SPENT SHALE COMPACTION FOR VOID VOLUME GENERATION IN IN SITU OIL SHALE PROCESSING

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ABSTRACT

Explosive compaction of spent shale in an in situ retort has been suggested as a means of obtaining the void volume required for the successful generation of subsequent retorts. Static compaction experiments and explicit finite-difference calculations have been used to provide a preliminary evaluation of the spent shale compaction concept. These experiments have provided basic compaction data on fragmented and reconstituted samples of oil shale from the Tipton Member of the Green River Formation in Wyoming.

Data were obtained on samples initially at room temperature and on samples heated to retort temperatures as high as 600°C. The initial fracture void volume, before retorting, varied from 25 percent to 50 percent. The data demonstrate that the energy required for compaction decreases substantially as the retorting temperature increases. The grade of oil shale was also a factor, as richer shales appear to offer less resistance to compaction for the same retorting history. One-dimensional finite-difference calculations, representative of simplified field geometries, were used to evaluate the sensitivity of compaction behavior to explosive characteristics, seismic coupling and compaction properties. These calculations indicate that for compaction at elevated temperatures, no more than a few pounds of explosive per ton should be sufficient to provide adequate compaction for a continuous in situ process. That is, all the void volume required for a new retort module may be economically obtained by explosively compacting the adjacent spent module. Further studies, including dynamic compaction experiments and two-dimensional finite-difference calculations, are required to refine the design of specific in situ operations.

INTRODUCTION

Generation of void volume and concordant permeability remains one of the major obstacles to the development of a successful in situ oil shale processing technology. Although the specific minimum void volume and permeability required remains to be established, it is well accepted that some significant void volume will be required in the generation of any successful in situ retort. At present, there is considerable question as to the most cost effective technology available to establish this required void volume. To date, the required void volume has been obtained almost exclusively by the partial mining away of rock in the retort region before explosive fragmentation (McCarthy and Cha 1976; Stone 1976). True in situ explosive fracturing for void volume generation would require a great deal of site specific information and is probably limited to near-surface deposits of oil shale where surface heave effects could be important. It has been suggested that some or all of the increased porosity required for in situ retorts could be obtained by the compaction of spent shale in previously generated and burned retorts. Early in 1977, the Laramie Energy Research Center (LERC) began a careful evaluation of the spent shale compaction concept. In support of this effort, Science Applications, Inc., was awarded a contract (August 1977) to further analyze and evaluate the concept. The tasks undertaken by Science Applications included numerical modeling of retort kinetics and design and evaluation of engineering aspects of a field demonstration. Only the efforts in those tasks related to the determination of spent shale compaction characteristics and the integration of compaction into the simultaneous fragmentation of adjacent fresh shale are reported in this paper. Experimental and numerical results of this study, while not conclusive, indicate that significant compaction of spent shale and a concordant transfer of void volume to freshly fractured rock could be obtained with reasonable geometries and explosive loadings.

EXPERIMENTAL RESULTS

As any field evaluation of the spent shale compaction concept will be made at the LERC site near Rock Springs, Wyoming, all compaction experiments were carried out on material from the Tipton Member of the Green River Formation which underlies the site. The Tipton oil shale differs significantly from the Parachute Creek Member, found in the Piceance Creek Basin, in that clay minerals, including mixed-layer clays, are an important mineral constituent. The greater quantity of clay minerals in the Tipton give this rock lower fracture strengths for fresh material (Young and Smith 1978) and significantly lower compaction resistance for retorted material, as compared to Parachute Creek shale. Thus, the potential applicability of the compaction concept may be restricted to the Tipton and other clay-rich shales.

