wasted (vented to the atmosphere in burning natural gas) and that which was stored in the Cliffside field for 1969. Corresponding figures were not available to the author for 1970, 1971 and 1972. Unfortunately, the storage activities were stopped as of April 1973[8] and we are simply allowing a large fraction of the helium contained in natural gas (>90%) to be vented to the atmosphere. Therefore, while we are using some 600 million cubic feet a year we are dumping almost 10 times that amount into the atmosphere where it will be 80 to 230 times more expensive to retrieve.

Question: What will happen to helium resources up to the year 2000?

Since helium is part of our natural gas supply, it will be extracted from the gound in direct proportion to the demand for natural gas as a clean source of energy. Once it is out of the ground three things can happen to it;

a. It can be separated from the gas and stored,

b. It can be separated from the gas and utilized in the areas previously discussed,

or c. It could be carried along with the natural gas and vented to the atmosphere.

Haynes[9] has calculated how much helium will be available from the rich natural gas reserves (> 0.3% He) up to ~2000. His results are shown in Figure 2. It is seen that the annual volume of helium increases from ~10.5 billion cubic feet in 1972 to a maximum of 11.5 billion cubic feet in 1976. After this peak is reached the annual production of helium from natural gas will fall as we use up our gas reserves. Haynes projects that we will run out of this source of helium around the year 2000. Once

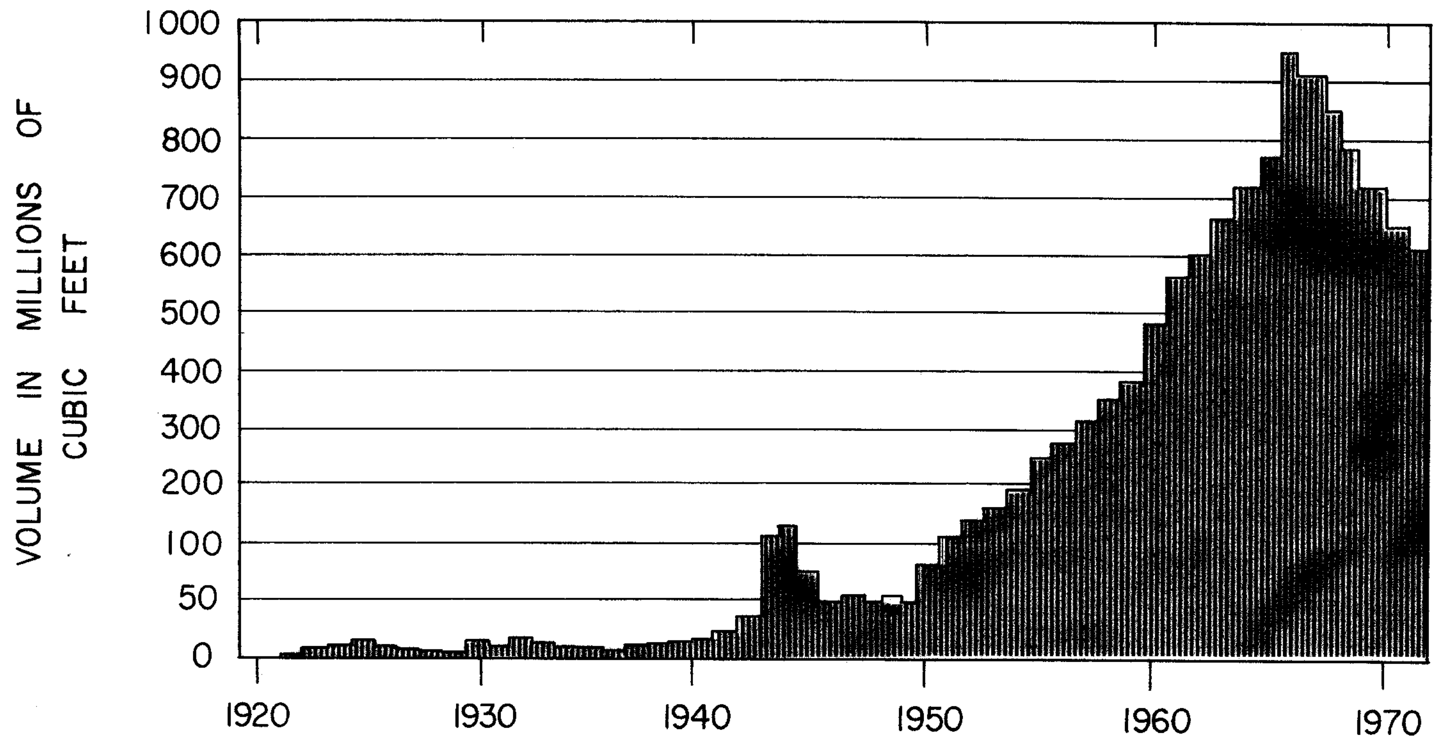

FIG. I Helium Sales in the United States, 1920-72
Adapted from Ward and Pierce

Table IV

Annual Consumption of Helium

	Million Cubic Feet at 16°C and 760 Torr 1969 [a]	1970 [c]
Wasting	3620 [b]	?
Aerospace	150	237
Inert Protective Atmosphere	90	68
Research	?	65
Welding	120	63
Lifting Gas	72	45
Leak Detection	55	42
Cryogenics	102	33
Chromatography	23	14
Heat Transfer	?	9
Synthetic Breathing Mixtures	2	4
Medical	3	7
Exports	?	60
Storage	4700 [b]	?

(a) Reference 7 except where noted.
(b) Reference 1.
(c) Bureau of Mines - via Reference 5.

