THE GEOLOGICAL SURVEY OF WYOMING

Daniel N. Miller, Jr., State Geologist

PUBLIC INFORMATION CIRCULAR NO. 16

HELIUM:
A VITAL NATURAL RESOURCE

by

Michael Clark

With a map of helium occurrences in Wyoming
compiled by Rodney H. DeBruin

LARAMIE, WYOMING

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INTRODUCTION

Helium, a by-product of radioactive decay, is commonly found as a constituent of natural gas. In fact, natural gas is presently our only commercial source of helium. As natural gas is produced, a small amount of the associated helium is extracted, a little more than enough to meet current helium demand. Some of the excess is stored. The vast amount of helium that is not extracted from produced natural gas is vented and lost into the atmosphere. As natural gas, a finite resource, becomes scarce, so will the helium supply. The U.S. Government and the scientific community are very concerned that the supply of helium will be insufficient to fuel our future "super-technologies". As a result, questions have been raised about the need to conserve more of our presently economically recoverable helium for the future.

Wyoming contains perhaps the largest known single nondepleting (i.e., currently untapped) helium reserve in the world. The Tip Top Field in Sublette County, Wyoming has measured and indicated nondepleting helium reserves that total at least 45 billion cubic feet. The Church Buttes Field, on the border between Uinta and Sublette counties has another 17 billion cubic feet of these nondepleting reserves. A great number of other natural gas fields in Wyoming are also rich in helium. Many of these fields are currently being produced for oil and gas without conserving the accompanying helium. Questions and concerns about our helium resources have prompted this summary of helium: it's uses, origin, accumulation and reserves.

HELIUM AND ITS USES

In 1868, Sir Norman Lockyer, a British astronomer, detected a strange, bright yellow line in the sun's spectrum. He knew that this line was the hallmark of a unique and special element. He named it helium, after "helios", the Greek term for sun.

In 1904, a well was drilled a short distance north of the end of Main Street in Dexter, Kansas. The goal was to find rich deposits of oil and natural gas. Visions of prosperity abounded in this tiny town as their well struck a pay zone only four hundred feet beneath the surface and "opened up a howling gasser." As much as nine million cubic feet of gas per day flowed for many days through the eight-and-one-quarter-inch pipe. Then, much to the despair of the townsfolk, it was discovered that gas from the Dexter well would not burn. The well was capped and sealed, along with Dexter's dream of becoming the Pittsburgh of the Midwest. In 1905, Erasmus Hayworth, the Kansas State Geologist, sent a sample of the infamous gas to the Chemistry Department at the University of Kansas. Dr. David F. McFarland and Dr. H.P. Cady found the gas sample to contain, amoung other things, 71 percent nitrogen and 12 percent "inert residue," including 1.84 percent helium. Helium had been discovered as a constituent of natural gas for the first time in this country (Seibel, 1968).

Helium, an inert gas born as a by-product of the radioactive decay of uranium and thorium, is one of the most simple and lightest elements, second only to hydrogen in these properties. Next to hydrogen, helium is also the most abundant element in the universe, found through spectroscopic analysis of even the hottest stars; the best gaseous conductor of heat and electricity; the best transmitter of sound; and the most rapidly diffusing element, moving even through seemingly solid rock and metal. Helium has the lowest melting point (-457.96°F at 26 atm.) and boiling point (-452.13°F at standard pressures) of any element, near

absolute zero (-459.82°F). This colorless, odorless, tasteless gas is also the only element that cannot be solidified under normal, sea level pressures by reducing its temperature — it is easly solidified under higher pressures — (Weast, 1967).

Because of helium's special properties, especially its inertness and low temperature as a liquid, it has a wide variety of uses. In fact, the uniqueness of its properties makes helium irreplaceable in many of its applications. In addition to filling balloons at county fairs, helium is used in many fields with expanding frontiers. Indeed, many researchers envision helium as playing a vital role in our future "super-technologies." The following listing summarizes the present and future applications of helium (Midwest Research Institute, 1977):

A. Cryogenics: Helium's low liquid temperatures freeze biological specimens in cancer research, cool sensitive communication receivers in satellite relay systems, duplicate the cold of outer space for simulated space testing, pre-cool rocket engines, and cool plasma containment chambers in nuclear fusion reactors. Liquid helium also cools materials to where they become super conductors of electricity. Some uses for superconductors are:

   Storage - Electricity will circulate indefinitely in a superconductor coil. It may be possible to store electricity in huge coils the size of football fields and tap them when needed.

   Transmission Lines - By using superconducting transmission lines, energy that is normally lost through friction could be conserved and put to use. These line losses are currently 13-20 percent of the transmitted energy.

   Magnetohydrodynamics - Extremely hot gases pass through helium-cooled superconductive magnets at high velocities to generate electricity.

   Computers - Superconducting magnetic memories can dramatically increase a computer's capacity.

   High Energy Physics - Superconducting magnets are needed to accelerate particles of matter to the high velocities necessary for nuclear fusion reactions.

B. Arc Welding: Because it is inert, helium is used as a welding atmosphere when precision is a necessity and when unusual combinations of metal are welded together, combinations involving magnesium, aluminum, stainless steel, high strength steel, copper, tantalum, and zirconium. This application is common in the construction of ships, aircraft, spacecraft, rocket structures, cryogenic equipment, and some electrical devices.

C. Pressurizing - Aerospace: Helium is used to pressurize the liquid fuel tanks of rocket boosters. Injecting inert helium into fuel tanks pushes the fuel into the rocket engines while maintaining sufficient pressure to prevent the collapse of the thin tank walls.

D. Breathing Mixtures: Helium combats inert gas narcosis and is therefore used in breathing mixtures for deep water diving and in deep tunneling projects.

E. Chromatography: By using helium as a carrier reference gas, mixtures of gases or liquids are separable into individual components quickly and accurately. This is achieved by flowing the helium-entrained sample through

a column packed with absorbent material. Different components of the gas sample will move through the column at different rates, depending on the mass of the component and the type of material in the column.

F. Leak Detection: Because of its ability to pass through minute openings and the simplicity of detecting it in trace amounts, helium is injected into high pressure systems and around vacuum systems to detect imperfections. Helium is used to detect leaks in piping systems in nuclear reactors, in television tubes, and in other items which depend on a leakproof system for safe operation and long service life.

G. Lifting Gas: In addition to filling balloons at the county fair, helium was used to fill naval patrol blimps in WWII and is still used to fill balloons for upper atmosphere research and weather forecasting.

H. Heat Transfer: As a result of its inertness, resistance to radioactivity, thermal conductivity, and stability at intense temperatures (1800+°F), helium is preferred as a heat transfer medium in both fission and fusion nuclear reactors. For example, the nuclear core of a high temperature gas-cooled reactor heats helium to 1400°F at 700 psia. This high-temperature helium is then circulated through a radiator system, converting water to steam. The steam then drives turbines to generate electricity.

I. Controlled Atmosphere: Helium provides an inert atmosphere during purification of such rare metals as titanium and helps prevent contamination in the growth of silicon and germanium transistor crystals.

J. Purging: Helium is used to sweep volumes clear of undesirable components. For example, in rocket engines, fuel and oxidizer tanks, piping, and accessories are purged with helium to dispel contaminating foreign matter before introduction of the fuel and oxidizer.

K. Medical/Clinical: Both gaseous and liquid helium are used as diagnostic and therapeutic tools for treatment of various diseases and relief of respiratory distress.

L. Other: Small volumes of helium are used in lasers, in gas lubricated ball bearings for high speed gyroscopes, in weapons research and development, in the calibration of various analytical instruments, as a tracer to monitor the movement of other gases, and many other ways.

Table 1 illustrates the quantity of helium consumed in the United States in 1977 and projects demand for helium through the year 2000.

The need for helium in cryogenics at present and in the future reflects expected growth of technology in this field, with superconductors playing an increasingly demanding role. The projected increased use in welding probably reflects the dependency of advancing technology on combinations of metals other than steel, especially lighter metals. However, the projected increase in demand between 1990 and 2000 is modest, between 2.8 and 4.5 percent per year. The Midwest Research Institute (1977) further reports that the cumulative demand for helium over the next twenty-five years will be between twenty-five and thirty billion cubic feet. Helium "super-technologies," whose major impacts are expected sometime beyond 2000, may dramatically increase demand for this unique gas in the next century.

Table 1. Past and projected helium consumption, based on analyses done in 1975 and 1977. (From Midwest Research Institute, 1977.)

End Use	1977 consumed (MMCF)	1990 demand (MMCF)	2000 demand (MMCF)	Average annual growth rate (percent)
Cryogenics	235.4	474.2	736.4	5.2
Arc Welding	137.8	259.0	374.2	5.6
Pressurizing	114.0	168.4	224.1	3.4
Breathing Mixtures	59.4	123.9	187.8	5.0
Chromatography	30.6	57.0	80.3	4.7
Leak Detection	29.7	53.9	81.7	4.8
Lifing Gas	26.0	36.8	62.8	4.0
Heat Transfer	23.9	32.0	52.1	3.2
Controlled Atmosphere	18.3	28.8	40.2	3.7
Purging	14.3	21.8	29.0	3.7
Medical/Clinical	2.7	4.1	5.8	3.6
Other	18.0	37.5	67.1	5.8
Total (average)	710.1	1297.4	1941.5	(4.8)

CONSERVING A FINITE RESOURCE

Helium occurring as an inert ingredient of natural gas is the only currently exploited source of helium. As in a mixture of BB's and marbles, the smaller helium molecules do not interact and become physically bonded to the natural gas molecules. Instead, the helium molecules float freely among the larger natural gas molecules. Since helium does not burn, it is a contaminant in natural gas used as fuel. However, helium represents only a small percentage of natural gas and is not normally taken out in purification processes. Helium is finally released into the atmosphere when the natural gas is burned.

Helium, a finite resource, is thus a wasted by-product of natural gas consumption. This needn't be the case, as methods have been perfected for detecting and separating helium from natural gas and storing it in natural subsurface reservoirs. The U.S. Bureau of Mines has taken steps to secure enough of this rare gas to meet the demands of present and future technologies.

FEDERAL GOVERNMENT CONSERVATION PROGRAMS

In 1960, Congress passed the Helium Amendment Act (74 Stat. 918). This action was taken to provide a sustained supply of helium for essential government programs, such as the space program and cryogenic research, and to encourage industry to develop and distribute supplies of helium for private enterprise. In 1961, the U.S. Bureau of Mines agreed to purchase helium from four private firms over a period of twenty-two years. Since that time, eleven helium extraction plants have been built by private industry. Most of these plants are located in the Texas Panhandle area. For its conservation program, the Bureau of Mines purchased 32.7 billion cubic feet of helium from these plants at a cost of nearly four hundred million dollars. That helium is stored in the Bureau's Cliffside Field near Amarillo, Texas.

In 1969, demand for helium began to decline following a reduction in the space and atomic energy programs.

