Leroy Storage Facility, Uinta County, Wyoming: A Case History of Attempted Gas-Migration Control

SPE 11180

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Summary

Leroy gas storage facility, an aquifer storage development by Mountain Fuel Supply Co. in Uinta County (WY), is presented as a case history. This field represents a complex problem in aquifer storage because of the uncontrolled migration of gas to the surface. Considerable effort in reservoir engineering and planning has resulted in apparent and probable arrest of uncontrolled gas migration, although more time will be needed to evaluate and monitor the results of recent efforts.

Incorporated in the evaluation of the leakage problem has been updated geological information, location and correction of possible well problems, computer simulation, extensive logging, tracer surveys, surface monitoring, and related engineering evaluation.

A computer program developed to simulate a unique history match, including the effect of a time- and pressure-dependent leak, and a comprehensive analysis of data leading to the possible control of the leak by proper operating storage pressures are described.

Introduction

Through continuous attention from the Reservoir Engineering Dept. and support by management, the operations have continued with reduced scope and it now appears that the quantity migrating away from the storage horizon is definitely decreasing.

This paper briefly documents the history and presents the status of the storage field, relating efforts to isolate and control the leakage.

The geography, geology, historical background, reservoir description, reservoir performance, and related engineering studies relevant to the case history are included. The computer simulation of history match including the leak, analysis of the results, subsequent reservoir engineering work, discussion of results, and conclusions are presented.

Background

The Leroy gas storage field is located in Uinta County (WY) in Township 16 North, Range 117 West. The field lies 80 miles [129 km] west of Rock Springs, WY, and approximately 100 miles [161 km] northeast of Salt Lake City, UT. This particular location was of interest to Mountain Fuel Supply Co. because it was favorably located relative to the pipeline supplying Salt Lake City. Interest in this area for prospective storage facilities dates back to 1969. Evaluation of data obtained from exploratory Leroy Well 3, originally drilled by the Shell Oil Co. in Summer 1951, suggested two potential storage formations—the Nugget and the Thaynes. The Nugget sandstone was rejected because of the questionable integrity of the caprock, the faulted structure, and abnormally high-pressure gradient.

Testing of the Thaynes formation in Leroy Well 3 began in Oct. 1970 following re-entry and deepening to 3,135 ft [956 m]. An extended flow test was run, producing 4,000 to 8,700 B/D [636 to 1383 m^3/d] water with an initial gradient of 0.508 psi/ft [11.4 kPa/m]. Initial test evaluation indicated excellent transmissibility and an expanded drilling/re-entry program followed. Leroy Wells 4, 5, and 6 were drilled and completed by Mountain Fuel Supply Co. in 1971. Leroy Wells 1 and 2 were also re-entered and completed as pressure observation wells. Interference and caprock integrity tests were conducted concurrently with the re-entry and drilling programs.

During initial development, lost-circulation problems occurred while the Nugget sandstone was drilled across with water-base mud. This problem was alleviated by allowing the Nugget water to flow to the surface during drilling and an intermediate string of casing was run when the underlying Ankareh formation was encountered.

Two potential horizons were initially considered for storage in the Thaynes formation, designated as the T-10 (upper horizon) and the T-20 (lower horizon). Preliminary testing with gas injection into the T-20 zone showed direct communication with the T-10 zone. Subsequent injection into the T-10 zone suggested favorable conditions for development.

Wells 7, 8, and 9 were completed by Aug. 1972, and 2.0 Bcf [0.06×10^9 m^3] of gas had been injected. Upon completion of the surface facilities, application was made to the Federal Power Commission (FPC)[1] to begin storage operations. The application was approved Nov. 17, 1972. Following FPC approval, storage operations proceeded for the 1972–73 heating season.

The following year, inventory had been increased to 3.5 Bcf [9×10^9 m^3] and Wells 9 and 10 were completed as injection/withdrawal wells. Soon after completion of

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Leroy Well 10 in Sept. 1973, with an inventory of 3.667 Bcf [0.11×10^9 m^3] (bottomhole pressure [BHP] was 1,740 psia [12 MPa]), gas began blowing out around the surface casing of Well 3. Preliminary temperature surveys confirmed the blowout to be coming from the nearby Well 4. The failure had occurred in the Twin Creek formation at approximately 1,360 ft [415 m] with subsequent gas migration to Well 3. Further investigations with noise logs supported the temperature-survey findings. Repairs of the damaged casing were attempted in Nov. 1974.

A survey* of both the 9⅝-in. [34.5-cm]-OD intermediate casing and the 7-in. [17.8-cm]-OD production casing (both failed) indicated that the corrosion was primarily caused by sulfide ion generated by anaerobic, sulfate-reducing bacteria present in the annular fluids at the time of completion or from the invasion of formation waters containing them.

Leroy Wells 11 and 12 were drilled during 1975. Repairs were attempted on Well 4 until May 1977 when it was plugged and abandoned. Leroy Well 4A was drilled during July 1977 as a replacement for Well 4 followed by Leroy Well 14 in Aug. 1977 as a step-out well. Well 13 was drilled during June of the following year as a deep aquifer observation well.

Gas migration was first confirmed on the surface as bubbling in the adjacent creek and pond during the latter part of Nov. 1978.

Leroy Well 15 was drilled during July 1979 to locate a possible collector zone above the reservoir and was completed as a Twin Creek/Nugget observation well (no significant gas shows were apparent).

A location map is shown in Fig. 1.

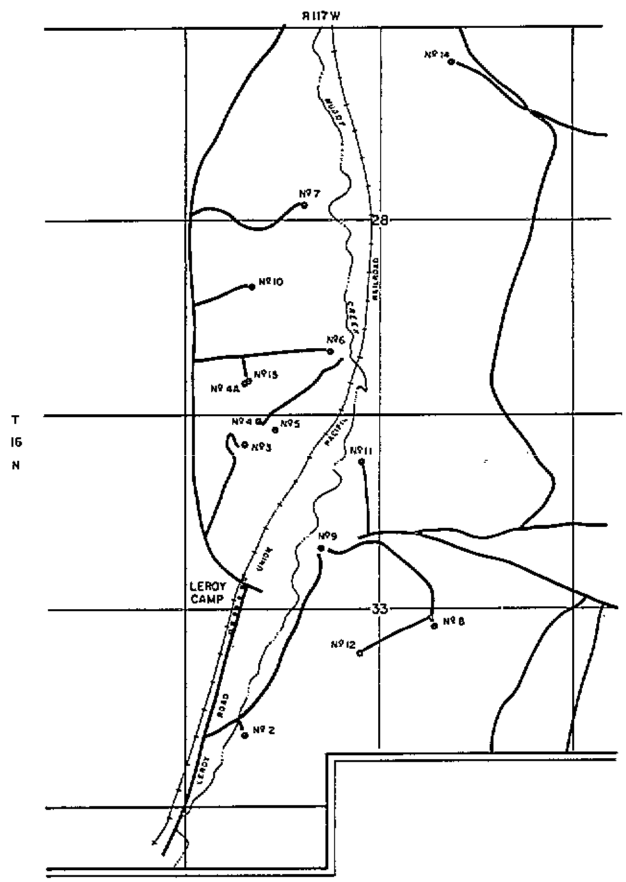

Fig. 1—Roads and location map—Leroy gas storage project.

