MEASUREMENTS OF OIL SHALE COMPACTION

L. John Fahy
James D. Schreiber
Bruce C. Sudduth
Western Research Institute
P.O. Box 3395, University Station
Laramie, WY 82071

ABSTRACT

Oil shale compaction has been measured in a series of laboratory experiments at the Western Research Institute (WRI). In these experiments, the compaction measurements have corresponded to stacked beds of shale bricks at low void volumes of 12% and 25% bed porosity. Compaction of the shale bricks during retorting was measured by applying a constant mechanical force of 138-689 kPa to the top of the shale bed. This range of mechanical compression corresponds to the weight of overlying shale rubble in commercial modified in situ retorts.

Laboratory tests indicate that rich shale particles deform freely, and the particle deformation is estimated to occur principally in the temperature range of 315-430°C. For shale grades greater than 125 L/Mg the bed compaction is proportional to the initial bed porosity, and the shale particles deform to fill all of the initial void volume when the shale grade is greater than 170 L/Mg. However, the compaction of leaner shale particles with grades of 104 L/Mg or less is constant regardless of initial bed porosity. These observations are consistent with the previously reported transition from a continuous to a discontinuous mineral matrix in the range of 125-145 L/Mg shale grade and other measurements of kerogen decomposition to a viscous bitumen intermediate at temperatures of 315-430°C.

All of the current compaction measurements were correlated with the shale grades, bed porosities, and applied forces in the laboratory retorting experiments. This correlation was incorporated into a one-dimensional oil shale retorting model, and 8% compaction has been predicted for Rio Blanco Retort 1 at the C-a lease tract. The model predictions agree satisfactorily with downhole video measurements of 12-16% compaction in the Retort 1 rubble bed. In Retort 1, this compaction and settling of the shale rubble has resulted in a large open cavity between the retort ceiling and rubble surface.

INTRODUCTION

Oil shale rubble is known to compact during retorting in large field retorts. For example, postburn investigation of the Rio Blanco Retort 1 at the C-a lease tract in Colorado shows significant shale compaction (Sudduth 1984). Such compaction can cause nonuniformity of retorting (Cha 1985) and the formation of large cavities at the top of in situ retorts. The development of large cavities can induce the collapse of the overburden which may result in significant environmental consequences.

A series of experiments were conducted to study oil shale compaction during retorting. The objectives of these experiments were to correlate oil shale compaction as a function of grade, void volume and overburden pressure and to compare the experimental results to results predicted by a one-dimensional oil shale retorting model. The experiments also studied the effects of mineral decomposition and particle size.

Experimental Preparation and Procedure

The compaction experiments were conducted in WRI's low-void retort (Figure 1). The retort is an upright rectangular box with a square 61x61 cm inside cross-section and consists of a lid section, a spool piece containing the shale sample, a grate, and the bottom collector. All pieces are flanged and bolted together. A hydraulic cylinder is located on the top of the retort for applying pressure to simulate the weight of the overlying shale rubble.

