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Underground Gas Storage Study: A Step to Meet Potential Demand of Pakistan

Raja Tahir Sultan[1] and Mehboob Ali Leghari [1]

ABSTRACT

This paper presents analysis of partially depleted Sadkal Gas Condensate Field a prospective candidate for underground Gas Storage. Gas storage reservoirs are used worldwide to store produced natural gas during periods of low demand for use during periods of high demand. Gas storage is the primary means of managing fluctuations in supply and demand. Proper selection of a gas storage reservoir is important to allow proper and economic operation of the project on a long-term basis. Gas storage reservoirs generally consist of good to excellent quality formations; Most of these are depleted, contain sweet natural gas (no H_2S) that are often located close to the ultimate demand source.

To meet the potential demand for gas in Potwar area of Pakistan during seasonal peak loads, which occur during the winter months of the year. The first ever-underground gas storage analysis has been carried out at Sadkal field in Pakistan, located near the city of Islamabad in Potwar area, which seems to be a prospective way to meet seasonal demand.

INTRODUCTION

Natural gas storage is the process of injecting natural gas into porous underground rock formations so that it can be withdrawn later to meet customers demand. These rock formations are at great depths and typically are depleted or abandoned natural gas fields.

The natural gas travels to the storage field facilities through large underground natural gas pipelines. Prior to injection into the rock formations, the natural gas must undergo compression. Then it can be injected into several specially designed wells that transfer it to the underground storage zones deep in the earth.

The evaluation of partially depleted Sadkal Gas Condensate Field as a prospective candidate for underground gas storage was carried out to meet the potential demand for gas in the Potwar area of Pakistan (Figure-1).

Sadkal Gas Condensate Field is situated in Attock District of the Punjab Province near Fateh Jang, about 45 KM south west of Islamabad. Sadkal is also strategically located near to the transmission line giving it ready access to the distribution systems in the Potwar area.

The structure of Sadkal Gas Condensate Field is in the Basal Exploration licence area in the Northern Potwar deformed zone. The crest of the structure is 2.5 KM north of Fateh Jang and is about 8 KM of Bhal Syedan.

The structure map and a gross thickness map of the Margalla Hill Limestone is shown in figures 2 and 3. Sadkal Gas Condensate Field comprised of numerous faults, particularly the major faults that compartmentalize the reservoir into at least four fault block regions A, B, C and D. Six wells have been drilled and five of the wells are completed in Margalla Hill Limestone, while Sadkal centre deep# 1 did not produce and was abandoned.

BACKGROUND OF UNDERGROUND GAS STORAGE

The first recorded natural gas storage facility was a depleted gas reservoir converted for storage service in 1915 in Welland County, Ontario, Canada. The first storage field in the U.S was the Zoar Field, located near Buffalo, New York. This field began operation in 1916, and is still in service today. These early fields provided the additional gas supply required by customers during periods of peak gas demand, particularly during the winter months. Natural gas produced from oil & gas fields was injected into the storage fields during the summer (low demand) months. This method also had the benefit of reducing gas curtailment in the producing fields. Due to this early success, other fields were converted to meet the growing demand for natural gas in the Midwest and Northeast U.S after World War II.

Aquifer storage was developed in the Midwest to serve the large market in the greater Chicago area, deeper depleted gas fields were developed in Pennsylvania, Ohio, and West Virginia, and the first bedded salt cavern storage was developed in Michigan. The first storage cavern in salt domes was completed in Mississippi by Transcontinental Gas Pipeline in 1970 as system supply backup for hurricanes.

Historically, available gas storage was used as a single-turn base loads, resulting in the most flexibility being provided by the pipelines, which were charging for the service. During the last five years, interest and demand for new storage has increased (Evans, 2000).

RESOURCES FOR UNDERGROUND STORAGE

The resources for underground gas storage include:

1. Salt caverns.
2. Mines.
3. Aquifers.
4. Depleted reservoirs.
5. Hard rock caverns.

[1] Oil and Gas Development Company Ltd., Islamabad.

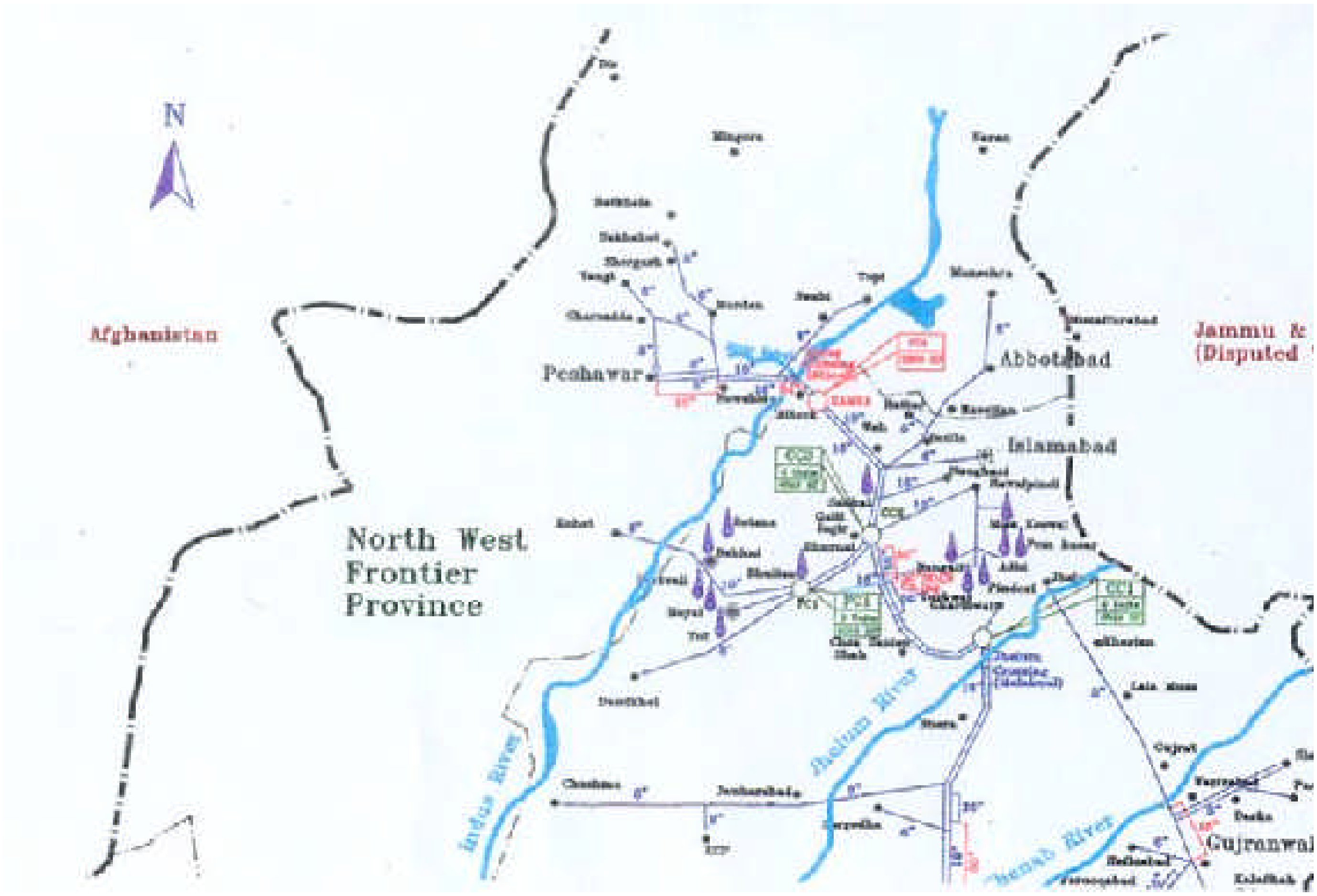

Figure 1- Strategic location of Sadkal Gas Condensate Field near to gas transmission line for distribution system in Potwar area.