Geological Description

Early geological work in the Leroy reservoir area was conducted by Shell Oil Co. and Union Pacific Railroad during the late 1940's.

Fig. 2 is an updated geological cross section of the field.** A brief summary of the stratigraphy is shown in Table 1.

Fig. 3 represents the Thaynes structure map derived from well control and seismic surveys (based on the top of the formation, not the top of the reservoir interval). The Thaynes represents a doubly plunging, faulted anticline. The downthrow of the major fault is to the west and divides the structure, effectively separating the reservoir. The storage reservoir was developed east of the fault with an assumed western limit at the fault. The initial reservoir pressure as of Sept. 8, 1970, taken at 2,953 ft [900 m] from ground level or +3,809 ft sea elevation [1161 m], was 1,500 psig [10.3 MPa] at 82°F [27.7°C].

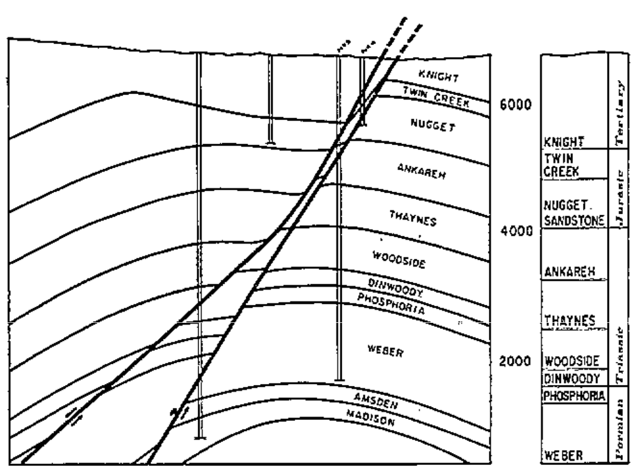

Fig. 2—Lithologic cross section—Leroy gas storage project.

Reservoir Performance

After the initial startup during 1973, the following year was spent in evaluation of reservoir performance and installation of facilities.

The inventory during 1974 ranged from 3.7 to 3.8 Bcf [0.10×10^9 to 0.11×10^9 m^3]. The gas bubble pressure was close to original aquifer at 1,500 psig [10.3 MPa]. Fig. 4 represents the growth of storage inventory between 1971 and 1982. It was noted and reported that the gas bubble pressure during 1975 and 1979 had been increased to 1,830 psig [12.6 MPa], about 330 psi [2.3 MPa] above the original aquifer.

During Nov. 1978 a survey of the project area indicated gas bubbling to the surface at two areas, one in the vicinity of Well 11 and the other near Well 7. Two

*Personal communication, Fincher Engineering Co., Houston (Sept. 5, 1974).

**Reese, D.L.: personal communication, "Geologic Report—Leroy Gas Storage Field, Uinta County, Wyoming" (Sept. 1978).

TABLE 1—STRATIGRAPHY OF LEROY RESERVOIR

Wasatch (Knight) Formation: Tertiary

Unconsolidated; fluvial; silts, sands, and shales with limestone stringers.

Twin Creek Limestone: Jurassic

Uncomformably underlies Wasatch, grey limey, oolitic finely crystalline, some calcareous shales; dense.

Nugget Sandstone: Jurassic

Upper: Porous, coarse-grained, arkosic, very permeable.
Lower: Variable clastic beds, poorly sorted, finer-grain, less porosity/permeability.

Ankareh Formation: Triassic

Typical red bed sequence with predominantly red shales and siltstones alternating with thin sandstones and green shales.

Thaynes Formation: Triassic

Dolomite with thin limestone beds.
Upper: Grey, finely crystalline with thin-bedded anhydrite and very fine-grain sandstone beds.
Middle: Predominantly red shales and siltstones with thin anhydrite and dolomite beds.
Lower: (Contains storage zones)
Top 5 to 8 ft: dolomitized sandstone, very coarse grain, porous, and permeable.
130 to 150 ft: red shale, very calcareous followed by 100 ft of dolomite with streaks of vugular porosity.

Woodside Formation: Tertiary

Triassic red bed sequence with predominantly dense, silty shales.

surface gas detection surveys were conducted on April 9, 1979, and November 9, 1979, both confirming some gas migration to the surface near Wells 7 and 11.

On June 17, 1980, a tritium tracer was injected into the T-10 zone through Well 4A, while all the other wells were shut in. The tritium tracer was identified in the very first surface sample taken near Leroy Well 11, nine days after injection.

^{85}Krypton and sulfur hexafluoride tracers were injected on Oct. 16, 1980, into Wells 3 and 10, respectively. Within 9 days, ^{85}krypton was detected in surface samples while the sulfur hexafluoride was confirmed at the surface 71 days after introduction.

On Sept. 3, 1981, tritiated methane was injected into the reservoir through Well 3. Injection was continued into the other wells. The tracer appeared in surface gas samples 32 days after injection.

Because of noise log indications of gas migration behind the pipe in Leroy Well 4A, a workover program was initiated to squeeze off any existing communication between the reservoir and near-surface formations. Subsequently, another tracer, tritiated ethane, was introduced on July 17, 1982, and had not appeared at the surface by the end of the summer. Previous tracer surveys indicated direct communication between the storage reservoir and the surface and it was hoped that at least part of the gas migration would be shut off by the workovers.

Subsequently, the tracer showed up 163 days after injection, indicating perhaps a longer path and reduced extent of migration.

Existing data suggest the leak event began sometime during 1975 or 1976.

Engineering Studies

The Reservoir Engineering Dept., with the cooperation of field personnel and the recently enlisted help of outside consultants,*[,2] has devoted considerable time and expense in the evaluation of this field and the associated leakage problems. A majority of the work accomplished since 1980 consists of a variety of reservoir engineering work, including the development of a new computer program.

History Match and Simulation of Leak. During Summer of 1981, a review of storage performance in Leroy indicated the need for a computer-simulated history match, including the effects of three crucial factors: (1) water drive in the unsteady state because of the surrounding Thaynes aquifer, (2) gas migration away from the storage horizon as evidenced by bubbling and sampling at the surface, and (3) inventory-pressure data relating to the overall performance of the storage bubble.

During recent work, a simple unsteady-state aquifer model was selected and simulated on a computer. The program specifically developed for the study was based on four parameters to include the effects of storage capacity, aquifer transmissibility, a leak rate coefficient and aquifer size. With the data available from geology, reservoir behavior, and past production-pressure performance, the four parameters were bracketed through a realistic range of numerical values until a satisfactory history match was obtained.

The reservoir parameters used in history match runs relate to aquifer capacity, ϕh, aquifer transmissibility, kh, aquifer size, r_e/r_b, and an equation simulating the leak.

