4.1.2. Washability of Ngao Coal

Judging from the test results of bulk sample, it is presumed that the conventional coal preparation method can be applied without difficulty, because a lot of coarse-grained portion with low specific gravity is contained in the sample. Although more data are required for detailed design of preparation plant, relatively simplified facilities, such as Jig system, may be used for processing of Ngao coal.

Concerning to the control of ash content of bulk sample, in the Christopher diagram (Figure 4-1), we can find that more than 10 mm size of fraction amounts to roughly 70 % and fraction of less than 1.4 in specific gravity amounts to more than 90 %. This coarse and light coal is easy to separate and the ash content is low.

Less than 0.5 mm size of fine grain fraction takes only 5 % and 0.5~3 mm size of fraction takes 10 %. In the small size of particles, specific gravity is rather high and fraction of less than 1.7 in specific gravity shows low ash content (around 15 % AR).

Concerning to the separation of sulfur, in the Christopher diagram of the bulk sample, sulfur content is almost same in every size and fraction (around 4%, AR). It means that the separation of sulfur is difficult by conventional coal preparation method. In the petrographic analysis, we can see very fine grain of pyrite (10~20 micron size), which is homogeneously dispersed in coal matrix. These matters also indicate that the separation of sulfur is difficult.

Washability curves of ash and Sulfur on PH3 core sample are shown in Figure 4-2 and 4-3. Washability curves on the other core samples are shown in Appendix-6.

The analysis result of core samples shows that the sulfur content varies by the areas. In some area, sulfur content is less than 3 %(AR), and in other area, more than 6 %(AR). They also indicate that the separation of sulfur is difficult.

Washability of ash is almost same in core sample and bulk sample. Selective mining and conventional washing method will be effective to reduce ash content.

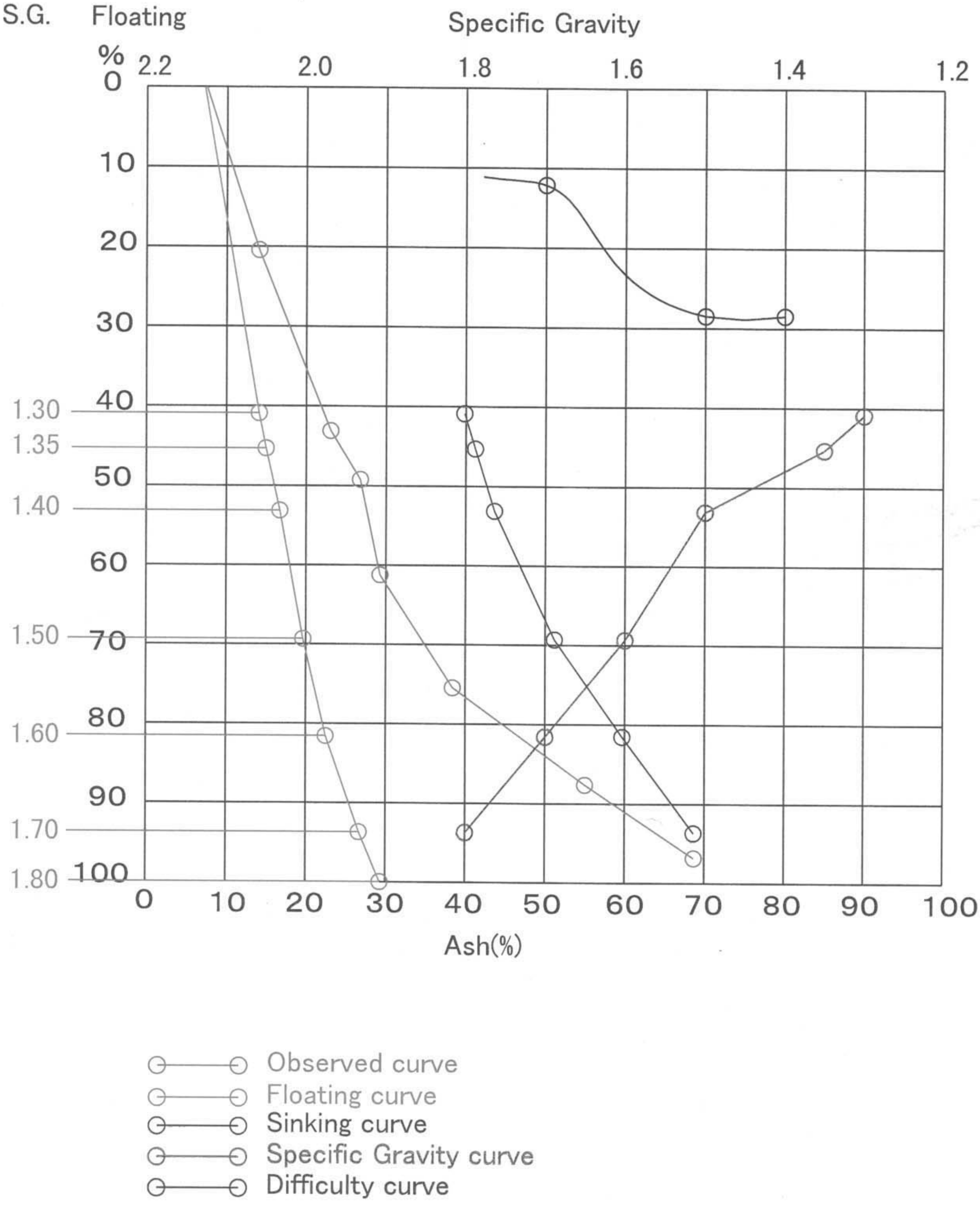

Figure4-2 Washability Curve (Ash) PH3 [+10mm]

