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The Helium Question

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Whether or not the United States should have an active program of extracting helium from natural gas and storing it for a future in which it will no longer be available from such a cheap source is a question that has concerned portions of the scientific and technologic communities for more than half a century (*1*, *2*).

Summary. Helium appears indispensable for certain energy-related uses that may be important 50 years from now, when helium-bearing natural gas, a much cheaper source than air, may be exhausted. Present demand, however, is lower than productive capacity, and much helium is being dissipated into the atmosphere as natural gas is burned for fuel. Controversy over the need for a government-directed helium-conservation program reflects fundamental differences in viewpoints on the economic future of industrial society, on the limits of substitution of labor and capital for a depleting resource, and on intergenerational equity and risk-bearing.

As helium-rich natural gas is burned toward exhaustion and most of its contained helium is dissipated into the atmosphere, from which it will be costly to recover, the concern intensifies and the debate begins to illustrate an unresolved problem of resource economics and politics: How to decide whether it is worthwhile to pay a present tangible and calculable cost to conserve a finite resource for uncertain and partly intangible benefits that will accrue mainly to future generations.

Helium, the second lightest of known gases, defies combination with other elements and does not become radioactive under neutron bombardment. It is the only known substance that remains liquid when cooled to the lowest temperature yet reached, almost absolute zero. Even at ambient temperatures of the earth's crust and surface, helium is remarkably fugitive, and can move through seemingly solid rock or metal.

Helium's bouyancy, inertness, vagility, and liquidity at very low temperatures have led to its use (i) for lifting, in preference to hydrogen, which is flammable; (ii) in welding and other processes when oxygen or other reactive gases must be excluded; (iii) in purging, leak-testing, and switching; (iv) as an undersea breathing gas; and (v) as a coolant in computers, certain nuclear reactors, and military aircraft.

The current demand for helium, however, is modest compared either to supply or to production capacity, and does not justify the concern that has been expressed for it as a depleting resource. Never has there been an economic shortage of helium, yet it has been the object of government production and conservation-storage programs. Past and present concern reflects an anticipation of much greater future demand for helium and a belief that it may prove indispensable as the refrigerant for superconducting metals. Substantially greater demand, however, cannot be expected to mature for 40 to 50 years, well after present helium-rich (0.30 percent or more by volume) natural gas supplies are exhausted, and possibly after supplies of helium-lean natural gas (less than 0.30 percent helium) also are gone.

The earth's atmosphere contains somewhat more than 5 parts per million (ppm) helium, but deposits of natural gases in the crust may contain nearly 10 percent (*3*, p. 15). Some helium can be found in almost all natural gas fields. Almost all known fields of helium-rich natural gas are in North America, mostly in the United States. Helium reserves in such gas are being depleted rapidly, mainly by dissipation into the atmosphere when the host gas is burned as fuel. Within 20 years, there is likely to be little helium-rich natural gas left, and the quantity available in the remaining helium-lean natural gas may be insufficient, even with helium now in conservation storage, to meet future needs. After exhaustion of helium-bearing natural gas the only source for large quantities will be the atmosphere. With existing technology, it would take perhaps 800 times more energy to recover helium from the atmosphere than it does to get it from natural gas containing 0.4 percent helium (Fig. 1), about the average that has been moving into separation plants (*4*).

The main uncertainties in the problem are (i) future supply from natural gas and the length of time that supply will be available, (ii) costs of obtaining helium from lean sources, including the atmosphere, (iii) future demand and the length of time it will take for that demand to mature, and (iv) how sensitive the demand will be to cost. Related uncertainties involve the possible development of substitutes for helium in some uses for which it is now indispensable and the nature of the society and the economy 50 years or more from now.

Recent Reports and Recommendations

Four recent reports illustrate the range of views on the helium question. In January 1978 the Helium Study Committee of the National Research Council (*2*) (i) urged an immediate halt to the venting to the atmosphere of helium from plants separating other gases from natural gas streams, (ii) recommended that helium belonging to the federal government and stored in the Cliffside field near Amarillo as a result of a terminated separation and

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purchase program be designated a national helium reserve, (iii) called for reactivation of all helium-separation plants idled by termination of the government program, and (iv) suggested building new helium-separation plants on all helium-rich gas streams. A wide-ranging review of conservation strategy options included the proposition that helium be separated from natural gas and delivered to storage at the expense of the producers; in this way, the consumers of natural gas, by an increased price, would finance a helium conservation program. This strategy was incorporated into H.R. 2620, introduced into the Congress by John Dingell of Michigan on 6 March 1979.

In February 1978 an Interagency Helium Committee issued a report (*5*) that expressed a much different view. This report (i) stated that helium will be available from natural gas during the next century, (ii) concluded that "high-cost options" for helium conservation are unwise in light of the long-term uncertainties of demand, (iii) noted that there is "an unlimited supply" of helium in the atmosphere, (iv) concluded that it is "unsound" for the federal government to buy helium for storage, and (v) came out strongly against the forced separation and storage of helium at the expense of consumers of natural gas, contending that "It is difficult to justify burdening any group with the total cost and responsibility of a general benefit, and even more so when the existence and magnitude of that benefit is uncertain." The study attempted to demonstrate that the helium resources in domestic natural gas to the year 2030 and beyond will be more than sufficient to meet the maximum anticipated demand.

