Optimization of Solution Mining Operations

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ABSTRACT

Solution mining operations in salt domes have been analyzed in terms of engineering and economic aspects by means of a numerical model that includes prediction of cavity development, calculation of operating pressure, power consumption and overall cost determination. Various operating parameters and methods of development have been compared for the hypothetical case of the development of a cavity with a volume of 1 million (1 MM) barrels.

INTRODUCTION

Solution mining operations in salt are generally undertaken with one of two objectives: a) development of space for underground storage or waste disposal and b) production of brine to be used as feedstock for salt production or chemical plants. In some instances it is possible to find both types of operations within one mining installation and even within the same cavity which is simultaneously used for storage of products and brine production. It is more common however to design cavities for the specific objective of either storage or brine production with the possibility of converting the latter to storage after the late stages of brine production have been completed.

In either case the cavities have to be designed for long term operations to insure that their intended objective can be successfully satisfied. There exist numerous possibilities in terms of the combinations of operating parameters and methods, each resulting in different performance. Proper design requires knowledge of these possibilities in order to fulfill design objectives.

Considerable work has been undertaken[1, 2, 3] on studies of cavity development and salt dissolution to provide criteria and guidelines for the planning of solution mining operations. Through experience, study and analysis of past operations, operating companies have developed performance curves that relate operating parameters with brine production and cavity development.

These performance curves are not only invaluable for design but also provide a means of monitoring the performance of operations and indicating possible deviations between the expected and actual development. However, they are of limited usefulness if numerous alternatives are to be considered in the planning and design of future operations.

A computer model had been developed[4] with the objective of predicting cavity development for the most practical operating condition. Application of the model to the simulation of development of various cavities, for which there also existed well-documented production records and shape surveys, has shown agreement between the actual and predicted performance. With confidence established in the model, it can be used effectively to aid in the design of solution mining operation. This required the development of the capability of considering operational factors which could be used to establish economic comparisons of various modes of operation. These elements include operating costs which are related to power expenditure and capital costs which are related to the configuration and mode of operation.

The objective of the present work was to develop these relations in conjunction with the cavity development model and to develop a method by which a proposed project could be analyzed from the standpoint of engineering and economic parameters resulting in the determination of an optimum development plan.

DESIGN OF SOLUTION MINING OPERATIONS

Design of solution mining operations involves selecting a combination of possible operating conditions and well configurations that will satisfy the intended objectives for the system within certain constraints.

Objectives. Solution mining design objectives will be stated differently for production of brine than for development of storage space, as follows:

Storage Development: In this case either one, or combinations, of the following may represent the specific objective: 1) develop a certain volume of storage space in a given length of time; 2) develop a certain volume of storage space in the minimum time; 3) develop a certain volume of storage space for the minimum cost; 4) develop a certain volume of storage space for minimum energy expenditure.

Production of Brine: For this type of operation either one or combinations of the following may represent the design objective: 1) satisfy brine rate of production in a given length of time; 2) maintain brine rate of production over a long range time span; 3) achieve a rate of brine production for the minimum cost; 4) satisfy a combination of the above requirements.

The objectives listed above are to be achieved while satisfying a number of conditions or constraints.

Constraints. Although some constraints may be characteristic of a specific installation the following can be considered to be the most common.

1. The resulting cavity shape has to conform with specific criteria dictated either by requirements of structural integrity or by the function of the cavity. Often the shape constraint is expressed in terms of a maximum allowable cavity radius in conjunction with a maximum cavity height or thickness of the salt roof, and distance to nearby cavities. For the case of storage cavities the shape constraints have to be satisfied over the projected life of the project after repeated filling and emptying cycles with ballast brine that may cause additional dissolution.
2. The salinity of produced brine has to be within certain values. When the brine is used as chemical feedstock, the salinity should be greater than an allowable minimum. In some instances where storage development is the main concern, brine salinity may have to be limited below a certain concentration in order to allow disposal of the weak brine.
3. Pumping operations have to be restricted below certain maximum power or pressure limits. This will generally be the case when existing facilities are to be used to develop additional cavities. Limitations may also be imposed on the circulating flow rate due to problems caused by excessive pipe vibrations, cavitation or erosion caused by turbulence.
4. In today's climate of increasing energy shortages and costs there is the probability of efficiency constraints expressed as minimum energy use to develop a given storage volume or to produce salt at a given rate.

In most cases the design objectives will be subjected to all of the above constraints each having different importance. The combination of objectives and constraints results in the complete definition of the design problem.

Controllable variables. Having defined the problem, its solution involves choosing from a given set of controllable variables a combination which will achieve or approximate the objective as closely as possible. In salt solution mining operations the controllable variables usually consist of the following:

1. Method of water circulation: tubing or annular injection.
2. Rate of water circulation.
3. Height of salt exposed to dissolution.
4. Depth to the bottom of the cavity (depth of tubing) and distance between tubing and casing shoes.
5. Sizes of tubing, casing and surface flowlines.
6. Distance between pumping station, well and brine delivery point.

In the majority of cases it is not likely to be able to consider all of the above as being independent variables, but as mentioned above their variation will be limited by specific restrictions.

Performance. The performance of the solution mining process is expressed in terms of rate of cavity growth, which also can be expressed as the amount of salt extracted per unit time. In terms of operating parameters this can be calculated from the circulating rate and the salinity of the produced brine. The first three variables above, (1, 2 and 3) are the major controlling factors in determining the saturation of the produced brine. Their interrelation was clearly established in earlier reports[4] and can be summarized in the following generalizations:

1. For a given cavity size the produced brine saturation is inversely related to circulation rate.
2. For a given rate the produced brine saturation increases as cavity volume increases or as height of salt increases.
3. For a given volume of cavity the location of the injection and production points determines the exact relationship between rate and saturation.
4. The combination of circulation rate and position of injection and production points determines the development of a given cavity shape.

The additional variables (4, 5 and 6), in conjunction with circulation rate and brine saturation, determine the pressure required to pump fluid through the system and therefore the amount of energy consumed in the process. In addition these parameters will also control to a large extent the capital investment necessary to establish a new installation.

With such complicated interaction it becomes very difficult to derive simple relations that allow practical description of the performance of cavity dissolution. This makes numerical modelling the most practical method to study alternative development programs to try to optimize the process.

THE NUMERICAL MODEL FOR OPTIMIZATION

The numerical model that has been developed is an extension of the dissolution model for cavity development to include calculation of circulating pressure and power requirements, and the capability of estimating operating and capital costs.

The model consists of three main sections: The dissolution model, the power calculation model, and the economic calculation model. These sections are combined according to the logic depicted in Figure 1. After starting the problem by reading pertinent data and calculating constants to be used for repeated calculations, the dissolution model calculates the density of produced brine, density of brine in the cavity and the amount of dissolution that has taken place over the desired time interval. Density values are then used to calculate hydrostatic and friction pressures in the system which are substituted in the appropriate pressure balance relation to obtain the circulating pressure. Combining flow rate and circulating pressure, the instantaneous power is calculated and converted to cumulative energy through summation over the desired time interval. In the economics calculation, energy is used in the calculation of operating costs while maximum power is used to estimate capital cost of pumping equipment. Other capital costs are estimated from physical parameters of the system such as pipe sizes, depths etc. Calculations are terminated when a specific criterion is satisfied.

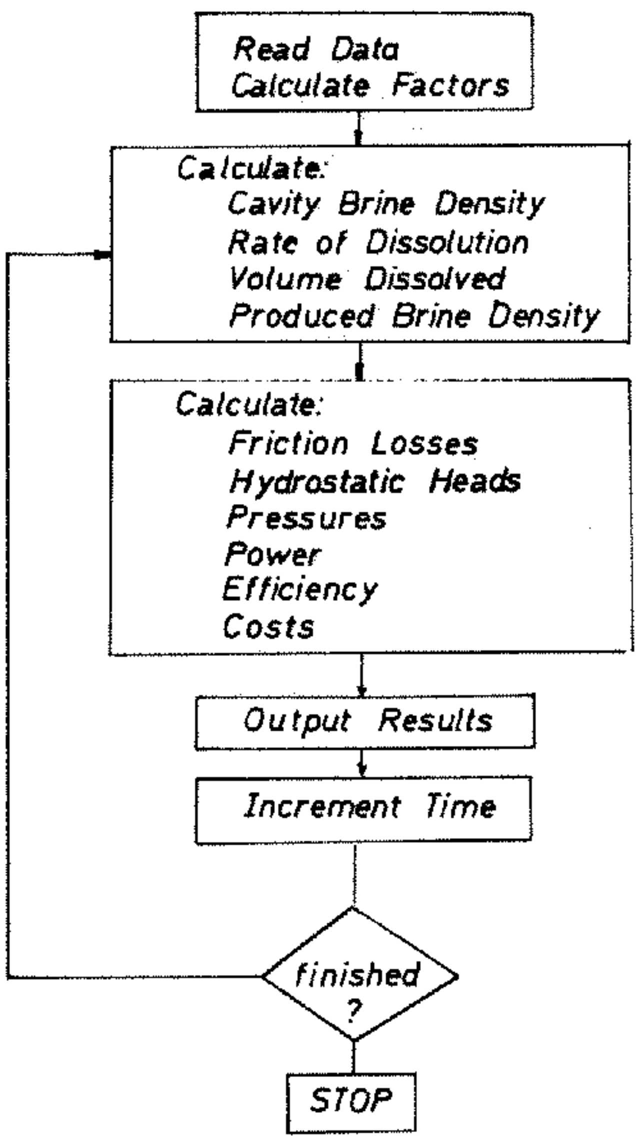

Figure 1. General logic of the program.

