MATERIALS ISSUES IN BUBBLING PFBC SYSTEMS

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ABSTRACT

In recent years, considerable experience and insight regarding the behavior of materials and components in the bubbling pressurized fluidized-bed combustion (PFBC) of coal has been developed, largely as a result of the operation of a fleet of 80-MW(e) PFBC-based power plants installed by ABB Carbon. The first plant went into operation over 10 years ago and it appeared timely to review this practical experience and to document areas where improvements have been made, or can be suggested.

In keeping with general bubbling-bed experience, the in-bed heat exchanger and water-wall tubes experienced metal loss. Other plant areas that experienced difficulties were the hot-gas cyclone system, the gas-turbine expander, and some balance-of-plant items including solids-handling equipment, valving, and expansion joints. The captured dust removal lines from the cyclones sometimes plugged sending high dust loadings over to the turbine expander. Consequently the turbine blades experienced material deposition and significant erosion damage. Concerns about turbine longevity in this application have led to attempts to develop high-temperature filter systems that protect the turbine by removing all the dust from the flue gas prior to expansion. These filters have themselves suffered from a range of materials problems, which is not unexpected for a relatively new technology. The current experience of these and other materials issues is reviewed.

INTRODUCTION

Pressurized, fluidized-bed combustion is a coal-based combined-cycle technology where both steam and gas turbines are used to generate power. The high-temperature, pressurized flue gas is expanded through a gas turbine, taking advantage of the more efficient Brayton cycle and raising overall generating efficiency. Steam for the Rankine cycle is raised and superheated in the fluidized bed, and an economizer circuit recovers some energy from the hot gas discharged from the gas turbine. To maintain flue gas temperature and maximize power generation by the gas turbine, no heat is removed from the flue gas after it leaves the surface of the bed.

The first PFBC pilot plant, rated at 3.5 MW(t), was at the Coal Utilization Research Laboratory (CURL) at Leatherhead, in England. Some of the early testing there was supported by Stal Laval who later built their own pilot plant, rated at 15 MW(t), at Malmö in Sweden. Work with this unit led eventually to the successful commercial PFBCs constructed by what later became ABB Carbon. The General Electric Company (GE) constructed a demonstration unit in Malta, New York that was essentially similar to the CURL unit. Following the CURL demonstration, an International Energy Agency (IEA) consortium involving the US, West Germany, and the UK governments built a large pilot-scale PFBC, rated at 45-60 MW(t), at Grimethorpe in England. Most of the detailed publicly-available information on materials issues in PFBCs was developed at Grimethorpe and, in particular, the first large hot gas particle filtration unit was installed there with EPRI support. In addition, EPRI supported GE to install a cascade of specimens resembling combustion turbine airfoils. A number of papers and reports describing the experience has been published(1,2).

Work on the Grimethorpe PFBC plant continued after the completion of the IEA program, supported by UK industry and led by the British Coal Corporation (BCC) and the Central Electricity Generating Board (CEGB). Most of the results from this work were classified, and have not been released. However, EPRI continued the hot gas filtration work, and this is in the public domain(3,4). The BCC and CEGB work led to the development of the Topping Cycle(5), which left only ABB Carbon to pioneer the commercial introduction of bubbling PFBC. The first commercial plant was based on the P-200 PFBC module, and is sited at the Värtan station of Stockholm Energi AB, in Sweden (now owned by Birka Vaerme AB, a Finnish company). Värtan consists of two P-200

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modules (including two GT-35P gas turbines) producing 135 MW(e) and 225 MW(t) for district heating. Coal was first fired in January, 1990.

The next plants, started up shortly after Värtan, were at the Tidd station of the Ohio Power Co. [a subsidiary of American Electric Power (AEP)] at Brilliant, Ohio, and at the Escatròn station of the Empressa Nacionale Electricidad S.A., (ENDESA), at Zaragoza, Spain. Each employed a single P-200 module to generate 75 MW(e), Two other plants based on a single P-200 module are at the Wakamatsu station, in Kita-Kyushu, Japan, and at the Cottbus station of ESSAG, in Germany(6). ABB Carbon also developed a larger (360 MW(e)) PFBC plant, the P-800, with over four times the power output of the P-200. The first P-800 plant was supplied to the Karita station of Kyushu Electric Power Company(7) and started up in 1999, entering commercial service in July 2001. This plant also includes supercritical steam conditions.

There are two other PFBC plants built by other companies and both are in Japan: the 85 MW(e) Tomatouatsuma Unit No. 3 built for Hokkaido Electric Power Company, Inc. by Mitsubishi Heavy Industries (MHI), which uses a ceramic filter(8), and Chugoku Electric Power Company's 250-MW(e) Ohsaki Plant from Hitachi. Following the successful operation of the Tomatouatsuma PFBC, MHI designed a 350 MW(e) plant intended to have a thermal efficiency of approximately 42 percent (higher heating value, HHV), using a subcritical steam cycle. This plant features dry coal-feeding, and a hot gas clean-up train consisting of a cyclone followed by a ceramic filter. Other manufacturers, for instance Foster-Wheeler/Ahlstom(9) and Deutsche Babcock(10) operated pilot plants and developed plans for full-scale circulating PFBC power systems but no such plants have been constructed. Table I lists some of the pertinent features of all the commercial PFBC plants constructed.

Table I. Summary Descriptions of PFBC Power Plants

		Värtan	**Tidd**	**Escatròn**	**Wakamatsu**	**Cottbus**	**Tomatou-atsuma**	**Ohsaki**	**Karita**
Plant type		ABB 2xP200, CHP*	ABB 1 xP200, condensing	ABB 1 xP200, condensing	ABB 1 xP200, condensing	ABB 1xP200, CHP	MHI	Hitachi	ABB 1 xP800, condensing
Start up		1989	1991	1991	1994	1998	1998	1999	1999
Gas turbine		2xGT35P	1 xGT35P	1 xGT35P	1 xGT35P	1xGT35P	MW-151P	GE F7EA (mod)	1 xGT140P
Gas clean up		cyclones (2 stages)	cyclones (2 stages)	cyclones (2 stages)	cyclone + ceramic filter	cyclones (2 stages)	cyclone + MHI ceramic filter	cyclones (2 stages)	cyclones (2 stages)
Bed T, °C		860	860	860	860	840	870	865	870
Steam T, °C		530	496	513	593/593	537/537	566/538	571/596	570/595
Steam P, bar		137	90	94	103	142	166	167	241
Fuel feed		paste	paste	dry pneumatic	paste	dry	dry	paste	paste
Output	MWe	135	70	79.5	71	74	85	250	360
	MWt	244	0	0	0	40/220**	0	0	0
Net efficiency, %, HHV (except Värtan)		89 (Lower Heating Value)	35 (existing steam turbine)	36.4 (existing steam turbine)	37.5 (existing steam turbine)	NA	41.2	>41.5	≈42

*CHP: combined heat and power

**220 MW(t) when using two gas-fired peak load boilers

GENERAL BACKGROUND

The key components of a PFBC plant are the pressurized fluidized-bed boiler, which is used to generate and superheat steam for expansion in a steam turbine, and the specially-modified gas turbine. The arrangement of an ABB Carbon P-200 PFBC power plant is shown schematically in Fig. 1. The combustor, ash cooler, bed ash storage vessels, and cyclones are housed in a pressure vessel which has penetrations for the coal/sorbent feed and ash removal, and feed water inlet and steam outlet. Input of pressurizing/fluidizing air from the turbine and outlet of hot flue gas to the cyclones are accomplished through a concentric pipe. The hot flue gas passes down the central pipe, the walls of which are kept cool by the lower temperature compressed air, thereby avoiding the need for a refractory-lined pipe. There are seven parallel cyclone trains, each train consisting of two cyclones in series. The primary cyclone normally collects 98 percent of the ash and the secondary cyclone removes approximately 25 percent of the remainder. The combined cyclone collection

