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AN ECONOMIC COMPARISON OF FIVE PROCESS CONCEPTS FOR USING EASTERN OIL SHALE

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INTRODUCTION

This study compared costs of retorting eastern oil shales using western shale retorting technologies that need no more development with the cost of processing the same shales using technologies designed specifically for eastern shales. The eastern shale technologies need more development. The study was designed to answer the question: Does process development work need to be done for eastern oil shale or will the existing western techniques suffice?

A calculation for a power plant that burned eastern oil shale to produce electricity was included in the study. We studied the following processes:

- the Institute of Gas Technology's (IGT) HYTORT (eastern shale process),
- the Paraho C-H (combination heated) (eastern shale process),
- the Paraho D-H (direct heated) (western shale process),
- the TOSCO II (western shale process), and
- power plant.

Our study achieves a different result than the report entitled "Synthetic Fuels from Eastern Oil Shale", (1) (also known as the Buffalo Trace Area Development District Study (BTADDS)). The BTADDS compared the HYTORT and the Paraho C-H processes using a shale with a higher Fischer Assay than the one used in this study.

BASIC OF CALCULATION

A Kentucky Sunbury shale, from IGT test Run 80BSU-11 (2) provided a material balance for the HYTORT process. This shale is similar in organic carbon content to the one used in the BTADDS. Table I gives the material balance data from Run 80BSU-11.

To make the comparisons as fair as possible, an effort was made to obtain a Fischer Assay from the shale used in Run 80BSU-11 (2). Unfortunately, shale from Run 80BSU-11 was not available, so the Fischer Assay was done on shale from Run 80BSU-10 (2). The shale from Run 80BSU-10 is a Kentucky Sunbury shale that has a higher organic carbon content than the shale from Run 80BSU-11. The Fischer Assay data were not received until the time-consuming HYTORT calculations with data from 80BSU-11 were nearly completed. Rather than change the calculations, we extrapolated the Fischer Assay data from Run 80BSU-10 to an 80BSU-11 basis predicted on shale carbon content. The extrapolated oil yield was 9.2 gallons per ton. Table II compares some of the most important material balance variables from Runs 80BSU-10 and 80BSU-11.

The material balance Fischer Assay yields for the shale from 80BSU-10 are given in Table III. These Fischer Assay data were obtained independently by Laramie Energy Technology Center. The Fischer Assay report indicates that the organic carbon content of this shale was 14.2 wt %. This value is slightly lower than the value of 15.04 wt % given in Table II.

Janka and Dennison (3) present a graphical correlation of Fischer Assay oil yield vs organic carbon content for eastern oil shales. Our value of 9.2 gallons per ton falls below this line, but it was well within the data scatter about the line.

For western shales, the product yields from the Paraho and TOSCO II retorts are comparable to the Fischer Assay product yields. We assumed that this would also be true for eastern shales. The Table I data were the basis for the HYTORT study and the extrapolated Fischer Assay data were used as the basis for the TOSCO II, the Paraho C-H and the Paraho D-H studies.

RESULTS

The product oil costs for each process in dollars per barrel are listed below.

- HYTORT $48.0
- Paraho C-H $70.0

- TSOCO II $ 75.0
- Paraho D-H $106.0
- Power plant $107.0 ($0.0607/kWh)

TABLE I

BASIC MATERIAL BALANCE DATA FROM IGT RUN 80BSU-11

Oil Shale			Gas		
Ultimate Analysis (Wt %)	Feed	Residue	Composition (Mole %)	Feed	Product
Organic carbon	13.40	4.52	H_2S		3.18
Mineral carbon	0.82	0.31	N_2	0.7	1.26
Hydrogen	1.61	0.33	CO		2.02
Nitrogen	0.42	0.24	CO_2		1.12
Oxygen	3.41	0.94	H_2	99.3	76.81
Sulfur	4.02	3.10	CH_4		9.34
Ash	75.17	92.17	C_2+		4.67
Total	97.85	101.61	C_2+		1.57
			C_6H_6		0.03
			Total	100.0	100.0

