Minimising liquid discharge from large power plants†

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Abstract

Eskom has, over the years, followed a dynamic programme to maximise the use of water at its power stations. With the advent of dry ash disposal and the resultant loss of an effluent sink, an alternative means of reuse and concentration of the cooling-water blowdown had to be found. After extensive on-site testing, electrodialysis reversal (EDR) and tubular reverse osmosis (TRO) emerged as those most likely to succeed. The further volume reduction of the brines would be through the use of evaporators.

The data contained in this paper in no way constitute the final result of this new approach, as improvements in operation and cleaning techniques are constantly being adapted.

Introduction

Water, the lifeblood of the country and its industry, is a resource which needs to be carefully conserved to ensure that adequate supplies are available to support future expansion, development and life itself.

One of the major water quality problems being experienced in South Africa is that of increasing total dissolved solids (TDS) content, a problem which not only increases the cost to industry of utilising water for various processes but in fact also impacts on the costs of controlling all effluent discharges.

In view of the deteriorating water quality, stricter measures are being implemented by the Department of Water Affairs to control high TDS discharges to rivers and streams. These measures are directed firstly at point sources such as industrial and municipal effluents, typically discharges from sewage works, factories and power plants and secondly, from diffuse sources such as seepage from disposal dumps.

Eskom has over the years followed a dynamic programme to maximise the use of water in its power stations and to eliminate the discharge of effluents which are capable of polluting water sources. This approach has led to the application of various water chemistry regimes which have reduced the volume of cooling water blowdown so that specific water consumption on the modern stations has been reduced from 3,2 ℓ/kW.h to around 2,2 ℓ/kW.h.

When Eskom embarked on a programme of dry ash handling, several new challenges were presented to its Chemical Engineering and Chemistry Division. Whereas traditionally the wet ash fields had provided a disposal capacity of 0,6 ℓ/kg ash for the disposal of effluents, the advent of "dry" ashing effectively reduced this capacity to 0,15 ℓ/kg ash.

An alternative means of reuse and concentration of the cooling water blowdown had to be found.

Water management concepts

A brief review is given of the development of Eskom's water management concepts.

If we look back to the pre-1970 era we see that cooling-water treatment consisted originally of blowdown and treatment with sulphuric acid to control carbonate scaling, the blowdown being accommodated by absorption into the ash with any excesses being discharged to waste.

As legislation tightened to reduce pollution, new chemistry regimes were introduced to allow the cycles of concentration of cooling-water systems to be increased, with a resultant reduction of the blowdown which would need to be accommodated in the ash disposal system. As a result, the amount of waste water available for discharge was also reduced significantly.

During this phase the approach consisted of a bypass clarification/lime softening treatment plant combined with minimal sulphuric acid dosing. This allowed cycles of concentration to be increased from around 3 to 20 with a significant reduction in blowdown as can be demonstrated easily.

As an example, for a typical 3 600 MW power plant, assuming 100% load factor and only evaporative losses for convenience:

Blowdown (BD) = Make up (MU) - evaporation (E)

E = (3 600 x 1 000)Wh x 24 h/d x 365 d/a x 1,8 ℓ/Wh
= 56 764,8 x 10^6 ℓ/a

$$MU = E \times \frac{\text{concentration (C)}}{C - 1}$$

For C = 3
MU = 56 764,8 x 10^6 x 3/2
= 85 146 x 10^6 ℓ/a
BD = (85 146 - 56 764) x 10^6 ℓ/a
BD = 28 232 x 10^6 ℓ/a

For C = 20
MU = 56 764,8 x 10^6 x 20/19
BD = (59 751 - 56 764) x 10^6 ℓ/a
BD = 2 987 x 10^6 ℓ/a

As can be seen from these simple calculations this results in almost a tenfold reduction in the amount of cooling-water blowdown to be accommodated, treated or discharged.

Following closely on the more stringent application of water pollution legislation was the change from wet to dry ashing systems at the new power stations, and the requirement for chemical process systems capable of dealing with the cooling-water blowdown which could no longer be absorbed into the ash field. As mentioned previously the effective effluent disposal in ash was reduced from 0,6 ℓ/kg of ash to 0,15 ℓ/kg of ash.