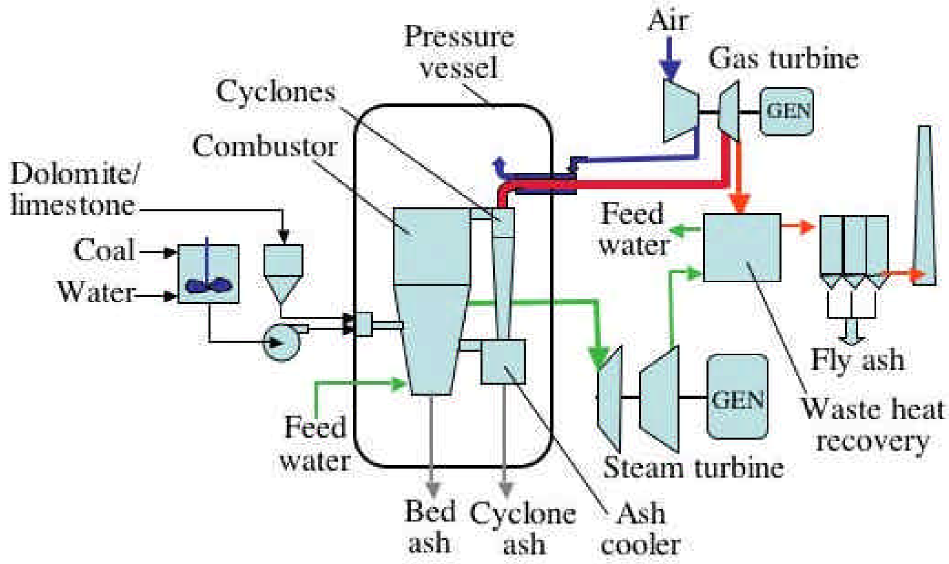


Figure 1. Schematic diagram of a PFBC power plant

efficiency of approximately 98.5 percent results in a dust loading in the flue gas passing to the gas turbine of 300 to 400 ppmw. Following the hot clean-up system, the gas is expanded through the gas turbine, passes through a waste-heat recovery boiler, and is exhausted to the atmosphere via a fine particulate removal system such as an electrostatic precipitator to reduce particulate emissions to the environmentally-required limit of 9 kg/h. The gas turbine drives a compressor that provides the pressurizing and combustion/fluidizing air, as well as an electricity generator.

The equipment inside the ABB Carbon pressure vessel can be arranged in different ways that can greatly affect the dimensions of the vessel. For the Värtan, Escatròn, and Tidd P-200 units, the cyclones and two bed ash storage vessels were placed to the side of the combustor. This required a pressure vessel 20 m tall with an outer diameter of 13.6 m. The later P-200 units, Wakamatsu and Cottbus, use a 'tower' design that places the cyclones and bed ash storage vessels above the combustor, resulting in a taller vessel with a smaller diameter. This pressure vessel is 29.6 m tall with an outer diameter of 11 m, and it can be produced at a lower cost than the Värtan-style design.

Table II lists the characteristics of the coals used at the various PFBC plants. The coal burned at Värtan typically has a low sulfur content (1 percent), and Swedish dolomite or limestone is used as the sorbent. A Pittsburgh No. 8 coal (3.5 percent sulfur) was burned at Tidd. Wakamatsu burned a range of coals. In contrast to the high-quality coals burned at Värtan, Tidd, and Wakamatsu, the Escatròn station is fired by low-rank, sub-bituminous (black lignite) local Spanish coal. The Cottbus plant was designed to burn a local brown coal. Coal is fed to the PFBC in the form of a coal-water paste containing nominally 25 percent by weight of water. The coal and limestone feed are crushed in roll crushers (note: at Tidd the sorbent was crushed in a separate hammer mill) to a size less than 6 mm and is then screened. For low-sulfur coal the crushed coal is mixed with fine (-250 micron) limestone in a water-paste mixer to give a Ca/S molar ratio of 1.8. This mixture is drawn into six hydraulically-driven piston pumps, each of which supplies an individual fuel nozzle located at the base of the combustor. For higher-sulfur coal, as at Tidd, the sorbent was fed through a lock-hopper system, because to make the paste with the additional sorbent necessary for the high-sulfur coal also required additional water and this imposed too high an efficiency penalty. For ease of pumping, AEP reported that at least 20 percent of the coal must be crushed to less than 45 microns.

Use of low-rank (high-ash content) coals at the Escatròn and Cottbus plants required changes to be made in the design and operation of the PFBC to incorporate a dry feed system. In the dry coal-feed system, the ground coal and limestone are fed into the pressurized combustor by means of an injection tower, in which the pressure is raised from atmospheric to injection pressure in three stages of vessels. The fuel is pneumatically transported from the third vessel into the boiler through six injection lines by air taken from the combustor, with its pressure increased by a booster compressor.

Table II. Characteristics of Coals Burned

Coal Source	Värtan	Tidd	Escatròn		Wakamatsu	Cottbus
	Bituminous	Bituminous	Black Lignite		Bituminous	Brown Coal (sewage sludge)
			Typical	Range		
Sulfur sorbent	dolomite	dolomite	limestone		limestone	limestone
Heating Value, MJ/kg, LHV	24 to 29	23.3 to 28.5	12.34	8.5 to 19.0*	24.4 to 29*	19.0
Moisture, %	6 to 15	5 to 15	18.6	14 to 20	8 to 26	18.5
Ash, %	8 to 21	12 to 20	36.1	23 to 47	2 to 18	5 to 6
Sulfur, %	0.1 to .5	3.4 to 4.0	6.8	3 to 9	0.3 to 1.2	<0.8
Volatile matter, %	27		24.5	18 to 28		41
Fixed carbon, %	56		28.51	17 to 37		34.5

*HHV

As indicated in Table 1, the typical bed temperature is around 850°C, a temperature selected to minimize the release of alkali vapor into the flue gas. Any vapor present as the gas expands and cools through the gas turbine will result in alkali deposition causing fouling of the internals. Alkali salts can also penetrate the protective oxide coating on the blades exposing the substrate to attack by sulfur and causing premature failure. The operating pressure is around 13 bar, and is determined by the compressor characteristics. Steam is raised and superheated by the water-wall structure of the furnace and the in-bed tubes suspended within the fluidized bed. The boiler is a once-through, Benson-type so there is no steam drum, but the remainder of the circuit uses conventional Rankine cycle equipment. As is seen from Table I, sub-critical and supercritical steam conditions including reheat have been employed with the later units. In two cases (Värtan and Cottbus) steam is also used for district heating.

The gas turbine used in the P-200 PFBC modules is ABB’s Model GT-35P, which is a two-shaft, intercooled modification of an existing ABB gas turbine. This engine has a four-stage, constant-speed high-pressure turbine that drives a high-pressure compressor and the generator. The free-wheeling, one-stage low-pressure turbine drives a low-pressure compressor. Variable guide vanes before the low-pressure turbine control the low-pressure turbine/compressor shaft speed, and thus the air flow and the PFBC plant output. The air flow is controllable from 40 to 100 percent, which is a much larger range than can be achieved with single shaft, constant-speed gas turbines. The variable-speed low-pressure rotor arrangement also provides for improved part load efficiency of the PFBC. The turbine sections of this machine were ‘ruggedized’ to allow operation with coal ash. This involved increasing the number of rows of high-pressure blades to reduce the loading per row, increasing the use of reaction airfoil shapes to reduce the impingement angle of the dust onto the blades, making the blades thicker, and using of blade coatings to improve erosion resistance.

To reduce load, the inlet guide vanes are closed and the air flow and delivery pressure are reduced. As less air is introduced, the coal flow rate also falls and, as the fully immersed in-bed tubes remove the same amount of heat, the bed temperature will tend to fall. To avoid this, hot bed material is removed and placed in two bed ash storage vessels contained within the pressure vessel. As bed level falls and in-bed tubes are exposed, less heat is removed from the bed while bed temperature is maintained. However, less steam is raised and steam power output falls. The in-bed tubes exposed by the lower bed level start to cool the flue gas, and this reduces the turbine inlet temperature, reducing power output further. In the case of a plant trip, the safe shutdown of the boiler requires that the delivery of combustion air be stopped immediately. This is achieved by means of an intercept valve that is programmed to open upon a plant trip and deliver air from the compressor directly to the turbine, thereby bypassing the combustor.

Little is known about the modifications made to the GE F7EA gas turbine used in the Ohsaki PFBC, except that the thickness of the first stage vanes and blades was increased, and their profiles modified[11]. The Tomatouatsuma plant uses a single-shaft MHI MW-151P gas turbine that has a 19-stage compressor and a 3-stage turbine[12]. An adjustable vane is used before the 5th stage of the compressor to improve efficiency at low load. The turbine blades received unspecified corrosion-and wear-resistant coatings. No information was available at the time of writing on experience with this turbine. At this plant, the hot gas cleanup system is sited outside the pressure vessel, which is 13.5 m in diameter and 20 m high. The fluidized-bed container is essentially a tightly-welded boiler of membrane wall construction based on a once-through design, and is constructed of BS-1501 (part 2) steel, with a 50 mm-thick wall.

