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SCALEUP RISK OF DEVELOPING OIL SHALE PROCESSING UNITS

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МАСШТАБНЫЙ РИСК И УВЕЛИЧЕНИЕ АГРЕГАТНОЙ МОЩНОСТИ УСТАНОВОК ДЛЯ СЛАНЦЕПЕРЕРАБОТКИ

At the 13th Congress of the World Energy Conference (Cannes, 1986) the scaleup factors concerning the development of oil shale processing and combustion commercial units were criticized (J. Yerushalmi [1]). It was mentioned, that in the U.S.A. the development of synthetic fuel industry was based on unjustified high-scale enlargement of the retorts capacity.

For example, the failed 12,800 tons/day (11,600 t/day) Union B retort was erected in Colorado in 1983 with the enlargement of the capacity relative to the pilot unit (6 tons/day Union B test retort) of more than two thousand times, with a scaleup factor $M = 12{,}800 : 6 = 2{,}100$.

In contrast, the development of internal combustion oil shale retorts in the U.S.S.R. (Estonia) and China was mentioned where the capacity of retorts was increased step by step up to 275 t/day in China (1959) and 1,000 t/day in Estonia (1981).

The paper [1] presents also the Israel's plan towards commercial utilization of its oil shale resources. This plan is characterized by moderate scaleup steps.

At the 6th IIASA Resources Conference in Golden, 1981, Mir N. Heydari [2] associated the commercial risk factor of the development of new oil shale processing units with the scaleup factor of raising the capacity of the new commercial unit. The author estimated the risk at 25, 40 and 60 % according to the scaleup factors of the capacity rise: $M = 5-11$, $M = 30$ and $M = 90-1{,}300$.

In [3, 4] the approximate size (percentage) of the scaleup risk is expressed by the formula

$$r = a \log M \ (\%), \qquad (1)$$

where the value of a, on the basis of the author's experience in the field of developing oil shale burning boiler units, is between 15—25, M being the scaleup factor.

Scaleup Steps in Developing Oil Shale Retorts in China [5]

Fushun-type retort

The operation of the Fushun-type retorts dates back to the period of Japanese invasion in China. Since 1925, internal heating pyrolysis was carried out in retorts with an upper pyrolysis section and a lower gazification section:

1925 — 10 t/day test retort;
the late 1920s — 40 t/day test retort ($M = 4$);
1930 — 50 t/day commercial retorts ($M = 1.25$);

1934 — 50 t/day retorts were reconstructed into 100 t/day retorts ($M = 2$);
1939 — retorts of 180 t/day capacity ($M = 1.8$);
1945 — retorts of 200 t/day capacity ($M = 1.1$);
the late 1950s — studies on preheat sections added to single 100 and 200 t/day retorts, increasing their throughput about 30 %;
1959 — commercial retorts with preheating, 275 t/day each ($M = 1.1$).

In 1958 pyrolysis tests with gas combustion and the recycle gas as heat supply were carried out in 10 and 100 t/day retorts. In 1959—1961, twenty retorts of 100 t/day capacity were reconstructed into the gas combustion type. The single retort throughput was raised to 110 t/day ($M = 1.1$).

In the late fifties, the maximum total output of shale oil including recovered gas naphtha in Fushun was 0.78 million t per year. At the same time the amount of thermally processed oil shale was about 16.5 million t.

Maoming retorts

The exploratory study of the pyrolysis of Maoming oil shale was carried out in 10 and 100 t/day test retorts in Fushun in 1955—1956. The result was similar to that of Fushun oil shale, but Maoming shale differs from Fushun one in its 10—45 % higher heat consumption on thermal treatment.

The Maoming-type cilindrical retorts with the designed capacity of 160 t/day each (M more than 1.6) were built in 1968 and put into operation in 1969—1970 with the throughput of 140—160 t/day.

A test retort of 30 t/day capacity was built by the Huadian Shale Oil Company in the early 1958. After a successful run of this pilot unit, a rectangular gas combustion retort of 200 t/day capacity ($M = 6.7$) was built and put into operation.

Two rectangular gas combustion retorts of different capacity were also built at the Experimental Plant of the Petroleum Industry Company (PIC) for commercial scale testing at the end of 1958. In 1961, two batteries of gas combustion retorts were built. Under normal operation, the throughput of these retorts was 160—200 t/day, with onestream period 310—340 days.