In March 1979 a staff report (*6*) of the House Subcommittee on Energy and Power in support of the Helium-Energy Act of 1979 (H.R. 2620) concluded that the Congress must act soon "to ensure adequate supplies of helium in the future." Four helium-recovery scenarios were projected that, with the same three demand assumptions used by the Interagency Committee, showed a range of years "in which the United States is first unable to meet helium needs" from the year 2019 (high demand, no congressional action) to "after 2070" (low demand, enactment of the Helium-Energy Act of 1979). Estimates of the cost of recovery (in 1968 dollars) were $13.29 per thousand cubic feet of helium from gas containing an average of 0.522 percent helium; $50.26 from gas containing 0.109 percent helium; and $129.86 from gas containing only 0.041 percent helium. These amounts would add, respectively, 6.1, 4.8, and 4.7 cents to the cost per thousand cubic feet of processed natural gas (*7*).

Also in March 1979, the General Accounting Office (GAO) (*8*) criticized certain conclusions of the interagency study and recommended congressional action to conserve helium; in an included letter, the Department of the Interior strongly disagreed with the GAO analysis.

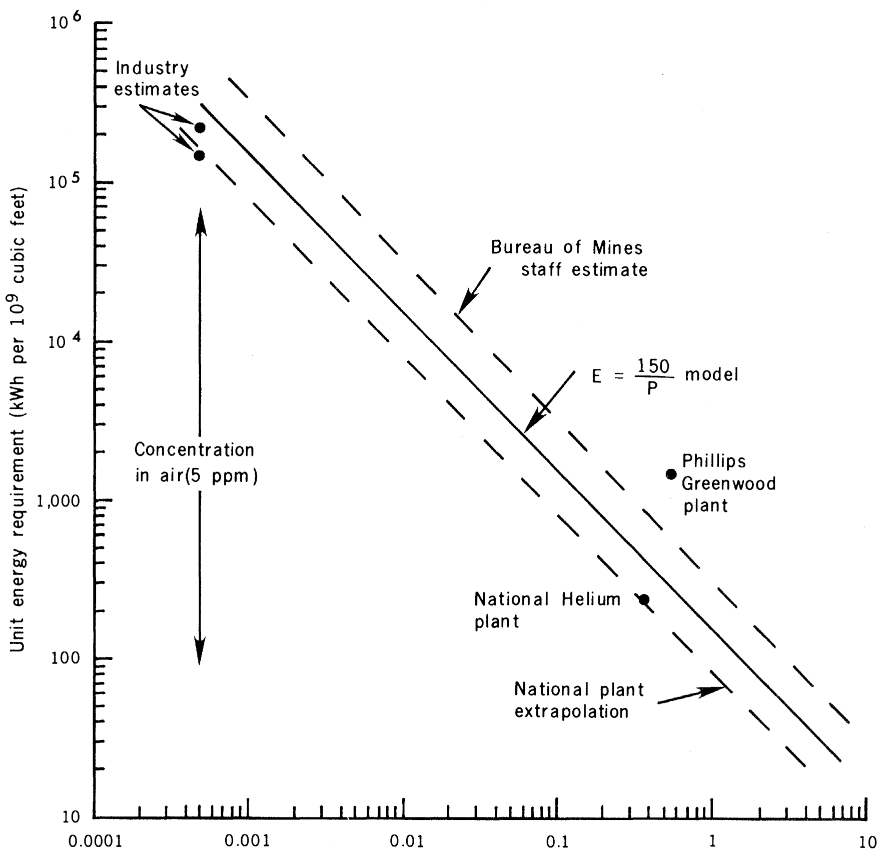


Fig. 1. Energy requirements to extract helium [redrawn from (*13*), p. 66]. Actual and calculated helium extraction energy requirements in kilowatt-hours per thousand cubic feet of helium as a function of the percent helium concentration. The solid line corresponds to the model $E = 150/P$ described in (*13*) where E is the energy in kilowatt-hours per thousand cubic feet extracted and P is the percent helium concentration. The dashed lines correspond to upper and lower limits to energy estimates for conservation-type plants.

Occurrence and Distribution of Helium

As Hurley (*9*, p. 301) has noted, "helium has a geologic occurrence and distribution unique among the elements." Helium is a product of radioactive disintegration of uranium and thorium within the earth's mantle and crust. It is increasing continuously in the crust, but flows to the surface at a rate less than that of its generation, because most of it is driven into the crystal structures of rock minerals until released by alpha radiation damage near radioactive concentrations. Mobile helium rising through the crust may then be trapped, along with other gases, beneath relatively impermeable barriers.

Pierce (*10*), however, believes that the helium in most fields of natural gas has been derived from the decay of trace amounts of uranium and thorium in the surrounding rocks; but, since the Cambrian and Ordovician gas fields of the Central Kansas uplift contain more helium than could be derived from the surrounding rocks, Pierce concludes that the helium in those fields came either upward from underlying rocks or laterally from nearby uraniferous shales. Other helium-rich gas fields, in Texas and Utah, are close to radioactive probable source rocks. Several investigators have noted the association of helium-rich gas fields with buried granitic domes or ridges.

Nitrogen is an inveterate associate of helium in natural gases; the genetic significance of this association is not known. Carbon dioxide is abundant in some helium-rich gas mixtures. These nonfuel gases have protected some helium reserves from dissipation by lowering the heating value of the mixture below the point of feasible exploitation. As the price of methane rises, a high content of nonfuel gases may no longer protect associated helium from depletion.

The apparent restriction of helium-rich gas fields to the United States and Canada finds no ready explanation in the major geologic features of the continents. However, North America does contain the largest amount of the known global reserves of uranium and thorium, from which terrestrial helium is derived.