The ABB Carbon P-800 module design at Karita includes a 75 MW(e) gas turbine (Model GT-140P), which is a scale-up of the GT-35P design[7]. Also, supercritical steam conditions are employed (see Table I). The pressure vessel is a 'tower' design with an outer diameter of approximately 15 m and a height of approximately 45 m. The fluidized-bed enclosure is hexagonal to occupy more of the vessel cross-section and permit a further reduction in the diameter of the pressure vessel. A dry ammonia selective catalytic reduction-type NO_x control system is used on the gas turbine outlet to maintain the NO_x emissions below 60 ppmv.

SUMMARY OF EXPERIENCE

Some of the inevitable problems experienced during the start-up phases of this new technology were reported by Almqvist[13], Anderson and Jansson[14], Dahl[15], and Alsparr[16] for the Värtan plant; for the Tidd plant by Marrocco et al.,[17], Hafer, et al.[18], and in the Clean Coal Technology Demonstration Program Project Performance Summary[4]; and for the Escatròn plant by Menendes and Mateo[19]. Jansson and Ostman[20] summarized some of the experience of materials and component performance in the first 75,000 hours of operation of all the ABB Carbon plants. Information on the other Japanese plants was published by Shimizu and Horiuchi[11], for the Osaki plant; Kubota[12], for the Tomatouatsuma plant; and Matsuo[21], for Karita. This narrative draws on these published reports, supplemented by direct observations made during the final inspection of Tidd by two of the authors (JS and JMW).

<u>Solids Handling Equipment</u>

Fuel Preparation and Delivery

In the early stages of operation at both Värtan and Tidd, problems were experienced due to overbed combustion, which appeared to have been related to gas channeling in the bed. Plumes of volatiles together with unburned carbon particles were carried into the freeboard and to the cyclone inlets where they combusted, generating excessively high temperatures in those locations. Channeling of the gas flow also resulted in burning volatiles and carbon particles being directed preferentially into specific cyclones. One consequence of these high temperatures may have been the cracking of the ceramic liners in the ash removal legs (discussed later), as well as sintering of fly ash collected in the cyclones. These post-bed combustion problems were traced to very localized release of coal volatiles and fine char near the fuel discharge nozzles. As a measure to disperse these plumes, V-shaped deflectors ('skateboards') were installed above the fuel nozzles to better distribute the entering coal slurry, as shown in Fig. 2. Installation of additional air distribution nozzles to increase the local fluidizing velocity in front of the coal nozzle further enhanced dispersion. These nozzles were also lengthened to limit the potential for the coal slurry to move downwards and adhere to the floor of the combustor.

At both Värtan and Tidd, some problems were experienced with plugging and slipping of coal between the coal preparation rollers when there was a significant change in the surface moisture of the coal. This problem resulted in a period of reduced capacity at Värtan, and in difficulties in producing the required coal size at Tidd. The minus 45 micron fraction varied from 12 to 15 percent, which required the moisture content of the paste to be increased to facilitate pumping which, in turn, adversely affected combustion performance. Modifications to the crusher at Tidd, including installation of larger drives, grooves on the roller surface, and the use of several different control modes were unsuccessful. Adding a recycle loop that allowed up to 100 percent of the feed coal to be fed through the crusher a second time finally solved the problem. At Värtan, the fuel paste delivery system has subsequently performed very well with no plugging of the pipework.

Rapid corrosion of carbon steel surfaces in contact with the fuel paste was experienced at Tidd, with significant corrosion damage to the coal paste mixer and coal paste pumps. The pH of the paste was found to be as low as 3, and this arose because of the high sulfur content of the coal. The remedy eventually adopted was to replace the carbon steel with austenitic stainless steel.

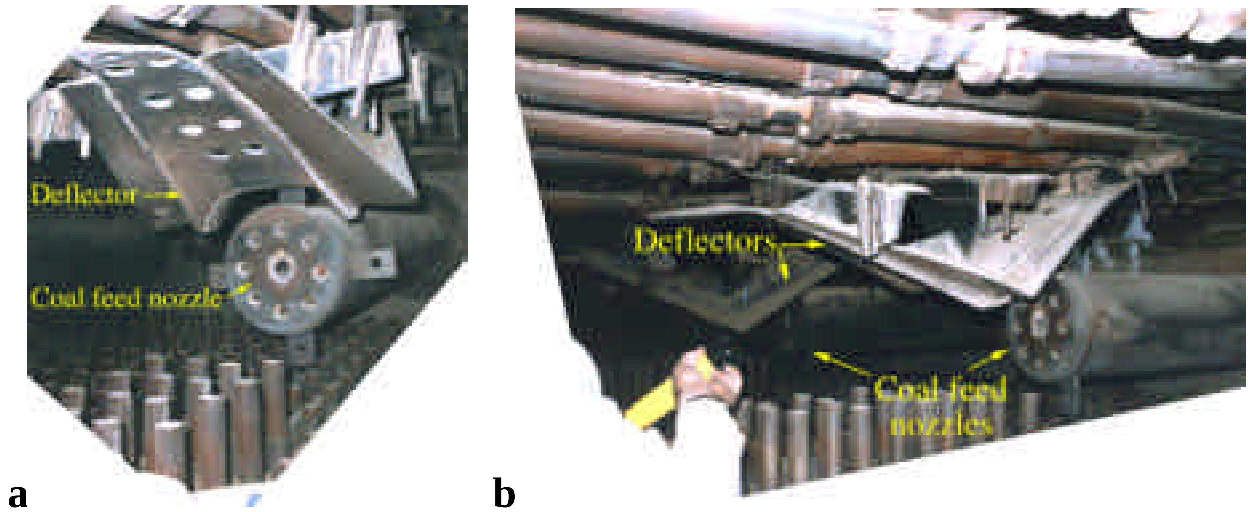


Figure 2. A ‘skateboard’ deflector above a coal feed nozzle at Tidd, and the added air nozzles.

Sorbent Injection System

Numerous operating difficulties were experienced with the sorbent injection system at Tidd, which were related to malfunction of the valve and rotary feeder, and to wear. Erosion of the sorbent transport piping also occurred. These problems were overcome through various materials changes and equipment replacement.

Deposits were found on the in-bed tube bundle above the two sorbent injection nozzles, and above adjacent coal nozzles. These deposits appeared to be agglomerated bed material and very fine sorbent particles, with no evidence of fusion. Such deposits were eliminated by shortening the sorbent injection nozzles to change the point of sorbent admission into the bed, and by slightly increasing the sorbent injection velocity.

Dry Coal Feed System

At Escatròn, frequent incidents in the fuel preparation and injection systems that had been modified to handle black lignite forced load reductions or shutdowns. Problems occurred mainly in the fuel injection system, especially after a plant trip. The fly ash loading was higher than in the paste-fed units, with 65 percent of the ash produced in the combustor entering the fly ash stream, the remainder being bed ash. As in the Värtan and Tidd plants, the fly ash is removed from the flue gas by passage through two stages of cyclones. However, the increased fly ash loading at Escatròn led to difficulties in operating the cyclones, and required the addition of external ash coolers using boiler feed water to supplement the compressed air-cooled ash coolers located inside the pressure vessel. To better handle the high dust carry over rate, Escatròn was provided with nine sets of cyclones, two more than at Värtan and Tidd.

In addition, lower than desired capacity of the air compressor and air leakage past the gas turbine intercept valve resulted in less than design combustion air flow rate to the furnace, which prevented the maximum gas turbine power output being achieved. Nevertheless, the successful development and use of this dry-feed system has led to it being offered as a standard option on ABB Carbon’s P-200 and P-800 plants[6].

<u>Pressure Vessel and Fluidized Bed</u>

Pressure Vessel Shell

During the 1991 summer outage at Värtan, cracking was observed in the pressure vessel welds to a depth of around 3 to 5 mm. The cracks were found to be heat treatment cracks in the heat-affected zones, and were removed by grinding. Three cracks were sufficiently deep to require repair by welding. During the 1992 annual outage, additional cracks were detected both in ground welds and in unmachined welds.

