A DISCUSSION of PROCESS and PROJECT DESIGN in OIL SHALE RETORTING

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ABSTRACT

Over the past decade a considerable number of studies have been devoted to such themes as kerogen decomposition reactions, optimum reactor design with a view to the influences of particle preparation and regime of conditions, and to classification and appraisal of retorting processes.

Rather than leading to a fundamental resolution of reaction kinetics with its branchings to selectivity, ultimate yield and product pattern, results of studies have remained on the descriptive plane, however extensive they have been. In process selection one trend stands out: modern designs tend to utilize fluid bed techniques.

In studying and developing shale oil production facilities of the 50 000 B/D class and larger we have come to realize that the particular design of the retorting reactor proper, as well as the exact reaction kinetics, influence the overall costs only in an indirect way as long as certain principles are adhered to. The balance of the many contributing factors in a total project, and their interplay towards achieving an optimum resource utilization and energy efficiency, carries high importance. In process selection and design the issues of scale and scalability play a more important role than was generally anticipated.

Based on these principles, we have worked on an improved retorting process and configuration. The results of our studies shed some light on the influence of general resource properties in determining the potential for technical and commercial realization of a project.

INTRODUCTION AND SURVEY

A number of years ago, inspired by the contemporary oil supply position and views on future supply, we undertook a new look at oil from shales. In this we chose to start afresh, while carefully appraising the techniques and procedures then available and those developed in the interim.

These investigations covered:

- Resources and Mining

  There is a vast amount of literature on shales, worldwide. It has been consulted extensively, and supplemented by additional investigations where necessary or desirable. There can be no doubt that shale projects demand mining operations which are among the largest known in today's industry. For surface-minable material one can build on experience in coal, and particularly brown-coal mining.

- Solids Handling

  As far as the operations of breaking, crushing and transport are concerned, again one can draw on similar experience in the mining and minerals industry.

- Retorting

  A novel version for carrying out retorting has been worked out, starting from the industry-wide development status and thinking further along the lines of modern processing techniques, together with theoretical requirements derived from an extensive case analysis.

- Product Work-up

  Much experience on laboratory and semitechnical scale has been gained in this field over the last decade. Use of this know-how, together with a background of modern refinery techniques, has provided a firm basis for our studies and conclusions.

- Project Design

  Even medium-sized shale projects represent large undertakings by average industry standards. For organization, lay-out design and appraisal, use has been made of existing experience in a number of related project fields.

Above all there is the finding that none of the above factors can be viewed in isolation when aiming at an overall appraisal of shale projects. In addition, significant leads have been uncovered in the field of retorting itself.

These aspects of our work are reported in this paper.

DEVELOPMENT OF RETORT TECHNOLOGY

It is temptingly easy to define shale retorting as heating of the shale minerals and recovery of evolved hydrocarbons by condensation.

Scanning through the evolution of engineering approaches we see that early processing followed the basic example of limestone burning, leading through many steps to the present-day Paraho and Petrosix designs. Early retorting developments in Sweden started from the rotary kiln used in the well-established cement industry, and steel balls were later added for heat transfer. This approach eventually developed into what is now known as the TOSCO II process.

The more recent developments, those of Lurgi and Chevron, use fluid beds and rely on the concept of providing heat by backmixing of hot combusted spent shale, while combustion takes place in dilute phase risers. They differ in the retorting vessel employed and in the way they achieve mixing between fresh and combusted shale. Also Australian workers have investigated the fluid bed approach to shale retorting (1), making use of a rather compact system for shale burning and recycle. Application of ceramic heat carriers, as used by the TOSCO II process, was put forward in a fluid bed application as the SPHER process (2). The motive was to utilize the scaling potential and the heat transfer capability offered by the fluid bed principle. Lawrence Livermore Laboratory have put forward a procedure, the LLNL cascading process (3), which provides good staging of the solids flow and, with this, the potential for high yields.

All these developments followed a path of logical reasoning. The basic motive remains that retorting should result in a high yield, with appropriate selectivity to the production of oil. The problem is how to administer the heat required. Furthermore, it should be stressed that a retort has to be feasible at the scales required for large commercial projects.