Outside North America, known instances of natural gas containing 0.30 percent or more helium are in West Germany (*11*) and South Africa (*12*). Natural gas with a helium content between 0.10 and 0.30 percent occurs in Algeria, Poland, and the British Sector of the North Sea (*13*, p. 76). Most of the very large gas fields of the world have a helium content below 0.10 percent.

Not only is helium-rich natural gas concentrated in North America, but within this continent it is further limited geographically. Most of it is found in two broad zones. One of these zones trends from the Four Corners region of the Southwest (Utah, Arizona, New Mexico, Colorado), where the helium content tends to be high, northward into Canada, where the content is relatively low. The other zone trends from southeast Colorado and the Texas Panhandle east to Ohio, thence northeast into Ontario, with the high helium content characteristic of the western part of the zone. In addition, there are scattered helium-rich gas occurrences in upper Ontario, north-central Texas, and (in one well) near Barrow, Alaska.

Although there are no helium assays in the mid-continental region (Kansas, Colorado, Texas, Oklahoma) as high as those from the Four Corners region, the volume of high-helium gas is much greater; consequently, the bulk of the nation's helium reserves are there. The Tip Top field of Wyoming (Sublette County) appears to have a high total helium content; its average grade is about 0.8 percent.

At the beginning of 1978, 84 percent of the proved helium reserves (in natural gas containing 0.3 percent or more helium) of the United States were in Kansas, Texas, and Oklahoma (Table 1), mainly in four large gas fields. About 60 percent of the total helium contained in proved reserves of U.S. natural gas is in helium-rich fields, of which there are about 100 in 10 states; about 40 percent is in the much more abundant helium-lean gas reserves.

Notable is the very low helium content of natural gas fields in coastal zones and offshore, commonly less than 0.007 percent; this statement appears to apply to the large gas fields of southern Mexico, northern Alaska, and the Persian Gulf area, as well as those of the coastal conterminous United States.

Except for a brief period (1960 to 1962), U.S. helium reserves have been dropping steadily during the past 25 years (Fig. 2). Since 1963, helium withdrawn from helium-rich fields has averaged about 8 × 10^9 cubic feet a year; about 1 × 10^9 cubic feet a year has been added to reserves by new field discoveries or revisions of prior reserve estimates; therefore, the rate of reserve depletion has been about 7 × 10^9 cubic feet per year. In the 14-year period from 1 January 1964 to 1 January 1978, 113 × 10^9 cubic feet of helium was withdrawn from helium-rich gas fields; of this total, 38 × 10^9 cubic feet was stored, 10 × 10^9 cubic feet was sold, and 65 × 10^9 cubic feet was allowed to dissipate into the atmosphere.

In the 5 years of record, 1972 to 1977, new field discoveries in the United States accounted for a meager 0.71 × 10^9 cubic feet of additional reserves, while revisions of prior calculations accounted for an increase of 9.2 × 10^9 cubic feet. The bulk of the helium is in older gas fields, which will reach exhaustion sooner than the average gas field. This relation is shown also by the fact that helium reserves were falling sharply long before national reserves of natural gas peaked (1967).

Uncertainty of Supply

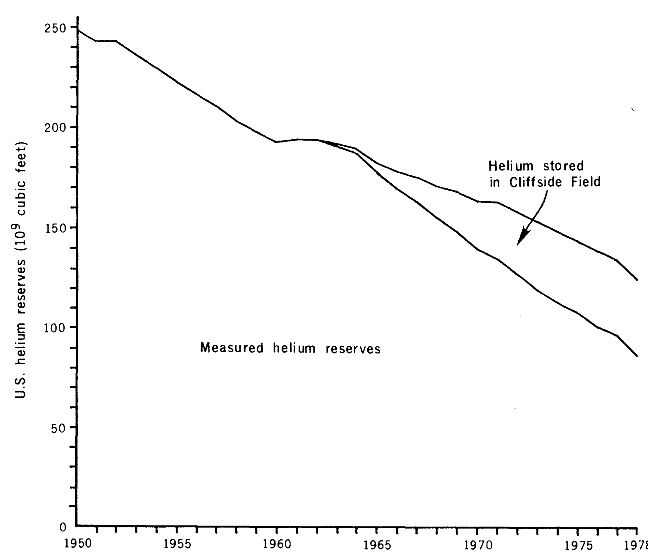
The first of the main subjects of uncertainty and controversy in the helium question is that of supply. Known reserves of helium-rich natural gas are overwhelmingly concentrated in the United States. When, however, an attempt is made to assess the resource potential of helium-lean gas, particularly gas that has yet to be discovered, difficulties become apparent.

Table 1. United States helium reserves (proved or measured reserves in helium-rich natural gas, but not including helium stored in the Cliffside field) at year's beginning. [Source: Division of Helium, U.S. Bureau of Mines]

State	Volume (10^9 cubic feet at 14.73 pounds per square inch and 60°F)						Change 1973 to 1978 (%)
	1973	1974	1975	1976	1977	1978	
Kansas	55.34	51.58	48.05	44.63	45.66*	42.40	−23.4
Texas	39.67	36.14	32.70	29.45	26.47	19.84	−50.0
Oklahoma	13.35	12.31	13.48*	12.43	11.57	10.33	−22.6
Wyoming	3.26	6.28*	6.28	6.32†	6.35	6.63*	+103.4
Utah	3.03	3.91*	4.10	4.14†	4.15	4.34*	+43.2
Colorado	1.67	0.44*	0.76†	1.07†	1.03	0.97	−41.9
Arizona	1.79	1.73	1.69	1.66	0.83*	0.83	−53.6
New Mexico	0.73	0.38	0.60*	0.75*	0.63*	0.29*	−60.3
Montana	0.58	0.58	0.58	0.58	0.47*	0.47	−19.0
West Virginia	0.11	0.12	0.12	0.12	0.12	0.12	−9.1
Total U.S.	119.52	113.47	108.36	101.15	97.28	86.22	−27.9

*Change from previous year resulted from revision of earlier reserve estimates. †Includes a new field.