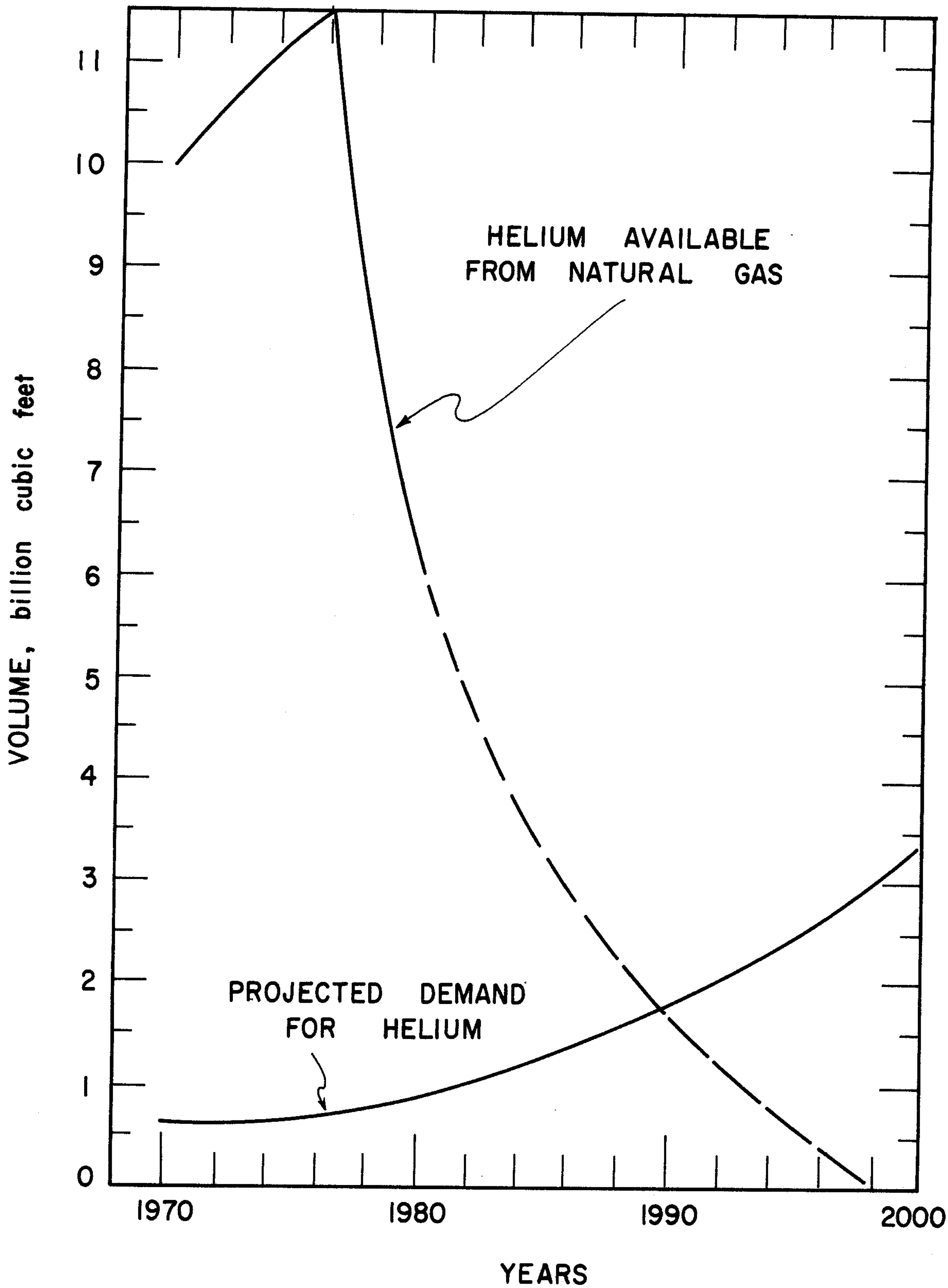

FIG. 2 ESTIMATED ANNUAL VOLUME OF HELIUM AVAILABLE IN RICH NATURAL GAS FROM PROVED RESERVES (Adapted from Reference 9)

the rich helium containing reserves are used up, we will be forced to extract helium from storage facilities or from much leaner sources such as those given by Evans in Table II.

The information in Figure 2 is relatively independent of the demand for helium so it is of interest to see how much of the extracted helium could be used directly. Estimates of the demand for helium have been made by Clark and Walker,[7] the Stanford Research Institute,[5] and the Bureau of Mines and these are listed in Table V. The estimates for the year 2000 vary from 1400 to 6500 million cubic feet. A simple average of all of these values is a 3400 million cubic feet demand per year in 2000. Since the use in 1972 was 601 million cubic feet, this represents a 6.4% annual increase in the helium demand from 1972 to 2000, a completely reasonable value in view of the increasing demand for other mineral resources. (Note that helium use increased at an average rate of ~13% per year in the time period from 1960-1966.) The projected demand is also shown in Figure 2 and it can be seen that if we do not store any helium, then we will have to start extracting helium from other sources after the year 1990. Obviously the first approach would be to use the some 38 odd billion cubic feet now stored in the Cliffside fields. This helium would last approximately to the year 2005 afterwhich we would be forced to rely on leaner and leaner supplies with of course, higher and higher costs per unit of gas.

At a continued 6.4% annual increase in the helium demand, we would use up the projected U.S. resources of 765 bcf (Evans)[1] or 935 bcf (Lipper)[2] in another 43 or 46 years respectively. Hence we might say that the U.S. has helium resources in the ground that will allow us a 6.4% growth rate in the use of helium up to the years 2048-2051. After that point in time we would probably have to "mine" the atmosphere for helium.

Up to now, we have not considered how fusion might effect these numbers. Let us now investigate that question.

Question: When could fusion reactors become a commercial reality so that they could have a significant impact on the helium demand?

The USAEC schedule to CTR commercialization will be assumed for this study.[10] This schedule is shown in Figure 3 and it calls for fusion feasibility to be demonstrated by 1980; a fusion test reactor to be built by 1984, a first experimental power reactor by 1989, a second experimental reactor by the mid 1998's and the first commercial demonstration plant to go on line shortly after the year 2000.

Table V

Projected Use of Helium up to 2000

Annual Rate-Million Cubic Feet

Year	1975	1980	2000	2025	2050
Bureau of Mines (5)	--	--	1,400-3,600	--	--
Stanford Research Institute (5)					
(High)	--	--	>3,000	12,000	44,000
(Low)	--	--	2,400	6,200	16,500
Clark & Walker (7)	1,000	1,900	∿6,500	--	--