The Typical Gas Storage reservoirs are generally having good permeability clastics or carbonates existing at intermediate depths and temperatures. In general, these reservoirs are depleted formations, which originally contained sweet (no H_2S) natural gas. Typically, these zones do not contain mobile water or active or partially active aquifers, oil legs or residual liquid hydrocarbon saturations, although this is not always the case (DOE US).

PURPOSES OF GAS STORAGE

Gas storage is the primary means of managing fluctuations in supply and demand, and is an essential component of an efficient and reliable regional natural gas transmission and distribution network. Following are the main purposes of gas storage:

- To meet seasonal demands for natural gas (base-load storage).
- To meet short-term peaks in demand (peaking storage), which can range from a few hours to a few days.
- Prevent disruption of supplies during mechanical or other problems in producing fields. (Buffer periods of peak demand).
- To ensure that adequate natural gas supplies are available to meet seasonal base-load customer requirements in winter.
- Natural gas storage also provides insurance for customers whose business need a reliable supply of natural gas.
- Allowing producers to comply with their contract obligations
- The storage of gas is needed to increase the efficiency of the gas distribution business.

DEVELOPMENT OF A GAS STORAGE RESERVOIR

Gas storage operation depends on the state and performance of the reservoir. Decisions to increase

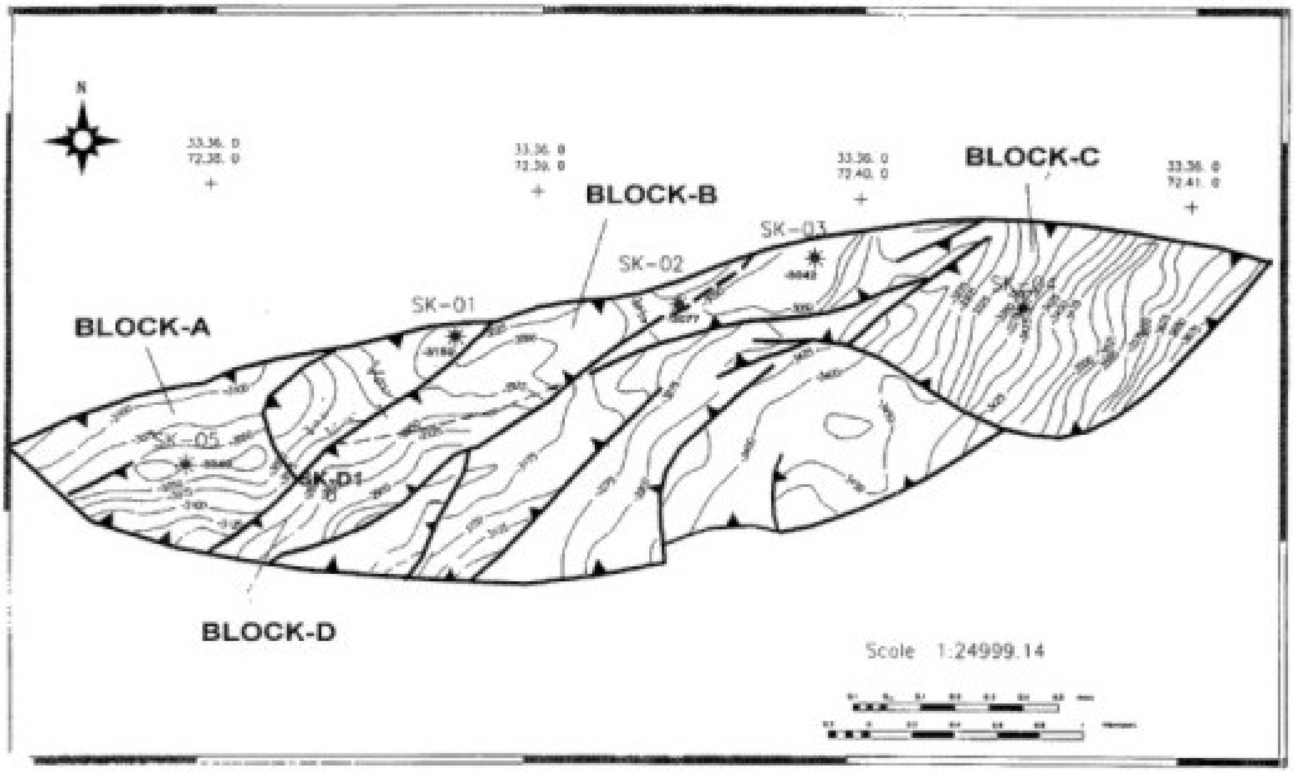

Figure 2- Structural depth contour map on the top of Margalla Hill Limestone.

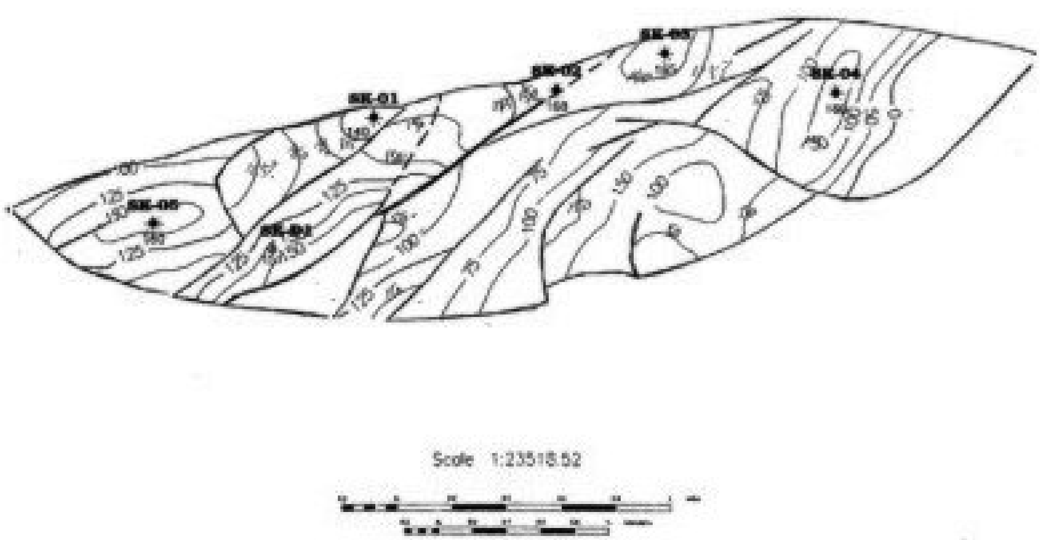

Figure 3- Gross thickness-isopach Margalla Hill Limestone.

cushion, working gas volumes and deliverability of the storage, drilling new wells as well as abandoning existing must be based on analysis and simulations to define the working envelope and investments (Lubimor, 2000).

For a reservoir to be a candidate for gas storage, the following criteria must be satisfied, when considering the development of a gas storage reservoir.

