regenerative flue gas desulphurization in european oil refineries – cost estimates based on a european application

Prepared by CONCAWE Air Quality Management Group's Special Task Force on Flue Gas Desulphurization Costs(AQ/STF-33)

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ABSTRACT

The OMV refinery at Schwechat, Austria commissioned in 1985 a Wellman-Lord regenerative flue gas desulphurization plant (FGD) to control emissions essentially from the power generating sector of the refinery. This experience is used to estimate costs of Wellman-Lord FGD which would be more representative for other European refineries. Costs are given for the Schwechat size FGD (600 000 Nm^3/h flue gas) and a typical refinery size FGD (150 000 Nm^3/h flue gas). It is concluded that FGD cost-effectivess is better when refineries burn higher sulphur fuels but small plant size has a significant detrimental effect. Wellman-Lord FGD can more than double the cost of liquid refinery fuel.

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SUMMARY

CONCAWE has studied costs of applying regenerative flue gas desulphurization in European refineries based on actual experience from the Wellman-Lord process in one refinery. It has been necessary to relate the situation there to the more general European refinery situation in order to identify cost influencing items. It appears that the actual application has benefitted from a number of favourable aspects such as a large flow of flue gas mainly from fuel oil combustion in a power station, availability of space for retrofitting, spare capacity in relevant process facilities/utilities e.g. sulphur recovery facilities and the ability to burn available high sulphur refinery liquid fuel. In refineries without these advantages capital costs could be 25-30% higher.

The capital costs of Wellman-Lord FGD in refineries largely determine the total annual costs, 75% being due to the capital charge. The results are summarized in the following table:

Capacity (flue gas 1000 Nm^3/h) Liquid fuel burnt (t/d) MW_{th} (approx.)	600 980 (actual capacity) 500		150 245 (typical capacity) 125	
Fuel oil sulphur content (% wt)	2.35	3.75	2.35	3.75
Cost $/t sulphur removed Cost $/t liquid refinery fuel burnt	3300-4200 75-95	2100-2700 75-96	5600-7000 125-157	3500-4400 124-157

The cost-effectiveness of sulphur removal from flue gases is significantly better when 3.75% sulphur fuel is burnt instead of 2.35% sulphur fuel.

A small plant size, more typical of what could be applied in European refineries, has a significant detrimental effect on sulphur removal cost-effectiveness.

When expressing costs per ton liquid refinery fuel, sulphur content has little effect, but plant size has a large effect. The application of Wellman-Lord FGD can more than double the cost of liquid refinery fuel.

1. INTRODUCTION

CONCAWE has reported on cost of flue gas desulphurization (FGD) in refineries in "Cost of control of sulphur dioxide, nitrogen oxides and particulate emissions from large combustion plants in oil refineries" Report No. 7/84 issued September 1984. The costs were based on process licensor's information since there were no FGD plants in operation in European refineries at that time.

In the meantime, OMV's refinery at Schwechat has installed a Wellman-Lord regenerative FGD plant which came into operation mid 1985. The installation and subsequent operating experience has enabled CONCAWE to review its refinery FGD costs based on first-hand data as reported in the following sections. The costs and operation of any FGD plant if installed in European refineries could differ from those specifically at OMV's refinery and due attention has been given to these aspects.

2. APPLICATION OF FGD AT SCHWECHAT REFINERY

2.1 GENERAL

The refinery has a rated capacity of 10 million tons of crude oil per year and as the major refinery in Austria, processes crude oils also for all major importers. All electricity and steam is generated by the refinery from two power plants which usually together generate 70 MW electricity and 600 t/h of steam. The fuel for these power plants is mainly vacuum flashed visbreaker residue which can have a sulphur content between 3 and 6% wt.

In 1983 it was decided to construct a Wellman-Lord regenerative FGD which was designed for 600 000 Nm^3/h flue gas containing 4-7 g SO_2/Nm^3 (with the regenerative section being able to handle maximum 2940 kg SO_2/h) originating from power station No.2 and from some process units. It was recognized and accepted that with the SO_2 handling restriction it would not be able to run the plant continuously at maximum throughput and maximum SO_2 intake. The intention was to meet a refinery SO_2 emission limit of maximum 800 mg SO_2/Nm^3. The desulphurization rate aimed for was greater than 90% and in fact up to 95% normally can be achieved.