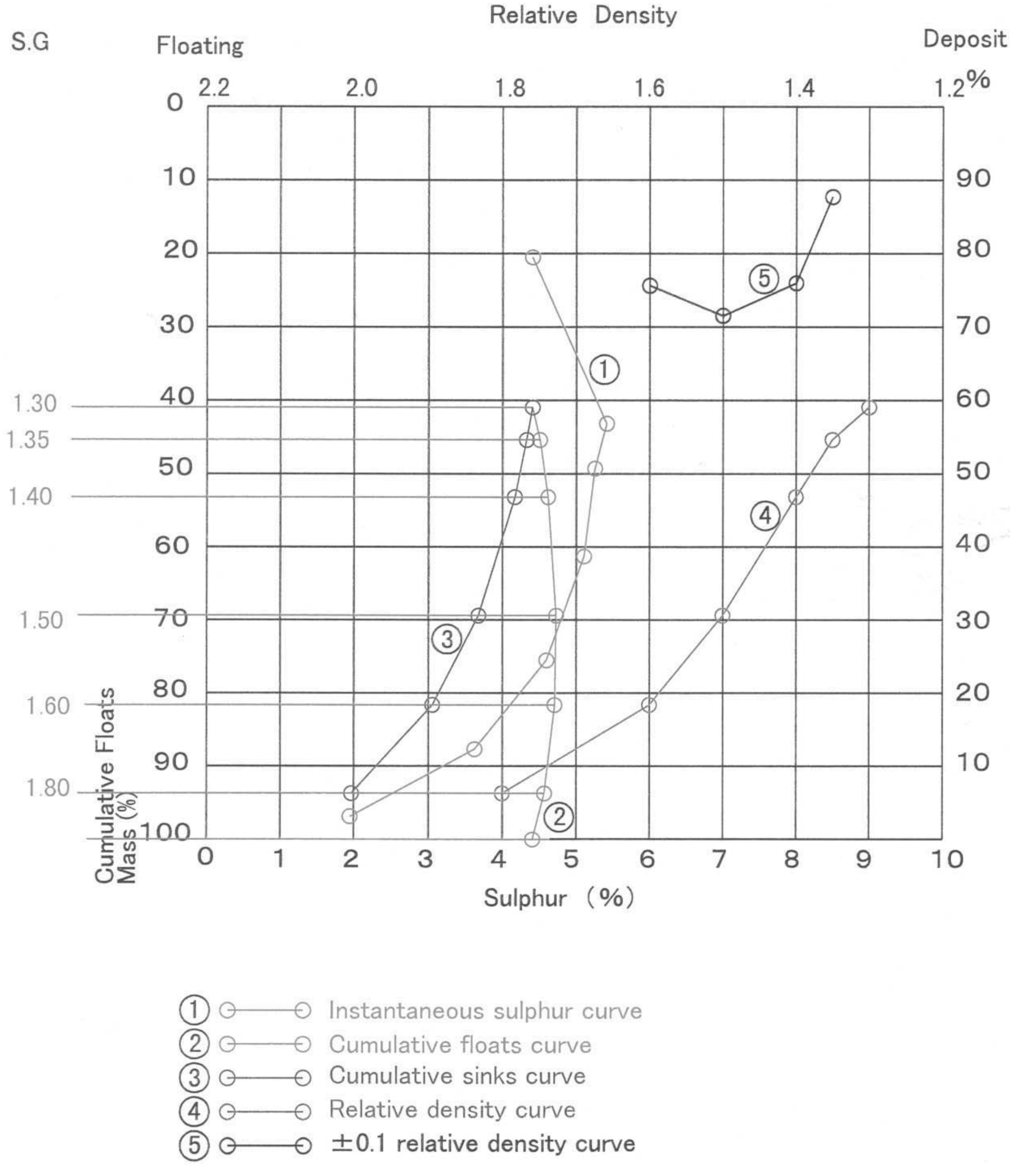

Figure4-3 Washability Curve (Sulphur) PH3 +10mm

Estimated sulfur contents of washed coal are fairly different by each sample. In case of bulk sample, it is around.4.5 %(AR). In case of core samples, it is around.2.5 %(AR) for N5-1, around 4.5 %(AR) for N3-6 and PH-3, and around 6.5 % for N1-3. (For PH-3, the separation of sulfur is impossible)

In the stage of detailed design of coal preparation plant, more specific data may be required. But in this Study, we recommend to apply simple Jig washing method for Ngao coal preparation.

4.1.3. Advanced Coal Preparation Technology

For the purpose of evaluating further degree of coal cleaning by means of advanced technology, float and sink test was conducted on pulverized bulk coal sample. Degree of liberation of ash and sulfur by crushing was examined in this test.

(1) Condition of Float and Sink Test

- Test sample: Size 10-25 mm
  S.G. 1.35-1.40, and 1.40-1.50
- Crushing size: -2.67mm, -0.5mm
- Separation density: 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8

(2) Test Result

The test result revealed that liberation of ash and sulfur by crushing could not be expected so much. Because a large portion of the sample is under 1.3 in specific gravity, the effect of liberation was seen only little, though the degree of liberation was similar to the Australian coal. In addition, it is impossible to cover the additional cost for crushing because of the low effect of liberation.

As it was not available in Thailand, float and sink test on fine-grained coal under 0.5 mm was done in Japan using centrifugal force.

(3) Comment on separation of sulfur

Based on the petrographic observation on grain distribution of pyrite sulfur in the coal matrix, pyrite grain size is very small and around 0.01 mm ～0.02 mm.

To liberate pyrite sulfur from coal matrix, we have to crash the coal at least less than 0.01mm. Technology to separate these fine grain size of particle is not yet established.

4.2. Upgrading Test by Drying Method (ACC Process)

4.2.1. Outline

After float and sink test, each 15 kg weight of coal sample under 1.3 in specific gravity was collected for the size of 3-10 mm, 10-25 mm and 25-50 mm. This portion is the main part of the sample, and it is assumed to be the clean coal from Ngao area after preparation process.

