

MOBIL OIL CORPORATION
Research Department
Rifle, Colorado

Anvil Points Oil Shale Research Center

MECHANICAL MODEL SIMULATION - A VALUABLE
TECHNIQUE FOR OIL SHALE RESEARCH

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Gentlemen:

REPORT NO. 67.72 AP
MECHANICAL MODEL SIMULATION - A VALUABLE
TECHNIQUE FOR OIL SHALE RESEARCH

This is the third in a series of seven final summary reports covering specific research programs performed under the auspices of the Initial Program at Anvil Points. A single final report containing a summary of the most important findings and conclusions related to the entire Initial Program will also be issued.

An extensive program of mechanical model simulations was carried out to support the Gas-Combustion Retorting research during both Stage I and Stage II of the Initial Program. The development of novel miniature-scale model techniques can be considered an important by-product of this effort as they produced quick, economical, and surprisingly accurate information. The major areas studied and the accomplishments in each are outlined below:

- A shale drawoff system was developed which will provide uniform particle flow in large vessels. This involved adapting moving-bed catalytic cracking technology after basic flow studies indicated that this technology was applicable. This system was tested successfully in Retort No. 3.

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- Internal hardware in the Gas-Combustion Retort must be positioned to minimize disruption to the shale flow pattern. Guidelines for designing the cross-sectional shape and symmetry of internals were established.
- A satisfactory retort feed system which minimized shale particle size segregation was developed. Criteria for the design of this system were established.
- Satisfactory air and recycle gas distributors for introducing these gases into the moving bed of oil shale were developed. Criteria for the design of these distributors were established.
- A semi-theoretical equation describing the impaction of shale oil mist in packed beds and a much improved understanding of the phenomenon was developed.
- Numerous studies were made which helped to define and, in part, to solve retort operability problems.

Additional research directed toward solving the remaining operability problems with the Gas-Combustion Retort could be performed quickly and economically by application of the mechanical model simulation techniques developed herein.

Yours truly,



R. H. Cramer
Program Manager

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MECHANICAL MODEL SIMULATION - A VALUABLE TECHNIQUE FOR OIL SHALE RESEARCH

INTRODUCTION

The former U. S. Bureau of Mines facility at Anvil Points, near Rifle, Colorado, was reactivated starting in May 1964 and was operated during 1965, 1966, and 1967. A research and development program was conducted to investigate the technical feasibility of room-and-pillar mining with explosives, crushing and Gas-Combustion Retorting techniques for oil shale. Mobil Oil Corporation acted as Project Manager for the cooperative industry group at Rifle which included Continental Oil Company, Humble Oil & Refining Company, Pan American Petroleum Corporation, Phillips Petroleum Company, and Sinclair Research, Inc. as Participating Parties. Costs of the Rifle operation were shared equally by the six participants. Each Participating Party was represented by personnel on the technical staff. The Colorado School of Mines Research Foundation, Inc. acted as lessor-of-record and supplied nontechnical personnel for administrative and logistic support.

The planned research program at Rifle consisted of two 18-month stages: Stage I, to determine retorting feasibility in small-scale pilot plant equipment and to provide information as to whether or not to continue the Rifle program; Stage II, to operate large-scale pilot plant equipment to develop information for scale-up to commercial-size retort elements and to conduct mining and crushing research. Because of technical difficulties with the retorting process, Stage I, which was initiated in May 1964, was extended by six months. These technical difficulties were resolved and Stage II commenced in April 1966. Experimental work was concluded in September 1967.

The final reporting from the Anvil Points project has been structured in pyramidal fashion. Reporting for three levels of interest has been implemented:

- General Management Summary - a single volume summary report covering the entire project.
- Technical Management Summary - seven reports, each summarizing work in a specific area, i.e. mining, crushing, retorting, mechanical model simulations, mechanical engineering, analytical laboratory, and economics.
- Technical Detail - the mass of data transmissions, Monthly Progress Memoranda, Technical Memoranda, Weekly Newsletters Technical Advisory Committee and Technical Observer presentations.

This is the Technical Management Summary report dealing with mechanical model simulations.

The experience of the U. S. Bureau of Mines at Anvil Points revealed deficiencies in several major areas, any one of which would hinder the commercial development of the Gas-Combustion Retorting Process. These problem areas included:

- Difficulties in obtaining uniform shale flow through large vessels (shale drawoff systems).
- Difficulties with particle segregation in shale feed systems.
- Difficulties in distributing gases uniformly in a bed of moving shale.

Therefore, the Initial Program at Anvil Points included plans to carry out studies in all three areas.

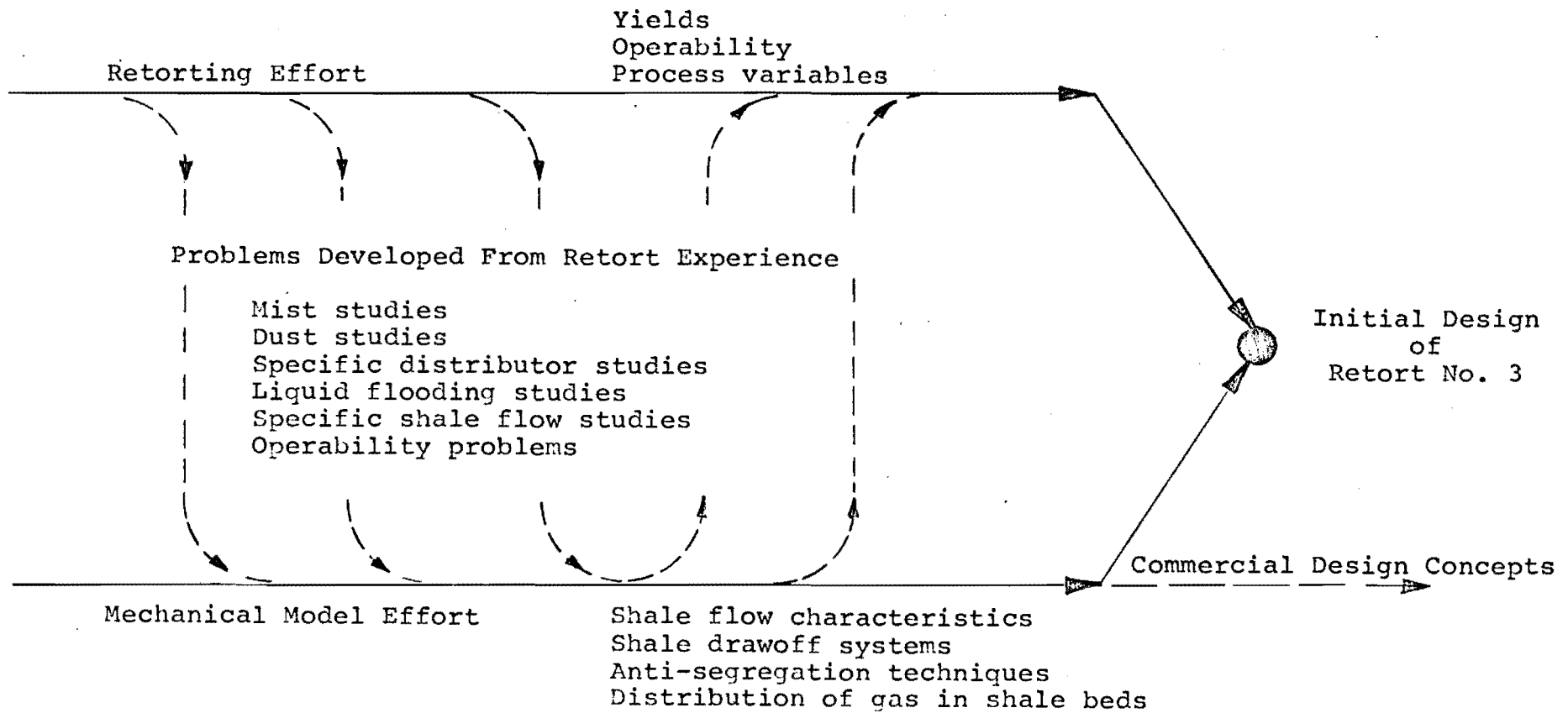
There was a striking similarity between these problems and those encountered in the early development of moving-bed catalytic cracking processes. Model techniques had been used successfully in that development and appeared to have promise in oil shale research even though the solids were quite different both in size and shape. Therefore, a model program was set up as a parallel effort to the retorting program as illustrated in Figure 1. It was recognized that other problem areas would develop as a result of the retorting experience and model studies were expected to be helpful in these areas also. It will be noted that the scope of the model program eventually included studies of the behavior of mist, dust, and liquid in shale beds. In addition, the model effort was broadened to include studies dealing with the retort operability problem.

The models used in this work were simple and flexible to get maximum information quickly and economically. They ranged in size from miniature models as small as 1/12th-scale to full-scale sections with facilities to circulate shale continuously. Generally they were constructed of plywood and plexiglass to facilitate visual observations. Motion pictures were taken whenever possible to assist in analyzing the data, to provide a permanent record of the work, and for use as a visual aid in education.

It should be emphasized that these model studies were carried out at room temperature although the pertinent rates simulated conditions in a hot retort. Furthermore, the shale flow studies were generally carried out with particles in a dry state wherein the particles flow individually. Certain zones exist in a retort where this is not so. Therefore, the models are intended to simulate - not duplicate - a retort condition and their value rests in the guidance and understanding they provide.

FIGURE 1

PARALLEL EFFORT OF RETORTING AND MECHANICAL MODEL SIMULATIONS



SUMMARY

The mechanical model work - both large and small-scale - provided reliable guidance throughout the program. Consequently, it was a very valuable research tool. The development of miniature-scale model techniques can be considered an important by-product of this effort as they produced quick, economical, and surprisingly accurate information. Similarly, the liberal use of motion pictures provided useful visual aids for educational purposes during the program and they should be of even greater benefit in the future.

A. Basic Shale Flow Studies

The basic flow studies carried out with crushed oil shale revealed that it behaves much like small, spherical catalyst particles in spite of the differences in size and shape. Therefore, the solids-flow technology developed in moving-bed catalytic cracking is applicable to moving-bed retorting.

B. Shale Drawoff Systems

The primary example of applying past technology is the successful development of the single-level drawoff system as a means of obtaining uniform particle flow in a retort. This system - which utilizes a multiplicity of static pipes - has been used with 1/8-inch diameter bead catalyst in Thermoform Catalytic Cracking units for many years. This drawoff system performed successfully during a 10-day run in Retort No. 3 with the large, 1- to 2 1/2-inch, shale fraction which accounted for 83% of mine run ground to minus 2 1/2 inch. We believe that it would be equally satisfactory with the full range, 1/4- to 2 1/2-inch shale (96% of mine run ground to minus 2 1/2 inch) although the system was not adequately tested with this fraction. There is some question as to its suitability with small, 1/4- to 1-inch shale (12% of mine run ground to minus 2 1/2 inch). This question relates to the inability of the single-level drawoff system to crush agglomerates and clinkers which were prevalent with this fraction during upset operation. However, these problems generally occurred in the upper zones of the retort and pipe plugging in the drawoff system was a rarity. In any event, other process limitations are unique to the small shale and these are discussed in the Technical Management Summary which deals with retorting (1).

It is of interest that the initial evaluation of the single-level drawoff system was carried out in a shale storage bin and it was necessary to scale down the design by a factor of two for use in Retort No. 3.

(1) See references listed in Bibliography.

The drawoff system utilizing rotating rolls, developed by the U. S. Bureau of Mines, was also operated successfully in Retort No. 3 with the full range (1/4- to 2 1/2- inch) and small (1/4- to 1-inch) shale fractions. Attempts to use drawoff techniques such as the mass flow bin and flow-correcting inserts were extremely disappointing as they were not capable of providing the desired uniformity of flow. Thus, these latter techniques were eliminated from consideration for use in Retort No. 3.

In the overall analysis, the single-level drawoff system appears to have the greatest potential as the basic commercial drawoff system supplemented by a more complex system if required for smaller shale sizes.

C. Shape and Spacing of Retort Internals

After uniform shale flow has been established in a retort, the internal hardware must be positioned such that there is a minimum disruption to the flow pattern. Miniature and full-scale model work showed that the shape and location of the internal hardware have a large influence on the uniformity of shale flow through a vessel. In general, the smoothest flow patterns were obtained with internals which had a sharp leading edge and a triangular top section. Unsymmetrical spacing (of air distributors relative to recycle gas distributors) and inadequate wall clearances can both result in localized shale slowdowns.

D. Anti-Segregation in Shale Feed System

The final step in the shale handling sequence is to feed the retort in such a fashion that particle segregation can be controlled. Full-scale model studies revealed that segregation of oil shale particles can be substantial unless deliberate steps are taken to minimize it. The extent of segregation that takes place in a vessel is the result of two major factors:

- The range of particle sizes in the feed.
- The size of the pile that is formed when the particles are fed to the top of the vessel.

Known anti-segregation techniques such as confining the surface of the bed or surface baffling were found to be of minor benefit at best. Thus, segregation in Retort No. 3 was controlled by restricting the pile radius at the top of the vessel to less than 27 inches. This required one inlet pipe for every 10 square feet of retort area.

E. Distribution of Gas in a Bed of Oil Shale

Earlier, it was pointed out that the internal hardware had to be positioned such that the effect on shale flow would be minimized. However, gas distribution cannot be neglected. Adequate distribution must be maintained or operability, yields, and heat recovery will suffer. Therefore, the placement of distributor hardware must be a balance between shale flow and gas distribution.

Model work was carried out to study the introduction and distribution of gas in a bed of crushed oil shale. The following general conclusions were drawn from this work:

- The extent to which the combustion air will mix with the recycle gas stream and penetrate horizontally into a bed of shale depends primarily on the size of the shale. As the shale size increases, the radial penetration from a single air distributor element increases as illustrated in the following table:

<u>Nominal Shale Size, Inches</u>	<u>Diameter of Influence, Inches</u>
1/4 to 3/4	8
3/4 to 1 1/2	10 1/2
1/4 to 3	18 1/2
1 1/2 to 3	25

- The velocity and the angle at which the air is injected into the recycle stream have little or no effect on the penetration.
- The rate of recycle gas passing the air distributor has a rather small effect on the penetration.

In spite of the fact that this simulation was carried out at ambient temperature, the sphere of influence of a single distributor element in a hot retort was found to be very similar to that predicted by this study. This was true in Retorts No. 2 and No. 3.