The maximum annual shale oil production of the Maoming PIC was 0.18 million t, with the corresponding amount of processed oil shale reaching 5 million t.

The data illustrating the development of Fushun-type retorts as well as Maoming and Huadian retorts in 1925—1970 demonstrate that their capacity was raised step by step with moderate scaleup factors $M = 4—10$ at the pilot stages and with $M = 1.1—2$ at the commercial stages. The development was realized without any essential scaleup risk. By the formula (1) the scope of risk was overall less than 10 %, and corresponds to Chinese experience.

Other types of Chinese retorts [5. p. 109—112]

Starting from 1967, at the Maoming PIC particulate shale smaller than 15 mm previously discarded was tested in fluid bed pyrolyse (FBP) unit of 24 t/day capacity with shale ash heat carrier.

A jalousie-type retort was tested at the Research Institute of Shale Oil (now Inst. of Coal Research, Academia Sinica, Taynan, Shanxi) in the late fifties. Its commercial application was not justified.

In the late fifties, a pyrolysis test of shale fines was carried out at the Coal Research Laboratory, Academia Sinica. As heat carrier ceramic balls were used.

Table 1. **Scaleup Risk of Major Shale Oil Projects of the Late Seventies in Colorado and Utah**

Таблица 1. **Масштабный риск в проектах конца 70-х гг. по переработке горючих сланцев в штатах Колорадо и Юта (США)**

Project	Annual oil production target, million t/year	Retort type	Oil shale throughput, t/day: Demonstrated scale	Oil shale throughput, t/day: Proposed scale	Scaleup factor *M*	Scaleup risk, %
Cathedral Bluffs underground	2.7 by 1991	Oxy MIS	1,460*	2,100	1.5	5
Colony	2.3 by 1986	TOSCO II	900	10,000	11	15—25
Long Ridge	2.5 by 1990	Union B	5.4	11,600	2,100	50—85
Pacific	2.5 by 1991	Superior	227	20,000	88	30—50
Sand Wash	2.5 by 1988	TOSCO II	900	10,000	11	15—25
Rio Blanco: aboveground	1.3	Lurgi	11	4,000	370	40—65
Rio Blanco: underground	2.5	MIS	150	2,100	14	20—30
	3.8 by 1990					
White River	5.1 by 1990	Paraho or Superior	227 / 227	6,800 / 20,000	30 / 88	20—50
Paraho-Ute	1.5 by 1990	Paraho	227	6,800	30	20—40
	22.9 by 1991					25—40
Cathedral Bluffs aboveground	2.1 by 1991	Lurgi (?)	11	7,500 (?)	690	45—70

* Oil recovery was 63 % of predicted oil yield which was based on test retort 3E data:

		Oxy MIS 3E	60	2,100	35	25—40

Scaleup Risk of Developing Colorado and Utah Oil Shale Retorts in the Late Seventies [5—7]

Table 1 presents the scaleup factors and the scaleup risk calculated by the formula (1) for major projects from the late seventies, aimed at developing oil shale syncrude industry in Colorado and Utah.

The total investment of the projects, planned to start in 1985—1991 (presented in Table 1), was approximately US \$30 billion (in 1980 currency) with an average scaleup risk of about 25—40 % (\$8—12 billion). These projected plants, some under construction, were to employ giant retorts, each capable of processing thousands of tonnes of oil shale daily.

In the seventies, very high crude oil prices were predicted by the end of the century: \$300 per tonne (t) or \$42.50/bbl (in 1980 value) as minimum. For that time, the medium scenarios forecasted an annual shale oil production of about 100 million t in the U.S.A. Against such a background, the total scaleup risk of the projects to be realized in 1985—1991, was not more than 5—10 % of the annual shale oil syncrude production forecasted by the end of the century.