One of the findings of the past two decades of research work in this field is that high yields are promoted by fast heating rates, though the minimum rate to achieve this effect is difficult to establish from available experimental evidence. The fact remains that considerable yield gain is possible compared with the results of slow heating rates of a standard Fischer Assay procedure. In turn, higher heating rates are only possible with small particles of, say, the order of 1 mm. Internal resistances become controlling for particles above about 3 mm. One of the inferred reasons for yield losses during retorting of larger particles is intra-particle cracking to coke, but this may not be all. Rapid heating has also been shown to influence the cracking reaction path, perhaps by less dealkylation. In the well-known reaction kinetics presented by Wallman (4) this seems to be reflected by a higher activation energy of the primary decomposition reaction, but actually little is learned regarding selectivity differentiation. Workers in this field further agree that a higher reaction temperature is beneficial. Values of 500°C and higher are cited, though the whole temperature/selectivity effect is not borne out by the kinetic models so far put forward. Nor is it clear from reported data at what temperature levels the beneficial effects start to reverse. Though recent work has brought some more light into the underlying relations (5,6), it has to be concluded that relatively simple models for kerogen decomposition are inadequate when one needs to quantify the finer details.

A few remarks on kinetic analysis might be in order here. Kerogen, the organic part of shale, is a generic term for decayed organic matter, with which the process of transformation is still not complete. The material, as such, is therefore quite ill-defined. Exact stoichiometric relations, so important in kinetic analysis, can hardly be given. Even so, it remains relatively easy to define rate constants for the early part of the conversion reactions. The area of doubt concerns the final 10 to 20% of conversion. These data determine ultimate yields and have a large influence on model reaction orders. We may add that correlations between Fischer Assay and "true" ultimate conversion can be quite different for various sorts of shale, and as a matter of fact, Green River shale shows one of the smaller differences.

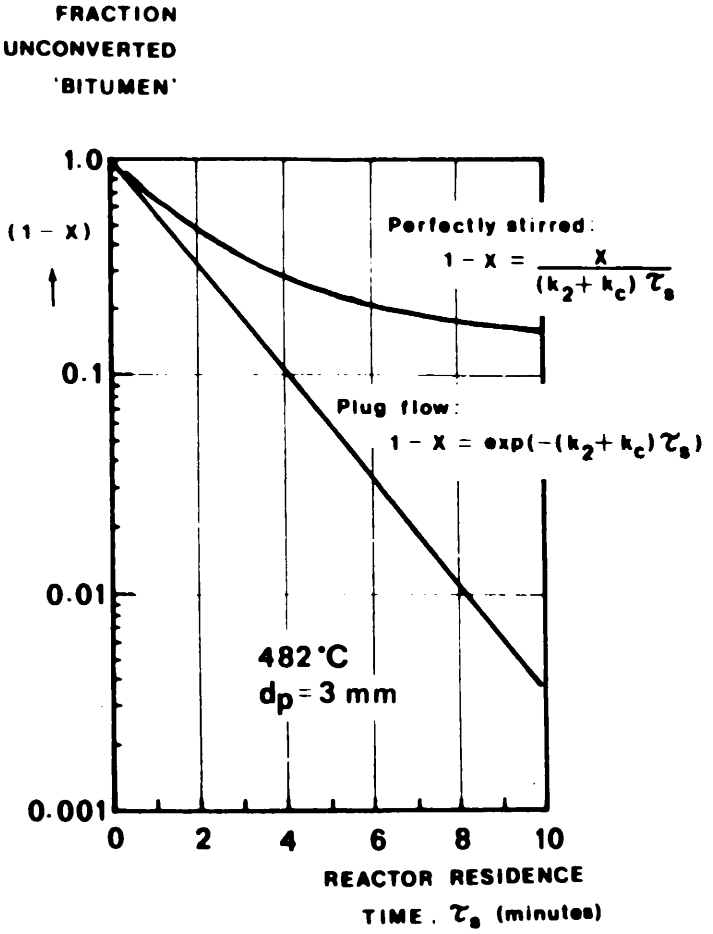

Figure 1. Example Calculation for Isothermal Plug-Flow and Single Stage Reactor Performances for 3 mm Colorado Shale Particles

Turning to the implications in terms of technical realization, we have to accept that both high heat tranfer rates and the handling of large quantities of rather small particles can only be managed by fluid bed techniques. Even at close to 500°C the overall thermal decomposition rates are such that several minutes are needed to reach high conversion levels. It is a first principle in reaction engineering that staging is required to reach high conversion under these circumstances.