Investigation of recycle distribution indicated it was not nearly as critical as air distribution. Penetrations were considerably greater because no other gas stream is involved at the recycle distributor.

F. Mist Studies

Model work, which utilized a drag stream of retort offgas, was also carried out to improve the understanding of

mist behavior in shale beds and recovery equipment. A semi-theoretical equation was developed for impaction in packed beds at low mist loadings of 1 to 2 lb oil/MSCF. This equation revealed that mist impaction increases when gas velocity or mist size are increased or when shale size is decreased. Bed height was found to be a negligible factor. At higher mist loadings (8 to 10 lb oil/MSCF), the impaction was found to be quite high with the small mist sizes. We believe this is related to the increase in mist particle size due to growth and coalescence. Furthermore, the impaction is probably aggravated by the scrubbing action that takes place when a heavy film of liquid builds up on the shale particles. Incipient flooding occurred when the superficial gas velocity reached about 3 ft/sec.

The flow studies in pipes and elbows showed that the mist in the retort offgas is extremely unstable and substantial impaction would occur in normal piping.

G. Studies Dealing With Retort Operability

The model work discussed up to this point was rather extensive and long-term in nature as it dealt with general understanding and design guidance. However, another important area of model effort was that of assisting in the solution of problems dealing with retort operability. These studies were shorter range programs. The more important examples of this type of work are summarized below:

- Provided the basis for an air distributor design capable of processing large, 1- to 2 1/2-inch shale successfully in Retort No. 2.
- Explored the behavior and accumulation of dust in a bed of oil shale. (Dust is formed by the decrepitation of shale during retorting and combustion.) Identified gas velocity, as the primary factor affecting dust accumulation and shale rate, area restriction, and temperature as the major factors affecting gas velocity.
- Explored the behavior and accumulation of liquid in a bed of oil shale. Demonstrated that liquid can be removed from a retort bed if a local flooded zone can be established and controlled in a region where the gas temperature is about 600 F and if the flooded zone has access to the disengaging facility.

DETAILED REPORT

A. Shale Flow Characteristics

This discussion begins with basic studies dealing with how oil shale particles behave in a flowing system. Following this, the shale system will be traced from the bottom of the retort to the top. This sequence was chosen because of the importance of establishing uniform shale flow through the vessel. Hence, the drawoff system will be considered first as it affects all the systems above it. Next, the placement of internal hardware will be discussed from the shale flow standpoint. The final consideration is the shale feed system where the primary concern is particle segregation.

1. Basic Studies

Solids handling enters into almost every phase of oil shale retorting. Thus, it was necessary to develop some basic flow characteristics in order to handle the material efficiently and economically. This work had long range implications in that it provided the basis for the development of shale drawoff systems for large retorts. However, in the short range, it was used to guide the redesign of the smaller retorts and storage bins early in the program.

a. Basic Flow Characteristics of Raw Oil Shale

The important characteristics of any solids-flow system are as follows:

- Physical properties of the material such as shape, bulk density, and particle size distribution.
- Angular properties of the material such as angle of flow, angle of repose, and coning angle.
- Critical dimensions of circular and rectangular openings to avoid bridging and insure continuous flow of the solid.
- Maximum flow capacity of pipes and circular orifices.

These characteristics were determined for five sizes of raw shale: 1/4 to 3/4 inch, 1/4 to 1 inch, 3/4 to 1 1/2 inch, 1/4 to 3 inch, and 1 1/2 to 3 inch (2).

These studies revealed that crushed oil shale behaves much like small, spherical particles in a flowing system in spite of the differences in size and shape. Therefore, the

solids-flow technology developed in moving-bed catalytic cracking is applicable to moving-bed retorting. A movie (3) was prepared which supplemented the report on this work.

b. Comparison of Flow Characteristics of Raw and Spent Shale

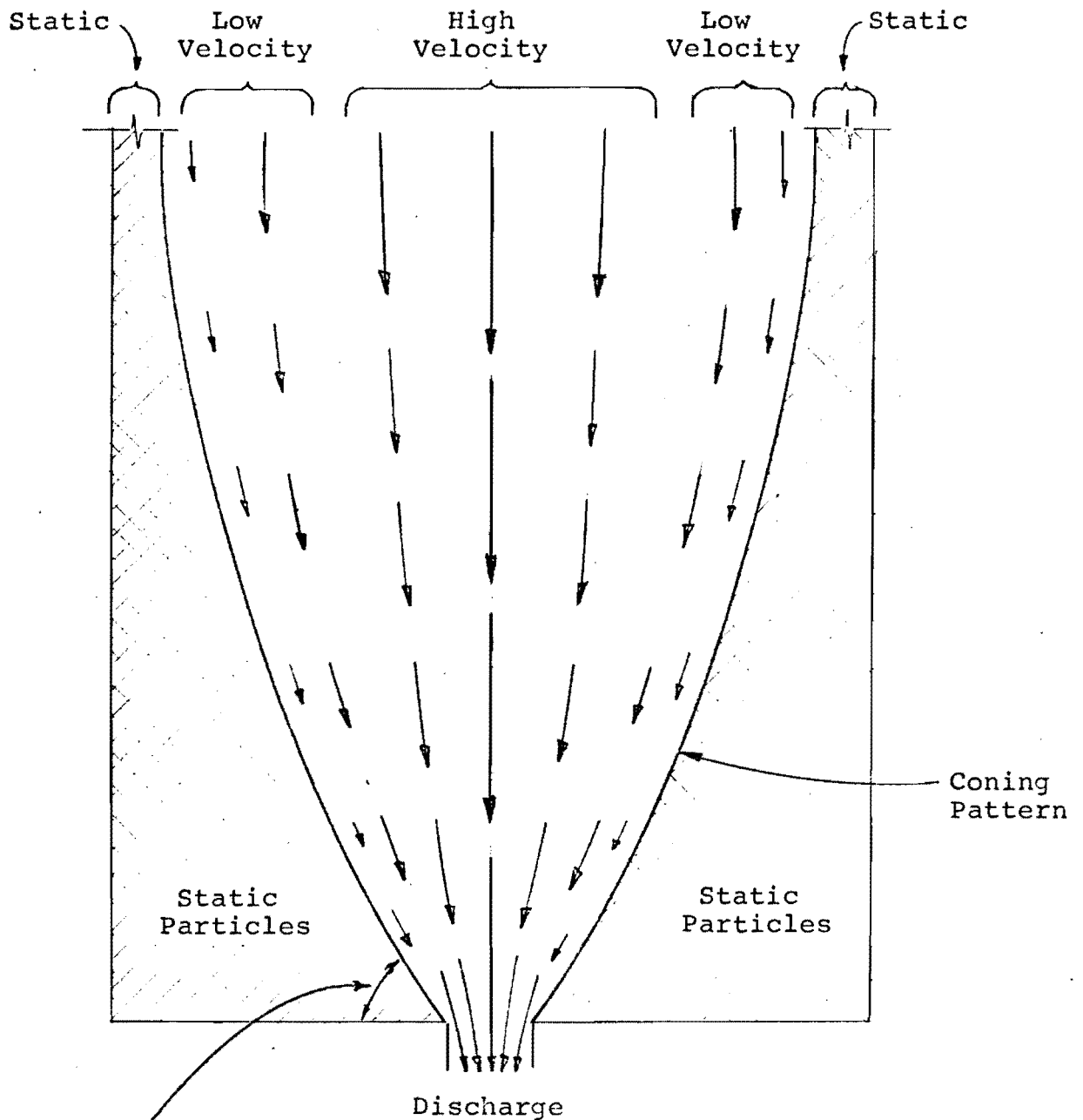
The retorting process differs from many solids-flow systems in that the solid undergoes a significant change in the process. Therefore, it is necessary to consider not only raw shale but spent shale as well. For all practical purposes, the flow properties are the same (4). However, the particle size of spent shale is smaller than raw shale and it contains a higher fines content. Because of its smaller size, spent shale will flow through smaller openings than raw shale without bridging. But it is necessary to design all clearances for raw shale during the circulation, startup, and shutdown periods; thus, the additional latitude with spent shale can be considered a safety factor. The fact that spent shale contains more fines than its raw shale counterpart influences a basic flow property known as the coning angle. For example, the coning angle of spent, 3/4- to 1 1/2-inch shale was observed to be some 5 to 13 degrees steeper than raw shale (5). An explanation of this flow property along with its importance is presented in the section that follows.

c. Importance of Coning Angle (Coning Pattern)

The coning angle or coning pattern of oil shale warrants special discussion at this point for several reasons. It serves to illustrate why uniform particle velocity is difficult to achieve in a large vessel. In addition, the pattern serves as a basis for drawoff techniques which utilize it in order to obtain uniform flow. Consider particles flowing in a large area and discharging from a relatively small opening as shown schematically in Figure 2. The moving particles form a rather steep angle with static particles at the outlet. This angle is in the order of 60 to 70 degrees at the outlet and approaches 90 degrees higher in the bed (6). The particle velocity is at a maximum directly over the outlet and diminishes to zero at the periphery. This is significant as it shows that in a very large vessel only a fraction of the total area is moving or is "live" when the vessel is flowing full. On the other hand, when the vessel is emptied, the surface will dip in the center until the angle of flow is reached; then, the dead particles at the wall will slough into the center and flow out in this fashion. This situation leads to extreme segregation problems. The coning pattern will be discussed further in the next section of this report which deals with shale drawoff systems.

FIGURE 2

CONING PATTERN OF OIL SHALE PARTICLES



Coning Angle - Approximately 60 to 70° around discharge and approaches 90° higher in bed

2. Development of Shale Drawoff Systems

In order to obtain uniform retorting, particles must flow through the retort at essentially the same velocity over the entire cross section. This is not difficult to obtain in a small vessel such as Retort No. 1 which is simply a 20-inch diameter pipe. It is not much more difficult to obtain in Retort No. 2 because the width from the flow standpoint was only 28 inches. However, in larger vessels, it becomes extremely difficult to obtain uniform flow because of the natural coning pattern of the particles which was discussed earlier. Therefore, a major effort was directed toward evaluating and developing techniques which would give uniform particle velocities in Retort No. 3 and commercial sections as well. The specific hardware required to accomplish this is called a drawoff system. It should be emphasized that the objective of this work was to obtain uniform flow across a width of 10 feet. This was the length of the long axis of Retort No. 3 and also was considered a convenient modular section of a commercial retort drawoff.

a. General Discussion of Potential Drawoff Systems

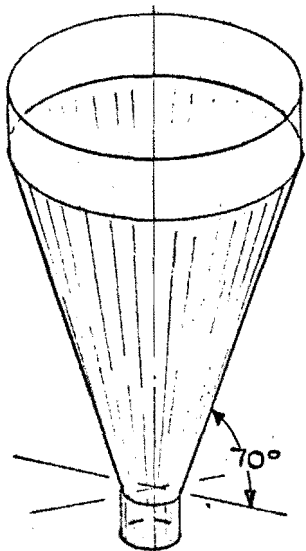
Before discussing the specific development work, it is worthwhile to consider the general types of systems available for evaluation. These are shown schematically in Figure 3. The simplest system by far is the mass flow bin shown in Figure 3a. This system relies on steeply-sloped walls to promote flow. Corrective inserts, shown in Figure 3b, have been used in the materials handling field to improve the flow in bins which are not of the mass flow type. The purpose of the insert is to obstruct the fast flow above the outlet and divert the flow channel to the walls.

All other systems utilize multiple coning patterns in one form or another. These systems attempt to achieve uniform velocity by creating a series of overlapping coning patterns. The single-level drawoff system (Figure 3c) and the multilevel slot drawoff system (Figure 3d) form overlapping coning patterns with static hardware. These systems use pipes or long slots to manifold the flow from a large area to a relatively small outlet. Thus, the only moving parts are on the single outlet. Two other systems, shown in Figure 3e and 3f, utilize rather complex moving hardware - rolls in one case and a grate assembly in the other. In both cases, there is no reduction in flow area as the rate is controlled over a large area and the particles are in free fall below the moving mechanism. The fact that the shale bed is discontinuous distinguishes these systems from those discussed earlier.

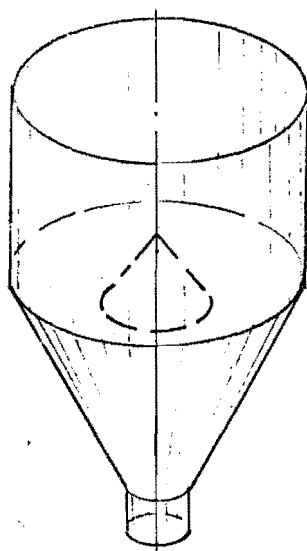
The single-level drawoff system (Figure 3c) and the system of rotating rolls (Figure 3e) both were tested