Membrane Walls

The water-cooled membrane wall of the combustor vessel is exposed to relatively low gas temperatures, and the results from testing at Stal Laval's Malmö pilot plant[20] indicated that it would not suffer erosion. Therefore, these walls were left uncoated in the first three PFBC plants (Värtan, Tidd, and Escatròn). This was contrary to the experience at Grimethorpe where the water walls were coated with refractory following high rates of metal loss from the tubing[22]. Some atmospheric-pressure fluidized-bed industrial boilers have also reported water-wall metal loss.

The Värtan plant experienced an early incident of membrane wall tube leakage in tubing that had been bent around an observation port. The resulting steam/water jet, together with entrained bed ash, destroyed several adjacent evaporator and superheater tubes in the bed. The tube bundles were lifted out to allow the tubes to be repaired, and the walls were studded to secure a sprayed-on silicon carbide refractory layer. The SiC refractory has a reasonably high thermal conductivity and so did not greatly reduce the heat pick up by the water-wall circuit. Inspection of the tube bundle at that point (operating time of about 3,000 hours) detected no evidence of <u>general</u> erosion with the exception of two pipe bends. After this refractory had been properly applied, there have been no further reports of problems of that type at Värtan.

Thinning of all four walls of the boiler at Tidd was observed in a region 1.5 m above the air distribution sparger ducts and 1 m below the top of the tube bundle. When the in-bed tube bank was partially removed following the final shut down, areas of the membrane wall such as those shown in Fig. 3 were found. Here, instead of being curved, the tube surfaces had been rubbed flat by what is understood to be the downward motion of the bed material at the wall. In the example shown, the wastage appeared to be influenced also by a local flow turbulence associated with a thermocouple penetration in the wall. By comparison, the Escatròn plant showed very little membrane wall wastage, presumably because the bed material was not very erosive. Nevertheless, based on the Värtan experience, wastage-resistant coatings were applied at the manufacturing stage to the membrane walls in the fourth P-200 plant at Wakamatsu.

Evaporator Tubes

The results from pilot scale testing[20,23] suggested that the low-temperature evaporator tubing (13CrMo44 steel; 1Cr-0.5Mo, weight percent) was much more sensitive to wastage than was the higher-temperature superheater or reheater tubing. This difference is believed to arise because the higher-temperature tubes are made of high-chromium steels that intrinsically form a protective oxide layer that is more resistant to wastage. The evaporator tubes do not form such a protective layer because they are made of low-grade steel and operate at lower temperatures. For this reason, ABB Carbon chose to apply a 1 mm-thick flame-sprayed coating [Metco-2 (Fe-14Cr-1Mg-1Ni-0.3C) with a sintered bond coating] to all the evaporator tube surfaces: none was applied to the superheater tubes. In addition, a low fluidizing velocity of 1 m/s was chosen, and particular attention was paid to the in-bed flow pattern with the aim of achieving a tube bank lifetime in excess of 20,000 hours.

During the 1995-6 heating season at Värtan, wear of the evaporator sections of the tube bundle was, in fact, the largest cause of unavailability. In one of the two units extensive flaking of the coating occurred; the bonding layer was heavily oxidized as a result of corrodents penetrating through the pores in the flame-sprayed coating. Also, the hardness of the coating was found to have increased, which presumably made it more brittle and susceptible to cracking. The affected evaporator tube bundle at Värtan was exchanged in the summer of 1996 for a new one that incorporated several design modifications to modify the bed flow pattern to minimize erosion, and to change the rate at which the load could be changed. The Metcoloy 2 coating was replaced with a sprayed-and-fused coating (Castolin 17535), which was thinner and more dense (and therefore was expected to be impervious to combustion gases) and had significantly higher bond strength. In fact, the Castolin coating proved to be less resistant to wastage than expected, so that new measures were required. These included adding a layer of Metcoloy on top of the existing Castolin layer. In 2000, a new steam generator tube bank was installed in one of the units, incorporating further (unreported) modifications. Also, in order to minimize the wastage potential in the Värtan plant, restrictions were placed on the content of alpha quartz in the coal burned.

Some flaking of the coating also was observed in some local areas in the Escatròn plant, but at Tidd the Metco-2 coating performed well, and only minor tube erosion was observed, apparently resulting from local flow disturbances in areas near the bottom of the tube bundle. No flaking or increase in hardness of the Metcoloy-2 coating was observed, and this was attributed to the lower steam pressure at Tidd resulting in a lower tube surface temperature than at the Värtan and Escatròn plants. This, and differences in the corrosive environments, were believed to have led to these differences in coating performance. Modifications were made to the in-bed boiler tube bundle at Tidd to add approximately 25 percent more in-bed surface to increase the heat absorption. The full bed height at Tidd was increased to 3.6 m, compared to the original 3.2 m.

Superheater Tubes

The primary superheater tubing in the Värtan Plant used uncoated 12 percent chromium steel [CrMoV121(X20); 12Cr-1Mo-0.3V-0.2C] for superheater-1, and an austentic stainless steel (SS2338-24; Fe-9/12Ni-17/19Cr-2Mn-1Si-0.08C+Nb,Ta) for superheater-2, and initially experienced some wastage in locations exposed to increased particle flow. This problem was corrected by the installation of sleeves, typically of a heat-resistant steel similar to those used at Tidd (and on UK FBC plants) and illustrated in Fig. 4. The austenitic secondary superheater tubing generally experienced

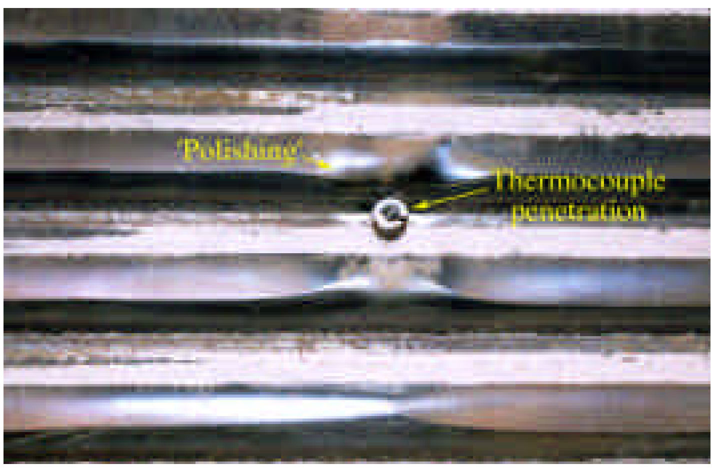


Figure 3. 'Polishing' of the waterwall at Tidd in the vicinity of a thermocouple penetration.

Figure 4. Shielding installed to protect the superheater tubes (bottom row) in the tube bundle at Tidd

negligible wastage, although some very localized wastage was observed in the 1995 inspection, and led to the application of sleeves to those areas. Inspection in the summer of 1996 indicated no additional wastage on the unprotected parts of the superheater tubing.

The primary superheaters in the Escatròn plant are made from a 9-Cr steel and have shown only a few local erosion marks. The secondary superheaters at Escatròn are made from a 12-Cr steel, and operate at a relatively low surface temperature; no wastage whatsoever has been observed on that tubing. For uncooled parts such as dummy tubes or tube supports in the tube bundles of the different plants, Avesta alloy 253MA (Fe-11Ni-21Cr-1.7Si-0.09C+N and Ce) has been used. While this material performed very well in Värtan and Tidd, it experienced severe metal loss in the Escatròn plant. It seems likely that this was due to the very high sulfur content of the Escatròn coal, which led to corrosive attack. All the uncooled parts in the Escatròn tube bundle have now been replaced with Avesta 353MA (Fe-35Ni-25Cr-1.6Si-0.06C+N and Ce), which is expected to perform well, based on the results of the metal testing program[20].

Expansion Joints

To accommodate differential thermal expansion in pipe runs on the Tidd plant, expansion joints are incorporated at certain locations. This is especially important for refractory-lined pipes, which have less ability than metal pipes to accommodate deflection. A metal bellows section provides the pressure boundary and these are constrained with “hinge” arrangements that turn to allow the connecting pipes to expand.

A major concern with this type of joint is failure of the bellows section through acid dew-point corrosion, the metal wall being less than 2 mm thick. The high oxygen partial pressure in a PFBC unit encourages the formation of SO_3, which can start to condense from the flue gas at temperatures below 135°C, the actual temperature depending upon concentration. The bellows section is designed to operate well above this temperature, at around 230°C, and using insulating blankets installed beneath and over the convolutions. Simply installing a blanket over the bellows would raise the metal temperature beyond its design point, so one is also installed beneath the bellows to limit the heat flux. In case of failure, a double-walled bellows section is used with the pressure in the gap being monitored. Each wall can withstand the working pressure and, if the inner wall fails, a pressure switch raises the alarm to initiate a controlled manual plant shut down.