Previous data on compaction of spent shale are given by Carpenter and Sohns (1974) and Burwell, Tihen and Sohns (1974). These data, obtained for the purpose of evaluating permeability changes in in situ retorts subjected to overburden loads, were obtained on oil shale material from the Parachute Creek Member. Although earlier data do serve to demonstrate the ease with which broken oil shale can be compacted at retorting temperatures, the low maximum loads utilized (less than 6.5 MPa) and the clay-poor nature of the shale required that data specifically relevant to the Tipton shale be obtained. The experimental program, which was conducted in cooperation with Colorado State University, involved static compaction experiments on two grades of oil shale at postretorting temperatures up to 600°C. All the experiments show that there is essentially zero resistance to compaction at the onset of loading, with final compaction strength depending upon degree of compaction and retorting history.

The experiments were performed in a 5.0 cm (2.0 in.) diameter compaction cell consisting of a thick-walled, stainless steel tube, with a wraparound resistance heater for retorting purposes. Figure 1 shows schematically the geometry of the compaction cell and the location of the oil shale sample between two stainless steel, spacer pistons. The top piston serves as a bearing surface for the load ram, while the lower one acts against a tightly fitting end cap. This end cap provides a sump for oil during retorting and, by nature of being attached to a siphon vacuum pump, allows for a large degree of control over the amount of air passing through the sample. The inner, thick-walled tube, with heater, is placed within a 20 cm (8 in.) diameter outer shell; ceramic insulating beads are poured between shell and heater. The overall experimental setup is indicated in figure 2. Copper tubing, attached to the outside of the shell, provides for water cooling of the outer shell.

In each experiment, a plot of load versus displacement of the loading ram

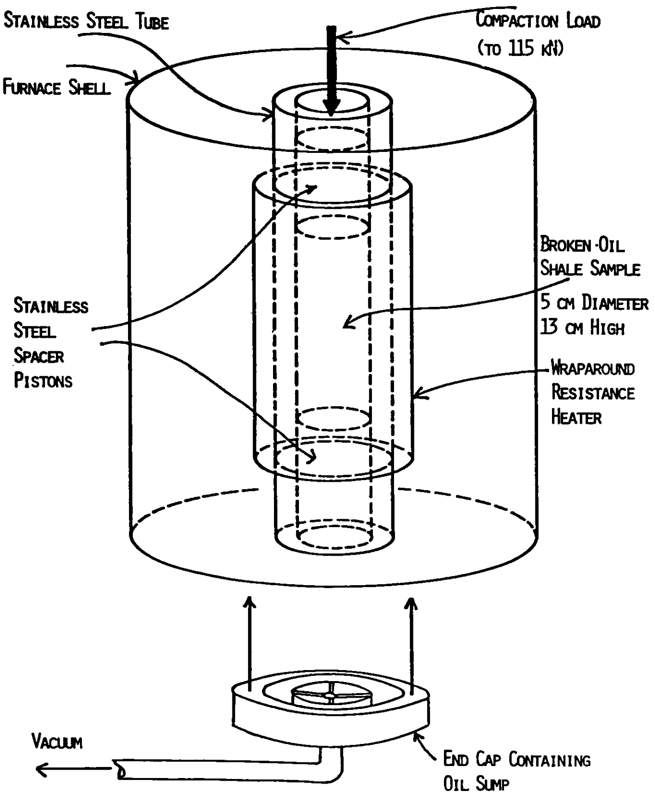

Figure 1. Schematic view of oil shale furnace and compaction cell used to study compaction characteristics after retorting at temperatures of up to 600°C.