Fig. 1 is an idealized graph illustrating the marked effect of staging at moderate to high conversion levels, emphasizing the need for staging. This fact possibly escaped early workers, and this may have come about because Fischer Assay data have always been taken as a yardstick. When 90%+ of Fischer Assay was achievable by straight forward means, there seemed to be limited incentive to look for more.

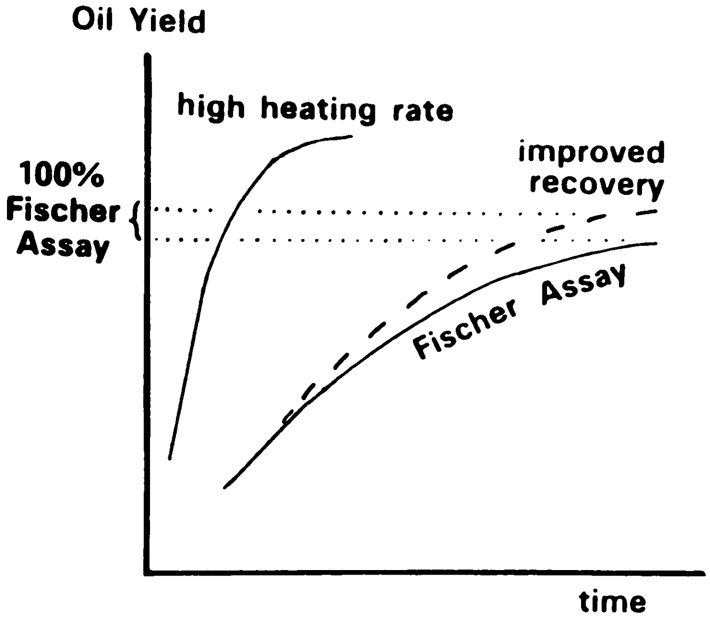

Figure 2. Idealized Comparison of Fischer Assay Conversion with "True" Conversion

As is shown in Fig. 2, Fischer Assay is quite a coarse standard, even taking into account the improved oil recovery techniques as introduced by TOSCO (7). Comparison with Fig. 1 highlights the fact that "100 % Fischer Assay" yields represent less than 90 % of the yield ultimately possible, and that this level of conversion can be achieved, essentially, without staging.

Returning to the issue of retort design, to enhance energy efficiency and to accommodate small particles in large solid flows we adhered to the principles which have also led to development of the Lurgi and Chevron retorts. This means burning retorted shale and recycling hot burnt shale to the retort. However, to accommodate staging and to afford scalability we have looked for new embodiments. Fluid beds have the important characteristic property that mixing in the vertical direction is generally much better than in the horizontal direction. To a degree this can be modified with suitable baffle or insert arrangements, but it is much easier to minimize horizontal mixing, which is the weaker mixing force.

This led to development of a horizontal arrangement for staging in a fluidized bed of the type shown schematically in Fig. 3.

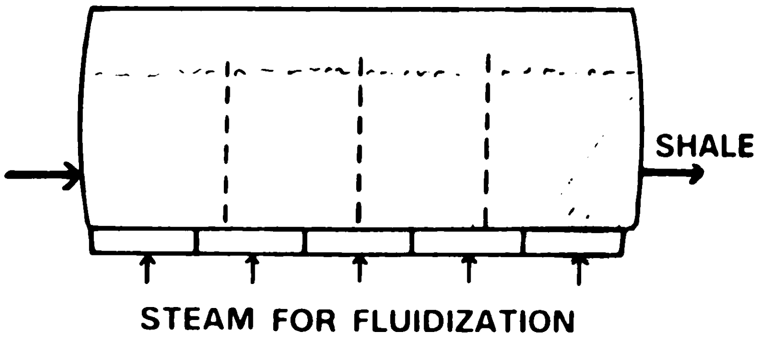

Figure 3. Principle of the Horizontally Staged Fluid Bed Retort

Apart from providing an easier way to design for staging, other important features of this arrangement are:

- The fluidizing gas, e.g. steam, has the primary function of keeping the solids fluidized; its rate can be limited to that duty.
- Product vapours leave the retort along the shortest possible path, thereby minimizing the opportunity for after-cracking and promoting higher yields.
- A large cross sectional area can be made available for escape of the produced oil vapours. The linear vapour velocity can be kept low enough to minimize carry-over of fines, one of the recognized difficulties in shale processing.

That such an arrangement approaches an optimum can be deduced along the lines of theoretical reaction engineering reasoning. This has been discussed more extensively elsewhere (8).

The arrangement has been termed the "cross-stream retort".

PRACTICAL REALIZATION OF THE RETORT

Before approaching the topic of technical realization of the cross-stream retort concept, we may reflect on the desirable size for a single piece of such equipment. Technical factors determining that size are:

- The degree of conversion desired, implying adequate staging.

  For a simple first order reaction, three stages are generally sufficient; for a mechanism of consecutive reactions at least six stages would be desirable. From a host of experimental data it appears that a mixed parallel and consecutive reaction mechanism could well be applicable to kerogen decomposition. We have settled for a basic requirement of the equivalent to five mixing stages, knowing that to achieve the equivalent of true stages in a backmixing fluid bed a degree of baffling will be required.

- Pre-heating and pre-drying.

  The heat balance around the retort is central to overall process design for higher thermal efficiencies. Preheating the shale to a temperature of 100 to 200°C utilizes some low-level heat and saves on hot shale recycle. Some shales contain considerable amounts of moisture, and with those it is particularly important not to load the retort with the heat duty of water vaporization.

- Hot shale recycle.

  The temperature of the hot shale is a design variable, to a degree. The required amount of the recycle is then a resultant. In turn, the recycle material itself adds to the required retort volume.

- Grade of the shale.

  Naturally, all the above factors are favourably influenced by better shale grades.

Our development work has not been restricted to one sort of shale. A first yardstick is the global rate of the pyrolysis reaction. Fig. 4 shows data reported by Nuttall (9) supplemented by some of our own. Though the differences appear large, the curves tend to converge towards the important area above 450°C. Nevertheless, differences of up to a factor of three are noteworthy.