Aquifer Parameter 1. Aquifer Capacity Parameter 1 is defined as

$$Q_A = h\phi c r_b^2 y, \text{ cu ft/psi [cm}^3\text{/kPa]}$$

where

h = aquifer formation thickness, ft [m],
ϕ = porosity (Thaynes aquifer), fraction,
c = effective compressibility, volume/volume×psi [volume/volume×kPa],
r_b = radius of gas bubble, ft [m], and
y = coefficient for pie shape of aquifers bounded by faults.

(In our case, 0.5 was used for 50% circular radial flow on aquifer and bounded by a north-south-trending fault.)

The value used for Q_A parameter was (0.5×962.50) cu ft/psi [1.99×10^6 cm^3/kPa].

Aquifer Parameter 2. The aquifer transmissibility Parameter 2 was defined as

$$T = kh/\mu$$

where

k = permeability (Thaynes aquifer), md,
h = thickness, ft [m], and
μ = viscosity of formation water, cp [Pa·s].

*Personal communication, Rocky Mountain Petroleum Consultants' Report, Salt Lake City, UT (Jan. 1981).

The value for T established in the course of history match runs was 75,000 md×ft/cp [md×m/Pa·s].

The Aquifer Size Parameter. After several trial and error runs the ratio of exterior aquifer boundary to equivalent gas bubble radius, r_e/r_b, was determined to be approximately 20.

Simulation of Leak from Storage Horizon. In determining a suitable coefficient to quantize the leak rate in terms of storage pressures, several models were considered. These included wellbore leaks occurring at variable depths to collector zones in the overburden, seepage and bubbling from collector zones to the surface, and reservoir leaks from the storage bubble through imperfections in the caprock. It was also recognized that the time dependency of the leak rate must be not only a function of maximum storage pressures but also the time duration when storage pressures remained above a critical value.

The Leroy gas storage hysteresis curve for the period 1975–1981 provided the early clues as well as the basic data for the development of the model that best described the leak in terms of gas storage pressures.

Fig. 5 represents a replot of the part of inventory pressure hysteresis data for the three consecutive injection seasons of 1978, 1979, and 1980. While the data reflects much "noise"—effect of water movement, local gradients, etc.—it shows that the slope of p/z vs. inventory became consistently flatter whenever p/z exceeded 1,800 psia [12.4 MPa]. Although this is probably partially a result of the decreasing injection rate for pressure

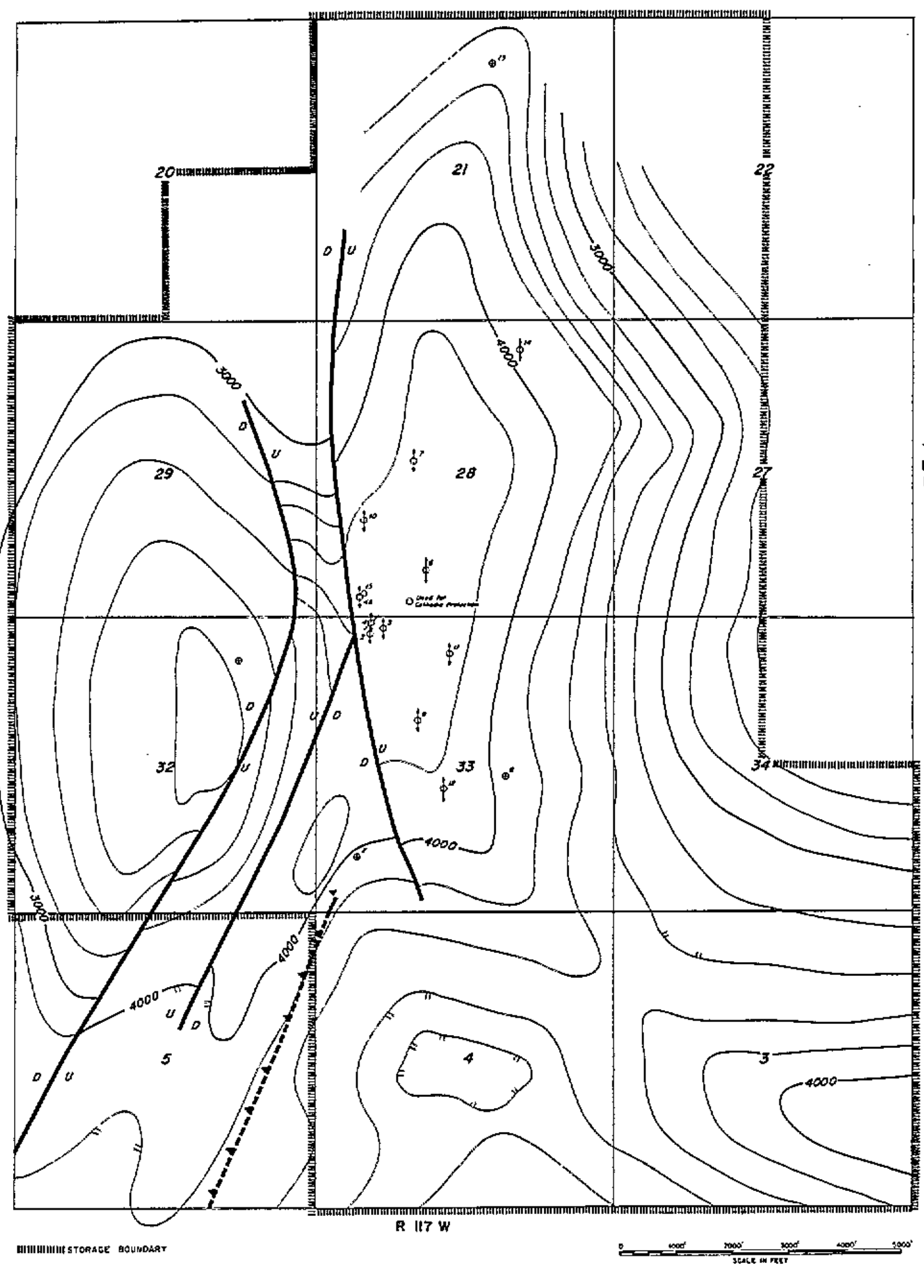

Fig. 3—Thaynes structure map—Leroy gas storage project.

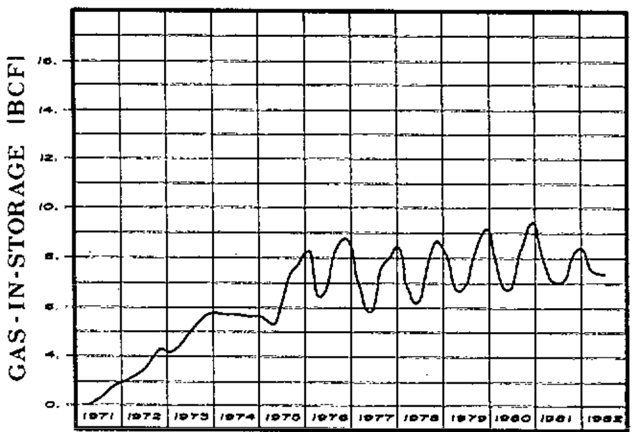

Fig. 4—Growth of storage inventory, Leroy storage project.