At Tidd, the insulating blankets were ineffective in keeping the bellows section hot, and corrosion of the inner wall occurred. This may have been exacerbated during startup when the bellows has to be heated to its operating temperature and so is more prone to dew-point corrosion. To overcome this problem, various forms of heating element were applied until a satisfactory one was found. Expansion joint corrosion occurred previously at Grimethorpe(23), and is believed to have occurred on other ABB Carbon units.

<u>Hot-Gas Clean Up System</u>

Cyclone System

The cyclones in the Värtan and Tidd units are made of Avesta alloy 253MA and operate uncooled at 850°C. After 20,000 hours of operation, there were concerns about embrittlement of this alloy. Steps to prolong the lifetimes of the cyclones include a heat treatment to redissolve the embrittling phases and weld repair using an appropriate welding rod alloy.

Figure 5 shows the remaining ash deposits on the inside surfaces of a primary cyclone at Tidd after final shut down. The section through which this view was taken had been removed to check for erosion damage.

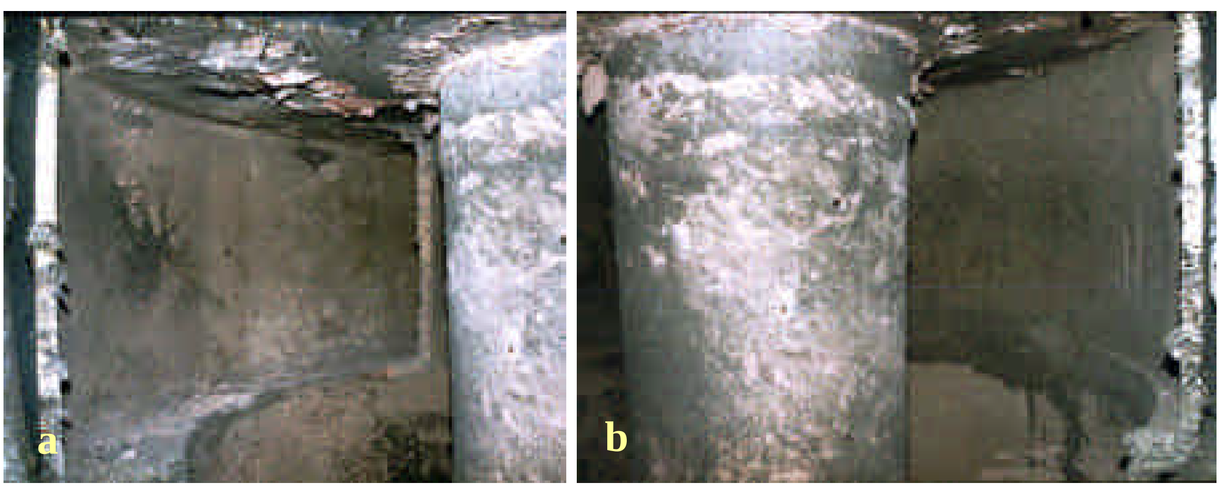


Figure 5. Inside view of a primary cyclone at Tidd showing residual dust deposits.

Plugging of the secondary cyclones and ash discharge legs caused a number of stoppages at both units. There appear to have been several causes for such plugging. Cracking and spallation of the ceramic liner in the cyclone ash removal legs occurred and led to blockages. At Värtan, a new type of ceramic liner installed in one of the units started to fail by cracking after approximately 200 hours of operation. One possible reason for this spallation was thought to be the high, localized temperature caused by the over-bed combustion experienced at both Värtan and Tidd. The original lining material was reinstalled following measures to minimize freeboard combustion. A further factor contributing to cyclone blockages at Tidd was a significant reduction in transport capacity of the ash system by air leakage into the cyclone leg at flanged connections inside the combustor vessel. The bolted connections in both the primary and secondary ash removal systems were replaced with welded connections where possible, and shop fabrication flaws in cast components were repaired. In addition, extensive quality control measures were applied to the tightening procedures for the bolted connections that could not be replaced.

The use of aged, spent bed material as the initial bed on start-up also led to plugging of the primary cyclone ash-removal system since this material tends to break-up easily. In addition, deposits of a hard iron/sorbent coating formed on the inside of the ash removal lines at Tidd and further obstructed the ash flow. This deposition seemed to be temperature dependent and occurred in specific temperature zones. Modifications introduced at Tidd included the use of sand instead of spent bed material for establishing a start-up bed after a long unit outage, and shortening the dip legs on the secondary cyclones by approximately 6.1 m to reduce ash build-up.

Ceramic Filters

Advanced Particle Filtration Facility at Tidd

An advanced particle filtration facility (APFF, provided by Westinghouse Electric Corp.; see Newby et al., ref. 24) was installed at the Tidd plant outside the PFBC pressure vessel. The gas and dust were taken from one of the primary cyclones, the secondary cyclone ash removal leg being blocked and effectively removed from service. The arrangement is shown schematically in Fig. 6. A bypass line around the APFF included a secondary cyclone, allowing the APFF to be taken off line without disrupting PFBC operation. A back-up cyclone was installed in the flue gas line leaving the APFF to remove dust in case of filter candle failure.

The APFF was designed to accommodate arrays of filter candle elements arranged in three vertical clusters, each made up of three arrays. Each cluster consisted of three plenums as indicated in Fig. 7. The top two arrays contained 38 candles each, with 52 in the bottom one. Ceramic candle filters made by Schumacher (F20 and F40), Pall (Vitropore 422T), Coors (P-100A), 3M (CVI SiC), and DuPont (PRD-66) were tested during a total of almost 6,000 hours of operation. The dust was filtered on the outside of the elements and when the pressure drop exceeded a proscribed value, the collected filter cake was displaced by a back-pulse of air delivered to the plenum above each candle array.

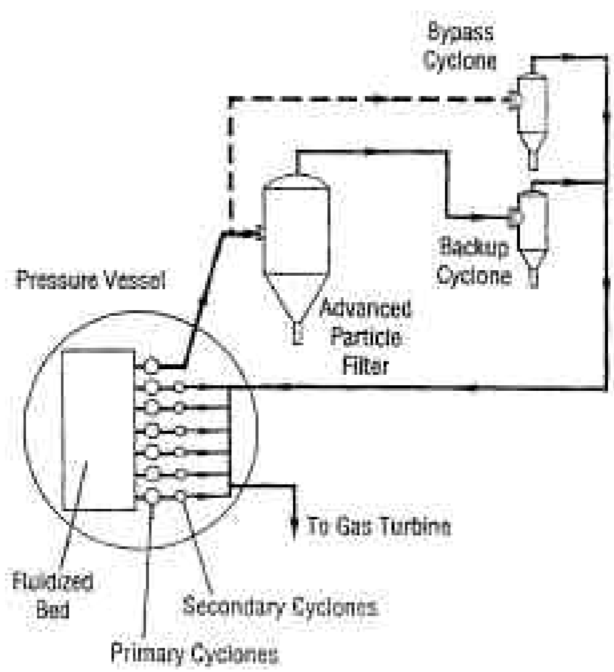


Figure 6. Schematic arrangement of the Advanced Particle Filter at Tidd (published by permission of AEP)

During initial operation, the relatively low inlet dust loading of fine fly ash particles transmitted from the primary cyclone proved to be very cohesive, particularly at temperatures above 760°C, and had a high tendency to agglomerate and sinter. This led to bridging between candles and difficulties in cleaning the candles and in draining the filter vessel. Besides reducing the effective filter area, the bridging resulted in the candles being ratcheted apart, eventually failing under tensile stress. Remedial measures were to remove 25 percent of the candles to create increased space between the candle elements and minimize the potential for bridging. This alleviated but did not eliminate the