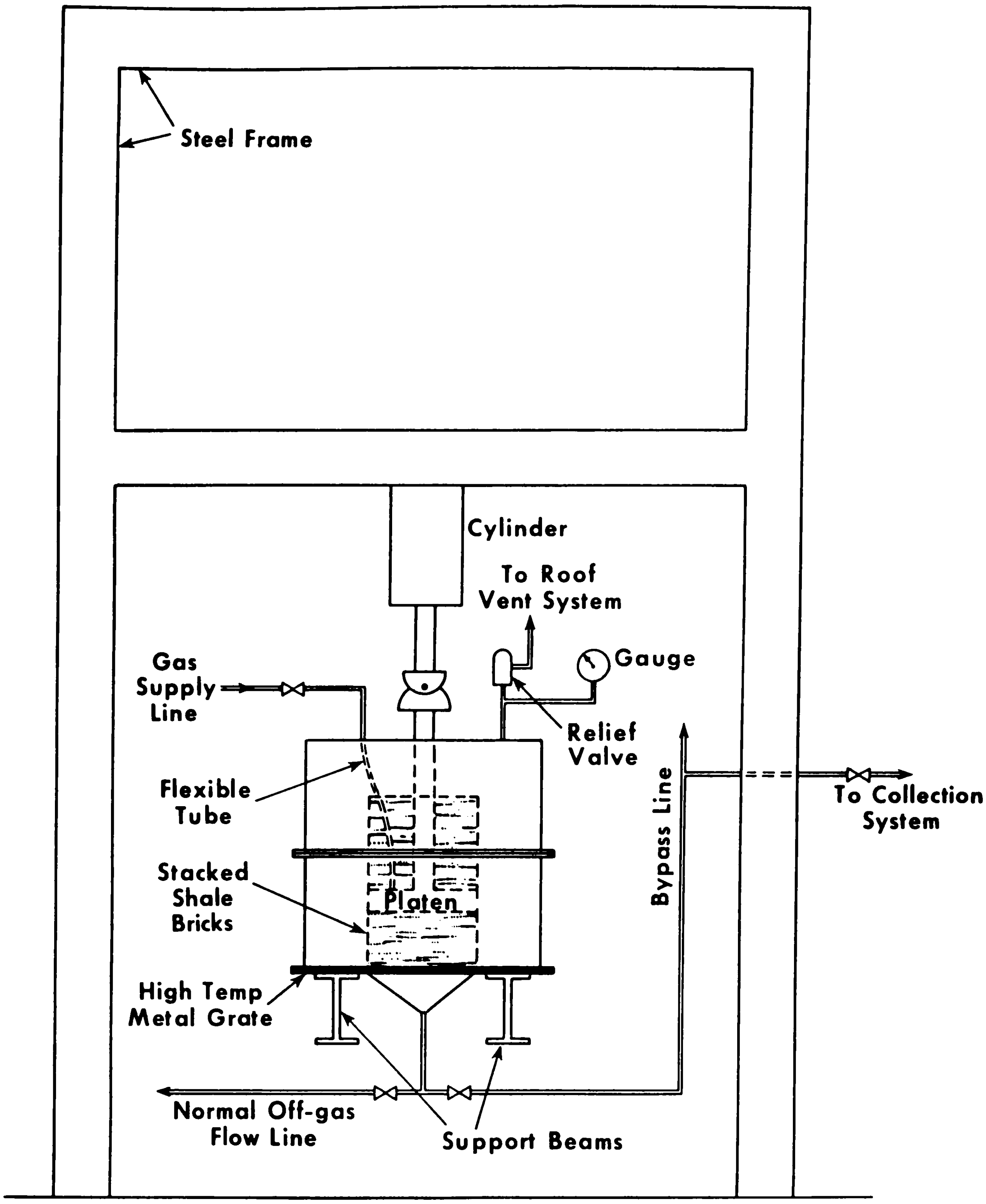

Figure 1. Schematic of WRI Low-Void Retort

The retort spool piece was loaded to a height of approximately 40 cm with four layers of 10x10x10 cm oil shale bricks for all but the first experiment (Table 1). For some experiments, fine oil shale rubble 0.18-0.32 cm diameter was placed between the oil shale bricks. The desired void volume was achieved by spacing a calculated mass of oil shale bricks, spacers, and rubble as equally as possible in the spool piece. The oil shale brick layers were staggered to provide a tortuous path for the injected gases.

The oil shale charges were either indirectly retorted with hot nitrogen or combustion retorted with air. Nitrogen or air was heated with calrod heaters and injected at the top of the retort. Produced gas and liquids were removed from the bottom collector and routed to the gas cleanup system. The injection and production gas streams were metered and the data were stored on a minicomputer for both real-time and end-of-test analysis.

Table 1. Oil Shale Compaction Experimental Conditions

Test	Shale Grade (L/Mg)	Void Volume %	Heating Rate (°C/hr)	Brick Size (cm)	Rubble	Overburden Pressure kPa	Retorting
1	104	12	16.9	5x10x10	No	689	Indirect
2	100	12	14.6	10x10x10	No	689	Indirect
3	109	12	3.9	10x10x10	No	689	Indirect
4	125	12	2.8	10x10x10	No	689	Indirect
5	175	12	1.8	10x10x10	No	689	Indirect
6	100	25	2.3	10x10x10	No	689	Indirect
7	146	25	2.2	10x10x10	No	689	Indirect
8	180	25	2.4	10x10x10	No	689	Indirect
9	175	25	1.8	10x10x10	No	414	Indirect
10	200	25	1.5	10x10x10	No	138	Indirect
11	75	12	19.3	10x10x10	Yes	689	Combustion
12	142	12	1.8	10x10x10	Yes	689	Indirect
13	142	12	49.6	10x10x10	No	689	Combustion

All but two experiments were conducted with a simulated overburden pressure of 689 kPa which corresponds to the theoretical pressure at the bottom of a full-scale in situ retort (Carley 1977). To study the effects of pressure at higher locations in a retort, two experiments were conducted at 138 and 414 kPa.

RESULTS AND DISCUSSION

Experimental

During the experiments, the start of compaction was preceded by a small amount of bed expansion. The 138 kPa test exhibited the greatest amount of bed expansion with an expansion of approximately 1.2% of the bed height. This is almost three times the bed expansion measured in the experiments conducted with 689 kPa overburden pressure. It is believed that this bed expansion occurred because the thermal expansion forces initially exceeded the compaction forces, resulting in a short period of bed expansion. When the oil shale starts to retort, it deforms due to the compaction forces acting downward and the thermal expansion forces acting upward. This results in an increasing amount of compaction as the retorting zone moves downward through the shale bed. At the end of each test, additional compaction was measured as the shale bed cooled. This compaction is attributed to thermal contraction.

The compaction that was measured in these experiments can be separated into the compaction that occurred during retorting and the compaction that occurred as the retort cooled down (Table 2).

Table 2. Compaction Test Results

Test	Retorting Phase Compaction % of Bed Height	Final Compaction % of Bed Height	Calculated Compaction, Eqn. 1 % of Bed Height
1	4.1	6.2	6.5
2	4.3	6.8	6.3
3	3.1	5.5	6.9
4	6.6	10.2	8.7
5	11.0	15.3	14.4
6	3.1	5.5	7.6
7	13.6	16.7	17.1
8	22.9	24.3	24.9
9	19.7	22.4	20.6
10	14.0	15.5	15.5
11	0.9	3.6	5.1
12	11.6	14.1	10.8
13	12.9	14.8	10.8

At the end of retorting, the 104 L/Mg oil shale charges compacted to about 3 to 4% of the bed height, while the richer oil shales compacted to a maximum of 23% of the bed height.

Oil shale compaction increased with an increase in grade (Figures 2 and 3). This finding correlates well with earlier research that suggests Green River shale is a two-component oil shale (Tisot 1967; Tisot et al. 1971). At low organic content (less than 125 L/Mg Fischer assay), the oil shale has essentially a continuous mineral matrix. The mineral particles in the leaner oil shales are bonded together and possess high mechanical strength. Conversely, the richer oil shales (greater than 145 L/Mg by Fischer assay) tend to have a discontinuous mineral matrix, and the organic matter forms the continuous phase. The mineral particles in the richer oil shales are loosely bonded and possess low mechanical strength. When the organic matter in the richer oil shales is removed, the mechanical strength significantly decreases, and the shale compacts more than the leaner shales because it is no longer a competent mass. Physical inspection of the retorted oil shale bricks indicates that the richer oil shale bricks (greater than 125 L/Mg) compact from the applied pressure and deform to fill part or all of the existing void space around the bricks.