- Sufficient reservoir volume to allow for storage of the required amount of gas without exceeding containment pressure constraints and without requiring uneconomic compression to high-pressure levels.
- Satisfactory containment of the gas by appropriate upper and lower sealing cap rock.
- Compatibility of Injected gas with the native gas.
- Sufficient inherent permeability to allow injection and production at required delivery rates during peak demand periods.
- Problems, which may be associated with the presence of free water or hydrocarbons in the storage reservoir (both mobile and immobile).
- Formation damage issues that often surround the drilling and completion of new wells in the gas storage reservoirs for development purposes.
- Absence of hydrogen sulphide gas (in-situ or bacterially generated)

Effective utilization of an underground gas storage reservoir requires the pre-delivery and storage of significant volumes of gas as "cushion gas" i.e. a minimum volume that is maintained in storage permanently. Additional volumes are injected and maintained above the cushion gas volume to establish pressure and volume conditions necessary to provide the withdrawal rate required from storage when called upon by the distribution system. For any particular storage reservoir, cushion gas requirements may vary from 25 to 75% of reservoir capacity.

Critical planning and operations are required to balance underground gas storage capabilities, available gas supplies and market priorities to serve efficiently a defined market within acceptable economic parameters.

SELECTION OF SADKAL FIELD FOR UNDERGROUND GAS STORAGE

To investigate the possible storage candidates for conversion to underground gas storage a number of partially depleted gas and oil reservoirs in the Potwar area i.e. Adhi, Dakhni, Ratana, Sadkal, Dhulian, Dhurnal, Meyal and Toot were considered and exatuated in initial screening process. Parameters used in the screening process included, reservoir type and location, compatibility of injected gas with the native gas, working storage capacity, estimated well deliverability, number of wells needed to meet peak day demand, and mechanical condition of wells. The partially depleted Sadkal Field appears to be a suitable candidate for conversion to underground gas storage to meet storage need, while other candidate reservoirs were eliminated in the screening process. Due to deficiencies identified included reservoir type, compatibility of injected gas with the native gas, inconsistent working storage capacity was not consistent with the peak day demand, inadequate permeability to deliver gas at required rates without converting or drilling an excessive number of withdrawal wells.

From a well deliverability perspective Sadkal is next to the Dakhni reservoir in flow capability. With a permeability-thickness of some 24,000 mD-feet, a typical Sadkal well was estimated to have a wellhead Absolute Open Flow (AOF) of some 70 MMSCF/D through 3½ inch nominal tubing. The partitioned nature of the Margalla Hill Limestone has the added feature of being amenable to sequential development as the peaking need for underground gas storage increases into the more distant future. Therefore Only the Sadkal, Margalla Hill Limestone with a smaller IGIP and its partitioned nature has merit as a storage candidate.

RESERVOIR GEOLOGY

Sadkal Gas-Condensate field has been divided into two reservoirs, the upper (the combined Chorgali & the upper Margalla Hill Limestone) and the lower Margalla Hill Limestone. The average depths of the reservoirs are 3500 M to 3600 M and the average thickness of the reservoirs are 78 M & 130 M respectively. A prominent shaly marker separates vertically both the reservoirs from each other. The upper reservoir (dolomitic limestone and limestone) has good matrix porosity (10-12%) whereas the lower reservoir has poor matrix porosity (1-2%) but has fracture porosity. All the fractures are originated due to tectonics in this reservoir. The Chorgali Formation is generally dolomitic with intercalations of shale and is less fractured than the underlying Margalla Hill Limestone that is cleaner and more fractured limestone (OGDCL, 1994)

FLUID PROPERTIES – PVT

Data which characterize the fluid properties of reservoir oil, gas and water are required to accurately simulate the behaviours of native gas and the make-up gas to be injected for storage. A number of laboratory analysis reports on fluid samples from Sadkal Gas Condensate Field are available for this study. These reports were reviewed for completeness and examined for systematic variation of key properties. The native gas composition based on the recombined gas analysis and other critical properties are listed in the table-1.

A detailed compositional determination was carried out on the native gas and the make-up gas to be injected for storage. Thus, the changes in fluid properties for various stages of the gas storage operation have been rigorously accounted for, in the analysis. Once the composition and properties of gas-in-place were determined for a given storage cycle, it was possible to calculate dew point pressure of the gas at any given temperature. Locus of dew point pressures over a wide range of temperatures established the 2-phase envelope, which is useful in determining the potential for liquid dropout from the gas either in the reservoir or during production and surface handling operations. The dew point envelope for the native reservoir gas suggests the reservoir fluid was initially a single-phase gas as the reservoir temperature exceeds the critical temperature. As pressure declines with depletion, the composition of the produced fluid will remain constant until the dew-point pressure is reached at 5098 psia. Below this pressure the liquid condense out of the reservoir fluid as a fog or dew. This condensation leaves the gas phase with a lower liquid content. As the condensed liquid adheres to the walls of the pore system of the rock, it is initially immobile and a residual liquid saturation is established. Thus the fluids produced at the surface will have ever-decreasing LGR (Liquid Gas Ratio) and an ever-increasing GOR (Gas Oil Ratio), which explains the varying and decreasing LGR performance of the wells.

This condensation continues and increases until a point of maximum liquid volume is reached about mid-way through the two-phase envelope. Thereafter, vaporization occurs during isothermal expansion, which gives meaning to the term retrograde condensation.

Based on an IGIP (Initial Gas In Place) estimated at 55 BCF and a cumulative production to year-end 2001 of 41 BSCF in the "B" block of Sadkal, leaves a remaining gas-in-place of some 14 BSCF. With reference to the supply demand schedule as indicated in table-3. It is estimated that some 13 BSCF must be injected to attain a gas volume of 25 BSCF necessary for appropriate deliverability rating for the 2003-2004 season. Thereafter, the fill-up can be staged with the full working gas volume of 6 BSCF and a GIP of some 55 BSCF being reached after three or four years. Based on the current gas-in-place and the above schedule of storage gas volumes the composition of gas-in-place for each storage cycle was calculated using molar recombination. Cycle 1, for example, 12 BSCF of native gas are mixed with 13 BSCF of make-up gas to storage. The cushion gas volume, with resulting composition of Cycle 1 gas-in-place, is then mixed with 10-42 BSCF of make-up gas for storage to calculate the composition of Cycle 2 gas-in-place, and so on. Phase diagrams for relevant mixes of native gas and make-up gases are shown in the figure –4.

PRODUCTION HISTORY

Three wells, SK-01, SK-02 and SK-03 are completed in the 'B' block of the field and have produced a combined cumulative volume of 39 BSCF of gas and 2.58 MMBBL of condensate as of December 31, 2001. Production from the field was discontinued in November 1999 due to low pressure and low deliverability. When the decline in reservoir pressure could no longer lift gas and oil to the surface against a wellhead pressure of about 700 psia. With the installation and commissioning of compression facilities at the Sadkal processing plant in February 2001, these wells were returned to activity. Just prior to their resumption in production, the shut-in tubing-head pressure (SITHP) flowing tubing-head pressure (FTHP) and flow rates were measured and recorded table 1.

Table 1. Pressure and flow rate prior to installation of compression facility at Sadkal Gas Condensate Field.

