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HYDROCODE SIMULATION OF THE OIL SHALE RUBBLIZATION EXPERIMENT AT ROCK SPRINGS SITE 12

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MASTER

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Abstract

An oil shale rubblization experiment will be performed by Sandia Laboratories personnel during late summer of this year (1977) at the Laramie Energy Research Center (LERC) field laboratory near Rock Springs, Wyoming. This experiment will involve the formation of three horizontal hydrofractures in an underground oil shale bed, the introduction and subsequent detonation of a slurry explosive in two of these hydrofractures, as well as various measurements of physical events and conditions associated with the dynamic experiment and with the environment. The measurements are intended to provide information needed to quantify the effects of the explosive detonation and also to provide data needed for the development and verification of computational procedures that can be used to predict the results of experiments such as the one of interest here. Preliminary calculations have been made with a one-dimensional hydrocode to assess some of the dynamic aspects of the upcoming experiment. The results of these calculations are presented in this memo along with a rather general description of the stress wave propagation, material motion, and fracture phenomena which will occur during and just after the explosive detonation. This memo is intended to be a timely discussion of the current plan and expected results of the rubblization experiment. The one-dimensional calculations, which approximate the actual physical processes of the explosive event, will be followed by additional calculations based on a two-dimensional approach to the problem; the results of these latter calculations will be considered in subsequent reports or memos.

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INTRODUCTION

The current schedule of the in situ oil shale rubblization experiment at the Rock Springs Site 12 field location calls for the execution of the main explosive event during late summer of this year. This experiment will entail the formation of three horizontal hydrofractures at different vertical elevations in the oil shale bed about 60 m (200 ft) below the surface of the earth. The hydrofractures will be initiated from three closely spaced (few feet) wells and will extend to radial distances of about 30 m (100 ft). Of primary interest is the region which lies within the central 15 m (50 ft) radial distance; stress and time-of-arrival gages of various types will be installed in instrumentation wells in this region. It is planned that the hydrofractures will be spaced at about 1.5 m (5 ft) intervals in the vertical direction and that crack openings will be maintained with sand proppant. On the day of the explosive event, a short time prior to detonation, a slurry explosive will be forced into the two lower hydrofractures from the wells used to induce the hydrofractures. Detonation will be initiated simultaneously in the two explosive layers from one of the wells in the central cluster. Detonation waves will thus propagate radially outward in the explosive layers. As a result of the explosive detonations, short duration compressive stress pulses will emanate from the explosive filled cracks and propagate into the surrounding oil shale. Eventually, the compressive pulses will be reflected as tensile pulses from the (nearly) free surfaces of all three hydrofractures. If the amplitudes of the tensile pulses are sufficiently large, the oil shale will be fractured. The intent, of course, is that the degree of fracture and associated fragment motion in the oil shale which lies between the upper and lower hydrofractures will be sufficient to produce a highly rubblized and permeable shale bed that can be efficiently and effectively retorted.

While the hydrofracturing, sand-propping, and subsequent explosive filling and detonation procedures that will be used at Site 12 have commonly been practiced in the oil and gas industry for several years, very little is actually known about what goes on underground. This pertains to the dimensions of the induced cracks (both thickness and radial extent), to the dispersion of sand in the cracks, to the flow of explosive into and through the sand proppant, as well as to the detonation characteristics of the explosive in the crack environment. In addition, it has not been demonstrated that reasonably uniform separation distances between hydrofractures can be realized. By the judicious application of both old and new instrumentation techniques, Division 5734 expects to remove many of these uncertainties as the Site 12 experiment proceeds. Along with the performance of the necessary site preparation activities, various preliminary tests and measurements are also being carried out to characterize the pre-experiment shale bed environment. In addition, an evaluation of the experiment using computational methods is also in progress.

DESCRIPTION OF COMPUTATIONAL PROCEDURES

In this memo, the results of some preliminary calculations made with the one-dimensional hydrocode, CHART D,¹ will be discussed. These calculations were performed primarily to address questions related to explosive crack openings and stress pulse propagation in the oil shale between the hydrofractures. The problem was set up for CHART D using the scheme illustrated in Fig. 1. For computational convenience, the zero vertical position for the calculations was taken to be midway between the explosive cracks; based on the plan for the experiment, this position corresponds to a depth below the surface of the earth of about 62 m (204 ft). Because of the nature of one-dimensional computational procedures, the explosive cracks, sand-propped crack, and surrounding oil shale medium are effectively unbounded in the radial direction. The stress pulses produced by detonation of the explosive layers propagate as

plane waves in both the positive and negative vertical directions. This, of course, represents an approximation of what will occur in the actual field experiment. Nevertheless, the one-dimensional approach can provide meaningful information pertinent to the dynamic expansion of the explosive cracks and to the propagation of the stress pulses in the shale medium.