Dissolution model. The cavity development model has been described in detail[4, 5]. The version that was utilized for this work includes the capability of simulating salt dome cavity development for the following cases: 1) Direct circulation (tubing injection, annular production). 2) Reverse Circulation (annular injection, tubing production). 3) Protected and unprotected roof and, 4) Isothermal conditions.

The model incorporates effects of fluid velocity, and inclination of salt surface on dissolution. For a given case and circulation rate the model calculates the amount of salt dissolution at various levels in the cavity, the salinity of the brine and the average radius of the cavity at these same levels. Totals of the volume of the cavity, salt produced and salt dissolved are calculated as a function of time and printed at constant intervals (usually 1 day).

Pressure calculation. In order to establish the amount of power required for fluid circulation it is necessary to undertake a calculation of the pressure at the inlet of the system. Figure 2 shows a general schematic of the system that was considered to represent a general case. It consists of surface flowlines for injection of water and production of brine, the tubing, the casing-tubing annulus, and the cavity.

In general the flowrate and the delivery pressure at the brine line outlet will be specified. The inlet pressure to the system (or pump outlet pressure) will have to overcome the frictional losses in the pipes and the hydrostatic head imbalance caused by the difference in density in the vertical sections of the system. Other losses such as kinetic energy changes across restrictions have not been taken into account since they are not believed to be significant.

Frictional losses are calculated based on flow regime (laminar or turbulent) using a Moody friction factor correlation. The equivalent diameter for the annulus is calculated based on field measurements. This is thought to reflect more accurately the effects of excentricity, resulting in more accurate estimates of pressure losses. Since the brine density will vary with time, as the cavity size increases, pumping pressure will be a function of time.

Energy consumption. The pumping pressure in conjunction with the circulation rate are converted to hydraulic

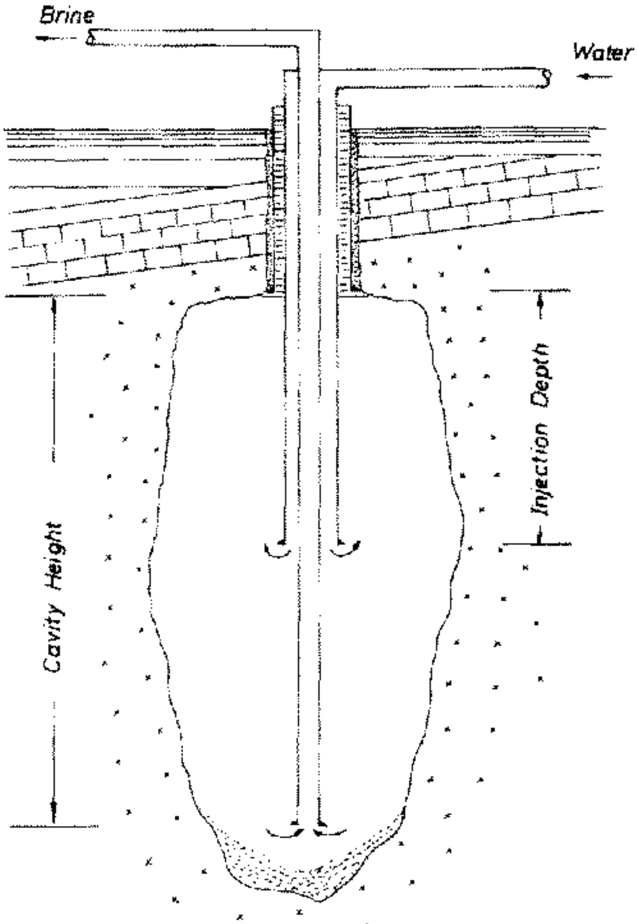

Figure 2. General configuration for solution mining operations.

power which through an efficiency factor is converted to input power to the pump. This power is assumed to remain constant over the time interval specified (usually one day) and is converted to expended energy. From the dissolution model are known the volume of produced salt and cavity growth over the same time interval. These values are converted to efficiency factors expressed as mass or volume of salt removed per unit of energy expended.

Cost calculation. The evaluation of specific cavity development plans has to be undertaken considering various parameters. Primarily the design objectives and constraints, which have been listed earlier, will have to be satisfied by the proposed project. It is not unlikely however to find several alternatives which satisfy these to similar approximations. In such cases it becomes useful to consider additional comparative factors such as cost of operation and investment required by the project. In addition if during the implementation of the project it becomes necessary to modify the plan, it is useful to know how these changes will affect its economics.

The cost model proposed here is designed to be as general as possible allowing the interested user to modify it to suit his specific organization. It further assumes that certain general cost parameters can be established from previous experience in similar operations and expressed as gross quantities without detailed breakdown.

The overall project cost is expressed as:

Project cost = Drilling Cost + Completion Cost
+ Surface System Cost + Operating Cost
− Income from Brine

with the assumption that it may be possible to derive some income from brine sales even during the development stages of the system.

The various elements are defined as follows:

1. *Drilling Cost:* expressed in \$/ft. represents the cost of drilling the well to total depth, including necessary logging, protective casing, cementing etc.
2. *Completion Cost:* includes cost of casing and tubing for circulation strings (\$/ft.), plus cost of wellhead, and rig time for completion.
3. *Surface System Cost:* includes cost of flowlines (\$/ft.) and of the pumping system expressed as \$ per installed HP.
4. *Operating Cost:* this includes fixed expenses either on a time or on a volume pumped basis, the pumping cost and the cost of disposing unusable brine as follows:
   Operating Cost = fixed expenses + pumping cost + disposal cost.
   where:
   fixed expenses: expressed either as \$/day or \$/Bbl.
   pumping cost: expressed as \$/Kw − Hr.
   disposal cost: expressed as \$/Bbl. It should be noted that disposal cost will be zero whenever the brine is sold, which depends on the brine saturation.
5. *Brine Income:* is expressed in terms of \$/Ton of salt. It will be zero whenever brine saturation is below a certain minimum value.

From this discussion it is apparent that some costs are dependent on the physical configuration of the system (depths, distances and diameters) others are time dependent and others are functions of rate of circulation. This makes the overall cost function very complex and difficult to express analytically, pointing again to the usefulness of a numerical model. In order to be able to use costs as a comparison criterion it should be noted that since different configurations will result in different project durations it becomes necessary to introduce a discount factor to obtain a present value of future income. This is applied to the difference between income and operating costs and is defined as discounted net income. Capital investment is defined as the aggregate of drilling, completion and surface system costs.

APPLICATION TO SAMPLE CASE STUDY

In order to illustrate the usefulness of the program as well as to explore some of the interrelations between the variables of interest a sample case study of the development of a storage cavity with a volume of 1,000,000 Barrels was undertaken.

The influence of the following variables was studied: circulation method, rate of circulation, size of circulation pipes and height of salt exposed to dissolution. The main objective was stated as development of the required volume without other restrictions. It is therefore a much broader case than one would normally encounter in practice. Values of specific parameters are listed in Table 1, and were chosen to be representative of average values encountered in salt dome storage development. The assumption was made that it was possible to market the produced brine provided its saturation was above 90%. This may be unrealistic and was included only to show the effect on the overall project cost.

TABLE 1
Case Study Data

Total desired volume: 1,000,000 Bbls
Reverse Circulation:
Rate range: 150–1200 GPM
Pipe position: 20–90% injection
Salt exposed to dissolution: 1000 ft.
Tubing depth: 5000 ft.
Pipe sizes: 10¾" Casing
7" tubing
Direct Circulation:
Range range: 150–1200 GPM
Salt exposed to dissolution 1000 and 2000 ft.
Tubing depth: 5000 ft.
Pipe sizes: 10¾" Casing 7" tubing
9⅝" Casing 7" tubing
9⅝" Casing 5½" tubing
8⅝" Casing 5½" tubing
Costs:
Drilling and Completion: 28.50 $/ft
Power: 0.03 $/Kw·Hr
Brine Disposal: 3.80 $/1000 Bbls
Fixed Costs: 10$/day
Pumping System: 50 $/HP
Brine Sales: Saturation limit 90%
income 1.30 $/TON of salt

REVERSE CIRCULATION

For a given height of salt exposed to dissolution in reverse circulation two variables are the major controlling factors of cavity development[4], the rate of circulation and relative position of injection and production pipes. The interaction of these two variables was studied in detail.