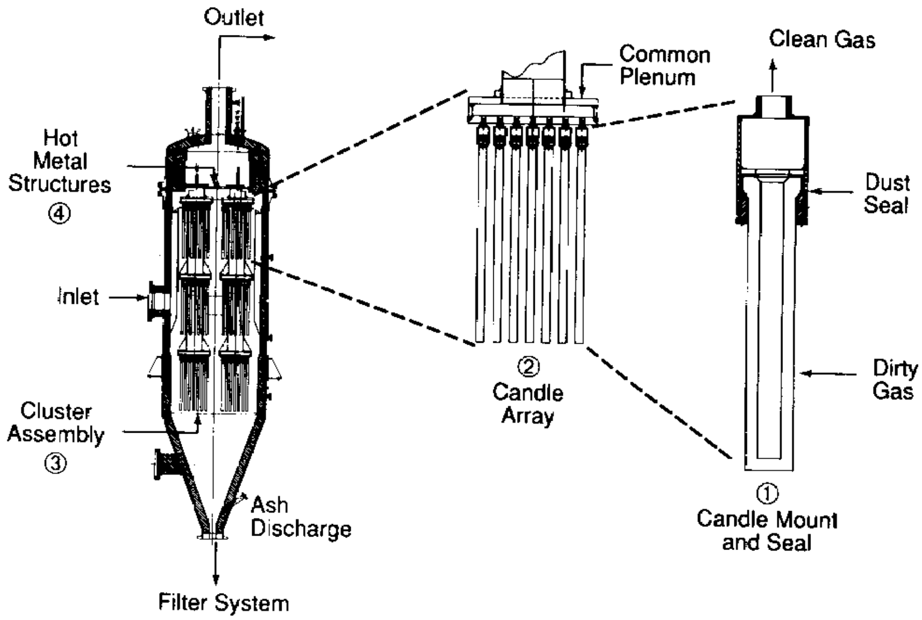


Figure 7. Details of the Advanced Particle Filter at Tidd (published by permission of AEP)

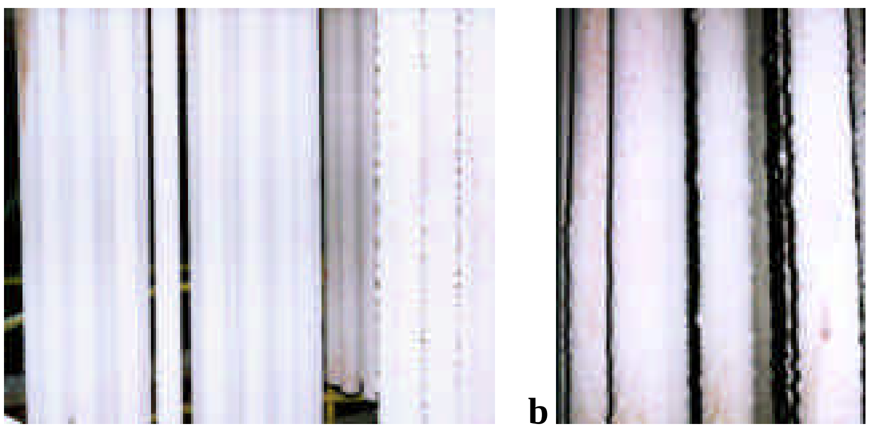
problem. Next, the primary cyclone was detuned to pass more large particles to the filter to reduce the strength of the filter cake. This had some success and eventually it was decided to effectively remove the cyclone from service by blocking the ash discharge leg. This increased the inlet particle loading to the candles by a factor of 50 and the mass mean particle diameter by a factor of 10. Subsequent filter operation was stable with a solids outlet loading around 1 ppmw, but because of heat losses the filter operating temperature did not exceed 780°C.

Figure 8a shows the appearance of a cluster of candles in the upper grouping following final shutdown. The inner ring of candles had been removed as part of the measures to avoid ash bridging. Three of the remaining candles were missing, and had probably been removed for post-test evaluation. The build-up of ash deposits on the non-porous regions at the top of the candles is shown in Fig. 8b. It is in this location that bridging was thought to initiate. Figure 9 illustrates the state of the candle filter surfaces after final shut down. No bridging was observed. Note the variation in appearance of the outer surfaces of the remaining filter cake on the sets of different types of candles.

Inspection of the head of the APFF pressure vessel following the final shut-down of the Tidd plant revealed damage due to aqueous (condensate) corrosion beneath the insulating material that been used to line the vessel (Fig. 10). It was thought that the insulating material was wetted by condensation, keeping the metal in a permanent acidic environment. It was concluded that a refractory lining would be preferable for future applications. However, this does not totally eliminate the problem as SO_3 can still reach the inner metal surface through diffusion, or convection through cracks. To prevent this from being a problem, the metal surface also needs to be protected in some way. One way is to fuse an acid-resistant polymer to the metal prior to applying the refractory. Alternatively, the refractory could be designed such that the metal surface operated above the dew-point temperature.

a **b**

Figure 8. Overall view of the upper candle arrangement in the APFF at Tidd. In a) three candles have been removed for post-test evaluation; (b) heavy ash deposition above the porous regions of the candles



a **b**

Figure 9. Appearance of the filter candles in the Tidd APFF after final shutdown. Note the different appearance of the filter cake on different sets of candles.

Figure 10. Damage to the head of the APFF vessel at Tidd from aqueous corrosion

Candle Filters at Escatròn

Escatròn has run with one of the nine sets of cyclones replaced by a hot gas filter developed by Babcock & Wilcox Espanola[25]. This filter uses Schumacher SiC candle filter elements that are supported at both ends to reduce sensitivity to mechanical stress. The filter apparently performed well in terms of filtration and life of the elements; however, details were not available at the time of writing.

Advanced Ceramic Tube Filter at Wakamatsu

At Wakamatsu, a full-scale advanced ceramic tube filter (ACTF) system developed by the Asahi Glass Company, Limited was installed downstream of the seven parallel trains of cyclones[26]. The ACTF consists of 81 vertically-arranged filter tubes. Flue gas from the cyclones enters the top of the ACTF, flows down the inside of the tubes, through the filter tube walls, regenerators, and gas outlet ducts before entering the exhaust manifold. Unlike the filter candle elements, filtration takes place on the inside of the tube. The filter tubes consist of a direct-bonded cordierite matrix (containing no glassy phase) with a small percentage of sintering aids. The self-circulating blow-down system consists of risers and an inlet ejector: in the original design, 75 of the 81 filter tubes were used as downcomers and six were risers in which the gas induced by the inlet ejector flowed upward. This system provides enough downward flow velocity inside the tubes to avoid flow stagnation where combustion of unburned carbon particles may occur. It also assures a uniform velocity profile in the inlet chamber and hopper. The filter cake is removed by injecting air into the clean gas outlet and reversing the flue gas flow momentarily.

Filters were run for a total of 3,830 hours in three test periods (the longest run at full load lasted 216 hours); five tube failures were experienced. During continued operation with a failed tube during the third period, very large dust cakes (up to 300 mm thick) formed on the first tube sheet, and eight tubes suffered internal plugging. The tube failure was traced to cracking at notches made by a grinder when finishing the stainless steel cover after welding insulation around the upper end of the tube. Hairline cracks had initiated from the V-shaped notches and had propagated as a result of back pulsing. Plugging resulted from the large amounts of dust inside the tubes, and from falling dust cakes. Other tube failures were due to either dust plugging or combustion inside the tubes associated with successive failures to ignite the kerosene start-up burner, and with clogging of some of the coal feed slurry nozzles during the startup of the run. Impact of the broken pieces from one tube caused failure of others.

The procedures initiated to minimize these problems included: application of insulation at both ends of the filter tube between tube sheets to reduce the thermal stress caused by radiation cooling; a significant increase in the cooling water flow to the tube sheet; and an increase in the water supply pressure.

Tomatouatsuma

The Tomatouatsuma plant uses a hot gas cleanup train consisting of a cyclone separator followed by a ceramic filter, both of which are located outside the pressure vessel. The ceramic filter was designed by MHI. It consists of six bundles of vertical, parallel tube filters in an upper 'pack', followed by a single bundle of longer, vertically-aligned, parallel filter tubes in the main filter bank. The two sets of filters are housed in the same vessel. The flue gas from the cyclones enters the top of the filter vessel and flows into the inside passageways of the filter tubes in the upper bank. Flue gas not filtered by the upper filters continues out of the bottom of these filter tubes, over the top tube plate of the main filter bank, and into the insides of the lower filter tubes. Back-pulsing with compressed air through the filter walls dislodges the filter cake, and the ash falls into the ash hopper.

Since starting commercial operation in March 1998, considerable effort has been spent dealing with problems encountered with the ceramic filter. Elements were damaged as a result of interference with the support structure from differential thermal expansion, as well as dust leakage from the filter seals. Modifications to the design of the supports, and a change in the materials and shape of the seal packing have apparently resolved these problems[12].