POTENTIAL SHALE DRAWOFF SYSTEMS

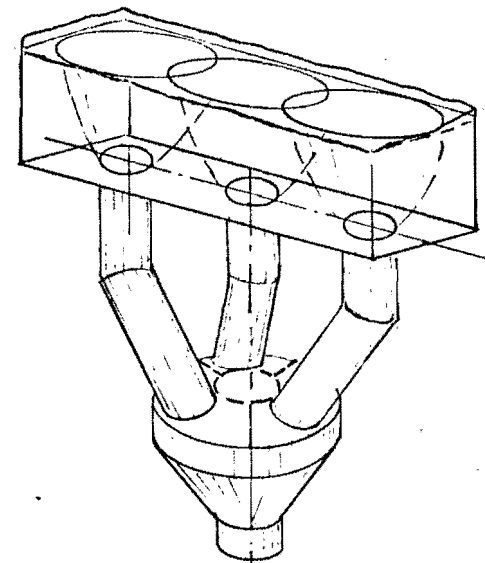
(a)
Mass Flow Bin



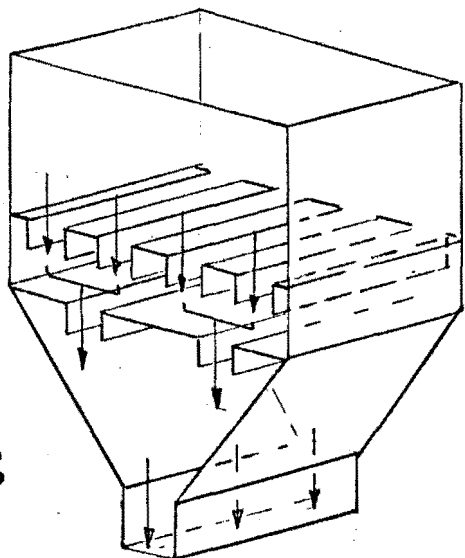
(b)
Flow-Correcting Insert



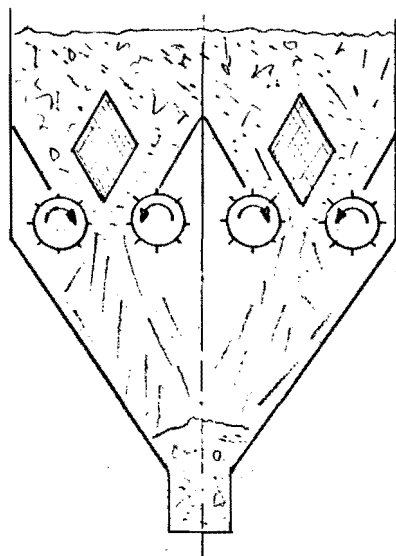
(c)
Single-Level Drawoff System



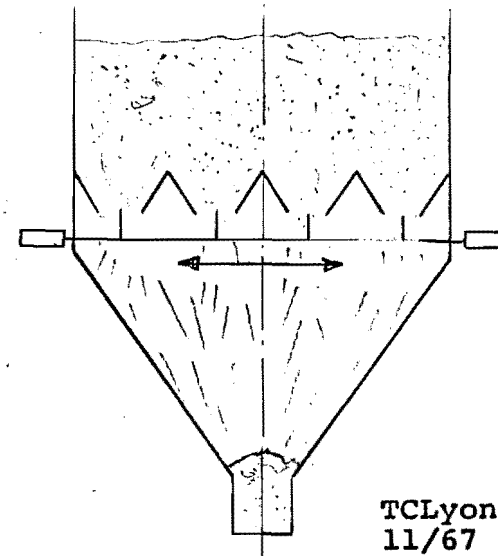
(d)
Multilevel Slot Drawoff System



(e)
Rotating Rolls
(U. S. Bureau of Mines)



(f)
Oscillating Grate
(Cameron and Jones, Inc.)



successfully in Retort No. 3. The multilevel slot system (Figure 3d) was developed successfully in a full-scale model and was considered for installation in Retort No. 3. However, it was bypassed in favor of the single-level system which had more overall flexibility. The mass flow bin (Figure 3a) was evaluated in a full-scale model and rejected because the flow pattern was only slightly better than the basic coning pattern. The use of corrective inserts (Figure 3b) improved the flow pattern to the point that this system was useful in storage bins but the flow uniformity and scale-up confidence were not satisfactory for retort consideration. The oscillating grate system (Figure 3f) developed by Cameron and Jones, Inc. (7) was not tested at Anvil Points. However, based on reported observations of cold flow tests at Petrobras, Brazil, it appears to be capable of providing adequate uniformity of flow.

b. Development of the Single-Level Drawoff System

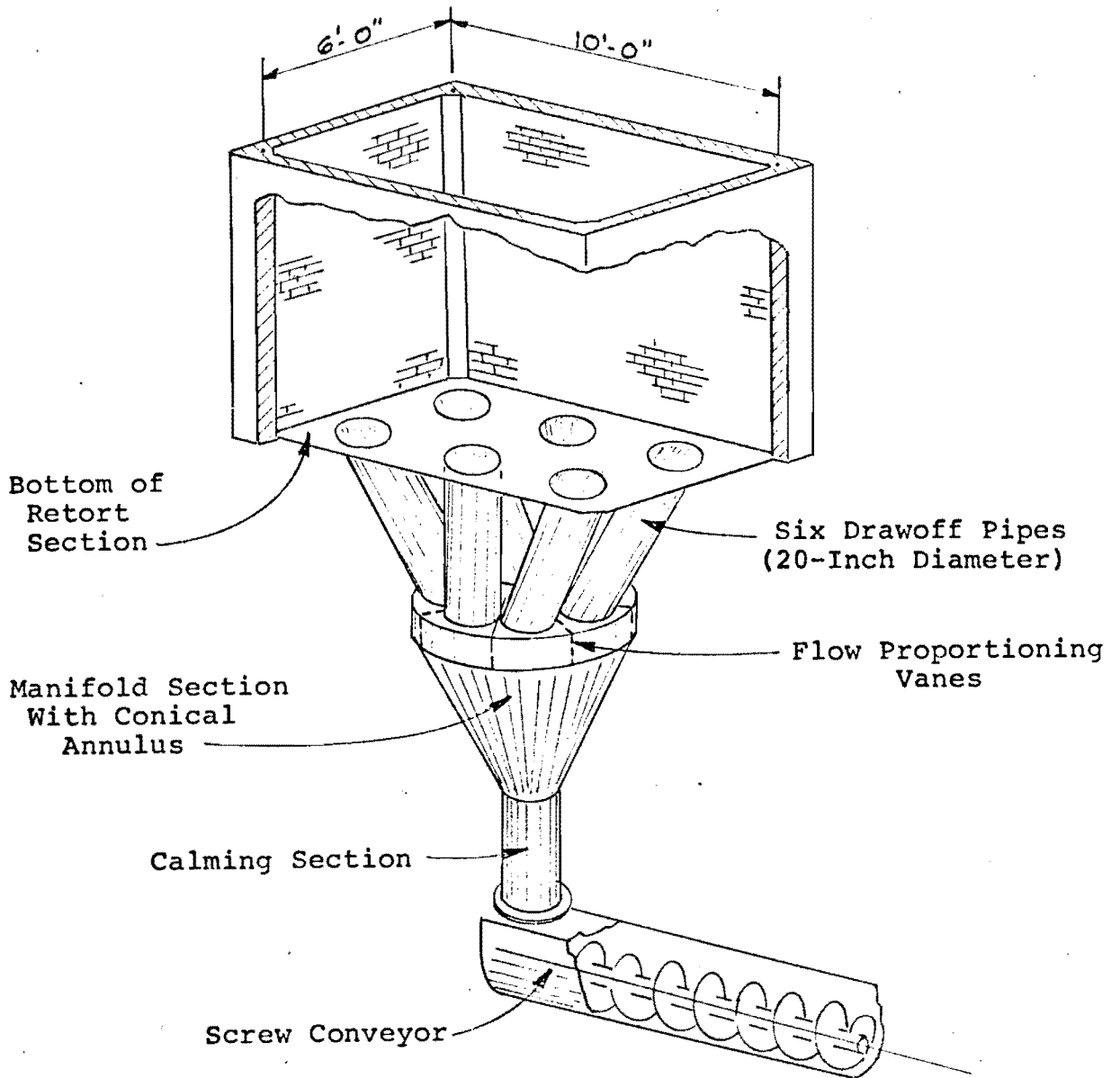
The failure of the mass flow bin to provide uniform flow confirmed earlier thinking that a rather sophisticated drawoff system would be required - one which utilized multiple or overlapping coning patterns. Two systems were available early in the program. The system of rotating rolls had been used by the U. S. Bureau of Mines to achieve satisfactory flow in Retort No. 3. This system could have been installed in the initial rehabilitation of the unit. In addition, the technology of the oscillating grate could have been purchased from Cameron and Jones, Inc. However, both of these techniques shared a common drawback. Both systems were extremely complex mechanically because of the dependence on moving hardware over much of the retort area. Thus, it was considered highly desirable to develop a drawoff technique which utilized static hardware. Such a system had been used successfully in moving-bed catalytic cracking units with small spherical particles which were 1/8 inch in diameter. Furthermore, the basic flow studies indicated that known moving-bed technology was applicable to oil shale.

(1) Design Installed in Retort No. 3

The installation of the single-level drawoff system in Retort No. 3 is shown in Figure 4. This system utilizes a single deck in the bottom of a vessel. The deck contains a multiplicity of pipe downcomers which gives the overlapping coning patterns and the uniform flow in the vessel. The pipes are manifolded into an annular region which feeds the single outlet of the vessel. Flow proportioning vanes divide the annulus into equal areas - one for each pipe. The specific installation in Retort No. 3 contained six pipes which served 60 square feet of retort cross section or one pipe for each 10 square feet of area. Thus, this technique was capable of reducing

FIGURE 4

SINGLE-LEVEL DRAWOFF SYSTEM INSTALLED IN RETORT NO. 3



the flow area from 60 square feet to 2.2 square feet (20-inch diameter pipe) with static hardware while maintaining uniform flow.

(2) Performance in Retort No. 3

The single-level drawoff system performed satisfactorily in Retort No. 3 during a sustained 10-day operation with 1- to 2 1/2-inch shale (8). Furthermore, it performed well during several days of exploratory studies with a wider, 3/4- to 2 1/2-inch fraction (8). These fractions are estimated to be roughly 83% and 89% of the mine run shale ground to minus 2 1/2 inch, respectively. Thus, this drawoff system has demonstrated its ability to perform with a major portion of the crusher production. Unfortunately, the picture is clouded beyond this point.

In May 1967, drastic process and hardware modifications were made in order to gain operability in Retort No. 3 with the 1/4- to 1-inch fraction (roughly 12% of mine run shale ground to minus 2 1/2 inch). One part of a four-part package of modifications was the removal of the single-level drawoff system in favor of the rotary rolls of the U. S. Bureau of Mines. The other three modifications included a revised startup procedure; a streamlined, minimum-hardware air distributor; and the use of hot dilution gas. The drawoff system was changed to gain the capability of crushing any agglomerates which might pass into the bottom of the retort with the proposed processing scheme. Along this line, it should be noted that pipe plugging in the single-level drawoff system was a rarity even in the periods of poorest operability. Almost invariably, the clinkers were retained in the air distributor hardware. However, with the proposed distributor design which was much less restrictive, agglomerates could possibly pass into the lower section of the retort more easily. Thus, the rolls were included for their insurance value.

Operability with 1/4- to 1-inch shale was achieved at a rate of 300 lb/(hr)(ft²) as a result of this modification package. Unfortunately, the part that the roll feeders played in the successful operation was never established because of time limitations. The roll assembly remained on Retort No. 3 throughout the balance of the program. Consequently, the single-level drawoff system was not in service during the sustained run with the full range, 1/4- to 2 1/2-inch shale.

A discussion of Retort No. 3 performance is far beyond the scope of this report. Only the pertinent details that relate to the performance of the drawoff systems have been presented. Separate Technical Memoranda have been issued which deal with the performance of Retort No. 3 with 1- to 2 1/2-inch shale (8), 1/4- to 1-inch shale (9), and 1/4- to 2 1/2-inch shale (10). Another Technical Memorandum (11) deals with the

overall problem of retort operability. All this work is summarized in the Technical Management Summary which covers retorting (1).

To summarize the performance of the single-level drawoff system in Retort No. 3, it was entirely satisfactory with the larger shale sizes which make up over 83% of the crusher product. Beyond this it is a matter of technical judgment. We believe the system would work equally well with the full range, 1/4- to 2 1/2-inch shale. We are somewhat less confident of its performance with the small, 1/4- to 1-inch shale with present process know-how.

(3) Development Studies in Model Simulations

The initial development work (12, 13, 14) was carried out in a circular shale storage bin which had an area of 108 square feet or almost twice that of Retort No. 3. The assembly contained twelve drawoff pipes or one pipe for every 9 square feet of bin area. The technique showed considerable promise with several shale sizes including 1/4 to 1 inch, 3/4 to 1 1/2 inch, 1 1/2 to 3 inch, and 1/4 to 3 inch. Therefore, the development work (15, 16) was continued in a full-scale, one-half-section model of Retort No. 3 which was capable of circulating shale continuously. The dimensions of the flow model were 10-feet wide, 3-feet deep, and 19 feet high. One face - 10 ft by 19 ft - was plexiglass for observation purposes.

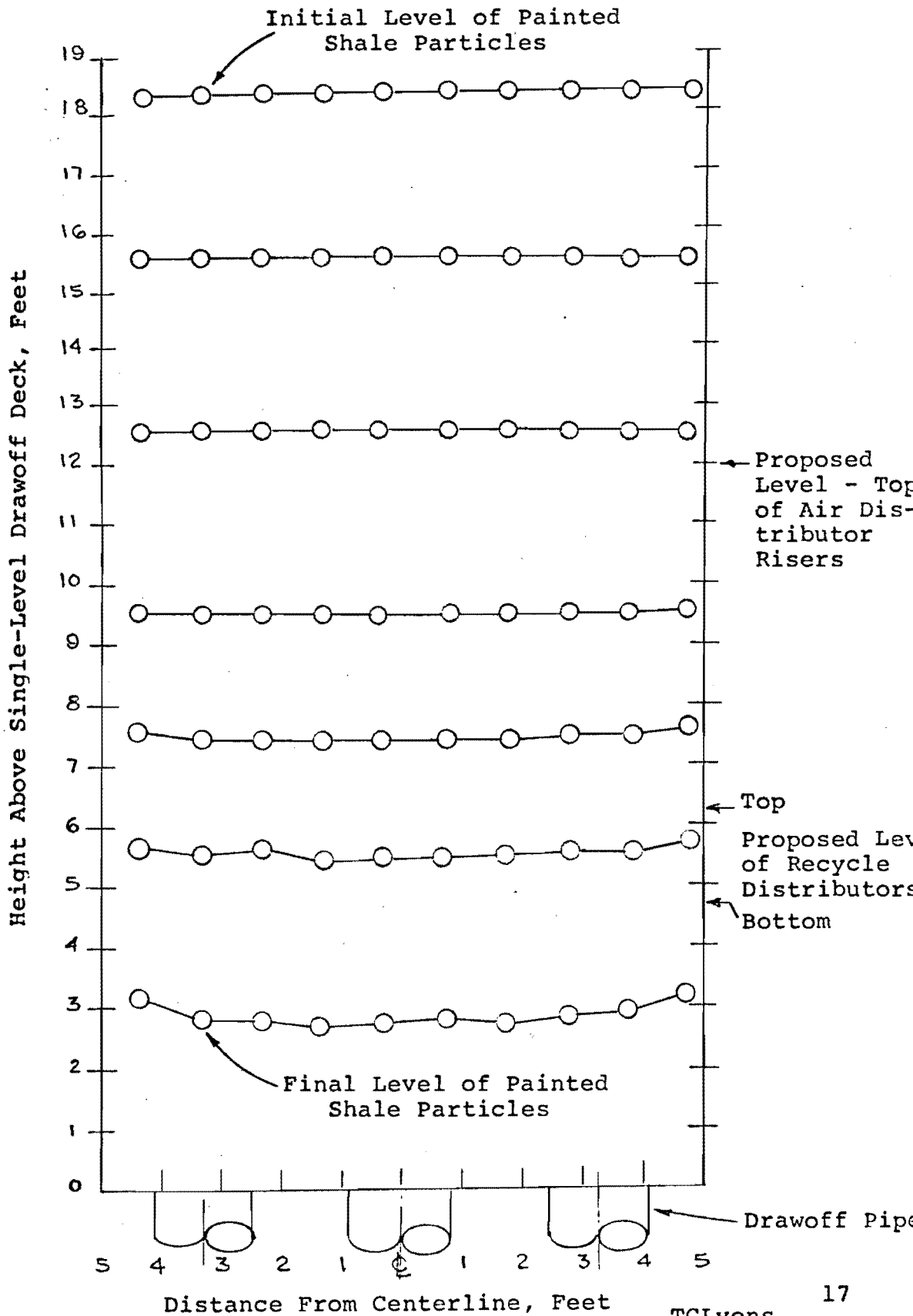
An example of the near-perfect flow pattern that this system is capable of giving is shown in Figure 5. The flow was uniform across the entire 10-foot width to within 3 feet of the vessel floor. Similar patterns were observed for the small, 1/4- to 1-inch shale. In this work, the model was filled and circulated for at least an hour to loosen the bed. The flow was stopped momentarily in order to paint a number of particles along a horizontal level at the top of the bed. Flow was resumed and the marked particles were observed as they passed down through the model.

c. Development of the Multilevel Slot Drawoff System

While the single-level drawoff system was undergoing initial evaluation in the storage bins, an alternate drawoff system was under development in a full-scale flow model. The alternate system, shown schematically in Figure 3d, uses several decks with long slots to give overlapping coning patterns and to manifold the flow into a single outlet. As before, the objective was to obtain uniform flow across a 10-foot width.