The relative position of the injection point (annulus) and production point (tubing) is expressed in relation to the height of salt exposed to dissolution. Referring to Figure 2, the distance from the cavity roof to the injection point divided by the height of salt and expressed as a percentage, is defined as %-injection. This parameter which most commonly varies between 20% and 90% was used in conjunction with a variation of injection rate between 150 and 1,200 GPM to study the resulting cavity development. Results are presented in Tables 2 through 9.

Time to develop cavity volume. A wide variation was observed in the time required to develop the required volume as a function of injection rate and pipe position. This time ranged from 1230 to 181 days as shown in Figure 3.

The increase of rate of circulation has the most important effect in decreasing development time, especially at the lower rates (150–600 GPM) where doubling the rate approximally reduces time by half. At the higher rates (600–1200 GPM) doubling the rate produces a reduction of

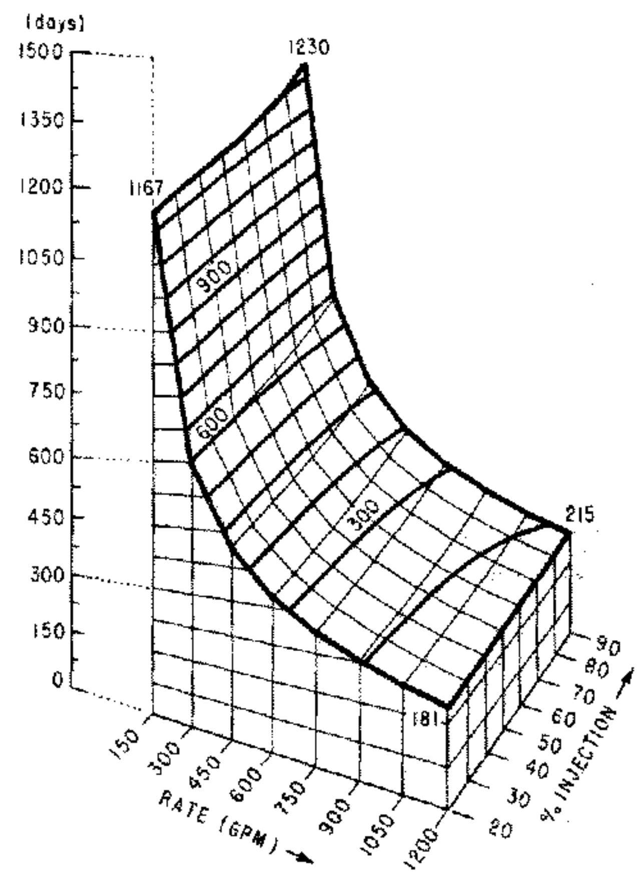

Figure 3. Time to develop 1 MM barrels.

TABLE 2

Reverse Circulation, 20%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4200 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1166	604	416	322	266	228	202	182
Maximum Pressure, Psi	383	406	443	493	557	634	724	827
Maximum Power, H.P.	41	87	142	210	297	405	540	705
Cumulative Energy, MW-Hr	845	919	1026	1172	1360	1588	1872	2201
Efficiency, Tons/KW-Hr	.388	.361	.326	.287	.248	.213	.182	.156
Efficiency, Bbls/KW-Hr	1.183	1.091	.977	.855	.738	.632	.538	.458
Operating Cost, $	37336	34863	37884	43538	51681	61647	74328	89111
Income Less Cost, $	368214	361696	336887	301184	251138	191232	117604	30078
Discounted Net, $	339295	345866	325870	292824	244667	186383	114326	28542
Capital Investment, $	257647	259939	262693	266130	270455	275898	282634	290976

TABLE 3

Reverse Circulation, 30%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4300 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1166	604	416	322	266	229	202	182
Maximum Pressure, Psi	391	414	450	501	566	643	734	838
Maximum Power, H.P.	42	88	144	214	302	411	547	714
Cumulative Energy, MW-Hr	863	936	1043	1189	1389	1622	1893	2225
Efficiency, Tons/KW-Hr	.379	.353	.319	.281	.243	.209	.179	.153
Efficiency, Bbls/KW-Hr	1.159	1.071	.960	.841	.726	.621	.529	.450
Operating Cost, $	37908	35600	38610	44660	53181	63856	76879	92335
Income Less Cost, $	366339	355916	330790	288069	231854	160510	82378	−15579
Discounted Net, $	337498	340171	319863	279872	225648	156131	79718	−14937
Capital Investment, $	259023	261358	264154	267637	272014	277519	284329	292768

TABLE 4

Reverse Circulation, 40%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4400 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1168	606	418	326	268	232	204	184
Maximum Pressure, Psi	399	422	459	509	573	652	743	848
Maximum Power, H.P.	43	90	147	217	306	417	554	723
Cumulative Energy, MW-Hr	882	955	1063	1219	1405	1654	1932	2272
Efficiency, Tons/KW-Hr	.371	.346	.312	.275	.238	.205	.175	.149
Efficiency, Bbls/KW-Hr	1.136	1.049	.942	.826	.712	.609	.519	.442
Operating Cost, $	38569	36509	39830	46403	55174	66941	80794	97214
Income Less Cost, $	364260	349858	320378	277178	212210	136910	37061	−71520
Discounted Net, $	335411	334111	309492	269972	206232	132837	35261	−70904
Capital Investment, $	260398	262775	265612	269139	273565	279130	286009	294539

TABLE 5

Reverse Circulation, 50%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4500 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1170	608	422	328	272	234	208	186
Maximum Pressure, Psi	408	430	467	517	582	661	759	859
Maximum Power, H.P.	44	92	149	221	310	422	561	731
Cumulative Energy, MW-Hr	900	973	1087	1240	1439	1683	1988	2316
Efficiency, Tons/KW-Hr	.363	.339	.306	.270	.233	.200	.171	.146
Efficiency, Bbls/KW-Hr	1.112	1.029	.923	.810	.699	.597	.508	.432
Operating Cost, $	39247	37448	41406	48449	58026	70178	85785	100425
Income Less Cost, $	361225	341997	307309	252600	185277	97619	−13572	−100425
Discounted Net, $	332383	326280	296429	247019	179626	94262	−14269	−99098
Capital Investment, $	261773	264190	267634	270634	275147	280727	287671	296288

TABLE 6

Reverse Circulation, 60%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4600 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1176	614	426	332	276	238	210	190
Maximum Pressure, Psi	416	438	474	525	589	668	761	868
Maximum Power, H.P.	44	93	152	224	314	427	567	739
Cumulative Energy, MW-Hr	920	994	1108	1264	1470	1722	2018	2380
Efficiency, Tons/KW-Hr	.356	.332	.299	.263	.228	.195	.167	.142
Efficiency, Bbls/KW-Hr	1.089	1.008	.905	.793	.684	.584	.496	.421
Operating Cost, $	40054	38862	43349	51255	61719	75142	91358	103015
Income Less Cost	358189	330417	285252	218946	140997	37459	−91358	−103015
Discounted Net, $	329207	314622	274542	211456	136106	35406	−89996	−101622
Capital Investment, $	263146	265599	268517	272136	276670	282294	289295	297991

TABLE 7

Reverse Circulation, 70%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4700 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1184	622	434	338	282	244	216	196
Maximum Pressure, Psi	423	444	480	530	595	675	768	875
Maximum Power, H.P.	45	95	154	226	317	431	572	745
Cumulative Energy, MW-Hr	939	1015	1134	1291	1505	1769	2080	2463
Efficiency, Tons/KW-Hr	.348	.325	.293	.257	.222	.190	.162	.138
Efficiency, Bbls/KW-Hr	1.066	.987	.886	.775	.667	.569	.483	.409
Operating Cost, $	41012	40824	45973	55234	67713	82937	94110	106479
Income Less Cost, $	352149	309414	257742	168091	62126	−63659	−94110	−106479
Discounted Net, $	323018	293656	247242	161504	59060	−62875	−92665	−104993
Capital Investment, $	264516	266994	269940	273580	278145	283886	290975	299623

TABLE 8

Reverse Circulation, 80%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4800 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1200	634	444	350	292	252	224	204
Maximum Pressure, Psi	430	449	483	533	598	678	771	880
Maximum Power, H.P.	46	96	155	228	319	433	575	749
Cumulative Energy, MW-Hr	959	1036	1162	1331	1552	1819	2150	2558
Efficiency, Tons/KW-Hr	.341	.318	.286	.251	.216	.184	.156	.133
Efficiency, Bbls/KW-Hr	1.044	.966	.865	.756	.649	.551	.466	.395
Operating Cost, $	42378	43913	51099	62354	77027	86634	97386	110675
Income Less Cost, $	342202	270260	186061	77899	−60970	−86634	−97386	−110675
Discounted Net, $	312729	256062	176975	73630	−62766	−85084	−95833	−109065
Capital Investment, $	265880	268375	271313	274970	279534	285284	292420	301087

TABLE 9

Reverse Circulation, 90%.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4900 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1230	658	464	366	306	266	238	214
Maximum Pressure, Psi	432	449	482	531	597	676	770	879
Maximum Power, H.P.	46	96	154	227	318	431	573	747
Cumulative Energy, MW-Hr	980	1062	1189	1368	1601	1894	2260	2658
Efficiency, Tons/KW-Hr	.334	.310	.278	.243	.208	.177	.150	.126
Efficiency, Bbls/KW-Hr	1.021	.943	.842	.733	.626	.530	.447	.377
Operating Cost, $	45059	49775	60722	73325	80974	90671	102729	115325
Income Less Cost, $	312498	192855	51936	−73325	−80974	−90671	−102729	−115325
Discounted Net, $	282782	179336	47557	−71435	−79218	−88956	−100987	−113563
Capital Investment, $	267215	269715	272629	276284	280847	286502	293596	302523

time of only 25% and the trend indicates that even less benefit is achieved at even higher rates. The effect of pipe position is to increase development time as the injection point is placed lower into the cavity. Constant time contours show that a given development time can be achieved over a range of rates by selecting a specific pipe position.