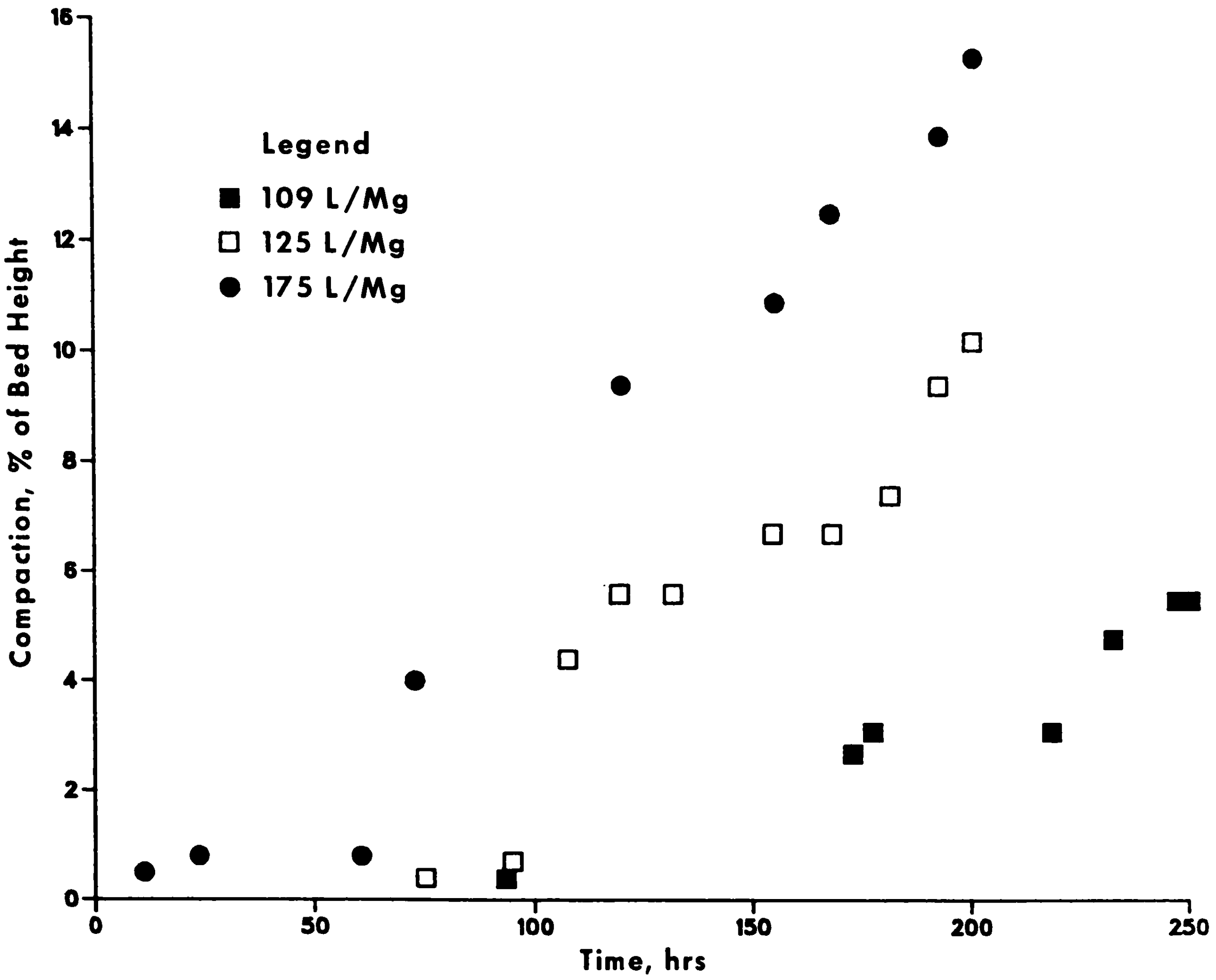

Figure 2. Oil Shale Compaction Profile at 12% Void Volume

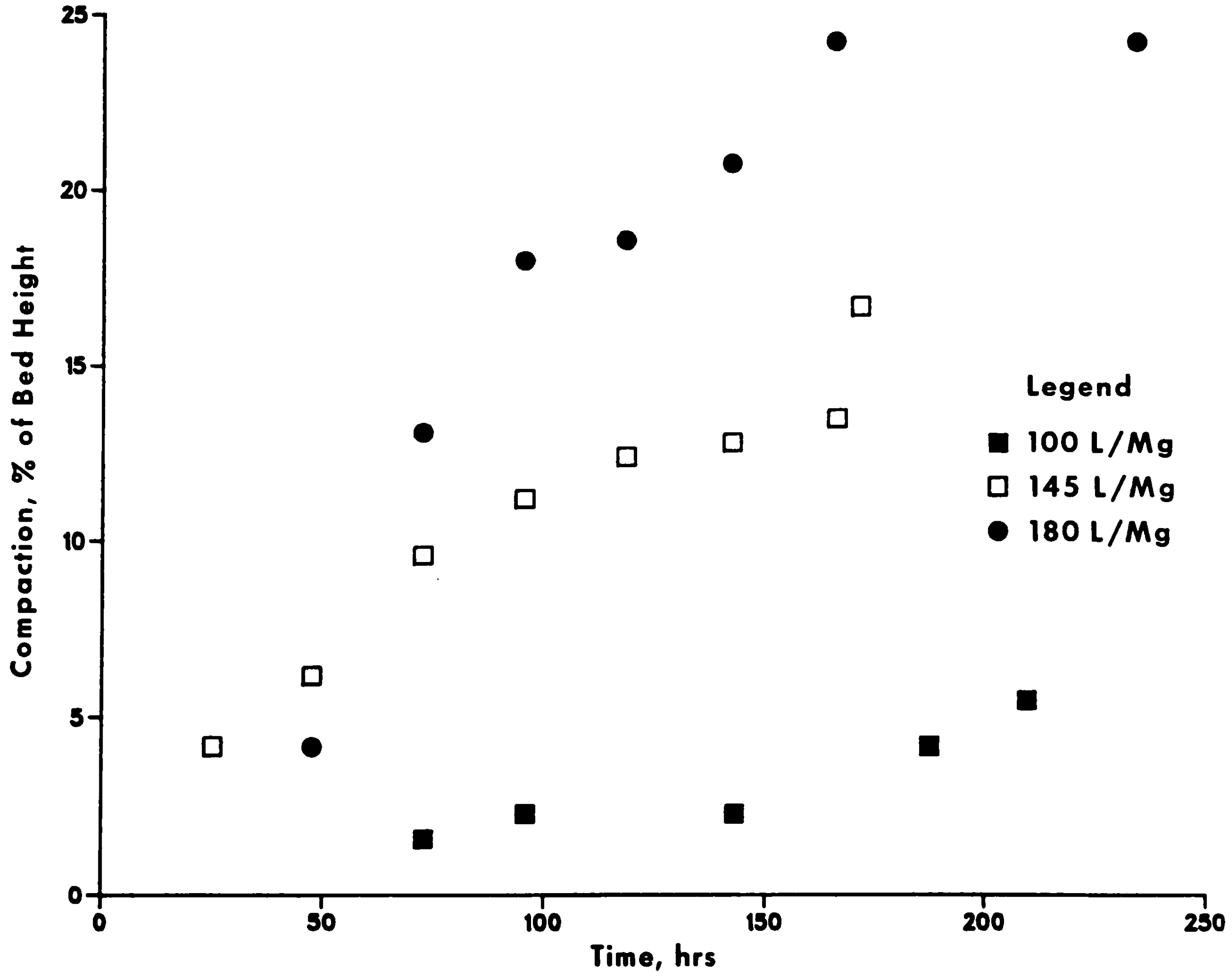

Figure 3. Oil Shale Compaction Profile at 25% Void Volume

An increase in void volume did not change the amount of compaction for shale charges with a grade less than 125 L/Mg. However, the richer oil shales (greater than 145 L/Mg) experienced more compaction with an increase in void volume. Compaction of the 175 L/Mg shale approximately equaled the available void volume. Oil shale compaction as a function of void volume is presented in Figure 4.

While the overall compaction could be measured, the temperature range in which compaction was occurring could not be observed directly at different levels within the shale bed. The approximate temperature range for compaction has been estimated by comparing the rate of bed compaction with the velocity of different temperatures moving through the shale bed. An example of the cumulative heating and compaction in the shale bed is presented in Figure 5. The solid lines in Figure 5 represent the measured cumulative heating of the shale bed to a particular temperature. The dashed line represents the measured cumulative compaction.

Comparisons of the shale heating and compaction rates indicate that compaction occurs over a narrow temperature range between 315 and 430°C. This is consistent with earlier studies that indicate compaction is influenced by the bitumen intermediate acting as a lubricant prior to or during kerogen decomposition (Tisot et al. 1971).

As expected, a decrease in the simulated overburden pressure resulted in a decrease in the amount of compaction (Figure 6). However, the amount of compaction measured at the low pressures was still significant. A reduction in pressure from 689 to 138 kPa is equivalent to moving from the bottom of the retort to almost the top of the rubble column in a large retort. This reduction in pressure decreased the overall compaction by only 36%, suggesting that compaction of rich shale is likely to occur throughout an in situ retort.