This sample was used for the tests of drying method, including drying test and liberation test for ash and sulfur. The test is based on the ACC process developed in the USA.

4.2.2. Preparatory Test

Thermo gravimetric analysis under the flow of air and nitrogen gas was conducted on the sample of 10-25mm in size with a small-scale apparatus for differential thermal analysis, and drying loss was measured. The results are shown in Figure 4-4 and 4-5

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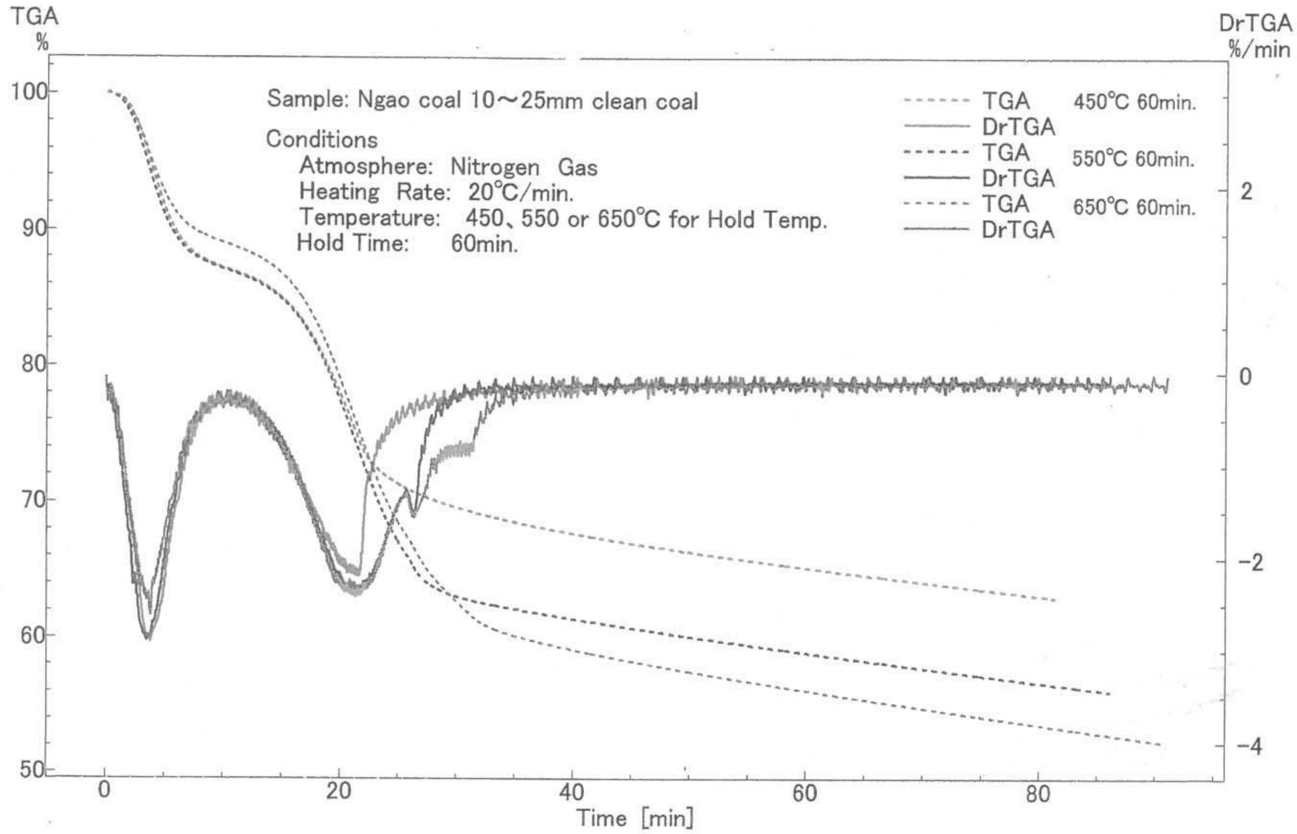

Figure4-4 Comparison of Hold Temperature(Thermogravimetoric Analysis)