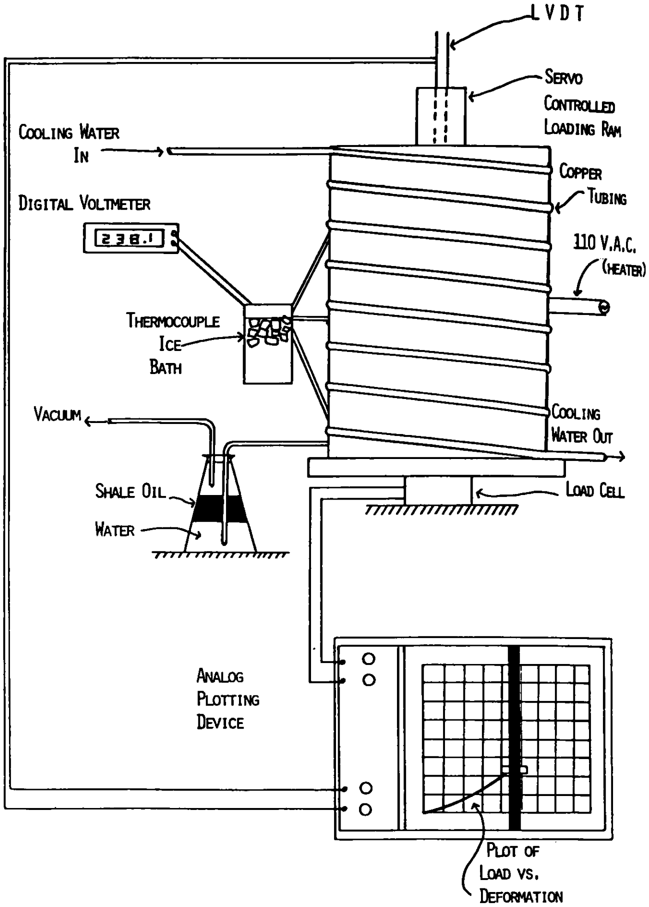

Figure 2. Schematic arrangement of static oil shale compaction experiment.

was obtained with the use of a load cell and a linear variable differential transducer (LVDT). The temperature of the experiment was constantly monitored by three thermocouples located at the top, middle and bottom of the sample. The digital voltmeter provided quick and accurate measurement of temperature, allowing rapid modification of power to the heater and air flow through the samples. Oil shale samples (roughly 300 grams each) were rubblized, mixed together and heated to a predetermined temperature before application of the compaction load. Compaction of retorted oil shale results from the reduction of both fracture porosity and porosity introduced by the removal of kerogen during retorting. A decrease in fracture void volume is believed to make the most significant contribution to compaction. Compaction of rubblized unretorted shale was also performed.

Since the actual experimental curves express the compaction in terms of load versus displacement, and since the initial height of the samples is not constant, it is more convenient to express the deformation in terms of percent by volume (or height) change. These reduced data are presented in figures 3 and 4 and summarized in table 1.

Figure 3 illustrates compaction data on oil shale with initial void volumes of roughly 45 percent. Although the first three experiments were loaded to less than 7000 kN/m^2, they show the same

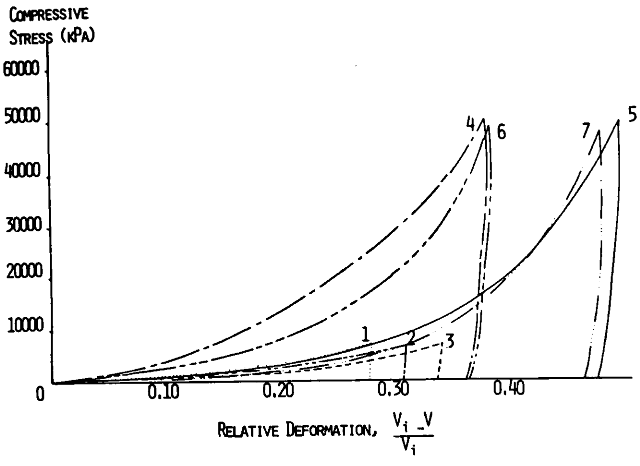

Figure 3. Static compaction of oil shale: compressive stress vs. relative deformation for samples with initial void volumes of 41 percent to 51 percent.