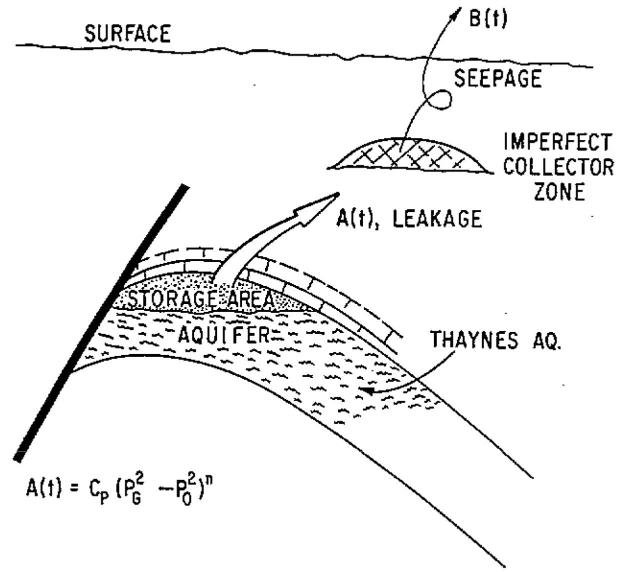

Fig. 6—Schematic representation of migration of storage gas.

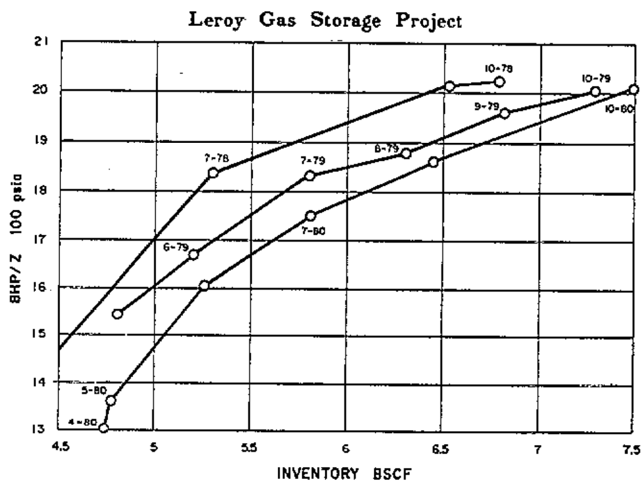

Fig. 5—Injection curves for 1978, 1979, and 1980.

maintenance, it suggested to the writers a strong likelihood of a check-valve effect—that a pressure threshold existed below which the aquifer storage grew with a proper hydraulic seal and above which the loss and continued migration of gas occurred. The difference between the nearly parallel upper slopes indicated that the annual leak was maximum between 1978 and 1979 when storage pressures remained high for an extended period of time.

This and other theoretical and empirical considerations formed the basis for a mathematical model that fit the data and substantially improved the history match.

Fig. 6 represents a schematic view of leakage from the storage area to the overburden, possibly from several sources (wellbores, caprocks, fractures, faults, etc.). The seepage from collector zone(s) to surface is also shown.

Using pressure-inventory data and reasonable assumptions, we found that the leak equation that best fit the data turned out to be:

$$q_1 = 3.74 \times 10^{-7}\ (p_G{}^2 - 1{,}600^2)^n$$

where q_1 was the daily leak rate in MMcf/D and p_G is the maximum gas bubble pressure in psia. Exponent n was assumed to be equal to 1.0.

Analysis of Computer Results. The simulation of storage operations in Leroy involved a computer model developed to reflect unsteady-state water influx/efflux, reservoir volume changes caused by prescribed pressure or inventory changes and, at the same time, a pressure-dependent leak occurring whenever a pressure threshold was exceeded.

Mathematical Basis for Calculation of Leak.

In modeling the performance of the storage bubble developed on the aquifer, an unsteady-state material balance was invoked involving the storage gas occupying its reservoir pore volume, either inventory or pressure change caused by cyclic storage operations, and water influx/efflux into the gas bubble in response to injection or withdrawal of storage gas. In addition, the resident inventory in the reservoir was corrected during each timestep by the amount that would leak out whenever the pressure exceeded a threshold limit.

Accordingly, the calculations at any current timestep involved then-prevailing formation pressure, pore volume, and implicit calculation of water influx/efflux per Van Everdingen/Hurst solutions with superpositions. These calculations also took into account the reservoir volume change resulting from metered inventory change and pressure-dependent leaks.

The model developed for the computer simulation of the storage reservoir consisted of a semicircular horizontal gas bubble surrounded by a porous and permeable radial flow aquifer having lumped ϕh and kh parameters as determined by history match. The calculation procedure involved an input of either inventory or pressure schedule. When inventory (i.e., injection/withdrawal quantities) was specified, the model developed calculated the resulting reservoir pressure at each timestep. The procedure also included a "leak model"

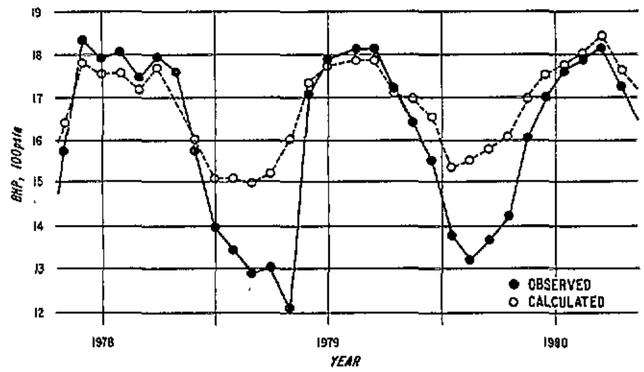

Fig. 7—Sample of history-match results.

that determined the unmetered inventory loss as a function of prevailing storage reservoir and a prescribed leak threshold pressure. When pressures were specified for each timestep, the computer model calculated both the leak rate and the inventory change, updating both during each timestep.

The Results. Fig. 7 shows a sample of a history match between observed and calculated pressures. Note that agreement is better during injection while the pressure is high. The wide discrepancy during the end of each withdrawal season is a result of inaccurate pressure data. The reservoir pressures were calculated from recorded wellhead pressures, assuming that no liquid was present in the hole.

Fig. 8 shows the annual leak rate obtained from the history-matched computer runs. The leak process appears to have started sometime during maximum storage pressures. In the plot, the computer-calculated leak rates are shown as blank dots occurring at discrete points representing the years 1976 and 1977, 1977 and 1978, etc. Also, the projected leak rates for three simulated cases are depicted in Fig. 8. Case 1 represents the lowest operating pressure, while Case 3 represents the highest pressure. Case 2 corresponds to a reservoir pressure of 1,650 psig [11.4 MPa], which was the actual operating pressure during the 1981–82 season. The cumulative leak quantities determined by the computer program have been annualized by difference, then transformed to an instantaneous and continuous curve by a technique called "differencing the data." The procedure involved first obtaining the annual leak rate and plotting it as a bar-graph as shown in Fig. 9.