FIGURE 5

FLOW PATTERN OF 1- TO 2 1/2-INCH SHALE IN HALF-SECTION MODEL OF RETORT NO. 3 WITH NO INTERNAL HARDWARE



The initial evaluation (17, 18) indicated that a four-slot deck was not necessary as a two-slot deck would suffice for a 10-foot width. Further development led to the configuration shown in Figure 6 which gave satisfactory flow patterns with all shale sizes tested (19, 20). The angle of 50 degrees for the sloping plates at the slot inlets was found to be critical. It is interesting to note that an angle of 70 degrees resulted in a double mass flow bin serving a 10-foot section. However, the flow pattern was extremely poor in this case.

The multilevel slot drawoff system was considered for initial installation in Retort No. 3 but was bypassed in favor of the single-level system. The relative merits of both will be discussed later in this section of the report.

d. Attempts to Apply the Mass Flow Bin Concept and Flow-Correcting Inserts

(1) Evaluation of the Mass Flow Bin Concept

The mass flow bin (Figure 3a) was evaluated because of its simplicity and wide-spread publicity. However, it fell far short of expectations as a drawoff system. The concept was tested in a full-scale model which was 10-feet wide, 2-feet deep, and 26-feet high. Bottom slopes of 60 degrees and 70 degrees with the horizontal were tested with little success (21, 22). For example, with a bottom slope of 70 degrees and using 3/4- to 1 1/2-inch shale, there was very little flow at the walls as high as 21 1/2 feet above the outlet. Furthermore, the tendency of particles to flow rapidly down through the center was evident throughout all these studies.

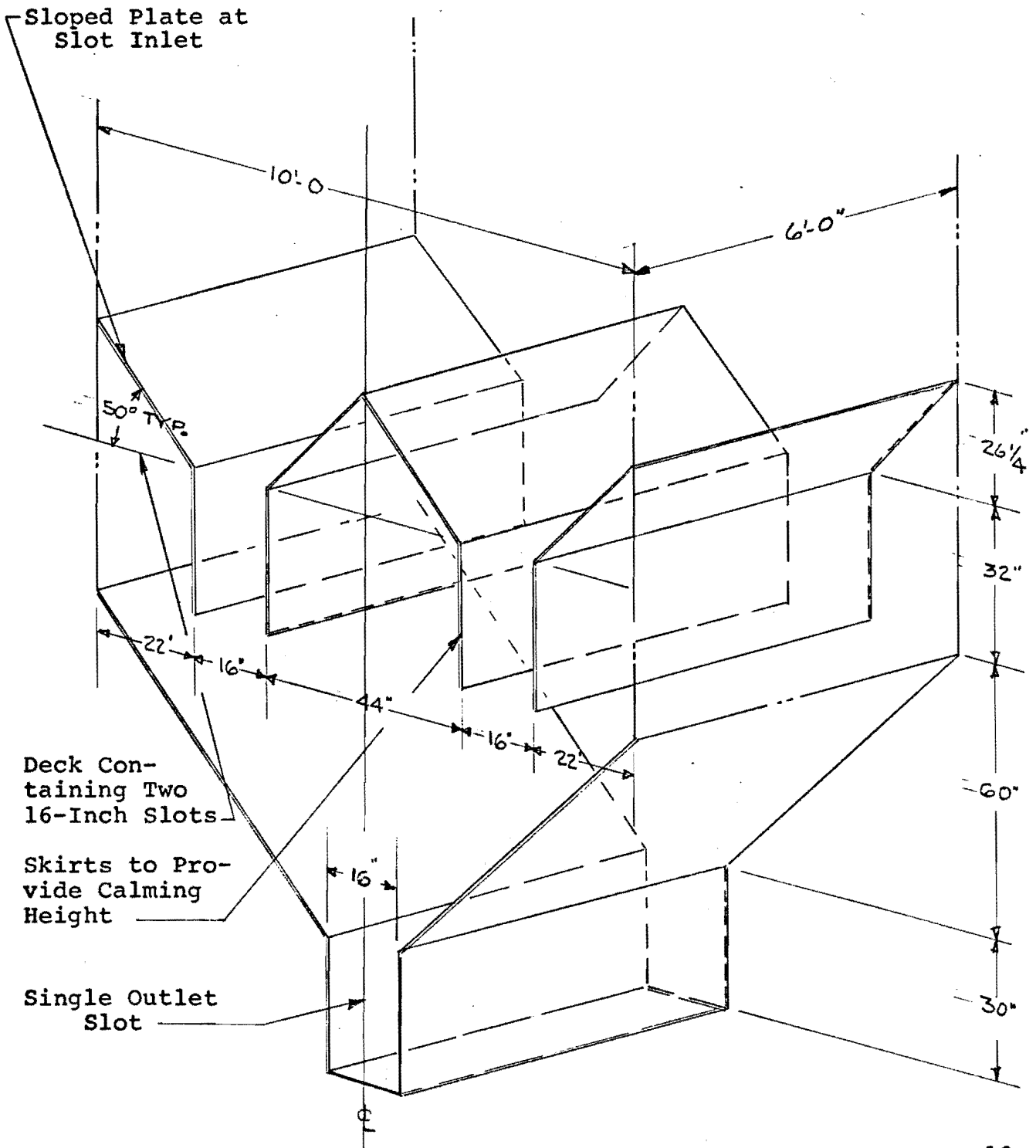
Multiple mass flow bins were also unsuccessful as a drawoff system as discussed in the previous section of this report.

At this point, it is logical to raise the question as to why the mass flow idea was so unsuccessful. The answer became apparent at the AIChE Symposium on Materials Handling on September 18, 1966 (23). The requirements of flow which are imposed on a retort vessel are much more stringent than those generally demanded in the materials handling field. Most people are concerned with the following flow problems:

- Flow stoppages due to arching or bridging.
- Nonuniform rate of discharge from a vessel.
- Loss of bin volume because bed is not "live."

FIGURE 6

MULTILEVEL SLOT DRAWOFF SYSTEM CONSIDERED FOR
INSTALLATION IN RETORT NO. 3



There is no doubt that the mass flow concept has been of great value in these situations. However, in retorting, it is necessary to go further and demand an "ideal live bin." This is one in which the particle velocity is uniform from wall to wall throughout the major portion of the bin volume. It is in this requirement that the mass flow bin fails.

(2) Use of Flow-Correcting Inserts

Flow-correcting inserts (Figure 3b) were used with moderate success in the 100-ton shale storage bins. These bins are wide (18-foot diameter) and shallow (10-foot high) which is an extremely poor design from the standpoint of solids flow. Prior to the modification, the characteristic flow pattern was a fast-moving "rathole" in the center of the bin with static walls. This situation resulted in severe size segregation particularly with the wide range fractions.

Since there was little experience or knowledge with the use of inserts, a 1/12th-scale model of the bin was constructed out of plexiglass. This model was then used for exploratory flow studies with scaled-down shale. The model work (24) resulted in the addition of two inserts into the bins as shown in Figure 7. The insert package was much more extensive than desired and many trim adjustments were required. However, it yielded a "live bin" with an improved flow pattern from the standpoint of reducing segregation - but it did not give the flow uniformity desired in a retort. Therefore, the use of corrective inserts cannot be considered a potential drawoff technique for large retorts.

The successful use of a miniature model is an important facet of this work which should be emphasized. The model provided quick, economical, and surprisingly accurate information. It successfully predicted:

- The effect of size and relative position of inserts on the flow pattern.
- The sensitivity of flow pattern to insert position.
- The sensitivity of flow pattern to shale size.

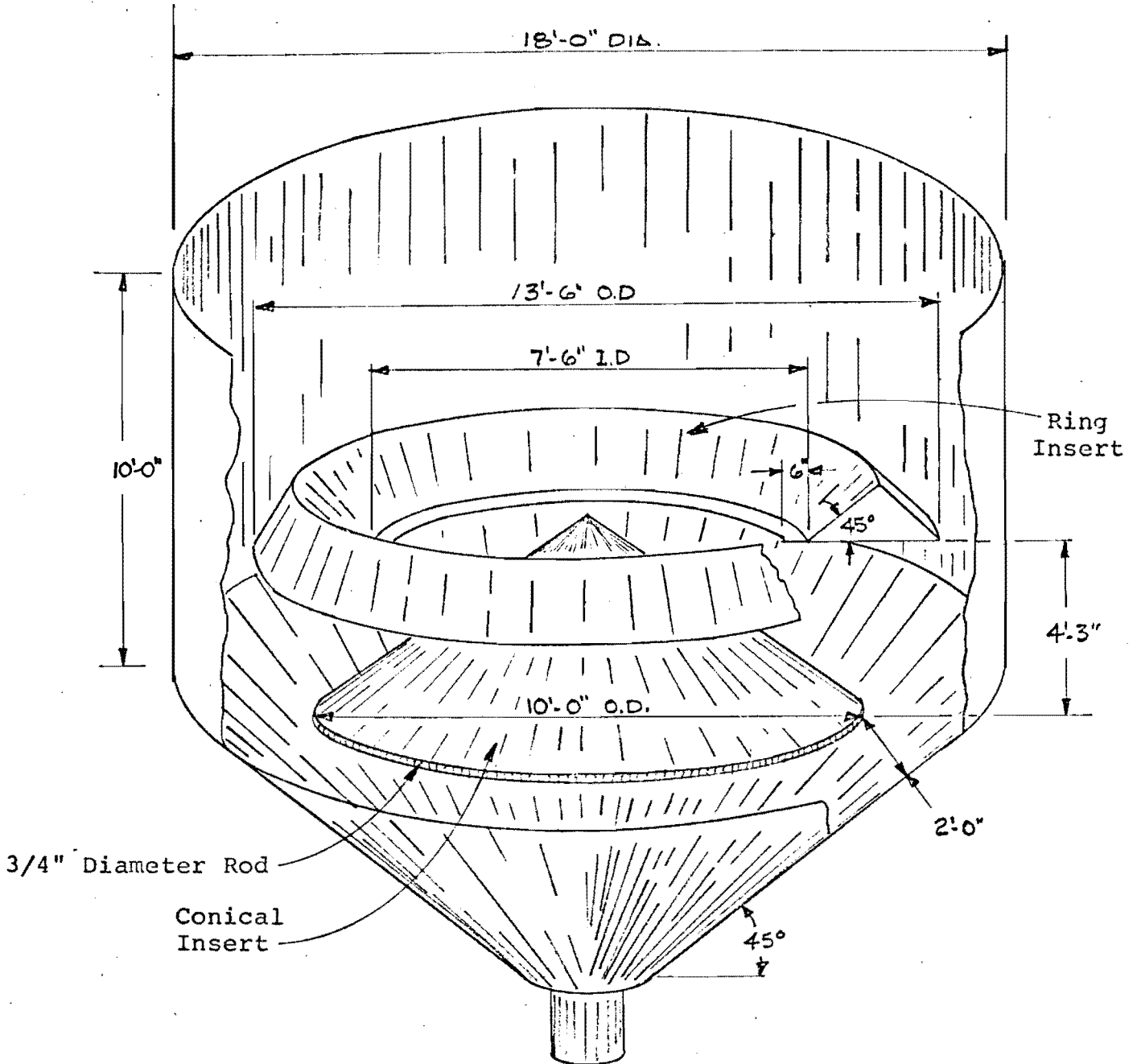
In general, it was a very useful research tool in this application.

e. General Evaluation of Drawoff Systems in Light of Development Work and Retort Experience

Some general comments are felt to be worthwhile to focus attention on the advantages and disadvantages of each drawoff system.

FIGURE 7

USE OF FLOW-CORRECTING INSERTS IN 100-TON SHALE STORAGE BINS



(1) Single-Level and Multilevel Slot Drawoff Systems

Both of these systems were developed to the point that they could be installed in the initial design of Retort No. 3. Both utilize static hardware which can be considered a major advantage for these systems. However, the single-level system was chosen for the initial design because of its greater flexibility. An important consideration was the fact that it is suitable to both circular and rectangular retort configurations whereas the multilevel system is suitable only to the latter. Furthermore, the single-level system appeared to be insensitive to particle segregation and the flow profile could be easily corrected by making adjustments in the flow proportioning vanes. A detailed comparison of the two systems and the basis for the choice are given in Reference (25). In retrospect, the choice still appears to be well founded.

The single-level system has been proven in actual retort service. The ability to scale-up this system to cross-sectional areas twice as large as Retort No. 3 has already been demonstrated. Furthermore, one set of hardware was capable of giving uniform flow with complete interchangeability of small, large, and full range shale sizes.