Helium demand, which had reached a peak of 929 million cubic feet (MMCF) in 1968 (893 MMCF for domestic use and 36 MMCF for export), bottomed out in 1972 when the domestic demand was only 580 MMCF (Henrie, and others, 1978). With the declining market, several helium extraction plants were shut down. In 1973, the Secretary of the Interior terminated the Bureau's four helium purchase contracts because of the decline in demand, competition from private enterprise, and the increasing indebtedness of the conservation program. Also, it was deemed that the reserves at Cliffside were sufficient to supply the government's needs through the year 2030 (Markle, 1979). Currently, the Bureau of Mines offers to store crude helium for private industry in its Cliffside Field. The Bureau charges nominally for storage, and for purification services, in an effort to promote helium conservation by industry (P. Tully, oral communication, 1981). For a more detailed history of helium production and conservation efforts see Henrie and other (1978).

THE HELIUM DILEMMA

Because the Bureau of Mines ceased its purchasing program, and vast quantites of helium are still vented with natural gas production, questions have been raised about the need to conserve helium. Many of the scientific community are encouraging conservation of what they term an "irreplaceable item," which, if once lost, may never be recovered (Morgan, 1979). They also predict a dramatic growth in helium demand in years to come. For example, the Fermi National Accelerator Laboratory in Batavia, Illinois presently uses 3.53 million cubic feet of helium per year. Upon completion of a new 4.6 mile circular nuclear accelerator track, their annual use of helium will increase to 105.9 million cubic feet (Morgan 1979). If other such projections are correct, this is but a fraction of future demand. In 1975, the U.S. Energy Research and Development Administration estimated that, by the year 2030, the cumulative helium requirements for fusion reactors alone could be as high as 52 billion cubic feet (Davis 1979).

As the result of natural gas production, Staats (1979) reports that 13 billion cubic feet of helium are dissipated into the atmosphere each year and that as much as half of our country's original helium resources may already be gone. Davis (1979) fears that, if these estimates are correct, we may run out of helium just as our investments in helium-dependent energy technologies begin to pay off.

On the other hand, Markle (1979) warns against immediate changes in the Bureau of Mines' present stand against purchasing and storing more industrially produced helium. He gives several reasons:

1. The projection of substantial demand beyond the year 2000 not only does not account for likely demand reductions in response to price increases, but also is based on technologies not yet developed.

2. The environmental and inflationary implications of an intense helium conservation program are vast when considered over the time frame involved.

3. Various government experts, including those of the U.S. Department of Energy, are satisfied with the present status of the helium conservation programs.

4. Given the ultimate exhaustion of natural gas as a source for helium, it may be wiser to reduce the dependency of future technologies on helium and to research separating helium from the atmosphere.

The helium dilemma is unresolved. Private industry presently produces

enough helium to meet the demands of private enterprise. The Bureau of Mines is providing helium to meet government needs. However, the private sector does not have extensive helium stockpiles against future shortages, as does the Federal Government. As long as natural gas reservoirs are producing, private enterprise can obtain the helium it needs. As natural gas reservoirs are depleted, the price of helium will rise accordingly. Dr. Earl Cook (1979) best describes the helium dilemma:

"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 calculated cost to conserve a finite resource for uncertain and partly tangible benefits that will accrue mainly to future generations."

Perhaps as reservoirs become depleted, technology will develop an economic means for extracting helium from the atmosphere. Otherwise, as our natural gas resources are exhausted, helium will simply not be available.

ORIGIN OF HELIUM

There are two prominent theories for the origin of helium (Seibel, 1968). The first proposes that helium is primordial, having been formed the same time the earth was formed, with some helium escaping into the atmosphere and some trapped in pore spaces within the earth. Ages later, this primordial gas migrated from its terrestrial traps and infiltrated overlying sedimentary rocks, accumulating in natural gas reservoirs. The second theory suggests that helium is derived from the radioactive decay of uranium and thorium, which were originally randomly distributed throughout the earth. Some amounts of these elements have since been redistributed in the crust and often occur in concentrated deposits in sedimentary strata. This process, active since the earth began to form, has produced helium in low concentrations in the country rock and in higher concentrations near uranium and thorium deposits. Primarily because the first theory does not explain the uneven distribution of helium occurrences found today, the most widely accepted and applied theory of helium origin is based on the radioactive decay of uranium and thorium (Tongish, 1980).

Ramsay and Soddy (1903) proved that helium is a by-product of the decay of certain radioactive elements. The radioactive decay series of uranium and thorium produce alpha particles which become helium-4 atoms with the acquisition of two electrons (see Figure 1). Helium is produced in the earth's mantle and crust at the rate of 1.125×10^{33} atoms per year (Reimer, 1976a), or 1.562 billion cubic feet per year (calculated at 14.7 psi and 60°F). Helium diffuses from the crust into the atmosphere and is then lost into outer space at the rate of 7×10^{30} atoms per year (Reimer, 1976a), or 9.724 million cubic feet per year. Hence, much more helium is being produced than lost. In fact, the total helium content of the atmosphere could be produced in only two million years (MacDonald, 1963). The helium produced in the mantle and crust that does not migrate into the atmosphere is trapped in pore spaces and crystal lattices of subsurface rocks (Reimer, 1976a).

This helium is derived from two

$$^{232}Th \xrightarrow{1.4 \times 10^{10}\ \text{Years}} {}^{208}Pb + 6\,{}^{4}He$$

$$^{235}U \xrightarrow{7.1 \times 10^{8}\ \text{Years}} {}^{207}Pb + 7\,{}^{4}He$$

$$^{238}U \xrightarrow{4.5 \times 10^{9}\ \text{Years}} {}^{206}Pb + 8\,{}^{4}He$$

Figure 1. Number of helium-4 atoms produced from radioactive thorium and two radioactive isotopes of uranium, U-235 and U-238, all decaying to different isotopes of lead. The half-life of each isotope is shown in years. (Reimer, 1976a).

source zones within the earth. The first zone involves the core and mantle; the second and more important zone is the crust. Within the first zone, great convection cells allow molten mantle material to rise from all levels in the core and mantle. Some material penetrates into the crust. As the mantle material rises, it degases and releases helium. In the second zone, radioactive uranium and thorium scattered throughout the crust are responsible for most helium production. Helium occurring in concentrations at or near the earth's surface may result from these source zones separately or in combination.

HELIUM DERIVED FROM THE CORE AND MANTLE

Uranium and thorium, assumed to be randomly dispersed, are constantly decaying in the core and mantle. Helium is produced in these regions as a by-product of this decay. The gas is subsequently either locked in crystal lattices of uranium-bearing minerals or released into minute vesicles and pore spaces in the molten and solid portions of the earth's interior. At great depths, tremendous pressure keeps helium molecules locked into crystal lattices and prevents the formation of gas vesicles. As molten mantle material rises toward the surface of the earth, pressures are lessened, and helium molecules that were locked into crystal structures become free to migrate. They may migrate into vesicles, along with other degassed magmatic volatiles. In a fluid magmatic body, the vesicles can rise toward the top of the diapir and eventually escape into the atmosphere if the body reaches the surface or if it is connected to the surface through a fault system. If the helium does not escape into the atmosphere, it may infiltrate and become trapped in the earth's crust.

Molten magma is first brought up from the core and mantle through a global system of convection cells, an important driving force for plate tectonics (see Figure 2). These currents rise in areas of mid-ocean ridges, where the upwelling magma causes the oceanic plates to spread laterally. As the ocean plates separate, molten mantle material is injected into the ridge areas, where it hardens and becomes a new part of the ocean crust. During this upwelling in the ocean floor, the magma is also degassing, losing some of its helium. This helium is then probably lost through the ocean waters into the atmosphere; the author knows of no traps to retain helium in the ocean floor. As the convection currents pass beneath the continental crust, the magma can migrate along large fault systems near a plate's boundary and become a source of volcanic activity in which large volumes of volcanic gases, including helium, are expelled into the atmosphere.

The magma beneath the continental plate might also become a source of material for diapiric uprising (bodies of magma migrating through the crust toward the earth's surface). As these

magmas rise, both temperature and pressure decrease. Subsequently, helium and other volatiles, degassed from the magma, are expelled and either lost to the atmosphere through volcanic activity or trapped in the sedimentary rocks of the continental crust.

Work in Japan by Wakita and others (1978) illustrates the relationships between diapiric upwelling of magma from the mantle and concentrations of helium near the earth's surface (see Figure 3). They believe that plumes of magma considerably less than 0.6 miles in diameter will produce only local hot springs at the surface, with little helium association. Plumes considerably larger than 0.6 miles in diameter, however, will produce volcanic activity. On the other hand, surface concentrations of helium are commonly associated with intermediate size magma plumes, approximately 0.6 miles in diameter.

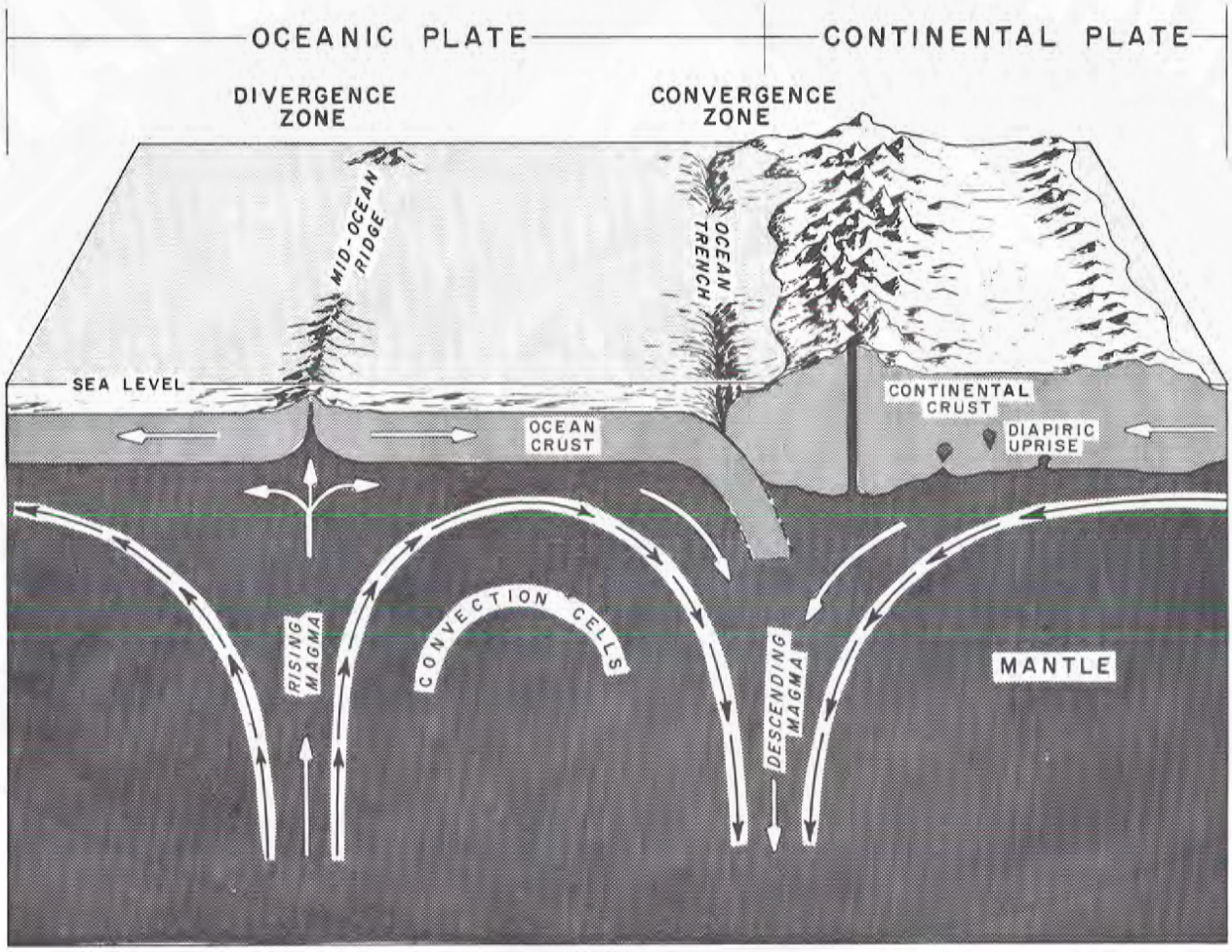

Figure 2. Convection cells in the mantle. Magma becomes a source of helium as it rises, degases, and interacts with the crust.