Cavity shape. The resulting cavity shape at the specified final volume of 1 MM barrels will vary according to the development rate and pipe position. These are shown in Figure 4. For a given pipe position the cavity diameters as a function of height tend to be more uniform as the circulation rate increases. However, all cavities are characterized by a significant enlargement at the point of injection.

Proper evaluation of the desirability of a given cavity shape has to be established in relation with the intended future use of the cavity as well as stability considerations. Although large shape variations are observed especially as a function of pipe position, it is possible to define regions in which the resulting cavity shape is similar over a range of operating conditions.

Energy requirements. These are represented by the pump delivery pressure and the horsepower required, as shown in Figures 5 and 6. The exponential increase in pressure with increasing rate is characteristic of turbulent flow. In addition there can be noted an increase in pressure head caused by deepening of the injection point (about 50 psi from 20% to 90% injection). Pressure and flow rate are combined in the determination of the maximum power required, which as shown in Figure 6 varies over a significant range. (Approximately a 16 fold increase in power for an 8 fold increase in rate.) Recalling that pressure will vary with time as brine saturation increases, it should be noted that these are the maximum values for the specific plan of cavity development. Instantaneous values of power are summed over the total time required for development and are presented in Figure 7 as the total energy expended. The possible tradeoff between time of development and energy consumption becomes apparent by comparing Figures 3 and 7, and noting that the decrease in development time by increasing circulation rate is accompanied by significant increase of energy utilization. It is possible to express the efficiency of the process by relating the expenditure of energy with the volume dissolved and the amount of salt produced. These quantities are shown in Figures 8 and 9, which indicate that efficiency improves with decreasing circulating rates and decreasing %-injection. This agrees with the concept that the maximum efficiency will be achieved for the circulation rate for which a unit volume of injected water will "re-

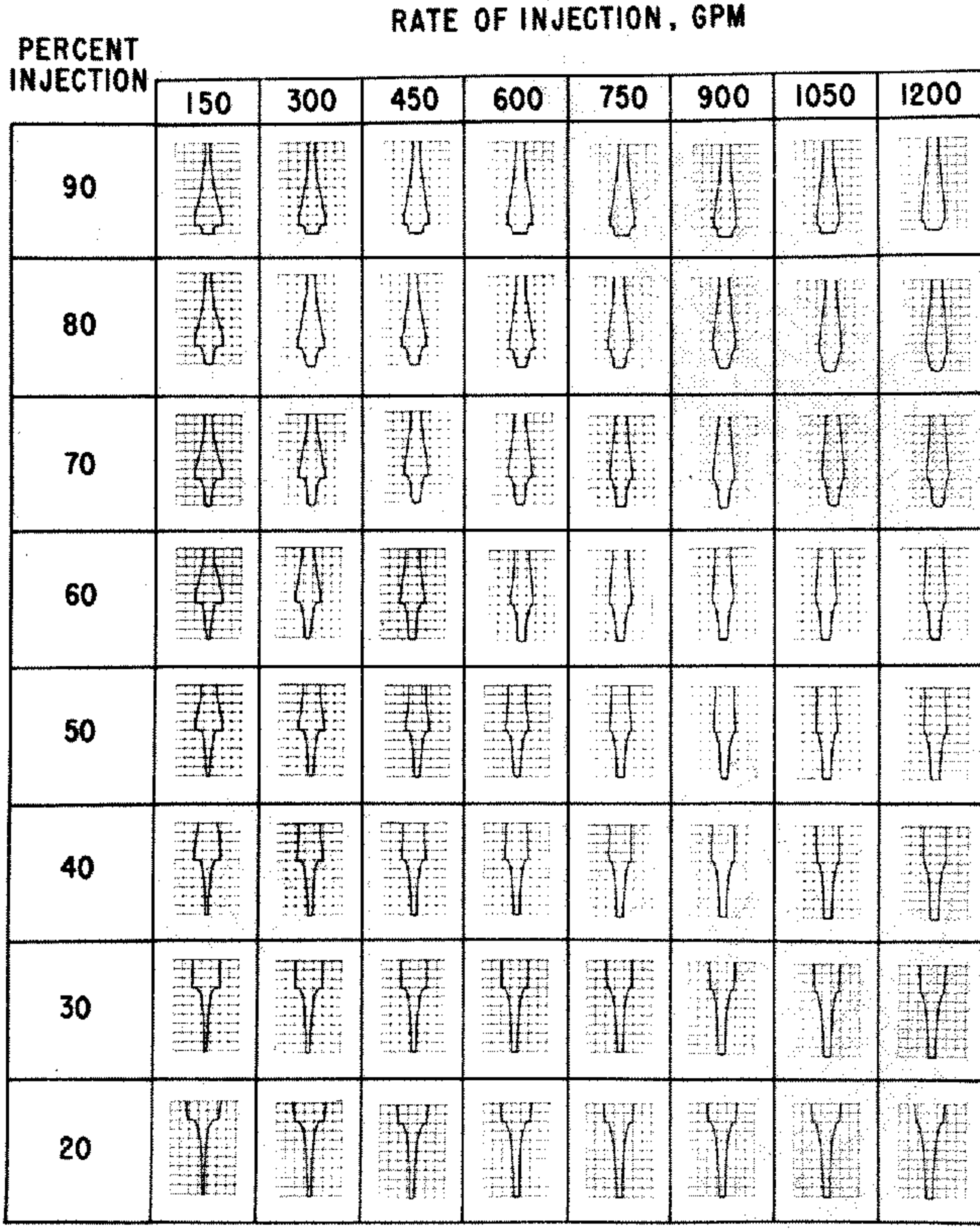

Figure 4. Resulting cavity shape at completion for 1 MM barrels. Vertical unit equals 100 feet, horizontal unit equals 25 feet.

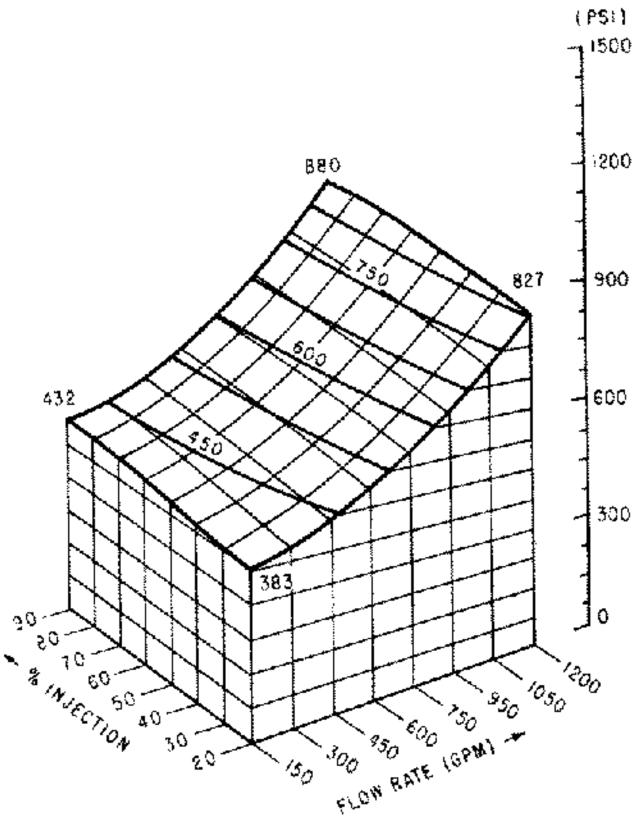

Figure 5. Maximum pump pressure in psi.