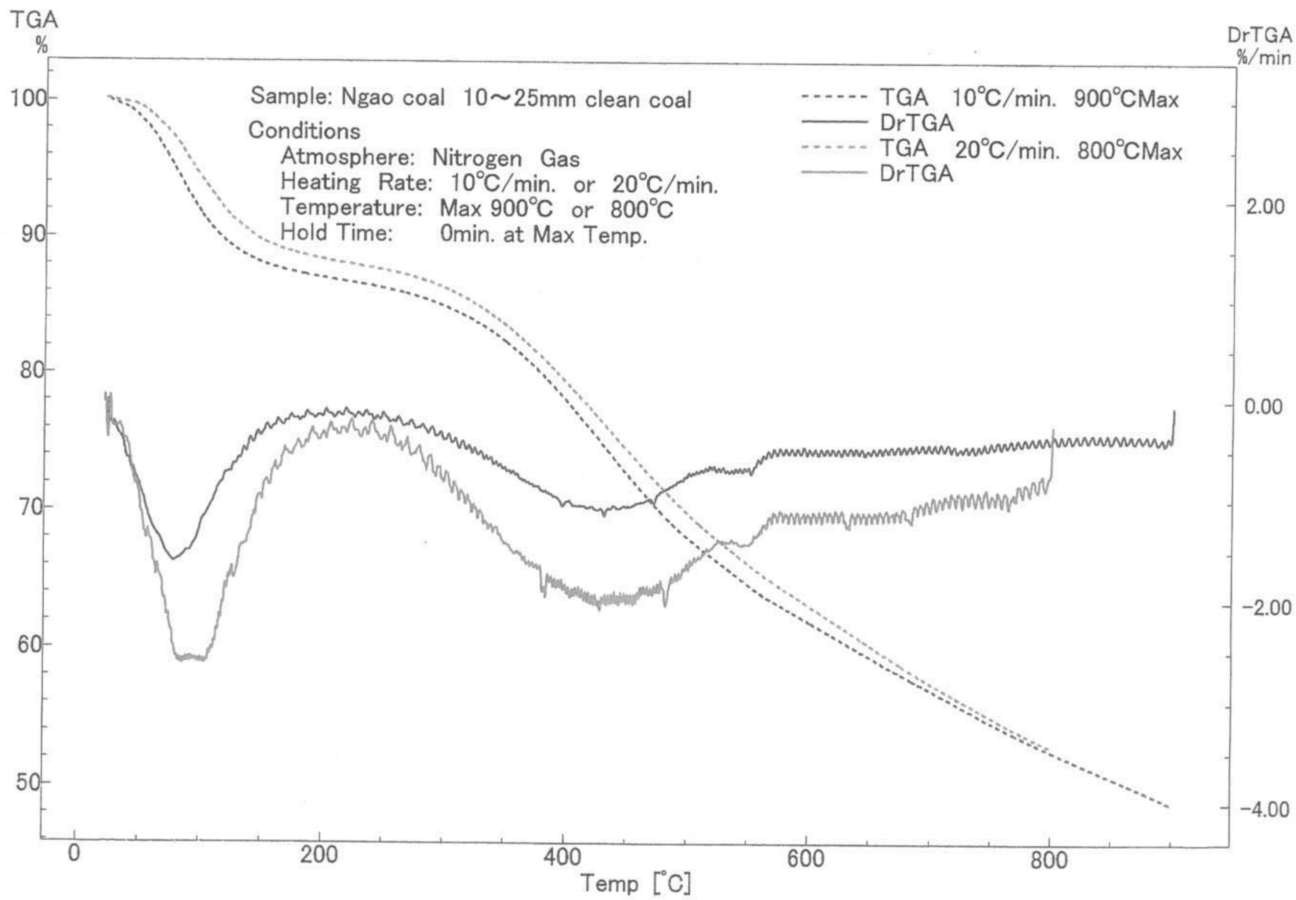

Figure4-5 Comparison of Heating Rate(Thermogravimetoric Analysis)

4.2.3. Drying Test

(1) Apparatus and Conditions of Test

Drying test was conducted with an apparatus shown in Figure 4-6 and Ph-10 under the following conditions.

・Sample: 500g.

・Drying atmosphere: Under the flow of heated gas

(Nitrogen gas - 230℃, Steam - 320℃)

・Drying time: 45, 60, 120, 240 minutes

・Sample size: 3-10, 10-25, 25-50 mm.

The following tests were conducted on the dried sample: proximate analysis, ultimate analysis, and measurement of specific surface area, spontaneous combustibility test. In addition, the effect of degradation by drying was examined by measuring ash and sulfur content in the fine-grained portion of dried sample after screening by 0.5mm and 2mm in size.

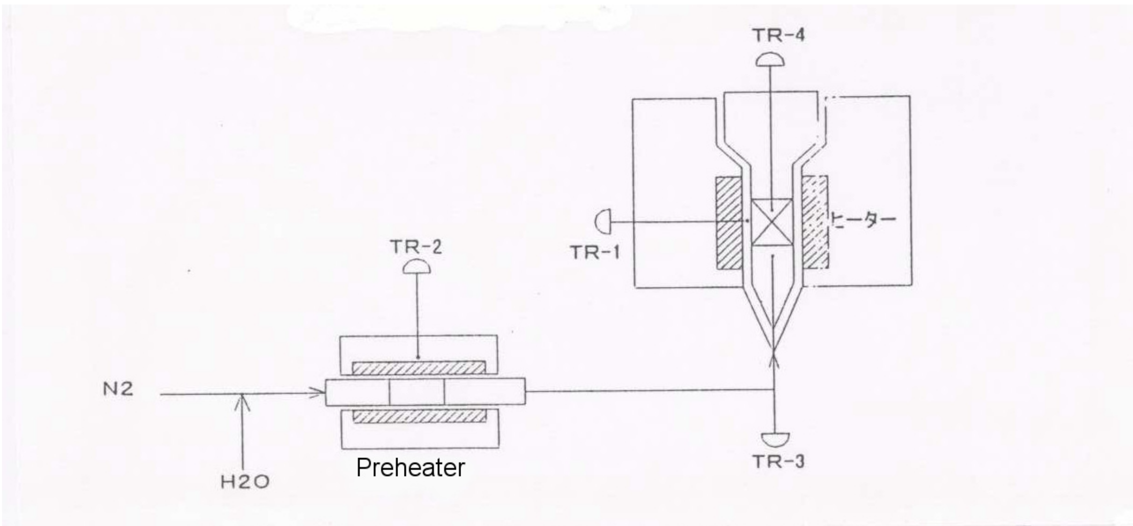

Fig. 4-6 Drying Test Apparatus

(2) Test Result

Advantages of ACC process are that de-ash and de-Sulfur are possible simultaneously with drying process. In the present test, drying was possible under the above conditions, and drying result was obtained as expected. However, the degree of degradation was lower than that of Powder River coal in USA, and liberation of ash and sulfur by degradation was hardly recognized in the sample.

As far as the test of bulk sample is concerned, an applicability of ACC process is negative.

In the petrographic analysis, we can see very fine (10~20 micron size) pyrite grain, which is homogeneously dispersed in the coal matrix. These matter also indicate the difficulty of separation of sulfur.

According to the analysis of drill core samples, sulfur content of each specific gravity fraction is almost same figures (ref. core data of PH3), this fact also indicate that pyrite is dispersed in the coal matrix homogeneously.

As a result, ACC process is not effective for Ngao coal upgrading.