After gaining operating experience at flue gas throughputs of about 420 000 Nm^3/h it was decided to link in power station No. 1, with a new flue gas duct line, to take full advantage of the 600 000 Nm^3 capacity of the FGD.

2.2 DESCRIPTION OF PROCESS

The flue gases are routed from various sources to a mix drum where temperature adjustment within the range of 160-180°C can be attained. Thereafter, ammonia is injected to convert SO_3 to ammonium sulphate for acid dew point reasons and in order to minimize sodium sulphate formation in the FGD system. The gas is further treated in two parallel trains. The bulk of the ammonium sulphate together with combustion particulates are removed by an electrostatic precipitator (ESP). The gases are cooled via a gas/gas heat exchanger to 90°C, given a prewash with water to remove remaining solids and then contacted with sodium sulphite - bisulphite solution in an absorption tower (Reference Fig. 1). This removes most of the SO_2 and the clean gas, which is now at 55°C, is reheated by the above-mentioned heat exchanger to about 130°C and routed via a clean gas collector vessel to the stack.

In the regeneration section (Reference Fig. 2), the SO_2 is stripped from the absorber solution and the SO_2 rich gas is conveyed to the Claus unit. The regenerated sulphite solution is pumped back to the absorption section for reuse. Sodium sulphate which is formed in side reactions (mainly influenced by oxygen content of the flue gas) is removed by a separate purge system and processed along with the refinery effluents.

The SO_2 rich gas is partially reduced by hydrogen to hydrogen sulphide in a Redotherm-chamber before disposal to the Claus unit where liquid sulphur is produced (Reference Fig. 3).

2.3 CAPITAL INVESTMENT

The total FGD investment was 780 million Austrian Schillings (ATS) spent essentially in 1984. This included the following items:

- FGD equipment and machinery
- NH_3/caustic soda, storage and feed system
- raw and clean gas collectors
- electrostatic precipitators
- modification to the Claus unit including Redotherm
- H_2 purification plant

In addition, to transport flue gas from power plant No. 1 (see Section 2.1).

- 800 m flue gas duct costing 85 million ATS in 1987

The project was carried out as a turn-key (construct and commission) contract. An indication of the cost breakdown provided by OMV was as follows:

- equipment and machinery	37%
- piping	26%
- electrical equipment	8%
- control equipment	8%
- engineering	12%
- construction	9%
	100%

2.3.1 Land requirement

The area required to build the FGD plant is as follows:

- absorption section	3400 m^2
- regeneration section	1950 m^2
- storage section	1370 m^2
	6720 m^2

The land requirement for liquid sulphur handling is not included, however it is assumed that it will be available in a typical European situation.

2.3.2 Manpower

For normal continuous operation the manpower requirement per shift is:

- for the absorption section 1.25 men
- for the regenerative section 1.5 men

In addition, 20 man hours per week for process analyses are required by the laboratory.

2.3.3 Utilities/materials

Experience at Schwechat refinery has shown that utility and materials consumption is dependent on different parameters such as the amount of sulphur removed, the quantity of flue gas being handled or the size of the plant. The following items are grouped according to dependency.

Dependant only on amount of sulphur removed:

- hydrogen 0.17 t consumed/t sulphur
- 12 bar steam 1 t produced/t sulphur
- LP steam (mainly 1.4 bar waste-heat based)

t/d of sulphur	t steam/t sulphur
10	23
18	20
35	15

- ammonia 40 kg/t sulphur
- solids disposal 180 kg/t sulphur

Dependant only on amount of flue gas:

- electricity	150 000 m^3/h	1100 kW
	400 000 m^3/h	2300 kW
	600 000 m^3/h	3900 kW

Other items are:

- air	700 Nm^3/h
- cooling water	630 m^3/h
- caustic soda (20%)	360 kg/h
- additive (EDTA)	0.6 kg/h
- 12 bar steam for preheating	2 t/h
- raw water	15 m^3/h
- *condensate (sealing water)*	*5 m^3/h*

2.3.4 Operating experience

Some significant problems were encountered at the start, most of which were traced back to choice of construction material and these problems have been satisfactorily solved.