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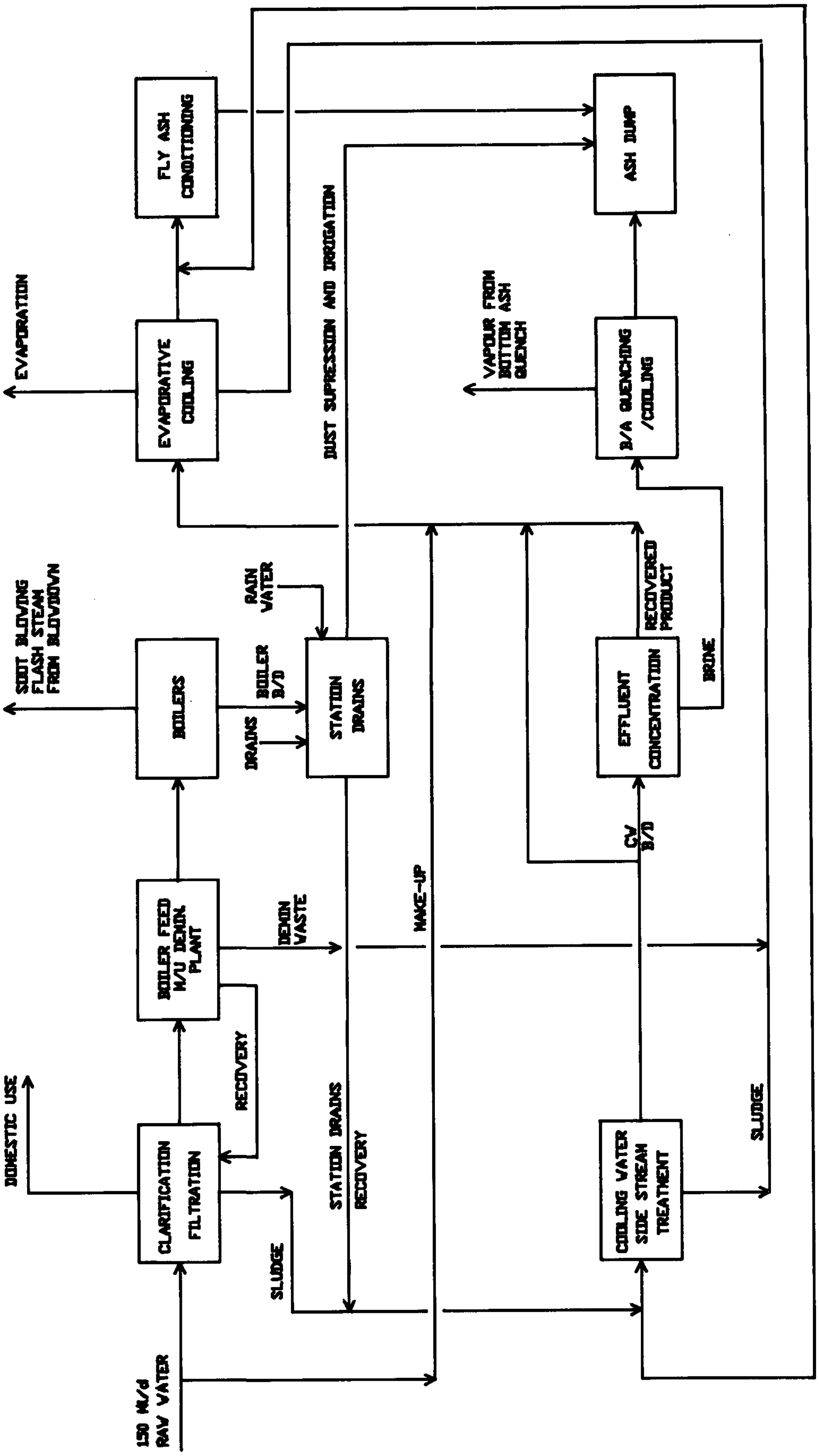

Figure 1
Schematic water management flow diagram for zero liquid discharge

TABLE 1
EFFLUENT DISPOSAL - COMPARISON OF "WET" AND "DRY" ASHING 3 600 MW POWER STATIONS

	"Wet" ashing	"Dry" ashing
Source of effluent		
Cooling water blowdown	8 200	8 200
Clarifier sludge	750	750
Ion exchange regeneration	500	500
Total effluents - m³/d	9 450	9 450
Disposal of effluent		
Combined with ash	4 130	1 020
Return ash water (to clarifiers)	5 320	-
	9 450	1 020
To effluent concentration	-	8 430
Total disposal - m³/d	9 450	9 450

The net result on a typical 3 600 MW power plant was a surplus of up to 9,0 Mℓ/d of total disposable effluent as indicated in Table 1.