As these moderate size spheres of magma (approximately 0.6 miles in diameter) rise toward the surface, their temperatures decline and crystallization of andesite begins. Volatile materials in the magma, such as water, hydrochloric acid, carbon-dioxide, sulfur dioxide, nitrogen, and helium, are expelled. These ascending magmatic fluids, mixed with local groundwater, increase pore pressure and decrease stress in pre-existing tectonic stress fields, and fracturing and increased earthquake activity result. Groundwater flowing through these fractures may carry released hydrochloric acid through calcareous strata, dissolving calcium carbonate to produce carbon dioxide. Groundwater can then transport this carbon dioxide, along with helium, nitrogen, and other volatiles degassed from the magma, to the surface through newly formed fracture systems. Abundant carbon dioxide can dilute the original gas from the magma chamber and form a carbon dioxide spring at the surface. In this case, helium would not collect in anomalous concentrations. However, if helium migrates to the surface through faults in noncalcareous zones, the original gas composition may be preserved, and high concentrations of helium may be found at the surface.

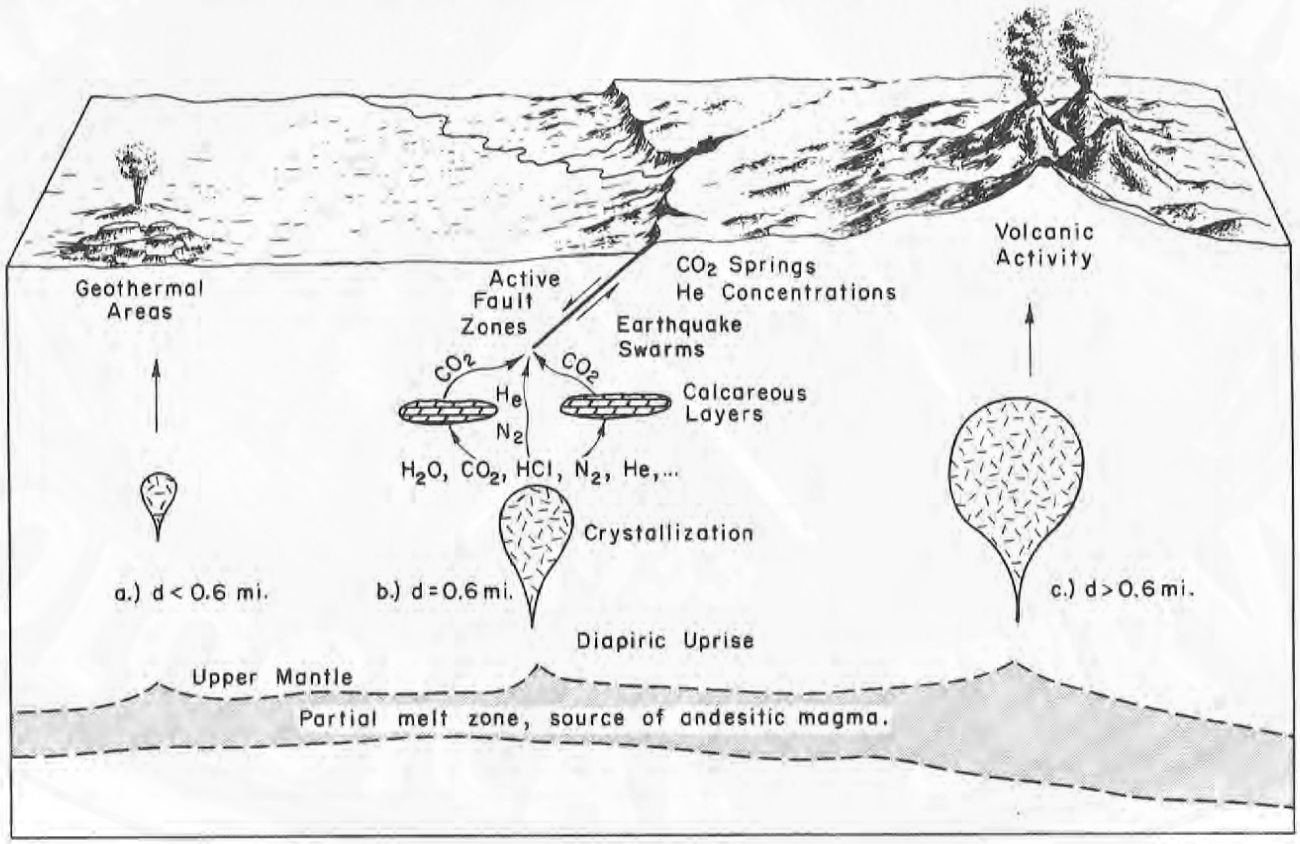

Figure 3. Schematic diagram of diapiric uprise of upper-mantle-derived magma and subsequent occurrence of helium concentrations at the surface. Different volumes of the original, roughly spherical diapir would result in different phenomena: a diapir (a) of diameter, d, less than 0.6 miles would cause only local geothermal effects; (b) of diameter approximately equal to 0.6 miles would cause earthquake swarms; (c) of diameter greater than 0.6 miles would cause volcanic activity. (Modified from Wakita and others, 1978)

This scheme, developed for the Matsushiro area of Japan, (Wakita and others, 1978), illustrates how helium developed in the mantle can reach the earth's surface. Small spheres of magma typically produce limited hot spring effects with no mechanism for helium transport to the surface except by diffusion. The largest spheres produce volcanic activity where helium is expelled with other volcanic gases; this helium is currently not exploitable. Only the intermediate size spheres allow the passive release and slow nonviolent bubbling up of helium, yielding possibilities for helium exploitation.

The theory of Wakita and others (1978) does not hold in all areas where helium is related to the diapiric uprising of magma. For example, some large bodies of magma (batholiths, stocks, and laccoliths) which are greater than 0.6 miles in diameter don't produce volcanic activity. Helium may be degassed from these bodies and either transported to the surface through associated fault systems or trapped in the subsurface country rock. Another exception is hot springs, which are not limited to magmatic plumes less than 0.6 miles in diameter, but may overlie large bodies of magma that have risen passively. Geothermal areas with anomalous concentrations of helium are also associated with areas of former volcanic activity, as in Yellowstone National Park. In these areas, helium may be carried to the surface by groundwater moving along fracture systems. As evidence, Hinkle (1980) and Reimer (1979a) have identified anomalous helium concentrations with several geothermal areas.

HELIUM DERIVED FROM CRUSTAL ROCKS

Since helium often accumulates in crustal rocks, the exploitable sedimentary rocks of the crust are more important sources of recoverable helium than mantle and core materials. As in the mantle and core, radioactive materials are randomly dispersed throughout the crustal rocks, and continue to form helium as they decay. Again, this gas is trapped in crystal lattices of uranium-bearing minerals and more commonly in the interstitial pore spaces of associated rocks. Helium in pore spaces is free to migrate laterally or vertically in the sedimentary section. Helium might migrate on its own or with subsurface fluids such as groundwater or natural gas. Migration may concentrate the helium in oil and natural gas deposits associated with structural or stratigraphic traps. This migration may also allow the escape of helium into the earth's surficial sediments or atmosphere.

HELIUM ACCUMULATIONS

SOIL GAS

The gaseous component of the regolith, the layer of decomposed rock fragments and soil just above the solid rock of the earth's crust, is referred to as soil gas (Reimer, 1979a). Soil gas contains helium in concentrations below normal atmospheric concentration (5.2 parts per million) to over seventy-five times the atmospheric concentration. Background concentrations of helium in the soil gas (about five parts per million) result from both atmospheric helium inflitrating down into the regolith and helium diffusing up from underlying groundwater (Reimer, 1979b). Normal helium concentration in groundwater re-

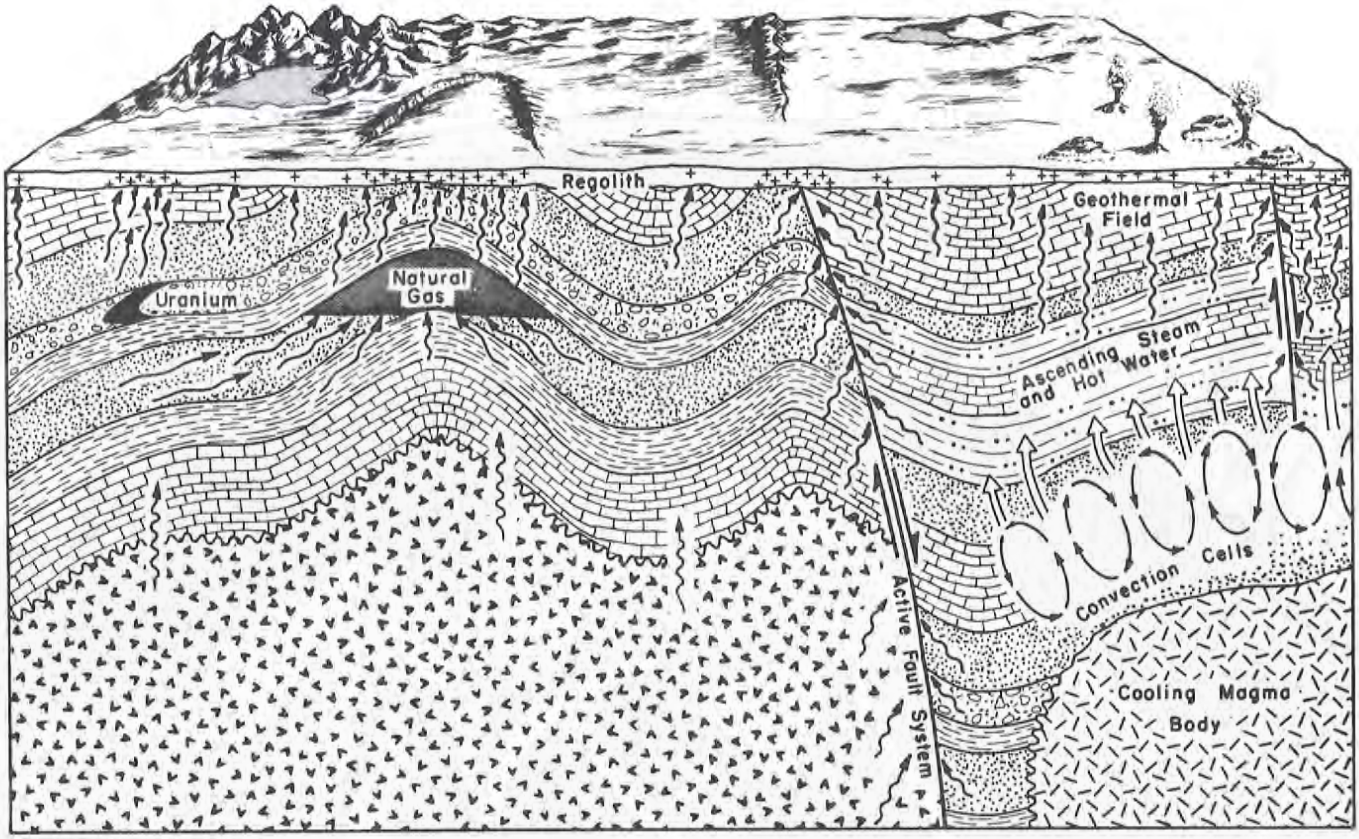

Figure 4. Various origins for anomalously high helium concentrations in the soil gas of the regolith. (Wavy arrows depict various routes for helium migration.)