Mineral carbonate decomposition appears to have little or no effect on the amount of compaction that will occur during oil shale retorting. The effects of mineral decomposition were determined by comparing results from two experiments that had identical 142 L/Mg oil shale charges where one was indirectly retorted with hot nitrogen and the other was combustion retorted. The indirect retorting test was operated using maximum shale bed temperatures ranging from 677°C in the top layer to only 316°C in the bottom layer. These low temperatures resulted in only 37% of the mineral carbonates being decomposed. In contrast, the combustion retorting experiment was operated at temperatures in excess of 871°C in all four layers, and 67% of the mineral carbonates were decomposed. The final overall compaction measured for the two experiments was similar even though there was a twofold increase in the amount of mineral decomposition during combustion retorting (Tables 1 and 2).

Different size oil shale bricks were retorted under identical conditions with basically the same amount of compaction (Tables 1 and 2). Also, two experiments were conducted with fine rubble placed between the bricks. Oil shale compaction results both with and without fine rubble were plotted as a function of oil shale grade (Figure 7). The data indicate a similar trend of increasing compaction with an increase in oil shale grade with and without the fine rubble.

Modeling of Shale Compaction

A model for oil shale compaction was developed that incorporates these experimental data along with a vertical pressure distribution model into the one-dimensional retorting model developed by Braun (1981). The model retains all of the features of Braun's original model but also allows for the effects on the entire retorting process of the reduced void fraction following compaction to be taken into account.

