PREPARED TESTIMONY BY H. J. GRUY AND ASSOCIATES, INC.

MATTER OF KERR-MCGEE CORPORATION

AMMENDMENT TO SOURCE MATERIAL

LICENSE SUB-1010, ATOMIC ENERGY COMMISSION

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INTRODUCTION

The simulation of a reservoir and its performance refers to the construction and operation of a model whose behavior is equivalent to that of an actual reservoir. The model may be physical, such as a laboratory sand-pack, or mathematical, depending on a set of equations to describe the physical processes occurring in a reservoir under a set of assumptions.

Although most of the development in mathematical modeling has come from the petroleum industry, the same concepts and basic equations are applied to hydrologic studies for predicting aquifer performance. The equations are well known to the reservoir engineer and have been used to describe the movement of fluids through porous media for many years. The simulation of an aquifer, with water as the only mobile phase, is greatly simplified from the complex procedures required in hydrocarbon reservoirs to predict the simultaneous flow of three phases. This is especially true because the phase, viscosity and compressibility functions for a hydrocarbon system are much more pressure sensitive than is water.

The following discussion on simulation is presented to illustrate the evolution from basic tank models to the modern multi-cell, multi-dimensional reservoir simulator such as the one used to perform the calculations in our study of the Kerr-McGee Sequoyah No. 1, Waste Storage well. The following concepts are limited to the single-phase of

water in order to simplify the presentation.

DISCUSSION

The Single-Cell Model

Before the development of the modern digital computer, reservoir models were relatively simple. Practical data and computation limitations forced the reservoir engineer to represent aquifers or hydrocarbon reservoirs using average values for the rock properties, porosity and permeability. Estimates of average reservoir pressure were also used to determine fluid viscosities and compressibilities. Models based on average properties, are frequently termed tank models or single-cell models (see Exhibit G-1-A). Such a reservoir model is zero dimensional because from point to point all rock, fluid and pressure values are the same. This tank model is the basic building block for reservoir simulators and a material balance is normally used to describe its performance. A simple expression for a water material balance equation is the following:

The cumulative net withdrawal of water =

(the original water in-place) - (the amount of water remaining)

If we consider a reservoir where the two halves of the reservoir vary in lithology (character of a rock formation), a better approximation of performance can be achieved by representing each half of the reservoir with its respective average properties. Thus, the reservoir consists of two tank units or cells. The material balance may be used to describe the fluid behavior in each cell; however, the net withdrawal term from each cell becomes more complicated because there can be migration of

fluid from one cell to the other depending upon the pressure values between the two cells. The fluid transfer between the two cells can be calculated by Darcy's law. This model is no longer zero dimensional because reservoir parameters may vary between the two cells. It is now a one-dimensional model because it consists of more than one cell in one direction and only one cell in the other two directions (see Exhibit G-1-B). Thus, representation of reservoirs can be extended in two or three spatial dimensions by merely grouping the number of cells required to represent the reservoir. (G-1-C, D)

Regardless of the number of dimensions or cells used, the material balance is the basic equation describing the fluid behavior within a cell and Darcy's law describes the fluid flow between the cells. Because a simulator can consist of hundreds of cells, the calculation becomes a formidable bookkeeping operation, which is ideally suited to digital computation. The principles in the equations used in reservoir simulation are not new. The only advantage offered by numerical simulation is that by dividing the reservoir into many cells to represent heterogeneity, changing lithology, and pressure distribution we may more accurately predict the reservoir performance by area or by vertical layer.

Mathematical Considerations

The basic equations required for the engineer to understand reservoir simulation are, the material balance and Darcy's law. Darby's law is:

$$\frac{q_w}{A} = \frac{k}{\mu_w} \frac{(\Phi_o - \Phi_i)}{L}$$

where:

q_w = Volumetric flow rate

A = Cross-sectional area

k = Permeability

μ_w = Water viscosity

L = Length of flow

Φ_o = Flow potential at out-face = $p_o + g\rho_w h_o$

Φ_i = Flow potential at in-face = $p_i + g\rho_w h_i$

p_o = Pressure at out-face

p_i = Pressure at in-face

g = Gravity acceleration

ρ_w = Density of water

h_o = Height of out-face

h_i = Height of in-face

Note: $(\Phi_o - \Phi_i)$ is equal to pressure drop $(p_o - p_i)$ if flow system is horizontal

Specific applications sometimes require concepts developed by Fourier (heat conduction) or Fick (diffusion or dispersion). Models considering the vertical dimension usually contain functions representing the gravity and capillary effects. The special application functions for heat conduction and the functions required for multi-phase flow, such as relative permeability were not considered in the model applied to the study and are omitted from this discussion. The equations of state usually incorporated into numeric simulators to account for hydrocarbon phase distribution are not required for water models and have also been omitted.

The material balance is a reservoir engineering means for expressing the law of conservation of mass. It is sometimes referred to as the continuity equation. For the sake of simplicity, consider a cell in a one-dimensional reservoir simulator as shown in Exhibit G-1-A. The water volume entering the cell during a time increment Δt, expressed in reservoir units, minus the water volume leaving the cell during the same time increment equals the change in water volume within the cell.

If we let q_{in} equal the rate of flow of water into the cell from adjacent cells, then the volume of water entering the cell during Δt time will equal $q_{in}\Delta t$. The volume of water leaving the cell to neighboring cells during the same time period will equal $q_{out}\Delta t$. If water is withdrawn from the cell from a water well and we represent this withdrawal rate by q_w, then the total volume of water leaving the cell during Δt equals $(q_{out} + q_w)\Delta t$. The change in volume of water in the cell during Δt expressed in surface units equals:

$$\Delta x \Delta y \Delta z \left[\left(\frac{\phi S_w}{B_w} \right)^{n+1} - \left(\frac{\phi S_w}{B_w} \right)^{n} \right]$$

where:

ϕ = Porosity of rock

S_w = Water saturation, fraction of pore volume occupied by water, 1.0 in this problem.

B_w = Water formation volume factor, reservoir volume per surface volume accounting for water compressibility.

n = Beginning of time step.

$n + 1$ = End of time step

therefore: $\frac{\Delta x \Delta y \Delta z \phi S_w}{B_w}$ represents the volume of water in the cell at any time.

Substitution in the material balance equation and dividing by Δt results in the equation:

$$q_{in} - q_{out} - q_w = \frac{\Delta x \Delta y \Delta z}{\Delta t} \left[\left(\frac{\phi S_w}{B_w} \right)^{n+1} - \left(\frac{\phi S_w}{B_w} \right)^{n} \right]$$

...(1)

However, by Darcy's law, assuming the direction of flow to be from left to right as shown in the exhibit.

$$q_{in} = \frac{\Delta x \Delta z k}{\mu_w B_w} \left(\frac{\Phi_{i-1}^{n+1} - \Phi_{i}^{n+1}}{\Delta y} \right)$$

...(2a)

and

$$q_{out} = \frac{\Delta x \Delta z k}{\mu_w B_w} \left(\frac{\Phi_{i}^{n+1} - \Phi_{i+1}^{n+1}}{\Delta y} \right)$$

...(2b)

where: $\Delta x \Delta z$ is the cross-sectional area of the cell, Δy is the length of the cell, Φw is the flow potential across the cell, i refers to the cell of interest, $i - 1$ refers to its left-hand neighbor and $i + 1$ refers to its right-hand neighbor. The flow potential Φw equals pressure plus gravitational potential. Substituting Equation 2 in Equation 1 and dividing through by $\Delta y \Delta x$ yields:

$$\frac{1}{\Delta y}\left[\frac{\Delta z k}{\mu_w B_w}\left(\frac{\Phi_{i-1}^{n+1}-\Phi_i^{n+1}}{\Delta y}\right)-\frac{\Delta z k}{\mu_w B_w}\left(\frac{\Phi_i^{n+1}-\Phi_{i+1}^{n+1}}{\Delta y}\right)\right]-\frac{q_w}{\Delta x\,\Delta y}$$

$$=\frac{1}{\Delta t}\left[\left(\frac{\Delta z\,\phi\,S_w}{B_w}\right)^{n+1}-\left(\frac{\Delta z\,\phi\,S_w}{B_w}\right)^{n}\right] \qquad \ldots (3)$$

Equation 3 is rearranged to give:

$$\frac{1}{\Delta y}\left[\lambda_{i+1/2}\left(\frac{\Phi_{i+1}^{n+1}-\Phi_i^{n+1}}{\Delta y}\right)-\lambda_{i-1/2}\left(\frac{\Phi_i^{n+1}-\Phi_{i-1}^{n+1}}{\Delta y}\right)\right]-\frac{q_w}{\Delta x\,\Delta y}$$

$$=\frac{1}{\Delta t}\left[\left(\frac{\Delta z\,\phi\,S_w}{B_w}\right)^{n+1}-\left(\frac{\Delta z\,\phi\,S_w}{B_w}\right)^{n}\right] \qquad \ldots (4)$$

where: $\lambda = \frac{\Delta z k}{\mu_w B_w}$ and the subscripts $i + 1/2$ and $i - 1/2$ indicate that the quantity is evaluated as an average for the $i + 1$, i and the i, $i - 1$ cells, respectively. Different programs use different averaging techniques.

Equation 4 is the mass balance or material balance equation in one-dimension in difference form as used in simulation calculations. In two and three-dimensions the x and z direction terms, identical with the above y direction, are added. Equation 4 may be written in differential form as:

$$\frac{\partial}{\partial y}\left(\lambda\frac{\partial \Phi}{\partial y}\right)-\frac{q_w}{\Delta x\,\Delta y}=\frac{\partial}{\partial t}\left(\frac{\phi\,\Delta z\,S_w}{B_w}\right) \qquad \ldots (4a)$$

In deriving Equation 4, we have used the value of Φ at the n + 1 time level, that is, at the end of the time step. This difference technique is called the implicit method and is the most commonly used one. However, the implicit method is considered the most stable and was used in this calculation.