Gas Turbine Expander

Blade Resonance Problems

The most significant, unexpected problem with the gas turbine has been high-cycle fatigue damage to the originally-installed cast IN-738, variable-speed, low-pressure turbine blades. Cracks were found at the blade shanks in one of the two machines at Värtan during 1992, and in those at

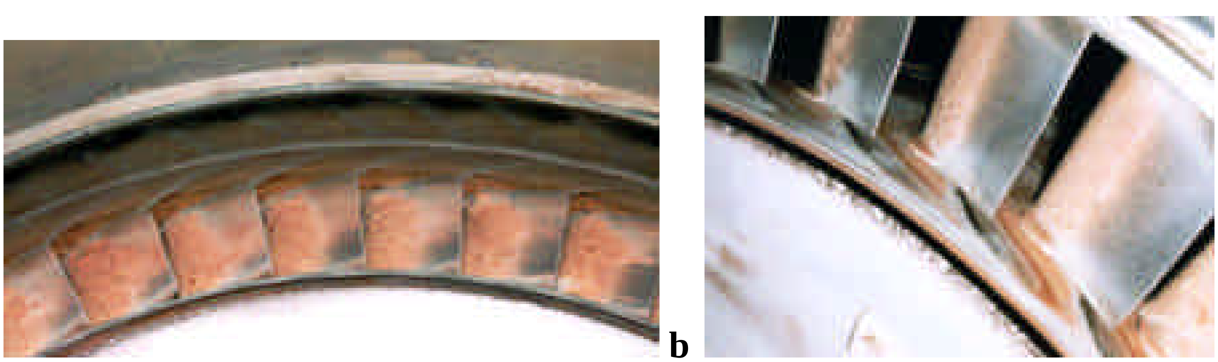
Escatròn and Tidd. It was determined that the damage resulted from a resonance that was correlated with the number of guide vanes ahead of the low-pressure turbine. This problem was countered at Värtan by modifying the blades to reduce stress concentrations in the trailing edge regions of the blade roots, and by the introduction of some speed restriction; this meant that prolonged operation within a certain narrow speed range was prohibited. However, during the 1994-95 heating season, some level of operation in the restricted speed range was necessary with the result that failures of low-pressure turbine blades were again experienced. A contributing factor to this failure was found to be asymmetric positioning of the adjustable guide vanes used for controlling the gas turbine load. This asymmetry caused disturbance of the gas flow which, in turn, created turbulence and vibrations. Further, abnormally high dust loadings made inlet guide vane movement sluggish and caused them to twist.

The cast low-pressure turbine blades were replaced with new blades forged from alloy IN718. These are expected to have higher resistance to high-cycle fatigue and to provide service lives up to 16,000 hours (32,000 hours with refurbishing). The modified blades were installed at Värtan, Tidd, Wakamatsu, and Escatròn. No further gas turbine problems were encountered at the Escatròn Plant, nor at the Tidd plant until it was finally shut down at the end of March 1995.

Deposition-Erosion-Corrosion

The gas entering the turbine during normal operation contains several hundred parts per million of very fine (less than 5 micron) solid particles, which obviously creates the potential for deposition, erosion, or corrosion of the various components. Further, during a cyclone upset the loading and particle size will increase greatly. The original design included corrosion-resistant coatings on the turbine blades, and considered the possibility that erosion-resistant coatings might later be applied at locations where the phenomenon appeared. In practice, heavy, hard deposits of dolomite were found on the gas turbine blades at Värtan following a start-up under conditions where moisture had precipitated on the surfaces. Modifying the start-up procedure eliminated this problem. Some erosion has been measured on the turbine blades at Värtan, but the extent apparently has been insufficient to cause significant effect on the turbine performance. Somewhat more serious erosion has occurred on an inner ring of the guide vanes.

The gas turbine was the leading source of unavailability problems during the first three years of operation at Tidd. Problems with intercept valve seal leakage resulted in a portion of the air from the high-pressure compressor by-passing directly into the gas turbine. Such leakage resulted in a limitation on the unit firing rate[20], but was corrected through an improved seal arrangement. During normal unit operation very little erosion occurred in the gas turbine, but the rate of erosion increased significantly when cyclone ash removal legs were plugged. The most serious erosion was observed after running for a period of 31 days with one cyclone train out of service. Plugging of a primary cyclone ash removal leg had led to plugging of the corresponding secondary cyclone. This eliminated one of the seven cyclone trains and increased the dust loading to the gas turbine more than 10 fold. More importantly, the dust contained particles as large as 250 microns, which are far more damaging than the 5-micron particles normally transmitted when the cyclones are fully functional. As a result of these problems, after 2,100 hours of coal-fired operation the gas turbine at Tidd exhibited measurable erosion damage.



a **b**

Figure 11. Inlet guide vanes to the high-pressure turbine blades, showing heavy deposits on the suction surfaces

Inspection of the gas turbine following the final shut down of Tidd found red-colored deposits on most of the hot gas path surfaces. Figure 11 shows some of these deposits on the Row 1 inlet guide vanes (heavier on the suction side than the high-pressure side). The tips of the Row 1 blades exhibited obvious erosion or wear damage, as shown in Fig. 12. One possible cause of such erosion is the formation of vortices at crevices, trailing edges, and other locations which cause flow disturbances that may entrain particles and cause localized erosion where the vortices impact on neighboring turbine components. Wear lines on the outer (Fig. 11a) and inner part (Fig. 11b) of the vane housing may support this supposition. Tip wear also may have been due to an increased dust loading at the casing due to centrifuging of the dust.

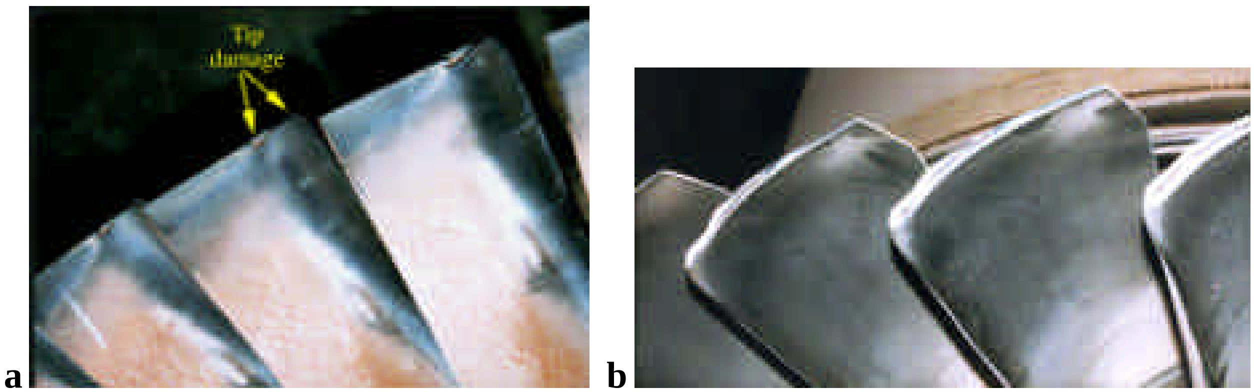


Figure 12. Erosion/wear damage to the high-pressure turbine blade tips (a) suction side of cooled (Row 1) blades with damage around the cooling air channel exits (b) deposit-free high-pressure side of HP blades

Figure 13 shows ash deposits on the pressure side of a row of uncooled, low-pressure turbine blades. If such heavy, tenacious deposits are typical of those present during operation, they would be expected to have affected shaft balance, possibly contributing to the vibration problems reported for this turbine. There were also signs of distortion and impact damage on these blades, more than would have been expected from 250-micron ash particles. This impact damage may be associated with an earlier compressor blade failure arising from vibration-induced stress.