An empirical correlation based on these experiments relates the final bed compaction (C) to the initial void fraction (ε), the shale grade (G) in L/Mg, and the overburden pressure (P_v) in MPa:

$$C = 0.02\varepsilon\,[F(G) - 5]\,\ln\,(10P_v + 1) + 0.05 \qquad (1)$$

where F(G) is an implicit function of grade (nearly linear for richer shales) (Figure 8). Calculated compactions are compared with measured values in Table 2. Since it is based on relatively few data, this correlation is strictly valid only for shale grades greater than 75 L/Mg, void fractions greater than 0.12, and vertical stresses greater than 138 kPa.

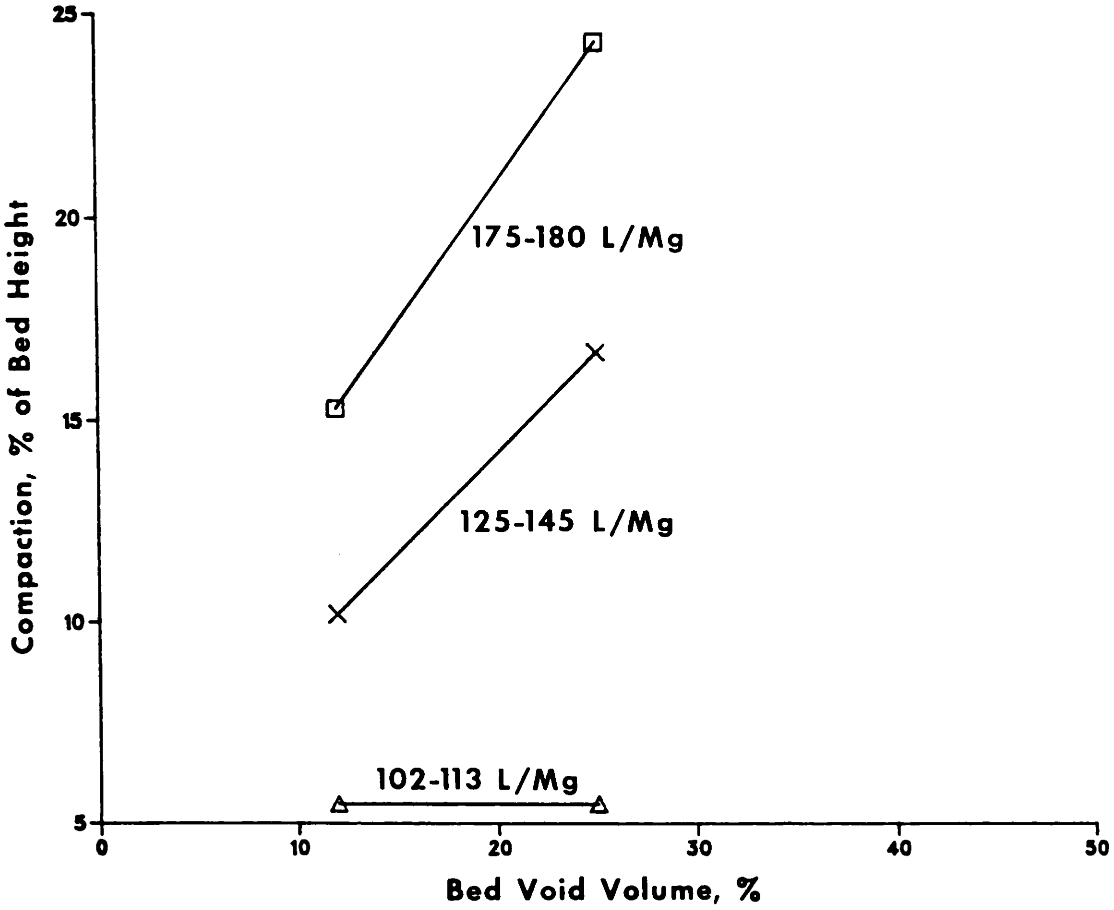

Figure 4. Oil Shale Compaction With 689 kPa Simulated Overburden Pressure

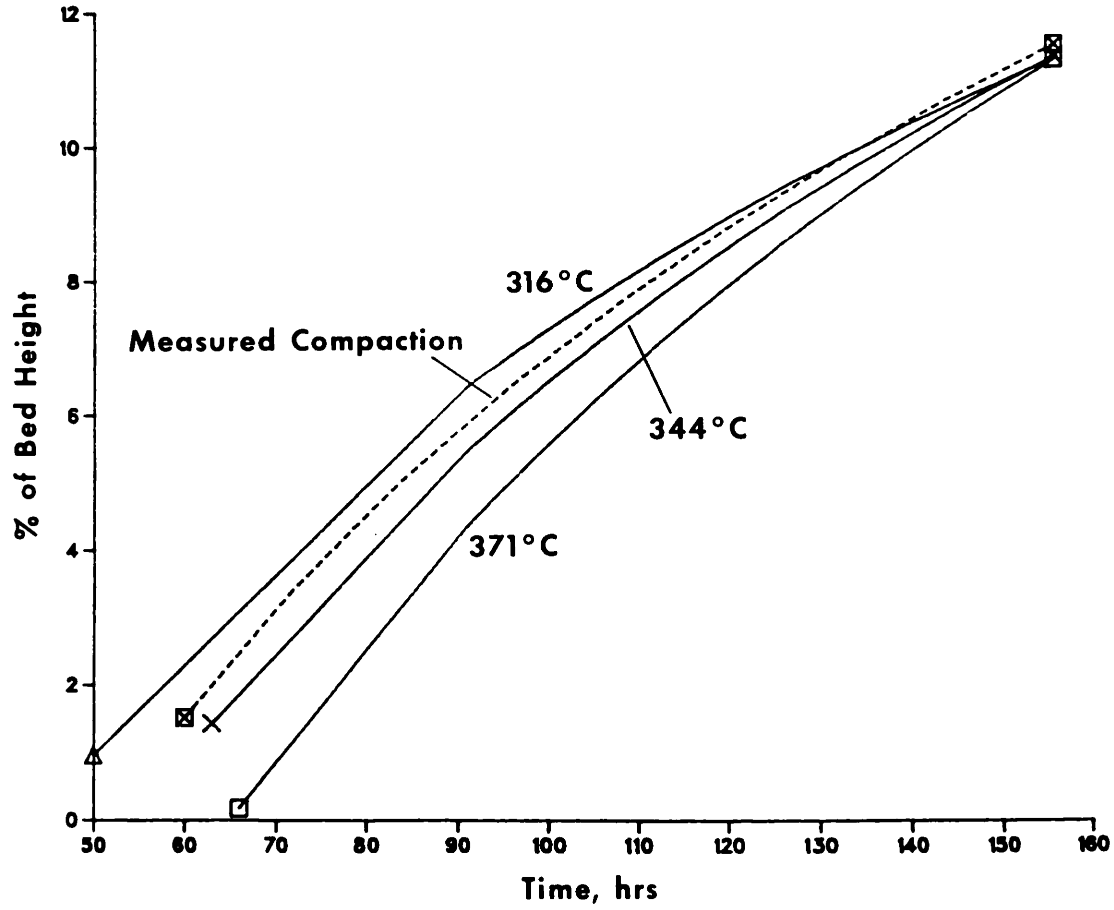

Figure 5. Comparison of Cumulative Heating and Compaction for 175 L/Mg Oil Shale at 12% Void Volume