Construction of a Model

Preparation of the data for a model requires that the reservoir be divided into a number of cells. This is accomplished by laying out a grid system on the reservoir. A vertical or depth grid must also be established if the model is for three spatial dimensions. Each cell must be identified by its x, y and z coordinates. The flow conditions around the perimeter of the reservoir are next established. Normally the reservoir boundary is considered sealed, but influx or efflux and an assigned pressure or rate may also be specified. This condition is later confirmed or adjusted by comparing the performance of the model with actual history.

The next step is to assign the rock properties, fluid saturation and distribution and fluid properties to each of the cells. The rock properties consist of specific permeability, porosity and sometimes capillary pressure. The fluid properties include compressibility and viscosity. The cell geometry includes the depth, thickness and locations of the wells. Wells are usually assumed to be at the center of the cells in which they fall and grids are normally laid out to accommodate this assumption. The average pressure of each cell at initial time is also required as a starting point for the calculation. Based on the assigned

data, sets of partial differential equations expressing the conservation of mass and energy are established for each of the cells in the model. A computer program may be written to utilize various numerical techniques in solving the equations. Regardless of the mathematical method used to solve the partial differential equations simultaneously, the end target is the same. Given a value for the pressure and saturation at each cell at the beginning of a time step, new saturations and pressure values are found at the end of the time step. These values in turn represent the starting point for the next time step. This step wise process is continued until the desired amount of time has been predicted.

A proper numerical simulation model will neither create nor destroy matter in the calculation and will result in a proper accounting for the water produced from or transferred between cells.

Validity of the Model

The best method for obtaining a valid reservoir description is to determine that model which results in the best agreement between calculated and observed field performance. This technique is called history matching or calibrating the model. In the study of the Kerr-McGee No. 1 Sequoyah Waste Storage well, careful analysis was made to match two separate performance considerations; (1) the calculated flow into and from the separate layers in agreement with that observed on radioactive tracer injection studies and (2) the calculated wellbore pressure fall-off curve. When adequate field data exist, as in this problem, experience has shown that reasonably accurate performance predictions can be made for even complex reservoir systems.

APPLICATION OF RESERVOIR MODELING TO INDIVIDUAL WELL ANALYSIS

Aspects of Transient Pressure Testing

Well tests such as pressure build-up, drawdown, injection and fall-off tests have become one of the most powerful methods for obtaining a description of an aquifer or hydrocarbon reservoir. These tests involve creating a pressure disturbance in the reservoir and measuring subsurface pressure behavior in a well as a function of time. The pressure disturbance is purposely created by changing the injection or production rate of a well. This change in rate causes a pressure wave to eminate from the well and move through the inner connected pore space of the reservoir in a manner similar to the diffusion process. Since the displacement of fluids in a reservoir is dependent on the physical characteristics of the reservoir rock and reservoir fluid, it follows that the measured pressure-production or injection behavior of a well is related to the reservoir rock and fluid properties. Thus, the basic problem involved in well testing is an indirect evaluation of physical reservoir rock properties through a subsurface fluid-flow experiment, since the fluid properties are known.

To calculate reservoir properties from information obtained from well testing, it is necessary to simulate the reservoir, reservoir fluid and test conditions by a mathematical model either analytic or numeric. Analytical models are often used to obtain descriptions of relatively homogeneous reservoir systems. Multi-layer cases such as the Arbuckle system communicated to the Kerr-McGee No. 1 Sequoyah Waste Storage well are best evaluated with a numeric model as discussed

in the previous section. In either case, it is often possible to obtain an evaluation which closely matches measured data and accurately describes subsurface geometry and reservoir properties such as permeability, static pressure, volume and boundary distances. A most reliable reservoir description is achieved when information from each source, pressure, geologic and wellbore flow data, functions as a companion to others.

Case History Example

A case history example of use of a model based on a well test and the subsequent confirmation of the reservoir description by geologic and seismic knowledge is presented as Exhibit G-2. This example illustrates the results of obtaining an accurate reservoir description from transient pressure test, geologic and seismic data in an exploratory drilling venture. The consistency of the fault-boundary and the gas-water contact distances determined by transient-pressure analyses with the boundary and contact locations obtained by geologic and seismic data yielded confidence in an accurate reservoir description. A knowledge of this reservoir description allowed the operator to make important decisions regarding the lease farmout locations shown on this exhibit in the left-hand portion of the reservoir area and avoid the drilling of dry holes which were subsequently drilled by other parties.

As will be shown in subsequent portions of this testimony, we have attempted, in a similar manner, to obtain an accurate description of the Arbuckle aquifer communicated to the Kerr-McGee No. 1 Sequoyah well through the combined application of sensitive pressure gauges, radioactive tracer surveys, pressure fall-off testing and geologic knowledge.

Discussion of Well Testing and Modeling of Kerr-McGee No. 1 Sequoyah Well

A detailed engineering study by H. J. Gruy and Associates, Inc. was previously submitted as Exhibit A in the May 10, 1972 Kerr-McGee application. In summary, this study included the combined applications of electric well logging, radioactive tracer and temperature profiling, pressure fall-off testing, regional geology and three-dimensional, single-phase numeric modeling. The conclusions of this study showed that the Arbuckle reservoir communicated to the test well can be described by five separate layers having different values of permeability and thickness. The layers were further demonstrated to have no vertical communication except at the wellbore and sealing boundaries on all sides with the exception to the furthermost limit of the third and fourth layers in a top to bottom sequence. In this instance it was shown by the geologic study that a fault boundary is located west of the well at a distance which is greater than the calculated distance of approximately 29,600 feet to a nearest possible boundary in Layers 3 and 4. It was further demonstrated during the Bethesda meeting of November 20, 1972, that the engineering and geologic studies functioned as complimentary sources which locate the nearest fault boundary between 1,100 and 1,200 feet from the test well. These points and others which are germane to the joint issues of this hearing are amplified in the following portions of this engineering testimony.

An outline of the testing performed and the application of each unit of data follows:

Test Data Studied

I.	Electric Well Logs	Formation Correlation
	A. Caliper	Determine hole volume
	B. Density	Determine zone porosity
II.	Static Pressure Survey	Establish initial undisturbed reservoir pressure
III.	Water Injection With Radioactive Tracer Survey and Temperature Survey*	Establish no leak in casing or around casing shoe. Determine permeable intervals accepting fluid and amount entering each zone.
IV.	Shut-In Test of 145 Hours With Sperry-Sun Pressure Instrument	Provide wellbore pressure performance for reservoir description.
V.	Water Injection With Radioactive Tracer* Followed by Profiling During Shut-In	Confirm permeable zones, and existance of counterflow

* Three separate injections with tracer runs (one is shown as Exhibit G-3) and one shut-in profile (Exhibit G-4) were performed during the well test program.

Determinations of the Thickness and Permeability of Each Active Layer Prior to the Pressure Fall-Off Test of 7/6-12/71

Evaluations of the injected water distribution by layers were achieved from analyses of radioactive tracer surveys. Three surveys were conducted during injection periods and one survey was conducted during a shut-in period after the fall-off test. These evaluations were formerly submitted along with published techniques used in the radioactive tracer analyses as Exhibits B and C of the previous application.

Determinations of the water injection distribution for tests on July 5, prior to the fall-off test of 7/6-12/71, are shown by Exhibit G-3.

Tracer profiles as measured by tracking each radioactive shot down the wellbore are displayed on the left side of this exhibit. Instrumentation used for these measurements consists of two gamma sensitive detectors spaced five feet apart on a conduction cable. A small volume of radioactive Iodine-131 is released from the tool by a surface signal. This slug is tracked downstream in the wellbore as shown on the exhibit. Injection rates are computed by knowing the wellbore volume in a five-foot interval and the time required for the radioactive slug to travel over the interval. The quantity of radioactive tracer released is tracked by raising or lowering the instrument through the "shot" as it moves along the wellbore with the injected water. As porous and permeable zones are passed a portion of the radioactive "shot" will be injected along with the water. The amount of tracer remaining in the wellbore as determined by the radioactivity recorded on the successive instrument passes, is used to calculate the percentages of the total injected fluid accepted by each zone or interval. The continuous movement of the injected fluid and the successive passing of the instrument through the tracer tends to mix and diffuse the tracer shot. When the profile of the radioactivity indicates the shot to be "spread-out" beyond accurate use, tracking is interrupted until the tracer is completely injected and another tracer shot is placed just above the point where the prior shot became of questionable use. The logging of the wellbore continues using as many shots and passes of the instrument as are required to describe the injection profile. On the right side of this exhibit the distribution of injected water is shown as determined from the tracer profiles. The cross-hatched distribution results from adjusting

the tracer profiles with the aid of the caliper survey (a continuous measurement of the borehole diameter). The final groupings into five reservoir layers for numeric model analysis are delineated by brackets on the right side of this exhibit. Your attention is directed to Shot No. 1 at the top of this exhibit where a radioactive slug was emitted in the cased interval of the well at a depth of 1,000 feet or approximately 620 feet above the casing seat. This slug traveled undisturbed to a point in the open hole region of the wellbore or approximately 200 feet below the casing seat. Therefore, it is concluded that no leaks were present through or around the casing during this test. It is also clear from this exhibit that 55 percent of the injected water was entering the two higher flow capacity intervals of Layer Nos. 4 and 5.

Exhibit G-4 illustrates the results of radioactive tracer surveys conducted during a shut-in period after the fall-off test. The pronounced upward direction of the tracking vectors shows strong water flow or counterflow up the wellbore from Layer No. 5. This evidence of counterflow is indicative of little or no vertical communication between layers in the reservoir. This result, coupled with the fact that Layer No. 5 accepted progressively smaller volumes of injected water throughout the injection profile tests, indicates that one or more boundaries were influencing the observed behavior of Layer No. 5.