Fig. 2. Measured helium reserves in the United States and helium stored in the Cliffside field, 1950 to 1978. Reserves include only helium in helium-rich (0.3 percent or more) natural gas, both depleting and nondepleting. [Source: Division of Helium, U.S. Bureau of Mines]



The term resource is used by U.S. government agencies in a way that disturbs some geologists and infuriates others. By this term is meant all of the desired commodity, say helium, that will ever be found and recovered for use. The several categories of resources range widely in the probability or uncertainty of their existence, from proved or measured *reserves* to speculative *resources*, and consequently, they should not be summed to yield total resources. For example, a recent Department of the Interior tabulation of world helium resources (*5*, p. 63) presents total helium volumes for various countries and regions without indication of the average grade of the "ore" (natural gas) and without mention of a cutoff grade below which helium-lean gas may not have been regarded as a resource. In the same publication, a grand total of 714 × 10^9 cubic feet of helium resources is indicated for the United States; unfortunately, although some of this is in the bank, most of it has not been discovered.

Such tabulations are not useful in comparative resource assessment. As a resource, a cubic meter of helium dispersed in natural gas at 0.05 percent concentration (in 2000 cubic meters of gas) is not at all equivalent to a cubic meter of helium at 0.50 percent concentration (in 200 cubic meters of gas), because the 0.05 percent helium will cost about ten times as much in energy or work to recover as will the 0.50 percent helium (Fig. 1). Consequently, the latter "resource" is worth much more than the former; in fact, it is approximately ten times more valuable. On this assumption, I have converted available helium resource volume data into helium resource value units (Table 2) by multiplying each helium volume by its known or estimated concentration, in percent, in natural gas. By such weighting, it can be seen that (i) 95 percent of known helium resources are in the United States, Algeria, and the Soviet Union, (ii) the United States has more than half of the known resources, and (iii) the potential reserves of the Tip Top field may have a greater value than the now known helium resources of the United States, or of all foreign countries.

In the United States, part of the uncertainty of future helium supply has to do with varying estimates of remaining undiscovered natural gas. Estimates used by the Bureau of Mines exceed those of other groups. If we use an average of recent estimates by the Exxon Corporation (*14*) and the U.S. Geological Survey (*15*) of undiscovered natural gas remaining to be discovered and produced in conventional reservoirs in the United States, we can make some calculations of the helium potential in undiscovered gas (Table 3) to compare with those prepared by the Bureau of Mines. By this method, the total helium content of natural gas remaining to be discovered and produced is 239 × 10^9 cubic feet, less than half of the Bureau of Mines estimate of 512 × 10^9 cubic feet (*5*, p. 52) for their "indicated," "hypothetical," and "speculative" helium resources. Even this reduced figure may be unduly optimistic in that use of the average helium content of all gas (0.068 percent) as the multiplier for all new discoveries of inland gas assumes that helium-rich gas will be discovered at a rate proportional to its present quantitative relation to helium-lean gas, contrary to the experience of the past 20 years.

Calculation of helium resource value units (Table 2) in no way reduces the uncertainty of the existence of undiscovered resources. A case in point is the Tip Top field, potentially the greatest helium resource in the world; its helium content may exceed that now in storage at Cliffside (Potter County, Texas) and may be obtainable at less than half the cost. This field is a factor in the current policy controversy, the Department of the Interior contending that no congressional action should be taken until Tip Top is developed and its helium resources become known.

The helium potential of Tip Top was discovered at a well drilled in 1961. In 1974, a private consultant's report (*16*) estimated proved producible helium reserves of 6.1 × 10^9 cubic feet and probable reserves of 38.5 × 10^9 cubic feet; the estimated average content was 0.79 percent. The Bureau of Mines, however, increased its Wyoming reserve total (see Table 1) that year by only 3.0 × 10^9 cubic feet, and there seems to be substantial reluctance in the industry to accept such high estimates from a single well.

Mobil Oil Corporation in 1978 started a drilling program to develop the Tip Top field for its methane content. Carbon dioxide and hydrogen sulfide, the two principal impurities in the gas, will be removed to raise the heating value from 250 to 730 Btu (British thermal units) per cubic foot, after which the gas, its helium content intact, would be blended with a higher quality stream to bring the product to acceptable grade for burning as fuel (*17*). No firm plan exists for separating the helium, although the government

Table 2. World helium resources, 1978.