Due to the high flue gas exit temperature of the process furnaces it was difficult to maintain the total raw flue gas temperature in the range 160-180°C before ammonia injection. This difficulty in the first stage, fortunately, was minimized because process heaters could be fired with gas and the flue gas partially bypassed. The overall 800 mg/Nm^3 SO_2 requirement was met by just treating the flue gas from power station No. 2 followed by recombination with the bypassed flue gas.

Some modifications were made to the electrostatic precipitator (ESP) to facilitate solids removal (pneumatic operation). Difficulties with solids removal are still experienced from time to time because they can be of a sticky nature. This problem still requires some additional maintenance effort.

3. DIFFERENCES WITH TYPICAL EUROPEAN REFINERY SITUATIONS

While the costs of FGD as applied at Schwechat refinery can be calculated based on actual experience, their extrapolation to more general European refineries requires consideration of possible differences that could have cost consequences. The following aspects are highlighted.

3.1 CAPACITY

A flue gas capacity of 600 000 Nm^3/h represents about 1100 t/d liquid refinery fuel depending upon its calorific value and amount of excess air. In 1985 the average European refinery was burning 300 t/d liquid fuel, the remainder being gas. The application at Schwechat refinery is therefore large by average European standards. A flue gas capacity of 150 000 Nm^3/h is more representative of what could be applied in a typical size European refinery.

3.2 FUEL SULPHUR CONTENT

Schwechat refinery can produce a very heavy, high sulphur (up to 6%) fuel which means that FGD can be very effectively used. As mentioned in Section 2.1 the regenerative section can handle a maximum of 2.94 t/h of SO_2 which is equivalent to a feed sulphur content of some 3.75% (basis 95% desulphurization) at maximum flue gas capacity of the plant. In 1985, the average sulphur content of liquid fuel being burnt in European refineries was 2.35% wt. However, many European refineries have a significant amount of conversion capacity, which produce heavy fuels with much higher sulphur content. FGD application in European refineries based on liquid fuel with sulphur contents in the range 2.35 - 3.75% wt can be considered as reasonably representative. This translates into 22 t/d and 35 t/d sulphur recovered respectively for the 600 000 Nm^3/h case, and 5.5 t/d and 8.75 t/d sulphur recovered for the 150 000 Nm^3/h case.

3.3 SOURCE OF FLUE GAS

Schwechat refinery produces its own electricity from two power stations which are the main sources of the 600 000 Nm^3/h flue gas. The quantity and temperature of flue gas is therefore relatively stable and only moderate control measures are required. Most European refineries take their electricity from the grid. Their main source of flue gas is therefore from process units which means that quantities, qualities and temperatures are fluctuating.

Therefore consideration must be given to control measures to ensure reliable and safe operation. Such measures could include flue gas cooling facilities and flue gas collection facilities from a number of small stacks. This must be carried out in such a way that interaction between various sources can be controlled in an acceptable manner.

3.4 NUMBER OF STACKS

The operation of FGD at Schwechat refinery is based upon ducting to two separate stacks. The average European refinery has 3.3 stacks above 50 MW_{th}. Therefore the majority of European refineries will require ducting to three stacks. The cost quantification is based on the FGD being positioned close to one stack and larger ducts being provided for the other two stacks. It is assumed that the costs incurred at Schwechat refinery would also be applicable but in specific situations there might be additional costs.

3.5 AVAILABILITY OF BACK-UP FACILITIES

Fig. 4 shows input and output to the FGD plant. In the case of Schwechat refinery, all facilities for handling the various streams and materials were available except NH_3 and caustic storage. Feed supply systems and additional process facilities were required to modify a Claus unit together with hydrogen purification facilities. For European refineries in general, there is a high probability that investment costs would be required for some of the following items:

- production of hydrogen
- production of 400 t/d LP steam
- recovery of additional sulphur
- storage of chemicals
- cooling water facilities.