The effective permeabilities of each layer, shown in Figure 3 of the Gruy report (previous Exhibit A), were determined from the aforementioned injection profile data (Exhibit G-3) and the calculated

total permeability-thickness. This product is obtained as illustrated by Item B of the legend for Exhibit G-5. The shut-in pressure is plotted versus an injection rate-time function. If the injection rate was variable or discontinuous prior to shut-in, the product must represent the summation of products for each rate period. This situation occurred in the No. 1 Sequoyah testing and we accordingly applied the principle of superposition to establish the horizontal scale as shown on the exhibit. The utility of this plot is that it enables the analyst to establish the proper straight-line and boundary effect regions of measured pressure behavior. Calculated properties from these time regions are described in the analysis of the Kerr-McGee data attached as the legend to Exhibit G-5. The point of stabilization where afterflow became insignificant was determined to be Point A (0.1288-hours shut-in). This point establishes the beginning of the straight-line region and a least-squares fit of the fall-off data points yields the solid line shown on this exhibit. The calculation of total permeability-thickness is performed as described by Item B of the Legend.

The highly sensitive pressure gauges used for recording the fall-off pressures detect a definite departure from the straight-line trend at Point C on the fall-off profile. This departure is interpreted to be a reflection of the nearest reservoir boundary in the most permeable zone, Layer No. 5. The degree of sensitivity of the pressure gauges is substantiated if one notices that significant pressure changes are detectable on the fall-off profile with a vertical-scale of 0.2 psi per division. Item

C of the legend describes the calculation of the nearest boundary distance of approximately 1,200 feet. Because of the high sensitivity of the pressure instruments or their ability to detect a small pressure departure, this calculated result of the nearest boundary distance is believed to be accurate. The reflection of a boundary in Layer No. 5 is consistent with the previously discussed results of the radioactive tracer tests during injection and shut-in. With the additional aid of the numeric model it was ultimately indicated by the analysis that Layer No. 5 is a zone of limited areal extent and volume.

Evaluation of the Arbuckle Reservoir in Communication With The Kerr-McGee No. 1 Sequoyah Well

Efforts in the Gruy engineering study were concentrated on obtaining a reliable match between measured pressure fall-off test data and theoretical pressure fall-off data. Taking into account the injection and back-flow data, theoretical fall-off data were computed with the aid of a three-dimensional, single-phase num ric model. The model included five reservoir layers having different values of permeability, porosity, thickness and boundary distances. Individual layer-boundary distances from the well were systematically varied in the model until a best-fit match was achieved. The reservoir description which yielded the best-fit was summarized by Figure 1 and 3 of the Exhibit A submittal. The effects of areal and vertical variations in permeability and boundary leakage were also studied and reported on pages 11-13 of Exhibit A and the model calibration and the effects of variations in boundary distances are detailed on pages 8-10 of the report.

Transient pressure testing, such as pressure fall-off testing in the Kerr-McGee No. 1 well provides measurements of the physical characteristics of a reservoir. Since fluid displacement occurs in the reservoir while a test is conducted, the influence of reservoir properties is dynamically measured and therefore, calculated property values are properly averaged for large volumes of the reservoir. The pressure behavior of a well is relatively insensitive to small-scale heterogeneities in the reservoir. However, if a significant property change occurs in the areal or vertical dimensions of the reservoir such as a change in permeability, its effect is reflected in the measured pressure behavior and the calculated value is properly weighted. Thus, in this engineering study we have included evaluations of the observed effects of multiple-permeability layers without vertical communication in the reservoir as well as the observed effects of boundary locations and shapes. In effect the engineering study has evaluated the areal and vertical heterogeneities which are dynamically significant in a complex reservoir.

More than 30 executions of the numerical simulator were performed before a set of boundary assignments resulted in a reasonable match between calculated and observed performance. Additional minor adjustments in the assumptions would have "fine tuned" the match; however, it was felt that the cost for the additional computer runs did not materially increase the confidence in the solution.

A question has been raised as to whether or not channeling or flow in a preferential direction could be detected (causing the injected

water to advance in one direction instead of radially) by analyses of the test data. It has been proved and accepted in technology that if channeling along a fracture or if flow in a preferential direction were occurring, the nature of the flow system would be linear instead of radial. Linear and radial flow systems have different pressure behaviors which are easily detected in the early-time regions of a pressure fall-off test such as the one conducted for this study.

No indication of linear flow was observed in the test data and it is concluded that the injected water is advancing radially into the permeable zones.

As mentioned in previous portions of this testimony, the use of sensitive pressure recording gauges during a test is very important because it not only enables the analyst to detect reflected anomalies such as faults and permeability changes (which might not be recorded by insensitive gauges); but it also allows him to obtain a more accurate reservoir description. These points are illustrated by Exhibits G-6 and G-8 of this study. In Exhibit G-6 we have superposed a shaded band over the measured pressure points to illustrate how the precision of pressure measurement influenced the determinations of boundary distances. The width of this band is equivalent to 0.55 psi or the precision of the pressure gauge used during the fall-off tests. Model Run No. 32, the best fit obtained with measured data, is shown by the "x" points on this plot of pressure as a function of shut-in time. Exhibit G-7 summarizes the boundary descriptions of this model run. The west boundary limit of Layers 1 and 2 were varied between 11,000 and 24,000 feet for these results shown on Exhibit G-6 while all other

properties were held constant. A constant total pore volume was maintained by adding or subtracting equivalent volumes to the furthermost limit or western boundary of Layers 3 and 4. By comparing the width of this band with the differences between model and measured points, it became clear in the study that the west or left boundary of Layers 1 and 2 must be located approximately 13,000 feet from the well. The discussion in regard to model results and gauge sensitivity on page 10 and Figure 11 of the Gruy report further substantiates this result.

The precision of pressure measurement is also displayed by a shaded band on Exhibit G-8. On this plot of pressure versus time the model calculations of possible leakage at the 1,200-foot boundary are studied and compared with measured data. It is clear from this exhibit the boundary permeability which causes undetectable pressure changes of less than 0.55 psi would be less than a value of only 0.1 millidarcies. From this result it was concluded in the study that the nearest boundary has insignificant or no effective permeability to water.

Monitoring of Operations

A numerical simulation model presently established for the Kerr-McGee No. 1 Sequoyah Waste Storage well may be used to predict the pressure-time performance under the assumed rates of injection. These predictions may be used as yardsticks for confirming the validity of the model. So long as the observed performance matches to a reasonable tolerance, the predicted performance, there will be confidence that the material is being stored in accordance with the predictions. If, however, divergence from the predictions is noted, immediate investigations

as to the cause for the divergence can be initiated. Unquestionably, some fine tuning of the simulator will be in order when operational data are available for matching. If a serious divergence or a sharp break in the observed performance occurs, emergency actions including procedures to back-flow the well can be initiated.

The above monitoring will require that periodic transient pressure tests be performed in the reservoir. This should provide no operational difficulty because it is proposed to inject into the well in cycles. The transient tests can be performed immediately after an injection cycle on a frequency schedule deemed to be adequate for monitoring the reservoir. More frequent test analyses should be performed during the early stages of operation becoming less frequent with operating experience. As pressure in the immediate vicinity of the wellbore increases from injection, the feasibility of using wellhead pressure data for the monitoring calculations increases.

During operations we recommend daily checking of injection pressures. We suggest fall-off curve analyses be performed monthly for the first quarter of operations and quarterly for the remaining of the first year. During the first year the model should be adjusted for any necessary changes and effects of any cavitation should be considered. We believe that such daily monitoring will eliminate the need for additional observation wells at this time.

The drilling of additional wells is expensive and could result in inconclusive information. A well has been proposed north of the No. 1 well to confirm the location of the Webbers Falls fault. The

location of this fault is now based on analyses of the pressure test data and it is confirmed only as a permeability barrier in the Arbuckle reservoir. If the barrier is in fact a very minor fault or a lithologic barrier, the additional well may fail to indicate the barrier. On the other hand, as monitoring time increases on the injection well, the integrity of this barrier is further tested in regard to a pervious or impervious condition. Therefore, because there is no question that such a barrier must exist to honor the observed well performance, we believe the second well to be an unwarranted expense.

A well completed to monitor from the top of the Simpson zone to the top of the Arbuckle is also believed not to be necessary at this time. If impervious barriers exist in the zones above the Arbuckle between the location of the proposed well and the location of the No. 1 well, then a pressure response would not be detected in the No. 2 well even if leakage from the Arbuckle occurred. The model studies do not reflect cross-flow in the reservoir now and the radioactive tracer study shows the completion techniques to have effectively sealed off the zones above the Arbuckle from the Arbuckle in the wellbore. The one sure means for detecting leakage from the Arbuckle, by whatever means, to either the surface or other zones remains through monitoring of the injection well.

The drilling of another injection well to serve as a monitor within the Arbuckle is not believed to be necessary if prudent monitoring of the existing injection well is performed. The consideration of using the second Arbuckle well as a back-up to the No. 1 well for waste injection

is not economically justified as the existing storage pits could be used to store the waste for the time required to drill another disposal well if this should ever become necessary.

CONCLUSIONS

In conclusion, field tests have shown that the well will take water and that there is no leak in the casing or around the casing shoe. Tests also prove conclusively that all permeable layers are closed on all sides with the exception of Layers 3 and 4 which are closed on three sides and still open at a distance of about 29,600 feet from the well. The geology indicates a fault at about 32,000 feet.

Assuming that the boundaries actually occur at 26,000 feet (placing them closer causes definite departure from measured pressure performance) so that the reservoir is a minimum size will allow injection of 652 barrels per day for 60 months with a wellhead pressure increase of only 150 psi. If the reservoir is larger, the pressure build-up will be less. If the pressure build-up ruptures a fault seal, a detectable change in pressure behavior would be very quickly apparent. Because the injected material will remain in the vicinity of the wellbore, the greatest hazard would be forcing of formation water to the surface or into a potable water zone. Only slight damage could result from formation water coming to the surface. Should such an event occur, it would be along one of the bounding fault zones and would be immediately apparent. In conclusion, injection of this material into the Arbuckle formation through the Kerr-McGee No. 1 Sequoyah well, in our opinion, is the best solution to the storage problem.