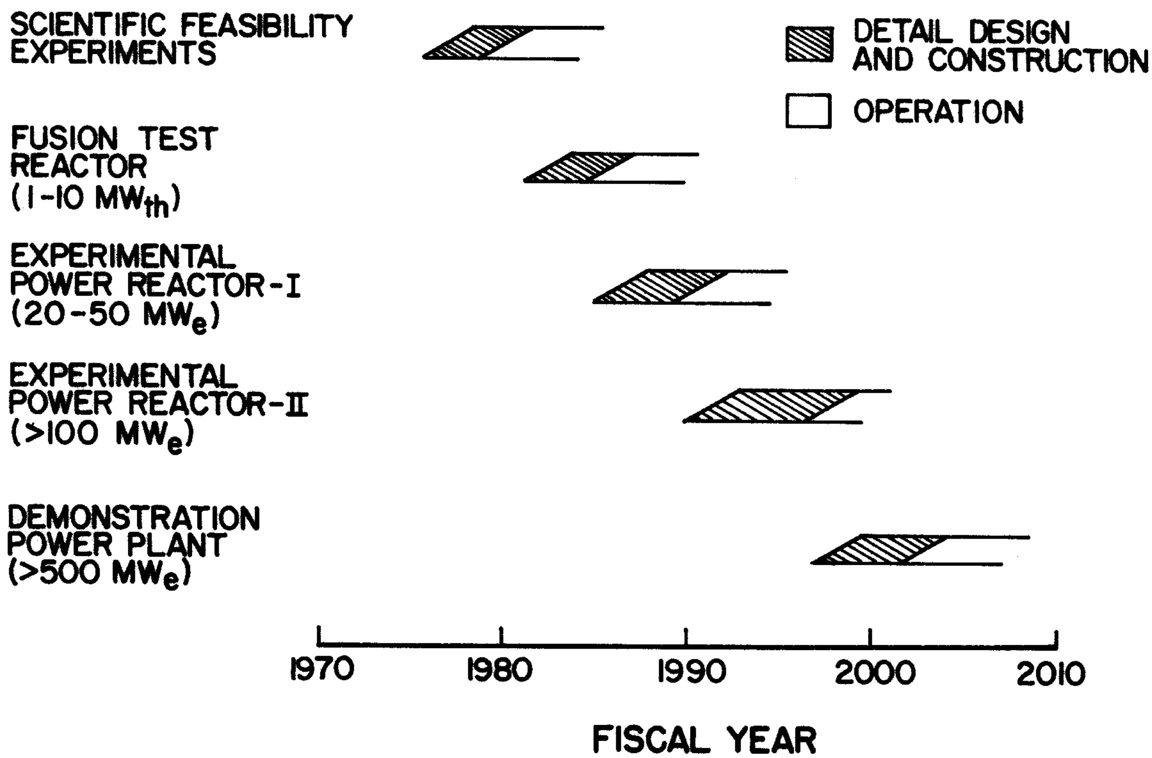

FIG. 3 BAR CHART INDICATING PHASING OF MAJOR STEPS IN A FUSION-REACTOR DEVELOPMENT PROGRAM.

Question: What is the expected U.S. installed electrical capacity in the year 2000?

There have been several estimates of the demand for electricity between now and the year 2000.[11] These estimates are summarized in Table VI. A simple average of the values in Table VI predict a total installed electrical capacity of 634,000 MWe in 1980, 1,150,000 MWe in 1990 and 1,839,000 MWe in the year 2000. It is interesting to note that the above values represent a 6.1% annual increase in electrical demand between 1980 and 1990, followed by a 4.8% annual increase between 1990-2000. Another way to interpret the numbers in Table V is that the electrical installed capacity is expected to increase at an annual rate of 5.5% from 1980 to the year 2000.

Several estimates of the installed nuclear capacity are shown in Table VII along with a simple arithmetic average of the values. It can be seen that the installed nuclear capacity rises very fast from ~6,000 MWe in 1970 to ~138,000 in 1980, ~482,000 in 1990 and to ~990,000 MWe in the year 2000. In both Tables VI and VII, the Associated Universities Inc. (AUI)[12] projections seem to be the most conservative from the standpoint of total and nuclear installed capacity. The AUI report also projects the mix of electrical generating capacity to the year 2020. Therefore, in order not to overestimate the demand for electricity, or for fusion power, and to obtain results out to 2020, we will use the AUI's estimates in this study. The author thinks such an assumption is justified in view of increasing difficulties in development of new power stations and the growing awareness of the public that there is a limit to our vital resources. The reader should take note that the estimates in this report will tend to be lower limit numbers which will underestimate the demand if we continue on our present rate of growth (>7% per year) in electrical generating capacity.

A conservative estimate of the situation in the year 2000 is given in Table VIII.

Table VI

Estimated Installed Electrical Capacity in the U.S.[11]

Study	1970	1980	1990	2000
		Thousands of MWe		
AEC-WASH-1139	349	630	1150	2000
Interior Dept.		660		1880
FPC Nat. Power Survey	340	665	1260	
Westinghouse		590	1165	
Assoc. Univ. Inc.[a]	~352	~625	1023	1636
Average		634	1150	1839

(a) Reference 12 and interpolation of AUI's numbers.

Table VII

Estimated Installed Electrical Capacity from Fission Reactors in the U.S.[11]

	1970	1980	1990	2000
		Thousands of MWe		
AEC-WASH-1139 (High)	6	144	602	1500
(Low)	6	127	412	825
(Most Likely)	6	132	508	1200
Interior Department		120		960
FPC Nat. Power Survey	6	147	500	
Nat. Pet. Council (case III)		150	500	980
Assoc. Univ. Inc.[12](a)	~5	140	420	829
Average	~6	138	482	992

(a) Interpolation of AUI's Numbers

Table VIII

Projected Installed Capacity in 2000
Used for This Report

Hydroelectric	72
Fossil	735
Fission	829
Total Electrical Demand	1636

Table IX summarizes the projected mix of electrical generating units from 1969 thru 2020 as given in the AUI report.(12) It should be noted that allowances have been made for a drop in the traditional annual rate of demand from 7.2% in the 1950's to 5.9% for 1969-1977, 5.1% for 1977 to 2000, 4.25% for 2000 to 2010 and 3.9% for the period 2010 to 2020. Figure 4 graphically depicts how the various forms of energy (i.e. hydroelectric, fossil and fission) arepredicted to satsify the demand for electricity.

Question: How fast could fusion penetrate this market?

It seems reasonable that fusion might penetrate the electrical generating market at a rate similar to that experienced by nuclear fission reactors into the fossil dominated electrical generating market.(13) The only scientific limitation to the penetration of CTR's is the doubling time for tritium production and that is on the order of several months to a year. This problem will be most severe in the early years of CTR introduction but should not inhibit growth after 5 years or so. Figure 5 shows a smooth curve for the fraction of new additions which were nuclear from the year at which fission became economically competitive. Using the data in Table IX for calculating what fraction of new additions to the electrical generating market beyond the year 2000 should be fusion powered, we find the results presented in Table X and depicted in Figures 6a and 6b. It was assumed that the CTR additions would be at the expense of fission and fossil plants proportionate to their projected increase in that time period. Variations on this assumption are the subject of another paper.(14)

Table IX

Projected Mix of Electrical Generating Units in the U.S.[12]

(10^3 MWe)

Without Fusion

	1969	1977	2000[a]	2010	2020
Hydro	53	53	72	79	86
Fossil	275	381	735	1047	1360
Fission	4	90	829	1358	2182
	332	524	1636	2484	3628

(a) extrapolated

It is interesting to note that the present analysis indicates that fusion reactors could be generating ~29% of the total electricity in the country at the year 2020 which would amount to 1063 x 10^3 MWe.