sults primarily from helium diffusing from decaying radioactive uranium and thorium randomly dispersed in the country rock. Normal concentrations of helium in groundwater may also come from high concentrations of helium that have been diluted to background levels. Anomalous concentrations of helium in soil gas are the result of helium migrating from uranium deposits (Reimer, 1979a), from geothermal fields (Denton, 1977; Hinkle, 1980), from oil and gas reservoirs (Roberts and others, 1976), and from certain structural features, dominantly fault zones (Reimer, 1979b; Doering and Freidman, 1980a). Figure 4 illustrates how helium migrates from various sources in the subsurface and accumulates in the regolith.

URANIUM

Migrating groundwater can leach originally disseminated uranium from one area of a stratigraphic unit and re-deposit it in another area in tabular deposits or, more important to the Wyoming mineral industry, roll-front deposits. Uranium may also "stack up" in faults where flow of uraniferous groundwater is interrupted. These concentrations of uranium then produce helium in excess of the helium content in the surrounding country rock. The gas can then migrate toward the ground surface and produce helium

anomalies in the soil gas. Although these concentrations of helium do not lend themselves to commerical production, the U.S. Geological Survey's Denver office is experimenting with soil gas surveys to locate these anomalies as a means of prospecting for uranium deposits (Reimer, 1976a).

OIL AND GAS

It is generally believed that the helium found in natural gas is primarily derived from the radioactive decay of uranium and thorium scattered throughout the sedimentary section. Helium is also derived from the decay of uranium and thorium in concentrated deposits and uraniferous shales in close proximity to some gas reservoirs. Katz (1969) concluded that:

"Uranium and thorium are everywhere present in concentrations at the parts per million level in sedimentary rocks. The shales (and limestones) often pointed to as a source bed for natural gas, contain these generators of helium in low concentrations. Material balances can be made to show that the uranium and thorium are of the right order of magnitude of concentration to generate in the source beds the amount of helium found in such fields as Hugoton."

Disseminated helium is picked up from the country rock by migrating natural gas and transported to the reservoir, where it can reach concentrations as high as eight percent. Once concentrated in the trap, some helium may diffuse through the caprock toward the surface, causing helium anomalies in the soil gas. Of all terrestrial accumulations of helium, only natural gas reservoirs lend themselves to commercial helium production.

GEOTHERMAL

Helium degassed from a relatively shallow magma body beneath a geothermal field may directly diffuse through the overlying strata to produce an anomaly in the soil. It may also mix with hot water, steam, and vapors degassed from the cooling magma body and migrate through permeable rock or along some fracture zones. This gas passively infiltrates the surface groundwater and ultimately enriches the soil gas with helium. This rising system of gas and hot water can also act to transport helium that is already present in the country rock to the surface. Other fracture zones lead to hot springs, steam vents, and geysers, where the helium is expelled into the atmosphere rather than emplaced in the soil gas.

STRUCTURAL RELATIONSHIPS

Rich helium accumulations were originally thought to be located above domes and ridges in the crystalline basement. A.P. Pierce (1961) reasoned that large quantities of helium could migrate from a crystalline source into a nearby natural gas reservoir. Cambrian and Ordovician fields in central Kansas have more helium than could have been derived from the surrounding rock. Hence, helium had to either migrate upward from the crystalline basement or laterally from nearby uraniferous shales. On the other hand, Jodry and Henneman (1963) suggested that the proximity of helium-rich natural gas to crystalline rocks of tectonic ridges, platforms, and uplifts is more coincidental than critical. These accumulations of natural gas and helium simply indicate that there are regional structural and stratigraphic traps in which the gases may accumulate. Yet, crystalline uplifts may be an indirect source of helium in the sedimentary rocks. Erosion can move radioactive materials originally in the crys-

talline rocks and deposit them in adjacent basins. The uranium and thorium then further decompose and produce helium. Helium can then be redistributed and concentrated in structural and stratigraphic traps. High helium concentrations have been demonstrated in association with groundwater in active fault zones. Anomalously high helium concentrations were found over a part of a major Sierra Nevada frontal fault within, and other faults outside, the Long Valley Cauldera in east central California (Hinkle and Kilburn, 1980). In the tectonically active Matsushiro area of central Japan intense earthquake swarms, as many as six hundred earthquakes in one day, were recorded from 1965 to 1967. The helium concentration in the soil gas above the fault zones was higher than that of the surrounding area (Wakita and others, 1978). In the Soviet Union, geologists are using helium soil gas surveys to locate deep-seated faults (Bulashevich and Bashorin, 1971).

Helium in the subsurface seems to migrate toward faults. The mechanism for this migration is unclear, but may have to do with pressure differentials and fluid flow in the structural environment surrounding a fault. Reimer and Adkisson (1977) believe that a fault would collect helium from country rock at any depth and act as a channel for helium flow to the surface. At great depth, a fault might tap into a magmatic diapir and transmit helium and other degassed substances toward the surface. Bulashevich and Bashorin (1970) also suggest that faults are zones of greatest helium flow from deep in the crust. They cite the high helium concentrations of springs lying above a major fault near Lake Tanganyika in Africa as an example of helium migration along faults.

Soil gas surveying for helium may prove to be an important tool in predicting earthquakes. Doering and Friedman (1980b), from a survey of helium concentrations in natural water wells and springs in southwest Montana, report that helium concentrations in groundwater associated with an active fault fell to near zero seventeen days preceeding a major earthquake. Immediately after the earthquake, which had an intensity of 4.7 on the Richter scale, helium concentrations rose to values several times higher than normal. This deviation in helium concentration was observed at only one monitoring station. With more control and understanding, some trend of helium variation might be established to forecast earthquakes several days in advance.

STRATIGRAPHIC RELATIONSHIPS

NATIONAL ANALYSIS

In 1980, the U.S. Bureau of Mines completed a survey of 6,455 natural gas reservoirs in 35 states (Tongish, 1980). This survey has revealed significant relationships between helium content, geologic systems, and reservoir depth. Such associations may provide insight into the environments under which helium-rich natural gas reservoirs might accumulate. Most of the reservoirs surveyed are of Paleozoic age. The more helium-rich reservoirs also appear to occur at shallow depth. The results of these analyses are important additions to our knowledge of helium geology.

Sixty-six percent of all helium-significant natural gas reservoirs that were sampled are of Paleozoic age, seventeen percent are of Mesozoic age, and seventeen percent are of Cenozoic age (see Figure 5). Five geologic

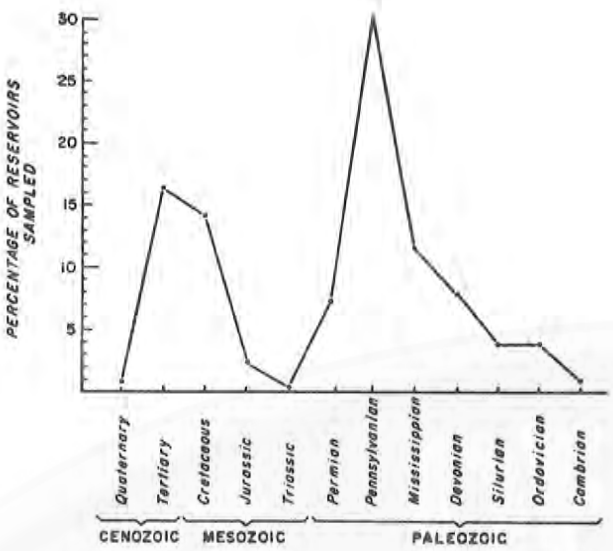

Figure 5. 6,455 nationally surveyed natural gas reservoirs with significant helium content plotted by geologic system. (Data from Tongish, 1980.)

systems, Pennsylvanian, Tertiary, Cretaceous, Mississippian, and Devonian, account for over eighty percent of the reservoirs sampled. The natural gas reservoirs sampled are least abundant in the Quaternary, Triassic, and Cambrian Systems. Figure 6 illustrates how helium content varies with the age of the natural gas reservoir. The Triassic and Permian Systems contain the reservoirs richest in helium, while the maximum helium concentrations in Quaternary, Tertiary, Cretaceous, and Silurian reservoirs are comparatively small.

Rogers (1921) first indicated that there might be a linear relationship between the helium content of a natural gas reservoir and its depth. He suggested that reservoirs below 2,500 feet deep would contain little helium. However, Jodry and Henneman (1963) suggest that the depth below which helium concentrations drop off is 7,000 feet. Tongish (1980) also maintains that at about 7,000 feet, helium concentrations in natural gas reservoirs drastically decline. Figure 7 shows that most reservoirs with significant helium concentration are less than 8,000 feet deep. This observation may, at least in part, result from the smaller number of wells drilled to greater depths. Figure 8 shows that the helium concentrations of 6,270 of Tongish's surveyed reservoirs are much greater at shallower depths, and decline below depths of 8,000-9,000 feet. Hence, maximum and average helium concentrations tend to decrease with increasing depth. Although the geologically older reservoirs generally contain higher helium concentrations, they are not necessarily the deeper reservoirs.