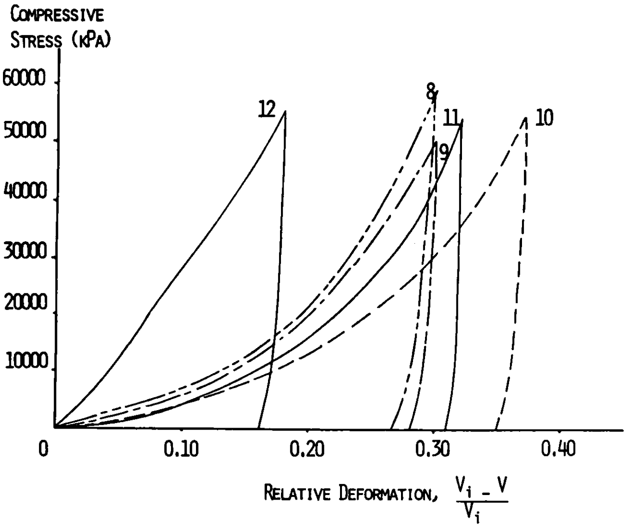

Figure 4. Static compaction of oil shale: compressive stress vs. relative deformation for samples with initial void volumes of 24 percent and 41 percent.

Table 1. Summary of static oil shale compaction experiments.

	Test Number	Density (g/cc)	Initial Height (cm)	Initial Weight (gm)	Initial Fracture Void (%)	Retorting Temperature (°C)	Maximum Load (kN)
Figure 3	1	2.2	13.97	312	49.9	500	13.3
	2	2.2	14.60	318	51.2	500	13.3
	3	2.2	12.85	296	48.3	400	14.0
	4	2.2	13.33	299	49.7	no retort	100.0
	5	2.2	12.70	305	46.1	600	100.0
	6	2.0	13.97	335	40.8	no retort	97.9
	7	2.0	12.06	269	45.0	500	95.6
Figure 4	8	2.0	10.18	310	24.9	600	120.0
	9	2.0	10.08	310	24.2	500	89.0
	10	2.0	11.43	310	33.1	600	111.2
	11	2.0	13.97	331.5	41.5	no retort	115.6
	12	2.0	10.39	310	26.4	no retort	111.2

general response as experiments 5 and 7 which were loaded to almost 50,000 kN/m^2. All five curves show significantly softer response than experiments 4 and 6 which were performed on unretorted shale. It is important to note that the curves in figure 3 represent response to load after retorting at an initial void volume of over 40 percent, while the void volume in actual underground operations is likely to be closer to 20 percent.

Figure 4 illustrates the effects of lower initial void volume upon compaction. Of particular interest are curves 8, 9 and 12 which indicate compaction characteristics of shale retorted at 600°C, 500°C and unretorted shale, respectively. These three experiments all began with an initial void volume of roughly 25 percent.

The spent shale compaction concept is best illustrated by use of a preretort "fracture" void volume. By considering an unfractured, solid volume of oil shale V_s which is subjected to a rubblization process, resulting in a larger volume V_2 (for the same mass), the preretort "fracture" void volume is given by

$$f_v = \frac{V_2 - V_s}{V_2} \ .$$

If this new volume is then consolidated to a new volume V the instantaneous fracture void volume is simply

$$f_v = \frac{V - V_s}{V} \ .$$

When compaction is sufficient to compact the volume back to the original volume V_1 the fracture void volume is seen to be zero

$$f_v = \frac{V_s - V_s}{V_s} = 0 \ .$$

An extremely high load would be required to reduce rubblized unretorted oil shale back to its original unrubblized volume. Removal of kerogen and loss of mechanical strength due to retorting, however, make the compaction of spent shale back to its original volume a relatively simple task. As an example, consider experiments 8 and 12 which begin with preretort "fracture" void volumes of 24.9 and 26.4 percent, respectively. Experiment 8 was retorted to 600°C and then compacted. The energy required to compact the rubblized spent shale back to its initial unrubblized volume represents the energy that would be required in a continuous, on-going process. If the abscissa in figures 3 and 4 is defined as