But rising costs and a slump in crude prices have dealt a blow at synthetic fuels industry. With one exception, none of the projects, listed in Table 1, has been realized. In construction status there were three significant projects: Cathedral Bluffs underground (MIS), Colony and Long Ridge. The only exception, the Union's Long Ridge project in Parachute Creek was realized with the erection in the late 1983 a single Union-B-type retort (the first of 10—15 retorts planned by the end of the century). The single retort was designed to process 11,600 t/day of oil shale and to produce 10,000 bbl/day (1,390 t/day) of raw shale oil and had the highest scaleup risk factor ($r = 50—85$ %) among the other projects. The Union was awarded a products purchase contract by the Department of Energy under the Defense Production Act. According to the contract, the Union had to deliver 7,000 bbl/day of diesel and 3,000 bbl/day of military jet fuel to the Department of Defence for a federally guaranteed price of $42.50/bbl, indexed for inflation for 7 years.

But after startup trials for over two years, the Union's plant was shut down for five months to solve technical problems. The retort's shale ore throughput in 1987 averaged 55 % of planned capacity. Cumulative synthetic crude oil production was about 83,400 t, which is approximately 20 % of the planned capacity of the retort.

The experience at the Union's plant demonstrates that the rate of the scaleup risk may really be in logarithmic dependence on the scaleup factor.

The fate of the large Union B retort is similar to that of the Estonian oil shale 2 × 3,000 t/day retorting plant using the retorted shale as a solid heat carrier (known also as the Galoter process).

Examples of Moderate and Unwarranted High Scaleup Risks of Oil Shale Processing Units in the U.S.S.R. (Estonia)

Internal heating pyrolysis retorts [3, 8]

Internal heating pyrolysis retorts for processing Estonian oil shale (called also 'gasifiers') were developed step by step during 70 years:

1921 — first internal heating *Pintsch* (Germany) test retort with shale ore throughput of 8 t/day at Kohtla-Järve;

1925 — first commercial 33—35 t/day retorts ($M = 4$) at Kohtla-Järve plant;

the 1930s — new 40—42 t/day retorts ($M = 1.2$);

the 1940s — 100 t/day test retort ($M = 2.5$) at Kohtla-Järve plant;

the 1950s — 90—115 t/day retorts ($M = 1—1.2$);

the 1960s — 115—180 t/day retorts ($M = 1.3—2$);

the 1970s — reconstruction of existing 190—200 t/day ($M = 1.1—1.7$) retorts employing on gas combustion and heat carrier rectangular flow;

1981 — internal heating gas combustion and rectangular heat carrier flow commercial test retort designed for concentrated shale ore throughput of 1,000 t/day ($M = 5—6$, $r = 10—20$ %) and raw shale oil production of 180 t/day. In 1981—1982, the capacity of 800—900 t/day was achieved;

the late 1980s — commercial retorts of 1,000 t/day at Kohtla-Järve plant. The 1,500 t/day retorts ($M = 1.5$, $r = 3—5$ %) are in construction stage.

Retorting with spent shale as solid heat carrier [3, 9]

The pyrolysis of oil shale fines with the spent shale as a solid heat carrier (the Galoter process) was also apparently developed step by step:

1949—1956 — pilot scale step with oil shale throughput of 2.5 t/day;

1954 — industrial test retort with the capacity of 200 t/day ($M = 80$);

1964—1973 — commercial test retort of 500 t/day · ($M = 2.5$). During this period the retort's shale ore throughput averaged 100 % of planned capacity, the cumulative raw shale oil production was 182,100 t. But the quality of the oil · (mineral ash content) as well as of the spent shale · (water soluble sulphides content) did not meet their quality requirements;

the 1970s — projects of annual processing of 50—70 million t of Estonian and Leningrad oil shale by solid heat carrier retorts with the daily throughput of a single retort 3,000 and 10,000 t;

1980 — the first step of a commercial test plant with the throughput of 6,000 t/day · ($M = 12$); the first retort of the plant, with the planned capacity of 3,000 t/day · ($M = 6$);

1982 — the second retort of the plant, with the designed capacity of 3,000 t/day · (a copy of the 1980's retort).

In spite of many reconstructions for solving technical and environmental problems, the maximum annual cumulative throughput of the plant with the planned annual throughput of 1.9 million t of shale, was only 369,000 t in 1989. Cumulative raw shale oil production · (mostly unconditional oil) was 42,800 t.

The maximum annual throughput of a single retort was 230,000 t which is about 25 % of the planned annual capacity.