APPENDIX I

RESPONSES TO QUESTIONS PRESENTED DURING THE PRE-HEARING CONFERENCE OF TUESDAY, AUGUST 14, 1973

The identification numbers preceding the following paragraphs represent the page and line number of the transcript for the above hearing that contain the question being addressed.

30-5 Dr. Babcock stated it would be quite helpful to the Board if we would give a resume of the experimental work done on the No. 1 Sequoyah Waste Storage well. He further requested that we indicate what portions of the data were used as input to the computer program and how this input was treated in arriving at the conclusions presented.

The No. 1 Sequoyah Waste Storge well was subjected to a series of field tests designed to provide the data necessary to construct a numerical simulation model of the reservoir in communication with the wellbore. A suite of electrical well logs were available from the drilling and completion of this well which were useful in identifying the several permeable layers in the Arbuckle formation as well as in providing a continuous measure of the diameter of the open-hole section of the well. The testing performed to supplement this information included injection tests, a pressure fall-off test, the injection of radioactive tracers to indicate the percentage of the total injected fluid entering each of the permeable layers and temperature surveys of the wellbore. The pressure data recorded during injection and shut-in periods were recorded by

a highly sensitive Sperry-Sun bottom-hole pressure instrument. The radioactive tracer survey was performed by WACO and consisted of injecting water-soluble Iodine-131 at various depths in the wellbore. Two gamma sensitive detectors on a conductor line were subsequently tracked through the radioactive slug as the material was pumped into the formation. The percentages of the fluid being accepted by the permeable layers were calculated based on the quantity of tracer remaining in the wellbore. A careful record of the wellbore pressure versus time was recorded during the injection and for a period after shut-in of the well in order to provide a performance history for matching in a numerical simulator.

32-23 Dr. Babcock has inquired as to the constants that were introduced into the simulation run.

The numerical simulation model was forced to satisfy two different considerations recorded during the testing program. Both the wellbore pressure response and the percentages of water accepted by the significant layers in the Arbuckle formation required matching for the model to be representative. The thicknesses of the zones as indicated by the injection profiles were held constant and a single set of water fluid property functions (compressibility and viscosity) were used. Values of rock porosity, calculated from the electric well logs were assigned to each of the layers found to be accepting water by the tracer injection profile study. Permeability

values of each layer were determined from the injection profile intervals and an analysis of the early-time region of the pressure fall-off profile.

32-25 Dr. Babcock inquires as to the variables that were left to be adjusted by the simulation operator.

The variables adjusted in the simulator included the distances between the boundaries and wellbore of each layer, layer permeabilities, layer pore volumes and boundary conditions (pervious or impervious).

33-7 Dr. Babcock questions how accurate a fit between the simulator and actual data is required in order to say for sure that, (a) the well casing does not have a leak that communicates to a vertical fissure and allows major escape for the waste water that eventually leaks to the surface, (b) let us assume there is a 1/4-inch pipe that penetrates the Arbuckle formation. Would the leakage through this pipe be detected in the simulator test, (c) how much leakage through the nearest fault can be detected or predicted by the simulator test. In other words, Dr. Babcock is trying to determine the magnitude of possible error in the conclusion that there is not major leakage.

In answer to the first question, a confirmation that no leakage occurred either through or around the casing during testing was obtained by releasing a radioactive shot up in the casing and tracking it downward into the open-hole region below the casing seat. Reference: Exhibit B of May 10, 1972, application, and Exhibit G-3 attached.

If a 1/4-inch pipe is assumed to connect the Arbuckle to the surface and if we assume a bottom-hole pressure during injection of about 1,400 psi, then calculations indicate that over 100 barrels of water per day would be produced (depending widely on friction factor representing pipe roughness) through the pipe. This amount of leakage would be observed using the numerical model along with the monitoring data.

On pages 11-13 of the Gruy report recorded as Exhibit A for the May 10, 1971 application we describe an execution of the numerical model where permeabilities of 0.01 and 0.1 millidarcies were assigned to the nearest boundary. It was found that a leakage rate of only 4.4 barrels per day (0.13 gallons per minute) could occur at the nearest boundary and remain undetected. At a leakage rate greater than this amount the pressure response calculated by the model fell outside of the band of precision for the measuring instrument and became detectable. It appears that any leak less than 4.4 barrels per day 1,200 feet from the well would go undetected.

33-20 Dr. Babcock notes that the computer printout does not exactly follow the pressure falloff. The computed pressures fall off less slowly than the measured pressures during the initial portion of the test. Thereafter, the computed pressures falloff more rapidly than the actual test. He questions, is this significant?

The numerical simulator was constructed by the Gruy staff prior to any knowledge of the area geology. The individual boundaries and layers were constructed rectangular rather than somewhat skewed as geology now suggests the reservoir to be. The simulator was also constructed to represent a heterogeneous reservoir through the use of parallel layers having different properties. This is a technique frequently used to represent a heterogeneous system. Five layers were considered to be adequate to represent this flow system. There is no question that one or more of the layers selected may, in fact, be subdivided. Papers have been presented to demonstrate that at some optimum number of layers, adding additional ones lend little to the accuracy of the calculation. We call to your attention that the pressure instrument has a tolerance of precision. This is represented on our exhibits by a band showing the minimum and maximum values possible with the equipment used on the test. Any value calculated by the model within or near the limits of the band should be considered adequate for history matching. Although some deviation from the pressure lines is observed in the late-time region, please note that the actual absolute difference only ranges from 0.81 to 1.38 psi and that after 105 hours this Δpressure remains virtually constant with exception to the last point. Also note that the tracer injection profiles indicate there to be backflow from Layer 5. This could only occur if Layer 5 had limited

volume. This is confirmed by the simulation model. There is no question that fine tuning of the model could ultimately achieve a closer match than the one presented. This would be accomplished byadjusting the geometry of the flow system slightly as suggested by geology and perhaps by subdividing some of th~ layers. The calculated boundaries, however, would not be significantly different than those presented and the cost for continuing the executions for closer agreement in our opinion are not warranted unless additional information becomes available.

34-4 What is the significance of the continued divergence between the simulator and the actual data beyond the test duration, which was something like 150 hours. You are obviously concerned with many tens of thousands of hours and if there is a divergence there at the end of 150 hours , does this effect the conclusions that you have given?

The numerical model constructed is very sensitive to any change in its boundaries or properties. The fact that the model holds with $\pm$ 0.75 psi through 145 hours of comparison in our opinion is good engineering agreement. Also, note that the differences between measured and calculated pressures is 1.11 and 1.13 psi at shut-in times of 115 and 125 hours, respectively; therefore, the larger pressure difference of 1.38 psi at 145 hours shut-in is out of line and probably influenced by statistical error in pressure

measurement. This has no effect on conclusions because it can be proved by material balance and average pressure calculations ($\bar{p}$) that each trend is approaching an asymptotic value which will yield an insignificant and constant Δp.

34-11 I note that you predict that there is a fault some 1,100 feet from the well, but in the verbal description in the report of the faults, you say the nearest fault is approximately one mile away. I would like this divergence discussed. The engineering study by Gruy mentions the fact that there are known faults around the simulator test. The simulator test predicted a fault at a further distance, and I wanted that explained.

At the time of the engineering study Kerr-McGee geologic interpretations indicated the nearest fault to be the Carlisle fault about one mile from the injection well (Exhibit C-C). The engineering study discovered strong evidence of an additional reservoir boundary between 1,100 and 1,200 feet from the wellbore. A subsequent review of the geology found supporting evidence of this boundary in the form of the Webbers Falls fault. This "new" evidence was submitted at the Bethesda meeting on November 20, 1972.

35-8 Dr. Babcock questions would an increase in the density of the injected fluid be helpful in keeping the water that is injected from eventually finding a way to the surface.

In our opinion, increasing the density of the injected fluid by evaporation may have adverse effects to the injection operation. First, if a significant density difference between the injected and the natural waters occurs, the injected fluids may underrun the lighter formation water along the bottom of the respective zones rather than piston displacing the indigenous water as is desired. This by-passing or underrunning beneath the indigenous water has been observed in the waterflooding of certain oil fields. It is also unlikely that density can be increased without increasing the viscosity. Increasing the viscosity so that the mobility ratio between the injected and the displaced fluids becomes adverse could cause fingering and by-passing if the well should be back-flowed. Because diffusion between the two fluids will only occur at the interface, both fingering, channeling or the tendency to run under the indigenous water will expose larger surface areas for mixing. This is adverse in the event recovery is desirable. The potential increase in viscosity also will increase the pressures required for injecting the fluid which is also undesirable.

35-20 If evaporation were the process used to increase the density, should the reduction of the amount of water be helpful in the well injection procedure?

The amount of waste to be injected is not very large by oil field standards. The increased density and viscosity makes the material more difficult to pump with the result that any benefits from reducing volume is countered. We do not forsee any significant benefits to the Kerr-McGee operation by reducing the volume at the expense of increasing viscosity and density.

36-14 Mr. Kornblith requests that the written testimony contain enough material to give a person with a reasonable but not specialized technical background an appreciation of how one goes about evaluating the performance of a well as it affects this application.

A simplified explanation of the simulation process is presented in the prepared testimony attached. At this point in history, reservoir simulation has moved from the laboratory where it was developed into the hands of application engineers. A review of the files on this subject performed while preparing this testimony revealed more than 100 technical papers on the subject. Most of them were written as a result of a specific reservoir assignment, therefore, they represent actual case histories.