	Shale Oil	Residue	Gas
C/H weight ratio	10.02		
Sulfur, wt %	1.89		
Nitrogen, wt %	2.18		
Specific gravity (60/60°F)	0.996		
Liquid hydrocarbon yield, lb/lb shale fed	0.0755		
Water yield, lb/lb shale fed	0.0518		
Residue shale yield, lb/lb shale fed			
By direct measurement		0.791	
By ash balance, scf/lb shale fed		0.811	
Product gas yield, scf/lb shale fed			3.83
Feed gas, scf/lb shale fed			4.77

TABLE II

COMPARISON OF MATERIAL BALANCE VARIABLES FROM RUNS 80BSU-10 AND 80BSU-11[a]

Variable	IGT Run 80BSU-10	IGT run 80BSU-11
Organic carbon content, wt % (dry)	15.04	13.4
Liquid hydrocarbon yield, lb/lb shale fed	0.0829	0.0755
Product gas yield, scf/lb shale fed	6.22	3.83

a. Numbers obtained from (2).

The Paraho C-H process combines, in one vessel, a retorting step and a combustion step. The combustion step uses the carbon on the spent shale to produce steam and electricity. The combustion section of the Paraho C-H retort was simulated using RETORT, a shale retort modeling program written by R. L. Braun (4). RETORT calculations show that when large amounts of carbon are left in the spent shale, as in this Fischer Assay, the large quantities of oxygen and diluent gases required to burn all of the residual carbon from the shale actually quench the combustion.

TABLE III

MATERIAL BALANCE FISCHER ASSAY YIELD FOR 80BSU-10 SHALE

(Organic carbon content - 14.2 wt %)

Fischer Assay	Original Run	Second Run
Oil, wt %	3.07	3.79
Water, wt %	6.06	5.97
Gas plus loss, wt %	2.09	3.74
Retorted shale, wt %	88.18	86.5
Oil, C/H weight ratio	8.89	8.73
Oil, sulfur, wt %	2.41	2.40
Oil, nitrogen, wt %	1.06	1.14
Oil, sp gr 60/60°F	0.938	0.953
Oil, gal/ton	9.4	9.5
Gas Analysis		
cf/ton	516	516
Btu/cf	946	960
Vol % - H_2	40.79	41.17
CO	4.32	3.23
CH_4	13.45	13.89
CO_2	10.46	9.80
C_2H_4	1.21	1.24
C_2H_6	6.19	6.38
C_3H_6	2.05	2.10
C_3H_8	3.10	3.21
C_4's	3.66	4.19
C_5's	2.16	2.51
C_6's	0.94	1.00
C_7's	1.59	0.86
H_2S	9.76	10.09
NH_3	0.32	0.33

By introducing the combustion feed gas at several points within the combustion section, we achieved a design for which RETORT predicts stable combustion.

The TOSCO II retorting process design was based on Fischer Assay data from Table III. Because of the large amount of residual carbon that is discarded with the spent shale, the cost of oil from this process is very high.

The material balance for the Paraho D-H retorting process was computed using RETORT to extrapolate the Fischer Assay data from Table III to direct heating conditions. The costs are high for two reasons: first, because the residual carbon is discarded; second, because of the large quantities of dilute gases that must be processed, the acid gas cleanup is very costly.

A process for burning eastern shale to produce electric power was simulated with the ASPEN computer program. The capital costs for this process were estimated based on a similar Electric Power Research Institute (EPRI) study (5). The power costs were converted to dollars per barrel equivalent fuel oil.

The presentation of flow sheets and material balances for each of the processes is beyond the scope of this paper. This information with capital cost information and a discussion of each process module is given in (6). Some of the more important factors that are required to compute product costs are given in Table IV.

TABLE IV

COSTS FACTORS

	Total Capital Cost ($\$10^6$)	Oil Production (bbl/stream day)	Operating Costs ($\$10^6$/yr)	By-Product Income ($\$10^6$/yr)
HYTORT	2187.5	58,575	428.2	63.0
Paraho C-H	2220.2	34,740	390.8	159.8
TOSCO II	2240.0	36,620	389.8	69.0
Paraho D-H	3140.0	29,220	428.2	220.7
Power plant	577.0	7,277[a]	49.9	-

a. Equivalent oil computed at 1758 Kwh/bbl.

PROCESS ECONOMICS

We made the following assumptions. The retorts in each case processed 145,764 tons of shale per stream day. This number was picked to produce oil at a rate of approximately 50,000 barrels per stream day for the better producing systems. The plants are located near a mine. The delivered shale is purchased at $4.00/ton (7).