$$\varepsilon_c = \frac{V_i - V}{V_i} \quad \text{and} \quad f_v = \frac{V - V_s}{V} \ ,$$

where V_i is the initial, rubblized volume, then

$$f_v = 1 - \frac{V_s/V_i}{1 - \varepsilon_c} \ .$$

Using this relationship, the fracture void volume may be determined for any relative deformation ε_c if the volume of solids V_s and the initial rubblized volume V_i are known. Figure 5 shows compressive stress, plotted as a function of fracture void volume, for experiments 8 and 12. As explained earlier, the experimental curve from test 12 approches the zero fracture void volume line asymptotically, while the retorted sample reached

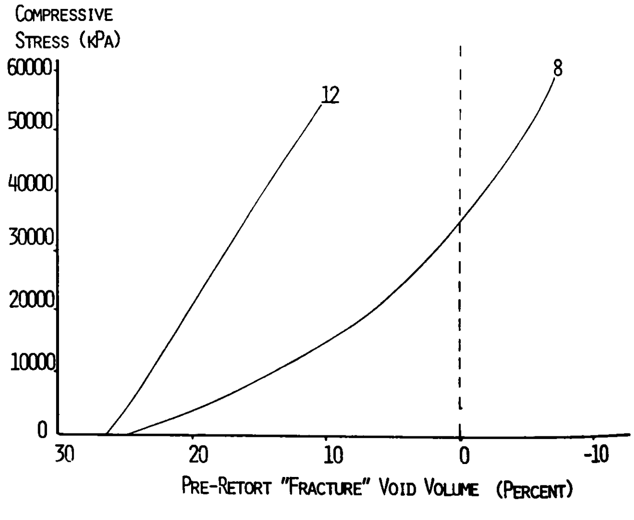

Figure 5. Compressive stress vs. preretort "fracture" void volume (percent) for experiments 8 and 12.

its original unrubblized unretorted volume at about 35,000 kN/m^2, due to the availability of additional pore volume caused by kerogen removal.

The energy needed to compact spent shale to a given degree of residual fracture void volume is readily calculated from the experimental load-displacement curves. The work required to compact the 310 grams (preretort mass) of spent shale in experiment 8, from 25 percent preretort fracture void volume to 0 percent is 621 J, or 1.82×10^6 J/ton. By contrast, 973 J are required to compact 310 grams (2.85×10^6 J/ton) of unretorted material (experiment 12) from 26 percent void to 10 percent void. The energy required to compact spent shale, with a preretort fracture void volume of 25 percent to 0 percent residual fracture void volume required for continuous in situ operation, is less than the equivalent energy of one pound of explosive per ton of processed rock. The efficiency of explosive coupling to rock fracture, broken rock momentum and finally spent shale compaction is, thus, a critical question to be answered.

It has generally been shown that ease of compaction increases as retorting temperature increases, and as Fischer assay of the oil shale increases. It should be noted that the experiments described in this report rely on quasi-static measurements of a process which is fundamentally dynamic in the in situ environment. Development of an experimental apparatus to monitor typical dynamic properties is a simple and logical extension of the work performed to date. Analysis of dynamic tests is critical; the dynamic properties of both fresh and spent shale must be known, and the coupling efficiencies of energy being imparted to the rock must be estimated, before any rational design of an underground explosive program can be initiated.

RESULTS OF CALCULATIONS

A series of one-dimensional, numerical modeling experiments were carried out to evaluate the ways in which explosive properties, shock wave propagation, rock fracture and various geometries of explosive loading might affect the compaction process. The numerical experiments utilized STEALTH* Explicit Finite-Difference Codes, developed by Science Applications. These codes are user-oriented and are based, in large part, on theory and algorithms developed at Lawrence Livermore Laboratory, Sandia Laboratories (Albuquerque) and other national laboratories.