Well	Sk-2	SK-3	SK-4	SK-5
FTHP (Psig)	690	690	700	2200
SITHP (Psig)	1200	1125	950	
Gas Rate (Mmscf/d)	4.00	2.50	3.00	8.50
Condensate Rate (bopd)	103	107	34	1000
Gas Equiv. Rate (mmscf/d)	4.07	2.58	3.02	9.23

The SK-01 well was suspended in November 1998 and has been subsequently abandoned No comparable flow data exists for this well. Meanwhile, the well SK-05 has flowed continuously to the surface on its own since being placed on production in July 1999 (Table 2).

Table 2. Comparable statistics for the wells in the Sadkal Gas Condensate Field.

Well	SK-1	Sk-2	SK-3	SK-4	SK-5
Production Start Date	Jun-93	Aug-93	May-94	Apr-95	Jul-99
Peak Date Deliverability (mmscf/d)	10.7	12.5	11.7	12.4	12.6
*Cum.Gas Production (bscf)	11.18	16.57	11.52	7.78	8.80
*Cum.Oil Production (mmbbl)	1.04	1.05	0.50	0.42	1.24
*Cum.Wtr. Production (mbbl)	28.4	8.2	7.3	6.2	17.8

*December 31, 2001

The Cumulative oil production, which gives a cumulative average LGR of 72 BBL/MMSCF and suggests a moderately rich gas condensate system. As discussed earlier under the fluid properties section this liquid undoubtedly represents the production of a retrograde condensate, which condensed during early depletion and is now being vaporized and produced during late depletion. Once the gas storage operation commences, vaporization would be expected to continue warranting surface processing for some time. The gas equivalent of 725 SCF/BBL was derived for the liquid production and recognized in the gas production volume. Much of the water production experienced to date can be attributed to water of condensation. At original reservoir conditions the water of condensation is 0.55 BBL/MMSCF.

Table 3. PVT analysis data of Sadkal Gas Condensate Field.

Component	Sadkal-01 %	Sadkal-02 %	Sadkal-04 %	Sadkal-05 %	All Average %
H2S	0.00	0.00	0.00	0.09	0.02
CO2	0.15	0.09	0.16	0.06	0.12
N2	0.22	0.11	0.09	0.14	0.14
C1	75.96	75.61	77.21	76.61	76.35
C2	8.39	8.30	8.12	8.47	8.32
C3	3.49	3.56	3.44	3.60	3.52
i-C4	0.86	0.87	0.84	0.84	0.85
n-C4	1.26	1.26	1.18	1.26	1.24
i-C5	0.56	0.59	0.54	0.55	0.56
n-C5	0.56	0.59	0.53	0.55	0.56
C6	0.82	0.83	0.73	0.75	0.78
C7	0.90	1.10	0.94	0.97	0.98
C8	0.81	1.37	1.20	1.16	1.14
C9	0.91	1.04	0.90	0.85	0.94
C10	0.73	0.75	0.68	0.65	0.70
C10+	4.32	3.93	3.44	3.45	3.79
	100.00	**100.00**	**100.00**	**100.00**	**100.00**

MW OF C7+			171	174
Density of C7+			0.81	.081
GOR, scf /bbl	5402	6121	9180	8075
LGR, bbl / mmscf	185	163	109	201
Tank gravity, API				48

Table 4. Bottom hole pressure and temperature summary of Sadkal Gas Condensate Field.

Datum depth = 3128 mss

Well Name	Date	Test Type	Perfed Intervals (m)	Depth (m)	KB (m)	Depth (mss)	Pressure (psi)	Pressure @datum (psi)	BHT (°F)
Sadkal-1	24.04.92	DST	3670-3661	3645	480	3165	9886	9876	211
	02.05.94	PBU	3670-3661	3675	480	3195	6655	6630	213
Sadkal-2	14.08.93	PBU	3696-3608	3690	470	3220	9300	9255	208
Sadkal-3	28.03.94	DST	3688-3654	-	483	-	6805	6805	200
	05.04.94	DST	3558-3556	-	483	-	6647	6647	200
	02.09.01	PBU	3558-3527	3542	483	3058	1390	1446	202
Sadkal-4	21.02.95	DST	3945-3941	3925	474	3450	10799	10591	245
	15.05.95	MIT	3945-3941	3974	474	3500	7984	7768	245
	06.09.01	PBU	3945-3847	3926	474	3453	981	798	218
Sadkal-5	14.08.99	PBU	3585-3537	3514	497	3017	9100	9186	215

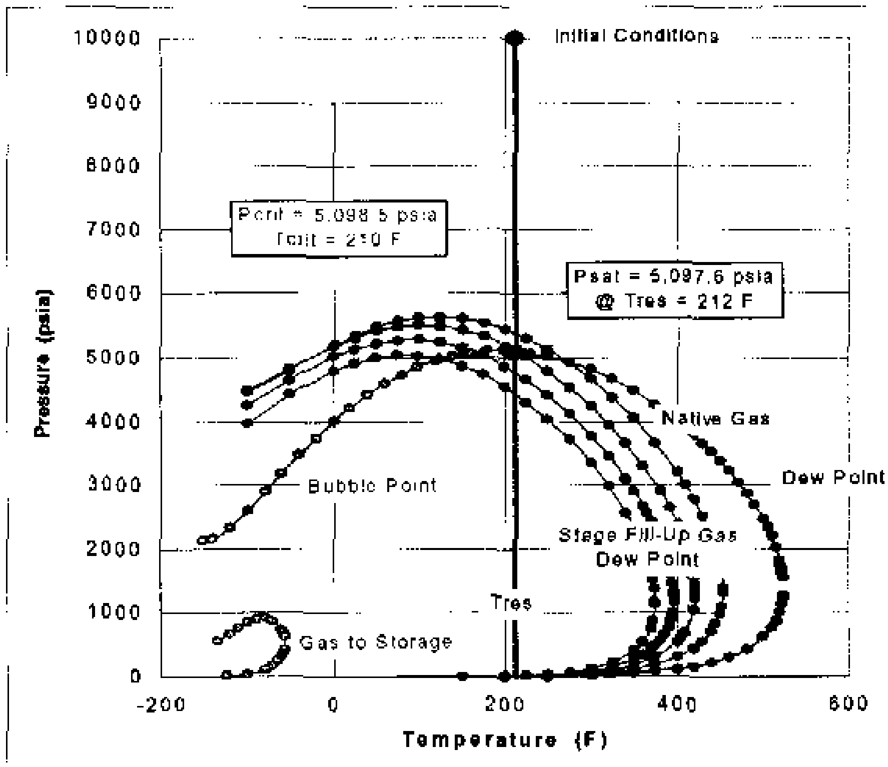

Figure 4- Phase diagram showing mixes of native and make-up gases.