4.2.4 Comment

Based on the present test data, simpler test will be applied for evaluating ACC process. Because the applicability of the process seems to be different by areas or coal quality, further study should be done together with the test data on drill core samples in the next stage, if needed.

Small-scale test is effective to evaluate ACC process for the coals other than Ngao.

4.3. Upgrading Test by Low Temperature Dry Distillation Process (SGI Process)

4.3.1. Outline

Test of low temperature dry distillation was conducted based on the SGI process proved in USA and upgrading by this process has been examined. Coal sample of 10-25 mm in size and also less than 1.3 in specific gravity was collected from bulk sample after float and sink test and used for test.

4.3.2. Preparatory Test

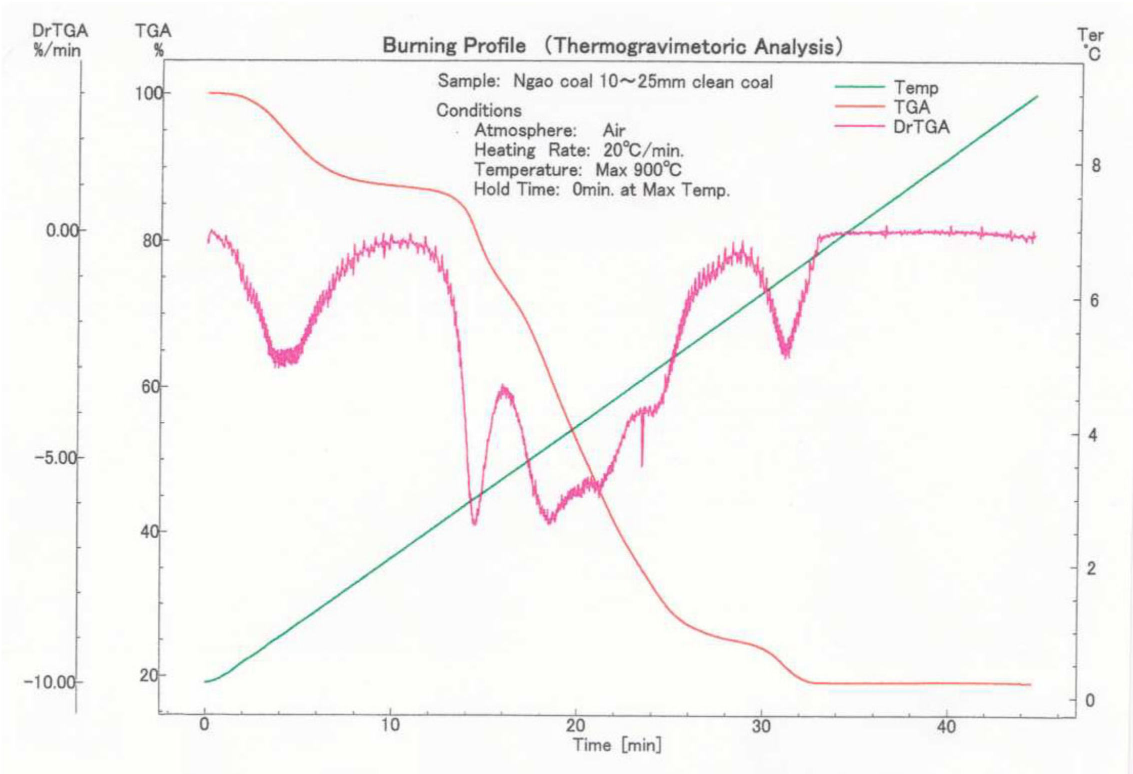

Figure4-7 Burning Profile(Thermogravimetoric Analysis)

Thermo gravimetric analysis under the flow of nitrogen gas was conducted on the sample of 10-25 mm (－1.3 in specific gravity) with a small-scale apparatus of differential thermal analysis. Speed of de-volatile matter by dry distillation was measured to obtain the data for design of dry distillation test. The result is shown in Figure 4-7.

4.3.3. Dry Distillation Test

(1) Preparatory Drying

Prior to dry distillation test, preparatory drying was conducted with the same apparatus as the one used in the drying test. Test conditions were as follows.

・Used gas and temperature : Nitrogen gas, 260℃

・Drying time: 60 minutes

・After removing moisture by drying, dried sample of 5kg were obtained.

(2) Apparatus and conditions of Test

The apparatus used for the test is shown in Figure 4-8 and Ph-11. Test conditions were as follows.

・Sample: Size; 10-25 mm, Specific gravity; under1.3

・Sample amount: 200g

・Dry distillation temp.(℃): 450, 550, 650, 750, 850

・ Retention time (min): 30, 45, and 60

Solid product, liquid product and gas obtained on each condition were weighed, and various tests were conducted, including proximate analysis, ultimate analysis, calorific value, measurement of specific surface area and forms of sulfur.