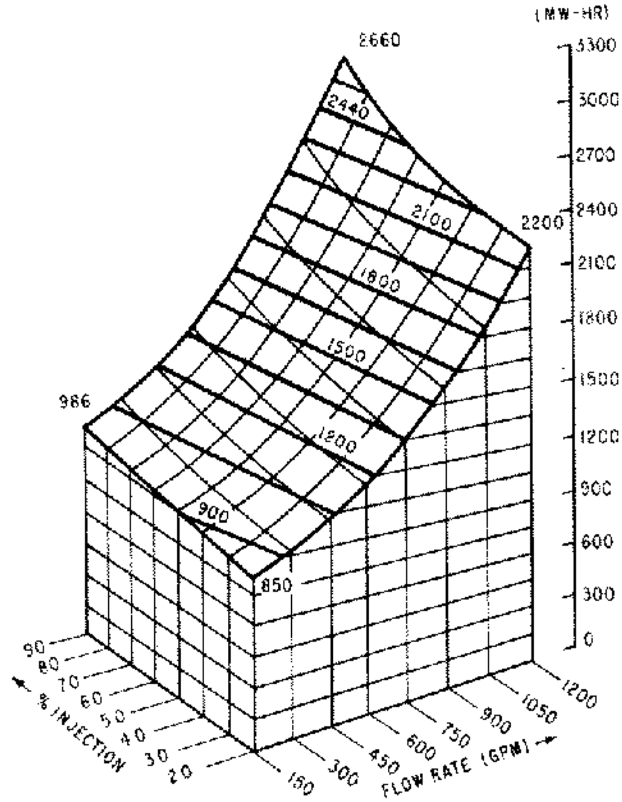

Figure 7. Total energy consumption, MW/hr.

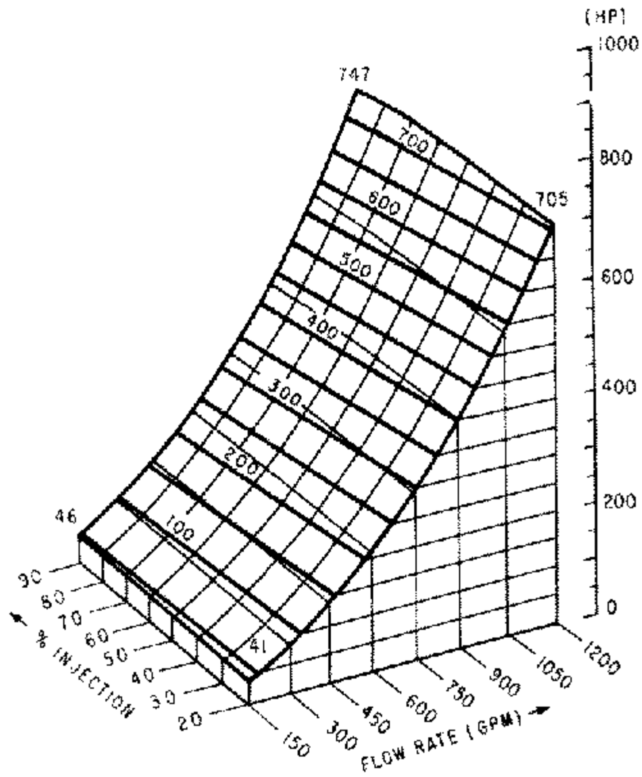

Figure 6. Maximum pump power in horsepower.

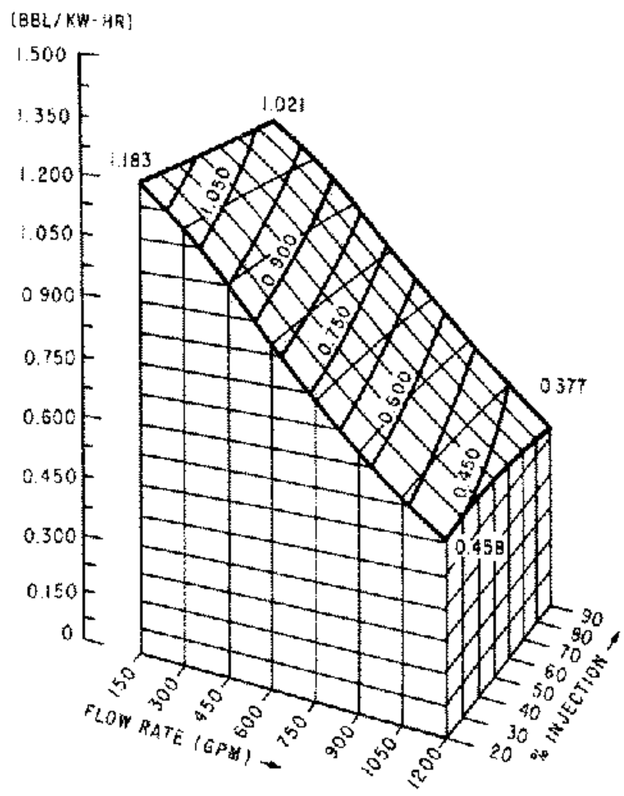

Figure 8. Volume per unit energy, bbl/kW-hr.

main" in the cavity exactly the length of time required to become saturated. At lower rates it will saturate prematurely and will not produce additional dissolution and at higher rates it will not have sufficient time to become fully saturated. In either of these cases energy will be expended to circulate the fluid without contribution to the dissolution process. Operation at the "optimum" rate is generally precluded by other constraints, however, Figures 8 and 9 show that a certain efficiency can be insured by proper adjustment of rate and pipe position.

Brine saturation. Produced brine saturation will vary during the development period. This is illustrated by Figure 10 where is plotted the time elapsed from initiation of development until brine saturation reaches 80%. (This value was chosen because for some of the cases considered a higher saturation was not reached before developing the 1 MM barrels volume).

It can be observed that both rate of circulation and pipe position have a marked effect on the speed of brine saturation buildup. The effect of rate of circulation on saturation was investigated further as a function of cavity growth for the specific case of 20% injection. Results are presented in Table 10 and Figure 11. These show that as the cavity size grows it is possible to increase rate of circulation without a decrease in brine saturation following a rate schedule along the constant saturation contour.

Economics. The foregoing discussion has taken into consideration the major physical aspects of the problem. When these are combined with cost figures then the corresponding economic desirability of the various alternatives become apparent.

Operating costs are shown in Figure 12 as a function of circulation rate and pipe position. As rate increases above 300 GPM the cost increases because of the increase in energy expenditure. For circulating rates below 300 GPM there also is an increase in operating cost. This increase is due to the increase in development time at these slow rate which combined with the fixed expenses ($/day) cause an increase in the total operating cost. The rate corresponding to the minimum cost (in this case approximately 300 GPM) will vary depending on the relative magnitude of fixed and power costs. The important point is that the operating cost function generally will exhibit a minimum within the operating conditions of interest.

Assuming that it is feasible to sell the produced brine during the development period, if its saturation is sufficiently high (in this case greater than 90%) and there is a market for it, then this income can be subtracted from the

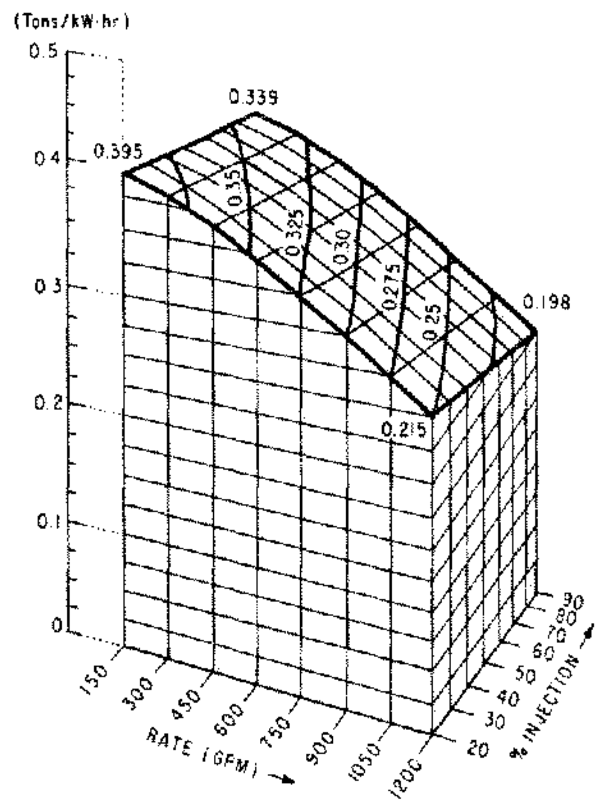

Figure 9. Tons of salt per Kw-hr.

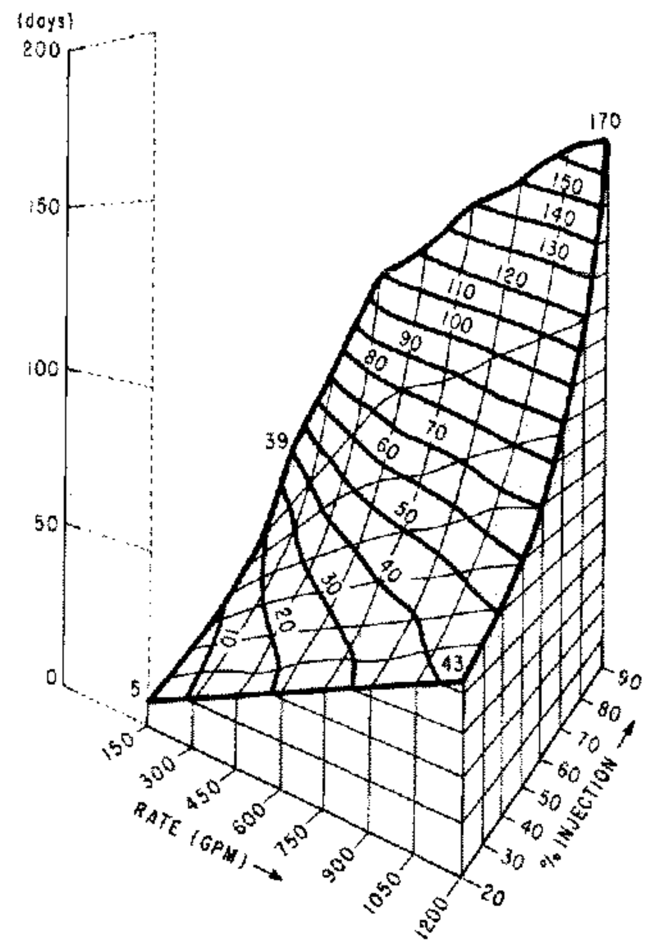

Figure 10. Time to reach 80% saturation.