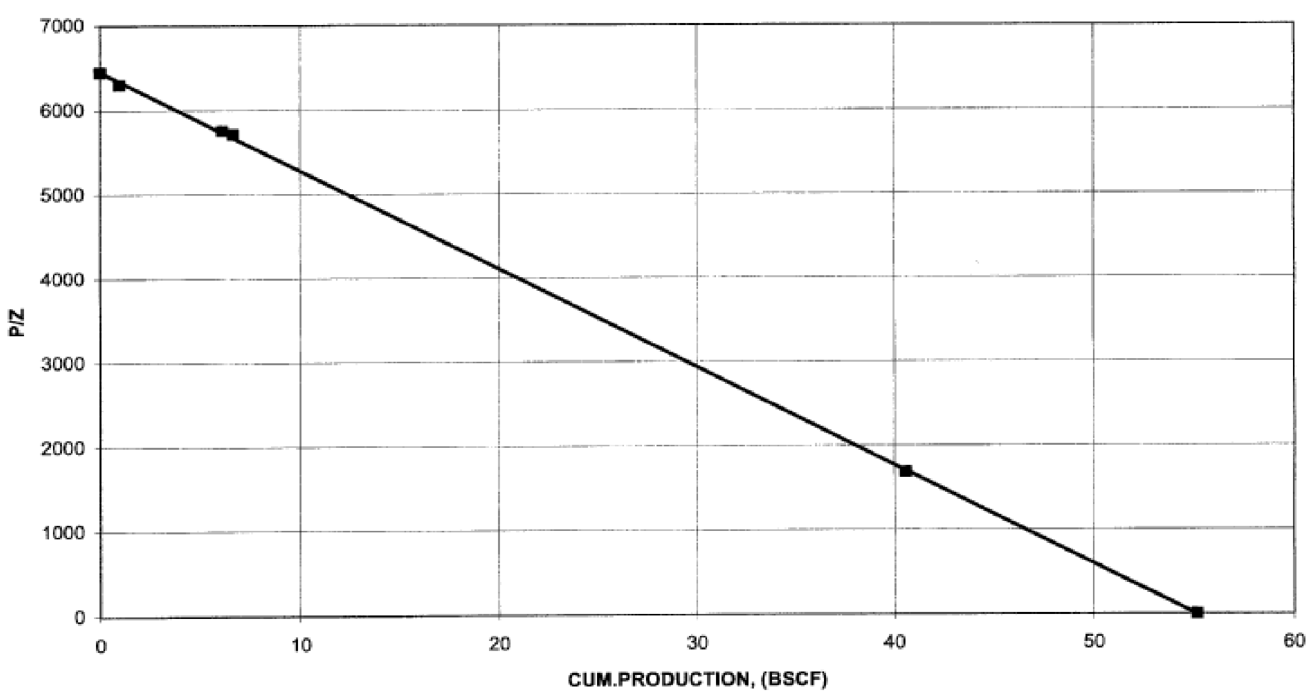

Figure 5- Pressure production data for the reservoir of B-Block showing P/Z versus cumulative gas production of B-Block, Sadkal Gas Condensate Field.

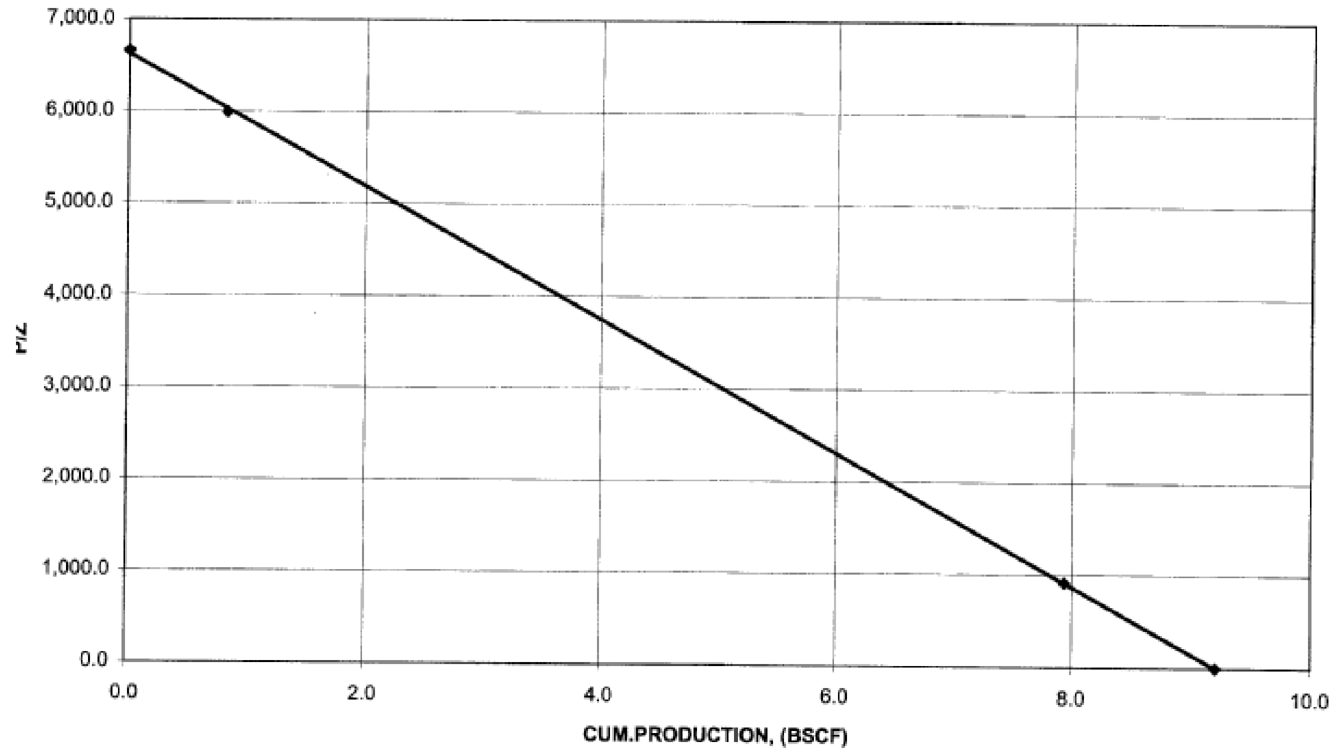

Figure 6- Pressure production data for the reservoir of C-Block showing P/Z versus cumulative gas production of C-Block, Sadkal Gas Condensate Field.

PRESSURE HISTORY

The key results of the pressure surveys conducted over the time are summarized in table-2 and, corrected to a common datum of 3128 mss, of the main horizon of interest i.e. Margalla Hill zone.

INITIAL GAS-IN-PLACE

Material balance technique is used to determine the gas-in-place for better accuracy. A plot of pressure production data for the reservoir of B-block in the form of P/Z versus Gp as shown in figure-5 estimates an IGIP of 55 BSCF. In this analysis the Gp values include the condensate production as a gas equivalent volume based on a molecular weight of 145 and a density of 0.79 for the liquid production. The gas equivalent conversion factor is 0.725 MSCF/BBL.

Figure 6 shows a similar plot of pressure production data for the C-block of the field in the form of P/Z versus Gp indicating IGIP volume of 9.4 BSCF.

GAS DEMAND & SUPPLY

The seasonal demand exceeds supply of the Sui Northern system-Seasonal peak loads, which occur during the winter months, cannot be met due to both system supply and transmission constraints. Figure-7 shows that the peak day demand rate occur 30 to 35 days each year intermittent and are generally limited to an eight-weeks period centred at mid-January. A forecast of the peak day and average day demand is presented in table-5 (Ikml 2002).

WORKING STORAGE CAPACITY

For gas reservoirs the cumulative production and associated pressure decline gives an indication of the reservoir voidage value. The graphical approach to the material balance for gas not only gives the total gas initially in-place but also can be converted to give the gas produced (or stored) per pound of pressure decline (or increase). Using the Sadkal field data to exhibit the B-block of the Margalla Hill Limestone had an initial discovery pressure of 10400 psig and showed an estimated pressure decline of 8000 psi while producing 26 BSCF. The ratio of production divided by pressure decline adjusted for the compressibility factor yields 6 MMSCF/psi of pressure drop as a storage capacity. Assuming as a gas storage reservoir the B-block operated between 10400 and 8700 psig this portion of the reservoir would have a working gas capacity of 10 BSCF. The peaking need (working gas volume) of 7 to 9 BSCF represents 16% of the IGIP and about 20 % of the recoverable gas reserve of B-block. From the demand and supply analysis a maximum requirement has been estimated to over a 35 days period during the winter months and the deliverability of the three wells (Tables 6 to 8). It is noted the capacity of three wells is adequate to meet the pipeline shortfall at least upto 2009-2010.