An interesting sidelight to Figure 6 is that the minimum doubling time for the single plant in the year 2000 is ~4 months, in 2001 it is almost 8 months in order to meet the projected growth rate, required for the plants in 2001, in 2002 it is ~1 year, it is extended to 5.4 years at 2010 and is almost 10 years at the year 2020. These numbers can be translated into minimum required breeding ratios by assuming the cycle time of 1 day for tritium in the reactor[15]. One finds that breeding ratios of 1.16 are required in the year 2000, 1.04 in 2002, and 1.02 and lower after 2005.[15] Since it is not difficult to calculate breeding ratios of 1.3-1.5 for current facilities, one can see that we will have to "spoil" breeding after the first few years or switch to an economy where we have mixtures of breeders and burners. This topic will be addressed in more detail in the future.

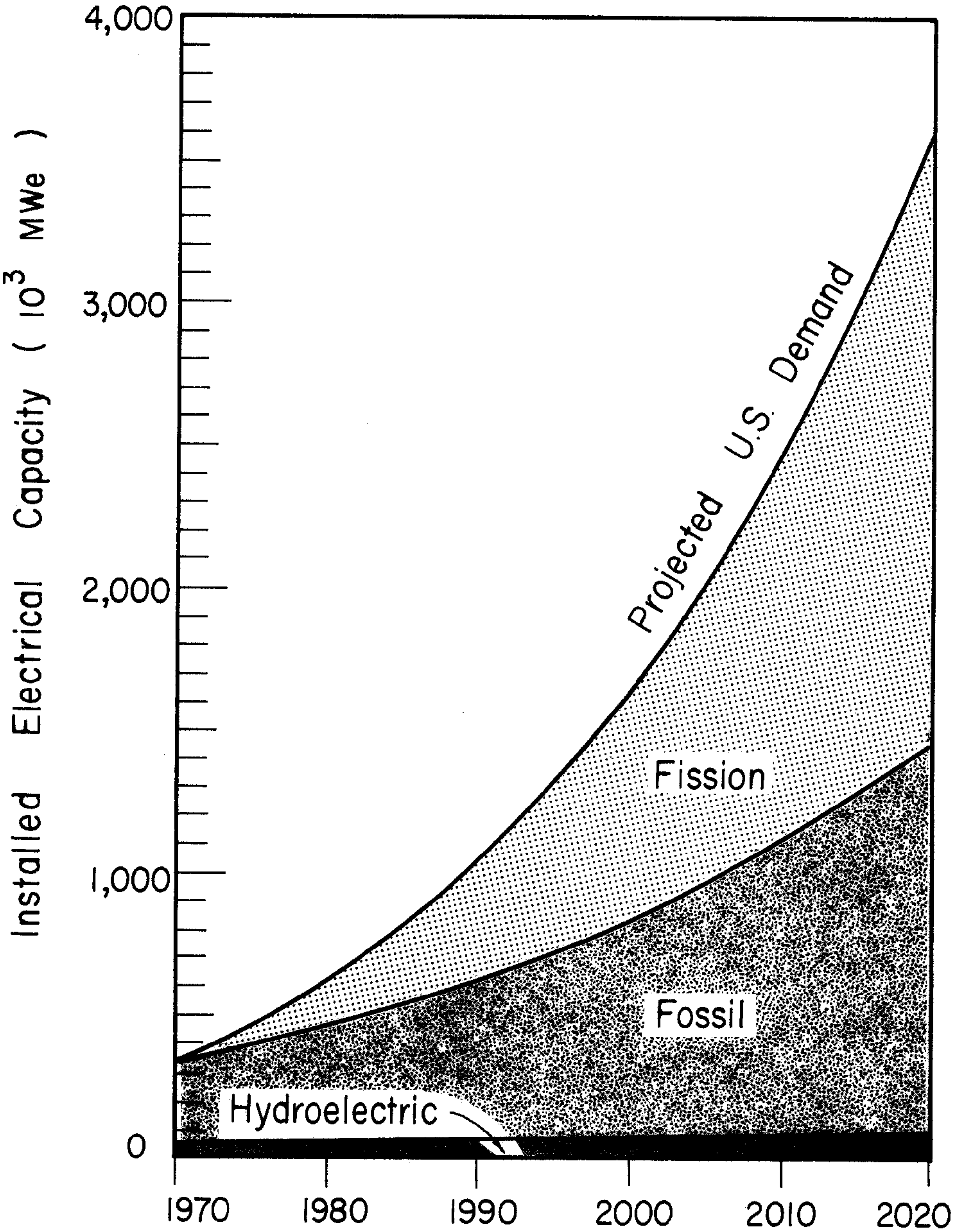

FIG. 4 Projected Mix of U.S. Electrical Generating Capacity

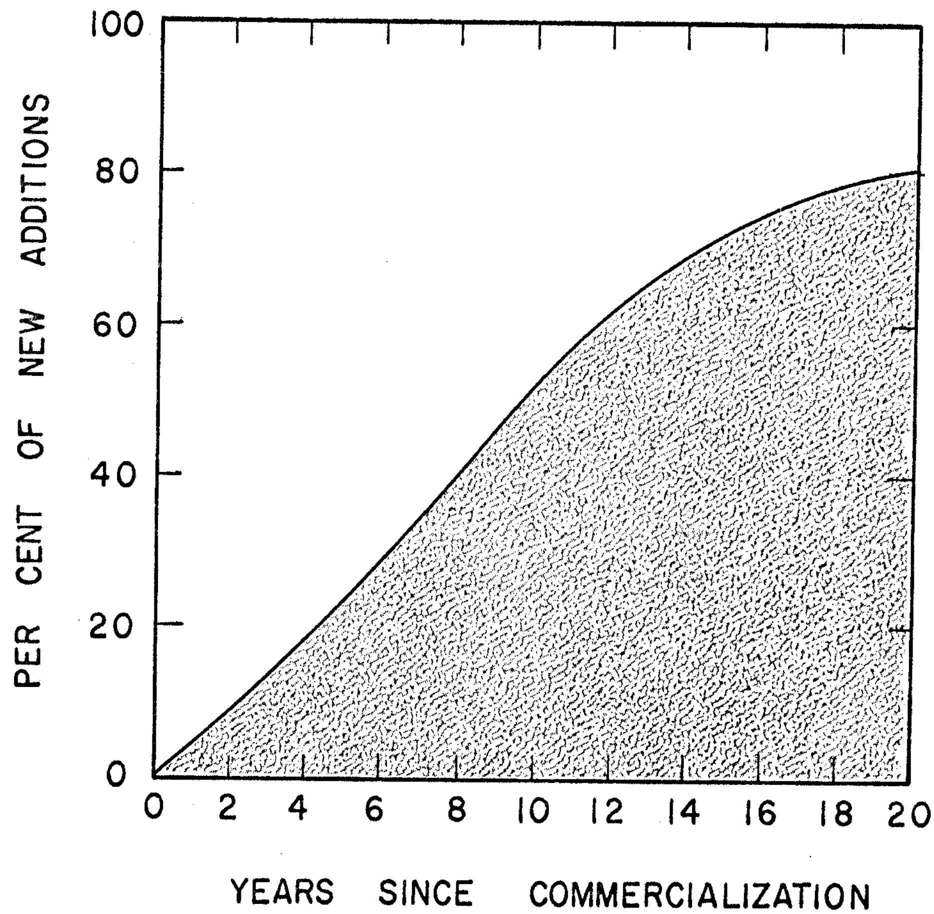

FIG. 5 PROJECTED PENETRATION OF FUSION INTO ELECTRICAL GENERATING MARKET

TABLE X

Projected Penetration of Fusion Into the Electrical Generating Market After the Year 2000