Country or region	Helium: Resources (10^9 cubic feet)*	Helium: Average in natural gas (%)†	Helium: Resource value units‡	Percent of total proved value units
United States				
Proved (measured) reserves:				
In storage	39	0.5§	19.5	
He-rich natural gas	86	0.49	42.1	
He-lean natural gas	63	0.026	1.6	
Total			63.2	52.0
Potential reserves:				
Tip Top field	41	0.8	65.6‖	
Potential natural gas reserves offshore	07	0.007	0.1	
Potential natural gas reserves onshore	191	0.068	13.0	
Probable growth of known fields	41	0.026	1.1	
Total			79.8	
Canada	39	0.08	3.1	2.5
Algeria	89	0.17	30.2‖	24.8
U.S.S.R.	450	0.05	22.5	18.5
Netherlands	23	0.05	1.2	1.0
United Kingdom	8	0.03	0.2	0.2
Australia	21	0.05	1.1	0.9
Middle and Far East	4	<0.03	0.1	0.1
Total foreign			58.4	48.0
Total proved			121.6	100.0

*For the United States, the figures used by the Bureau of Mines for undiscovered (potential) natural gas have been replaced by an average of those of Exxon (*14*) and the U.S. Geological Survey (*15*), adjusted for a somewhat different geographic distribution of the undiscovered gas. For other countries, the Bureau of Mines figures are reproduced unaltered. Quantities of helium-lean gas resources have not been adjusted for the fact that it probably will never be economically feasible, because of the distribution of fields and the small size of many pipelines, to process all such gas for helium. †Concentrations are from U.S. Bureau of Mines data and estimates for the United States, Canada, and the U.S.S.R.; from (*13*) for the others. ‡Figures in this column obtained by multiplying those in first two columns. §"Valued" at concentration from which it was obtained. ‖The Tip Top field and Algeria are given double resource credit because, in both cases, helium can be separated by further liquefaction of an inert gas stream that will be separated for other reasons; therefore, helium separation should cost half or less what it would as a sole separation product.

could require that most of it be separated, because 95 percent of the field, as it is believed to exist, is under federal land.

Possible additional domestic sources of helium are the so-called unconventional reservoirs of natural gas or methane. Such reservoirs include (i) geopressured hot saline waters beneath the Louisiana and Texas coastal plain, (ii) "tight" shale formations of the Appalachians, Michigan, and Colorado, and (iii) coal. The natural gas of the geopressured waters is enormous in amount but, as one would expect from its location and occurrence, contains 0.01 percent helium or less (*18*). The helium content of the few samples of natural gas from the Devonian shales of the Michigan and Appalachian basins so far analyzed by the U.S. Bureau of Mines is less than 0.1 percent. The low content of helium in the gas of such reservoirs and the probable rather modest amounts of recoverable gas in them render them of little interest for future helium supply.

The time factor in the supply problem can hardly be overemphasized. Helium-rich gas is going fast. Within a few years, Tip Top gas will be depleting. Some experts (*19*) believe the complete cycle of U.S. natural gas production, except from Alaska, will be nearing its close in 2030, about the time when helium demand may be rising sharply. Within 20 to 30 years, if no more domestic helium is separated and stored, helium from Algeria may be the cheapest available, except for that which still may be held in the Cliffside field.

Fifty years hence, world reserves of natural gas probably will be nearing exhaustion, but, if there remains at that time some gas with 0.05 percent helium in it, it will still be much cheaper to separate helium from that gas than from air; even the lean (0.007 percent helium) coastal zone gas of the Louisiana-Texas Gulf Coast would appear to be a richer (10 to 12 times) source than air; however, at such low concentrations industry sources believe that the cost of obtaining helium from natural gas may approximate the cost of recovering it from the atmosphere (*20*).

Table 3. Helium content of potential gas reserves in the United States.

Item	Potential natural gas (10^9 cubic feet)		Probable helium concentrations (%)	Probable helium content (10^9 cubic feet)	
	Exxon (*14*)	USGS (*15*)		Exxon (*14*)	USGS (*15*)
Offshore	101,000	107,000	0.007*	7	7
Inland	186,000	377,000	0.068†	126	256
Probable growth of known fields	111,000	201,600	0.026‡	29	52
Total	398,000	685,600		162	315

*Average helium content of natural gas being produced from coastal zones of Texas and Louisiana and in all of California. †Average helium content of all measured natural-gas reserves in the United States, including helium-rich gas. ‡Average helium content of helium-lean natural gas measured reserves in the United States, most of which are inland.

Uncertainty of Demand

Future demand for helium on a much larger scale than at present will depend on the development and deployment of sophisticated technologies that either do not exist now or are in a state of infancy. These include magnetic containment systems for fusion reactors, breeder and high-temperature gas reactors, high-temperature gas turbines, laser-based missile-defense systems, magnetic propulsion units for new transport systems, helium refrigeration systems for military aircraft, advanced energy conversion cycles—particularly magnetohydrodynamic systems—and low-temperature energy transmission, distribution, and storage. None of the helium demands represented by any of these technologies can approach maturity until well into the 21st century. An Argonne National Laboratory committee (*21*) has estimated the demand to 2050 for three of these emerging technologies. The estimated cumulative demand is about 14 times the amount of helium now stored in the Cliffside field (40×10^9 cubic feet) and the annual requirement estimated to replace helium lost by leakage is 17 to 26 times current consumption (0.6×10^9 cubic feet). The level of inventory requirement suggested is at least four times the amount of helium contained in all U.S. proved natural-gas reserves and probably exceeds the helium content of all natural gas remaining to be produced in the United States. The maximum possible helium-conservation program, started at once, might only buy time to adjust to air as the sole source, if these estimates become real.

But there are great uncertainties on the demand side as well as on the supply side. We cannot be certain that fusion power will become technically and economically feasible. Cryogenic transmission of electricity, already technically feasible, may not be able to justify its high capital cost in competition with ultrahigh voltage subaerial transmission. Superconducting energy storage may turn out to be the most economically feasible of the three technologies under discussion, because the known alternatives are so inefficient or site-dependent.