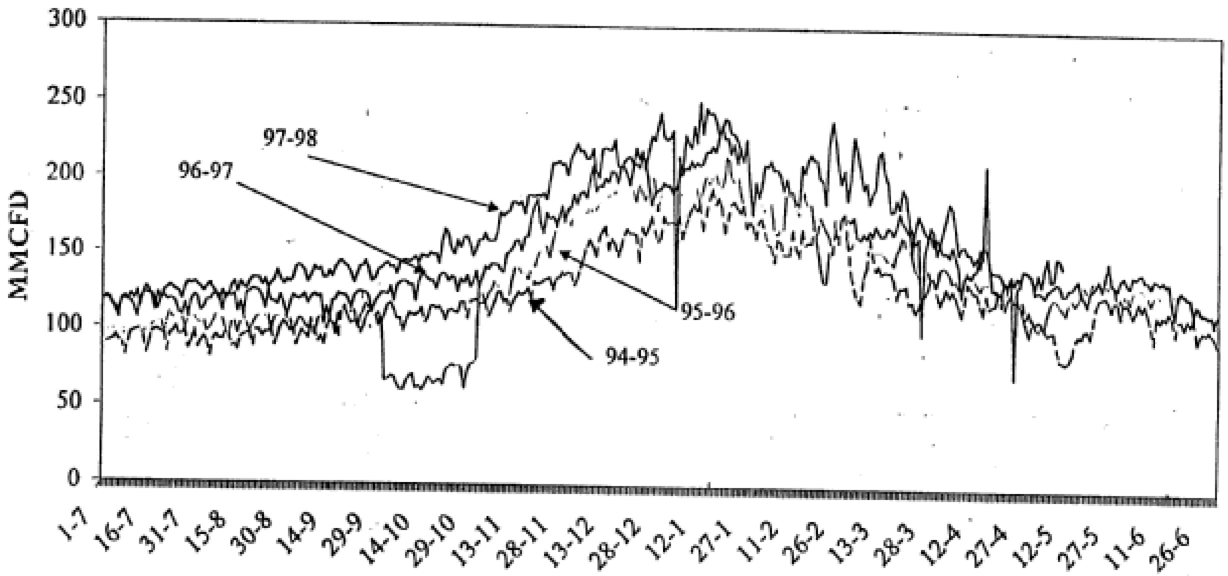

Figure 7- Daily gas sales of northern areas in different years.

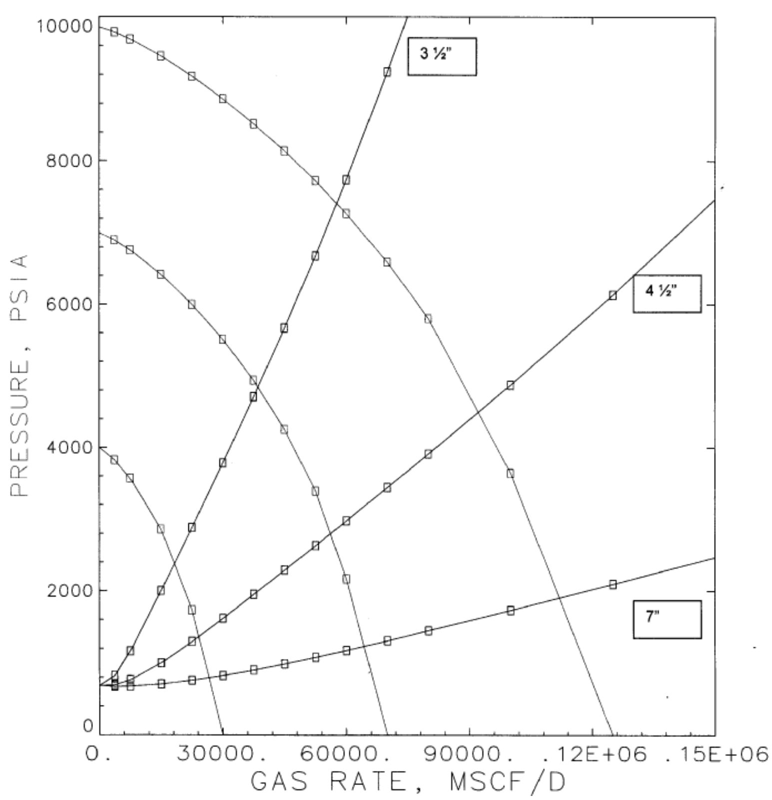

Figure 8- Deliverability rate of Sadkal Well-2 for different tubing sizes.

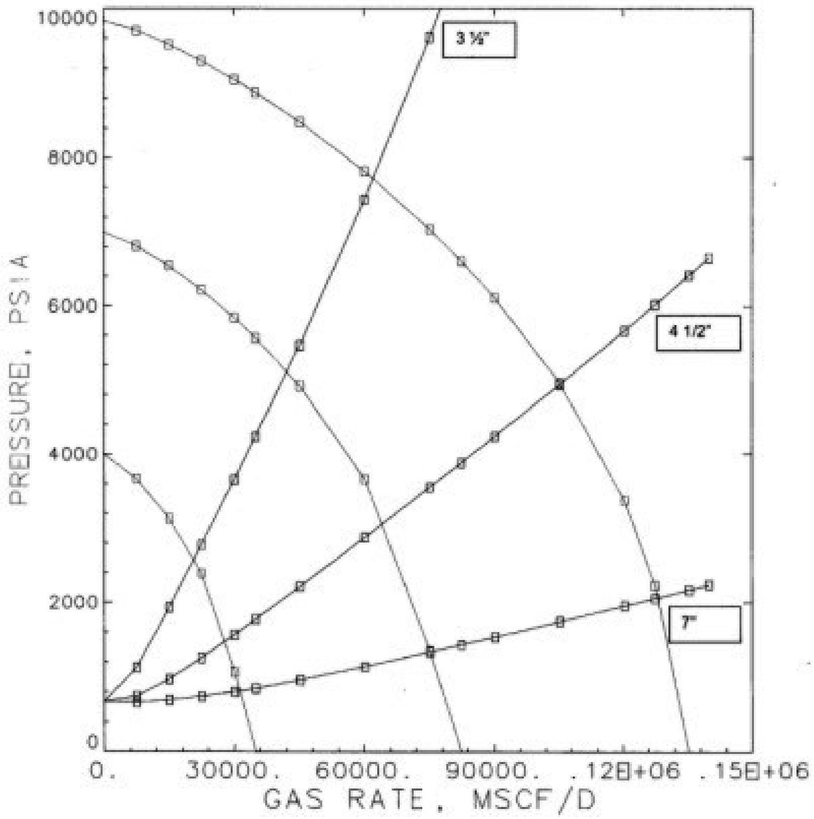

Figure 9- Deliverability rate of Sadkal Well-3 for different tubing sizes.