Year	10^3 MWe Added	10^3 MWe Cumulative
2000	1	1
2001	2.8	3.8
2002	5.8	9.6
2003	9.9	19.5
2004	14.2	33.7
2005	19.0	52.7
2006	24.1	76.8
2007	30.5	107.3
2008	37.4	144.7
2009	44.8	189.5
2010	52.8	242.3
2011	55.1	297.4
2012	61.2	358.6
2013	67.5	426.1
2014	73.2	499.3
2015	79.3	578.6
2016	85.7	664.3
2017	91.2	755.5
2018	97.0	852.5
2019	101.9	954.4
2020	108.3	1062.7

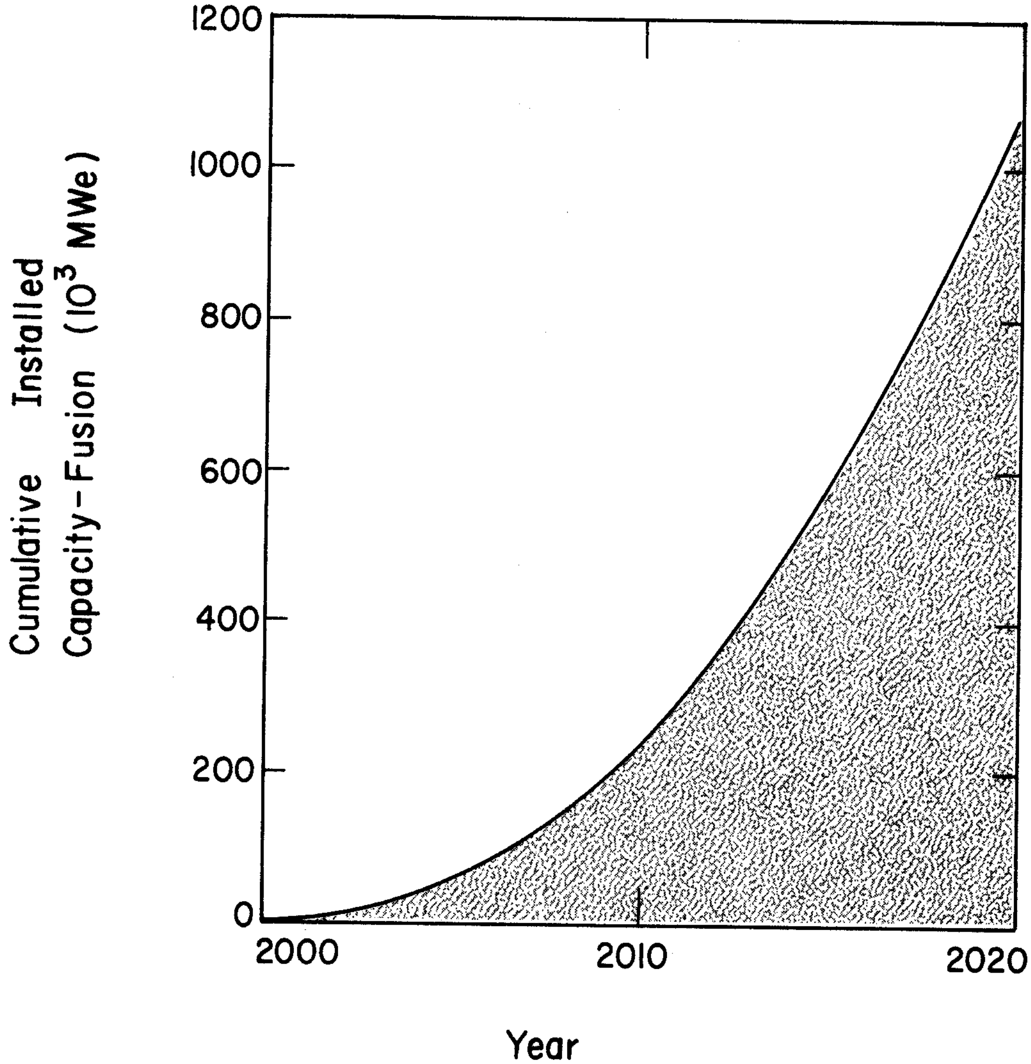

FIG. 6a POTENTIAL FUSION POWER IN THE PERIOD 2000-2020

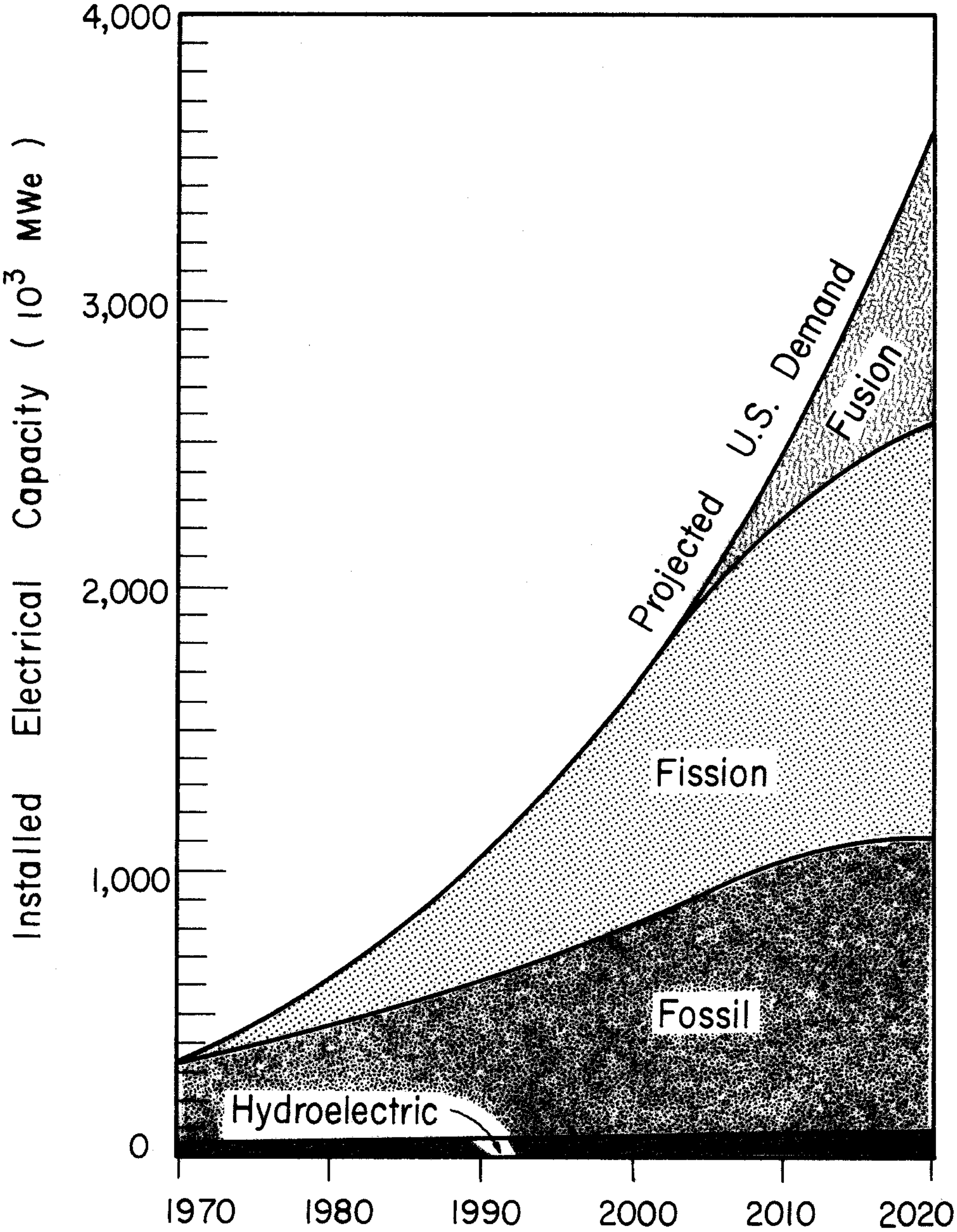

FIG. 6-b Projected Mix of Electrical Generating Capacity with the Introduction of Fusion

Question: How much helium is required per MWe in CTR's?

This number can not be determined very precisely at this time and the calculated values vary by more than an order of magnitude depending on which magnetic confinement scheme is used, i.e. pulsed, mirrors, or tokamaks. However, we can establish a range of possibilities and we will make some observations about the extremes.

The largest amount of helium used in a CTR is that used for magnet cooling. Table XI summarizes the calculated numbers for five reactor designs.

Table XI

Helium Requirements for Magnet Cooling in Various CTR Designs

	Power (MWe)	Liquid Liters	1000 scf/MWe
Tokamak-PPPL[16]	1840	647,000	10.3
ORNL[17]	2000	2,270,000	28.0
Wisconsin[18]	~1500	450,000	10.6
Theta Pinch LASL[19]	4600	10,000,000	57.9
Mirror LLL[20]	270	340,000	13.8

The large number for the LASL system is attributable to the magnetic energy storage system required for that reactor concept. It is not readily apparent why the ORNL design uses ~3 times as much helium as does the Wisconsin & PPPL design but the difference should not be over-emphasized at this early stage of reactor design. It should also be noted that loss rates of ~5% per year might be expected in the currently designed system.