Figure 1 is typical of the water management systems developed (Melzer, 1982) to cater for a power station "zero liquid discharge" concept, using a hierarchical cascade system which maximises the reuse potential of water.

Process selections

The selection of processes in this new venture required innovative approaches to the problem and this was addressed by a team comprising representatives from the Chemical Engineering and Chemistry Division, Engineering Investigations Division of Eskom, as well as the Water Research Commission (WRC), together with various suppliers.

In view of the almost total lack of information, both locally and overseas, on the desalination of concentrated open recirculating cooling water, pilot-plant studies were set up to evaluate various membrane systems for the preconcentration (desalination) step.

After extensive on-site testing, the electrodialysis reversal (EDR) and tubular reverse osmosis (TRO) techniques emerged as those most likely to succeed under the tough operating environments to which they would be subjected (Schutte *et al.,* 1987). A decision was also made that the concentrates or brines would be further reduced in volume through the use of evaporative techniques.

The volume reduction, or concentration of the effluents under this development centred around desalination of effluents producing a reusable quality water, then evaporation of the concentrate, again producing a usable product with the brine (concentrate) reduced to a volume which could be accommodated in the dry ashing system.

Figure 2 shows the general concept which was developed.

The EDR process

Following the pilot-plant EDR studies, Eskom prepared a specification for the desalination of blowdown from the evaporative cooling water system of the 3 600 MW Tutuka Power Station near Standerton with the zero liquid discharge concept in mind.

In order to achieve equilibrium in the system the EDR plant had to be capable of removing from the cooling water blowdown a salt load equal to the salt load of the make-up water, minus that removed by the side stream clarifiers.

The EDR plant was to be installed in phases in line with the overall power station commissioning programme and the following typical results were achieved form Phase I shortly after commissioning:

Total feed flow to EDR	4 036 m³/d
Recovered water (86%)	3 471 m³/d
Concentrate to evaporators	565 m³/d
Plant availability	60%

	Feed	Product	Reject
Total dissolved solids (TDS) (g/m³)	2 476	766	13 005
Salt load (kg/d)	9 993	2 645	7 348

Not long after the commissioning of Phase I of this project the Klip Power Station near Meyerton was decommissioned and an additional small EDR plant became available for transfer to Tutuka Power Station in order to increase the treatment capacity.

The initial problems experienced on the EDR plant which contributed to the poor availability comprised the following:

- Failures of the 3-way motor operated valves (MOV).
- Poor control of feed-water treatment resulting in premature fouling of the first stage membranes and increased frequency of downtime for membrane cleaning.
- Electrode failures.
- Inadequate preventative maintenance, especially of the membrane stacks.

The above problems have been addressed extensively and efforts by the power plant personnel have resulted in the availability improving steadily.

- Failures of the 3-way MOVs have been virtually eliminated by application of appropriate maintenance techniques.
- Control of feed-water treatment has been improved, but further modifications will be introduced to upgrade the quality of the feed to the EDR.
- The success of the programmes in restricting cooling-water blowdown has resulted in high levels of salinity in the EDR feed and the resultant high current densities have shortened the electrode lifespan. The introduction of a potable water rinse to the electrode compartment has been successful in increasing electrode life to acceptable levels.
- Correct preventative maintenance in respect of plant components such as the membrane stacks (regular torque adjustment and electrical probing to detect hot spots) has reduced downtime relating to the stacks.

Application of proper cleaning techniques has also enhanced membrane performance.

Plant performance is currently as follows:

Total feed flow to EDR	5 434	m³/d
Recovered water (80%)	4 347	m³/d
Concentrate to evaporators	1 089	m³/d
Plant availability	90%	

	Feed	Product
Total dissolved solids (TDS) g/m³	2 700	940
Salt load (kg/d)	14 670	6 085