The major drawback of the single-level drawoff system is its inability to crush agglomerates or clinkers. As discussed earlier in this report, the seriousness of this drawback has not been established. In any event, should the agglomeration-clinkering problems be solved by process modifications in the future, there is no reason why this drawoff system would not be applicable to any shale size.

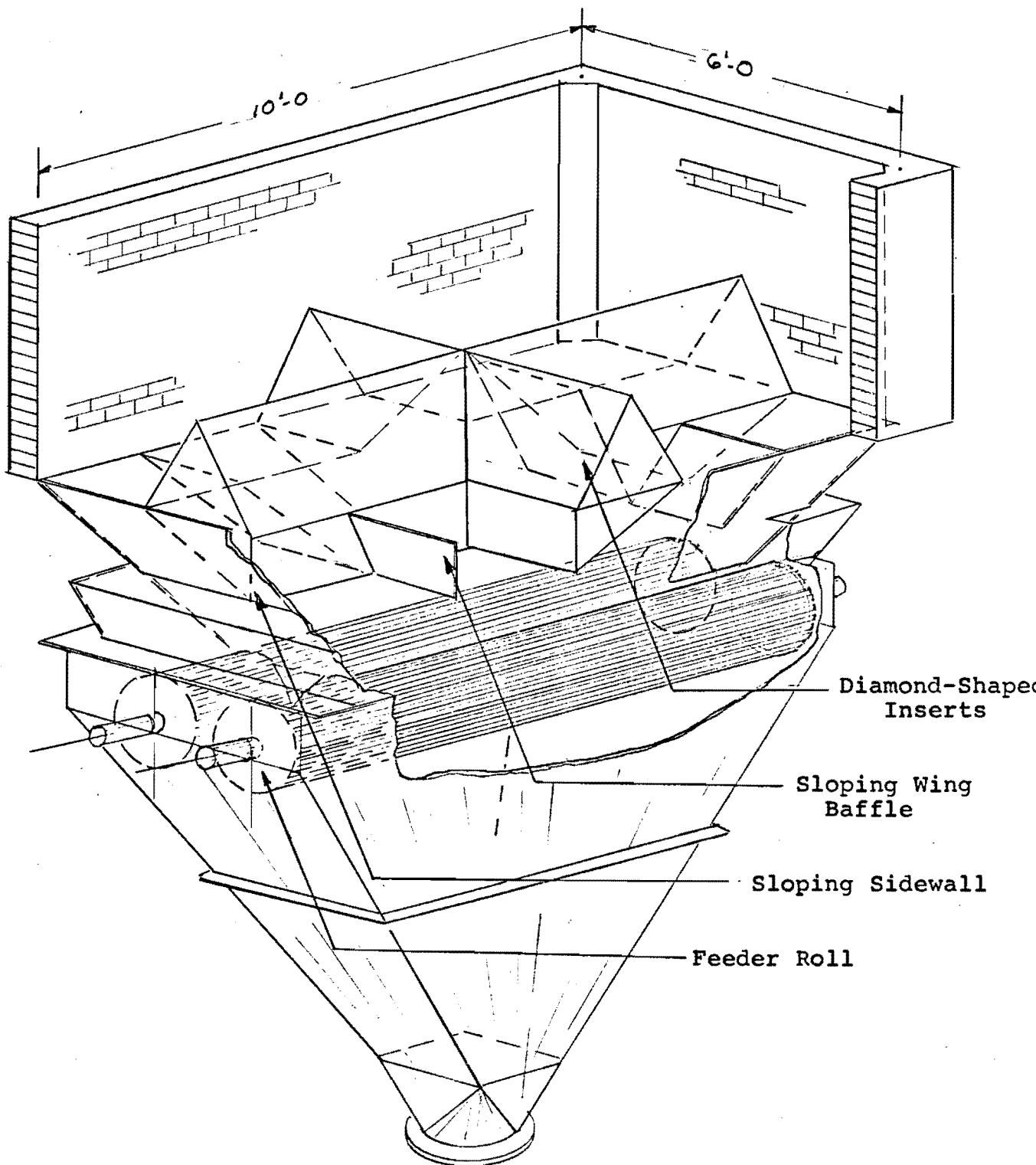
In the overall analysis, the single-level drawoff system is judged to have the greatest potential as the basic commercial drawoff system, supplemented by a more complex system if required for smaller shale sizes.

(2) Rotating Rolls as Developed by the U. S. Bureau of Mines

The capability of the rotating rolls as a drawoff system has been proven in Retort No. 3 during the U. S. Bureau of Mines operation and again in the current program. It operated satisfactorily for several short runs with the 1/4- to 1-inch fraction (9) and also during a 17 1/2-day sustained operation with the full range, 1/4- to 2 1/2-inch shale (10). The Retort No. 3 installation is shown in Figure 8. The major advantage of this system is its ability to crush any agglomerates or clinkers that reach the rolls.

FIGURE 8

U. S. BUREAU OF MINES ROLL FEEDER INSTALLATION
IN RETORT NO. 3



Unfortunately, the system is not without disadvantages. It is extremely complex mechanically and it required considerable maintenance. Of course, this was complicated by the necessity of using old equipment. This system is only adaptable to rectangular retort configurations and there is also some reason for concern as to its scalability to larger vessels. The system was developed specifically for Retort No. 3 and it is highly empirical. The system required an extensive insert and several other baffles to provide the desired uniformity of flow. The necessity of some of these inserts is not obvious which further indicates the empirical nature of the design. Thus, it has all the inherent scale-up problems that were encountered in the use of flow-correcting inserts in the 100-ton bins. Attempts to evaluate a simplified insert design (26) were unsuccessful because of excessive power requirements on the rolls. In fact, the power requirement was such that flow tests with a simplified design were not possible.

In the design as developed, one set of rolls served a width of 6 feet. It is unlikely that this width could be increased in light of the work done in connection with the multilevel slot drawoff system. (It will be recalled that two slots served a width of 10 feet.) Consequently, two complete sets of rolls and extensive baffling would be required for every 12 feet of retort width. There is also the question of the practical limit of the length of the rolls. Although the long axis of Retort No. 3 is 10 feet the baffling reduced the effective length of rolls to 6 feet. Thus, there is some question concerning how to scale-up the system along the axis of the rolls.

In summary, the rotating roll technique performed quite well in the present retorts at Anvil Points. However, the designer is faced with a perplexing scale-up problem.

(3) Oscillating Grate as Developed by Cameron and Jones, Inc.

This system (Figure 3f) is the only one which was not evaluated to some degree at Anvil Points. Therefore it is the least familiar. It appears to be capable of providing uniform flow after initial adjustments are made. Along this line, the Petrobras personnel indicated that substantial development work was required over and above the published information (7). The design is suitable to circular and rectangular configurations. Furthermore, there is probably a height advantage because manifolding is unnecessary.

The primary drawback appears to be the extreme mechanical complexity. There is also some question

as to its ability to crush clinkers in spite of the moving parts. This relates to the inability of the clinkers to reach the moving hardware.

The overall potential of this drawoff system appears to hinge on a demonstration of mechanical integrity over a sustained period in an operating retort.

(4) Mass Flow Bin Concept

The mass flow bin cannot be considered as a potential drawoff system because of its inability to provide uniform shale flow.

(5) Use of Flow-Correcting Inserts

The use of inserts yielded a definite improvement in flow uniformity over that obtained with the mass flow bin. However, it was not adequate for a retort design. The technique is highly empirical and scale-up problems would exist even if a system of inserts had been developed for Retort No. 3.

Thus, a system based solely on the use of flow-correcting inserts appears to have little promise as a drawoff technique for large retorts. However, the use of inserts can be a major factor in connection with other systems such as the rotating rolls.

f. Calming Height Requirements

Calming height is an important consideration in any drawoff system which utilizes a continuous bed of solids from the vessel proper to the outlet. This is another concept developed in moving-bed catalytic cracking and it relates to the vertical height required at the outlet so that all flow distortion from the feeder mechanism will be eliminated. This is analogous to the straight run of pipe placed upstream and downstream of an orifice in a gas or liquid line to "calm out" the flow distortion and insure reliable measurements. In a stream of flowing solids, the calming height insures that the flow distortion is not transmitted into the vessel proper.

The objectives of this work were twofold. First, it was necessary to provide a general understanding of calming height including the need for it and the factors that influence it. In addition, it was necessary to provide design guidance for attaining adequate calming height in storage bins and Retort No. 3.

This model study (27) revealed that the calming height requirements for oil shale particles ranged from 1.4 to 4.5 channel diameters (or widths). The magnitude of the requirement was found to depend on the type of shale (raw or spent), the channel geometry (circular or rectangular), and the channel size.

Spent shale generally required a greater calming height than its raw shale counterpart (3/4 to 1 1/2 inch in the study). This difference could not be attributed to size alone since the calming height was found to be the same for both the 3/4- to 1 1/2-inch and the 1/4- to 3/4-inch raw shale fractions in a given pipe or duct. However, the spent shale which was evaluated contained 10 to 30% weight of fines which were smaller than 8-mesh. Thus, it was concluded that particle size has little effect on calming requirements unless the fines content is high. This is consistent with the observations made of the flow characteristics of raw and spent shale in a previous study (5).

The calming requirement of a rectangular duct was found to be substantially greater than that of a circular pipe of equivalent width (diameter). This is probably the result of the smaller area in a circular section which concentrates the coning pattern so that uniform flow can be obtained in a shorter distance.

As might be expected, the calming requirement increased as the width or diameter of a channel was increased. Thus, minimum calming heights are obtained with circular sections of the minimum diameter which will give adequate flow.

This work revealed that particle velocity has a negligible effect on calming height. Velocities ranged from 0.1 ft/min to as high as 8 ft/min in some cases but the effect was negligible with raw and spent shale in circular pipes as well as rectangular ducts.

The calming height considerations for Retort No. 3 were guided by this study. A circular outlet pipe was chosen to minimize the height requirement. The pipe was 20 inches in diameter to obtain adequate flow area with the large, 1- to 2 1/2-inch shale. Therefore, 60 inches or three pipe diameters of vertical calming height were provided. Only two pipe diameters would have been required for raw shale but the extra diameter was required to account for spent shale. Actual drawdown tests confirmed that it was adequate for all sizes of raw shale investigated in Retort No. 3.

3. Effect of Retort Internals on Shale Flow

Up to this point, the discussion has been concerned with the ability of a drawoff system to provide uniform shale flow across the entire area of a large retort. In addition, consideration must be given to the placement of internal hardware so that the flow uniformity is maintained to the greatest possible extent. It should be recognized that any hardware in a bed of moving solids will cause some degree of flow distortion. This relates to the fact that the particles flowing directly above the hardware must deviate from their vertical path and move laterally in order to flow around the obstacle. As a result of this lateral movement, they must displace other particles which are already flowing in their own vertical path. Thus, this competition of particles at an obstacle results in a flow distortion above it. The objective of this work was to design and position the distributor internals such that the desired gas distribution could be obtained with a minimum of distortion to shale flow. In short, a balance between gas distribution and shale flow was required. This section of the report deals with the aspects of shale flow.

It should be emphasized that this model work was carried out at ambient temperature; therefore, the particles are dry and free-flowing. However, in an operating retort, cohesive flow may exist in the retorting zone above the air distributors. In cohesive flow, the particles are held together by a tarry binder; consequently, they flow as larger masses (agglomerates) rather than as individual particles. This binder is generally destroyed in the combustion zone and the particles become free-flowing again. It is not the purpose of this report to discuss agglomeration of particles during retorting. However, it is important to point out that this condition can exist. Thus, the shale flow in the critical retorting zone can be poorer than is shown by the cold model studies. Nevertheless, the objective of this work was to obtain the most uniform shale flow possible in the cold, free-flowing state.

Exploratory flow studies in a 1/12th-scale model of Retort No. 3 indicated that the shape and location of the recycle gas distributors had a great influence on the uniformity of shale flow through the vessel. A comparison of results from the 1/12th-scale and full-scale models indicated that the overall conclusions were the same (28). Therefore, an intensive screening evaluation was carried out in the small model to study shape and location of internals.

a. Effect of Distributor Shape

The shape of the distributor element has a pronounced effect on the shale flow. The width of the element

should be as narrow as possible to minimize distortion. In general, the smoothest flow patterns were obtained with elements which had a sharp leading edge and a triangular top section. Blunt or round configurations at the top of the element resulted in greater resistance to shale flow. This conclusion was confirmed in the full-scale flow model (29).

b. Effect of Distributor Spacing and Symmetry

Following the screening study in the miniature model (30), a final systematic check of the position of internals was made in the full-scale, one-half-section model of Retort No. 3 (31, 32). This involved adding the recycle gas distributors to the basic drawoff system and checking the flow pattern. Then, the entire air distributor assembly was added and the flow pattern was evaluated again.

The initial design of Retort No. 3 called for four recycle gas distributors along the 10-foot dimension to obtain the desired gas distribution. From the standpoint of shale flow, it was found that these distributors should be spaced equally on 24-inch centers as shown in Figure 9. Note that the flow pattern remained near perfect when compared to the base case with no internals which was shown in Figure 5. Attempts to locate the outer distributors closer to the wall to improve the gas distribution were unsatisfactory as the shale flow was impeded in the wall regions particularly with the larger shale sizes.

The optimum horizontal spacing of recycle gas distributors is influenced by the type of shale drawoff system. In general, the spacing appears to be more flexible with the single-level drawoff system which has a greater number of overlapping coning patterns than the two-slot multilevel system (33).

Vertical spacing of recycle gas distributors is also important. It is necessary to position the distributors in the region where the coning patterns overlap fully and the flow is uniform. The base flow pattern without internals (Figure 5) showed that the flow was uniform to a level within 3 feet of the deck. The recycle gas distributors were positioned almost 5 feet above the deck to provide some safety factor for the steeper coning patterns expected with spent shale.