Another potential use for helium in CTR's is as a coolant for the blankets. In fission reactors such as Peach Bottom and Ft. St. Vrain, the amount of He required per MWe to cool the reactor is ~2400 to 2600 scf per installed MWe.[7] It is reasonable to assume, on the basis of the above numbers, that CTR's could use 2500 scf/MWe. This would amount to a 24% increase in the amount of helium for the Wisconsin design but only a 4% increase in the LASL system. One must also include loss rates of ~13% per year or more in high temperature cooling systems.[7,21]

We are now in a position to estimate the range of helium requirements that might be incurred in a CTR based economy. We will assume that the entire CTR electrical generating capacity comes from one of the following four CTR designs and present the results in those terms:

1. A theta pinch reactor with He cooling (60,400 scf/MWe)
2. A mirror reactor with He cooling (16,300 scf/MWe)
3. A Tokamak reactor without He cooling similar to the Wisconsin design (10,600 scf/MWe)
4. A laser reactor which is cooled by helium (2500 scf/MWe)

The incremental amount of helium for CTR's required in the i^{th} year, U_i, is

$$U_i(\text{standard ft}^3) \cong [X+Y]I_i + [aX + bY][T_{i-1} + \frac{I_i}{2}]$$

where

X = standard cubic feet of He required per MWe to cool magnets
Y = standard cubic feet of He required per MWe to cool reactor
I_i = incremental installed CTR capacity in i_{th} year.
a = annual loss rate for cryogenic system
b = annual loss rate for reactor cooling system
T_{i-1} = cumulative installed capacity for i-1 year

The values for X, Y, a and b for the four systems outlined previously is given below

Case	X	Y	a	b
1	57.9×10^3	2.5×10^3	0.05	0.13
2	13.8×10^3	2.5×10^3	0.05	0.13
3	10.6×10^3	0	0.05	0.13
4	0	2.5×10^3	0.05	0.13

The results of these calculations are given in Table XI and displayed in Figure 7 for the cases 1-4 for the period 2000-2020. It can be seen that Case 1 (the helium cooled theta pinch reactor) could require 86 billion cubic feet up through the year 2020. This number drops to some 24 billion cubic feet for a helium cooled mirror system and to ~15 billion scf for a non-helium cooled Tokamak. If one uses He as a coolant for laser systems, then only 5 billion cubic feet would be required up through the year 2020.