Retorts No. 1 and No. 2 of the plant were in operation alternatively. The daily throughput of a single retort in operation was near to the planned capacity: between 2,800—3,000 t · (in 1989 average throughput was 2,880 t/day).

But long standstills between the runs for cleaning the systems from ash deposits as well as other technological and economical factors and operation personnel problems reduced the in-operation-time and the average annual capacity of the plant to the level of 20—25 % from the designed capacity · (Table 2).

The reason, why the enterprise with two 3,000 t/day retorts failed by such moderate scaleup steps as $M = 80$ · (step from pilot scale at the demonstration stage), 2.5 · (step at the first commercial stage) and 6, was the incomplete development of the technology at all the steps. The problem of the spent shale finest dust particles removal from the oil vapours before the condensation section was not solved at any stage of

Table 2. **Operation Time and Production of 3,000 t/day Solid Heat Carrier Retorts in Estonia during 1988—1989**

Таблица 2. **Эксплуатационные показатели УТТ-3000 (Эстония) за 1988—1989 г.**

	Year	Retort No. 1	Retort No. 2
Operation time, h	1988	973	1,719
	1989	1,953	1,142
Processed shale, t	1988	107,000	204,000
	1989	230,000	139,000
Average throughput of shale, t/day	1988	2,640	2,850
	1989	2,850	2,920
Production of raw shale oil, t	1988	12,400	24,200
	1989	25,000	17,800
Average yield of raw shale oil:			
t/day	1988	310	340
	1989	310	370
bbl/day	1988	2,250	2,460
	1989	2,250	2,680

development. The problems related with the spent shale and environment remained unsolved either. Therefore the apparently moderate scaleup steps did not lead to the introduction of the real technology, and some important and determining parts of the 3,000 t/day units (e. g. the dust removal system and the thermal handling of processed shale in the air-blown firebox into heat carrier and refuse ash) were built at a level lower than that of the pilot plant. Consequently, the real scaleup factor of the units was over $M = 80 \times 2.5 \times 6 = 1{,}200$ with a scaleup risk up to 75 % and more.

Summary

The experiences in oil shale processing in three large countries, China, the U.S.A. and the U.S.S.R. have demonstrated, that the relative scaleup risk of developing oil shale processing units is related to the scaleup factor.

On the background of large programmes for developing the oil shale industry branch, e. g. the $30 billion investments in Colorado and Utah or 50 million t/year oil shale processing in Estonia and Leningrad Region planned in the late seventies, the absolute scope of the scaleup risk of developing single retorting plants, seems to be justified.

But under the conditions of low crude oil prices, when the large-scale development of oil shale processing industry is stopped, the absolute scope of the scaleup risk is to be divided between a small number of units. Therefore, it is reasonable to build the new commercial oil shale processing plants with a minimum scaleup risk.

For example, in Estonia a new oil shale processing plant with gas combustion retorts projected to start in the early nineties will be equipped with four units of 1,500 t/day enriched oil shale throughput each, designed with scaleup factor $M = 1.5$ and with a minimum scaleup risk, only $r = 2.5$—4.5 %.

The oil shale retorting unit for the PAMA plant in Israel [1] is planned to develop in three steps, also with minimum scaleup risk: feasibility studies in Colorado with Israel's shale at Paraho 250 t/day retort and other tests, demonstration retort of 700 t/day and $M = 2.8$ in Israel, and commercial retorts in the early nineties with the capacity of about 1,000 t/day with $M = 1.4$. The scaleup risk of the PAMA project $r = 2$—4 % is approximately the same as that in Estonia.

The knowledge of the scope of the scaleup risk of developing oil shale processing retorts assists on the calculation of production costs in erecting new units.

РЕЗЮМЕ

На XIII конгрессе Мировой энергетической конференции (Канн, 1986) проблемам переработки и сжигания горючих сланцев был посвящен доклад [1], в котором подверглась критике практика некоторых фирм, развивающих оборудование для термической переработки сланцев с чрезвычайно высокими масштабными факторами и, таким образом, с неоправданным риском. В качестве противоположного, то есть удачного, опыта в докладе указано на постепенное повышение мощности сланцевых реторт внутреннего горения (газогенераторного типа) в СССР и Китае — до пропускной способности 1000 т сланцев в сутки в Эстонии и до 275 т/сут в Китае (Фушунь).