Fig. 1 -- Illustration of hydrofracture geometry assumed for CHART D calculations referenced to location in shale bed.

Calculations were performed assuming three different crack widths: 0.60 cm (1/4 inch), 0.30 cm (1/8 inch), and 0.15 cm (1/16 inch). Crack width is designated as ΔZ , initial crack width as ΔZ_0 . The span between 0.15 and 0.60 cm essentially

covers the range of uncertainty in crack width as it is now seen. For a given calculation, the sand-propped and explosive cracks were assumed to have the same widths. The actual presence of sand was ignored in the calculation; i.e., the explosive cracks were assumed to be completely filled with explosive and the sand-propped crack was assumed to be void. At least for the explosive cracks this procedure can be justified. It has been found in recent tests that slurry explosives in general do not detonate after being pumped through a crack which contains a significant amount of sand. As a result of this observation, several alternate plans for performing the experiment are being considered. One rather promising concept involves the introduction of only a minimal amount of proppant into the explosive cracks at the time of hydrofracturing. It is expected then that the shale bed will settle to some extent after the pressure on the hydrofracture fluid is relieved; thus, the cracks will likely be narrower than if a more normal amount of proppant had been used. It is planned that the cracks will be reopened when the explosive is emplaced and that the desired crack widths can be maintained until the detonation is initiated. If this concept proves to be feasible, the explosive cracks will contain essentially no sand. The sand-propped crack, however, is a different matter, but can be thought of as being filled with highly porous material having a very low modulus in comparison to the oil shale. With regard to stress pulse reflection properties, the low modulus makes the assumption of a void reasonable. The closure of the sand-propped crack, however, will be rather poorly described in the calculations but this feature is not particularly important for the present calculations.

A final selection of the explosive that will be used in the Site 12 experiment has not as yet been made. Because of this, and also because very little is actually known about any of the candidate explosives, it was decided to assume the properties of a common liquid explosive, nitromethane, for the calculations.² For illustrative purposes, the energy released

by detonation of nitromethane relative to other explosives is shown in Fig. 2. At least one potential supplier of explosive for the Site 12 event claims their product is more energetic than nitromethane. We shall await the actual selection of an explosive to finally assess the reasonableness of assuming nitromethane for the calculations.

Fig. 2 -- Illustration of energy release properties of various explosives. Nitromethane is second from bottom in the middle column.

GENERAL DESCRIPTION OF DYNAMIC PROCESSES

Before proceeding with the discussion of the results of the one-dimensional calculations, it is useful to qualitatively consider the physical processes which will occur dynamically during the field experiment. Graphic illustrations will be used to aid in the descriptions of these processes. The oil shale regions that will be most significantly affected by the detonations lie between the two explosive cracks and between the upper explosive crack and the sand-propped crack. We will consider these two regions separately because the dynamic events which occur in them are distinctly different.

An illustration of how the stress wave propagates in the region between the upper explosive crack and the sand-propped crack is shown in Fig. 3. Four schematic plots are shown,

Fig. 3 -- Schematic illustration depicting stress wave propagation through the oil shale between the upper explosive crack and the sand-propped crack.

each of which depicts the spatial profile of the stress pulse at a specific time after detonation. Initially, the compressive pulse enters the oil shale from the explosive layer with a rather high amplitude (several tens of kilobars) and a short duration (about a microsecond). As the wave propagates, it attenuates and becomes more disperse. This can be visualized from the progression illustrated in the upper three plots in Fig. 3. The third plot in this sequence depicts the stress pulse just before the important interaction at the lower surface of the sand-propped crack occurs. This interaction is important because it results in a reflected tensile pulse (bottom plot), which, if of sufficient amplitude, will cause fracture of the oil shale. The interaction of the stress wave with the lower surface of the sand-propped crack will cause this surface to move upward and eventually result in closure of the crack; this feature is not illustrated in Fig. 3.