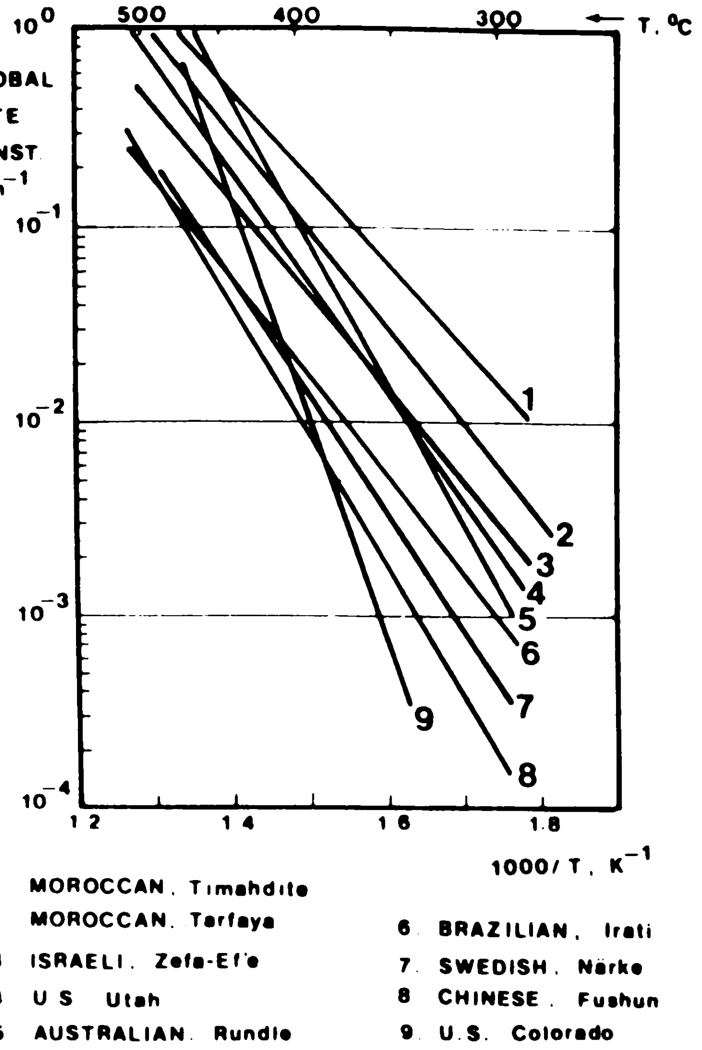

Figure 4. Overall Rates of Shale Pyrolysis

Making certain average assumptions, carrying out a complete set of process engineering calculations and setting a fluid bed height of some 3m, the following approximate retort-bed plan areas emerge:

Production, B/D	25000	50000	25000	50000
Shale Grade, l/t	65	65	100	100
Plan area, m2	400	800	240	480

Such large vessel containment areas are difficult to realize in vertical cylindrical configurations. One approach offering a solution is the use of rectangular vessel constructions. Study type designs to considerable depth of detail have been made. The fact that the retorting process is carried out at virtually atmospheric pressure adds to the feasibility of such designs. Retorts of, for example, 12 x 40 m cross section have been constructed on the drawing board, and there is no apparent limitation to scale-up to the commercial sized units envisaged.

It will be clear that retorts for rather large projects can, in principle, be constructed in one module. Why this is desirable will become clear later in this paper.

COMBUSTION OF SPENT SHALE

It must be borne in mind that the air requirement for the combustor is dictated by the amount of carbon to be burnt, and is therefore coupled with the energy balance over the process. This air requirement together with the flow regime itself determines the size of the combustor.

Considering the problem of burning relatively fine particles of spent shale these options come to mind: A bubbling fluid bed, as presently used for burning of coal (FBC), is certainly a possibility. Typical air velocities in such units are of the order of 2 to 2.5 m/s, though with the particle sizes applied here these velocities would have to be somewhat lower. The lack of air-to-particle contact with the rather small particles involved would lead to more bed height than normally used in coal burning. These effects together would lead to rather large units with many hundreds of tons of shale inventory. The other extreme is a dilute phase riser with high air velocity and a rather small shale inventory. The riser has obvious scale-up limitations and for large throughputs multiple risers would be required. The lifting power of the riser is commendable. To circulate the shale through the processing equipment as a whole, lifting is a necessity. On the other hand, rather tall risers would be necessary to reach adequate burn-out.

A compromise between these two options is a technology currently known as the fast circulating fluid bed combustor (FFBC). It combines lifting action with very good contacting and burn-out. Inventories are intermediate, as are the air velocities involved. Rather large units, approaching 10 m in diameter, have recently been commissioned for coal firing, and the technology as such can be considered to be proven.

OVERALL PROCESS CONCEPT

The combination of a horizontal fluidized bed retort with circulation of hot combusted shale from an adapted FFBC leads to the basic shale process lay-out shown in Fig. 5.

This lay-out is rather flexible and can be adapted to shales of various origin and composition. High water contents place more emphasis on milling/drying and preheating. Variations in the kinetics of pyrolysis are accommodated by retort temperatures, controlled by the recycle rate, and by the retort size. Carbon content on retorted shale and overall energy demand largely determine combustor size.