The capital costs are based on mid-1981 dollars. Our approach to capital cost calculation was to survey the literature and make up-to-date charts of plant capacity vs direct capital costs. We estimated maintenance and operating costs to be a percentage of the capital costs.

The following economic parameters were used to determine the product oil and power cost:

- 90% stream factor,
- 20-year plant life,
- debt-to-equity ratio of 75/25,
- 12% interest on debt, and
- 18% rate of return on equity.

(This rate of return is high, but it fits the mid-1981 time frame.)

Several areas that affect product price need more study. The five areas of greatest uncertainty are the following:

- retort capital costs,
- acid gas removal,
- product oil hydrotreating,
- sulfur remaining in the burned shale, and
- actual retort oil yield.

Retort Capital Costs

Large discrepancies in retort costs exist in the literature (1, 2). Because of this, we computed the effect of uncertainty in the retort module capital costs upon the selling price of the oil produced. The calculations were made for retort module capital costs of 50 and 200% of the best estimate. They were made for the HYTORT, Paraho C-H, TOSCO II and Paraho D-H cases. Figure 1 is a graphical representation of these calculations.

Figure 1 shows that the relative positions of the best and worst cases, HYTORT and Paraho D-H, are not changed.

The graphical method described above for computing capital costs does not work well with large field-fabricated items like retorts. Chicago Bridge and Iron (CBI) gave us some helpful suggestions for computing the capital cost for vessels like the retorts. The technique is based on dollars per pound of retort. We also obtained a written cost estimate from IGT that they had obtained from CBI. It included a sketch of the vessel. The CBI estimate was used as a basis for the HYTORT retort costs. Our HYTORT retort costs compare very well with those in (2), but are much lower than those in the BTADDS.

Staff members from the design engineering section of our Technical Engineering Support Group estimated the vessel weight for the Paraho retort based on the drawings in the BTADDS report. The Paraho C-H retort module costs on a dollar per pound basis were also less than those in the BTADDS. The Paraho D-H retort module cost was lower than we expected, but because of the uncertainty involved, this estimation method was assumed to be the best available and most consistent.

Not enough information was available to compute the retort costs for the TOSCO II retort module by this method. These costs were computed by scaling cost information from (8). These costs seem high relative to our other costs.

Acid Gas Removal Systems

Acid gas removal for these processes is expensive. In all cases, capital costs are high. Acid gas removal also has high operating costs. Process optimization would require finding the best acid gas removal scheme for each retorting process; however, optimization was beyond the scope of this study. For the HYTORT process, we used amine absorption for acid gas removal and the U. S. Steel Corporation Phosam Process (1, 9) for ammonia removal. The Phosam process is good for high-pressure use (9). Hence, it was used for the HYTORT process as it was in the BTADDS.

The other low-pressure retorting schemes use the SULFAMMON process, which was used in the BTADDS for Paraho C-H acid gas and ammonia removal. The low ammonia and carbon dioxide contents of the BTADDS sour gas make the low capital cost SULFAMMON process look ideal. The sour gas compositions used in our study are derived from the Fischer Assay data in Table III. Ammonia-laden off-gas from the hydrotreater must also be cleaned in the acid gas plant in our study. This combination of sour gases presents a tougher acid gas removal problem for the SULFAMMON plant than occurred in the BTADDS. Some modifications had to be made to the BTADDS scheme for the SULFAMMON process to work on our gases.

Large quantities of low-Btu sour gas are produced in the Paraho D-H retort. Cleaning this gas so that it can be burned in an environmentally acceptable manner is expensive. The SULFAMMON process was used because of the low capital cost. In spite of this, the capital costs for cleaning large quantities of dilute gas are staggering.

Hydrotreating

Hydrotreating and the production of hydrogen for hydrotreating add significantly to the cost of the product shale oil (10). To prepare the shale oil for refinery use, the nitrogen content must be reduced by hydrotreating. A product oil containing 500 ppm nitrogen was assumed to be a suitable refinery feedstock.

In this study, an empirical technique based on very little data was used to estimate the hydrogen consumption and, therefore, the costs of this expensive process.