The dynamic events which occur in the shale region between the upper explosive crack and the sand-propped crack are relatively easy to visualize because only a single stress pulse propagates. In the region between the two explosive cracks, however, the situation is more complex because two stress pulses are present. A sequential illustration of stress pulse propagation in this region is shown in Fig. 4. The top two plots here each show two stress pulses propagating away from the explosive cracks and toward the center of the region. During the time period represented by these two plots, the propagation properties of each of these pulses are identical to those of the single pulse in the region above the upper explosive crack (Fig. 3). This identical behavior ends as soon as the waves interact. The third plot from the top in Fig. 4 illustrates the reinforcement of amplitudes that occurs when the pulses collide. After this rather pronounced interaction at the center of the region, the waves pass through each other and continue to propagate. The interaction, how-

Fig. 4 -- Schematic illustration depicting stress wave propagation through the oil shale between the two explosive cracks.

ever, is not complete as yet since each wave propagates in the wake of the other. This causes compressive stress amplitudes to be higher than at corresponding locations above the upper explosive crack. When the two reinforced compressive pulses reflect from the surfaces of the explosive cracks (these cracks now are gas filled and expanded), tensile pulses propagate back toward the interior of the region (second plot from bottom of Fig. 4) and eventually meet at the center (bottom plot). We will see later in this memo that the interactions between stress pulses in the region between the explosive cracks are quite significant because they cause tensile stress amplitudes to be enhanced and consequently cause the probability for fracture in this region to be greater than in the region between the upper explosive crack and the sand-propped crack.

The schematic illustrations of stress pulse propagation in Figs. 3 and 4 are most readily understood within the context of one-dimensional wave propagation and material motion, i.e., plane stress waves propagating in the positive and negative vertical directions. As was mentioned previously, the one-dimensional approach to the problem is an approximate, but nonetheless useful, representation of the actual field event. A graphic illustration of what will occur in the field event is shown in Fig. 5. This figure in essence is a snapshot of the experiment region taken at about 0.8 ms after the start of detonation and shows instantaneous positions of the detonation waves in the explosive cracks, of the compressive and tensile stress wave fronts in the oil shale, and of the upper and lower surfaces of the explosive and sand-propped cracks. While the graph is intended only for illustrative purposes, it was drawn on the basis of information deduced from the one-dimensional calculation for the case in which the explosive and sand-propped cracks were 0.60 cm wide. We have assumed that the explosive detonations were initiated at the radial position of zero so that at 0.8 ms, which was the termination time for the one-dimensional calculation, the detonation waves have propagated to radial distances of about 5 m in the explosive cracks.

Fig. 5 -- Plot illustrating positions of the detonation waves, compressive and tensile waves, and crack surfaces at 0.8 ms after the start of detonation.

The dashed lines in Fig. 5 represent the leading portions of the stress waves in the oil shale; the arrows designate directions of wave propagation. The solid lines represent the positions of the upper and lower surfaces of the cracks. Because the dimensions of crack openings are small relative to the overall dimensions of the experiment region, the vertical positions of the crack surfaces are depicted using the expanded scales shown at both ends of each crack.

The compressive stress waves shown on the far right of the figure initially propagate into undisturbed oil shale. In the shale region above the upper explosive crack, the wave propagates with no interactions until it reflects from the lower surface of the sand-propped crack. There, it reflects as a tensile wave. The lower surface of the sand-propped crack starts to move upward at this time and eventually collides with the upper surface. This collision sends a compressive wave into the shale region above the sand-propped crack and another compressive wave into the shale below the crack. The latter compressive wave causes the trailing portion of the tensile wave to be somewhat curtailed, but this should not affect fracture since maximum tensile stress amplitudes occur very close to the dashed line on the right of the region labeled "tension".

The compressive waves which propagate in the region between the two explosive cracks initially propagate toward each other through undisturbed shale. The intersection of the two dashed lines that represent the compressive wave fronts marks the point at which the strongest interaction of the two waves occurs. To the left of this intersection, each compressive wave is propagating in the wake of the other wave. The interactions of the compressive waves with the now expanded explosive cracks results in tensile waves which propagate back into the shale as well as in changes in the directions of motion of the affected explosive crack surfaces. Prior to the interaction with the compressive wave, the upper and lower surfaces of each explosive crack were moving away from each other in a symmetric fashion. After the interaction, however, the lower surface of the upper explosive crack, and the upper surface of the lower crack, reverse their directions of motion. Crack opening maxima are thus realized at this time. These crack openings are important because they provide space into which fragments of fractured shale can move. The fractures, of course, are produced as the tensile waves propagate after the

reflections. On the left side of Fig. 5 we see the dashed lines which represent the tensile wave fronts. Like the compressive wave fronts, the tensile fronts intersect and cause regions of reinforcement to exist.