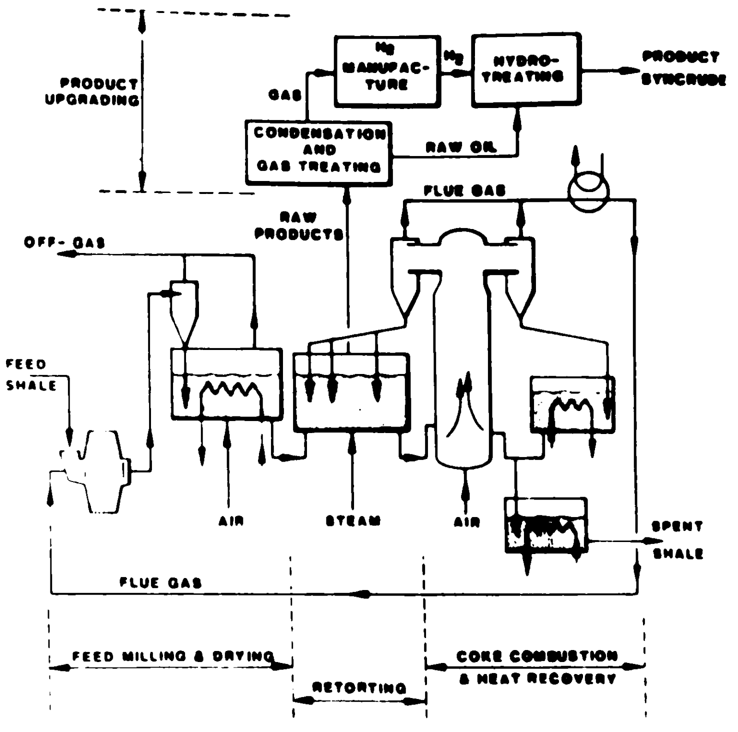

Figure 5. Basic Plant Configuration

The overall energy demand leads to the problem of achieving energy balance. Typical shale projects would generally be in remote locations, so the term "energy demand" includes meeting the total project and infrastructure energy requirement. This defies the scientific definition of an "energy balance index" related only to the core of the retorting process. A more modern approach to resource utilization, moreover, suggests that the primary use of high-calorie retort gas should be the production of hydrogen for product treating, and only a surplus may be free for energy applications.

In project appraisal, therefore, the overall energy balance in this comprising sense is the important factor.

It is reassuring to note that for many shales, among which Colorado and some of the Queensland (Australia) cases, near-complete energy balancing can be achieved.

Energy-tight situations are typically those involving a shale with a high water content and a relatively low coke make upon pyrolysis. A high sulphur content of the produced oil, demanding more stringent treating, is an additional indicator. A solution is to sacrifice a few percent of ultimate oil yield, aiming for slightly lower conversion, and so transferring more energy to the combustor. Another possibility is to include some external fuel, for example coal.

Energy-long situations are often the consequence of geologically old shale, or the inclusion of lignitic seams, causing relatively more coke to be produced upon pyrolysis. The most prominent examples of this situation are Eastern U.S. shales.

PRODUCT RECOVERY AND WORK-UP

Every shale retorting scheme employing fluidization of small particles and recycle of combusted spent shale has to take special precautions against fines in the product. Those fines not held back by hot cyclones within the retorting vessel are wetted in a quench section and washed down in recovery tower(s). A slurry return to the retort removes the highest boiling part from the product, which is subsequently pyrolyzed. There is little loss connected with this stream, which is more difficult to treat anyhow.

The remaining product is condensed in stages with partial heat recovery. The design has to accommodate a large quantity of steam in the product gases, both from pyrolysis water and from fluidization steam. There are many potential projects where this water must be recovered.

The nature and severity of further treating is rather project dependent. It has to be noted that even 50 000 B/D is a relatively small stream in terms of present-day refinery practice, and the units involved, from distillation to hydrotreating, hydrogen manufacture, sulphur and ammonia recovery, etc., are not in principle limiting factors in determining project scale.