TABLE 10

Saturation of Produced Brine as a Function of Rate and Cavity Volume. Circulation Method: Reverse 90%; Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4900 Ft.

Rate of Circulation, GPM→	150	300	450	600	750	900	1050	1200
Cavity Volume, Bbls								
50,000	85.3	75.8	68.7	62.8	58.3	54.3	51.0	48.1
100,000	89.9	81.0	74.7	69.5	65.5	61.7	58.5	55.6
200,000	91.9	85.4	80.1	75.6	72.0	71.3	68.3	65.6
300,000	93.3	87.6	83.1	81.0	77.6	74.6	72.4	70.0
400,000	94.2	89.2	86.2	83.0	80.1	77.6	75.3	73.9
500,000	94.8	91.1	87.6	84.5	82.0	80.1	78.0	76.0
600,000	95.8	91.9	88.6	86.2	83.8	81.5	79.5	77.6
700,000	96.2	92.4	89.8	87.2	84.8	82.6	80.7	79.3
800,000	96.5	93.3	90.5	87.9	85.7	83.6	82.2	80.3
900,000	96.7	93.8	91.0	88.6	86.7	84.8	83.0	81.2
1,000,000	96.9	94.0	91.5	89.3	87.4	85.4	83.6	82.0

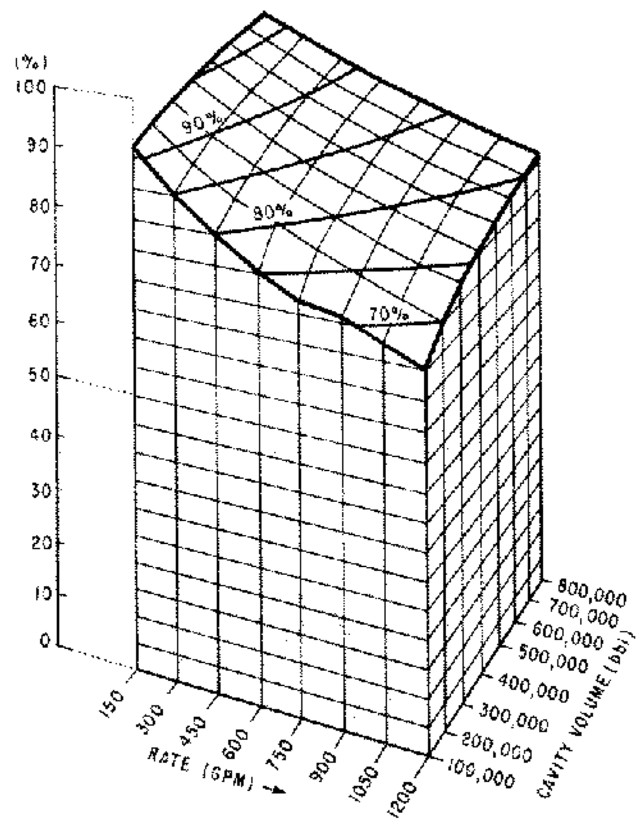

Figure 11. Saturation vs rate-volume.

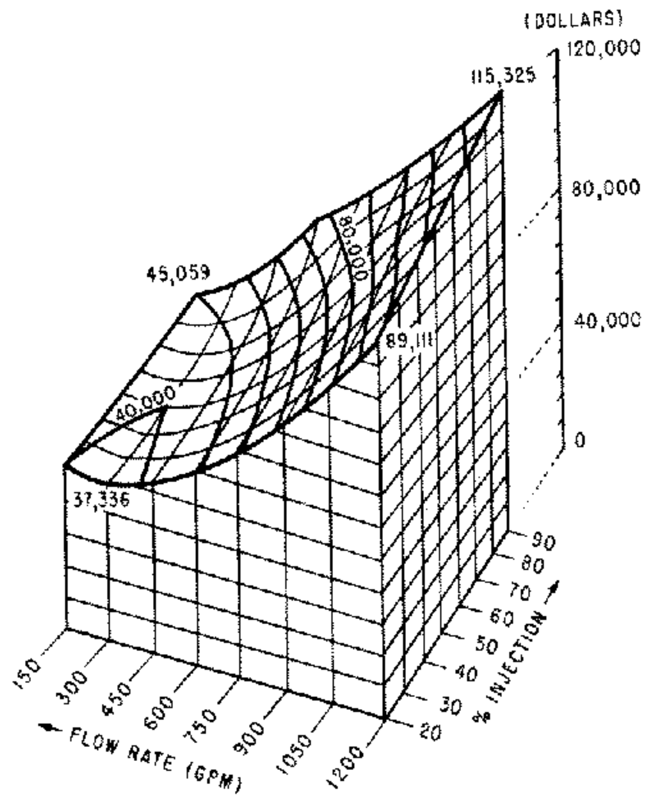

Figure 12. Operating cost in dollars.

operating cost. This allows us to consider the net cost of the development project. The result is shown in Figure 13, in which for reasons of visibility the axes have been rotated 180 degrees. This figure indicates the great variation of this parameter in function of the operating conditions. The region of negative values, shown as dotted lines, represents conditions where the required saturation is not achieved at all or only during the last stages of development. This region covers the range of high circulation rates and again shows the possibility of tradeoffs that might be considered in the planning stages.

DIRECT CIRCULATION

In this method the major independent variables are the rate of circulation, the height of salt exposed to dissolution and the pipe sizes.

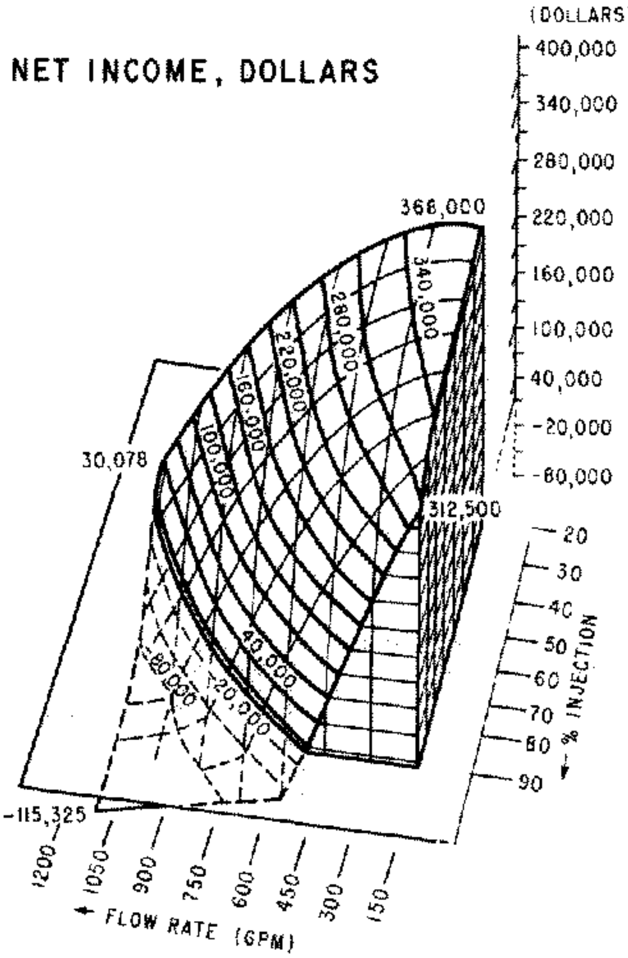

Figure 13. Net income in dollars.

Rate effects. For a given height of salt exposed to dissolution (in this case 1000 ft.) Figure 14 shows the effect of flow rate on the cavity cross section. The diameter of the cavity becomes more uniform as circulation rate is increased. For comparison purposes the corresponding reverse circulation (90% injection) cavity shapes are presented, showing that except for the bottom section of the cavity a very similar configuration can be obtained by either method of circulation.

Figure 15 presents information regarding development time and development cost. This figure shows that time of development decreases with increasing rate and that the direct circulation method is slightly faster than the reverse method. Development cost shows a minimum at approximately 300 GPM as well as an inflection point at 600 GPM. The first represents the effect of daily costs gaining in importance as time of development increases, while the second is caused by the cost of weak brine disposal. There is no disposal cost below 600 GPM since saturated brine is produced and is sold. Figure 15 also shows the effect of salt height. At all rates for the 200 ft. cavity the time of development and operating costs are below those for the shorter salt cavity.