Each of the bars in Fig. 8 corresponds in height to the cumulative leak rate for each year obtained by differencing the computer-calculated cumulative leak. The width of each bar covers, horizontally, the distance of the particular year during which the cumulative leak has occurred.

Once the five bars representing the annual gas leak are plotted side by side, Curve C was drawn in such a manner that the area underneath was equal to the sum total of the areas under the bars.

To provide a measure of correlation, the maximum storage pressures that occurred during the 5 years in question were plotted at the midpoint of each year span-

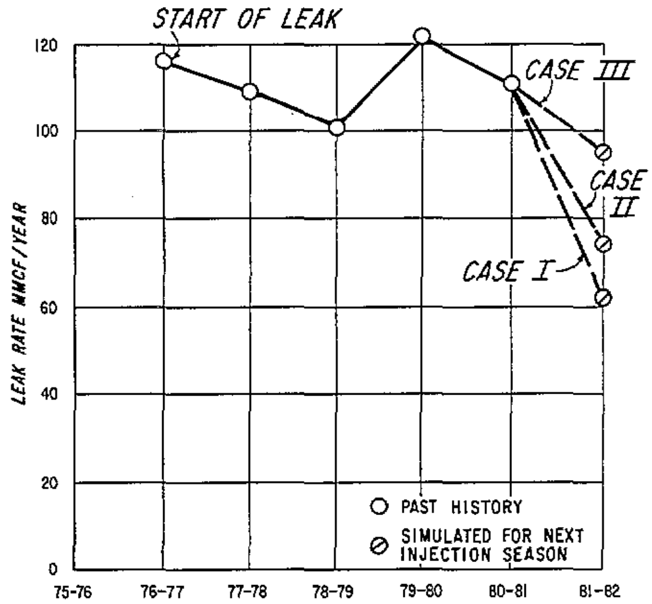

Fig. 8—Past history of leak from pressure inventory data and computer runs.

ning the particular time period involved. It can be seen that Curves C and C′ follow the same trend, being nearly parallel, and can be correlated against one another. This correlation is shown in Fig. 10.

The leak rates reported by Coats, conservatively estimated from his computer runs, are shown to follow a trend similar to the approximate leak rates calculated by differencing the data.

Subsequent Reservoir Engineering Work. Continuing studies suggest the following areas to be of future importance and will undoubtedly be pursued.

Noise Logs. Noise logs were the earliest indication of possible gas movement near the wellbores. Logging programs have since identified mechanical problems and fluid movement behind the pipe. These logs have figured prominently at times in designing workover programs.

Temperature Surveys. Temperature surveys have been essential for location of leakage from the wellbores and possible migration paths behind the pipe. These surveys coupled with noise logs have been used concurrently with workover operations in Wells 4A and 11 during the summer of 1982.

Corrosion Analysis. Several corrosion-analysis logging programs have been conducted in most of the wells and should be continued on a regular basis. Recent corrosion-analysis logs have already prompted the running of new production casing strings in Well 11.

Tracer Programs. Injection of tracers and monitoring thereof have been an ongoing project for approximately 2 years and continue as positive measures of gas movement and migration to the surface.

Monitoring of Surface Bubbling. Gas bubbling has been monitored and quantitatively measured using inverted barrels equipped with rotameters that are set over bubbling areas and sealed at the base. Although the data obtained in this way are inherently "noisy," they do show the following trends.

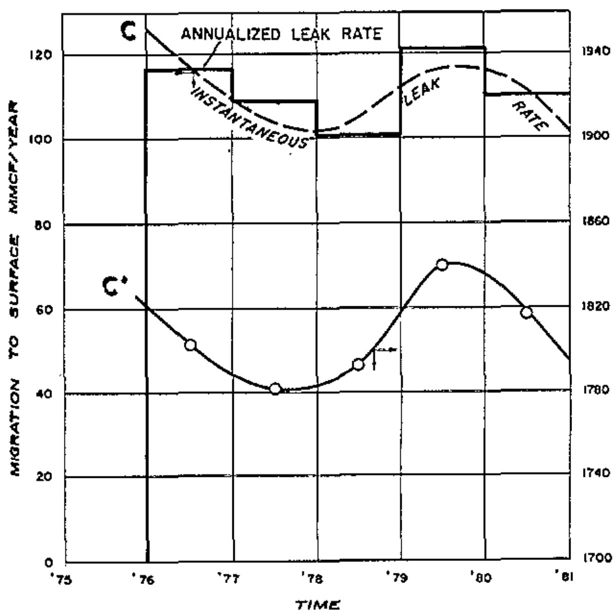

Fig. 9—Bar-graph plot showing the relationship between the migration and maximum storage pressure, Leroy, 1978 to 1981.

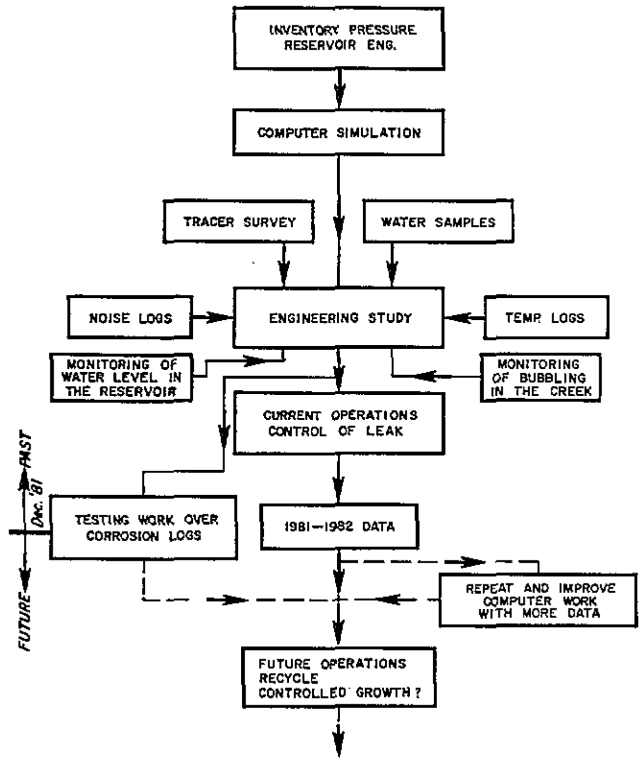

Fig. 11—Coordination of various subtasks on Leroy storage engineering study.