Reasons for these relationships are not fully understood, and there is room for speculation. Helium concentrations are generally higher in the older Paleozoic reservoirs, perhaps because radioactive elements have had more time to decay and produce

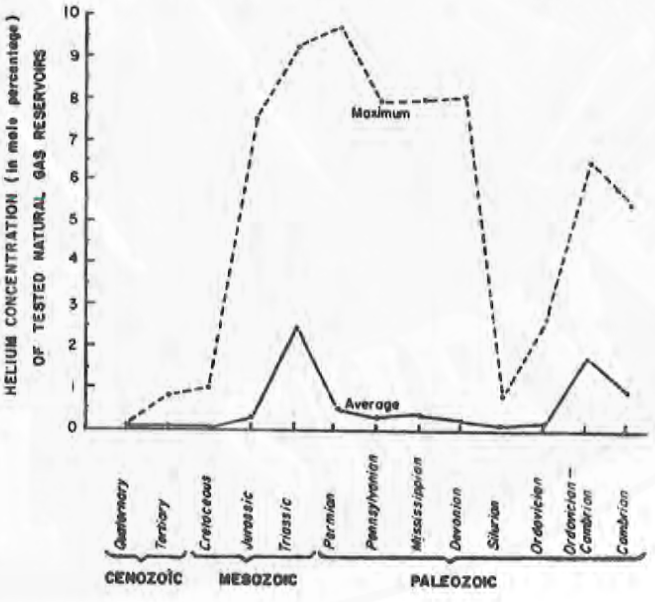

Figure 6. Maximum and average helium content of reservoirs within each geologic system (From Tongish, 1980).

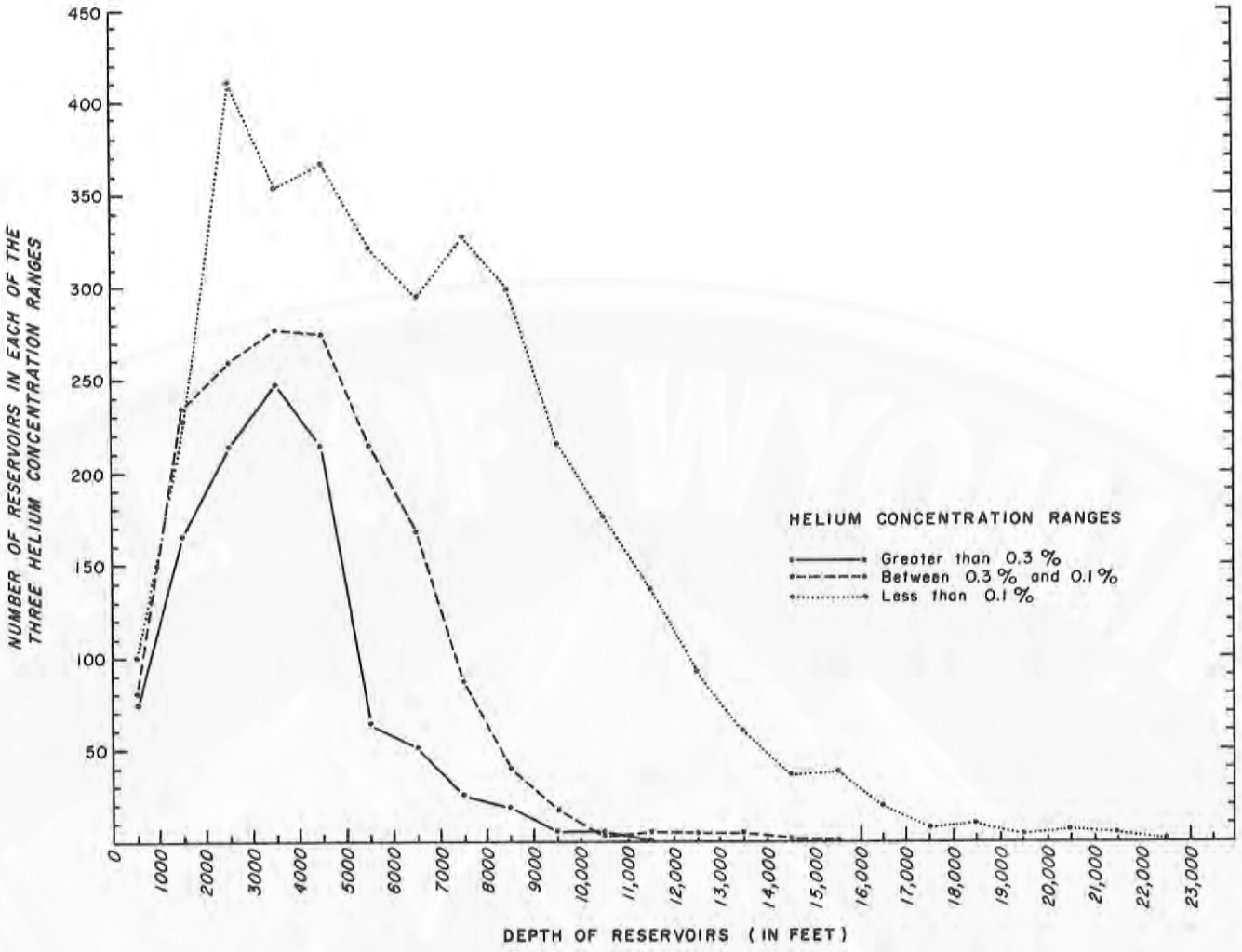

Figure 7. Number of nationally surveyed natural gas reservoirs containing (a) greater than 0.3 percent, (b) between 0.3 and 0.1 percent, and (c) less than 0.1 percent helium plotted according to the average depth of the reservoir. (Data from Tongish, 1980.)

helium than those in younger strata. Also, the proximity of older reservoirs, closer to basement source rocks which contain uranium and thorium, may be another reason. With respect to the correlation between helium concentration and reservoir depth, Jodry and Henneman (1963) suggest that since the diffusibility of helium increases with increasing pressure and temperature, there may be a critical depth below which traps can no longer seal helium into reservoirs. Evidence suggests that this critical depth is between 7,000 and 10,000 feet.

WYOMING HELIUM

Three hundred seventy-five natural gas reservoirs in Wyoming have been surveyed for helium content. This survey includes data on natural gas reservoirs drilled both recently and as far back as the early 1900's, some of which are now depleted. The most recent data were collected by the Bureau of Mines through 1978 and are supplied by B.J.

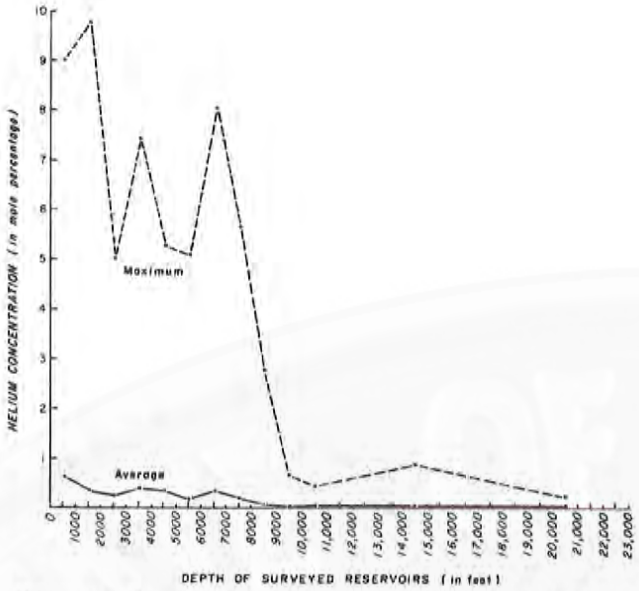

Figure 8. Helium concentration, in mole percent, of 6,270 nationally surveyed natural gas reservoirs, plotted according to reservoir depth. (Modified from Tongish, 1980.)

Moore (1980, personal communication) of the U. S. Bureau of Mines. Significant helium concentrations were found in reservoirs of all ages but Silurian (Silurian strata are very rare in Wyoming and contain no oil or gas). Sixty-six percent of those reservoirs are of Cretaceous age, a reflection of more wells drilled into Cretaceous rocks than any other. Apparent correlation between helium content of Wyoming natural gas reservoirs, their age, and their depth may be biased in favor of shallower and younger reservoirs, since they are much more numerous in Wyoming than older and deeper reservoirs.

Figure 9 illustrates how maximum and average helium concentrations of natural gas reservoirs vary with the age of the reservoir. With the exception of Devonian (only one reservoir surveyed) and Silurian (none surveyed) and Permian reservoirs, average helium

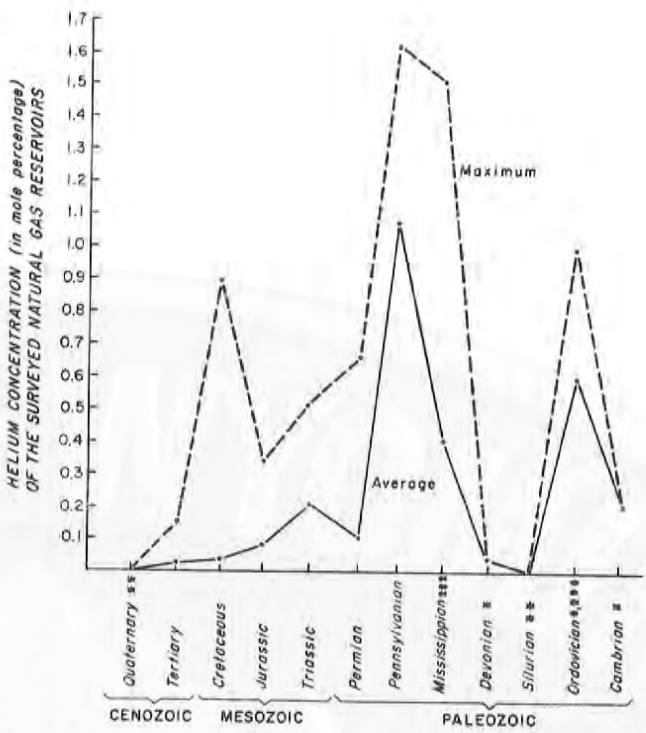

Figure 9. Maximum and average helium concentrations, in mole percent, of 375 Wyoming natural gas reservoirs, plotted according to reservoir age. (Data from Moore, 1980, personal communication.)

* *Fewer than five reservoirs in the survey fell into these systems.*

** *The survey has no reservoirs of these ages.*

*** *Includes data from a recently completed wildcat by American Quasar Petroleum with 1.0% helium (Petroleum Information Corporation, Rocky Mountain Region Report: v. 54, no. 7, Jan. 14, 1981, p. 57).*

concentrations are highest in Paleozoic reservoirs (0.64 percent helium, collectively), followed by Mesozoic (0.04 percent helium) and Cenozoic reservoirs (0.03 percent helium). The reason for this might be that there is more time for helium to accumulate in older reservoirs and to migrate from nearby basement source rocks below. In comparison with Tongish's nation-wide survey (Figure 6), helium concentrations in Wyoming are relatively high in the Cambrian and Ordovician systems. Pennsylvanian reservoirs in Wyoming have the highest average helium concentration, while nationally, reservoirs of Triassic age have the highest.

Figure 10 shows how the helium concentration of natural gas reservoirs in Wyoming varies with depth. To a depth of 12,000 feet, helium concentrations decrease, in agreement with the national trend, (Figure 8). However, the highest average helium concentrations occur below 12,000 feet, much in contrast to Tongish's results. Significant helium reservoirs, such as the Tip Top Field (12,600 to 15,200 feet deep) and Church Buttes Field (18,050 to 18,624 feet deep), are found at these depths. In all, twenty-nine Wyoming reservoirs, collectively averaging 0.26 percent helium, occur below 12,000 feet, well above the average helium content for any single thousand foot interval less than 12,000 feet deep. Reasons for this relationship are open to speculation.