Following the evaluation of the recycle gas distributors, it was necessary to check the proposed air distributor design for its effect on shale flow. In this case, a deterioration was observed when the complete air distributor assembly was added to the system. This pattern, shown in Figure 10, indicates slow shale flow in the center region. Further investigation

FIGURE 9

**FLOW PATTERN OF 1- TO 2 1/2-INCH SHALE IN HALF-SECTION
MODEL OF RETORT NO. 3 WITH FOUR RECYCLE
GAS DISTRIBUTORS IN PLACE**

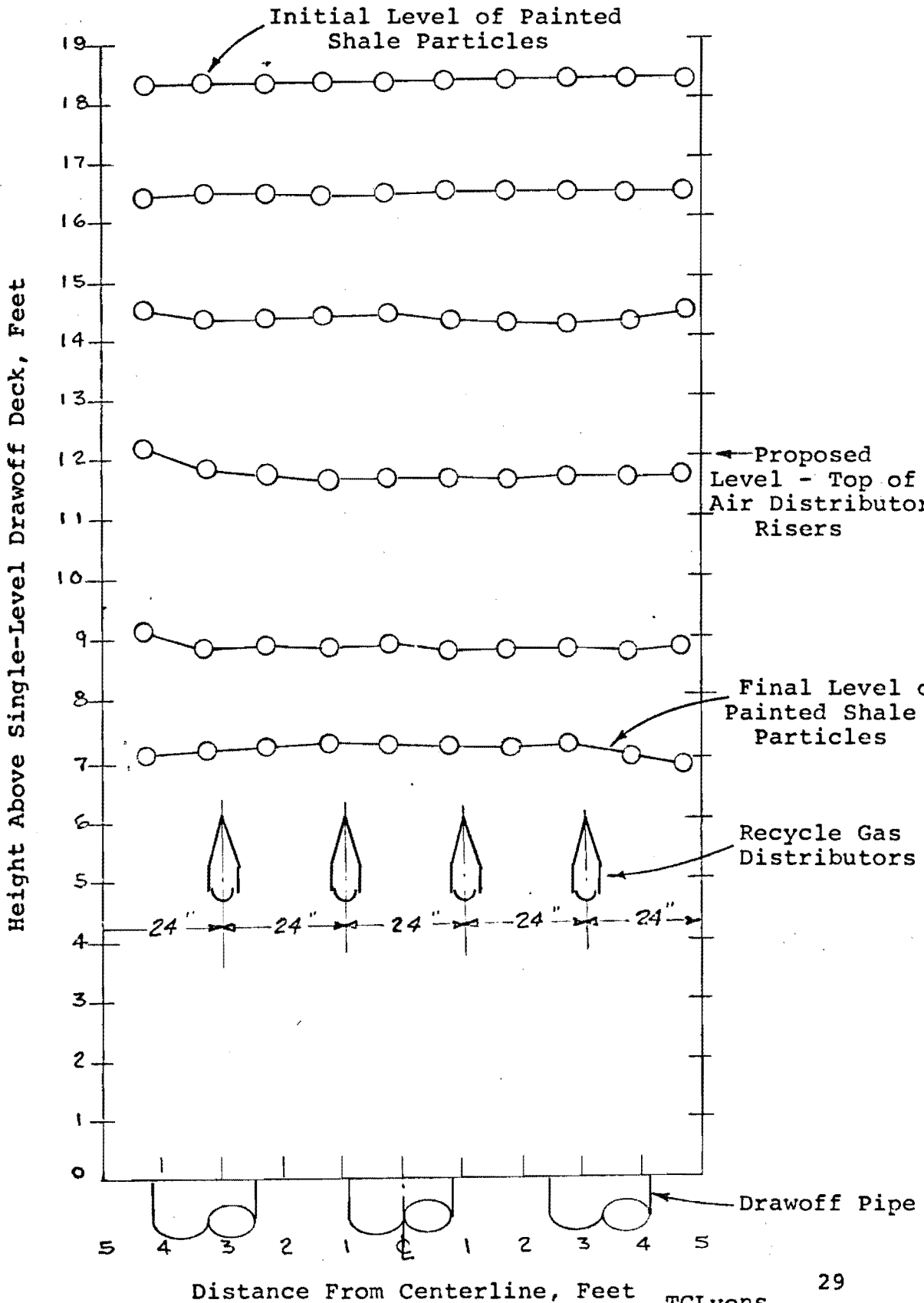
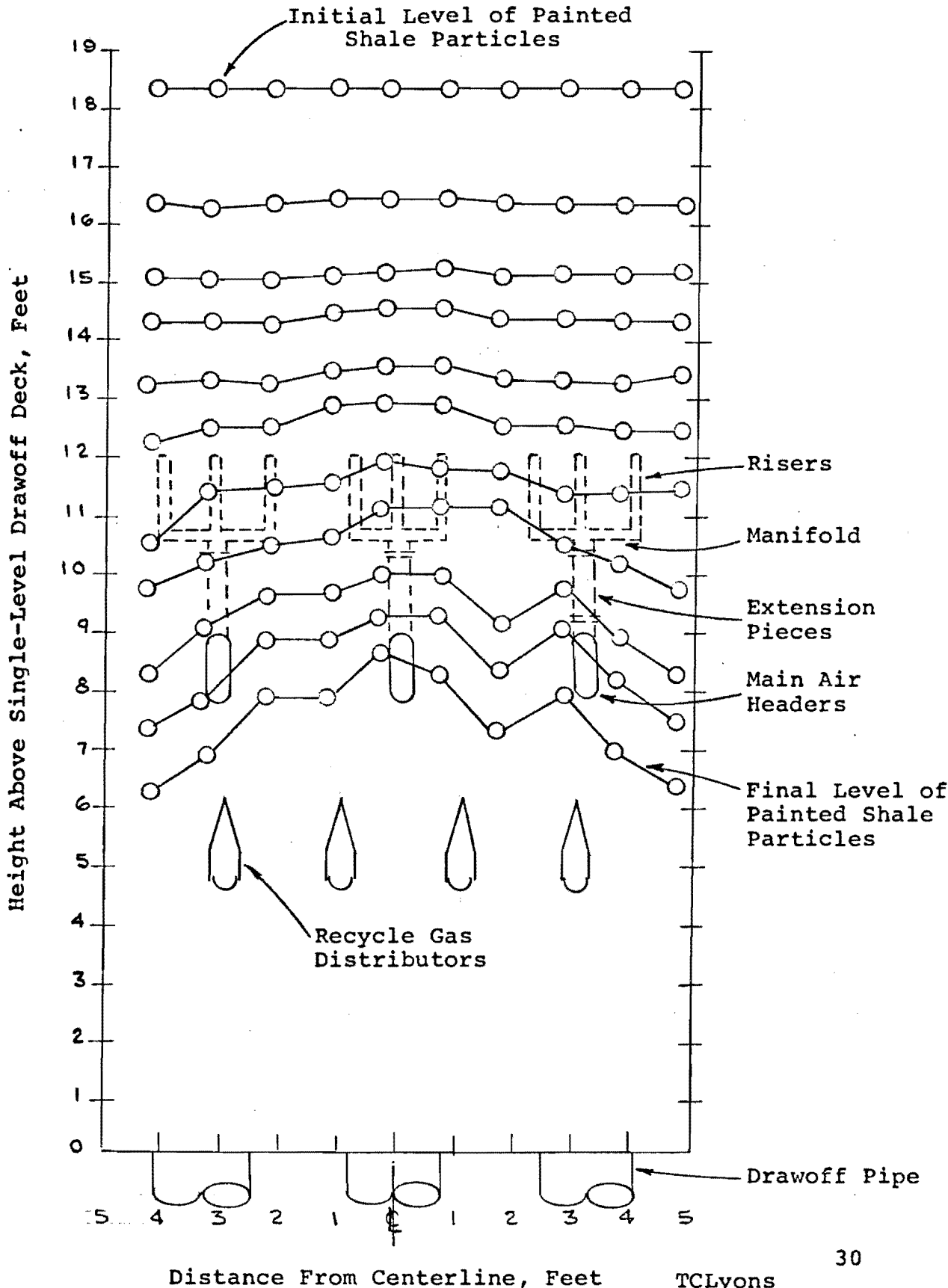


FIGURE 10

FLOW PATTERN OF 1- TO 2 1/2-INCH SHALE IN HALF-SECTION MODEL OF RETORT NO. 3 WITH FOUR RECYCLE GAS DISTRIBUTORS AND COMPLETE AIR DISTRIBUTOR ASSEMBLY IN PLACE



revealed that it was a problem of hardware symmetry between the four recycle gas distributors and the three air headers. The position of the middle air header with respect to the recycle gas distributors was causing this shale slowdown. This situation improved dramatically when the number of recycle gas distributors was reduced from four to three and the center element was located directly under the middle air header. The shale flow pattern with this configuration is shown in Figure 11. The flow is uniform with the exception of the particles which travel down the line of hardware.

It was not possible to make this change in the initial design of Retort No. 3. However, it was made at a later date and was considered to be a major factor in obtaining improved operability with the large 1- to 2 1/2-inch shale (34). Later in the program, symmetry problems were avoided by positioning the recycle gas distributors perpendicular to the air headers. Of course, this could cause additional design complexity in certain types of commercial configurations.

Further details of distributor design are given in Reference (35).

4. Segregation of Oil Shale Particles in a Flowing System

At this point in the discussion, uniform shale flow has been established by the drawoff system and it has been maintained by the proper placement of the internal hardware. Thus, the final consideration is feeding the raw shale to the unit such that segregation is minimized.

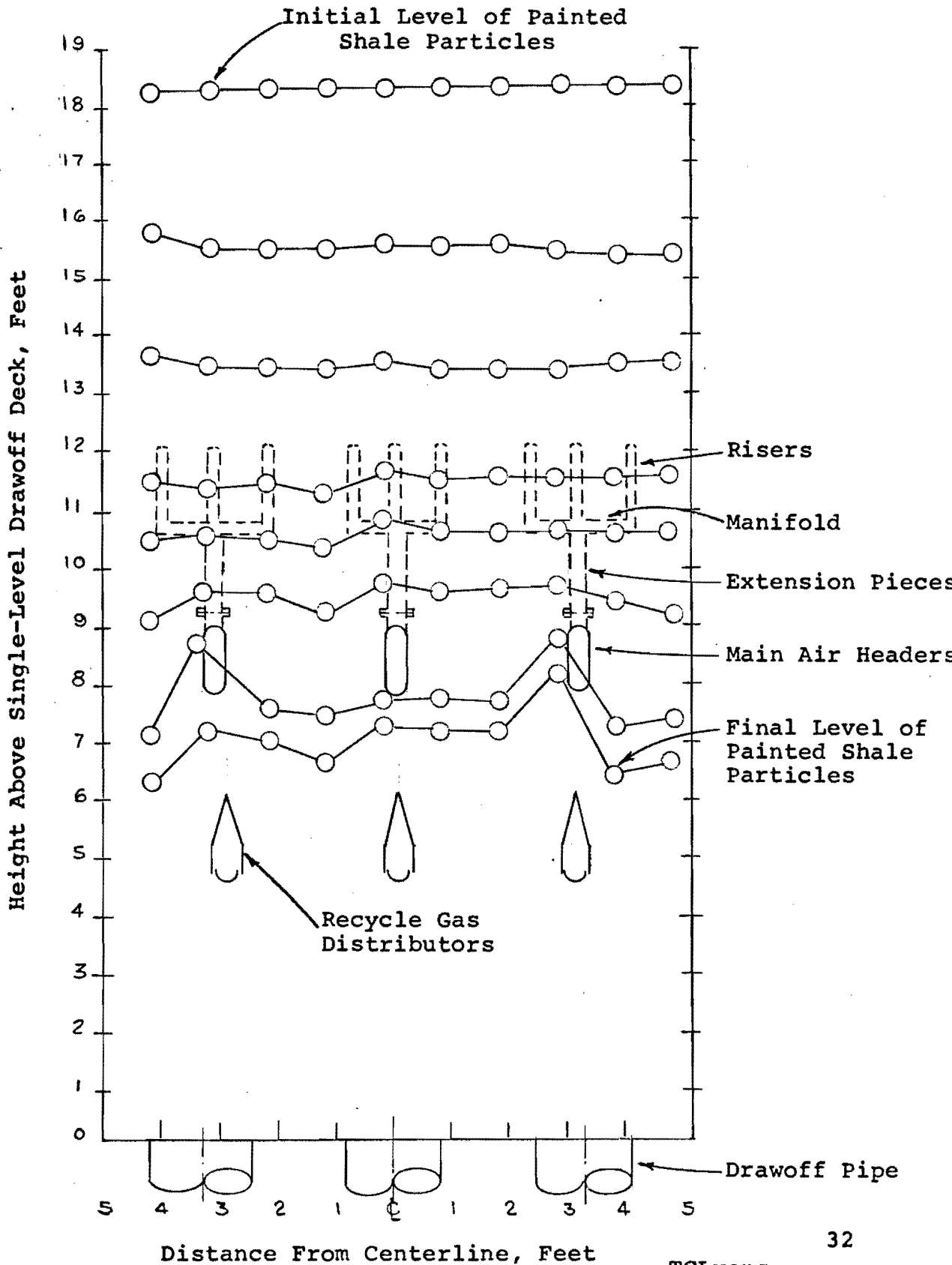
Particle segregation is an important consideration in any solids-flow system in which there is a range of particle size. This is especially true when processing oil shale since the size range of the feed can be very wide. Therefore, Stage I of the Research Program included a major effort to study the segregation associated with the handling of oil shale.

The objectives of this work were as follows:

- To develop a general understanding of particle segregation.
- To determine the degree of segregation which would be encountered in the design of retorts and storage hoppers for oil shale.
- To develop techniques to minimize segregation of oil shale particles.
- To develop a specific design for minimizing segregation in Retort No. 3.

FIGURE 11

**FLOW PATTERN OF 1- TO 2 1/2-INCH SHALE IN HALF-SECTION
MODEL OF RETORT NO. 3 WITH THREE RECYCLE GAS
DISTRIBUTORS PLACED SYMMETRICALLY BELOW
THE AIR DISTRIBUTOR ASSEMBLY**



It should be emphasized that the investigation was limited to anti-segregation methods utilizing static hardware. Mechanical spreaders, rotating throwers, etc. are used effectively in the materials handling field and could have a place in controlling segregation while feeding intermediate storage bins. However, in the top of a retort the additional mechanical complexity could outweigh the advantages since the spreader would be inaccessible for maintenance.

A full-scale model was constructed for this investigation and the work revealed that segregation of oil shale particles can be substantial unless deliberate steps are taken to minimize it (36).

a. Effect of Pile Size and Feed Range on Segregation

The extent of segregation that takes place in a vessel is the result of two major factors:

- The range of particle sizes in the feed.
- The size of the pile that is formed when the particles are fed to the top of the vessel.