During a Claus unit shut-down, it is assumed that low sulphur fuel is available or a waiver can be obtained to burn high sulphur fuels without FGD. Therefore, investment in a spare Claus unit has not been considered for this study.

An alternative to hydrogen for the reduction of SO_2 to H_2S could be the use of natural gas which would avoid additional investment for hydrogen. However, this would only be a solution in about 20 % of European refineries because of currently limited access to a natural gas grid.

3.6 SOLID DISPOSAL

Schwechat refinery can dispose of 200-300 kg/h solids (essentially sodium/ammonium sulphates) locally incurring only transport costs. The more typical case is likely to involve long haul transfer from the refinery to a suitable dump with attendant high costs.

3.7 SHUT-DOWN TIME FOR RETROFITTING

Schwechat refinery was able to avoid the special shut-down of plant to install the FGD by maximizing preparation of equipment off-site and using a scheduled maintenance shut-down of the relevant units. Clearly, refineries in general will try to use the same approach. It is assumed that refineries will not incur additional shut-down costs but this could be the consequence where, for example, there is a crowded site with poor unit accessibility. In this case the retrofitting operation would have to be spread over sequential maintenance shut-downs of the various plants.

3.8 LAND REQUIREMENT

The land requirement for FGD at Schwechat refinery was 6700 m^2 of which 3400 m^2 was close to the flue gas collection facilities and in fact was available. It is considered that most refineries also will have sufficient space available and therefore costs for aquiring extra land should not be accounted for.

4. COST METHODOLOGY

The costs of FGD based on the regenerative Wellman-Lord application at Schwechat refinery are built up from the following elements.

Capital costs

Schwechat refinery capital costs are taken as a basis and escalated to mid 1987. An estimate is made of additional capital costs that could be incurred in European refineries based on information given in Section 3 and are reported in Appendix 1.

Capital costs of a 150 000 Nm^3/h plant are estimated by a scaling factor of 0.65 supplied by the process licensor.

Operating costs

- Capital charge is taken as 25% of capital cost in line with CONCAWE's practice. The treatment of capital charge calculations in general is described in CONCAWE Report No. 88/51.

- Fixed and variable operating costs are attributed to:

  - manpower
  - maintenance
  - overheads
  - steam
  - electricity
  - air
  - cooling water
  - caustic soda (NaOH)
  - ammonia (NH_3)
  - additive (EDTA)
  - raw water
  - condensate
  - solid disposal

- Credits result from:

  - sulphur recovered
  - steam produced

The total operating costs including capital charge can be expressed in a number of ways e.g. cost/ton sulphur removed, cost per ton of liquid fuel burnt etc.

The following currency equivalents are applicable to costs in this report, which are based on a mid 1987 European situation:

1 USD = 12.75 ATS = 127 ESP = 1348 ITL = 2 NLG = 0.61 GBP = 0.87 ECU

By December 1987, the USD had devalued to 0.80 ECU.

5. RESULTS

The detailed bases for calculations of the various elements are reported in Appendices 2 and 3.

Participating companies have carried out calculations based on their own cost data. The results obtained are summarized in the following table in terms of the average for each case studied.

Summary of calculated FGD costs

Case	1		2		3		4	
Case description	CAPEX based on OMV site situation(b)		CAPEX taking account of European situation		CAPEX scaled from OMV site situation		CAPEX scaled from European situation	
Sulphur removed t/d	22	35	22	35	5.5	8.75	5.5	8.75
Capacity 1000 Nm^3/h	600		600		150		150	
Liquid fuel burnt t/d(a)	980(c)		980(c)		245(c)		245(c)	
MW (th)(approx.)	500(c)		500(c)		125(c)		125(c)	
Capex $\$10^6$	78		100		32		41	
Capital charge $\$10^6/yr$	19.5		25		8		10.2	
Fixed cost $\$10^6/yr$	4.3		5.3		2.2		2.7	
Variable cost $\$10^6/yr$	2.8	3.3	3.3	4.1	0.7	0.8	0.8	1.0
Sub-Total $\$10^6/yr$	26.6	27.1	33.6	34.6	10.9	11.0	13.7	13.9
Credit $\$10^6/yr$	1.0	1.5	1.0	1.5	0.2	0.4	0.2	0.4
Total $\$10^6/yr$	25.6	25.6	32.6	32.9	10.7	10.6	13.5	13.5
Cost/ton sulphur removed $	3300	2100	4200	2700	5600	3500	7000	4400
Cost/ton liquid fuel burnt $	75	75	95	96	125	124	157	157