For statistical purposes, Moore (1979) further catagorizes helium concentrations as follows: (a) less than 0.1 percent, (b) between 0.1 percent and 0.3 percent, and (c) greater than 0.3 percent. In general, helium is economically extracted from natural gas containing at least 0.01 percent helium and becomes more economical as concentration rises.

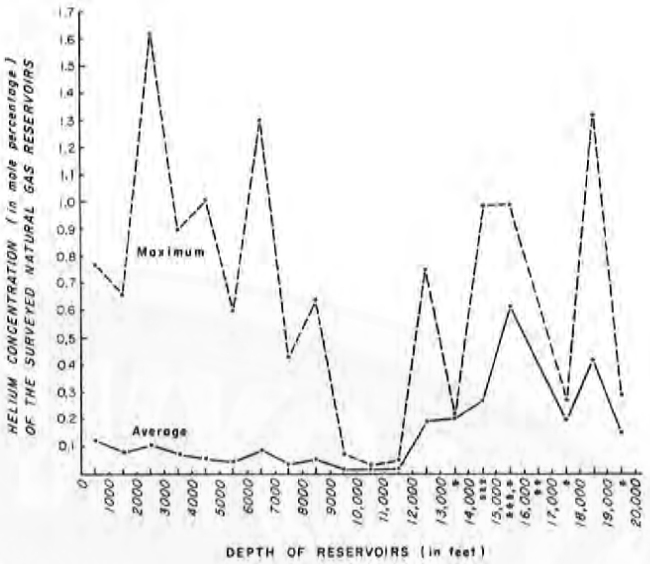

Figure 10. Maximum and average helium concentrations of 375 Wyoming natural gas reservoirs, plotted according to reservoir depth. (Data from Moore, 1980, personal communication.)

* *Fewer than five reservoirs were in this depth interval.*

** *No data*

*** *Includes data from a recently completed wildcat by American Quasar Petroleum with 1.0 percent helium (Petroleum Information Coporation, Rocky Mountain Region Report: v. 54, no. 7, Jan. 14, 1981, p. 57).*

Of the 375 reservoirs surveyed in Wyoming, 321 (85.6 percent of the total) contain less than 0.1 percent helium, 35 (9.3 percent) contain between 0.1 percent and 0.3 percent helium, and 18 (5.1 percent) contain over 0.3 percent helium. 15 of the 18 reservoirs with greater than 0.3 percent helium are in the Paleozoic system. One is of Cretaceous age (in the South Baxter Basin Field, Sweet-

water County); one of Jurassic age (15 miles east of South Baxter Basin Field); and one of Triassic age (immediately east of Teton National Park). Thirteen of these eighteen are found above a depth of nine thousand feet. To date, the highest concentration of helium reported in Wyoming was from the Pennsylvanian Amsden Formation in the Mule Creek West Field of Niobrara County. This natural gas contianed 1.62 percent helium (Moore, 1980 personal communication). The field, now depleted, produced over 87 billion cubic feet of natural gas (Barlow and Haun, 1978).

COMMERCIAL HELIUM PRODUCTION

With present technology, natural gas reservoirs are the only economical sources of helium. The only other feasible sources are groundwater and the atmosphere.

Although helium occurs in groundwater, its local concentration varies drastically. In a study area of southwestern Montana, Doering and Friedman (1980b) noted concentrations of 0 to 400 parts per million, most commonly near 0. Helium content in groundwater is apparently influenced by faulting, geothermal activity, climate, and other factors not fully understood. Low concentration and extreme variability of helium in groundwater preclude groundwater as a commercial source of helium.

The concentration of helium in the atmosphere ranges from 0.0004 percent at sea level to 1.32 percent at an altitude of sixty-two miles, averaging 0.00052 percent or 5.2 parts per million (Weast, 1967). Even at this low concentration, Markle (1979) reports that the atmosphere contains 5,000 cubic miles of helium, a virtually inexhaustable and constantly replenished supply. However, with our present level of technology, it would take up to 800 times as much energy to extract helium from the atmosphere as it would from natural gas containing 0.49 percent helium (Cook, 1979). Further, astronomically high production costs, 180 times greater than the cost of extraction from natural gas (Staats, 1979), preclude recovery of helium from the atmosphere.

Consequently, since helium occurs in relatively high concentrations in natural gas and is a by-product of an existing natural gas industry, production from natural gas is presently our best avenue for securing large quantities of helium.

SEPARATING HELIUM FROM NATURAL GAS

The most efficient commercial method of obtaining Grade-A helium (99.995 percent pure) from natural gas is a low-temperature process involving three steps: (a) the natural gas is first treated to remove carbon dioxide and water; (b) crude helium (sixty to ninety percent pure) is then separated from the natural gas; and (c) the crude helium is purified to a marketable product (Deaton and Haynes, 1961). This process is used by all of the helium production plants built by the U. S. Bureau of Mines.

Initial Natural Gas Treatment

Before crude helium can be separated from natural gas, carbon dioxide and water must be removed. The carbon dioxide is removed chemically through a monoethanolamine-diethylene glycol treating process which reduces the carbon dioxide concentration to 50 parts per million. Through dehydration and filtering processes, water content is then reduced to

less than 0.002 pounds per million cubic feet of natural gas. Once carbon dioxide and water are removed, crude helium can be separated from natural gas by cryogenic processing.

Crude Helium Separation

In this low temperature process, the previously treated natural gas is initially cooled to -60°F, condensing and separating heavy hydrocarbons which are then returned to the natural gas stream. The remaining vapor is processed through a series of cooling and condensing stages, reaching temperatures down to -300°F and pressures from 225 to 450 psig. This process separates essentially all hydrocarbons, which are returned to the natural gas stream. The final product of this phase is crude helium averaging about seventy-five to eighty percent helium, twenty to twenty-five percent nitrogen, and 0.1 percent hydrogen.

Crude Helium Purification

In preparation for the purification process, hydrogen content of the crude helium is reduced from 0.1 percent to less than 0.01 percent by catalytic oxidation (forcing the hydrogen atoms to combine with oxygen atoms to form water molecules) at 50 psig. The resulting gas is dried with activated alumina and compressed to 2,750 psig. This clean, water-free, pressurized crude helium is further purified by three additional low-temperature-condensation stages. These stages gradationally cool the crude helium to -340°F at a pressure of 3 psig. This cooling allows separation of nitrogen as it condenses and liquifies, leaving helium in the gaseous state. The product is 99.5 percent pure helium. The helium is filtered through activated charcoal bathed in liquid nitrogen for further refinement. The final product is Grade-A helium, 99.995 percent pure.

HELIUM PRODUCTION PLANTS

There are presently ten helium production plants in the United States, all capable of extracting helium from natural gas (Markle, 1979). Four of these plants are owned and operated by private industry; five plants were built to produce helium for sale to the Federal Government under four purchase contracts. The remaining plant is owned and operated by the U. S. Bureau of Mines.

The four plants owned and operated by private industry produce Grade-A helium for domestic and foreign markets. These plants produce more than double the current demand for helium. Approximately one third of the excess is stored; the remaining helium is vented into the atmosphere. The companies operating existing helium production plants are (Henrie and others, 1978):

1. Alamo Chemical Company, at Elkhart, Kansas.
2. Kansas Refined Helium, at Otis, Kansas.
3. Cities Service Cryogenics, at Ulysses, Kansas.
4. Western Helium Company, at Shiprock, New Mexico.

The five government-sponsored plants produced and sold crude helium to the Federal Government from 1963 to 1973 as part of the government's helium conservation program. These plants are connected with the Cliffside Field through the Bureau of Mines' 425-mile-long crude helium pipeline. The owner/

operators of these plants are (Henrie and others, 1978):

1. Northern Helex Company, at Bushton, Kansas.

2. National Helium Corporation, at Liberal, Kansas.

3. Cities Service Helex (Jayhawk Plant), at Ulysses, Kansas.

4. Phillips Petroleum Company (Dumas Plant), at Dumas, Texas.

5. Phillips Petroleum Company (Sherman Plant), in Hansford County, Texas.

Since the termination of their helium-purchase contracts in 1973, these plants have not sold helium to the Bureau of Mines.

A tenth helium production plant is the Keyes Plant, owned and operated by the U.S. Bureau of Mines, near Keyes, Oklahoma. It extracts helium from the Keyes Field at the rate of 0.3 billion cubic feet annually; two-thirds is used by the Federal Government and the rest is stored at the Cliffside Field. The Bureau of Mines has two other facilities. The Excell Plant at Masterson, Texas is designed to process the crude helium stored at Cliffside. The Amarillo Plant, Amarillo, Texas is a distribution facility where helium is shipped in small cylinders as a pressurized gas or in bulk containers as a liquid at 2000-3600 psi and 70°F.

HELIUM STORAGE

Currently, all processed helium in storage in this country, both government and privately owned, is stored by the U. S. Bureau of Mines. It is kept in the Bureau's Cliffside Field, fifteen miles northwest of Amarillo, Texas and in their 425-mile crude helium pipeline that extends from the Cliffside Field to the helium production plant at Bushton, Kansas. Bush Dome is the structural trap into which crude helium is injected for storage, in the Cliffside Field. Of the 44.4 billion cubic feet of helium in the Cliffside Field, 40.4 billion cubic feet is processed helium stored by the Bureau and 4.0 billion cubic feet is present in the native natural gas (P. Tully, personnel communication, 1981).

Bush Dome (Figure 11) is a structural dome with 500 feet of vertical closure and an areal extent of 13,760 acres. It is part of the buried Amarillo Mountain structure on the north edge of the Palo Duro Basin. The main gas production and helium storage horizon is in the upper member of the Permian Chase Group, known locally as the Brown Dolomite (Tade, 1966). The Brown Dolomite, found 3,300 feet below the surface, consists dominantly of dolomite with some anhydrite, shale, and sandstone stringers. It is 250 to 300 feet thick in the Cliffside Field, and has porosity of four to eleven percent. Permeability averages 10 millidarcies (md). Overlying the Brown Dolomite and serving as the cap rock for the helium reservoir is the Panhandle Formation of the Wichita Group. The Panhandle Formation averages 400 feet thick and consists largely of impermeable anhydrite. The Brown Dolomite is underlain by granite in Bush Dome (Markle, 1979). The field has a gas/water contact which seals the helium reservoir laterally.