Segregation is not a problem if the particles are uniform in size. However, if the feed is not uniform, the tendency to segregate increases as the range of particle size increases. Unfortunately, economic and process factors dictate the range of particle size; therefore, limiting the range cannot be considered as a primary means of minimizing segregation although it is an advantage of using closely screened fractions. Thus, the only alternative left to the designer is to feed a vessel through a multiplicity of pipes in order to keep the piles small at the surface.

b. Effect of Inlet Geometry on Segregation

This study showed that the feed leg geometry has a large influence on the segregation in a vessel. In a sloped feed leg, segregation will take place in the leg itself and will add to that which occurs in the feed pile. Therefore, to minimize segregation, feed legs should be as steep and short as possible.

c. Application of Known Anti-Segregation Techniques Such as Surface Confinement and Surface Baffling

Anti-segregation techniques which are effective in controlling segregation in moving-bed catalytic cracking units

were found to be of only minor benefit with oil shale. By confining the catalyst pile surface below its normal angle of flow, segregation of small, spherical particles can be reduced by as much as 70%. The fact that this technique was not as effective with oil shale indicates that the segregation results from the sifting or filtering of small particles through larger voids rather than larger particles rolling or sliding along the pile surface. This sifting phenomenon has been observed in the flow studies and is illustrated quite vividly in the shale flow movie (3).

d. Anti-Segregation Considerations in Design of Retort No. 3

Using the segregation studies as guidance, it was judged that one feed pipe was necessary for about every 10 square feet of Retort No. 3 area. This required feeding the shale to the retort through six pipes. Therefore, most of the retort area was served by shale piles with radii of 24 inches or smaller. In no case, did the radius exceed 27 inches. The design of the raw shale feed system for Retort No. 3 is shown in Figure 12. A rotating chute distributed the shale in free-fall into an annular area. This annular area was shaped like an "hour glass" to facilitate control of the shale level which was held in this region. The shale was drawn out of the annulus and distributed to the retort through six feed pipes. The sloped portion of these feed legs was designed as steep as possible. The angle varied from 60 degrees on the outer pipes to 80 degrees on the central pipes (measured from the horizontal). The retort bed height was adjusted by means of vertical extensions of the six pipes. Being vertical, these extensions did not have any influence on segregation.

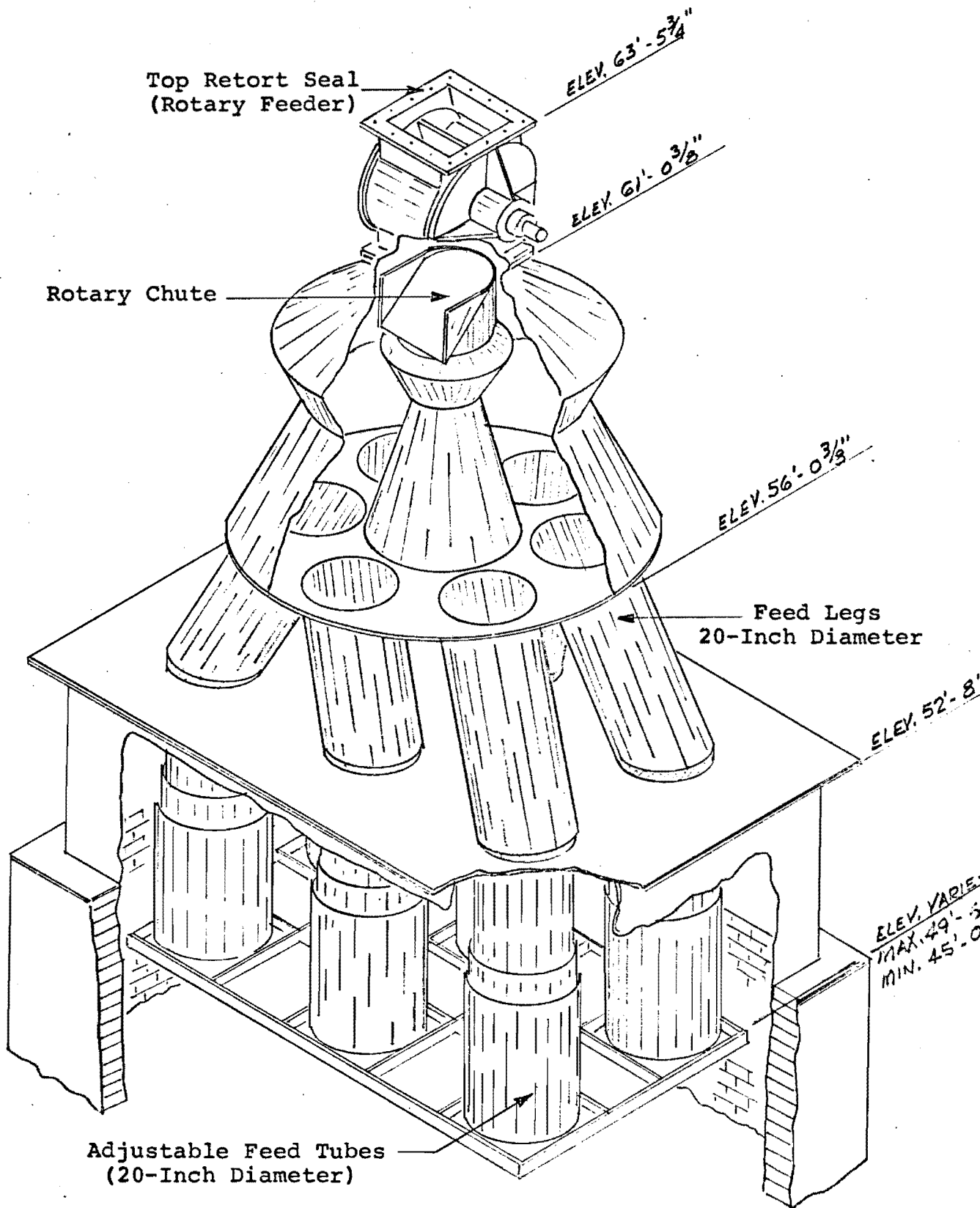
It should be emphasized that this design was a matter of judgment. It is impossible to isolate the part that segregation - and the resultant gas channeling - plays in retort operability. Thus, the designer must hold segregation at a low level consistent with the hardware complexity. The design chosen for Retort No. 3 favored a fractionated feed with narrow ranges such as 1/4 to 1 inch and 1 to 2 1/2 inches. It was recognized that significant segregation could occur with a wide range shale, such as the 1/4- to 2 1/2-inch fraction. Thus, a more complex system would have been required to hold the segregation at a comparable low level. However, the operability of Retort No. 3 with 1/4- to 2 1/2-inch shale (10) indicates that a significant amount of segregation can be tolerated although it may not be desirable.

5. Scale Model of Initial Retort No. 3 Design

Prior to the rehabilitation of Retort No. 3, a 1/12th-scale model of the proposed design was constructed out

FIGURE 12

**ANTI-SEGREGATION DEVICE
RETORT NO. 3**



of plexiglass. This model was used for shale flow studies but it also served to illustrate the gas distributor hardware and the shale feed and drawoff techniques which had been developed during Stage I. A movie was made of this model (37) and was distributed to each Participating Party along with a detailed commentary (38). The film serves as a valuable visual aid for education and demonstration purposes.

B. The Introduction and Distribution of Gas in a Bed of Oil Shale

In the Gas-Combustion Retorting Process, a sweep gas (recycle) flows upward through the retort and acts as the heat transfer medium. This recycle gas cools the spent shale in the bottom zone and heats the raw shale in the top. A second gas (air) is injected into the retort at an intermediate level to burn recycle gas and the carbon on the retorted shale, thereby providing the heat for the process.

The region where the combustion air is injected into the recycle gas is a critical one as it determines how the heat is generated in the process. This in turn influences yields and operability since it governs such factors as uniformity of retorting and clinkering tendencies. Therefore, the initial Research Program for Stage I included exploratory studies which were designed for learning more about the process of distributing one gas stream into another in a bed of oil shale. A more specific objective was to provide guidance for the design of gas distributor hardware for Retorts No. 2 and 3.

The work was carried out in a plywood and plexiglass model such that the gas flow patterns could be observed and photographed. The use of smoke bombs was effective in tracing the flow of a gas stream.

1. Air Distribution

A major effort was directed toward studying the gas flow patterns in the air distributor region (39). The following conclusions were drawn from this work.

- The extent to which the combustion air will mix with the recycle gas stream and penetrate horizontally into a bed of shale depends primarily on the size of the shale. As the shale size increases, the depth of penetration increases.
- The velocity and the angle at which the air is injected into the recycle gas stream have little or no effect on the depth of penetration. This conclusion holds over the velocity range of 30 to 200 ft/sec and at injection angles of 30 degrees above the horizontal through 30 degrees below.

- There appears to be almost as much spread laterally along the horizontal distributor element as there is in the direction of the jet even though there is no velocity component in this direction. This suggests that the jet is broken up very rapidly - probably when it hits the first particle of shale.
- The rate of recycle gas passing the air distributor has a rather small effect on the air penetration. This conclusion was found to hold over a wide range of recycle gas rates from 50% to 130% of the normal rate which in this simulation was about 13,000 SCF/T. Below 50%, the horizontal penetration increased substantially.

Thus, the investigation revealed that shale size is the major variable which governs the horizontal penetration of combustion air into a bed of shale. The average penetrations for each shale size are summarized in Table 1. The sketch should be helpful in defining the term penetration. The minimum clearances required for shale flow are included in the table to show that the penetration from two opposing distributors is substantially greater than the required clearance between them. (It should be noted that these are minimum clearances and not recommended dimensions.) Thus, it is possible to obtain adequate air distribution and shale flow for any given shale size greater than 1/4 inch. However, these data also indicate that a universal air distributor design - capable of handling a number of shale sizes - is out of the question. A movie (40) and commentary (39) have been issued summarizing this work.

In spite of the fact that this study was carried out at ambient temperature, the results agree quite well with the subsequent analysis of a hot retort. An evaluation of air distributor designs in Retort No. 2 led to the conclusion that "air penetration studies reported by the mechanical models group are valid approximations of penetration to be expected in an operating retort" (41). In addition, the operating experience with 1/4- to 1-inch shale in Retort No. 3 (9) showed that the sphere of influence of a distributor was similar to that predicted by this model work.

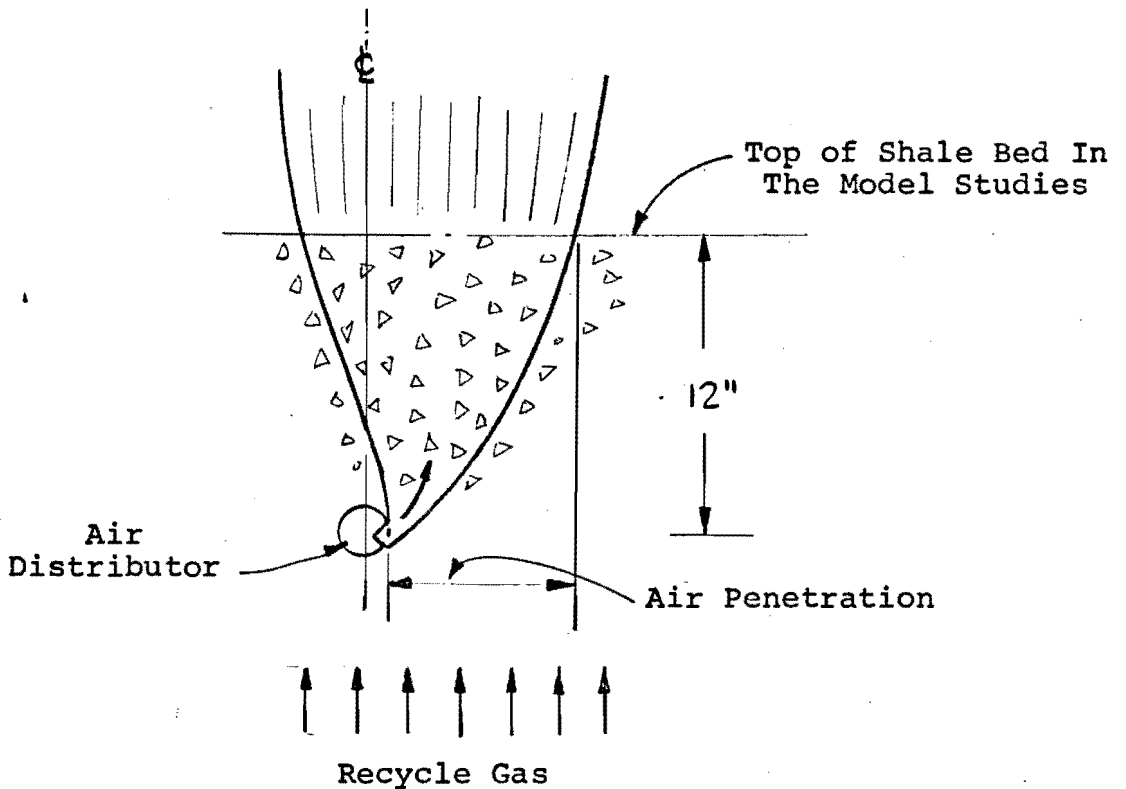
2. Recycle Gas Distribution

The air distributor studies also gave some guidance on recycle gas distribution. If the sweep gas normally passing an air distributor element is eliminated, the element then simulates a recycle distributor. One such study (39) indicated that the horizontal penetration under conditions at the recycle gas distributor is roughly 2 1/2 times that of an air distributor in the same size shale. Another study (42) designed specifically to simulate conditions at a recycle distributor indicated that

TABLE 1

THE EFFECT OF PARTICLE SIZE ON AIR PENETRATION
IN A BED OF OIL SHALE

Shale Size, Inches	Minimum Clearance Required For Shale Flow, Inches	Average Air Penetration From a Single Distributor Element, Inches	Average Air Penetration From Two Opposing Distributor Elements, Inches
1/4 to 3/4	2	4	8
3/4 to 1 1/2	4	5 1/4	10 1/2
1/4 to 3	8	9 1/4	18 1/2
1 1/2 to 3	10	12 1/2	25



the horizontal penetration would be as far as 26 inches in very small shale (one inch minus). This increased penetration is attributed to the fact that there is no competing gas stream at the recycle distributor.