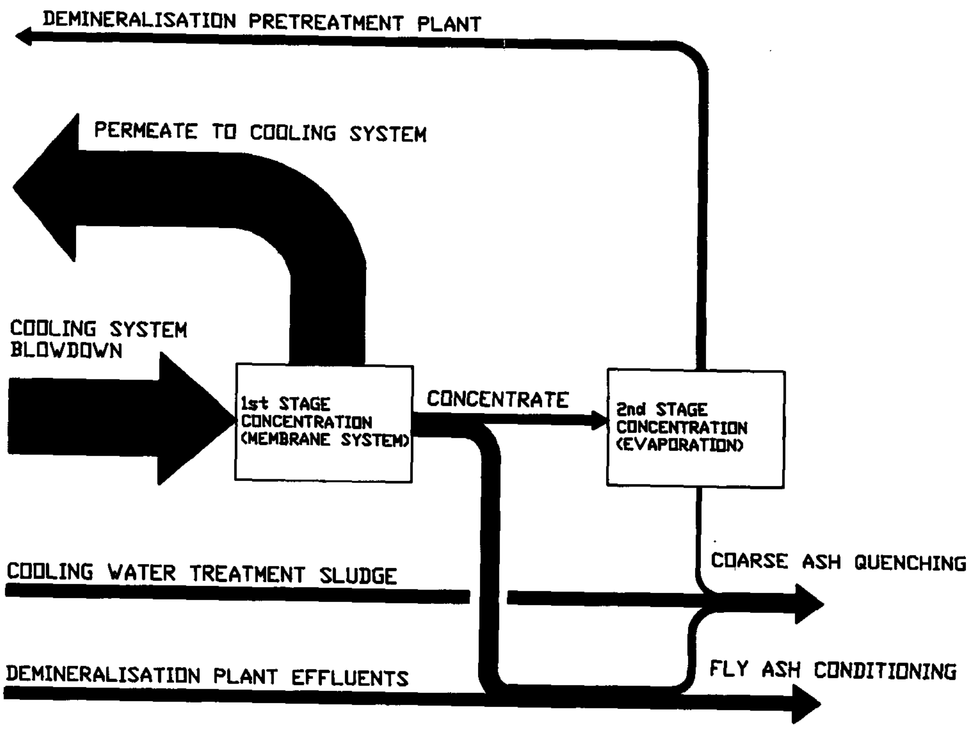

Figure 2
Volume reduction of effluent produced by cooling system blowdown

It is apparent from these figures that the plant availability has been improved significantly and this is a tribute to the efforts of the power plant personnel and the suppliers. The small drop in rejection does not reflect a deterioration but is due to the way the plant is being set up in terms of daily salt removal and effluent concentration requirements.

Tubular reverse osmosis

At about this time local technology had, with funding by the WRC, developed sufficiently to develop a competitively priced tubular reverse osmosis system and it was decided to pilot-test this concept under similar conditions to the EDR plant in order to collect comparative data.

On the basis of a successful pilot-plant test programme Eskom prepared specifications for the desalination of blowdown from the 3 600 MW Lethabo Power Station (near Vereeniging) evaporative cooling water system based on the zero liquid discharge philosophy which, because of the environmentally sensitive siting, was considered essential.

The hydraulic capacity of the TRO plant is 9 000 m^3/d and the only real pretreatment applied is acidification and supplementary cooling, making this plant unique in the field of reverse osmosis where traditionally stringent pretreatment is practised to prevent membrane fouling. The TRO plant is split into three sections, each with its own high pressure feedwater supply pump and membranes contained in racks of 576 modules each. Each section is able to operate independently and contains 3 racks, giving a total of 1 728 membrane modules per section or 5 184 modules for the entire plant. Each membrane module contains 19 membrane tubes, a total of 98 496 tubes.

Early operating results for the plant were:

	Feed	Product	Reject
Feed flow m^3/h	375	263	112
TDS g/m^3	1 300	181	
Salt rejection	86%		
Water recovery	70%		
Plant availability (overall)	60%		
Plant availability (sectionalised)	80%		

Since commissioning the plant and the early operating results reported above, the TRO plant has shown a steady decline in performance and the following is typical of current performance data:

	Feed	Product
TDS g/m^3	2 010	740
Salt rejection	63%	
Water recovery	70%	
Plant availability (overall)	45%	
Plant availability (sectionalised)	60%	

Problems which have contributed to the declining performance of the TRO plant are:

- Plugging of the coarse 200-micron feed-water screens, due to carry-over of ash particles into the cooling water circuit.
- Difficulties which are experienced in controlling the feed-water acid dosing system and poor acid distribution, resulting in probable membrane hydrolysis contributing to the decline in salt rejection capability.

- Problems with the programmable logic controller (PLC) and the adjustment of the recovery rate which has resulted in recovery rates of 90% or more, leading to calcium sulphate scaling on membranes in some areas of the plant.
- Civil modification due to instability of the terrain.
- Membrane failures which include weld line failures and hydrolysis of membrane due to inadequate pH control and scaling conditions. Membrane fouling due to problems associated with the design of the sponge ball cleaning systems.
- Frequent stop/start operations which in turn promote mechanical failures.
- High pressure (HP) pump failures and the lengthy repair periods for these custom-built pumps.
- Lack of adequate isolation facilities on the membrane rows which means entire plant shutdown to repair leaks or replace membrane modules.