The potential for storing helium in the Brown Dolomite of the Bush Dome sturcture was demonstrated from 1945 to 1959 (Tade, 1966). During the period 1945 to 1953, 87 million cubic feet of surplus helium produced from the Amarillo and Excell helium plants were injected into the Brown Dolomite through a two-inch-diameter, high-pressure pipeline. From October 1953 to September 1959,

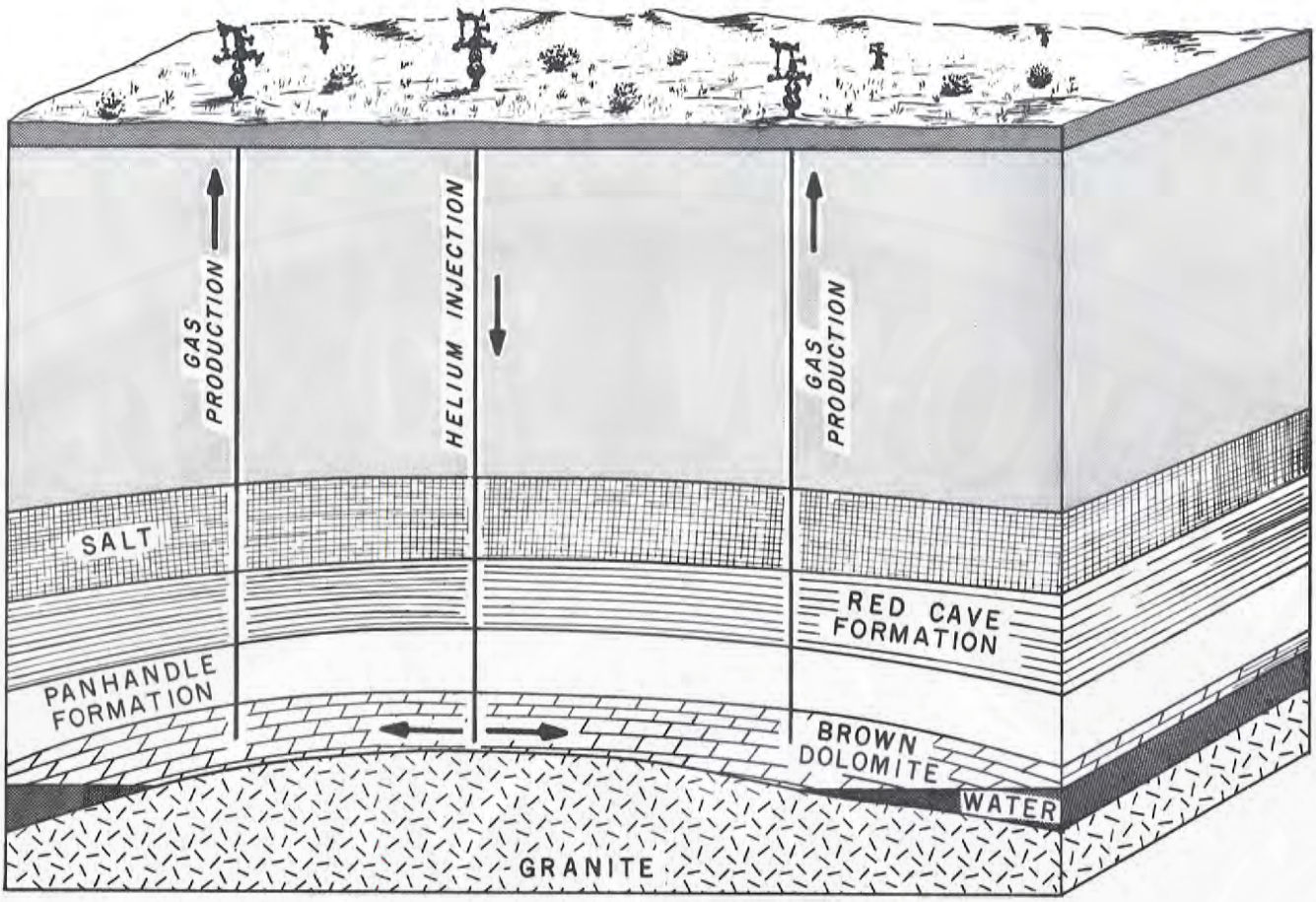

Figure 11. Geology of the U. S. Bureau of Mines helium storage facility at the Cliffside Field near Amarillo, Texas. Helium is injected into the Brown Dolomite of the Bush Dome structure. (Modified from Markle, 1979.)

over 80 percent of the injected helium was withdrawn from storage. Analyses of reservoir performance and gas data indicated that if recovery had continued, nearly 100 percent of the helium could have been withdrawn. To detect any helium leakage through the cap rock, five observation wells monitor the helium content in the Red Cave Formation at the base of the Clearfork Group, immediately overlying the Panhandle Formation. There has been no leakage discovered.

Crude helium is injected into Bush Dome through a series of six wells spaced 1,800 feet apart and aligned roughly north-south. As helium is injected into the reservoir, native natural gas is withdrawn through 18 wells surrounding the injection wells. This allows space for helium storage and insures against excessive reservoir pressure (Munnerlyn, 1979). The average reservoir pressure is currently 730 psig. A sufficient quantity of natural gas is left in the reservoir

to maintain desired pressures and for use in the future in the event that all helium has to be swept from the reservoir.

A 425-mile-long, eight-inch-diameter, high-pressure (1,800 psig) crude helium pipeline was constructed by the U. S. Bureau of Mines in 1961. The pipeline was intended as a gathering system for helium produced from the helium-rich natural gases of the Keyes, Greenwood, Panhandle, and Hugoton gas fields in Kansas, Oklahoma, and Texas. The objectives of the system were: (a) to gather crude helium from the five privately owned and operated crude helium extraction plants (b) to deliver the helium to the Cliffside Field for storage; and (c) to serve helium production plants owned and operated by the Bureau of Mines.

40.4 billion cubic feet of crude helium are stored at Cliffside: the Federal Government owns 36.4 billion cubic feet, 2.5 billion cubic feet are privately owned under contract, and 1.5 billion cubic feet were accepted under court order, (P. Tully, personal communication, 1981). Most of the stored government-owned helium was purchased as crude helium from the five government-sponsored helium extraction plants. From 1963 to 1973, the Bureau's pipeline gathered 35 billion cubic feet of helium from those plants. Purchase contracts for that helium were terminated in 1973. At present, the only helium added to the Cliffside storage reservoir is that produced by the Bureau or that stored under contract with private industry.

HELIUM RESOURCES AND RESERVES

GENERAL

The U. S. Bureau of Mines estimates the helium resources of this country to be 727 billion cubic feet as of Janaury 1, 1979. This estimate is about 17 billion cubic feet greater than their estimate of January 1, 1977. The increase is due in part to increased natural gas resource estimates in the Overthrust Belt of Wyoming, Utah, and Idaho (Moore, 1980). Moore (1979) tabulates these helium resources in four catagories (also see Figure 12):

1) Measured helium resources include helium in natural gas reserves for which estimates of helium content are believed to be within 20 percent of the true value (comparable to "proven" reserves in the natural gas industry). Measured resources also include helium in storage.

2) Indicated helium resources include helium in natural gas reserves for which estimates of helium content are made by using reasonable engineering and geologic projections (comparable to "probable" reserves in the natural gas industry).

3) Hypothetical helium resources include undiscovered helium that may reasonably be expected to exist in an existing gas producing area with known geologic conditions (comparable to "possible" resources in natural gas industry). Once exploration confirms these deposits and reveals the quantity and quality of helium, hypothetical resources are reclassified as indicated resources.

4) Speculative helium resources include undiscovered helium that may occur either in known types

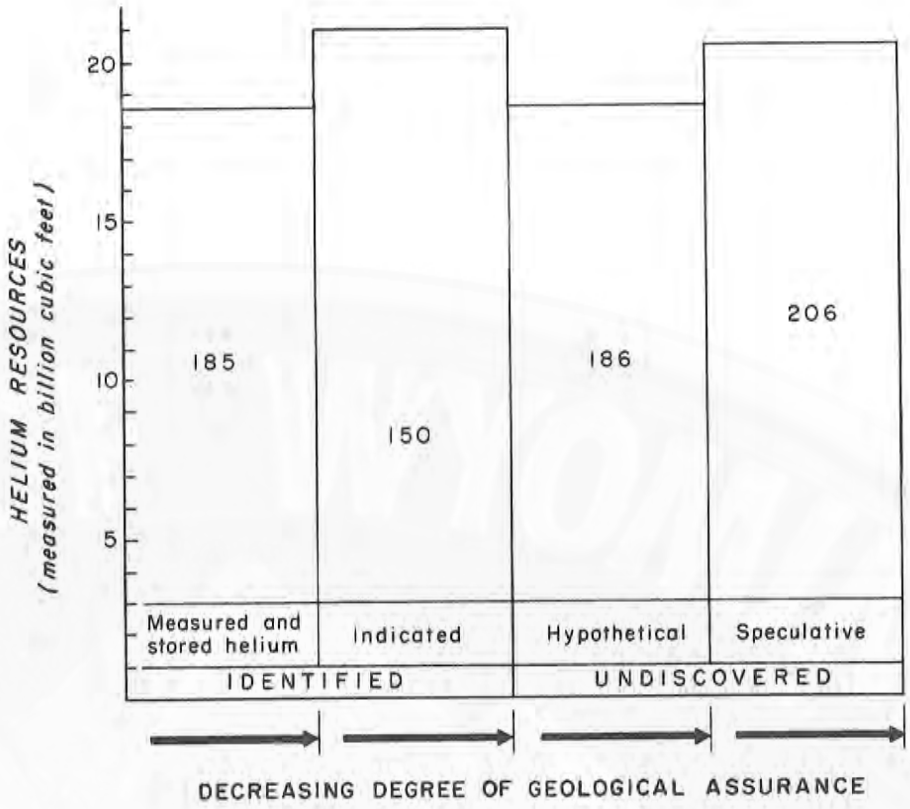

Figure 12. Helium resources of the United States as of January 1, 1979, according to category of resource (measured at 14.74 psia and 60°F). Total resources are 727 billion cubic feet. (Modified from Moore, 1980.)

> of deposits in a favorable geologic setting where no discoveries have been made or in unknown types of deposits that remain to be recognized.

Helium reserves consist of helium that has been discovered, developed, and is producible but has not yet been produced, plus stored helium; i.e., helium in the measured and indicated resource catagories greater than 0.3 percent helium.

Helium reserves are further classified as depleting or nondepleting reserves (Moore, 1980). Depleting helium reserves occur in natural gas reservoirs that are being exploited for their valuable natural gas. This helium is normally not extracted in the natural gas production process, but is vented into the atmosphere and wasted. Nondepleting helium reserves, which total 132 billion cubic feet in the U.S., occur in natural gas reservoirs from which there is no production. Normally these reservoirs are not produced because the natural gas has too low a heating value to be marketable, and often has a high concentration of nitrogen, on the order of twenty to seventy percent. Tongish (1980) suggests a linear correlation between helium and nitrogen concentrations in these natural gas reservoirs. Among the nondepleting reserves are the reservoirs of Wyoming's Tip Top Field and the deeper reservoirs below the current pay zones of the Church Buttes Field. Nondepleting reserves also include the helium in storage at the Bureau of Mines' Cliffside Field.

The world's helium reserves are concentrated in North America. Cook (1979) estimates that the United States has fifty-two percent of the world's economically valuable measured helium reserves (see Table 2). Cook's esti-

Table 2. World's economically valuable helium resources as of 1978. (Modified from Cook, 1979.)

Country or Region	Percent of Total Helium reserves
United States	52.0%
Algeria	24.8
U.S.S.R.	18.5
Canada	2.5
Netherlands	1.0
Australia	0.9
United Kingdom	0.2
Middle and far east	0.1

mates are weighted averages based on relative helium concentrations and the costs of recovering helium from natural gas reservoirs. His estimates are derived from measured helium resources only. Furthermore, the helium-rich natural gas reserves in this country apparently occur in distinct geographic zones; see Figure 13.