Raw eastern shale oil presents a different hydrotreating problem than does raw western shale oil produced by the same retorting method. One reason is the lower hydrogen-to-carbon ratio in the eastern shale oil. Furthermore, eastern shale oil produced by a Fischer Assay technique presents a different hydrotreating problem than eastern shale oil produced by the HYTORT method (11).

Hydrotreating data are available for oils produced from Colorado shale by the Paraho technique (10), but the data are not for eastern shale oil. Hydrotreating data are available for oils produced from eastern Sunbury shales, but they do not cover the oil nitrogen ranges used in this study (2, 12). These data were combined to estimate the hydrogen consumption required by the hydrotreaters in this study. Details of these calculations are given in (6).

Table V lists some assumptions and results of the hydrotreater calculations.

TABLE V

HYDROTREATER ASSUMPTIONS AND RESULTS

	HYTORT OIL	Fischer Assay Oil (Paraho and TOSCO)
Feed oil nitrogen	2.2 wt %	1.5 wt %
Feed oil gravity	10.5° API	19.3° API
Product oil nitrogen	500 ppm	500 ppm
Product gravity	36.2° API	47.0° API
Hydrogen consumption	2300 scf/bbl	1600 scf/bbl

Sulfur Retention in the Burned Spent Shale (Paraho C-H Case)

Sulfur retention in the burned spent shale in the Paraho C-H case is an important economic parameter. Disposing of the sulfur in the gaseous and liquid streams is expensive. In the Paraho C-H process, all sulfur that does not go into the gaseous and liquid streams is carried with the retorted shale to the combustion section. This sulfur must be removed as SO_2 or retained in the burned spent shale. Removing SO_2 from the flue gas stream is expensive. The more sulfur that is retained in the burned spent shale, the more economical the total process is. Again, the information that most strongly affects the cost of an expensive process (sulfur retention in the burned spent shale) had to be estimated based on very little data. The only data found for sulfur retention in burned spent shale were in the BTADDS. The plant material balance in the BTADDS, however, did not reflect the actual data in the same report. The discrepancy was never resolved, so an independent source, an EPRI study of a lignite-fired fluidized bed power plant (13), was consulted. The EPRI report indicates that sulfur retention is a function of combustion temperature, CaO and possibly some of the other alkali oxides present. $CaCO_3$, often reported as a function of the mineral carbon (see Table I), will decompose to CaO and CO_2. This CaO and any other CaO in the shale can combine with the sulfur to form $CaSO_4$, which will remain in the burned spent shale.

Our estimate for the burned spent shale sulfur retention is based on the data in the EPRI report and the mineral carbon content in 80BSU-11 shale. The details of the calculation are presented in (6).

Retort Oil Yield

The amount of oil produced from each retort is a very important parameter for computing the cost of the product oil. With western shales, the Fischer Assay oil yield is predictable if the organic carbon content is known. This may not be true for eastern shales.

Janka and Dennison (3) give a plot of Fischer Assay oil yield vs organic carbon content for eastern oil shale, as does the BTADDS. There is a significant difference between the two plots (see Figure 2). Rather than choosing between these two correlations, we chose to have a Fischer Assay done independently on a sample of shale that had also been retorted by the IGT HYTORT process. The value obtained by the independent Fischer Assay is plotted in Figure 2. The value is within the data scatter about the lower line. Therefore, we assumed that this Fischer Assay was a fair basis for our study. We used 98% Fischer Assay oil yield for Paraho C-H and 100% for TOSCO II, based on 9.2 gallons per ton.

Shortly before this study ended, we obtained some data indicating that thermal retorting of eastern shales can produce higher oil yields than normal Fischer Assay (14, 15). Figure 3 is taken from (14). Some of the information on the original drawing was removed for clarity. Figure 3 indicates that heating rates above the Fischer Assay heat-up rate can increase the oil yield from eastern shales. These data suggest that eastern shales should not be treated as low-grade western shales. Yields greater than Fischer Assay can be obtained from eastern shales by thermal retorting methods. We do not know the economic benefits or penalties associated with these heating rates in full-scale equipment. Reference (15) states that proper thermal retorting may produce oil yields of up to 125% Fischer Assay from eastern shales.