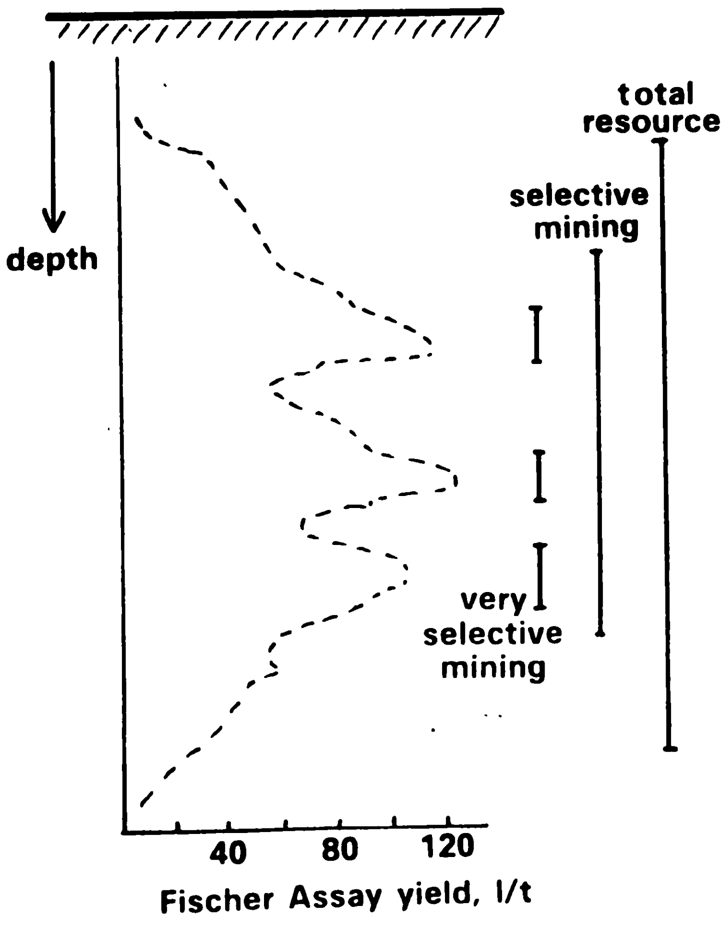

Figure 6. Typical Shale Sequence and Mining Profile

IMPLICATIONS OF MINING AND RESOURCE

It is not the purpose of this paper to go into this topic in any depth. It is our experience that realistic conclusions can only be drawn for specific locations. However, for surface minable resources some general remarks can be made. Take a typical shale quality profile, as shown in Fig. 6:

There is always an optimization to be made:

- take a thicker slice of the mineral:

  this leads to a lower overburden ratio and generally to cheaper mining; the grade will, however, be worse and the retorting process more expensive

- mine shale more selectively:

  here mining will be more expensive per barrel of oil contained, and resource utilization lower, but the process will be cheaper

There is no simple answer for this optimization programme, and several cases must be worked out in some detail. It is not possible to state an exact "cut-off" grade since the economic optimum depends on so many factors, one of which is definitely the retorting technology applied. The favourable scaling properties of the cross-stream retort principle means that the penalty entailed in processing lower grade shales is less felt than with most other technologies. In a given case, this shifts the optimum grade for mining to lower values, and improves overall process economics.

COST ANALYSIS IN THE LIGHT OF SCALING

Although a profound influence of the quality of the resource itself cannot be denied, some of our findings for specific locations probably have a general bearing. The influence of project scale has been studied for a surface minable resource with medium grade shale, and results are shown in Fig. 7.

The "economy" is shown in the form of an all-in relative oil production cost which avoids the controversial issue of oil price predictions. This does not give more than a very general indication. However, these rather capital intensive projects, reaching far into the next century, are so strongly influenced by capital service charges, socio-economic factors, fiscal regime and benefits, and above all by inflation and price projections that specific quantitative figures can never be given without a detailed condition scenario.