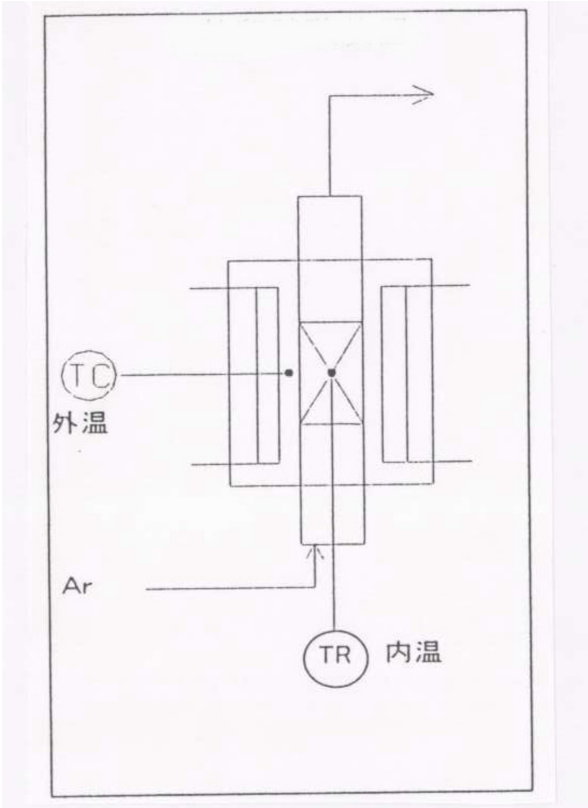

Fig4-8 Drying Distillation Test Apparatus

4.3.4. Test Result and Discussion

(1) Test result

Inherent moisture of bulk sample was 21 %. It is presumed that moisture content of washed Ngao coal is about 30 %(AR). Solid product by dry distillation process is supposed to be about 50%, provided that 30% of moisture is removed by preparatory drying and remained 20% is gas and liquid.

Judging from the dry distillation test result, it will be suitable that reaction temperature is 450~550℃ and reaction time is 45minuts.

Table 4-1 shows the test result on the relation between distillation temperature and form of sulfur of the solid product.

Table 4-1 Form of Sulfur of the Solid Product

(Comparison with Drying Coal and Dry Distillation Coal)

Drying Coal		Inorganic Sulphur						
Condition	T.S.	sulfate	pyrite	organic	moisture	ash	Kcal/Kg	s/cal
280℃ 1.0 hour	7.18	0.17	2.53	4.48	7.70	17.69	5490	
280℃ 1.0 hour	7.39	0.15	2.99	4.25	7.10	18.56		
280℃ 1.0 hour	7.43	0.15	3.07	4.21	7.40	18.82		
300℃ 4.0 hour	7.56	0.17	3.11	4.28	2.00	18.56	5500	1.37

Dry Distillation Coal		Inorganic Sulphur						
Condition	T.S.	sulfate	pyrite	organic	moisture	ash(dry)	Kcal/Kg	s/cal
450℃ 0.75 hou	6.00	0.22	1.81	3.97	6.40	24.80	5770	1.04
550℃ 0.75 hou	5.93	0.07	0.14	5.72	5.10	27.76	6110	0.97
650℃ 0.75 hou	6.49	0.06	0.05	6.38	4.40	30.08	6010	1.08
750℃ 1.0 hour	6.34	0.10	0.03	6.21	5.60	31.72	5980	1.06
850℃ 1.0 hour	6.61	0.06	0.04	6.51	5.80	32.68	5990	1.1

By dry distillation process, 50 % of pyrite sulfur was decomposed at 450℃, and more than 90 % of that was decomposed at 550℃ (de-sulfured as hydrogen sulfide gas). These facts may mean that pyrite (or marcasite) decomposed at 450℃ to pyrrhotite and then at 550℃ decomposed to iron. Heating value of the solid product is about 6100 Kcal/Kg.

Material balance was calculated based on the test result of dry distillation at 550℃. The result is shown on Table 4-2. Ratio of sulfur content equivalent to heating value was remarkably reduced.

Around 50% of Sulfur was reduced: (3.8/4.63)×(3770/6000)＝0.52 (by table 4-2)

Table 4-2 Material Balance and Product Quality

(Ngao Bulk Sample at 550 ℃ Dry Distillation)

Bulk Sample

	Ngao Coal	(Wyoming)
Moisture	30	29.12
V.M.	29.6	30.64
F.C	27.4	34.95
Ash	13	5.29
Heating V.	3770	4527
(Kcal/Kg)	100	100
C	40.47	49.09
H	2.91	3.41
N	1.01	0.72
S	4.63	0.38
O	7.99	11.99
	57.01	65.59
s/cal	0.012281	

Char	392	
Tar(Oil)	157	
Gas	105	
C.Water	45	
	699	

Ngao coal	143
Drying	
Vapour	43
Dried coal	100
Distill.	
Gas	15
C.water	6.5
Tar	22.5
Solid	56
Total	100

Solid product

	Ngao Coal	(Wyoming)
V.M.	14.7	20.4
F.C.	58	69.1
Ash	27.3	10.5
Heatin V.	6000	7000
	100	100
C	64.8	75.6
H	2.3	3.1
N	1.7	1.1
S	3.8	0.3
O		9.4
	72.6	89.5
s/cal	0.006333	

Sulfur reduction rate: 0.00633／0.01228＝51.

Liquid product

	Ngao Coal	(Wyoming)
C	73.9	83.8
H	8	9.6
N	1.5	0.4
S	4.5	0.3
O	12.1	5.5
Ash		0.4
	100	100

Yield of liquid product and gas was rather high. So for the practical plant design, milder reaction condition may be required. (lower temperature:530℃or shorter retention time).

It is said that 30～50 % of organic sulfur can be removed by dry distillation process as gas or liquid. As far as bulk sample is concerned, high content of sulfur is still remained in the product of dry distillation, even if 50 % of sulfur is removed. Lower sulfur content is recognized in some of drill core samples and in this case, there is possibility to obtain lower sulfur product by this process.

Further detailed study should be done on application of this process to core samples of mining areas and other Thai coal.

(2) Comments on sulfur

As stated above, pyrite sulfur of Ngao coal is almost perfectly decomposed by dry distillation at 550℃. On the other hand, pyrite was not decomposed at the condition of 300℃ and 240 minutes treatment. This indicates that the decomposition of pyrite does not happen by ACC process.

In case of Ngao coal, pyrite grain is very small (10~20 micron). Then, it is presumed that physical separation is difficult but chemical decomposition is easy.

Sulfur content of solid product from bulk sample was 3.8% and that of Liquid product was 4.5%. Marketing of high sulfur liquid product is important. Selection of lower sulfur feed coal is important also.