Table XI

Cumulative Helium Requirements for Various CTR Designs[a]

Millions of SCF

Year	Case 1	Case 2	Case 3	Case 4
2000	62	16.8	10.9	2.7
2001	239	64.9	41.8	10.4
2002	611	166	103	27.1
2003	1,260	342	216	56.6
2004	2,200	601	381	101
2005	3,490	954	605	162
2006	5,150	1,410	895	244
2007	7,290	2,000	1270	356
2008	9,950	2,740	1730	484
2009	13,200	3,640	2290	651
2010	17,100	4,720	2910	853
2011	21,300	5,890	3640	1,080
2012	26,000	7,220	4460	1,340
2013	31,400	8,720	5390	1,630
2014	37,300	10,400	6410	1,970
2015	43,800	12,200	7540	2,340
2016	51,000	14,300	8770	2,760
2017	58,800	16,500	10,100	3,220
2018	67,200	18,900	11,600	3,720
2019	76,300	21,400	13,100	4,270
2020	86,100	24,200	14,800	4,870

(a) Numbers have been rounded off

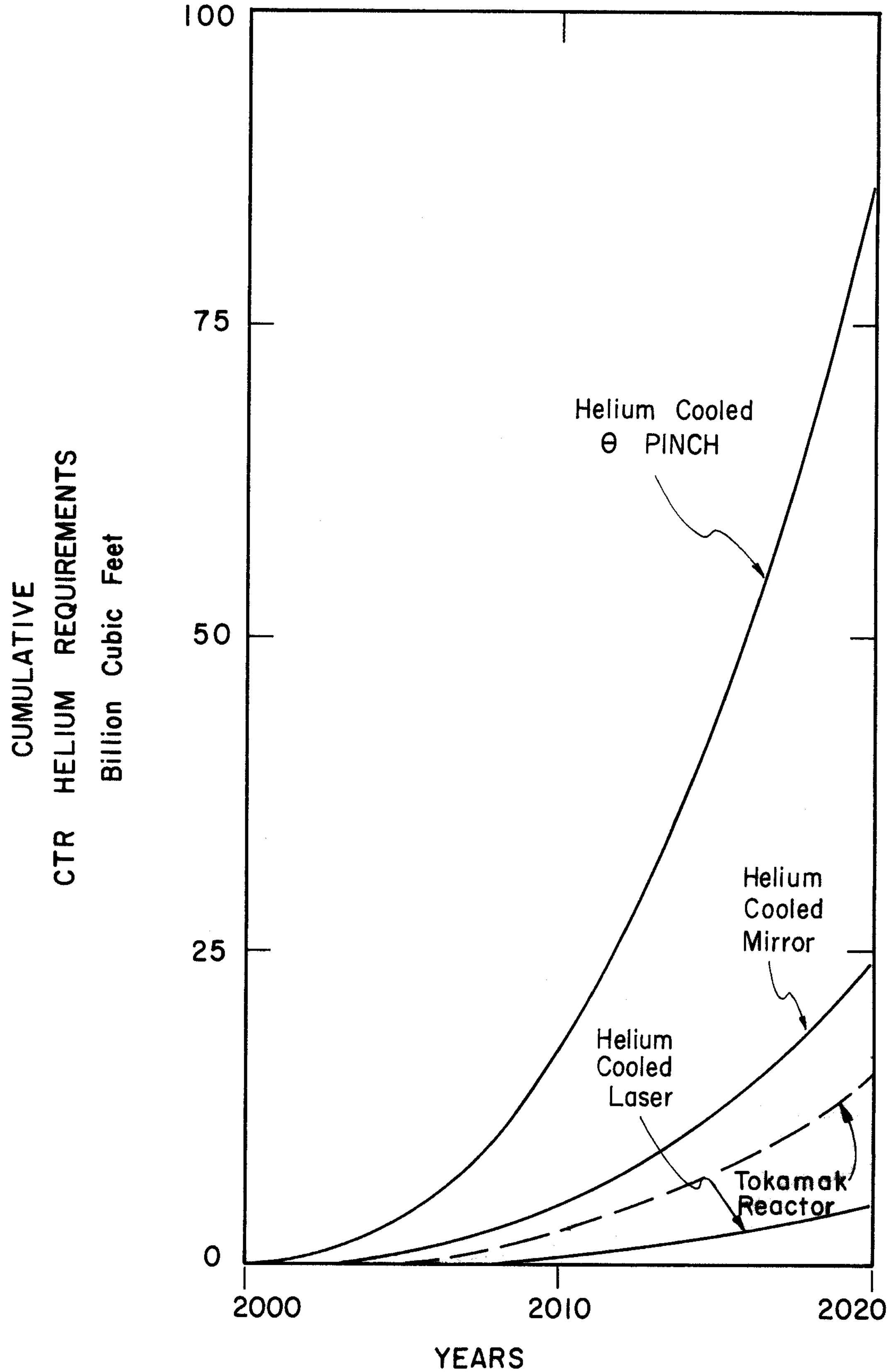

FIG. 7 POTENTIAL HELIUM REQUIREMENTS FOR VARIOUS CTR DESIGNS

Question: What effect would this demand for helium have on the time at which the U.S. would have to obtain He from the atmosphere?

The answer to this question is suprisingly simple. None of the above reactor cases would reduce this critical time period by more than a few years if a 6.4% annual increase in the helium demand for non-CTR uses continues in the future. However, it is noted that by the time fusion power is into its critical growth pattern (2000-2005), we will most certainly be extracting helium at ~\$75 per thousand scf which is 2-3 times its present price.

Question: What effect will higher helium prices have on the cost of fusion power after the year 2000?

Let us assume for the present that fusion power will become competitive at ~ \$500 per installed MWe. Table XII below shows what fraction of the capital costs are attributable to the procurement of He.

Table XII

Effect of Helium Costs on Total Cost/kWe of Installed CTR's

Design	Assumed \$/kWe	Helium Cost \$/kWe \$75/Mscf	Helium Cost \$/kWe \$3000/Mscf
Helium Cooled Theta Pinch	500	<4.3	174
Helium Cooled Mirror	500	1	41
Helium Cooled Tokamak	500	0.8	31
Helium Cooled Laser	500	0.19	7.5

It is interesting to note that fusion economics are not affected in any appreciable way by the increasing cost of helium from \$13 to \$75 per Mscf, but \$3000/Mscf helium could add anywhere from 2-35% to the reactor cost.

Question: What if a superconducting magnet could be built to operate at higher temperatures?

The first reaction is that this would allow liquid hydrogen (B.P. 20.4°K) to be used. There is no resource problem here although there exists a substantial safety and materials compatibility problem that must be faced.

The next possibility is to use liquid neon (M.P. 24.5°K and B.P. 27.2°K). Neon occurs as a trace element in the atmosphere at ~18 ppm and is obtained as a by-product the liquification of oxygen. The total amount of Ne in the atmosphere is ~2.5 x 10^{15} scf. Since Ne is approximately 3-4 times as abundant as He, it is reasonable to assume that eventually it would be 1/3 to 1/4 the cost of helium extracted from the atmosphere. Such a price reduction means that Ne might sell for 300 to 800 dollars per thousand cubic feet if it was processed in large quantities.

It goes without saying that superconductors which could operate in the 63-77^{o}K range would be a tremendous boon to mankind, eliminating all concern about coolant resources or cost. However, that large of a jump in technology should not be counted on if we are to move ahead with the timely development of fusion power.