37-22 Mr. Kornblith expresses his concern about the methods of determining the suitability of a well for disposal purposes.

Every unknown reservoir, rock, geometry and fluid property is reflected in the pressure-production performance of a well communicated to the reservoir. Analysis of these data unfortunately

is complicated and very technical. The most modern approach to determining the suitability of a well for production or disposal is the analysis of the reservoir pressure-production relationship. This may be done analytically if the reservoir is homogeneous or through numerical simulators as was performed in this study if the zone is heterogeneous.

40-18 Dr. Babcock states that the pressure fall-off concept is a relatively well understood and common technique for chemical engineers to analyze. He recognizes the procedure as being similar to radioactive decay, in other words decay to a steady-state. He observes that chemical engineers can draw straight lines for example through various portions of the data and can draw conclusions from these straight lines. He inquires if Kerr-McGee has done such analysis of these data and if they would present these data in graph form using appropriate equations or appropriate scales that are different from the linear scales shown in the report.

The discussion in the direct testimony beginning with the analysis of early-time test data on the bottom of page 15 and Exhibit G-5 are germane to the above question.

APPENDIX II
PERTINENT FACTORS RELATING TO
JOINT STATEMENT OF PROPOSED ISSUES

1. Whether the Webbers Falls fault exists and, if it does, at what distance is it located northeast of the proposed disposal well?

The existence of the Webers fault is supported by:

a. The pressure transient analysis definitely indicates a reservoir boundary at a distance of about 1,200 feet from the Kerr-McGee No. 1 Sequoyah well.

b. An escarpment is observed on the surface that corresponds to the calculated fault location.

c. The fact that all permeable layers demonstrate a reservoir boundary at about 1,200 feet suggests a fault rather than permeability pinchout.

d. A geologic interpretation omitting the fault requires an anomolous dip in the Wapanuka formation when compared to regional dip established by subsurface control.

2. Whether the South fault exists and, if it does, at what distance is it located southwest of the proposed disposal well?

Four of the five layers indicate truncation at a distance of about 24,600 feet from the well. The fifth layer is smaller. This is interpreted as the South fault because the Carlisle School fault and the South Fault of the Warner uplift are accepted to be about 32,000 feet apart, matching the open end dimension of Layers 3 and 4 about 29,000 feet.

3. Whether additional faults exist within the disposal formation (fault block) that may act as either barriers to fluid movement within the fault block or conduits for fluid movement within the formation.

   If any additional faulting served as conduits or barriers,such conditions would have influenced the pressure behavior in a detectable manner.

4. Whether the nature of the faults comprising the fault block are such that the faults will act as barriers to fluid movement under increasing fluid pressure.

   It is impossible to state that the faults will be or will remain sealing. The injected fluids will never reach the faults and the pressure increase at the faults is less than two hundred pounds after five years of injection. Oil field experience has shown most faults that are sealing maintain integrity to depletion differentials of several thousands of pounds.

5. Whether the five disposal zones composing the Arbuckle formation can be assumed to be homogeneous, isotropic, and constant in thickness, porosity, and permeability, thereby permitting the calculation of the movement of the disposed waste fluid from the wellbore.

   It has been shown that hetrogeneous zones can be represented by layered models using weighted properties for each of the model layers; however, at some point the increase in accuracy per layer added becomes small. We reference "A Method of Analyzing Transient Fluid Flow in Multi-Layered Aquifers" by Iraj Javandel and

Paul A. Witherspoon published in Vol. 5, No. 4 of Water Resources Research, Aug. 1969. We investigated the effects of altering permeability at distances from the well in our model (see Figure 13 in report). Within the area investigated by the test the heterogeneities are properly averaged and weighted by the pressure responses observed.

6. Whether a three-dimensional analysis of geohydrologic problems by the finite difference method, based on test data obtained from a single well, can accurately predict the nature and performance of the injection horizons.

Pressure transient analyses of data from one well have been used with a high degree of accuracy for more than 15 years in the petroleum industry to describe and predict size and performance of reservoirs. We have designed and studied hundreds of such tests such as Exhibit G-3 (which has been proved by subsequent drilling).

7. Whether monitoring by pressure testing at the wellhead is adequate to detect fluid movement, or whether there is a need for direct monitoring of the recipient formation.

We do not believe that direct monitoring of the recipient formation is required. Although wellhead (surface) monitoring alone may eventually prove adequate, we propose that initial monitoring utilize both wellhead and downhole instruments. Current plans are to equip the well with permanently installed borehole pressure

sensing devices which may be checked from time to time with wire line pressure gauges.

8. Whether in the event of a demonstrated leak in the retention reservoir or fault block the waste fluid can be recovered.

Should recovery become desirable, the similar viscosities and gravities and the miscibility between the fluids would allow good recovery. It is unlikely that the amounts unrecovered would cause damage.

Every effort has been made to understand the characteristics of the storage reservoir through the use of sophisticated technology. We are convinced that the proposed monitoring will provide good safegaurds against improper use of the injection well and the storage reservoir.

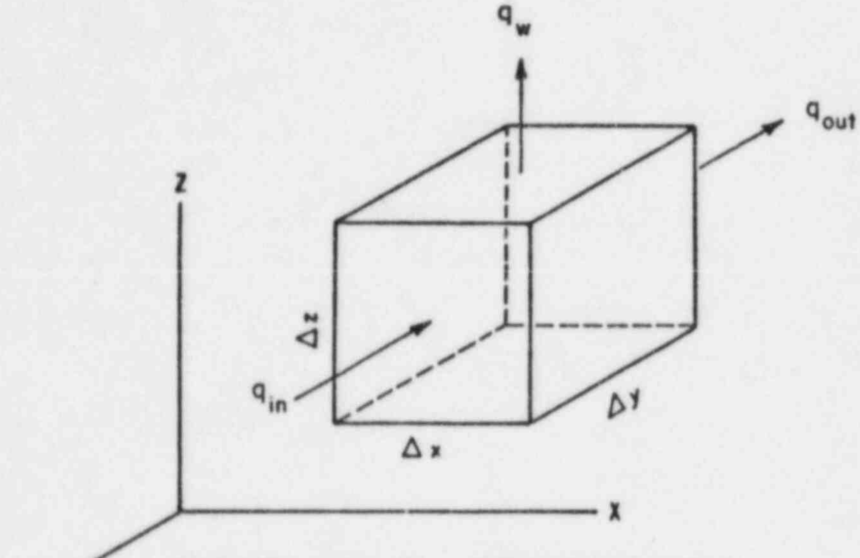
Medically speaking, we are advised that concentrations of the waste or of the Arbuckle waters noxious enough to be dangerous would be undrinkable because of taste while dilution of the materials to the point of suitable taste, eliminates the danger. Because the proposed monitoring would preclude any long-term exposure to escaping waste, we believe the storage through the use of the Sequoyah No. 1 well to be superior to any other current alternative.

EXHIBIT NO. G-1

DIMENSION CONCEPTS OF RESERVOIR SIMULATION

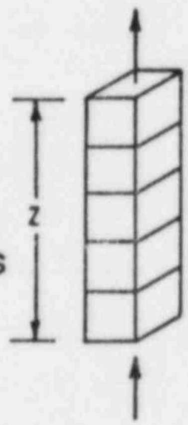
SEPTEMBER, 1973
DALLAS, TEXAS

H. J. GRUY AND ASSOCIATES, INC.

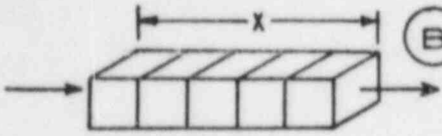


RECTANGLE COORDINATE

(A) SINGLE CELL MODEL

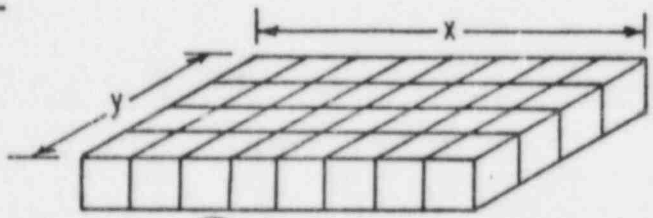


(B) ONE DIRECTIONAL MODELS

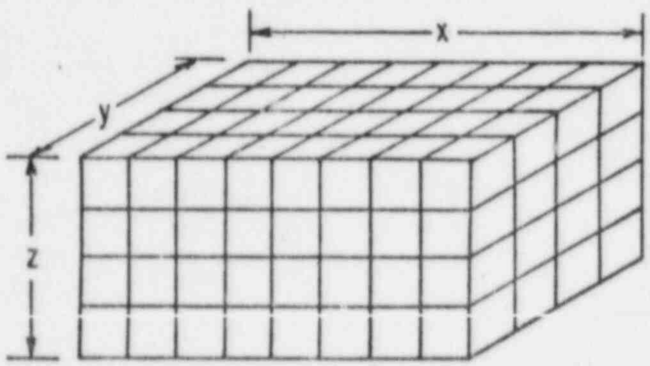


HORIZONTAL

VERTICAL



(C) AREAL MODEL



(D) THREE DIMENSIONAL MODEL

EXHIBIT NO. G-2

CASE HISTORY EXAMPLE OF A RESERVOIR DESCRIPTION OBTAINED FROM TRANSIENT PRESSURE TESTING

SEPTEMBER, 1973
DALLAS, TEXAS

H. J. GRUY AND ASSOCIATES, INC.

Determination of Reservoir Size and Configuration - Buildup and Drawdown Analysis

Buildup and drawdown tests were conducted and analysis made to establish reservoir size and configuration as a guide for future development. The test results indicated the presence of an impervious reservoir barrier at a distance of 1230 feet and a gas-water contact 670 feet from the test well. As shown on the figure, this analysis is consistent with geologic interpretation. Estimates of the hydrocarbons initially in place placed a reservoir limit between 4250 and 5000 feet from the test well.