Связь масштабного фактора *M* и масштабного риска *r* рассмотрена в [2—4]. Предложена приближенная формула, имеющая вид логарифмической зависимости величины риска от масштабного фактора

$$r = a \log M \ (\%), \tag{1}$$

где, по оценкам автора, коэффициент *a* равен 15—25.

В Китае при развитии сланцевых реторт внутреннего горения в период с 1925 по 1970 г. масштабный фактор был следующим: для опытных реторт $M = 4—10$, для промышленных $M = 1,1—2$. В г. Фушунь в конце 50-х гг. в таких ретортах перерабатывали до 16,5 млн. т сланцев в год, получая до 0,78 млн. т/год сланцевой смолы, а для заводов в г. Маомин в начале 70-х гг. эти показатели составляли соответственно 5 млн. т/год сланцев и 0,18 млн. т/год смолы [5].

Таким образом, в Китае сланцепереработка развивалась с минимальным масштабным риском — менее 10 % по формуле (1).

В США в конце 70-х гг. в штатах Колорадо и Юта, как видно из табл. 1, было начато осуществление гигантской программы, согласно которой производство синтетической нефти из сланцевой смолы в начале 90-х гг. должно было превысить 23 млн. т в год. Для достижения этой цели понадобились капиталовложения порядка 30 млрд. долларов со средним масштабным риском по формуле (1) 25—40 %, или около 8—12 млрд. долларов. Однако после резкого падения цен на нефть в начале 80-х гг. из перечисленных в табл. 1 проектов до рабочего состояния был доведен лишь проект в Лонг Ридже. Все другие, в том числе два в стадии строительства, были приостановлены. В конце 1983 г. в Лонг Ридже было закончено сооружение реторты типа Юнион Б [6], которая среди других намеченных для строительства выделяется самым резким масштабным увеличением ($M = 2100$) и максимальным масштабным риском ($r = 50—85$ %).

В 1987 г., после ряда реконструкций, мощность этой реторты составила лишь 55 % от номинальной/проектной, а годовая продукция синтетической нефти — всего 18 % от проектной [7].

В СССР (Эстония) реторты с внутренним горением (газогенераторы) [8] в период с 1921 по 1981 г. развивали с небольшими масштабными скачками ($M = 2,4—4$ на опытных этапах, $M = 1,1—5$ в промышленных условиях), при масштабном риске не более 10—20 %. Пропускная способность в начале 80-х гг. возросла при этом с 8 до 1000 т/сут. В то же время, несмотря на умеренные масштабные скачки ($M = 80$ при переходе от пилотной установки к демонстрационной, $M = 2,5$ и $M = 6$ на промышленных этапах), сооружение и пуск установки с твердым теплоносителем для переработки сланцевой мелочи оказались неудачными. В 1980—1982 гг. в эксплуатацию были сданы две УТТ-3000. Однако до 1989 г. годовая пропускная способность по сланцу одной из реторт так и не превысила 25 % от проектной (табл. 2), хотя проектная суточная производительность была достигнута. Причинами неудачи стали, с одной стороны, несовершенные технические решения на всех этапах разработки проблемы отделения мелкой пыли от парогазовой смеси, выходящей из реактора, а с другой — недоучет или игнорирование современных экологических требований к качеству отработанного твердого остатка. Таким образом, реальный масштабный фактор для УТТ-3000 оказался больше, чем увеличение после пилотной стадии, т. е. больше чем $M = 80 \times 2,5 \times 6 = 1200$, при масштабном риске более 75 %.

Представление о величине масштабного риска поможет в определении предполагаемой себестоимости продукции новых реторт.

Опыт развития переработки сланцев в трех больших странах показывает, что при низких ценах на нефть развитие сланцеперерабатывающей промышленности целесообразно только с минимальным масштабным риском. Ввиду небольших объемов производства нельзя ожидать большого выигрыша в случае, еси риск окажется оправданным. Сооружение новых заводов по переработке сланцев в Эстонии и Израиле предусмотрено с масштабным фактором $M = 1,4—1,5$ и масштабным риском не более 2—5 %.

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