Effect of pipe size. A reduction in pipe sizes will generally be accompanied by significant savings in pipe cost, and probably also in drilling and completion expenses since smaller wellbore, wellheads, valves etc. can be used. On the other hand this will have to be balanced against higher circulating pressure and power requirements which will cause increases in the pumping system initial, maintenance and operating costs.

To illustrate this effect the pressure and power requirements for four combinations of casing and tubing sizes are presented in figures 16 and 17. These show that at low flow rates (less than 600 GPM) the differences may not be significant and that the smaller pipe combinations might be considered as appropriate alternatives. This is not true at the higher flow rates.

Project economics. Assuming once more that produced brine can be marketed, the effect of the variables discussed above on the discounted net income was calculated and is presented in Figure 18. For the 1000 ft. salt height, the inflection point at 600 GPM represents the rate above which produced brine saturation drops below the minimum required for selling the brine. The dotted lines extrapolated

TABLE 11

Direct Circulation, 1,000 Feet of Salt.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 10¾"; Casing Depth: 4000 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1180	622	434	340	284	246	218	198
Maximum Pressure, Psi	442	452	480	522	577	648	732	829
Maximum Power, H.P.	47	97	153	222	307	414	549	705
Cumulative Energy, MW-Hr	985	1055	1161	1312	1513	1760	2052	2412
Efficiency, Tons/KW-Hr	.331	.312	.285	.253	.221	.191	.164	.140
Efficiency, Bbls/KW-Hr	1.015	.949	.861	.763	.664	.571	.489	.417
Operating Cost, $	41904	40145	47273	69346	75973	84092	93561	105298
Income Less Cost, $	357732	337192	240149	−69346	−75973	−84092	−93561	−105298
Discounted Net, $	328999	321398	230194	−67708	−74467	−82642	−92127	−103829
Capital Investment, $	255305	257773	260618	264081	268330	273682	280272	288230

TABLE 12

Direct Circulation, 2,000 Feet of Salt.
Tubing Size: 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 2000 Ft.; Casing Size: 10¾"; Casing Depth: 3000 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days	1162	598	410	316	258	220	194	174
Maximum Pressure, Psi	445	461	489	529	580	642	716	801
Maximum Power, H.P.	48	98	157	226	309	411	534	683
Cumulative Energy, MW-Hr	975	1028	1112	1231	1375	1560	1790	2052
Efficiency, Tons/KW-Hr	.334	.320	.297	.270	.242	.214	.188	.165
Efficiency, Bbls/KW-Hr	1.026	.975	.902	.816	.729	.643	.564	.492
Operating Cost, $	41073	37823	39937	44463	50864	59021	69536	84897
Income Less Cost, $	363299	356689	335142	304363	257671	204863	139669	7676
Discounted Net, $	335019	341387	324530	296290	251453	200094	136248	6671
Capital Investment, $	232842	235383	238292	241761	245942	251028	257207	264633

TABLE 13

Effect of Pipe and Tubing Sizes (9⅝" pipe, 5½"; Tubing. Circulation Method: Direct;
Tubing Size: 5½"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution 1000 Ft.; Casing Size: 9⅝"; Casing Depth: 4000 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days		622		340		246		198
Maximum Pressure, Psi		482		630		880		1232
Maximum Power, H.P.		103		268		562		1047
Cumulative Energy, MW-Hr		1125		1590		2410		3620
Efficiency, Tons/KW-Hr		.293		.209		.139		.093
Efficiency, Bbls/KW-Hr		.891		.629		.417		.278
Operating Cost, $		42242		77696		104437		141453
Income Less Cost, $		335094		−77696		−104437		−141453
Discounted Net, $		319389		−75862		−102625		−139484
Capital Investment, $		230218		238505		253222		277469

TABLE 14

Effect of Pipe and Tubing Sizes, (9⅝" Pipe, 7" Tubing. Circulation Method: Direct;
Tubing Size; 7"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 9⅝"; Casing Depth: 4000 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days		622		340		246		198
Maximum Pressure, Psi		532		816		1284		1935
Maximum Power, H.P.		114		348		819		1644
Cumulative Energy, MW-Hr		1244		2070		3505		5710
Efficiency, Tons/KW-Hr		.265		.160		.095		.060
Efficiency, Bbls/KW-Hr		.806		.483		.284		.176
Operating Cost, $		45805		92084		137334		204182
Income Less Cost, $		331531		−92084		−137334		−204182
Discounted Net, $		315976		−89912		−134973		−201344
Capital Investment, $		249323		261044		284702		325914

TABLE 15

Effect of Pipe and Tubing Sizes, (8⅝" Pipe, 5½" Tubing). Circulation Method: Direct;
Tubing Size: 5½"; Tubing Depth: 5000 Ft.; Salt Exposed to Dissolution: 1000 Ft.; Casing Size: 8⅝"; Casing Depth: 4000 Ft.

Rate of Circulation, GPM	150	300	450	600	750	900	1050	1200
Development Time, days		622		340		246		198
Maximum Pressure, Psi		515		752		1145		1690
Maximum Power, H.P.		110		320		730		1437
Cumulative Energy, MW-Hr		1200		1910		3150		4980
Efficiency, Tons/KW-Hr		.274		.174		.107		.068
Efficiency, Bbls/KW-Hr		.832		.525		.319		.202
Operating Cost, $		44615		87176		125711		182478
Income Less Cost, $		332722		−87176		−125711		−182478
Discounted Net, $		317116		−85120		−123549		−179942
Capital Investment, $		219646		230189		250740		286030

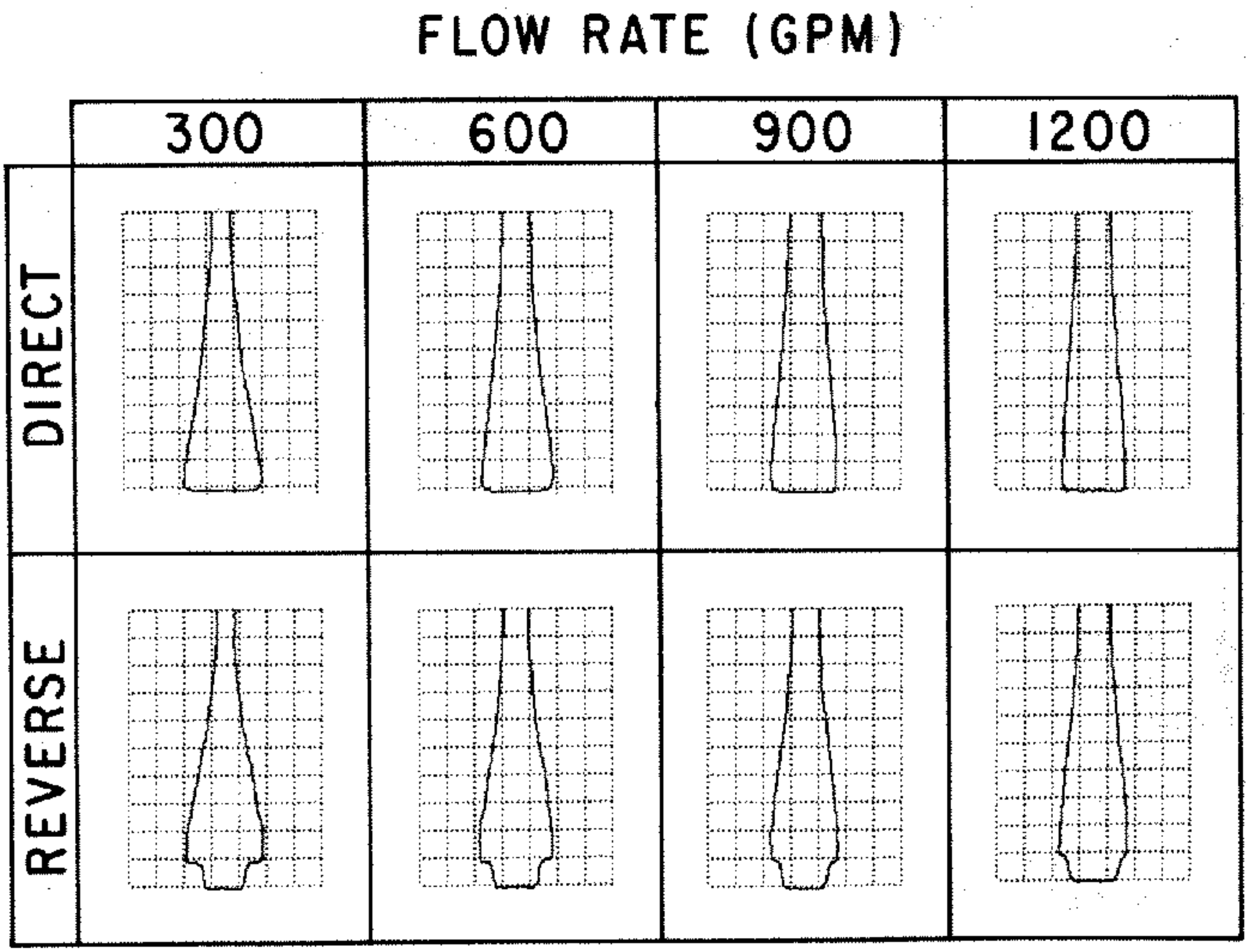

Figure 14. Resulting cavity shape for 1 MM barrels.