Confirmation of Results:

The results of this analysis were later confirmed by the drilling of two dry holes on a farmout after the test.

GENERAL

Reservoir: Wilcox (sand)
Depth: 11,200 feet
Reservoir Fluid: Gas and Condensate (12 Bbls/MMcf)
Porosity: 18 percent
Reservoir Temp.: 300°F

Location: South Texas
Net Pay Thickness: 19 feet avg.
Initial Pressure: 9190 psi
Water Saturation: 39 percent
Cumulative Production: 25 MMcf
Type of Trap: Structural

TESTS

Buildup Test: Duration: 194 hours; Radius of Investigation: 1750 feet; Instrumentation: Amerada

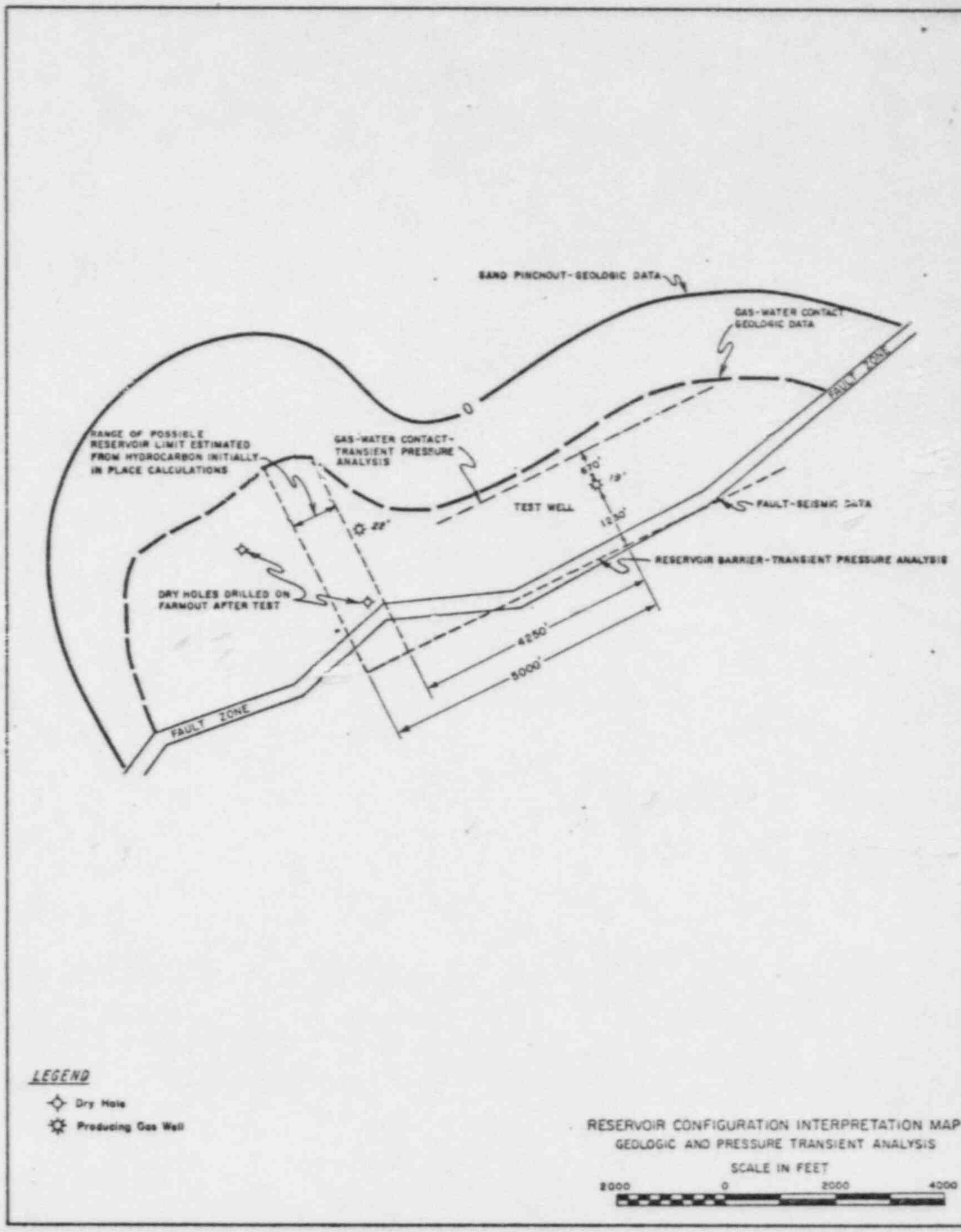
Drawdown Test: Duration: 211 hours; Radius of Investigation: 2650 feet; Flow Rate: 3 MMcf/D plus condensate Instrumentation: Amerada

RESULTS OF ANALYSIS

Skin Factor: +3
Static Res. Press.: 9130 psi

Producing Efficiency: 60 percent
Effective Perm.: 3 to 10 md.

Reservoir Barriers: 1230 feet, gas-water contact 670 feet
Hydrocarbons Initially In Place: 10 M^3cf of gas plus 121 MSTB condensate



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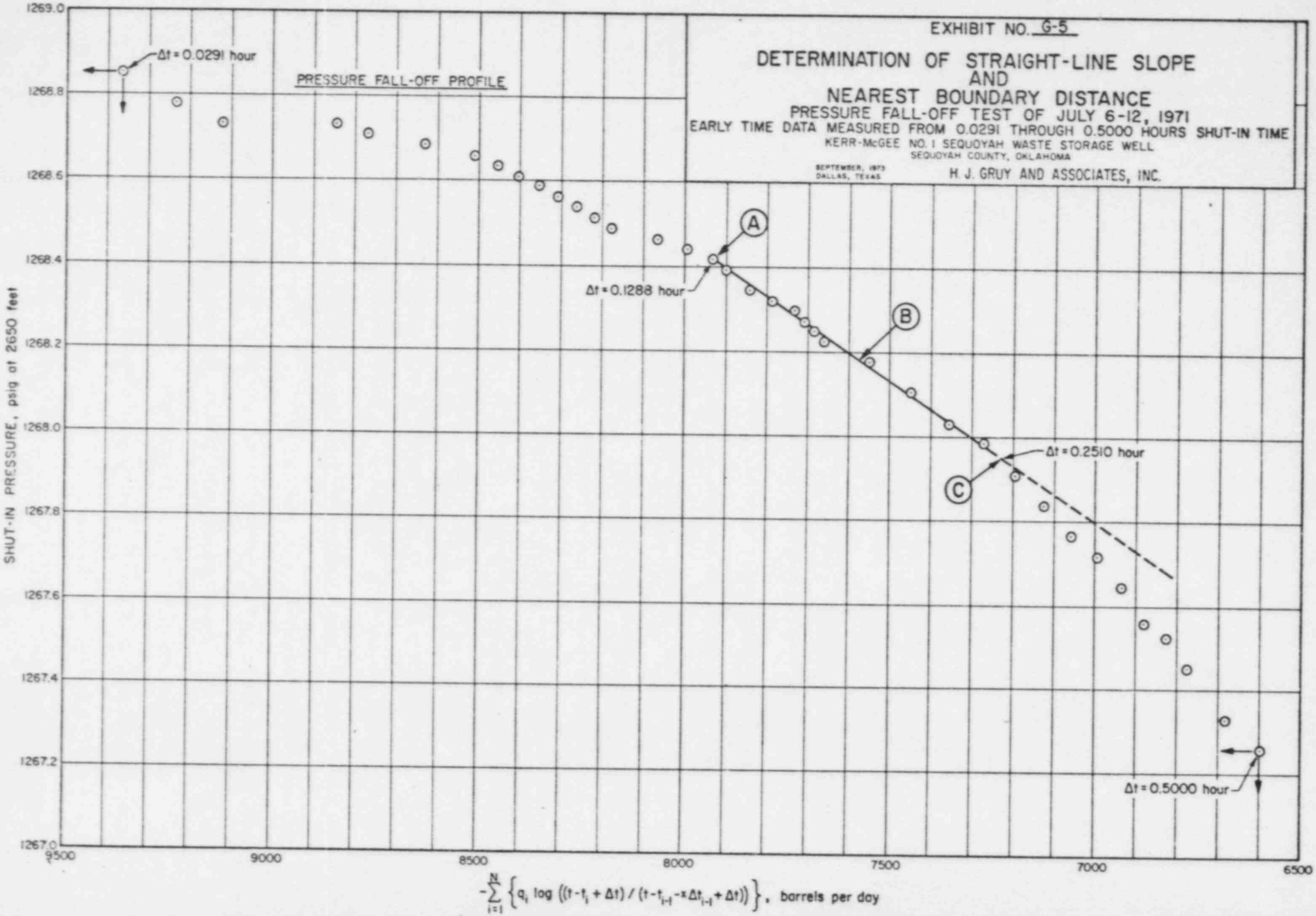


EXHIBIT NO. G-5
DETERMINATION OF STRAIGHT-LINE SLOPE AND NEAREST BOUNDARY DISTANCE
PRESSURE FALL-OFF TEST OF JULY 6-12, 1971
EARLY TIME DATA MEASURED FROM 0.0291 THROUGH 0.5000 HOURS SHUT-IN TIME
KERR-McGEE NO. 1 SEQUOYAH WASTE STORAGE WELL
SEQUOYAH COUNTY, OKLAHOMA
SEPTEMBER, 1973
DALLAS, TEXAS
H. J. GRUY AND ASSOCIATES, INC.
PRESSURE FALL-OFF PROFILE
Δt = 0.0291 hour
Δt = 0.1288 hour
Δt = 0.2510 hour
Δt = 0.5000 hour
A
B
C
SHUT-IN PRESSURE, psig at 2650 feet
1269.0
1268.8
1268.6
1268.4
1268.2
1268.0
1267.8
1267.6
1267.4
1267.2
1267.0
9500
9000
8500
8000
7500
7000
6500
$-\sum_{i=1}^{N} \left\{ q_i \log \left((t - t_i + \Delta t) / (t - t_{i-1} - x \Delta t_{i-1} + \Delta t) \right) \right\}$, barrels per day

Legend For Exhibit No. G-5

Analysis of Early-Time Pressure Fall-Off Data

Test of July 6-12, 1971

Kerr-McGee No. 1 Sequoyah Waste Storage Well

Sequoyah County, Oklahoma

(A.) Straight-line region of pressure fall-off profile begins at stabilization of mass transfer in wellbore and pipeline at a shut-in time of 0.1288 hour.