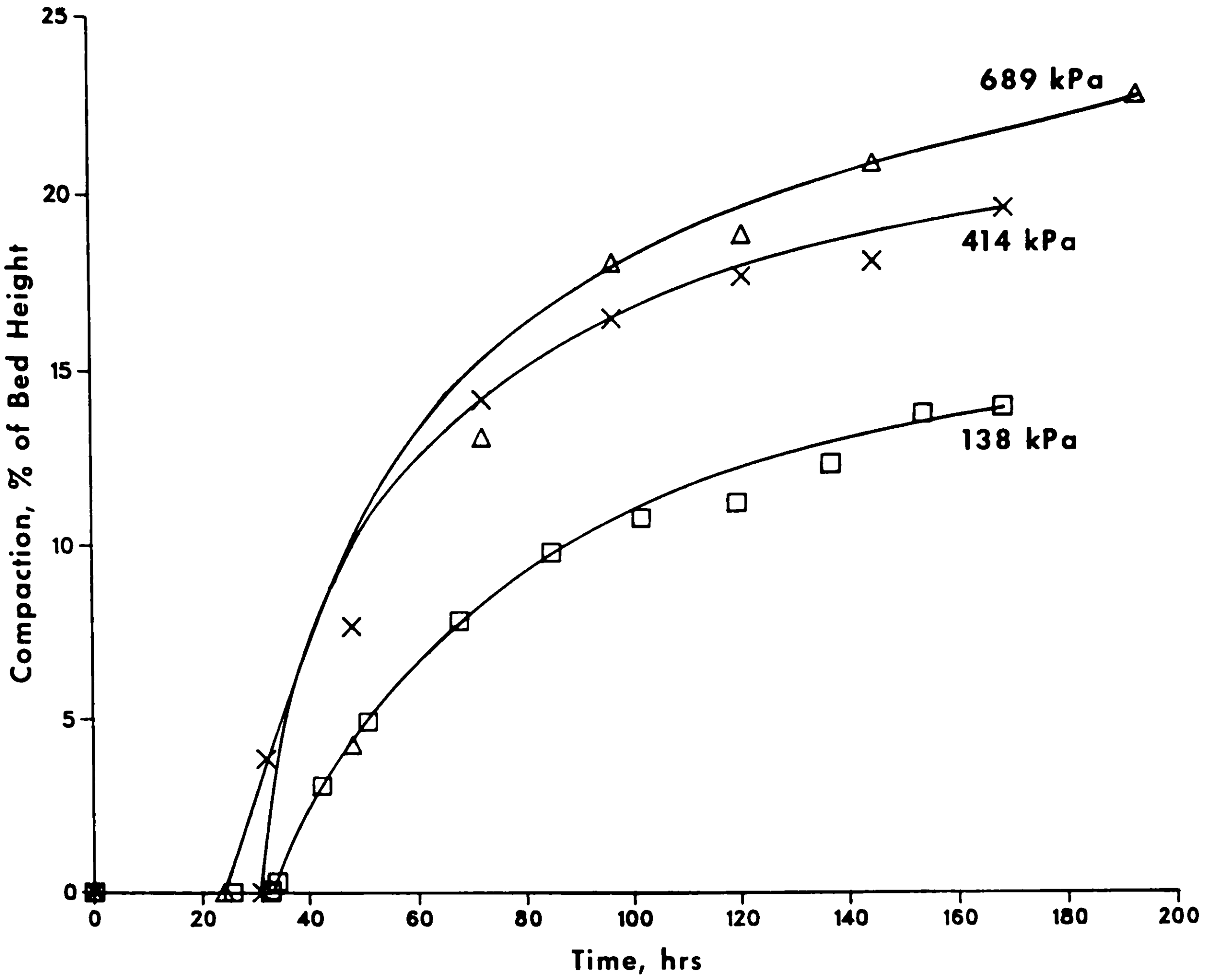

Figure 6. Effects of Pressure on Compaction With 125-200 L/Mg Oil Shale

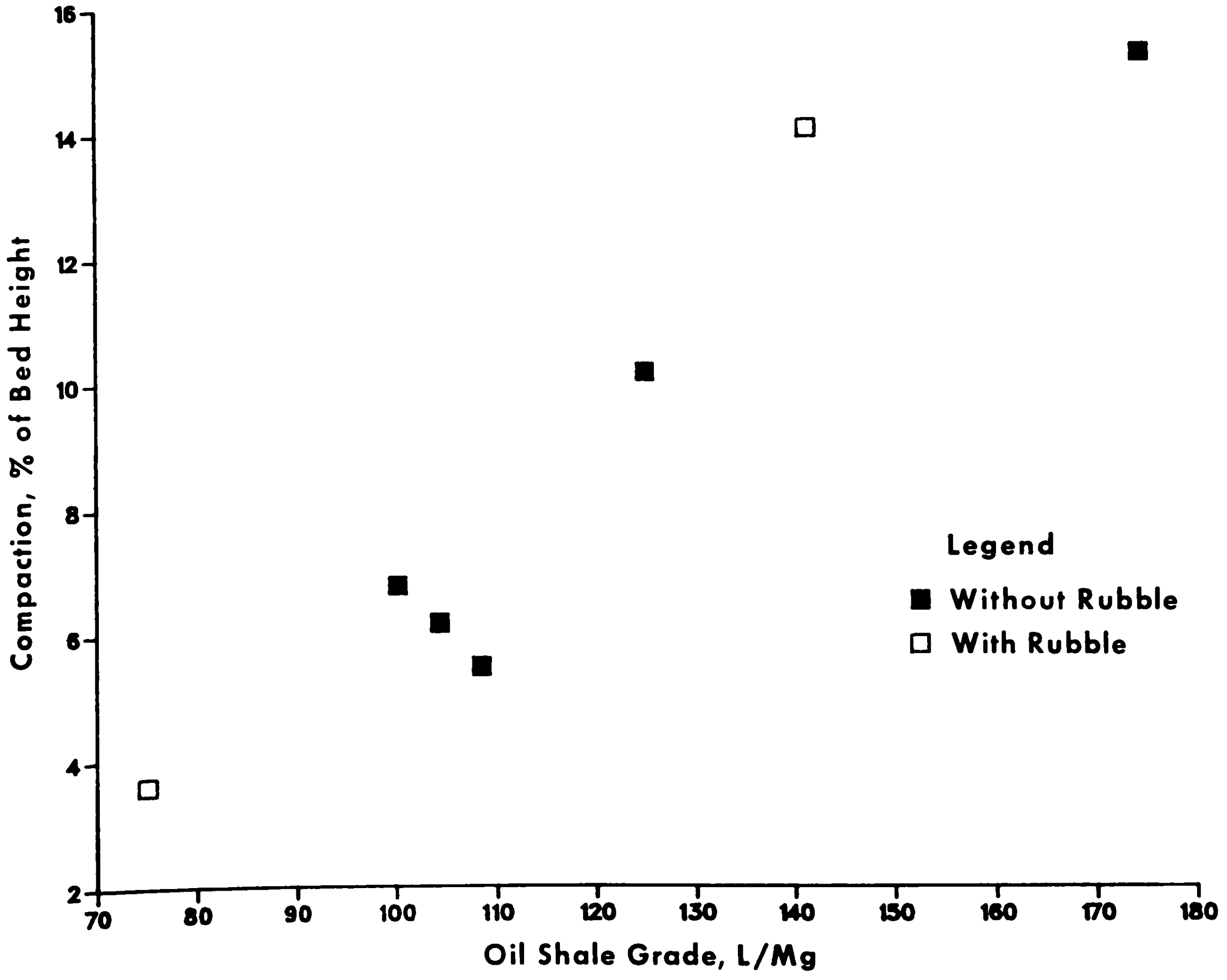

Figure 7. Effects of Oil Shale Rubble on Compaction at 12% Void Volume

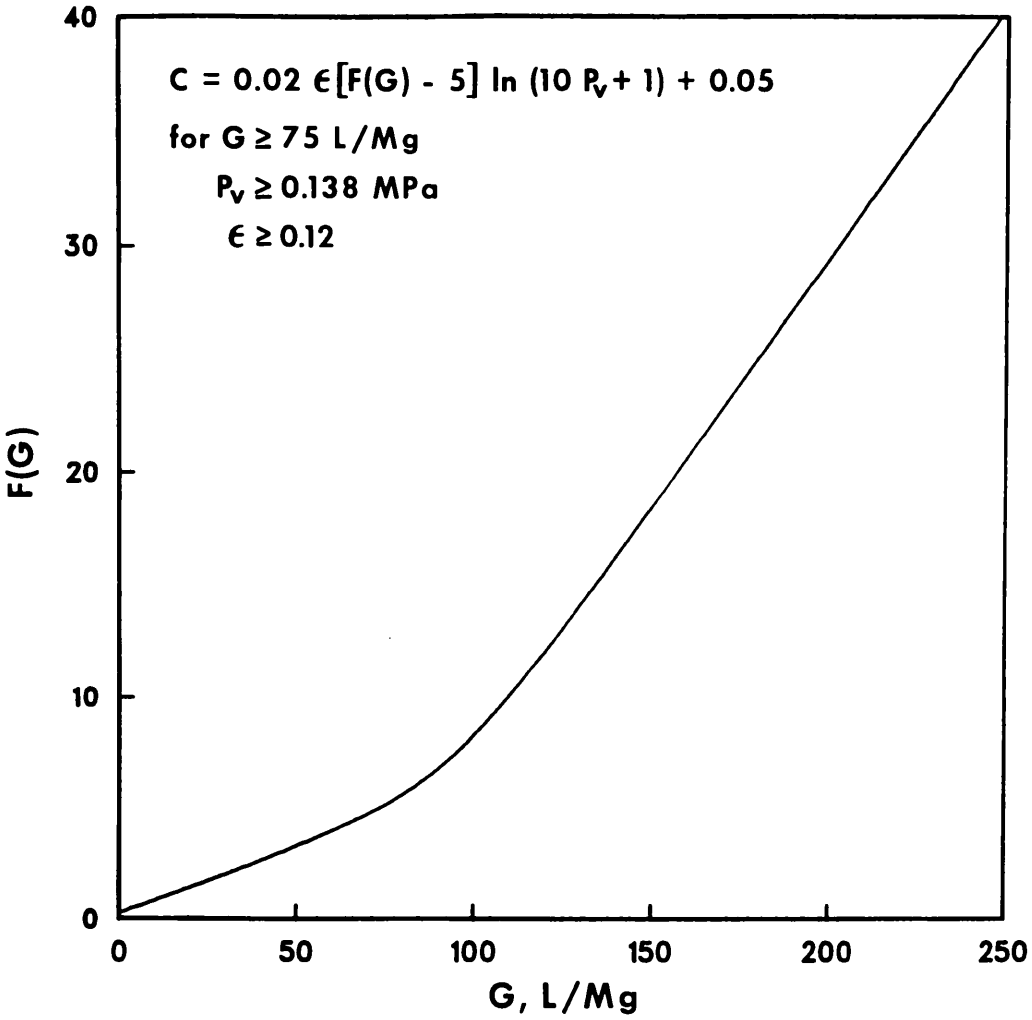

Figure 8. Correlation of Oil Shale Compaction Measurements

The overburden pressure distribution through the retort is given by a model developed by Carley and Thigpen (1977). For a cylindrical retort of radius R and length L, the vertical pressure P_v at the bottom is

$$P_v = A + (P_0 - A)\exp(-L/A) \qquad (2)$$

where P_0 is the pressure at the top of the bed, and $A=R\rho_b g/\mu K$. Here, ρ_b is the bulk density of the shale rubble, g is the acceleration of gravity, and μ is the coefficient of friction of shale. K is Rankine's coefficient of lateral earth pressure, $(1-\sin\alpha)/(1+\sin\alpha)$, and α is the angle of repose. Carley and Thigpen assume that $\mu=\tan\alpha$. Thigpen and Heard (1979) measured μ and $\tan\alpha$, finding that values $\mu=0.46$ and $\tan\alpha=0.55$ are most representative for 103- to 133-L/Mg shale, both before and after retorting. A value of $\mu=\tan\alpha=0.5$ is used in the current model. Equation 2 can be used to calculate the pressure throughout the retort. Since the retorting model calculates the shale density as it changes during retorting, the pressure P_v is obtained as a function of time and axial position in the retort.