In the region below the lower explosive crack, only a single compressive pulse propagates. This also is the case in the region above the sand-propped crack. Because no tensile waves develop in these two regions, all of the fracture is expected to be confined to the regions bounded by the upper and lower hydrofractures.

RESULTS OF ONE-DIMENSIONAL CALCULATIONS

The foregoing discussion has dealt primarily with qualitative descriptions of physical processes that will occur during execution of the Site 12 experiment. Through the remainder of this memo we will be concerned primarily with the quantitative results of the one-dimensional calculations. Emphasis will be directed at the time dependence of explosive crack openings and at the spatial dependence of both compressive and tensile stress pulse amplitudes. Results obtained for the three initial crack widths will be compared.

The graphs shown in Fig. 6 depict the extent to which the cracks will be opened by the detonations. We are looking here at the upper explosive crack; the curves plotted represent the positions of the upper and lower surfaces of the crack as a function of time after the start of detonation. Detonation was initiated at the center of the crack in the calculations and was completed in about 1 ms, or less, depending on initial crack width; this time interval is about one or two orders of magnitude shorter than time periods associated with the important physical events which occur in the oil shale. Looking at the curves for any initial crack width, we see that the upper surface starts to move rapidly at first; after a short time the rate of motion decreases but even at the end of the calcu-

Fig. 6 -- Illustration of time dependence of explosive crack openings.

lated time period there still is a continuous upward motion. In the actual experiment, the direction of motion of the upper surface will ultimately be reversed because of overburden pressure. Overburden pressure was not considered in the calculations; the consequences of neglecting the overburden will be discussed in a subsequent paragraph.

The curve for the lower surface of each explosive crack initially indicates a behavior that is similar to that of the corresponding upper surface. At about 0.4 ms, however, the direction of motion is reversed. This occurs because at this time the stress wave from the lower explosive crack arrives and drives the surface upward again. The maximum separation

between the two surfaces of the crack thus occurs at about 0.4 ms. It is desirable that this maximum separation be as large as possible and that the opening be maintained at near its maximum for as long a time as possible. This would permit shale fragments to twist and turn after the fractures occur and thereby cause the shale bed to be self-propped, and hence permeable. Clearly, it is advantageous to start with as large an initial crack as possible.

It was mentioned in a preceding paragraph that overburden pressure can influence crack opening. If this pressure is sufficiently large the maximum separation indicated by the calculation will not be realized. For the Site 12 experiment, with the depth of interest being about 60 m below the earth's surface, the overburden pressure is about 0.014 kbar (200 psi). Whether or not this can be considered small for the present analysis depends on the pressure that is maintained in the explosive gases during the time period of interest. This is illustrated in Fig. 7 for the three initial crack widths. We

Fig. 7 -- Pressure in explosive cracks as a function of time after start of detonation.

see that, even for the smallest crack, the gas pressure remains at least 30 times greater than the overburden pressure. We conclude then that neglecting overburden pressure is justified for the time period of interest in the present calculations. For another event, for example one at considerably greater depth, the conclusion may not be the same. Before leaving Fig. 7, it is interesting to note that at about 0.4 ms we again see the effect of the stress wave arriving from the other explosive crack.

Peak amplitudes of the stress pulses which propagate in the oil shale are plotted as functions of vertical position in Figs. 8, 9, and 10. Each figure corresponds to one of the initial crack widths considered in the calculations. The compressive pulses, which of course originate in the explosive cracks, are seen to attenuate as they propagate outward. The arrows on the curves indicate directions of propagation. As we have seen previously, the shale regions of primary interest lie between the cracks. In the region between the explosive cracks, the two pulses propagate toward each other for a time and soon meet at the center of the region. There they interact and amplitudes are reinforced. These interactions between waves constitute the important differences between the events that occur above and below the upper explosive crack; no interactions between waves occur above the upper explosive crack. As was mentioned previously, after the two compressive pulses have effectively passed through each other in the region between the explosive cracks, the interaction continues because each wave propagates in the wake of the other. An estimate of the degree of stress enhancement associated with these rather late time interactions can be obtained by comparing the peak amplitude at a given location between the two explosive cracks with the amplitude at a comparable location between the upper explosive crack and the sand-propped crack.

Fig. 8 -- Peak stress amplitude plotted as a function of position for the 0.15 cm initial crack width case.

Fig. 9 -- Peak stress amplitude plotted as a function of position for the 0.30 cm initial crack width case.

Fig. 10 -- Peak stress amplitude plotted as a function of position for the 0.60 cm initial crack width case.