It is only fair, however, to note the 80BSU-11 run (2) is not an optimum for the HYTORT case either. When compared on a normalized basis, Run 80BSU-10 produces a higher oil yield than Run 80BSU-11. Both runs are for Sunbury shale. Based on this observation, it is possible that the HYTORT process could produce 2 to 5% more oil than we estimated in our study.

The oil selling price was recalculated for the following processes using the increased oil yield percentages shown below:

- HYTORT (102% and 105%),
- Paraho C-H (110% and 125%),
- TOSCO II (110% and 125%), and
- Paraho D-H (110% and 125%).

The results of these calculations are given in Figure 4.

The 1.25 multiplying factor applied to the Paraho C-H case increases the oil production to nearly 11.3 gallons per ton. This value is close to the top Fischer Assay line in Figure 2. It is lower than the 12.5 gallons per ton used in the BTADDS calculations.

Increased oil production will bring down the selling price of the product oil significantly and will reduce the differences in the selling prices between the cases, but the relative ranking of the cases remains unchanged.

SUMMARY

We have tried to analyze each process impartially and believe that, based on our input data, the relative rankings shown earlier are correct. The oil yield data in (14) and (15) do, however, indicate that the differences between the HYTORT, Paraho and TOSCO II processes may not be as great as we have indicated.

Our oil costs are different from those of the BTADDS. There are several reasons for this.

1. Economy of Scale. The plants in this study are roughly five times the size of the plants in the BTADDS. Some economic benefit can be gained by going to plants larger than those in the BTADDS.

2. Capital Costs. Most of the capital costs from the BTADDS for individual process units are higher than those predicted by our correlations. On a cost vs capacity basis, our retort capital costs were significantly less than the BTADDS retorts. Overall, our capital costs are lower.

FIGURE 1

OIL SELLING PRICES FOR VARIOUS PROCESSES WITH DIFFERENT RETORT MODULE CAPITAL COSTS

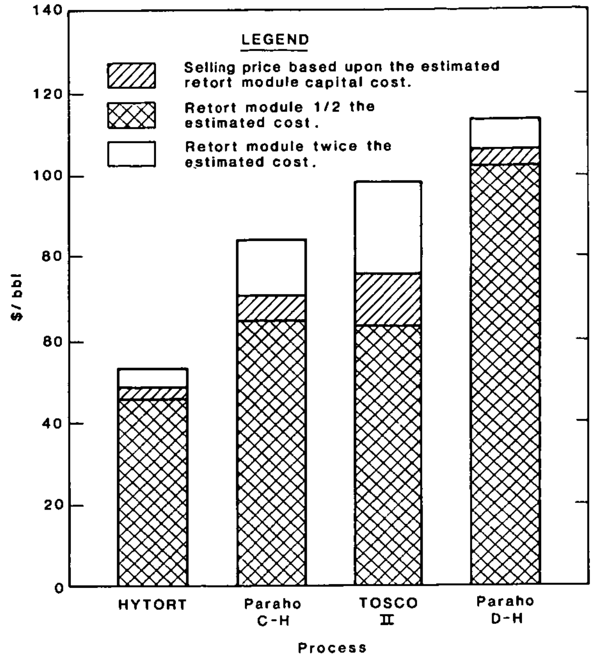


FIGURE 2

TWO DIFFERENT PLOTS OF FISCHER ASSAY OIL YIELD VS WT% ORGANIC CARBON FOR EASTERN OIL SHALE

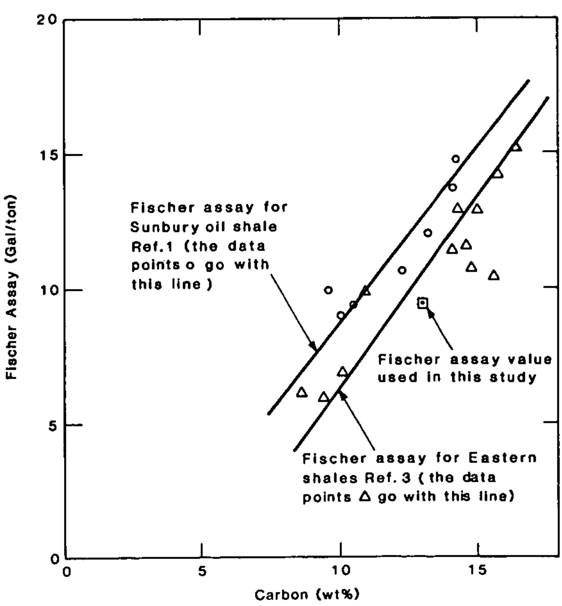


FIGURE 3

EFFECT OF HEATING RATE ON OIL YIELD FROM EASTERN AND WESTERN OIL SHALE (TAKEN FROM REF. 14).