Note (a): It has been assumed there are 350 stream days/year
Note (b): Operating costs are based on the average unit cost data reported by participants to the study.
Note (c): The conversion from flue gas quantities is approximate since it is dependent on fuel calorific value and excess air during combustion.

6. CONCLUSIONS

It is clear from the results that capital costs are by far the most important cost item, the capital charge being responsible for some 75% of the total annual costs.

Cases 1 and 2 represent CONCAWE's best estimate of the range of capital costs that could be expected when installing a 600 000 Nm^3/h (approx. 500 MW_{th}) Wellman-Lord FGD plant in a large European refinery.

Case 1 is based upon investment costs at OMV's refinery. Case 2 is a maximum cost case incorporating all cost increasing aspects that could be reasonably expected in a European refinery. In practice it can be expected that capital and total costs would lie between Case 1 and 2 for large refineries.

Cases 3 and 4 represent more typical cases in a smaller refinery or in a larger one where only relatively small amounts of flue gas (150 000 Nm^3/h) are suitable for application of FGD.

The range of fuel sulphur content (2.35 - 3.75% wt) studied can either represent availability of liquid fuel in the refinery or a mixture of high sulphur liquid fuel and refinery gas where segregation of the flue gas is not realistic.

With respect to cost per ton sulphur removed, the high sulphur feedstock cases are more cost-effective than the lower sulphur feedstock cases. This is a clear illustration of the benefit of treating a high sulphur containing flue gas when the aim is maximum sulphur removal at lowest cost. The effect of going to a more realistic small plant scale is dramatic, being 65% less cost-effective.

CONCAWE Report No. 7/84 quotes FGD cost of $2600-4500/t sulphur removed (1984 Netherlands basis 1 USD = 3 NLG) which covers a range of different FGD techniques based on a 2.7% sulphur liquid fuel. The regenerable processes are the most capital intensive and their costs are reflected by the high end of the range. There is therefore good agreement between the cost calculated in the 1984 study and in this study.

With respect to the costs per ton liquid refinery fuel, costs are rather insensitive to sulphur content of fuel but very sensitive to plant capacity. FGD could more than double the cost of liquid refinery fuel in the refinery.

APPENDIX 1 - CAPITAL COST CALCULATIONS

Capital cost FGD Schwechat refinery	780 million ATS	(1984)
- escalated to 1987 (5%/yr)	903 million ATS	(mid 1987)
- plus 2nd ducting	85 million ATS	(mid 1987)
Total	988 million ATS	(mid 1987)
- converted to USD (1$=12.75 ATS)	78 million USD	(mid 1987)

Additional capital cost for a European refinery

An additional (3rd) ducting (Ref. Section 3.4)	7 million $
Flue gas cooling facilities (600 000 Nm^3/h cooled 40°C)	0.6 million $
Flue gas collecting facilities and control system	1.0 million $
Refinery process items	
H_2 unit (10 t/d)	3 million $
Steam generation (400 t/d L.P. steam)	1 million $
Sulphur recovery unit (20 t/d)(99.5% recovery)	9 million $
Cooling water facilities	0.5 million $
Total	22.1 million $

On the basis of this data it was decided to look at two capex levels for 600 000 Nm^3/h capacity viz.

Case 1	As built at Schwechat refinery	78 million $
Case 2	Case 1 plus additional ducting, flue gas handling and refinery process facilities	100 million $

A further two capex levels for 150 000 Nm^3/h capacity were obtained by using a scaling factor of 0.65 to Cases 1 and 2 respectively.

Case 3	Case 1 scaled to 150 000 Nm^3/h	32 million $
Case 4	Case 2 scaled to 150 000 Nm^3/h	41 million $

APPENDIX 2 - OPERATING COST CALCULATIONS

- Fixed operating cost (utilization factors)

Manpower: based on five shifts manpower requirement is 15 man years.