WYOMING RESOURCES

The helium resources in Wyoming have not been tabulated according to the four catagories previously summarized. Plate I illustrates the location of helium-rich natural gas reservoirs, their geologic age, and their helium content by category: (a) greater than 0.3 percent (b) 0.1 to 0.3 percent, and (c) less than 0.1 percent.

Wyoming has by far the largest accumulation of nondepleting helium reserves in the country. Of the 88 billion cubic feet of nondepleting helium reserves in this nation (Munnerlyn and Sonnek, 1980), Wyoming's Tip Top and Church Buttes fields together account for 61.9 billion cubic feet, seventy percent of the national total. The 44 billion cubic feet of helium stored at Cliffside are not included in Munnerlyn and Sonnek's estimate.

Church Buttes Field

The Church Buttes Field underlies 49,760 acres of semiarid grassland 50 miles west of the town of Rock Springs and near the center of the Green River Basin of Wyoming (Plate I). Forty-nine percent of the Church Buttes Field lies under federally-owned land, forty-eight percent under private land, and three percent under State-owned land. The field lies in a local anticlinal closure, part of the Moxa Arch, a regional structural arch extending 120 miles from the northern edge of the Uinta Mountains in Utah to the Big Piney - La Barge Platform in southwestern Sublette County, Wyoming.

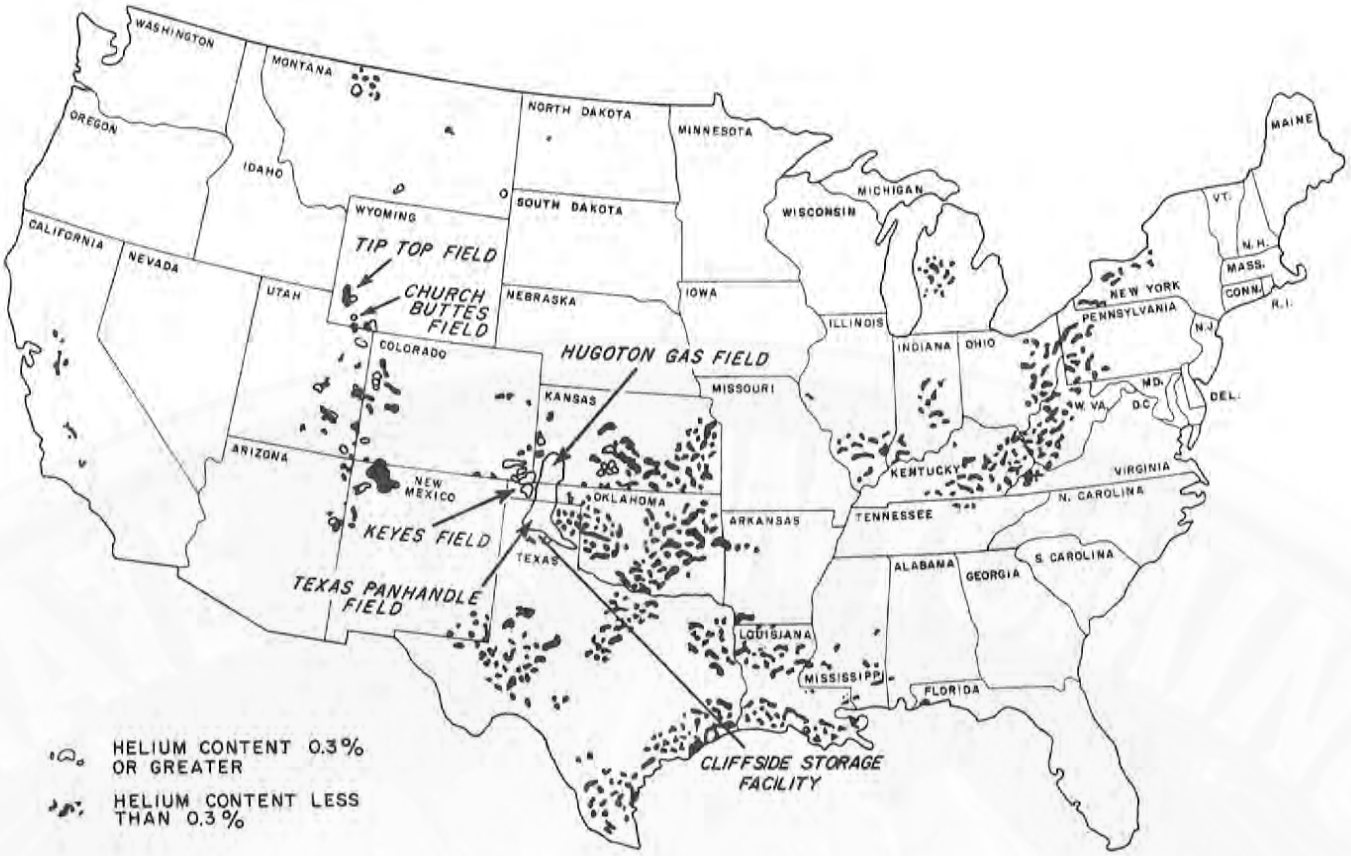

Figure 13. Geographic distribution of helium resources of the United States. (Modified from Staats, 1979.)

As determined from Mountain Fuel Supply's Church Buttes wells No. 19-Unit and No. 21-Unit in the southern half of the field and from their well No. 22-Unit in the field's northern half, the helium reserves occur in the Mississippian Madison Formation (Carr and Madden, 1975). The 19-Unit, the deepest well in the field, was drilled into the Gallatin Formation to a total depth of 19,526 feet. The Madison Formation was encountered at a depth of 18,234 feet: it included a 193-feet-thick reservoir with over five percent porosity. Natural gas from the Madison Formation contained 0.24 percent helium and 83 percent carbon dioxide as well as small concentrations of hydrogen sulfide, nitrogen, methane, ethane, and propane. Due to the high percentage of noncombustible gas, the Madison reservoir is not presently under production. The 21-Unit, which was drilled to a depth of 18,729 feet, encountered the Madison at 18,354 feet. In this well a 204-feet-thick, helium-bearing zone in the Madison showed over five percent porosity. The 22-Unit, which was drilled into the Madison to a total depth of 18,125 feet, intercepted a net 157-feet-thick zone of over five percent porosity in the Madison. In 1967, helium-bearing gas was also discovered in the 19-Unit in dolomites of the Pennsylvanian Morgan Formation. This gas, which is currently produced, contains 0.17 percent helium, but is not considered a part of the helium reserve estimates for the field because it is a depleting reserve. Table 3 summarizes nondepleting helium reserves of the Madison Limestone.

Table 3. Nondepleting helium reserves in the Madison Limestone at the Church Buttes Field, Uinta and Sweetwater Counties, Wyoming (measured at 14.65 psia and 60°F). (Modified from Carr and Madden, 1975.)

			Nondepleting Helium Reserves			
Formation	% He	Reservoir thickness	Measured resources (MMCF)'	Indicated resources (MMCF)'	Total (MMCF)'	Reservoir lithology
Madison(Mm)	0.24	193'	10,928	6,391	17,319	Dolomite-Limestone

'Million cubic feet

Tip Top Field

Tip Top Field is located fifteen miles southwest of the town of Big Biney, Wyoming, in the west-central Green River Basin (Plate I). The field is an anticlinal closure complicated by thrust faulting; it occupies the crestal part of the LaBarge Platform. The field underlies some 31,840 acres of mountains and semi-arid prairie on the east margin of the Wyoming Overthrust Belt. Approximately ninty-five percent of the Tip Top Field lies under federally-owned land.

The characteristics of the field were determined from Mobil Oil Corporation's No. 22-19 well in $NW\frac{1}{4}NW\frac{1}{4}$ sec. 19, T. 28 N., R. 113 W. This well was drilled to a depth of 15,435 feet, into the Cambrian Gallatin Limestone. Analyses of gas samples from the Permian Phosphoria, Pennsylvanian Tensleep, Mississippian Madison, and Ordovician Bighorn formations indicate the presence of substantial quantities of noncombustible gases, mostly carbon dioxide and nitrogen with small amounts of hydrogen sulfide, oxygen, argon, and helium (Madden, 1974). Table 4 summarizes the nondepleting helium reserves in these formations.

Total helium reserves at Tip Top may be as much as 45 billion cubic feet. At the current rate of consumption, this is enough helium to supply U. S. demands for the next fifty years (Lageson, 1980). Based on differing interpretations of seismic data and varying estimates of the extent of the helium-bearing formations, acceptable estimates of helium reserves in the Tip Top Field vary from 45 to 79 billion cubic feet. The Tip Top Field thus has helium reserves comparable to the 44.4 billion cubic feet of helium stored at the Federal Government's Cliffside Field. However, if the Paleozoic helium reservoir extends beyond the present field limits, there could be as much as 1,000 billion cubic feet of helium in the Tip Top area (Markle, 1979). These immense reserve estimates prompted the following statement from Markle (1979):

> *"Because of the possibility of huge helium reserves at Tip Top, we urge restraint in implementing high cost helium conservation efforts during the next few years."*

The helium reserve at the Tip Top Field is currently classified as a nondepleting helium reserve since the associated natural gas is not being produced (because of its low heat value). However, because Mobil Oil Corporation has announced plans to begin production from Tip Top in 1982 (Staats, 1979),

Table 4. Nondepleting helium reserves in Paleozoic units at the Tip Top Field, Sublette County, Wyoming (measured at 14.65 psia and 60°F). (Modified from Madden, 1974.)

Formation	% He	Reservoir thickness	Nondepleting Helium Reserves Measured resources (MMCF)'	Indicated resources (MMCF)'	Total (MMCF)'	Reservoir lithology
Phosphoria (Pp)	0.48	22'	9.2	57.8	67.0	Dolomite-Limestone
Tensleep (IPt)	0.80	270'	710.0	7,728.4	8,438.4	Sandstone
Madison (Mm)	0.78	380'	5,104.6	28,848.4	33,953.0	Dolo-Limestone, (highly fractured)
Bighorn (Obh)	0.90	145'	303.7	1,852.1	2,155.8	Crystalline Dolomite
TOTAL			6,127.5	38,486.7	44,614.2	

'Million cubic feet

current stands on helium conservation will again need review!

CONCLUSION

At present, private industry produces more than enough helium to meet its own demand. The U. S. Bureau of Mines is producing enough helium to supply current federal needs and has stored enough helium to fulfill their demand well beyond the year 2000. However, although the Bureau of Mines is encouraging private storage, industry has no large stockpile to guard against a potential helium shortage. Many members of the scientific community fear that our present supply of economically recoverable helium may be exhausted just as helium-dependent "super technologies" are developed. Beyond that time, if helium is still in demand, it will have to be extracted from the atmosphere, which is presently too expensive to exploit. Perhaps our goal should be to establish an economical means of extracting helium from the atmosphere, a virtually inexhaustible source. Meanwhile, with the aid of such sources as Wyoming's Tip Top and Church Buttes fields, we can insure a store of helium to meet private as well as Federal needs until an atmosphere-extraction technique can be developed.

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