Action plans have been developed to address the problems and improve availability and performance.

- New 200-micron screens with automatic cleaning facilities are to be installed.
- Modifications to improve feedwater pH control are being implemented.
- The PLC problems are being addressed by relevant experts.
- Membrane fouling will be reduced by the introduction of an automatic sponge ball loading device and by recommissioning the sponge ball cleaning system.
- HP pumps have been suitably maintained and will present less of a problem in the future.
- A row isolation facility is to be introduced which will allow isolations for mechanical repairs and membrane module replacements without the need to stop the plant. The reduction in stop/start operations will certainly reduce the number of mechanical failures and leaks being experienced and will allow for adequate membrane flushing to be carried out at shutdown which will help to reduce membrane fouling.

This plant has also achieved its purpose in assisting Eskom in its efforts to prevent water pollution.

It is anticipated that after addressing the problem areas mentioned above the plant will render improved and consistent results. We believe this system was the correct choice for the particular circumstances and the commitment is now in place to achieve the required results.

Evaporators

At both the above-mentioned power stations the brine from the membrane systems is transferred to an evaporation plant for secondary concentration and volume reduction. The product water can be routed either to the demineralising plant for purification to boiler feed-water standard, or to the cooling-water system. The latter is normally selected with the brine being absorbed in the boiler ash.

Each of these plants consists of two low-temperature horizontal tube falling film evaporators with the following design specifications:

Feed capacity per unit	25 m^3/h
Product capacity per unit	23,5 m^3/h
Brine capacity per unit	0,5 to 1,5 m^3/h
Feed TDS	350 g/m^3
Product TDS	1 g/m^3
Brine TDS	84 000 g/m^3

Initially these units proved to have poor availability, 20% overall, due to the following:

- compressor vibrations and damaged compressor blades;
- internal nozzle erosion;
- internal epoxy coating failure;
- demister blockages; and
- extensive tube scaling due to fluctuating feed quality.

The compressor problems have been resolved by applying appropriate cold start-up procedures and replacement of defective components.

The level of suspended solids in the body water has been reduced and has resulted in a lower rate of erosion.

Internal epoxy coatings have been renewed and the position of the demisters was changed so that they are closer to the body water surface. In addition the feed water is now introduced into the evaporator to provide a continuous washing of the demisters.

With a more consistent quality feed water being available as the power station commissioning has progressed, scaling is less of a problem than before. However, scaling does still occur and is the single most significant contributor to downtime.

New operating and chemistry regimes are being evaluated to improve this situation still further. Current availability of this plant is 50% overall for the plant or 90% for any one unit.

Costs

The comparison of costs between one system and another is always open to manipulation and is subject to the prevailing prices of the construction materials involved, as well as to factors such as the unstable foreign exchange rates, and differences in the quality of the feed waters.

The following costs are therefore given as a guide only, based on 13 Mℓ/d plant capacity and on arbitrary 80% plant availability.

TABLE 2
COMPARISON OF POWER STATION COOLING WATER DESALINATION COSTS

	TRO	EDR
Capital	R14 300 000	R19 500 000
Operating and maintenance	R 2 686 040/a	R 2 033 000/a
Unit cost (30 years life cycle)	R 391/Mℓ	R 372/Mℓ

Conclusions

The application of these concepts and processes at Eskom was a new approach and therefore problems had to be expected.

Primarily the problems which have occurred have resulted in extended downtime of the desalination systems at both sites. Nevertheless, both systems have proved of value in coping with the excess effluents which are generated on site, particularly during commissioning of the power generating units.

The major benefits of these systems can be seen firstly in that they eliminate point source pollution to public streams, and secondly that they allow the reuse of a scarce and diminishing resource.

Despite the problems which have cropped up we believe the selected processes are viable and we will continue our efforts to enhance and improve the availability of these plants to achieve Eskom's objectives.

Acknowledgement

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References

MELZER, J (1982) Water and effluent scheme for zero liquid discharge. Internal Eskom report.

SCHUTTE, CF, SPENCER, T, ASPDEN, JD and HANEKOM, D (1987) Desalination and reuse of power plant effluents: From pilot plant to full-scale application. *Desalination* Volume **IV** 255-269.

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