The next important interactions of the stress pulses are with the surfaces of the cracks. The reflections at these surfaces result in the fracture producing tensile pulses that propagate back into the oil shale. For the calculations that are depicted here, fracture was suppressed in order to determine maximum possible values for tensile pulse amplitudes. Other calculations were performed in which fracture was not suppressed; we will consider these later.

In Figs. 8, 9, and 10, we see rather pronounced differences between tensile pulse amplitudes in the two shale regions between the upper and lower hydrofracture. Between the explosive cracks we see reinforcement which will have a significant effect on fracture. While this pertains to all three initial crack widths, the advantage of wide initial cracks can readily be seen by comparing corresponding curves in Figs. 8, 9, and 10.

Consider, for example, the region between the upper explosive crack and the sand-propped crack for the narrowest crack (Fig. 8). Here the peak tensile amplitude only reaches about 1 kbar. This in fact is sufficient to cause fracture; however, only a very few spall planes will be formed in this case and these will lie close to the sand-propped crack. This was borne out in calculations where fracture was allowed; in these calculations a simple criterion was used in which fracture occurred when the tensile stress amplitude exceeded 0.4 kbar. For the 0.15 cm initial crack width, only a single spall plane was formed. This is in sharp contrast to the 0.60 cm case where about 20 separate fractures occurred over about two-thirds of the region between the upper explosive crack and the sand-propped crack.

In the region between the two explosive cracks, fractures were quite numerous for all three initial crack widths and were rather uniformly distributed over the entire region.

The results of the calculations where fracture was allowed are not considered to be quantitatively accurate because the method for describing fracture was overly simplistic. Nonetheless, the results do indicate that it is important to attempt to maximize crack width. All of the calculated results support this contention; this observation was perhaps obvious without the benefit of any calculations. An observation which is less obvious is that the region between the explosive cracks should be more effectively fractured than the region between the upper explosive crack and the sand-propped crack.

DISCUSSION OF RESULTS

The one-dimensional calculations considered in this memo have provided some important quantitative information pertinent to the Rock Springs Site 12 experiment. First of all, it is clear that there are two distinct shale regions in which

fracture will likely occur. In the region between the two explosive filled hydrofractures, we expect to see considerable rubblization because of the interactions between the stress waves. In the region between the upper explosive crack and the sand-propped crack, no such wave interactions occur and as a result the probability for significant rubblization is not as great as in the region between the two explosive cracks. Because of the distinctly different physical processes which occur in the two shale regions of primary interest, the planned geometry of the Site 12 experiments implies that two nearly independent experiments are actually being undertaken. It will be interesting to compare the post-detonation states of the oil shale in the two regions. On the basis of the calculations, it appears that the 1.5 m vertical separation distance between hydrofractures is reasonable. If initial crack openings near the large extreme considered in the calculations (0.60 cm) can be realized, considerable fracture can be expected in both oil shale regions. If initial crack openings are small, the probability of significant fracture in the region between the upper explosive crack and the sand-propped crack becomes rather small.

The fact that the explosive cracks are opened after the detonation is an important facet of the experiment. The space thus provided should enable the fractured shale fragments to become dislodged from neighboring fragments and separate from each other by significant amounts; this should reduce the likelihood of these fragments settling back into their initial positions. The fact that the stress fronts impinge on the crack surfaces at non-normal angles also is important because this means that a twisting action is imparted to the fragments as they move into the cracks. The explosively opened cracks and the induced fragment motion can work together to provide a shale bed that is not only fractured but also is permeable; the latter will result because the irregularly stacked shale fragments will self-prop the formation. It is not likely that

much of the twisting and self-propping will occur in the shale region between the upper explosive crack and the sand-propped crack because little space is available for fragment motion in the upper crack.

The experimental measurements made prior to, during, and after the explosive event in the field are expected to be very useful for evaluating the calculations presented here and also additional calculations which are being performed with two-dimensional computational procedures. With confidence in the results of such calculations, it should be possible to optimize the geometrical design of experiments or commercial endeavors such as the one discussed in this memo. It is possible that an optimal design will involve several uniformly spaced hydrofractures, all filled with explosive. On the other hand, it may be economically advantageous to load alternating hydrofractures with explosive and leave the others sand-propped. It is quite clear at this time that a single explosive filled hydrofracture will not cause significant rubblization. What is not clear is just how effective the multiple hydrofracture concepts are. The Site 12 experiment and associated analyses are being performed to answer such questions.

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