Maintenance: 3% on total capex.

Overheads: 50% manpower and maintenance costs

- Variable operating cost calculations (consumption factors)

Based on sulphur recovered		22 t/d	35 t/d
H_2 consumption t/d		3.74	5.95
Steam consumption t/d			
	LP	418	525
	12 bar	48	48
Electricity	kW h/d	96 000	96 000
Air	Nm^3/d	16 800	16 800
Cooling water	m^3/d	15 120	15 120
NaOH (20%)	kg/d	8 640	8 640
NH_3	kg/d	880	1400
EDTA	kg/d	14.4	14.4
Raw water	m^3/d	360	360
Condensate	m^3/d	120	120
Solid disposal	t/d	3.96	6.3
Steam produced (12 bar)	t/d	22	35

The above consumption figures refer to the 600 000 Nm^3/h flue gas capacity plant. For 150 000 Nm^3/h plant it is assumed that a quarter of the consumptions are applicable.

- Credit items

Two credit items can be identified:

a) sulpur recovered 22 and 35 t/d respectively

b) 12 bar steam produced from Claus unit 22 and 35 t/d respectively

Here again, these quantities refer to 600 000 Nm^3/h flue gas and are assumed to be a quarter for 150 000 Nm^3/h flue gas.

APPENDIX 3 - UNIT COST DATA USED

The following represents the average unit cost data reported by the participants to this study.

Manpower	36 000	\$/man year
Hydrogen (available)	262	\$/t
(new production)	665	\$/t
Steam		
LP	5.8	\$/t
12 bar	6.8	\$/t
Electricity (internal)	0.025	\$/kW h
(import)	0.054	\$/kW h
Air	0.0163	\$/Nm^3
Cooling water	0.02	\$/m^3
NaOH (20%)	0.052	\$/kg
NH_3	0.265	\$/kg
EDTA	1.04	\$/kg
Raw water	0.20	\$/m^3
Condensate	0.75	\$/t
Solid disposal	88	\$/t
Sulphur credit	119	\$/t