(B.) Least-square fit of straight-line region data yields a slope, m, of 0.0006599 psi/barrel per day and the following results:

(1) Equation of Straight-Line Region

$p_{ws} = 1,263.184 - 0.0006599(X_n)$

where

$$X_n = \sum_{i=1}^{N} (q_i) \log \frac{t - t_i + \Delta t_n}{t - t_{i-1} - X\Delta t_{i-1} + \Delta t_n}$$

q_i = producing rate of ith rate period, barrels per day

t = total injection time at shut-in, hours

t_i = total injection time at end of ith rate period, hours

t_{i-1} = total injection time at end of previous rate period, hours

$X\Delta t_{i-1}$ = incremental shut-in time between rate period, hours

Δt_n = shut-in time at point of nth pressure measurement, hours

i = iteration integer pertaining to injection rate schedule

n = integer pertaining to shut-in point number

N = total number of injection rates

(2) Permeability-Thickness Calculation Based on the Slope, m, and the Water Viscosity, μ_w

$(kh)_t = 162.6\mu_w/m$

$= 162.6 \times 0.925/0.0006599$

$= \underline{227,900}$ md - ft.

$\bar{k} = \underline{1965}$md avg. for h = 116 ft.

(C.) Nearest boundary reflected at 0.251 hour shut-in time in Layer No. 5, the most permeable layer. Calculated distance to boundary is shown as follows:

$$d_1 = (k_5 t/948\phi_5\mu_w c_t)^{0.5}$$

where

k_5 = effective permeability to water in Layer No. 5

t = transient time, hours

ϕ_5 = porosity of Layer No. 5

μ_w = water viscosity, cp

c_t = total water and rock compressibility, vol. per vol. /psi

based on radioactive tracer surveys,

$k_5 = (q_i/q_t)(kh)_t/h_5$

$= 0.37 \times 227,900/34$

= 2,480md for Layer No. 5 thickness of 34 feet

and

$$d_1 = (2,480 \times 0.251/948 \times 0.058 \times 0.925 \times 9.03\times10^{-6})^{0.5}$$

$= \underline{1,164}$ ft. $\approx \underline{1,200}$ ft. from well to nearest boundary in Layer No. 5

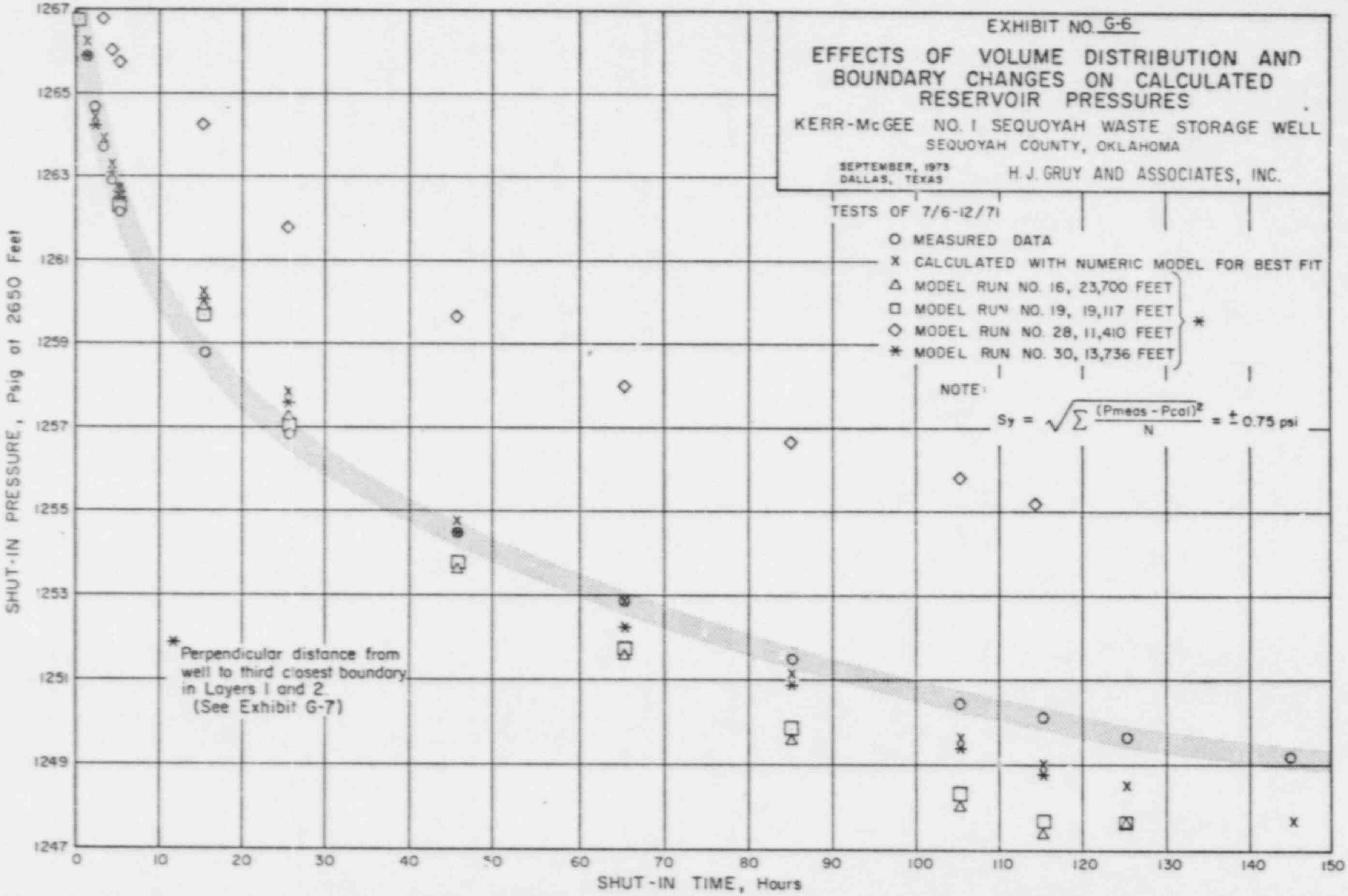


EXHIBIT NO. G-6
EFFECTS OF VOLUME DISTRIBUTION AND BOUNDARY CHANGES ON CALCULATED RESERVOIR PRESSURES
KERR-McGEE NO. 1 SEQUOYAH WASTE STORAGE WELL
SEQUOYAH COUNTY, OKLAHOMA
SEPTEMBER, 1973
DALLAS, TEXAS
H. J. GRUY AND ASSOCIATES, INC.
TESTS OF 7/6-12/71
O MEASURED DATA
X CALCULATED WITH NUMERIC MODEL FOR BEST FIT
△ MODEL RUN NO. 16, 23,700 FEET
□ MODEL RUN NO. 19, 19,117 FEET
◇ MODEL RUN NO. 28, 11,410 FEET
* MODEL RUN NO. 30, 13,736 FEET
NOTE:
$S_y = \sqrt{\sum \frac{(P_{meas} - P_{cal})^2}{N}} = \pm 0.75$ psi
* Perpendicular distance from well to third closest boundary in Layers 1 and 2. (See Exhibit G-7)
SHUT-IN PRESSURE, Psig at 2650 Feet
SHUT-IN TIME, Hours
1267
1265
1263
1261
1259
1257
1255
1253
1251
1249
1247
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