The one-dimensional calculations carried out with STEALTH were designed to be parameter sensitivity calculations in which the beneficial or adverse effects of various parameter variations could be determined. The one-dimensional compaction geometry, illustrated in figure 6, consists of a 2.75 m (9 ft.) thick zone of retorted and highly permeable shale; a 61 cm (2 ft.) thick zone of transition material, representing the expected degradation of solid oil shale in contact with an in situ retort and, finally, a 2.75 m-thick zone of fresh, massive (unfractured) oil shale.

The right boundary of the fresh shale is in direct contact with a one-dimensional explosive source that can be programmed to provide various explosive energy release characteristics and explosive energy-loss characteristics due to interactions between the explosive and the adjacent rock. The left boundary of the spent shale is modeled by a spring boundary condition with an impedance equivalent to that of fresh oil shale.

A typical calculation begins with explosive energy release in the explosive zone on the right. Explosive pressure, imparted to the fresh oil shale, propagates across this rock as a seismic wave whose rise time characteristics depend largely upon the explosive energy release

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*Solids and Thermal hydraulics code for EPRI Adapted from Lagrange TOODY and HEMP. Developed for the Electric Power Research Institute under Contract RP-307.

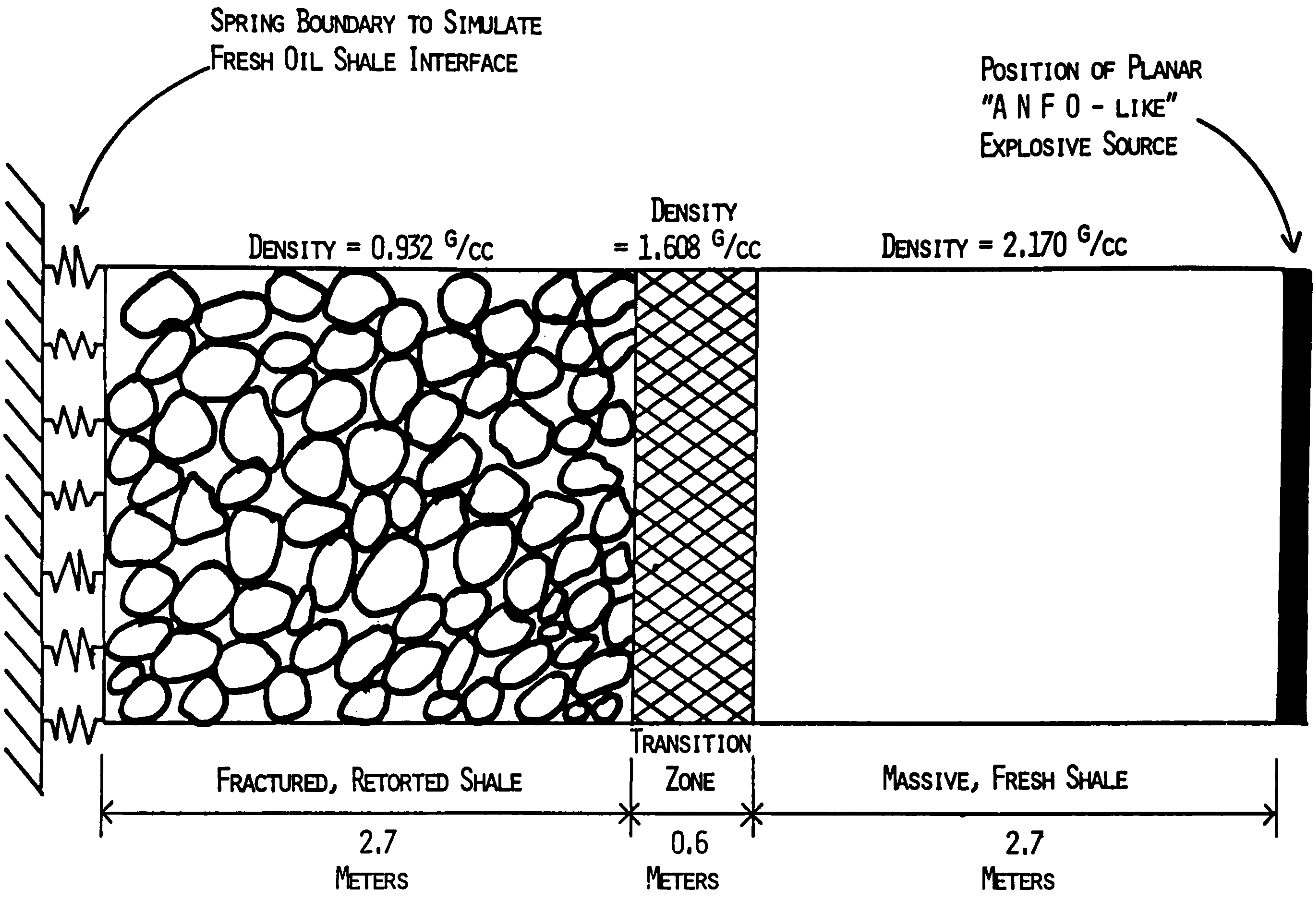

Figure 6. Schematic representation of one-dimensional geometry used in finite-difference parameter sensitivity calculations.