Superconductivity raises another uncertainty. Although it is unlikely, it is not inconceivable that superconducting materials may be developed that do not require the low temperatures that now make helium indispensable as a cooling medium, and may allow the use of a more abundant substance that will remain fluid at the temperature required. The history of superconductivity research and development shows occasional incremental progress toward this goal (*4*, p. 69). The possibility that another low-temperature coolant may be developed seems extremely remote (*22*).

It should be remembered also that helium is neither consumed nor rendered unusable in any use. A portion of the recent estimates of future helium demand represents the expectation of leakage. If leak-proof systems are designed so that no helium is lost, then a very high initial cost may be supportable for a virtually unlimited life of use.

Finally, the uncertainty of the shape and wealth of society 50 years from now needs to be mentioned. The technologies that may require a great deal of helium are sophisticated and expensive. Their use implies a continued affluent society and one in which the economies of scale are still being pursued in large energy systems. Our society half a century from now may not be wealthy. Perhaps for reasons other than cost, we may have decided to simplify and decentralize our energy systems. If we are wealthier than now, we may be able to afford helium from air, or to make do with less efficient substitute materials and systems. If we are poorer, we may need neither helium nor the substitutes.

History of Conservation Efforts

Early conservation concern related to the use of helium for lighter-than-air craft. When it was thought that dirigibles would be useful in military operations as well as in transporting freight and passengers on global routes, it was recognized that high-grade reserves of helium were, at least potentially, in short supply. A helium program was started within the Bureau of Mines, to identify helium resources and to encourage their development and conservation. The discovery of the existing reserves of helium, however, owes more to the development of a national market for natural gas and its emergence after World War II as the preferred fuel of the nation than to the helium-search program. The potential market for helium in air transport shriveled to the blimp level with the military dirigible disasters of the late 1930's and with the subsequent development of faster, more dependable, and more versatile fixed-wing aircraft. After World War II the high-technology markets for helium failed to develop as their enthusiasts had predicted. Still, the rapid depletion of high-grade helium resources and the tantalizing prospect of large new uses kept conservation concern alive.

In 1960, an interagency study forecast that the existing Bureau of Mines program would not produce enough helium to meet the demand that could be expected after 1985. This conclusion led to the 1950 Helium Act Amendments, which directed the Bureau of Mines to supplement its own production with helium purchased under contracts with private producers. Program costs were to be financed out of income from helium sales. Until sales income was adequate to meet program costs, the Bureau was authorized to borrow operating funds from the U.S. Treasury. Borrowed funds and accrued interest were to be repaid within 25 years.

To implement the 1960 act, the Bureau of Mines contracted for helium purchase with four companies, which started to supply helium to the government in 1962. Decline in demand, competition from private producers, and increasing indebtedness of the program led to termination of the purchase program in 1973 (*23*). The companies fought the termination order. Litigation continues. Initial judgments have gone against the government, but the helium purchase program remains suspended, and the government's stance against resuming the program under existing statutory authority has hardened.

Meanwhile, new lawsuits, not related to the contract terminations of 1973, have introduced another element of economic uncertainty into the helium picture. These suits relate to the value of helium as extracted from the earth. When contracts were first negotiated with landowners and producers of natural gas for helium-rich gas to be processed, no value was assigned to the helium itself. The landowners and producers of helium-rich gas now claim ownership of the helium and are seeking payment from the helium separators. One trial judge already has set $17 per thousand cubic feet as the just payment for the contained helium. If this judgment is sustained, it could constitute a major impediment to helium conservation. At present, any helium extracted and put in storage carries with it the risk of substantial, but unknown, future payments to landowners and natural gas producers.

Present-Value Criterion

Conservation assigns calculable costs to present generations, in utility or income foregone, in effort expended, or in both; it produces uncertain benefits, in the helium case accruing mainly to future generations. Economists refer to such a transaction as an integenerational income transfer. One approach to the political decision required is by means of a present-value calculation (*24*), based on an assumed future cost of helium and a selected discount rate. If the calculated present value exceeds the present cost of separating and storing helium, a conservation program is thereby justified.

The cost of separating helium from the atmosphere has been estimated from as low as $1000 per thousand cubic feet (*8*, p. 36) to as high as $9000 (*6*, p. 11), depending mainly on the cost assumed for the energy required. The GAO report (*6*), assuming the sole source of helium in 2030 to be the atmosphere, that helium can be extracted and brought to storage for $14 per thousand cubic feet, that the cost of storage is $0.04 per thousand cubic feet per year, and that all costs are discounted at 10 percent per year, concluded that any helium price in 2030 above $1619 per thousand cubic feet would make purchase and storage advisable today. This conclusion was strongly criticized by the Department of the Interior because of its assumption that helium would no longer be available from natural gas or storage by 2030 (the department's position is that about half of the current "resources" will still be available then) and because it ignored the cost uncertainty of the current helium-value lawsuits. In terms of the conservation decision, however, this contingent liability is not a real cost, only a financial transfer within the present generation.

Although the present-value criterion can yield only slippery answers to the helium problem, mainly because we do not know when, if ever, we will need helium badly enough to be willing to pay the high cost of getting it from the air, some may prefer it for that very reason, since underlying its use is the comforting assumption that discounting promotes economic efficiency and helps make the future richer than it otherwise would be; even if it does not have low-cost helium because our generation decided that the present value of a very distant good was too low to justify conserving today, the future will have something of equal or greater value because we made that negative decision and invested in something other than stored helium (*25*). Another economic assumption that supports the present-value criterion is that "the elasticity of substitution between natural resources and labor-and-capital-goods is no less than unity" (*26*, p. 31); in other words that the increasing leanness of an exploited resource such as helium or copper will be countered indefinitely by technological improvements and substitutions so that the overall cost (not the unit cost of the resource) to the economy will not increase.