Once the compaction of each grid element is calculated, the post-compaction void fraction is determined. This new void fraction is used in the Ergun equation to calculate the pressure drop over each grid element and in the calculation of heat and mass transfer coefficients in the retorted and burned zones of the retort. Since certain reactions, e.g., the steam-char reaction, depend upon both mass transfer rates and on the total gas pressure, while temperatures are obviously affected by heat transfer rates, the effects of compaction are indirectly imposed on the entire retorting process in this model.

The compaction/retorting model was applied to the Rio Blanco Oil Shale Company's (RBOSC) Retort 1, a vertical modified in situ retort that was processed from June to December, 1982. Postburn coring and tv-logging (Sudduth 1984) revealed that the retort bed compacted by 12-16%. Most of the details of this test are proprietary. It was necessary to assume some void fraction profile consistent with the reported quantity of shale removed during construction (RBOSC 1982). From this void fraction variation and Fisher assays of cores from the site (Trudell and Mason 1986), the variation of grade with depth was determined. A constant inlet gas flux of 0.23 mol/m^2·s, except during shutdown periods, allowed retorting to be completed in the reported 176 days.

The total compaction calculated for Retort 1 is 8.1%, which compares satisfactorily with the observed range, considering the lack of detailed information on the retort. Friction parameters used in the model may have been overestimated, thereby reducing the calculated compaction. Groundwater that flooded the retort long before the compaction measurements were made may have lubricated the shale particles, allowing the bed to settle more after retorting was completed. In addition, 3 to 5 m of ceiling fell some time after the top of the retort was cooled (Sudduth 1984). The shock to the bed undoubtedly compacted the bed more than could be accounted for in the model.

CONCLUSIONS

The following conclusions can be drawn from the oil shale compaction experimental and modeling results:

- Most oil shale compaction occurs early in the retorting phase between 315 and 430°C. Additional thermal contraction also occurs as the retort cools down.
- Compaction increases with an increase in oil shale grade.
- Compaction of richer oil shale grades (greater than 125 L/Mg by Fischer assay) increases with an increase in void volume.
- Compaction increases at greater depths in a retort, but the weight of the rubble column near the top of a VMIS retort is sufficient to cause compaction of richer oil shales.
- Experiments comparing pyrolysis and combustion retorting indicate that mineral decomposition does not significantly influence compaction.
- Neither the addition of rubble into the void space between oil shale bricks nor changing the oil shale brick size affected the overall compaction.
- The compaction model provides adequate estimates of the bed compaction that occurs during retorting.

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