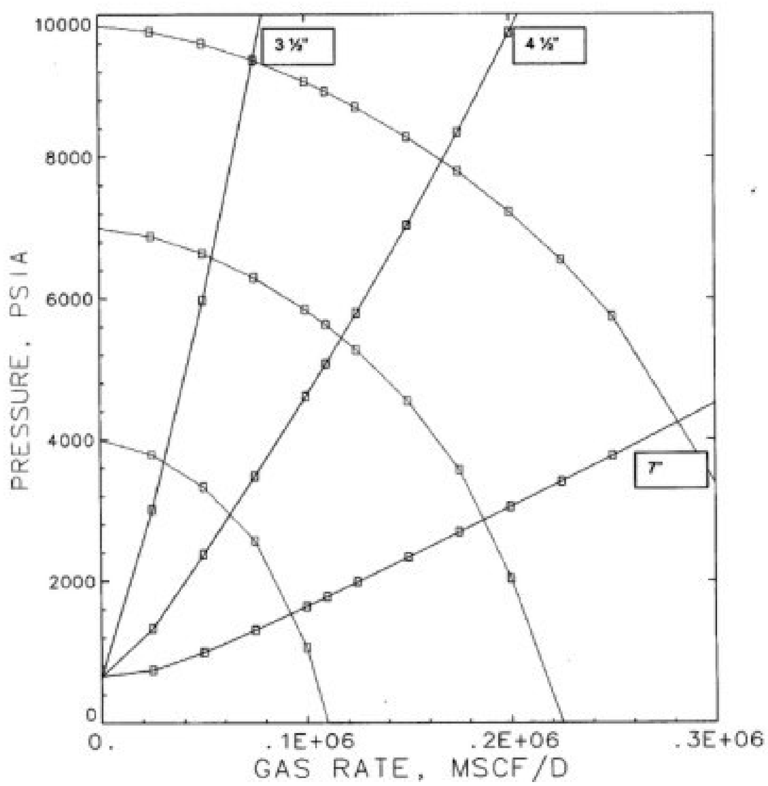

Figure 10- Deliverability rate of Sadkal Well-4 for different tubing sizes.

Table 5. A forecast schedule of gas based on peak and average day demand of Northern Areas, Pakistan.

Year	Peak Day Demand (MMSCF/D)	Avg. Day Demand (MMSCF/D)	Yearly Demand (BSCF)	Pipeline Capacity		Total Pipeline Capacity (MMSCF/D)	Gas Available (MMSCF/D)	Net Gas Available for Storage (BSCF)	Cum. Net to Storage (BSCF)	Max. Transmission Shortfall (MMSCF/D)
				Faisal Gali (MMSCF/D)	Potohar Basin (MMSCF/D)					
2000-2001	286	135	49.275	200	90	290	290	56.575	0	4
2001-2002	311	146	53.29	225	90	315	315	61.685	0	4
2002-2003	337	158	57.67	225	90	315	315	57.305	52.6	-22
2003-2004	362	169	61.685	260	90	350	350	66.065	52.6	-12
2004-2005	388	181	66.065	260	90	350	350	61.685	52.6	-38
2005-2006	413	192	70.08	260	90	350	350	57.67	52.6	-63
2006-2007	439	204	74.46	260	90	350	350	53.29	52.6	-89
2007-2008	464	216	78.84	260	90	350	350	48.91	52.6	-114
2008-2009	490	227	82.855	260	90	350	350	44.895	52.6	-140
2009-2010	516	239	87.235	260	90	350	350	40.515	52.6	-166
2010-2011	546	250	91.25	260	90	350	350	36.5	52.6	-196
2011-2012	571	262	95.63	260	90	350	350	32.12	52.6	-221
2012-2013	596	273	99.645	260	90	350	350	28.105	52.6	-246
2013-2014	622	285	104.025	260	90	350	350	23.725	52.6	-272
2014-2015	648	296	108.04	260	90	350	350	19.71	52.6	-298
2015-2016	673	308	112.42	260	90	350	350	15.33	52.6	-323
2016-2017	699	319	116.435	260	90	350	350	11.315	52.6	-349
2017-2018	725	331	120.815	260	90	350	350	6.935	52.6	-375
2018-2019	751	342	124.83	260	90	350	350	2.92	52.6	-401
2019-2020	776	354	129.21	260	90	350	350	-1.46	51.2	-426
2020-2021	802	365	133.225	260	90	350	350	-5.475	45.7	-452
2021-2022	828	377	137.605	260	90	350	350	-9.855	36	-478
2022-2023	854	388	141.62	260	90	350	350	-13.87	36	-504
2023-2024	879	400	146	260	90	350	350	-18.25	36	-529
2024-2025	905	411	150.015	260	90	350	350	-22.265	36	-555

Table 6. Deliverability of B-Block for tubing size (3 ½ inches dia) of Sadkal Gas Condensate Field.

Cushion Gas Volume (bscf)	Working Gas Volume. G= (a+b)*p/z (bscf)	P/Z (psia)	Gas Comp.	Reservoir Pressure (psia)	Well Head Shut-in Pressure (psia)	Well Head Flowing Pressure (psia)	Field Deliverability Rating (mmscf/d)	Time to Deplete (Days)
55.2	0.0	6454	1.18	7638	6442	2000	124	0
53.2	2.0	6220	1.15	7148	5998	2000	111	18
51.2	4.0	5986	1.12	6687	5583	2000	99	40
49.2	6.0	5752	1.09	6255	5197	2000	88	68
47.2	8.0	5518	1.06	5852	4839	2000	78	102
45.2	10.0	5284	1.04	5478	4510	2000	69	144
43.2	12.0	5050	1.02	5129	4206	2000	61	196
41.2	14.0	4816	1.00	4803	3924	2000	54	260
39.2	**16.0**	**4582**	**0.98**	**4488**	**3881**	**2000**	**47**	**339**
55.2	0.0	6454	1.18	7638	6442	1000	131	0
53.2	2.0	6220	1.15	7148	5998	1000	118	17
51.2	4.0	5986	1.12	6687	5583	1000	107	38
49.2	6.0	5752	1.09	6255	5197	1000	96	62
47.2	8.0	5518	1.06	5852	4839	1000	87	92
45.2	10.0	5284	1.04	5478	4510	1000	78	128
43.2	12.0	5050	1.02	5129	4206	1000	70	170
41.2	14.0	4816	1.00	4803	3924	1000	64	220
39.2	**16.0**	**4582**	**0.98**	**4488**	**3881**	**1000**	**67**	**280**
55.2	0.0	6454	1.18	7638	6442	500	133	0
53.2	2.0	6220	1.15	7148	5998	500	120	17
51.2	4.0	5986	1.12	6687	5583	500	108	37
49.2	6.0	5752	1.09	6255	5197	500	98	61
47.2	8.0	5518	1.06	5852	4839	500	89	90
45.2	10.0	5284	1.04	5478	4510	500	80	125
43.2	12.0	5050	1.02	5129	4206	500	73	165
41.2	14.0	4816	1.00	4803	3924	1000	64	220
39.2	**16.0**	**4582**	**0.98**	**4488**	**3881**	**1000**	**67**	**280**
55.2	0.0	6454	1.18	7638	6442	300	133	0
53.2	2.0	6220	1.15	7148	5998	300	120	17
51.2	4.0	5986	1.12	6687	5583	300	109	37
49.2	6.0	5752	1.09	6255	5197	300	98	61
47.2	8.0	5518	1.06	5852	4839	300	89	90
45.2	10.0	5284	1.04	5478	4510	300	81	124
43.2	12.0	5050	1.02	5129	4206	300	73	164
41.2	14.0	4816	1.00	4803	3924	1000	64	220
39.2	**16.0**	**4582**	**0.98**	**4488**	**3881**	**1000**	**67**	**280**

Table 7. Deliverability of B-Block for tubing size (4 ½ inches dia) of Sadkal Gas Condensate Field.