rate used for the explosive. As this wave arrives at the transition region, some of the energy is reflected back into the fresh shale due to the impedance differences between fresh and transitional oil shale. The great majority of this explosive energy, however, propagates through the transition zone until it reaches the interface with the retorted oil shale. Depending upon the compaction characteristics of the spent oil shale, and certainly for all of the compaction equations considered, nearly all of the initial seismic energy is reflected back from the interface between the transition shale and the fully retorted shale. In most calculations, this reflected energy was observed to completely fragment the transition and fresh oil shale. The limited scope of the calculations allowed only a simple spall model, based upon tensile strength criteria, to be used; rather than the more sophisticated fracture model certainly needed if the details of the fracture and fragmentation of the fresh shale were required.

The key objective of the one-dimensional, parameter sensitivity calculations was to evaluate coupling between explosive characteristics, the momentum imparted to the fresh and transition shale and the compaction of spent shale. As discussed above in the section on experimental results, the optimum objective would be to compact the spent shale to the extent that all preretort "fracture" void volume is recovered and a continuing process would thereby be achieved. The results of some of these calculations are shown in figures 7 and 8.

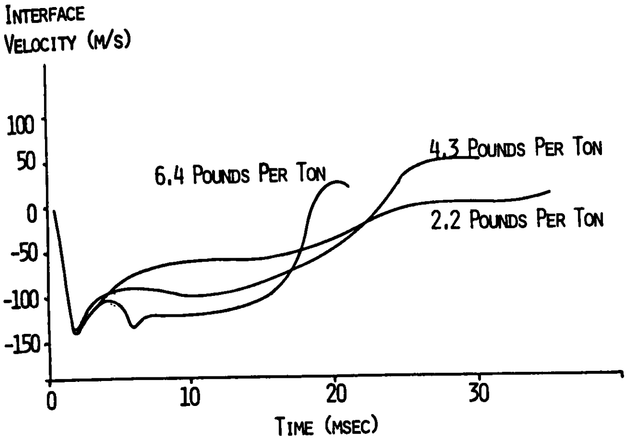

Figure 7. Velocity of the fresh/transition shale interface during explosive compaction of 600°C spent shale by an "ANFO-Like" explosive versus time (STEALTH output).