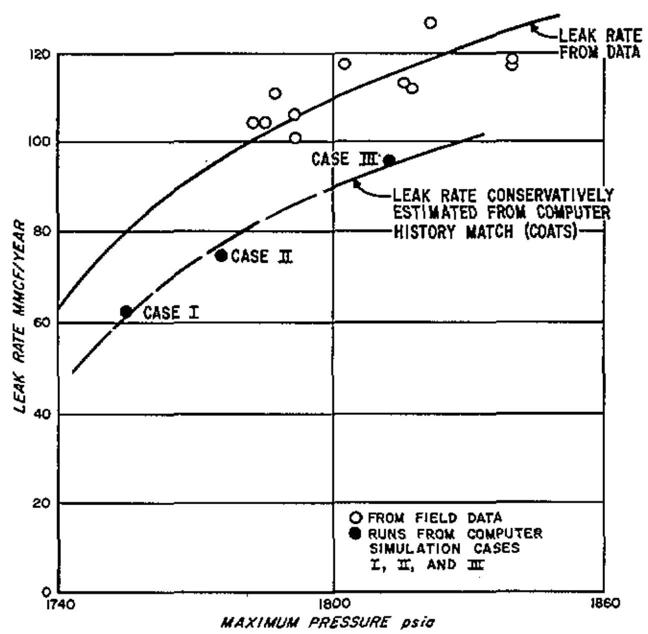

Fig. 10—Correlation of instantaneous leak rate with maximum storage pressure.

1. Some bubbling is dependent on storage operations (indicating that migration originates from the Thaynes horizon). Bubbling at certain stations ceased altogether while most of the wells and their drainage areas were flooded during the summer. Later, after the injection operations restored dry conditions in the matrices, the bubbling resumed.

2. Some bubbling appeared invariant with storage operations (indicating that the gas migration was originating from shallow collector zones).

These trends indicate direct reservoir-to-surface leakage and also leakage from an intermediate collector zone.

Water Sampling. Since the Nugget formation has a high-pressure gradient, it would seem logical that the water would flow to the surface. Repeated sampling of the water from the Muddy Creek consistently shows there is no apparent Nugget water following the gas leakage to the surface. This water should be easily identified because of its high salinity. A possible explanation would be the bypassing of this formation by the gas by means of the wellbores and/or through fractures at or near the major faults.

Fig. 11 shows the interrelationship of several subtasks coordinated during Leroy storage engineering study.

Discussion of Results

On the basis of earlier history-match runs that included the effect of water movement, leak rate and storage performance, it was possible to establish that the migration from the storage horizon started sometime during

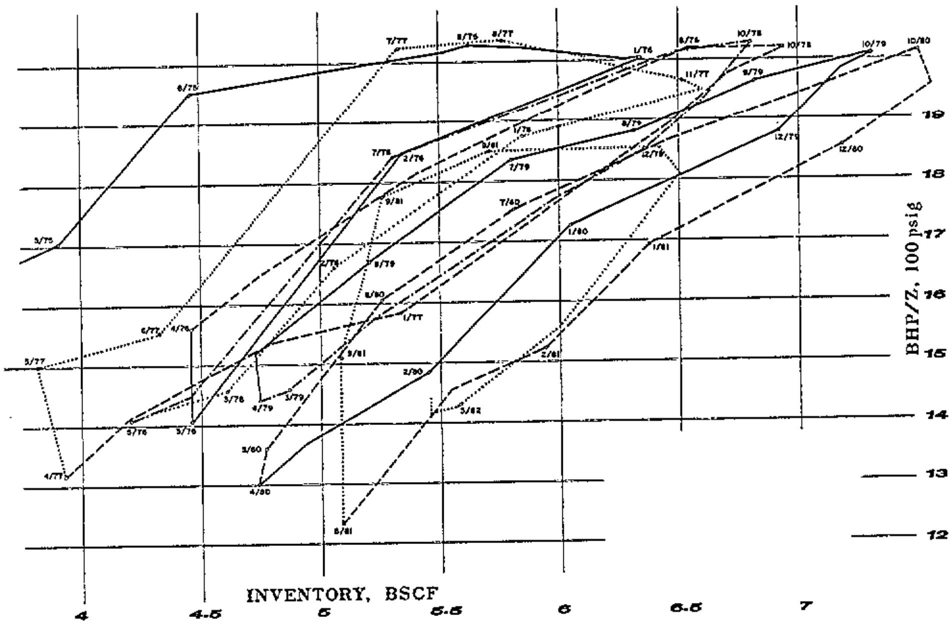

Fig. 12—Leroy gas storage, (Bscf), Uinta County, WY, hysteresis curve for the period 1975–1982.

1975–76. The total cumulative amount of migration over 130 months of storage history appeared to be about 600 MMcf [17×10^6 m^3]. Fig. 12 shows correlation of leak rate with maximum storage pressure. The inventory verification plots, in the form of p/z vs. inventory, over the many years of storage operations also tended to support the correlation between the rate of migration and storage pressures.

Analysis of the data on hand and related engineering studies suggested that the continuing leak was controllable and did not detract substantially from the capabilities of the storage reservoir. On this basis, the leak appears to involve pressure-triggered migration to a collector zone from which continuing seepage occurs to the surface.

As a result, after an extended shut-in period during early 1981, injection was resumed on a limited scope and extent during the summer of 1981. Because the possibility existed that the leak may be caused by wellbore imperfections, existing faults, and/or other structural imperfections, it was decided to continue the coordinated studies in all questionable areas. A comprehensive workover program was developed for Spring 1982. Leroy 4A was worked over to eliminate gas movement

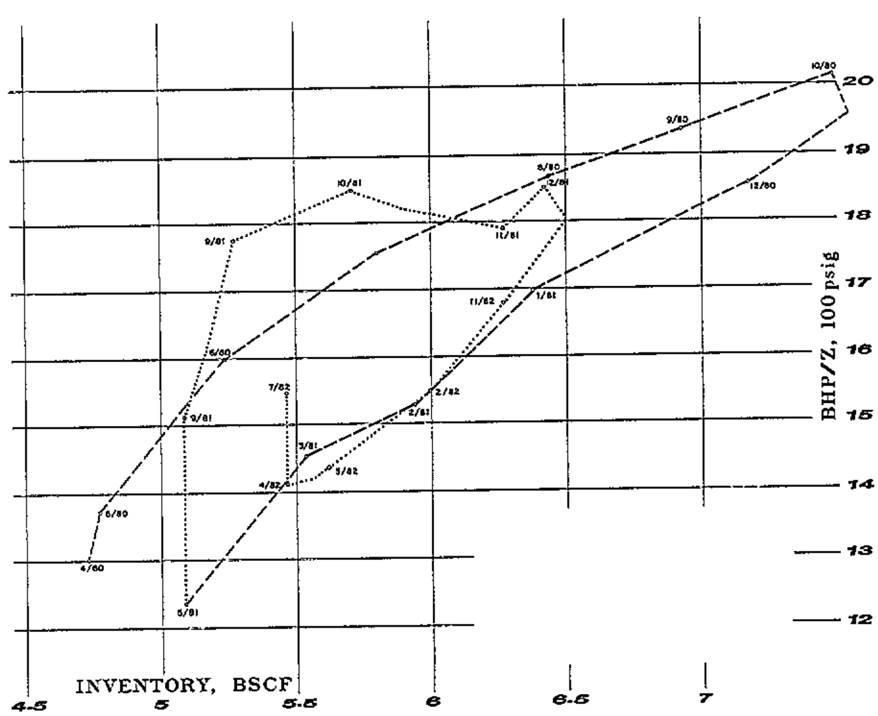

Fig. 13–Leroy gas storage, (Bscf), Uinta County, WY, hysteresis curve for the period 1980–1982.

behind the production casing. Corrosion problems were taken care of at Leroy 11 by squeezing several permeable horizons and running a new production pipe. Withdrawal data were collected during Winter 1981–82, and various monitoring schemes were continued.