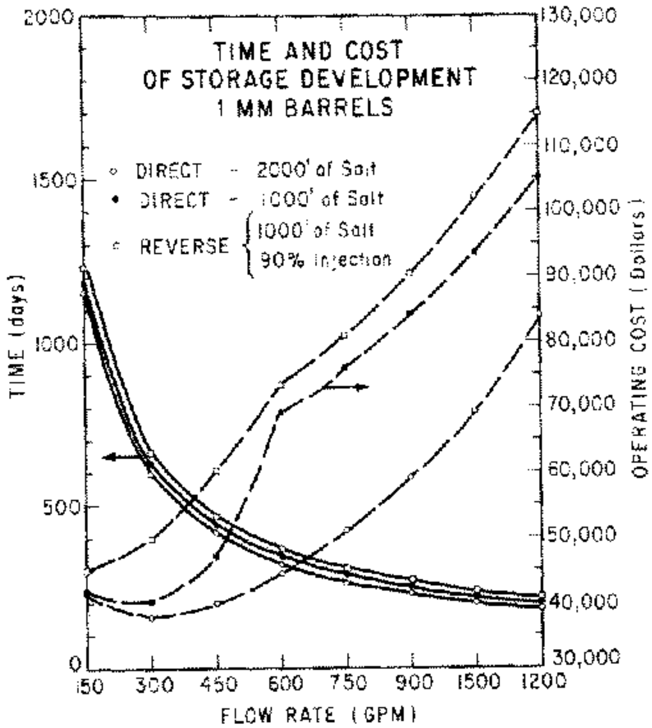

Figure 15. Time and cost of storage development, 1 MM barrels.

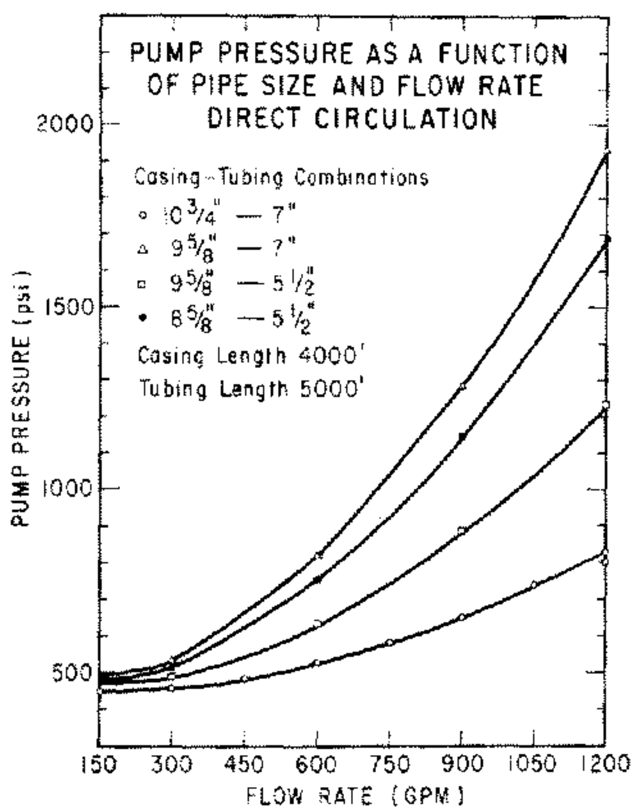

Figure 16. Pump pressure as a function of pipe size and flow rate, direct circulation.

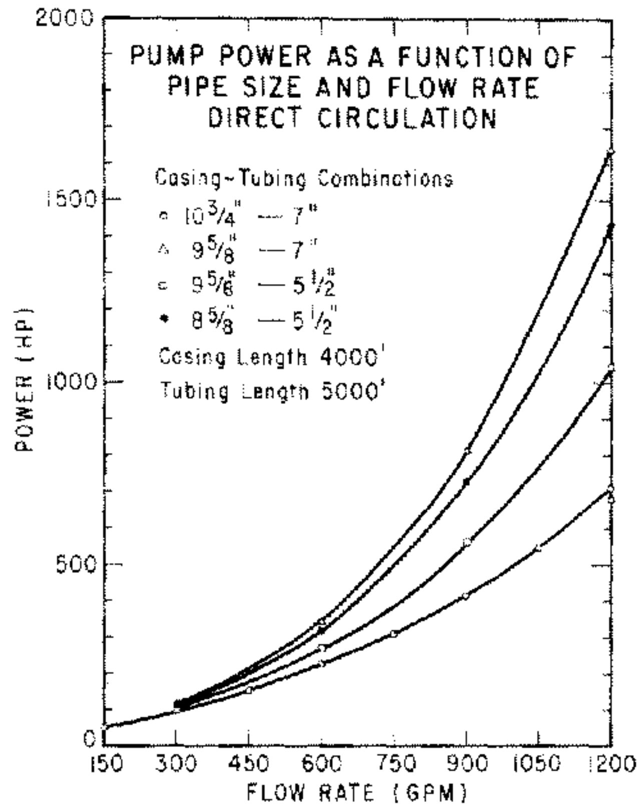

Figure 17. Pump power as a function of pipe size and flow rate, direct circulation.

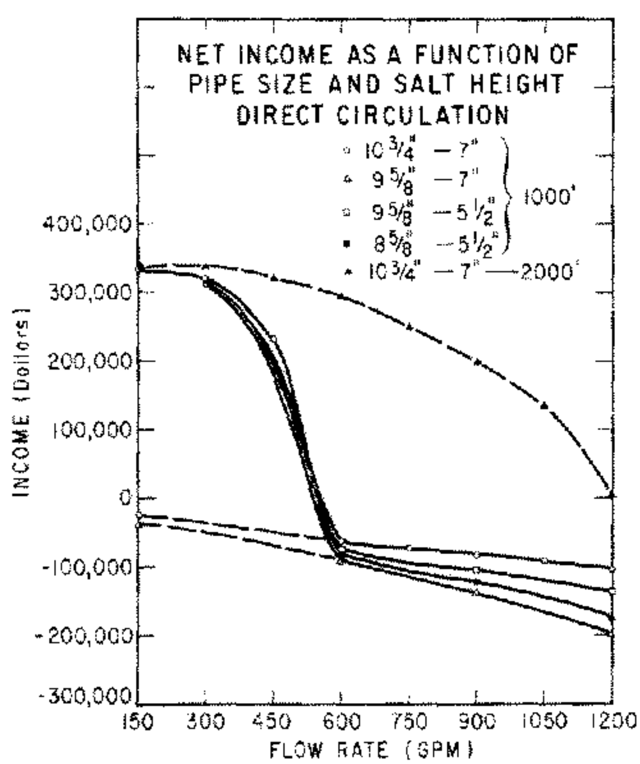

Figure 18. Net income as a function of pipe size and salt height.

to the left show the trend of decreasing costs as flow rate is reduced. For the 2000 ft. salt height the curves indicates that for all flow rates it was possible to produce brine that satisfied the sales requirements. Note that in both cases the curves exhibit a maximum.

CONCLUSIONS

The numerical model of cavity development in salt domes has been successfully combined with calculation of pressure and power required by the operation. In addition the new model undertakes cost calculations which can be used to determine the economic desirability of various operating alternatives. The model has been applied to analyze a sample case study of development of 1 MM barrels of storage. From this study the following general conclusions may be drawn.

A-Operating parameters—For annular injection, *increasing* circulating rate produces an *increase* in pump pressure, power, operating cost and time to achieve a given brine saturation, while it produces a *decrease* in efficiency and time to achieve the desired volume. *Decreasing* depth of injection produces a *decrease* in pump pressure, power, operating cost, time to achieve a given brine saturation and time to develop the desired volume. It produces an *increase* in efficiency.

For Tubing Injection—An increase in flow rate produces the same effects as in annular injection. An increase in height of salt exposed to dissolution produces a decrease in time of development, operating cost, and an increase in efficiency.

B-Cavity Shape—By proper combination of operating parameters and pipe positioning it is possible to have significant flexibility in obtaining a cavity cross section that will satisfy most requirements.

C-Brine Saturation—As the cavity size grows it is possible to maintain a given brine saturation by adjusting the rate of circulation to the appropriate level.

D-Economics—The operating cost function generally exhibits a minimum which is a function of rate of circulation, pipe position, pipe sizes, fixed costs and power costs. The cost function is very sensitive to these parameters, so that even if it may not be possible to operate at the minimum point it is useful to have a knowledge of how costs will be affected by changes in the development plan.

ACKNOWLEDGEMENTS

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