Question: What if we are not able to use superconducting magnets for CTR's?

The fact still remains that there are no superconductors which are capable of generating large magnetic fields at temperatures in the 20-27^{o}K range. Until such superconductors are developed, hydrogen and neon could only be used with conventional, cryoresitive magnets. Dr. R. Boom of the University of Wisconsin has calculated that if we were to attempt to produce the same magnetic field (87 kG) on axis of the UWMAK-I[18] with Al magnets, the total power associated with the magnets would be ~3000 MWe. This should be compared to ~6 MWe for superconducting Nb-Ti magnets. Since the UWMAK-I only delivers ~1500 MWe it is obvious that superconducting magnets are absoulutely essential to tokamak fusion power.

Conclusions

This rather brief investigation of helium for CTR's has revealed 8 major points.

1. Most, if not all, the low cost helium sources may be depleted before fusion power is expected to be a commercial reality.

2. Increasing the amount of helium stored from underground U.S. reserves will extend the supply of low cost helium for 5-10 years beyond the point where we will run out of easily extractable helium without storage.

3. Fusion power may not be the major source of helium depletion if an annual growth rate in the needs for helium is ~ 6-7%.

4. Fusion power plants will probably have to pay ~$75 per thousand cubic feet of helium in the early 21st century and this may rise to $1000-3000 per mcf towards the middle of the 21st century. at that point we, and the rest of the world, will be extracting He from the atmosphere either directly or from the exhaust streams of liquid oxygen plants.

5. The theta pinch reactor would have the greatest impact on helium reserves because of its large superconducting energy storage requirements. As much as 86 billion cubic feet of He would be required between 2000 and 2020 if fusion power penetrated the electrical generating market at a vigorous rate.

6. The use of helium as a reactor coolant will represent a minimal requirement for helium amounting to ~5 billion cubic feet over the 20 year period, 2000-2020.

7. Increasing the cost of helium by a factor of 100 over the current price, will change the cost of fusion power by 2-35%.

8. The total power requirements to extract helium from the atmosphere could vary by a factor of >100 depending on whether the helium is extracted directly from air or from the exhaust stream of liquid oxygen plants. These power requirements could vary from 3,400-560,000 MWe in the year 2020 for the helium requirements of a gas cooled theta pinch. This represents ~3-50% of the projected CTR capacity at that time.

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Appendix A

He concentration in air is 5.3 ppm by weight.

1 SCF of He weighs: $1\ ft^3 \cdot \frac{28.32\ell}{ft3} \cdot \frac{0.1625\ gms}{\ell} = 4.602$ gms.

Amount of air needed is:

$$\frac{4.602 \times 10^6}{5.3} = 86.83 \times 10^4 \text{ gms.}$$

Composition of air by weight is $N_2 = 75.35\%$, $O_2 = 23.32$

$A = 1.33\%$, He = 5.3 ppm, Ne = 18.18 ppm and

small traces of other gases.

Amount of gas to the extracted is:

$N_2 = 65.426 \times 10^4$ gms.

$O_2 = 20.249 \times 10^4$ gms.

$A = 1.155 \times 10^4$ gms.

Theoretical work needed to liquify these gases at ~70°K is:

$$\left.\begin{aligned} N_2 &= .1764 \text{ KWH/kg} \\ O_2 &= .2116 \text{ KWH/kg} \\ A &= .1323 \text{ KWH/kg} \end{aligned}\right\}$$

taken from "Cryogenic Engineering"
E. R. Lady. Engineering Summer Conf.
U. of Mich. 1965

Total work needed is

$$W_e = (654.26)(.1764)+(202.49)(.2116)+(11.55)(.1323) = 159.785 \text{ KWH.}$$

At 70°K work can be done at ~40% of Carnot efficiency

$$\therefore \text{ Energy needed at } 300°K = \frac{159.785}{.4} = 399.463 \text{ KWH.}$$

In order to remove the Ne from the remaining fraction it should be cooled to 20°K.

Cooling 4.602 gms of He and 15.78 gms of Ne from 70°K to 20°K requires $\sim 0.6 \times 10^{-3}$ KWH.

To liquify the Ne requires an additional 0.4×10^{-3}KWH.

Total cooling needed is $0.6 \times 10^{-3} + 0.4 \times 10^{-3} = 1 \times 10^{-3}$ KWH

Carnot work needed at 20°K to provide this is

$$W_c = 1 \times 10^{-3} \left(\frac{300-20}{20}\right) = 14 \times 10^{-3} \text{KWH.}$$

At 300°K and 20% of Carnot efficiency

$$\frac{14\text{x}10^{-3}}{0.2} = 0.07 \text{ KWH.}$$

Therefore total work needed to extract 1scf of He from the air is 399.463 +0.07 = 399.53 KWH.

Appendix B

Composition by volume Neon - Helium fraction removed from an air separation plant is

$$\left.\begin{array}{ll} N_2 & 70\% \\ Ne & 23\% \\ He & 7\% \end{array}\right\}$$

Taken from Cryogenic Engineering, R. B. Scott Table 3.1 pp 84

1013 ℓ of fraction should be treated to extract 1scf of He gas.

Removing N_2

The fraction is at 77°K and ~1atm pressure.

Theoretical work needed is:

$W_c = T(S) + h$ where S is the entropy of vapor at 77°K and h is the enthalpy

$$W_c = 77°K(17.2)\frac{cal}{mol\ °K} + 1310\ \frac{cal}{mol}$$

$$W_c = 2514\ cal/mole\ \text{or}\ 90\ cal/gm$$

Amount of N_2 removed is $1013\ \ell \times 0.70 \times \frac{4.59gm}{\ell} = 3254$ gms.

$$\text{Total } W_c = \frac{90\ cal}{gm} \times 0.3254\ gm \times 1.162 \times 10^{-6}\ \frac{KWHR}{cal}$$

$$= 0.34\ KWH$$

at 40% of Carnot efficiency

$$W = 0.85\ KWH.$$

Removing Ne

Amount of Ne $= 1013 \times 0.23 \times \frac{3.5\ gm}{\ell} = 815$ gms.

Sensible heat from 77°K, $C_p = 0.25$ cal/gm °K.

$$H_s = (815)(77-27)(0.25) = 10{,}187\ cal$$

Latent heat ≃ 20.7 cal/gm.

$$H_\ell = (815)(20.7) = 16{,}870\ cal$$

Total H = 27,057 cal = 0.031 KWH.

Carnot work needed $W_c = 0.031\ \frac{(300-27)}{27} = 0.313$ KWH

at 20% Carnot efficiency.

$$W = 1.56\ KWH.$$

Total work needed to extract 1 scf of He gas is 0.85 + 1.56 = 2.41 KWH.