Fig. 1 FGD ABSORPTION

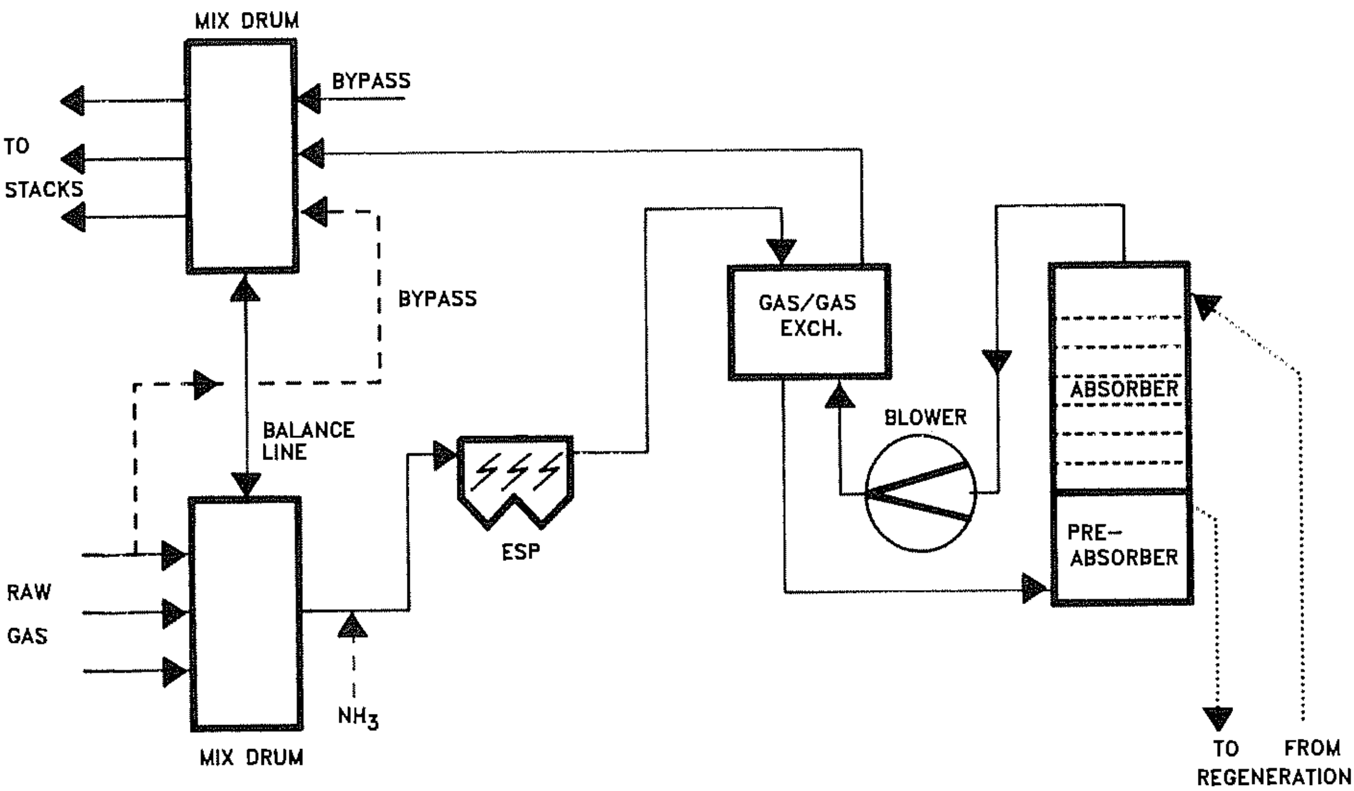

Fig. 2 FGD REGENERATION

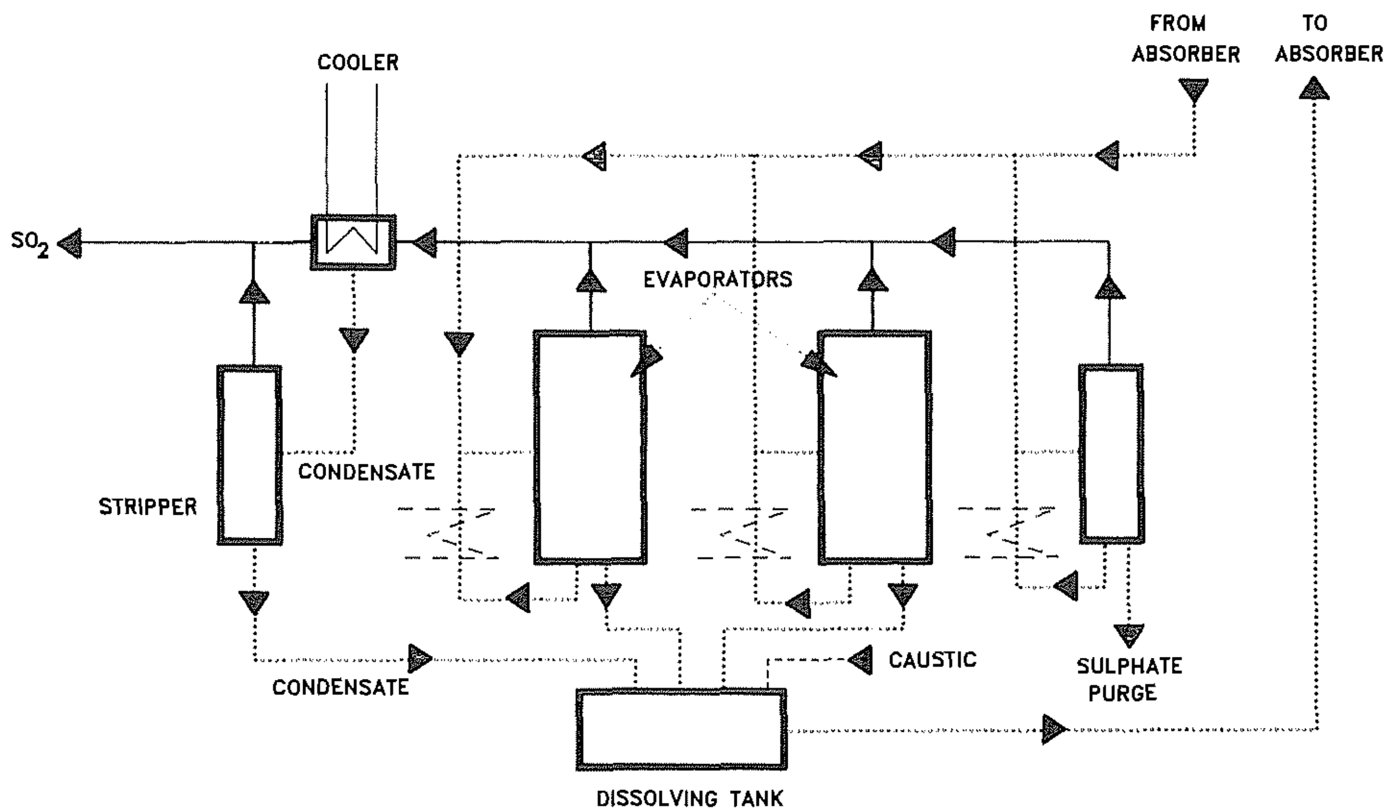