The pressure-content data plotted in Fig. 13 show the latest results and compare the most recent performance with that of a year earlier. It can be seen that the injection during 1981, where the BHP/z was kept below 1,850 psia [12.8 MPa], resulted in a withdrawal path nearly identical to the lower half of the withdrawal curve for 1980. It was significant that for the first time since 1973 the withdrawal pattern of 1982 did not migrate to the right on the pressure-content quadrant. The 1981–1982 withdrawal path stopped approximately 300 MMcf [8.5×10^6 m^3] short of the gas inventory injected last summer. The corresponding "gas bubble" pressure was approximately 100 psi [0.7 MPa] higher than the previous year.

The 300 MMcf [8.5×10^6 m^3] that appeared short on top gas and added to cushion inventory is caused by high water levels of the 1982 withdrawal season entrapping the gas beyond the reach of perforated intervals. Once the proper saturation and proper water levels are re-established, it is believed that the gas will revert back from cushion to top-gas inventory.

Migration from the storage horizon appears to be well controlled by limiting the maximum pressure during injection. The latest gas surface detector survey indicates a receding area compared to the previous one a year ago.

Conclusions

The case history of Leroy storage is unique because it involved definite migration away from the originally intended storage horizon as evidenced by seepage of gas to the surface.

Several techniques were coordinated in an effort to understand, monitor, control, and reduce the leak. These included various logging, surveying, sampling, and testing techniques, tracer work, computer simulation, and engineering analysis.

Among these, the computer simulation proved practical and effective in establishing a correlation between the leak rate and the extent of "overpressure" in the reservoir.

The final evidence totally eliminating all appearance of leak to the surface is not yet on hand. There remains some work to be done before a collector zone is found and other measures to be taken such as recompletion, recycling, venting, pressure control, or whatever may be indicated.

Meanwhile, the case history should be significant in documenting what has been learned and how relevant computer simulations, hand-in-hand with overall engineering studies, can help in planning safe and economic gas-storage operation.

Nomenclature

c = effective compressibility, vol/vol×psi [vol/vol×kPa]
c_p = performance coefficient for leak, MMcf/D×(psia^2)^n [10^6 m^3/d×(MPa^2)^n]
h = aquifer formation thickness, ft [m]
k = permeability, md
p = gas bubble pressure (stabilized), psia [MPa]
p_G = maximum storage pressure, psia [MPa]
q_1 = rate of leak, MMcf/D [10^6 m^3/d]
Q_A = Aquifer Parameter 1 $=\phi hcr_b{}^2y$, cu ft/psi [cm^3/kPa]
r_b = radius of gas bubble (interior radius for the aquifer), ft [m]
r_e = exterior boundary radius of the aquifer, ft [m]
t = time, days
T = Aquifer Parameter 2, transmissibility $=kh/\mu$, md×ft/cp [md×m/Pa·s]
y = coefficient for pie-shape aquifers bounded by faults (fraction of full circular flow), dimensionless
z = compressibility factor, dimensionless
μ = viscosity of brine, cp [Pa·s]
ϕ = fractional porosity, dimensionless.

Acknowledgments

We thank the management of Mountain Fuel Supply Co. for permission to publish this study in the interest of sharing with others what has been resolved, as well as what remains to be learned. Also, we thank T.B. Yeager for help in the final preparation of this paper.

References

1. Federal Power Commission, Docket #CP74-43 (1972).
2. Tek, M.R.: "Underground Storage, Theory and Practice," Kolossos Printers, Ann Arbor, MI.

SI Metric Conversion Factors

cu ft × 2.831 685	E−02	=	m^3
ft × 3.048*	E−01	=	m
psi × 6.894 757	E+00	=	kPa

*Conversion factor is exact.

JPT

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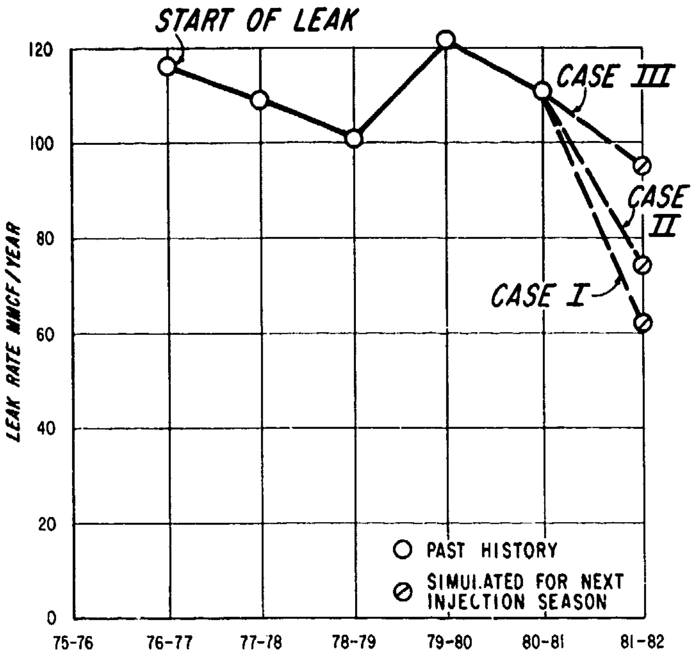