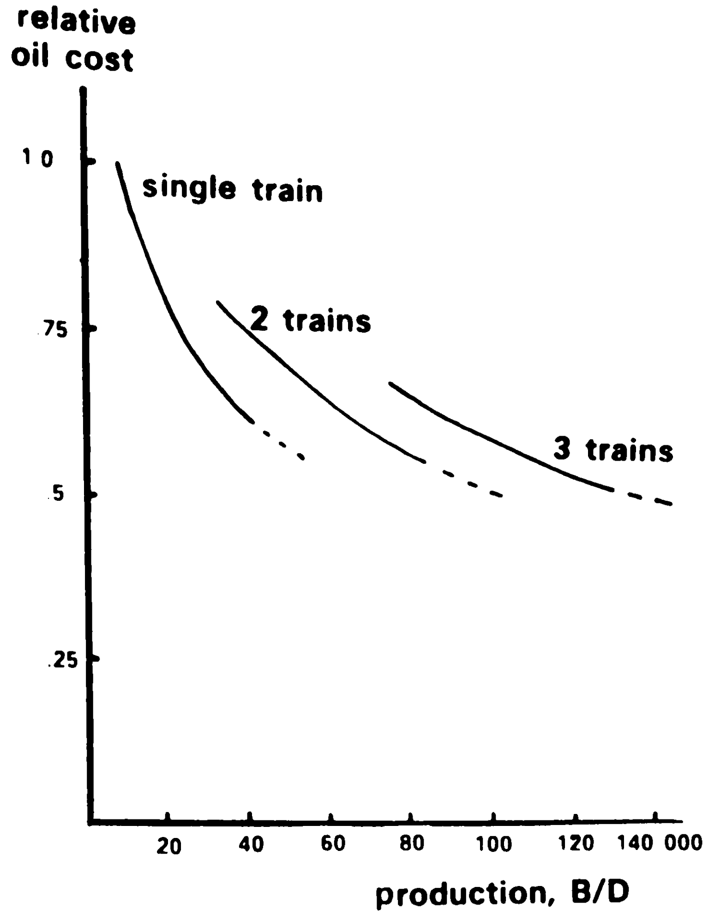

Figure 7. Economy of Shale Projects as a Function of Size

With a few of the projects we have studied, single train retorting was possible up to a size in the 50 000 B/D range. Above that, projects had to be designed with two-train units. There is an economic step-over when this transition occurs, and, if one has the choice, either the largest possible single train project or a somewhat larger one with twin process units should be selected. It should be stressed that the scale and feed grade at which this step-over occurs is shale, location, and process specific.

How does this profound effect of scale come about?

We have shown that shale composition and quality cause the various major parts of the retorting process to change in their relative sizes, and consequently in their relative costs. Some representative averages can, however, serve to illustrate the point. The figures presented below are intended to convey a general impression for a large shale project of the 50 000 B/D class, featuring a surface minable resource and including product treating.

	CAPEX %	annual OPEX %	scalability
mining	8	35	marginal
shale preparation	10	15	marginal
preheat-retorting	7	5	very good
combusting	15	12	very good
power/heat systems	20	12	medium
product work-up	25	16	very good
infrastructure	15	5	good
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	100	100	

It will be seen that the retort, including all tie-ins, represents only a marginal part of the total capital and operating costs. Its scalability, therefore, can have only a marginal influence on the economy of scale for a shale complex. The important point is that its good scaling characteristics allow utilization of the favourable scaling characteristics of other, more costly, parts of the complex.

Furthermore, high yields pay off not so much in the cost of the retort itself but in the reduced size and cost of most of the other elements in a shale complex.

CONCLUDING REMARKS

The fact remains that oil derived from shale is unable to compete economically with crude oil from current conventional sources. The real advent of oil from shale will come in a declining oil supply scenario, but then successful future shale projects will not only have to compete among other shale projects but also among other synfuel options. This makes it mandatory that a certain minimum economy is reached. To reach such a threshold, it helps to

- choose the project scale above a certain minimum;
- use a process which not only provides good yields but also allows one to cash-in on economies of scale;
- utilize a resource which affords reasonable mining costs at the scale envisioned.

Optimum project size is a long-debated point. Small projects are appealing on account of risk and capital exposure, but they may, however, lose out altogether on economic grounds. Projects cannot easily become too large, but at some point a diseconomy of scale will start, especially in mining, in terms of physical distances involved and the speed at which the accessible part of the resource may be exhausted. Socio-economic factors are also likely to place limits on project size, but, according to our current view, at sizes where the economy of scale for the process part is already diminishing.

A "cut-off" grade is not a useful concept except in early screening work. The economic optimum is the result of the integrated effects of all factors involved, mining, processing, energy integration and project setting.

The type of process employed plays a major role within this interrelation, strongly affecting overall project economy and optimization of project scale. The "cross-stream retort" offers a promising option.

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