EXHIBIT NO. G-7

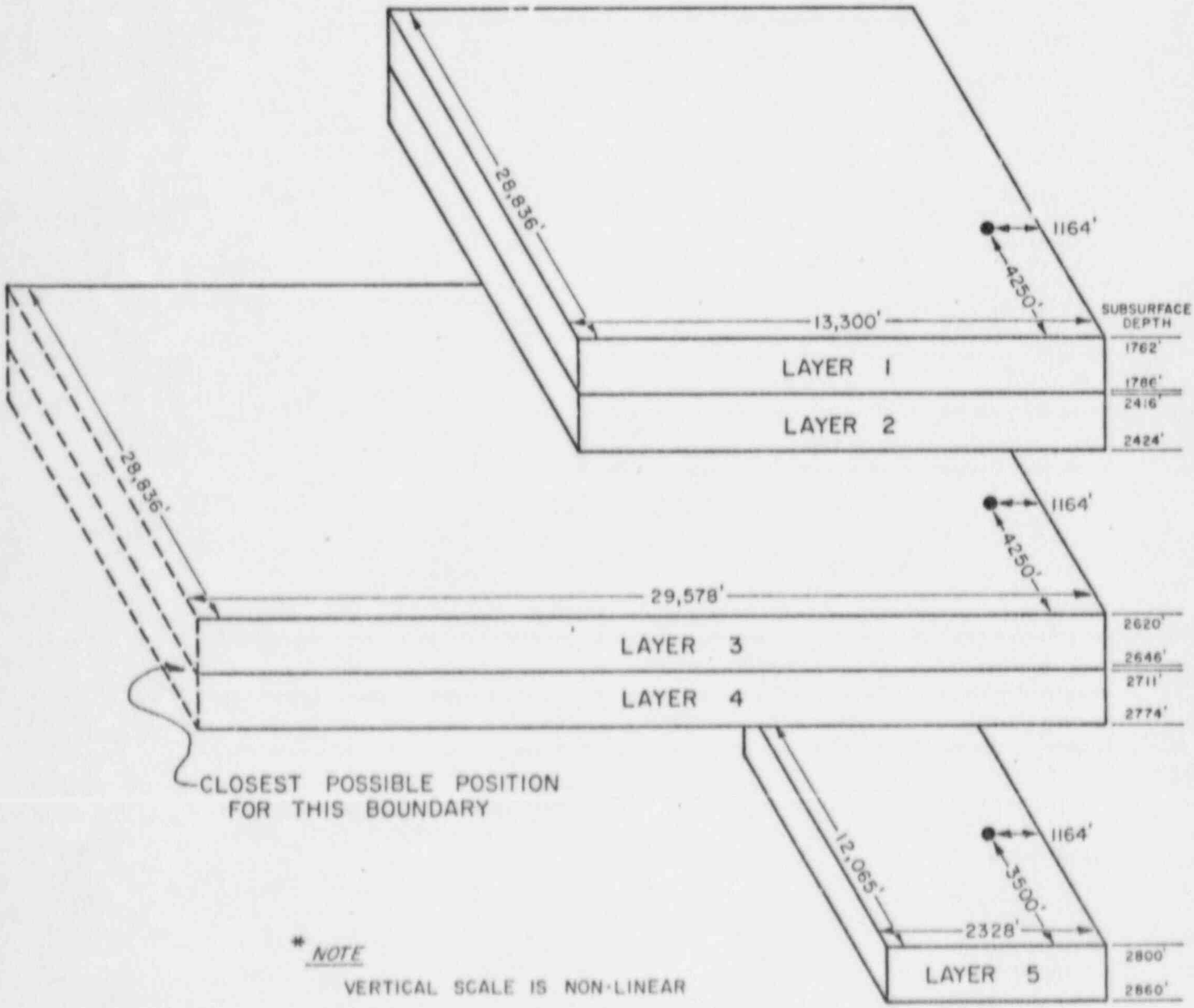
RESERVOIR MODEL
ARBUCKLE ZONE

KERR-McGEE NO. 1 SEQUOYAH WASTE STORAGE WELL

SEQUOYAH COUNTY, OKLAHOMA

SEPTEMBER, 1973
DALLAS, TEXAS

H. J. GRUY AND ASSOCIATES, INC.



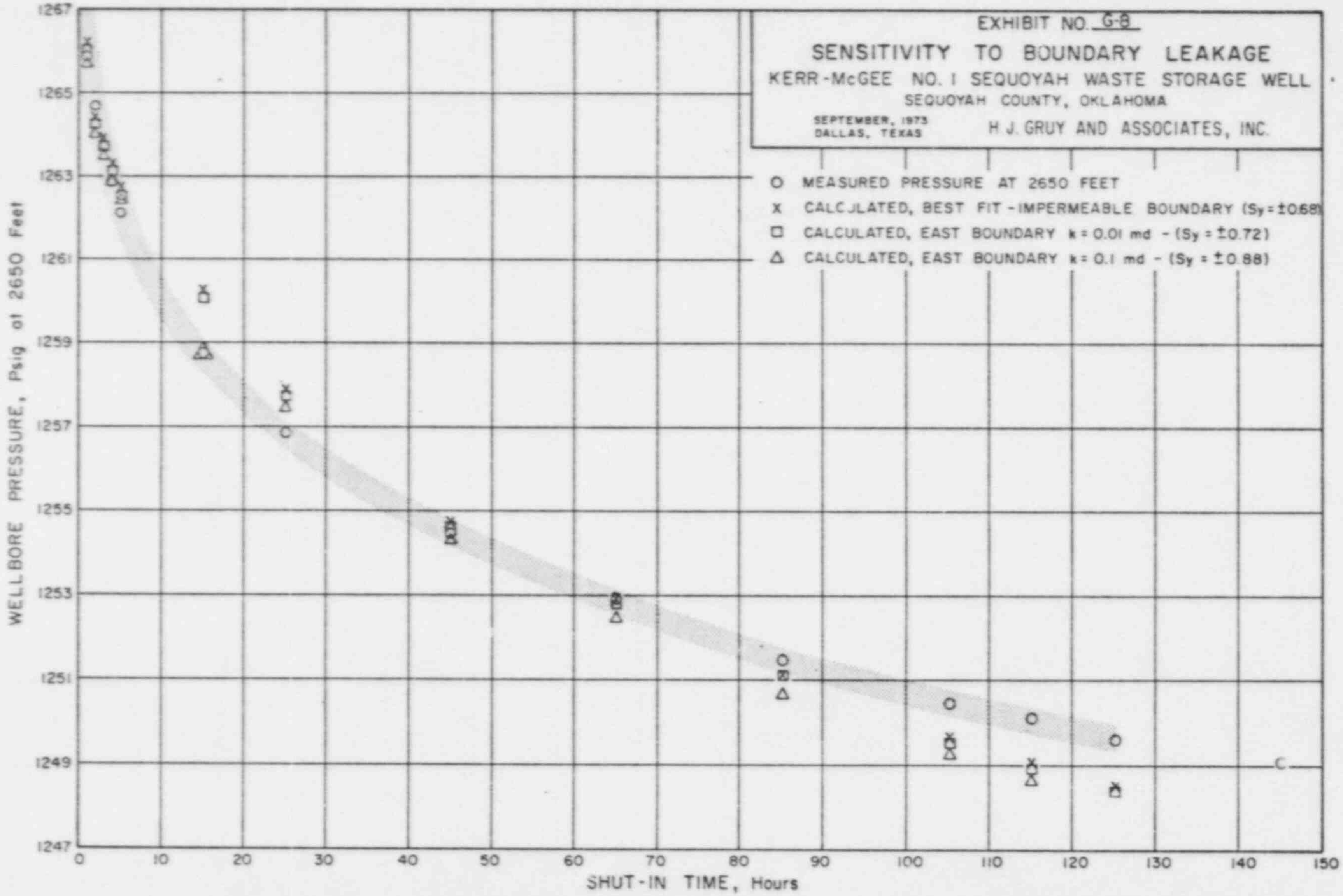


EXHIBIT NO. G-8
SENSITIVITY TO BOUNDARY LEAKAGE
KERR-McGEE NO. 1 SEQUOYAH WASTE STORAGE WELL
SEQUOYAH COUNTY, OKLAHOMA
SEPTEMBER, 1973
DALLAS, TEXAS
H. J. GRUY AND ASSOCIATES, INC.
O MEASURED PRESSURE AT 2650 FEET
X CALCULATED, BEST FIT - IMPERMEABLE BOUNDARY (Sy = ±0.68)
□ CALCULATED, EAST BOUNDARY k = 0.01 md - (Sy = ±0.72)
△ CALCULATED, EAST BOUNDARY k = 0.1 md - (Sy = ±0.88)
WELLBORE PRESSURE, Psig at 2650 Feet
1267
1265
1263
1261
1259
1257
1255
1253
1251
1249
1247
SHUT-IN TIME, Hours
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

H. J. GRUY

CHAIRMAN OF THE BOARD AND CHIEF EXECUTIVE OFFICER
H. J. GRUY AND ASSOCIATES, INC. AND GRUY MANAGEMENT SERVICE CO.
DALLAS AND HOUSTON

Mr. Gruy received a B.S. Degree in Petroleum Engineering from Texas A&M University in 1937 and was awarded the Professional Degree of Petroleum Engineer by that institution in 1956.

From 1938 until 1942, he was employed by Shell Oil Company as exploitation engineer at various locations in Louisiana, Arkansas and Texas. In 1942, he became District Engineer for the East Texas District and was the Shell Oil representative for a number of field engineering and geological committees.

From 1945 until 1950, he was a petroleum engineer and geologist with the consulting firm of DeGolyer and MacNaughton.

In 1950, Mr. Gruy organized his own firm and has been an independent petroleum consultant to the present time.

In addition to drilling and production, his experience includes evaluation of oil and gas producing properties, drilling blocks and non-producing leases. He has been in responsible charge of numerous reservoir and geologic studies throughout the United States, Argentina, Venezuela, Alaska, Australia, Turkey, Africa, the North Sea, and the Arabian Gulf.

His activities have included testimony before the Federal Power Commission on gas reserves and deliverability, before the Securities and Exchange Commission on oil and gas reserves and values, before regulatory bodies of various states on proration problems, and as an expert witness in both federal and state courts on behalf of various clients.

Mr. Gruy is a member of the American Association of Petroleum Geologists, the American Petroleum Institute, the Society of Petroleum Engineers of AIME, the Society of Petroleum Evaluation Engineers and the Texas Society of Professional Engineers. He was President of the Society of Petroleum Evaluation Engineers for 1964 and the District Representative for the Dallas District of the American Association of Petroleum Geologists for 1964-1966. He served as Treasurer of the Society of Petroleum Engineers of AIME from February, 1965 to February, 1967. Mr. Gruy was installed as

President of the Society of Petroleum Engineers of AIME at the annual meeting in New York in February, 1968. He served a three-year term on the Board of Directors of AIME and SPE as President-Elect of SPE in 1967, President in 1968 and Past President in 1969. He served as a Vice President of AIME for the year 1969. He was President of the Dallas Petroleum Engineer's Club in 1950, President of the Fort Worth Petroleum Engineer's Club in 1953 and Chairman of the Fort Worth Section of the American Institute of Mining, Metallurgical and Petroleum Engineers in 1953. He is a member of Tau Beta Pi, honorary engineering society; a Fellow of the Texas Academy of Science; and a registered professional engineer in the State of Texas. In 1965 and 1966, he served as a Distinguished Lecturer for the Society of Petroleum Engineers of AIME.

On February 25, 1966, at the National Engineers Week Banquet in Dallas, Mr. Gruy received an award "In Recognition of Outstanding Achievements in the Field of Petroleum Engineering."

PUBLICATIONS

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