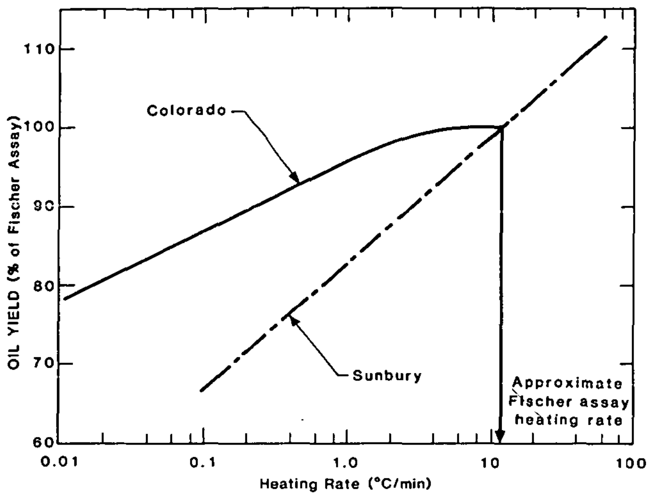
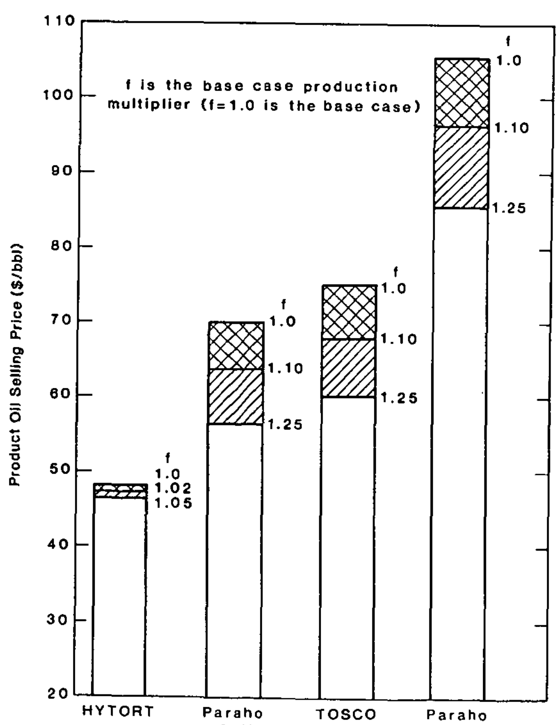


FIGURE 4

PRODUCT OIL SELLING PRICE FOR FOUR CASE STUDIES WITH INCREASED OIL PRODUCTION.



3. Mined vs Purchased Feed Shale. Our study uses shale purchased and delivered at $4.00 per ton. The BTADDS included the mine as part of their plant.

4. Hydrotreated Oil. Our design included oil hydrotreaters. The major product from the BTADDS was raw shale oil.

5. Different Financial Factors. The capital cost basis for this study was mid-1981. The capital cost basis for the BTADDS was fourth quarter 1980. Our study used an 18% return on equity. The BTADDS used what appears to be a 12% return on equity.

6. Different Oil Yield Input. We used a higher HYTORT oil yield, based on Run 80BSU-11 (Table I), than was used in the BTADDS. We used a lower Paraho C-H oil yield, based on extrapolated Fischer Assay data (Table III). These two factors explain why our study predicted that HYTORT produced a lower cost oil than Paraho C-H and the BTADDS predicted the reverse.

CONCLUSIONS

Our study, based on the input data used, indicates the following.

- Without further development, western shale retorting processes are not adequate for use with eastern shales.
- As described here, the HYTORT process produces oil at a cost nearly competitive with oil produced from western shale using western retorting techniques.
- Increasing oil yield with thermal retorting techniques by increasing the heat-up rate looks promising for processes like the Paraho C-H and TOSCO II.

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