A final assumption involving any discount rate related to the opportunity cost of capital is that the opportunities to employ capital productively will stay relatively constant or grow during the term of the investment. If the society and its economy are growing, such opportunity persists. If it weakens or approaches a steady state, there will be little to no such opportunity.

The Conservation Approach

One of the main arguments for a low discount rate for public investment leads directly to a very different approach to the helium decision. That argument, in favor of what Eckstein (*27*) called a "social rate of discount," is that a high rate may prevent a transfer of capital or income to future generations that the present generation may consider desirable, as a gift from which the present generation derives intangible satisfaction, and from which future generations may get technological options that they otherwise might not be able to afford. Those who contend that geologic-resource exhaustion is real and substitution limited, who doubt the ability of the market endlessly to prolong depletion and to provide separate but equal (or better) capital goods, may opt in the case of helium for a direct gift to the future, no strings attached.

Whereas ethical or moral judgments are disclaimed in the present-value approach, they are not in this conservation approach (*28*); advocates of the conservation contend that the dissipation of the natural legacy of low entropy represented by the wasting of helium in natural gas is a real wealth loss being assigned to the social budget of future generations and that it is immoral for this generation to do so simply because we have no economic use for the wasting helium. Curiously, an economist, Pigou (*29*, pp. 29–30) stated the conservationist position as well as anyone:

> It is the clear duty of Government, which is the trustee for unborn generations as well as for its present citizens, to watch over, and if need be, by legislative enactment, to defend the exhaustible resources of the country from rash and reckless spoliation.

Implicit in the conservationist approach is denial of the proposition that labor and capital are freely substitutable for exhaustible natural resources; indeed, a conservationist might contend that concentrated helium is a very real kind of capital of which dollars are neither a measure nor a surrogate.

In place of an economic calculation based on a discount rate that may reflect the present generation's time preference for immediate rather than delayed benefits, the conservationist may prefer an energy cost calculation that implies sharing with future generations (*30*).

A Middle Ground

Page (*24*, pp. 204–206) argues that there is no necessity to make a choice between the present-value and the conservation criteria, and suggests that the conservation criterion be used, through the instrument of a severance tax (*31*), to establish a context for markets, within which the present-value criterion could function.

In this regard, it may be fortunate that the helium question allows for a series of decisions, ranging from stopping the venting of separated helium and the reactivation of idle separation plants to the extraction of helium from lean gas and the purchase of helium from abroad. All decisions but one are revocable, should additional information on supply and probable need indicate that they should be. The one that is irrevocable is a decision to do nothing.

Conclusion

Helium conservation is a national issue in which thermodynamic certainty collides with economic uncertainty. Low-entropy helium is wasting into the atmosphere at least in part because there is no way to prove that future generations will be better off if it is saved for them. A helium conservation program was started, then aborted. A decision to resume storing helium will be a political decision based more on prevailing ideas of fairness in intergenerational risk-bearing and equity, and on current views of the qualitative impact on future society of materials scarcities, than on any quantitative forecasts of future needs and costs.