FIGURE 8

PAST HISTORY OF LEAK FROM PRESSURE INVENTORY DATA AND COMPUTER RUNS

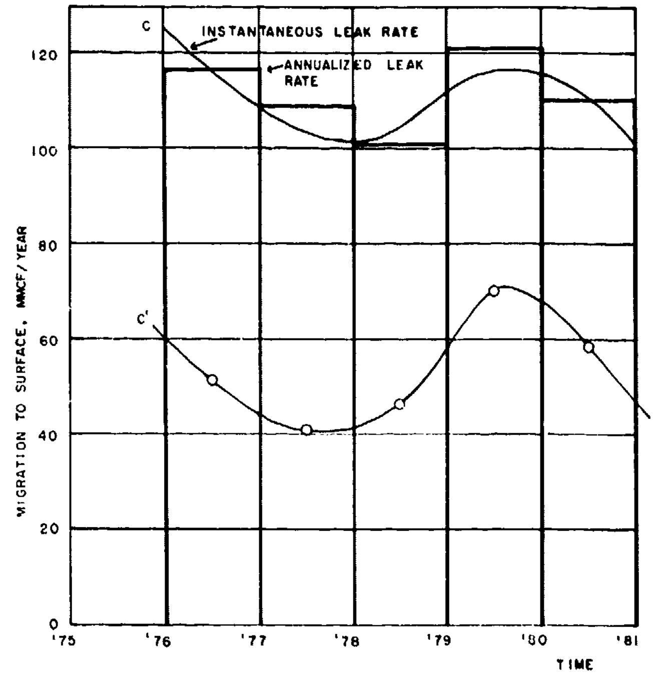
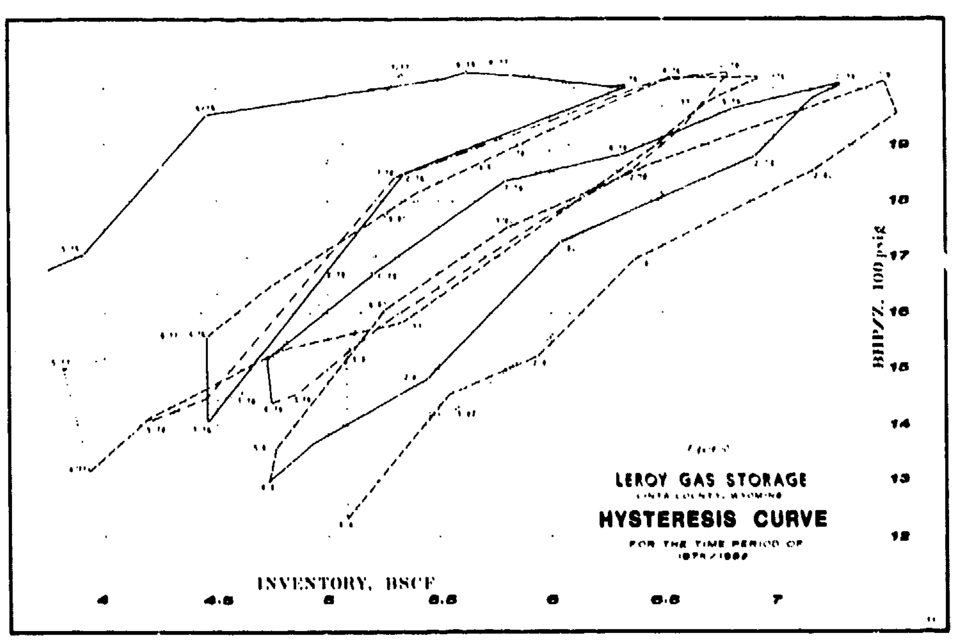


FIG. 9 BAR-GRAPH PLOT SHOWING THE RELATIONSHIP BETWEEN THE MIGRATION AND MAXIMUM STORAGE PRESSURES, LEROY 1975-1981



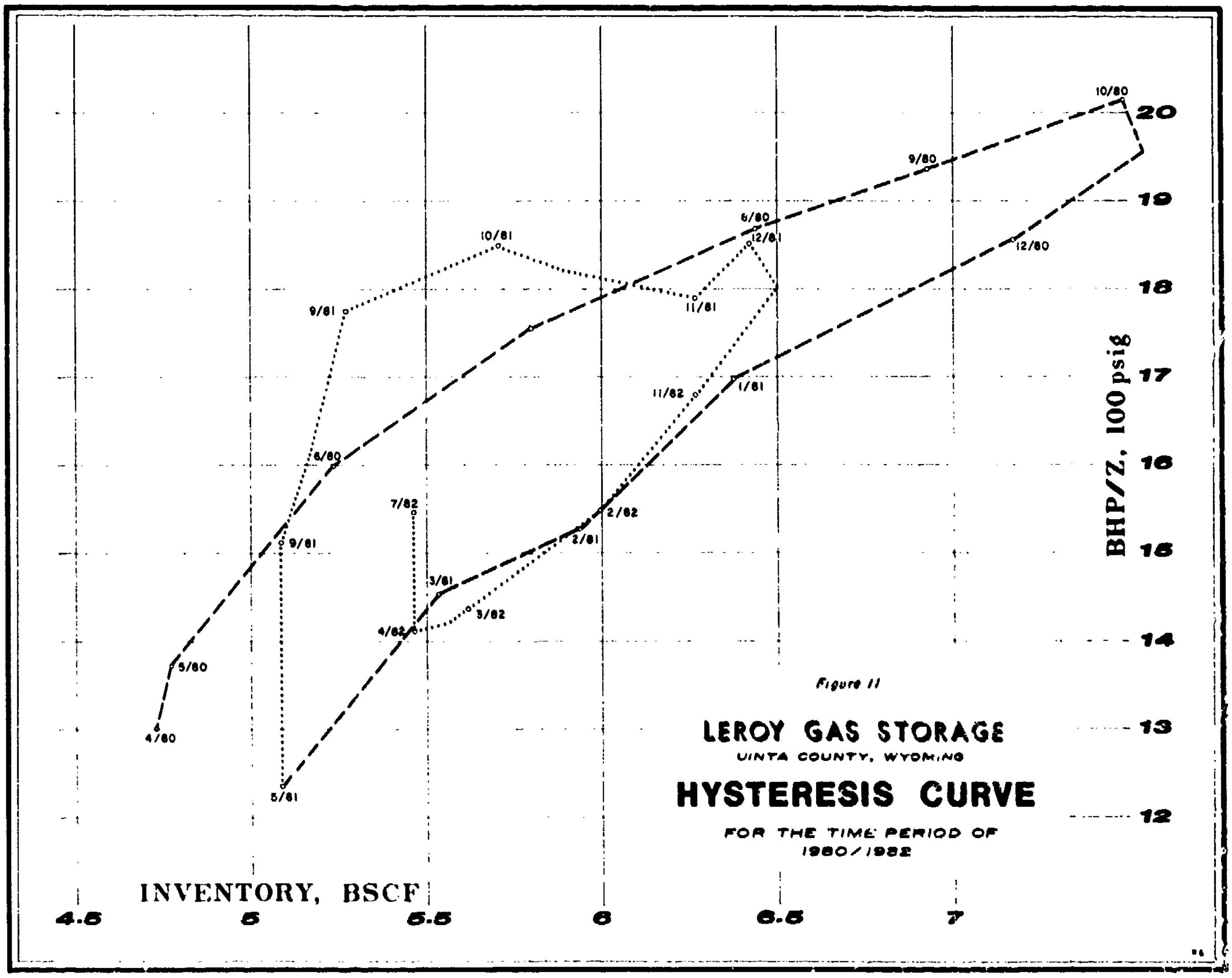


Figure 11
LEROY GAS STORAGE
UINTA COUNTY, WYOMING
HYSTERESIS CURVE
FOR THE TIME PERIOD OF
1980/1982
INVENTORY, BSCF
BHP/Z, 100 psig
4.5
5
5.5
6
6.5
7
12
13
14
15
16
17
18
19
20
4/80
5/80
6/80
8/80
9/80
10/80
12/80
1/81
2/81
3/81
5/81
9/81
9/81
10/81
11/81
12/81
2/82
3/82
4/82
7/82
11/82