Fig. 3 FGD SO_2 TREATMENT

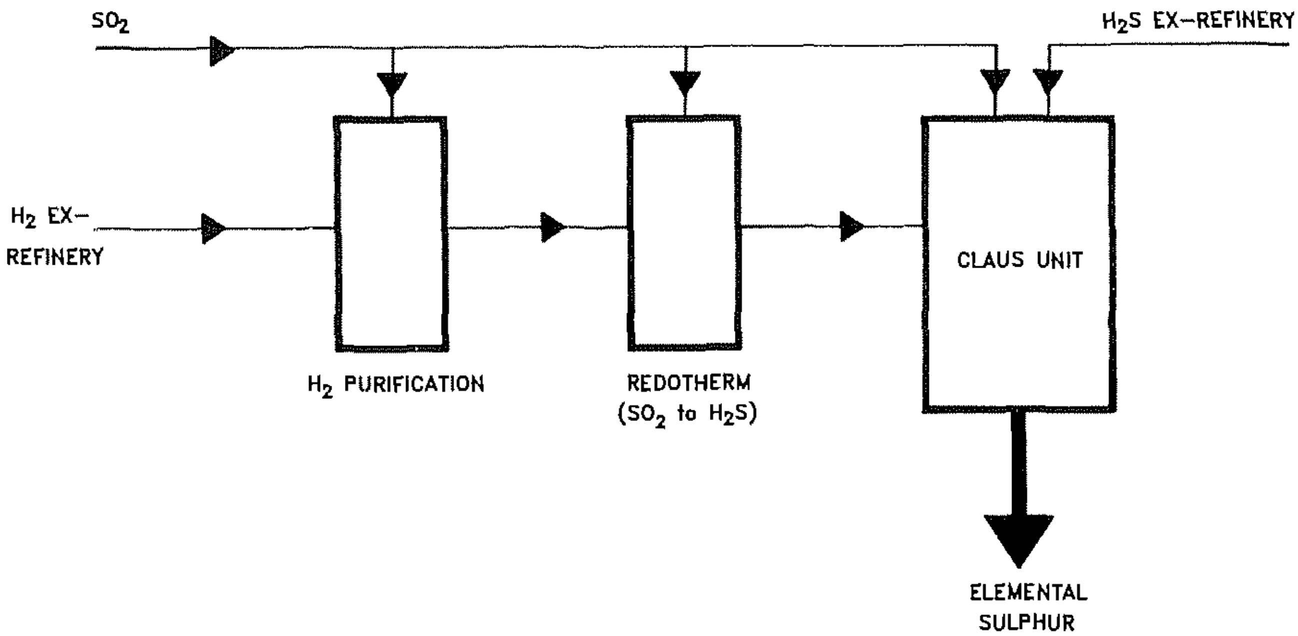

Fig. 4 WELLMAN–LORD PROCESS MASS DIAGRAM