References and Notes

1. C. W. Siebel, *Helium: Child of the Sun* (Univ. of Kansas Press, Lawrence, 1968). For the legislative, operational, and litigious history of helium during the past 20 years see (*2, 5, 6, 8*). Other summaries can be found in government documents.
2. Helium Study Committee, National Research Council, *Helium: A Public Policy Problem* (National Academy of Sciences, Washington, D.C., 1978).
3. U.S. Bureau of Mines, *Analyses of Natural Gases, 1917–74* (U.S. Bureau of Mines, Washington, D.C., 1976). This report contains 10,562 analyses, including helium, of gas samples from 37 states and 23 foreign countries.
4. The theoretical cost of energy for obtaining helium from the atmosphere is about 10 kWh per thousand cubic feet; the actual energy cost, however, as calculated by both industry and government sources, is more like 300,000 kWh per thousand cubic feet. According to A. W. Francis of Union Carbide (personal communication, July 1979), this might be reduced to about 100,000 kWh but probably not less.
5. Interagency Helium Committee, *Interagency Helium Study* (1978).
6. *Energy and Helium: A Crisis in Future Energy Supply* (House Subcommittee on Energy and Power, U.S. Congress, Washington, D.C., 5 March 1979).
7. These cost estimates, based on a Bureau of Mines formula, were challenged by L. Newmyer, consultant for Cities Service Company, in testimony before the House Subcommittee on Energy and Power, 24 May 1979. Chart 2 of his prepared statement indicates that gas containing 0.1 percent helium would cost 16 to 30 cents per 1000 cubic feet (in 1979 dollars) to process for helium separation, depending on the size of the plant. Helium-recovery costs, as calculated by Newmyer, run 45 to 62 percent above Bureau of Mines estimates.
8. *Unique Helium Resources Are Wasting: A New Conservation Policy Is Needed* (General Accounting Office, Washington, D.C., 1979).
9. P. M. Hurley, in *Nuclear Geology*, H. Faul, Ed. (Wiley, New York, 1954).
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11. W. Moore, U.S. Bureau of Mines, Amarillo, Tex., personal communication.
12. S. H. V. Bowie, *Nature (London)* **182**, 1032 (1958).
13. *The Energy Related Applications of Helium, ERDA-13* (Energy Research and Development Administration, Washington, D.C., 11 April 1975).
14. *Undiscovered Petroleum Potential in the United States* (Exxon, Houston, Tex., 1975).
15. B. M. Miller, H. L. Thomsen, G. L. Dolton, A. B. Coury, T. A. Hendricks, D. E. Lennartz, R. B. Powers, E. G. Sable, K. L. Varnes, *Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States* (U.S. Geological Survey, Washington, D.C., 1975).
16. D. M. Madden, "Reserves and geologic study, helium bearing formations, Tip Top Unit, Sublette County, Wyoming" (Fusselman, Winn, & Madden, Casper, Wyo., 1974), unpublished report.
17. R. D. Munnerlyn, U.S. Bureau of Mines, Washington, D.C., personal communication.
19. B. E. Hankins, Neese State University, Lake Charles, La., personal communication (September 1979). For example, M. K. Hubbert, whose views on this matter have not changed under the outraged assault of those who believe demand creates resources [see figure 64, p. 148, of his report, *U.S. Energy Resources, A Review as of 1972* (Senate Committee on Interior and Insular Affairs, U.S. Congress, Washington, D.C., 1974)].
20. A. W. Francis, Union Carbide Linde Division, personal communication.
21. C. Laverick, *Helium—Its Storage and Use in Future Years* (Argonne National Laboratory, Argonne, Ill., 1975).
22. M. Tinkham, Harvard University, personal communication.
23. Termination of the helium-purchase contracts, ostensibly a decision of the Secretary of the Interior, appears in fact to have been forced on him by the Bureau of the Budget (BOB), later the Office of Management and Budget (OMB). A student of political mechanics should seek out the Report of the Trial Judge (Spector) in the case of *Northern Helex Company* v. the *United States*, U.S. Court of Claims Trial Division, No. 454-70, filed 3 December 1974, in which the trial judge notes that during 1969 BOB selected the helium program as one that could be eliminated to save money, that Interior fought hard to save the program, but surrendered in the face of an OMB memorandum (4 January 1971) which stated that "the decision to terminate the helium conservation contracts should be upheld; the program is no longer justified." When litigation ensued, the government was forced to rely on what some consider a strained interpretation of the 1960 law, claiming responsibility only for predictable federal helium needs, not for a long-range national program. This legalistic position has hardened and needs to be kept in mind when reading (*5*) or other recent government documents on the helium program.
24. T. Page, *Conservation and Economic Efficiency* (Johns Hopkins Univ. Press, Baltimore, 1977) discusses and compares present-value and conservation criteria, stressing the ethical problem and noting that those who prefer the present-value criterion tend to think the world economy is not a "hardtack" one, while those who choose the conservation criterion tend to view the world economy as having hardtack tendencies, in other words, physical limits to economic growth (see chapters 7 to 9).
25. A strong argument is made for this position by G. Anders *et al.* [*Does Resource Conservation Pay?* (International Institute of Economic Research, Los Angeles, 1978)]. They imply that a discount rate even higher than "the going rate of interest" may be appropriate to conservation decisions because unforeseen technological change may make the conserved resource obsolete and because the sacrifice of the earlier generation may serve only "to make a vastly richer generation even richer." See also W. J. Baumol, in *Public Expenditures and Policy Analysis*, R. H. Haveman and J. Margolis, Eds. (Markham, Chicago, 1970), p. 285.
26. R. M. Solow, in *Symposium on the Economics of Exhaustible Resources*, G. Heal, Ed. (Review of Economic Studies, Glasgow, 1974), pp. 29–46.
27. O. Eckstein, *Water Resource Development* (Harvard Univ. Press, Cambridge, Mass., 1958).
28. See, for examples, H. Daly, in *Toward a Steady-State Economy*, H. Daly, Ed. (Freeman, San Francisco, 1973), p. 162; and H. H. Kellogg, "Toward a materials conservation ethic," 1978 Distinguished Lecture in Materials and Society of the American Society for Metals.
29. A. C. Pigou, *The Economics of Welfare* (Macmillan, London, ed. 3, 1929).
30. M. K. Hubbert (personal communication, August 1979) argues as follows: For natural gas with a helium concentration of 0.4 percent, the extraction cost, by the formula $E = 150/P$ (Fig. 1), is equivalent to 0.375 kWh or 3.75 cubic feet of natural gas as fuel (10 cubic feet is needed to produce 1 kWh of electrical energy) per cubic foot of helium. To retrieve helium from air, the cost is 300 kWh or 3000 cubic feet of gas. Since it takes 250 cubic feet of the helium-rich (0.4 percent) gas to produce a cubic foot of helium, the energy cost of dissipating to the atmosphere the helium in that gas is 12 times the energy in the gas (3000 ÷ 250). This is a measure of the magnitude of the wastage involved by allowing such dissipation. For natural gas with a helium content of 0.10 percent, the ratio is 3; for a concentration of 0.01 percent, it is about 2. Hence, it is still feasible energetically (if the formula holds in practice) to extract helium from gas with helium content as low as 0.01 percent.
31. If H.R. 2620 becomes law, the consumers of helium-bearing natural gas would pay the equivalent of a severance tax to finance the conservation of helium; within this conservation framework, the market would be allowed to operate, determining the economic value of the stored helium.

32. I thank Art Francis, Sr., Charles Howe, M. King Hubbert, William Petrie, and Michael Tinkham for reviewing this article.