Cushion Gas Volume (bscf)	Working Gas Volume. G= (a+b)*p/z (bscf)	P/Z (psia)	Gas Comp.	Reservoir Pressure (psia)	Well Head Shut-in Pressure (psia)	Well Head Flowing Pressure (psia)	Field Deliverability Rating (mmscf/d)	Time to Deplete (Days)
55.2	0.0	6454	1.18	7638	6442	2000	201	0
53.2	2.0	6220	1.15	7148	5998	2000	178	11
51.2	4.0	5986	1.12	6687	5583	2000	156	26
49.2	6.0	5752	1.09	6255	5197	2000	137	44
47.2	8.0	5518	1.06	5852	4839	2000	120	66
45.2	10.0	5284	1.04	5478	4510	2000	105	95
43.2	12.0	5050	1.02	5129	4206	2000	92	131
41.2	14.0	4816	1.00	4803	3924	2000	79	176
39.2	16.0	4582	0.98	4488	3661	2000	68	234
55.2	0.0	6454	1.18	7638	6442	1000	214	0
53.2	2.0	6220	1.15	7148	5998	1000	191	10
51.2	4.0	5986	1.12	6687	5583	1000	170	24
49.2	6.0	5752	1.09	6255	5197	1000	151	40
47.2	8.0	5518	1.06	5852	4839	1000	135	59
45.2	10.0	5284	1.04	5478	4510	1000	120	83
43.2	12.0	5050	1.02	5129	4206	1000	107	112
41.2	14.0	4816	1.00	4803	3924	1000	95	147
39.2	16.0	4582	0.98	4488	3661	1000	86	188
55.2	0.0	6454	1.18	7638	6442	500	217	0
53.2	2.0	6220	1.15	7148	5998	500	194	10
51.2	4.0	5986	1.12	6687	5583	500	173	23
49.2	6.0	5752	1.09	6255	5197	500	155	39
47.2	8.0	5518	1.06	5852	4839	500	138	58
45.2	10.0	5284	1.04	5478	4510	500	124	81
43.2	12.0	5050	1.02	5129	4206	500	111	108
41.2	14.0	4816	1.00	4803	3924	500	99	141
39.2	16.0	4582	0.98	4488	3661	500	88	180
55.2	0.0	6454	1.18	7638	6442	300	217	0
53.2	2.0	6220	1.15	7148	5998	300	194	10
51.2	4.0	5986	1.12	6687	5583	300	174	23
49.2	6.0	5752	1.09	6255	5197	300	155	39
47.2	8.0	5518	1.06	5852	4839	300	139	58
45.2	10.0	5284	1.04	5478	4510	300	124	80
43.2	12.0	5050	1.02	5129	4206	300	112	108
41.2	14.0	4816	1.00	4803	3924	300	100	140
39.2	16.0	4582	0.98	4488	3661	300	90	178

Table 8. Deliverability of B-Block for tubing size (7 inches dia) of Sadkal Gas Condensate Field.

Cushion Gas Volume (bscf)	Working Gas Volume. G= (a+b)*p/z (bscf)	P/Z (psia)	Gas Comp.	Reservoir Pressure (psia)	Well Head Shut-in Pressure (psia)	Well Head Flowing Pressure (psia)	Field Deliverability Rating (mmscf/d)	Time to Deplete (Days)
55.2	0.0	6454	1.18	7638	6442	2000	242	0
53.2	2.0	6220	1.15	7148	5998	2000	213	9
51.2	4.0	5986	1.12	6687	5583	2000	187	21
49.2	6.0	5752	1.09	6255	5197	2000	164	37
47.2	8.0	5518	1.06	5852	4839	2000	143	56
45.2	10.0	5284	1.04	5478	4510	2000	124	80
43.2	12.0	5050	1.02	5129	4206	2000	108	111
41.2	14.0	4816	1.00	4803	3924	2000	93	150
39.2	**16.0**	**4582**	**0.98**	**4498**	**3661**	**2000**	**80**	**200**
55.2	0.0	6454	1.18	7638	6442	1000	257	0
53.2	2.0	6220	1.15	7148	5998	1000	229	9
51.2	4.0	5986	1.12	6687	5583	1000	203	20
49.2	6.0	5752	1.09	6255	5197	1000	180	33
47.2	8.0	5518	1.06	5852	4839	1000	160	50
45.2	10.0	5284	1.04	5478	4510	1000	142	70
43.2	12.0	5050	1.02	5129	4206	1000	126	95
41.2	14.0	4816	1.00	4803	3924	1000	112	125
39.2	**16.0**	**4582**	**0.98**	**4498**	**3661**	**1000**	**100**	**160**
55.2	0.0	6454	1.18	7638	6442	900	261	0
53.2	2.0	6220	1.15	7148	5998	900	233	9
51.2	4.0	5986	1.12	6687	5583	900	207	19
49.2	6.0	5752	1.09	6255	5197	900	185	33
47.2	8.0	5518	1.06	5852	4839	900	164	49
45.2	10.0	5284	1.04	5478	4510	900	147	68
43.2	12.0	5050	1.02	5129	4206	900	131	92
41.2	14.0	4816	1.00	4803	3924	900	117	120
39.2	**16.0**	**4582**	**0.98**	**4498**	**3661**	**600**	**106**	**169**
55.2	0.0	6454	1.18	7638	6442	300	262	0
53.2	2.0	6220	1.15	7148	5998	300	233	9
51.2	4.0	5986	1.12	6687	5583	300	208	19
49.2	6.0	5752	1.09	6255	5197	300	185	32
47.2	8.0	5518	1.06	5852	4839	300	165	48
45.2	10.0	5284	1.04	5478	4510	300	148	68
43.2	12.0	5050	1.02	5129	4206	300	132	91
41.2	14.0	4816	1.00	4803	3924	300	118	119
39.2	**16.0**	**4582**	**0.98**	**4498**	**3661**	**300**	**108**	**162**

According to elementary economics and recognition for the recoverable cushion gas, the investment cost to develop a Sadkal gas storage facility ranges between 50 and 70 million dollars. However, 70% of the investment is cushion gas of which 90% is recoverable. The cost of service of developing 'B' block is estimated to be

US$ 3.48 per MSCF. The cost of service can be reduced to US$2.33 per MSCF by increasing the THP to 1000 psia and minimizing compression on the withdrawal cycle with limited loss in deliverability.

DELIVERABILITY

The two main factors in underground gas storage are working gas capacity and deliverability rating. To establish the rated deliverability of the Sadkal storage facility, for tubing and casing sizes of 3 ½, 4 ½ and 7-inch, the inflow-outflow calculations charts are shown in figures 8 to 10.

CONCLUSIONS

From Demand and supply analysis a maximum requirement has been estimated to over a 35 days period during the winter months. It is concluded that field deliverability calculation based on material balance (P/z versus working gas volume) and an initial gas-in-place volume of 55 BSCF, confirmed that the B-block of the Margalla Hill Limestone in the Sadkal Gas Condensate Field can fulfill the gas storage requirements identified over the next ten years for Potwar area of Pakistan.

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