(3) Cost consideration

Dry distillation seems to have much advantage as upgrading technology as stated above. This process is demonstrated by 1000 ton/day plant in Wyoming USA. Concerning about the possibility of commercial plant in Ngao area, further economic study is needed.

By selective mining and coal preparation, feed coal can be controlled on a reasonable quality.

It is assumed that the yield of product is almost same to the case of USA. But, sulfur content of product is fairly higher than that of USA.

According to economic consideration on Wyoming coal, on the basis of 50 % yield of solid product, processing cost is estimated at 5 $/ton-feed-coal by crediting the revenue of liquid product (Total of operation cost, depreciation and capital charge is about 15 $/ ton-feed-coal, and revenue by liquid product is 10 $/ton-feed-coal). 5$/ton-feed-coal is equivalent to 10$/ton-solid-product (because the yield is 50%).

Namely, processing cost is estimated at 450 Bahts/ton-solid-product. Cost of feed-coal is estimated at 315 Bahts/ton as mentioned later. Counting 50 % of the yield, cost of feed-coal is calculated at 630 Bahts/ton-solid-product.

Finally, cost of solid- product is 1080 Bahts/ton (450+630) at plant site.

The plant construction cost must be lower in Thailand than USA. If the total of operating and construction cost go down 10 %, the cost of solid-product is estimated 945 Bahts/ton.

Feed-coal cost : 15 $/t×0.9－10 $/t (credit of liquid-product)＝3.5$/ t

Solid-product-cost: (3.5$/t×2)×45 B/$＋630B/t＝945 B/t

This cost consideration is very rough and it is premature to make cost estimation at this stage.

To conduct preliminary feasibility study, we have to select raw coal and decide washed coal, then decide yield structure to design process condition. Product yield and plant cost is key factor for economic study of the upgrading technology.

At this point of economic consideration in Thailand, solid product of 5,800 Kcal/Kg (AR) may be produced by 900~1100 Bahts/ton at plant site.

Sulfur reduction may be 50~60%. Sulfur content of liquid product is still high (in case of bulk sample: 4.5%).

Because of high sulfur content of liquid product, product-marketing study is also important.

4.3.5 Recommendation

By dry distillation test on Ngao bulk sample, it seems SGI process is technically feasible. Ngao coal shows very high sulfur content, but test results indicate high reduction on Sulfur.

In Thailand there are many high surfer coal seams like Ngao. It seems to be important to evaluate these seams as a candidate of upgrading feedstock.

As a next step, we recommend to select appropriate feed coal and to conduct preliminary feasibility study.

4.4. Upgrading Test by Low-Temperature Liquid Phase Cracking Process

4.4.1. Outline

This process is under development by National Institute for Resources and Environment (NIRE) of Japan, and the application of this process was studied at the temperature of about 400℃. The effect of hydrogenation was also examined to improve the yield of liquid product.

The sample of 25-50mm in size with specific gravity of less than 1.3 was collected from bulk sample and used in this test. Coal from Ban Pa Kha mine of Lanna Lignite was also tested for comparative purpose.

4.4.2. Apparatus and Conditions of Test

An autoclave of 500 ml was used for the test as shown in Figure 4-9 and Ph-12. Test conditions are as follows.

・Sample: Ngao coal Powder: crushed into 200 mesh

Grain: crushed into 3-10mm

Ban Pa Kha Powder: crushed into 200 meshes

・Solvent : Terrain, Decalin, LCO

・Conditions: Solvent/Coal = 2/1

Reaction temperature (℃) : 380, 400, 420, 440

Retention time: 60 minutes

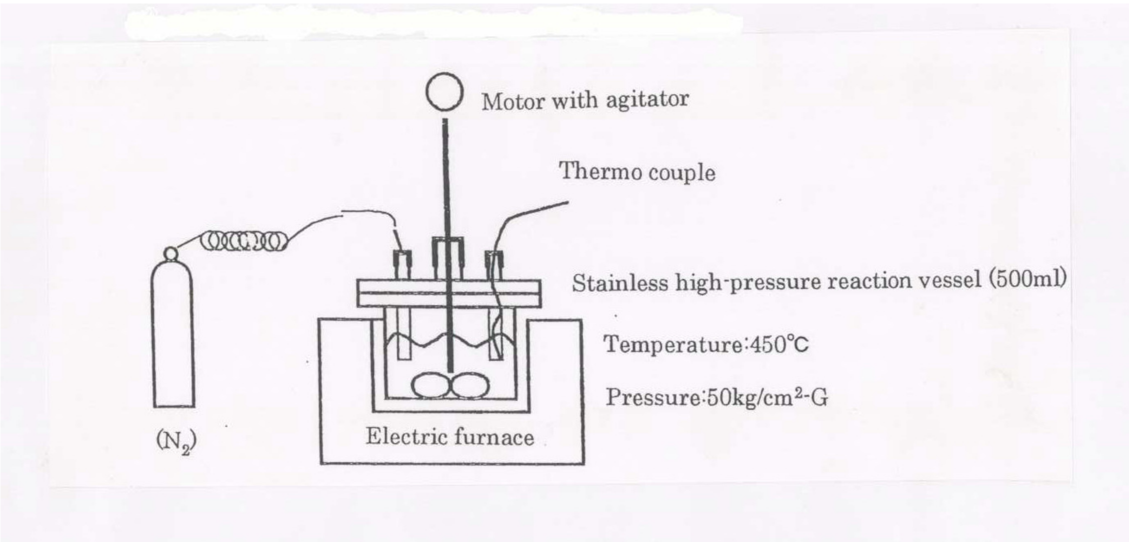

Figure4-9 Liquid Phase Cracking Test Apparatus

Details of test conditions under N_2 gas atmosphere are shown on table 4-3.