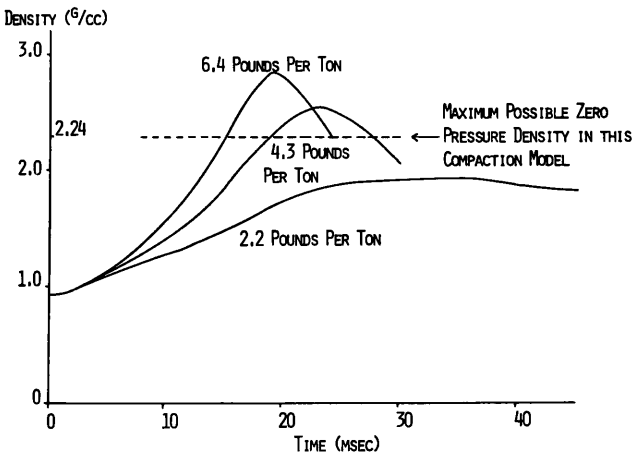

Figure 8. Average density in 600°C spent shale during explosive compaction by an "ANFO-Like" explosive versus time (STEALTH output).

Figure 7 illustrates the velocity of the interface between the fresh and transition oil shale as a function of time for three different explosive loading behaviors. All three calculations were performed with an initial 9.1 pounds of ANFO equivalent explosive per ton of fresh oil shale, and with a compaction equation of state, based upon an experimental test at 600°C and 46 percent initial "fracture" void volume. As a result of the energy quenching logic, the explosive energy delivered to the fresh shale is equivalent to 6.4, 4.3 and 2.1 pounds per ton, respectively, for the three cases shown in figures 7 and 8.

For most of the one-dimensional parameter sensitivity calculations, it was observed that final density of the spent oil shale, after compaction, was relatively uniform. Average density, as a function of time, for the spent shale, in the three cases discussed above, are shown in figure 8. The compaction model used in these calculations was such that the maximum density that could be achieved by the spent oil shale was 2.24 g/cc at ambient pressure. Thus, any densities higher than this value, such as shown in figure 8, could only be obtained during the dynamic compression of the oil shale during explosive loading. In both the 6.4 pound/ton and 4.3 pound/ton cases, the spent shale was compressed well above this density, indicating essentially 100 percent compaction. For the 2.2 pound/ton case, a peak density of 1.88 g/cc was realized, corresponding to 51 percent compaction of the initial spent shale with density of 0.93 g/cc. As the preretort fracture void volume was approximately 46 percent, the 51 percent compaction obtained would more than allow for a continuous in situ operation.

The one-dimensional calculations, although preliminary in nature, provide considerable understanding of the in situ compaction concept. The most significant conclusion is that the energy required to effect a considerable degree of compaction is not excessively large. To the extent that in situ retorts can operate with considerably less fracture void volume than is characteristic of the experiments and calculations discussed here, required compaction energy will be proportionately less. Two areas, most suitable for further computational analyses, and not as yet addressed, are the detailed fracture and energy transmission characteristics of fresh shale under explosive loading, and two-dimensional, geometrical effects characteristic of field conditions.

CONCLUSIONS

The experimental and calculational results obtained in this program have clarified the dynamics of explosive spent shale compaction in modified in situ processing and have shown the areas in which future research efforts should be directed. Experimental results show that the energy required to effect compaction is not excessively large. Further, these results suggest that compaction from a preretort fracture void volume of only a few percent could be commercially possible. Before an energy evaluation can be completed, however, further data must be obtained on the compaction of spent shale, after retorting in an oxidizing environment at temperatures in excess of 600°C, and on the compaction of shale which has a preretort fracture void volume of 20 percent or less.

Data on the dynamic compaction behavior of spent shale will also be required before a complete evaluation of the energy requirements for explosive compaction can be made. The relatively encouraging results obtained from the one-dimensional calculations suggest that properly designed field explosive loadings could effect significant compaction. A critical review, however, must still be given to aspects that could not be included in the one-dimensional calculations. The more important effects would result from seismic wave divergence, associated with the loading of discrete shot holes, and adverse edge effects on fracture and compaction, resulting from the finite dimensions of in situ retorts. Any further efforts to evaluate the in situ explosive compaction concept should include: dynamic experiments to properly determine all spent shale compaction characteristics and two-dimensional, plane strain calculations to account for edge effects and shot hole placement in realistic field geometries.

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