From this it was concluded that recycle gas distributor spacing was important from the standpoint of gas distribution but it was not critical. Thus, no great effort in the models was carried out in this area. However, a word of caution should be given concerning these data. The penetration values are probably reliable but when the spacing between the recycle elements is great, horizontal heat transfer becomes an important factor. This was not taken into account in the cold model studies. Thus, the spacing indicated from this type of study should be considered the maximum rather than recommended value.

C. Behavior of Mist in Shale Beds and Recovery Piping

In the retorting of oil shale by the Gas-Combustion Process the oil is removed from the retort after passing through the incoming raw shale bed in the form of a mist. The physical properties of this mist are determined by the conditions under which it was formed, and in turn determine how it will behave in flowing through the upper portion of the retort and through the mist-recovery section.

Because of the important position held by the mist in the Gas-Combustion Process it was decided to initiate a group of studies aimed at a better understanding of how mist is formed and how it behaves when being transported through packed beds, piping, and mist-recovery devices. Much of this work was performed on the operating retorts and is reported in the Technical Management Summary which deals with retorting (1). Model simulations dealing with the impaction characteristics of a mist as it flows through a packed bed of shale and through piping are summarized in this report.

Throughout this discussion it should be recognized that scrubbing is closely allied to impaction. As the amount of impaction in a bed increases, the amount of liquid reflux also increases. Thus, the scrubbing action of this liquid becomes more and more important until a flooding condition is reached. When flooding occurs, this scrubbing action is probably controlling. Time is obviously another important factor although it was not considered as a variable for purposes of this work.

1. Effect of Process Variables on Mist Impaction in a Packed Bed of Shale

The impaction characteristics of the newly-formed mist as it passes up through the raw-shale preheating zone are

very important. The overall amount of mist impacted determines the amount of oil refluxing which in turn affects the amount of thermal cracking to be expected. Refluxing of impacted oil to the retorting zone in conjunction with spent shale fines and dust is also believed to be the cause of the cohesive flow character of the shale in this region. The purpose of this phase of the study was to determine quantitatively the percentage impaction, or impaction efficiency, as a function of mist-particle diameter with superficial gas velocity, bed height, average shale-particle diameter, and mist loading as parameters.

A plexiglass model was located near Retort No. 2 such that a drag stream of offgas could be passed through a test bed of shale particles. The impaction that took place in the bed was determined by sampling the mist as it entered and exited from the bed. The model location was such that the mist loading in the gas was in the range of 1 to 2 lb oil/MSCF. With this mist loading, the variables which influence impaction are correlated by the following semi-theoretical equation (43):

$$E = 1 - e^{-0.438 P_p \sqrt{D_p^3 / 18 \mu D_c \lambda}}$$

- Where:
- E = particle impaction efficiency, %
 - P_p = density of mist particle, g/cc
 - $\sqrt{\quad}$ = superficial gas velocity, cm/sec
 - D_p = diameter of mist particle, cm
 - μ = viscosity of gas, g/cm-sec
 - D_c = width of a flow channel, 1/10 APD, cm
 - APD = average particle diameter of shale particles, cm
 - λ = mean free path of gas, cm

This equation reveals that the mist impaction increases with the following changes in key variables:

- An increase in superficial gas velocity.
- An increase in the size of mist.
- A decrease in the size of shale.

Bed depth had little effect on impaction over the range studied which was 0.5 to 1.0 foot.

Further studies were made at higher mist loadings (8 to 10 lb oil/MSCF) by relocating the test model such that it obtained mist directly from the top of the retort. The above equation failed under these conditions as the impaction was found to be abnormally high at the smaller mist sizes and somewhat low with the larger mist sizes. Both of these observations are

believed to relate to an increase in mist-particle size due to growth and coalescence. Furthermore, the impaction is probably aggravated by the scrubbing action that takes place when a heavy film of liquid builds up on the shale particles. In any event, the experimental results at the higher mist loadings are correlated by the following empirical equation:

$$E = 1 - e^{-0.39D_p} + 0.34$$

This equation is valid for mist loadings in the range of 8 to 10 lb oil/MSCF and for mist sizes in the range of 1 to 6 microns.

The final phase of the impaction studies involved the determination of gas velocities which were sufficient to cause incipient flooding in a bed of shale. These velocities - observed for the low mist-loading conditions - are summarized below:

<u>Nominal Shale Size, Inches</u>	<u>Superficial Gas Velocity Required to Give Incipient Flooding, ft/sec</u>
1/4 to 1	2.7
1 1/2 to 3	3.3

A motion picture (45), made in conjunction with this work, shows a striking illustration of the development of a flooded condition in a packed bed.

2. Impaction of Mist in Pipes and Elbows

Early observations indicated that over 50% of the mist was removed from the offgas by the time it reached the first recovery device (a multiclone). Thus, some model studies were initiated to investigate the flow characteristics of mist in pipes and elbows and to provide guidance for the design of mist recovery trains. Glass equipment was used to facilitate observation and photography.

This work (43) revealed that the mist was unstable and substantial impaction would occur in normal piping. This was particularly true in vertical pipes at high velocity (65 ft/sec) in which a surface film of oil formed; thus, exaggerating the impaction and the scrubbing. These flow characteristics also are illustrated in the film mentioned previously (45).

D. Studies Dealing With Operability Problems in the Gas-Combustion Retort

Up to this point, the model studies under discussion have been of a general nature and the need for them was obvious

early in the program. However, another category of model studies came about as the result of retorting experience. These dealt with specific problem areas which affected retort operability (1, 11). The most significant of these model studies are summarized in this section of the report.

1. Development of a Riser-Type Air Distributor for Large Shale in Retort No. 2

This study is an excellent example of the use of miniature models to investigate and solve shale-flow problems in full-scale units.

In the demonstration run series B817 (46), the eight-riser air distributor performed successfully in Retort No. 2 with 3/4- to 1 1/2-inch shale. However, with the larger shale sizes (1 to 3 inch and 1 1/2 to 3 inch), the shale flow was very erratic as evidenced by fluctuations in roll-feeder drawoff speed and level control. Flow studies in a miniature plexiglass model of Retort No. 2 (1/6th scale) confirmed the erratic shale flow and the presence of large voids in the bed in the region of the air distributors. Therefore, a model study was initiated to develop a riser-type distributor design which would give good shale flow while maintaining adequate air distribution.

The study revealed that four modifications were necessary to facilitate shale flow. These changes were as follows:

- The number of risers was reduced from eight to four.
- The horizontal headers feeding the risers were relocated to increase wall clearance.
- All angled pipes were eliminated by positioning the risers directly above the horizontal headers. (This emphasized shale flow at the expense of gas distribution since one-half of the air was injected into one-third of the retort area.)
- The shape of the horizontal headers was improved by providing a sharp leading edge rather than a blunt, round top. The width of the header was reduced to 2 inches compared to the 4-inch pipes used previously.

With the four-riser design, the flow of the larger shale through the model was comparable to that of 3/4- to 1 1/2-inch shale with the eight-riser configuration. This vastly-improved shale flow was also observed in the subsequent operation of Retort No. 2 with the four-riser design in demonstration run series B952 (47).

Motion pictures (48) were taken of the Retort No. 2 model in operation during these studies and a commentary (49) was prepared. The resulting film presents a very vivid illustration of the problem and the solution.

2. Behavior of Dust in Shale Beds

Early experience in Retorts No. 1 and No. 2 indicated that the presence of dust in the retort was a major contributor to poor operability and yield loss. Therefore, a model was designed and constructed to study the behavior of fines and dust in a bed of shale. It should be emphasized that these studies were exploratory in nature since it was impossible to duplicate the actual retort conditions especially in the regions where liquid is present. Nevertheless, the observations have contributed to a better understanding of the dust phenomenon.

An hour-glass shape was utilized in the plywood and plexiglass model to simulate the gas velocities in the combustion zone and at the surface of the retort bed. A piston assembly was used to move the shale through the throat of the model at the equivalent retort velocity. Spent shale dust and fines were injected into the model with the simulated combustion air.

The initial operation of the model revealed certain qualitative characteristics concerning the behavior of small particles in a bed of shale (50). It was observed that particles will reflux at any level in the retort where dry conditions exist. Refluxing occurs when the size and density of the particle are offset by the gas velocity (terminal velocity of the particle). Higher gas velocities will lift the particle and lower velocities will allow it to fall. Undoubtedly, there are particles to match every gas velocity found in a retort; therefore, it can be assumed that dust refluxing is occurring throughout the entire retort bed. In addition, it was observed that particles can rest on the top surface of a piece of shale and thereby be sheltered from the gas stream. Thus, in this fashion, some dust and fines can be drawn through the combustion zone even though the gas velocities exceed the terminal velocity of the particles.

The model was also capable of giving quantitative results (51). It revealed that particles smaller than 28-mesh (0.0232 inch) could be suspended in the upper regions of the retort as a result of the gas velocities which are normally encountered in the combustion zone at a shale rate of 500 lb/(hr)(ft²). Furthermore, it was demonstrated that the presence of an oily layer of shale in the top zone of the retort can suppress the elutriation of very small dust particles from the bed by causing them to agglomerate into larger particles.

At a shale rate of 300 lb/(hr)(ft²), the particles recovered in the upper zone of the model were generally smaller than 60-mesh (0.0097 inch). This is in contrast to a shale rate of 700 lb/(hr)(ft²) where particles as large as 20-mesh (0.0328 inch) were recovered above the combustion zone in substantial quantities. Thus, this study seems to illustrate why the U. S. Bureau of Mines did not become aware of a dust accumulation problem at their normal rates. In addition, it demonstrates how operability and yields could be affected adversely by the high dust loading at the 700 lb/(hr)(ft²) shale rate.

Shale size does not appear to affect the distribution of dust to any large extent.

Much of the dust generation is believed to take place above the air distributors and the temperature profile in this region affects the dust accumulation. If the dust is generated in a region of high gas velocity, more will be carried into the upper section of the retort. In addition, if the retort area is restricted where the velocity is already high due to temperature, the dust problem is aggravated even further. This is believed to be the major reason why the horizontal air distributors failed to perform satisfactorily as high temperatures were created in a restricted area (41).

3. Model Studies Which Supplemented the Task Force Investigation of Retort Operability Problems

At the conclusion of Run C1052 in July, 1967, the desired balance between operability and yield had not been achieved with 1/4- to 1-inch shale in Retort No. 3 (9). Operability had been achieved at a shale rate of 300 lb/(hr)(ft²) in June by the use of hot dilution gas, roll drawoff system, widely-spaced air distributors, modified startup procedure, etc. However, yields were substantially lower than desired. Eventually, the yields were improved by conventional air distributor modifications - more uniform distribution with more complicated hardware. Unfortunately, as yields improved, operability showed evidence of deterioration. Thus, the point had been reached that the desired combination of operability and yield could not be achieved with this fraction by conventional means.

In the spring of 1967, a local task force was established at Anvil Points to study the overall operability problems encountered in conventional Gas-Combustion Retorting. This was a very extensive effort as it included bench-scale studies of agglomerate and clinker formation; operation of 1-inch, 2-inch, and 3.6-inch diameter retorts; model simulations, hardware design, and full-scale evaluation in Retort No. 3. This work is reported in detail in a technical memorandum (11)

and is summarized in the Technical Management Summary which deals with retorting (1). The model simulations are summarized in this report. It should be emphasized that the model simulations are actually a very small part of the overall effort and they are included here primarily for reference purposes.

a. Flow of Shale Agglomerates

The task force concluded that clinkering was preceded by agglomeration in the retorting zone and subsequent wedging and sintering at the air distributor. A short model study was carried out to observe the flow of a large agglomerate through retort hardware. The agglomerate was simulated by chilling a sorghum-shale mixture.

The model illustrated how an agglomerate could be trapped in the air-distributor hardware and it was very similar to the clinker location observed consistently in Retort No. 3. A motion picture (52) of the model in operation shows the entrapment quite vividly. This motion picture was prepared to supplement the Task Force report.

b. Visual Observations of Liquid Loading and Flooding in a Packed Bed of Shale

The task force concluded that the accumulation of liquid in the retort was the dominant factor which contributes to poor operability. Therefore, considerable effort was directed toward disengaging the liquid from the retort bed during operation. Model simulations were used in this effort to improve the understanding of how liquid accumulates and to develop techniques for its removal.

One plexiglass model illustrated how liquid can accumulate in a low-energy zone of a shale bed. It was also possible to drain this liquid from the bed when a connection to the flooded zone was established. Furthermore, vapor flow in the direction of the liquid flow assisted in the removal by entrainment. This simulation is included in the motion picture discussed previously (52).

The technique chosen to disengage the liquid in Retort No. 3 involved dividing the bed above the air distributors into two sections. The condensation zone was separated from the retorting and combustion zones by means of an internal deck which contained six shale-downcomer pipes. A grid assembly was placed above the deck to remove the liquid which drained from the condensation zone. A model simulation was used to guide the design of this grid assembly.

Other model studies were made to explore the interaction of gas upflow and liquid downflow in the shale-downcomer pipes. At a shale rate of 300 lb/(hr)(ft²) in the pipes, considerable liquid flowed down the pipes against the gas flow. At 500 lb/(hr)(ft²), incipient flooding occurred in the pipes. At 1000 lb/(hr)(ft²), flooding also occurred but no liquid appeared to flow down the pipes. (All simulations were based on a total gas rate of 20,000 SCF/T raw shale and a gas temperature range of 150 to 600 F.) These simulations are included in the motion picture (52).

The final model simulation dealt with the region at the outlet of the shale downcomers at the top of the lower bed (retorting-combustion section). This is the region where the gas velocity increases as it passes from the bed into the downcomers. Splashing and local accumulation of liquid occurred at the surface of the bed when the model was operated near the incipient flooding point at mass rates of 400 and 500 lb/(hr)(ft²). (Gas conditions were the same as noted above.) Such a condition would be undesirable in an operating retort. This model simulation is also shown in the motion picture (52).

In summary, the disengaging experience in the small retorts and in Retort No. 3 coupled with the model simulations have led to certain conclusions. First, liquid can be removed from a retort bed under the following conditions:

- if a local flooded zone can be established and controlled in a region where the gas temperature is about 600 F.
- if the flooded zone has access to the disengaging facility.

Furthermore, accumulation of liquid below the controlled flooded zone must be avoided. The temperature of this region must be held at about 600 F. In addition, the surface of the lower bed should be confined such that liquid cannot accumulate on the top of the shale piles.

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