Table 4-3 Test Conditions under N_2 Gas Atmosphere

Sample	Solvent	Run No. and Temperature (℃)			
Ngao Powder	Decalin	380	400	-	440
Ngao Grain	Decalin	-	400	-	440
Ngao Powder	LCO	380	-	420	440
Lanna Powder	Decalin	380	-	-	440
Ngao Powder	Tetralin	380	-	420	440
Lanna Powder	Tetralin	-	-	-	440

Solid product, liquid product and gas obtained by the above test were weighed and material balance was confirmed. Each product was analyzed on proximate analysis, ultimate analysis, sulphur and calorific value.

4.4.3. Test Result

The principle of Low-temperature liquid phase cracking process is to obtain mainly solid product by circulating use of tar, which is mainly produced from coal itself and partly supplemented by cheap solvent, for example waste oil from automobiles.

The above test revealed that Ngao coal could be treated in the same way as Japanese coal and Indonesian coal. Therefore, it is expected that solid product equivalent to bituminous coal in quality is obtained by adding a little solvent (e.g. LCO: petroleum-derived oil) at more than 420℃ of reaction temperature.

Analysis data (Form of sulphur) of solid products obtained by liquid phase cracking is shown on Table 4-4.

Total sulfur of feed coal is 7.13 %, pyrite sulfur is 2.43% and organic one is 4.36%. After liquid phase cracking process at 400℃, pyrite is reduced to1.18%. And after that at 440℃, pyrite is reduced to 0.25%. Namely, around 90% of pyrite is reduced at 440℃.

Generally speaking, around 30% of organic sulfur is also decomposed into hydrogen sulphate at this temperature.

As this process is still under development stage, further development activity by NIRE of Japan is requested.

An additional test was conducted as an application of the test in direct coal liquefaction process; namely, reaction under hydrogenation pressure by using tetralin as a solvent. In this case, coal has been almost perfectly converted to liquid product in spite of high sulphur content.

In the test of liquid phase cracking of lump coal, it was recognized that Ngao coal was decomposed into fine powder during heating process. The fact indicates that crushing of feed coal is unnecessary in liquid phase cracking process of Ngao coal, although some means for recovery of circulating solvent must be considered.

Table 4-4 Result of Form of Sulphur

Sample	Total S. (dry basis)	Form of Sulfur (dry basis)			Moisture
Condition (Temp., Solvent)	%	Sulphate S. %	Pyritic S. %	Organic S. %	%
440℃、Dekalin (Ngao)	5.17	0.33	0.25	4.59	16.2
440℃、Dekalin (Lanna)	0.45	0.03	0.05	0.37	8.3
400℃、Dekalin (Ngao)	6.69	0.5	1.18	5.01	20.7
50～25mm －1.3 (Bulk Sample)	7.13	0.35	2.42	4.36	8.8
10～3mm －1.3 (Bulk Sample)	7.55	0.74	2.33	4.48	34.1
25～10mm ＋1.8 (Bulk Sample)	7.74	0.77	5.16	1.81	6.1

4.4.4 Discussion

Technology development of liquid phase cracking is still going on.

NEDOL (Coal Liquefaction process of NEDO) Process may be well applicable technically; but substantial volume coal reserve is needed from economical standpoint.

Further technical development is requested for liquid phase cracking.

4.5. Overall Examination and Evaluation

4.5.1. Examination of Each Process

(1) Conventional Coal Preparation

Screening and float-sink test were conducted on bulk sample. Then on core sample, float-sink test and analysis were conducted. The data obtained are sufficient for the design of coal preparation plant with conventional technology. The facilities will be simplified and the cost will be low. The effect of coal preparation will be relatively large, although substantial improvement on the quality of Ngao coal that is high ash, high sulfur and low calorific value, cannot be expected.

(2) Advanced Technology of Coal Preparation

The test result indicates that the liberation of sulfur and ash by crushing may occur little on Ngao coal. Besides, an additional crushing cost is required for conventional plant facilities. It is suggested that an application of this technology on Ngao coal will not be effective for quality upgrading.

(3) Drying Method

Although drying result was obtained as expected, reduction of sulfur and ash content was hardly recognized in bulk sample. Independent application of this method will not be effective, but combination with dry distillation method or liquid phase cracking method will be considered in the future.

(4) Low Temperature Dry Distillation Method

Improvement of calorific value of solid product was satisfactorily recognized in this process. Sulfur content of the product remained still high in this process, owing to the high sulfur content of bulk sample. There is some drill core sample with less Sulfur content (especially in Area-A) and in general, an application of this method on Ngao coal will be hopeful. Further study will be required on yield and quality of tar and engineering study on process facilities.

(5) Low-Temperature Liquid Phase Cracking Method

This process is applicable to Ngao coal but organic sulfur remains in both of solid and liquid products. Additional process for removing sulfur will be required; for example, hydrogenation process. In the test of hydrogenation, liquefaction reaction of coal occurred along with sulfur removal. An advantage of this method is that concentrated CO_2 gas can be extracted from raw coal.

4.5.2. Overall Evaluation

Judging from the limited study to date, the following three systems are to be considered.

① Combination of conventional preparation and low temperature dry distillation process.
Main product is solid one with high calorific value and reduced sulfur-content.

② Combination of Conventional preparation and liquid phase cracking process
Both of solid and liquid products are produced following the market demand.

③ Conventional preparation only
In this case, only relatively low sulfur coal can be used.

Option ② is not practical because liquid phase cracking process is still under developing.

We recommend to conduct preliminary feasibility study based upon option ①.

Because the present study is mainly based on the test result of bulk sample, further detailed examination on whole available data, including analysis of drill cores, should be carried out. And after selecting appropriate feed coal, final conclusion should be made, from not only technical point of view, but also economical and marketing points of view.

For your reference, a rough cost estimation on upgraded coal is shown on Appendix-9.