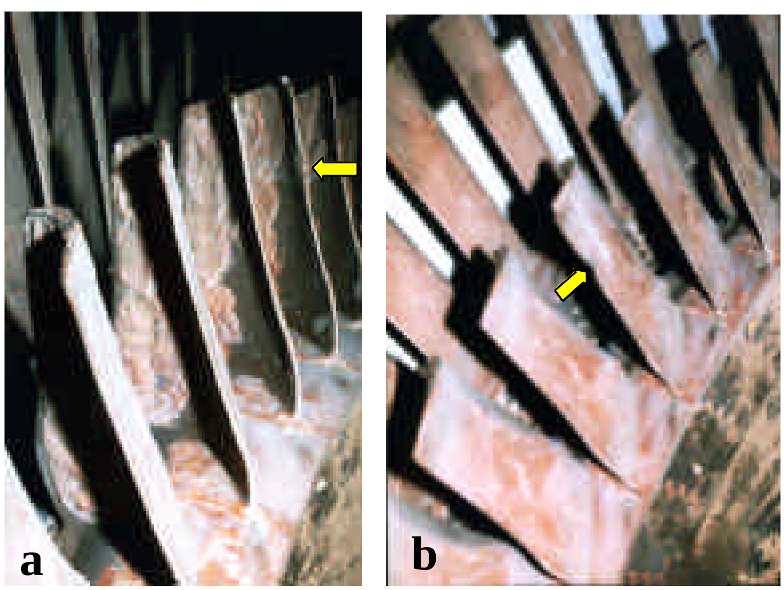


Fig. 13. Uncooled low-pressure turbine blades showing (a) heavy deposits on the pressure surfaces (b) view of the suction side distortion as well as impact damage (arrows)

Figure 14 shows the variable inlet guide vanes to the low-pressure turbine. These carried heavy ash deposits on both pressure and suction surfaces, and also showed evidence of erosive wear on both the inner and outer surfaces of the vane housing. In particular, there appeared to be significant erosion in the region where the vane shafts penetrated the housing—possibly areas of flow disturbance.

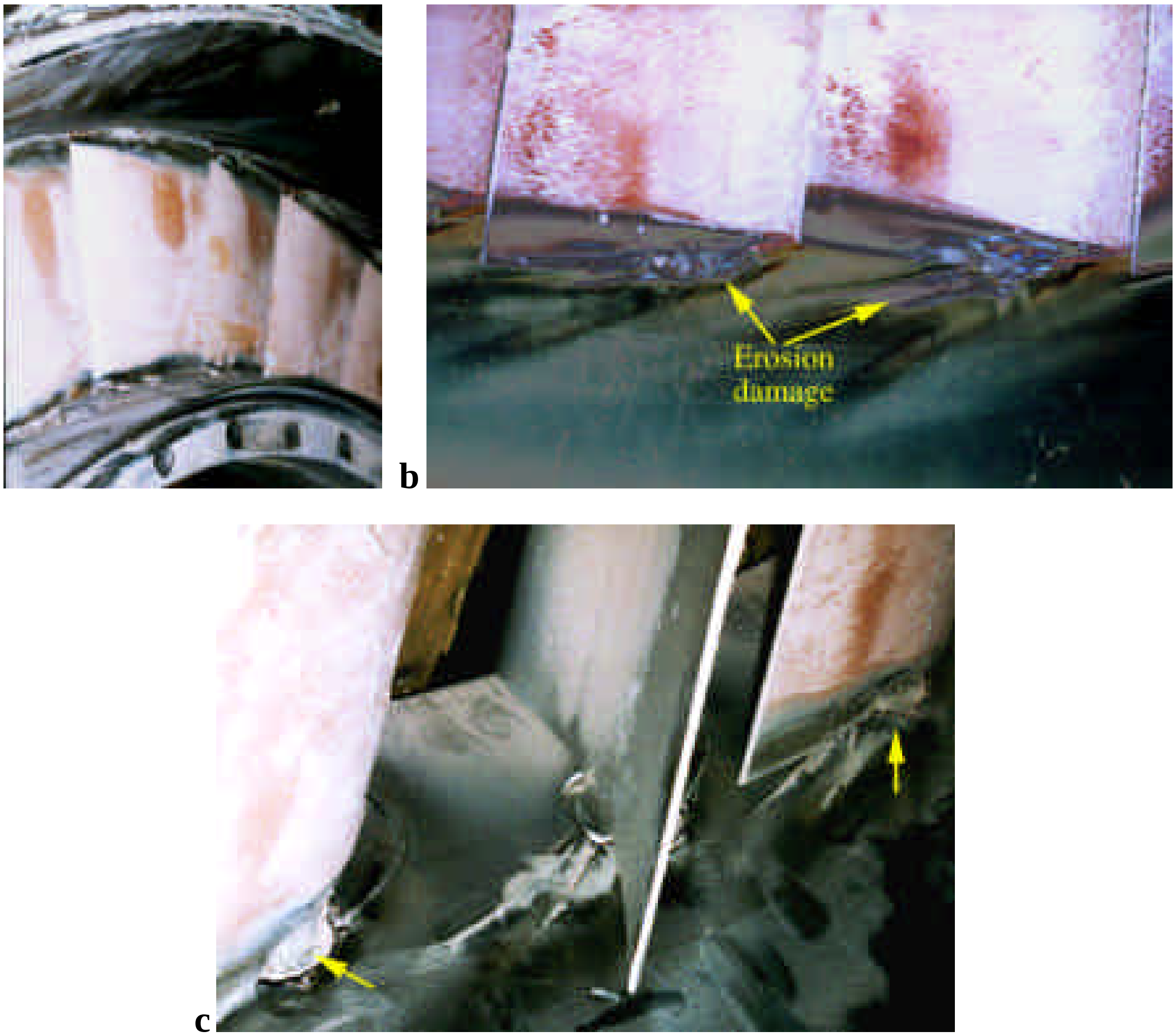


Figure 14. Variable inlet guide vanes to the low-pressure turbine with (a) deposits on the suction surfaces; (b) and (c) erosion damage where the vane shafts penetrate the housing (arrows).

Some deposition and erosion in the high-pressure gas turbine also were experienced at Escatròn. This was attributed to excessive dust carryover because of blocked cyclone ash discharge legs, as well as to particle agglomeration resulting from local high-temperature or reducing conditions. Subsequently, very little erosion has been experienced under normal operating conditions (with functioning cyclone ash outlets). One possible reason for the apparently lower erosion losses than at Värtan and Tidd is that the fine ash formed from the black lignite used at Escatròn is quite soft compared to that from Polish and eastern U.S. coals, respectively, used at the other plants.

The duct carrying the hot, dusty flue gas from the Tidd cyclones ran vertically downwards, very abruptly turned horizontal, and almost immediately entered the gas turbine. Centrifugal action at the final bend would have tended to move dust towards the outside wall of the duct and there would have been insufficient distance to allow the dust to re-distribute itself before entering the turbine. The wear tracks on the outer diameter of the inlet vane housing (Fig. 11) may be indirect evidence of a higher ash loading near the duct wall. Since erosion damage typically is directly proportional to the frequency with which erodent particles strike a surface, an obvious way of reducing erosion losses is to avoid features that concentrate the erodent particles. In this case, allowing a sufficient duct length to achieve a uniform dust distribution in the gas stream, and/or the addition of flow straightening or particle redistribution devices in the ducting are remedial measures that could be incorporated relatively easily at the design stage.

There is little documented information available on turbine performance at the Wakamatsu plant, but operation on a coal that appears to contain high levels of fine quartz has apparently caused some wastage of the turbine blading.

At Ohsaki, after 960 hours of continuous operation some abrasive damage was reported on the blade shrouds, which led to modification of the shape of the shrouds, and the addition of a flame-sprayed coating(11).

CONCLUSIONS

Given the fact that these commercial PFBC power plants represent the first deployment of a new technology, most of the materials problems experienced were not unexpected. Experience of in-bed wastage from pilot plant testing allowed preventative measures to be taken that greatly mitigated this problem in the commercial plants, although where the conditions that give rise to wastage are unavoidable there remains a need for a more effective materials solution than is currently openly available. Some of the practical difficulties with, for instance, fuel and ash handling had not been fully anticipated from pilot scale testing, but were in the category of 'teething' problems and were overcome by relatively simple modifications. A conclusion from experience at Grimethorpe and from the ABB plants is that if at all possible installation of expansion joints should be avoided. If they are installed, their performance needs to be closely monitored for important process and safety reasons. As a result of the understanding developed over the course of bringing these plants into service, solutions are now available for most of the problems encountered, and could be readily incorporated into future plants.

The area of greatest concern was the performance of the expander turbine and the associated particle removal devices. Initial operating difficulties demonstrated the extreme susceptibility of the turbine to particle deposition and erosion following any upset in the operation of the cyclones. The erosive wear experienced by the GT-35P, although sometimes severe, occurred mostly when the primary cyclone ash discharge legs were plugged, causing carryover of coarse ash particles to the turbine. Previous pilot plant testing had shown that this could occur, and the cyclone legs had been designed to minimize such plugging problems. The fact that disturbances in the combustion process can lead directly to cyclone plugging suggests that such problems could be encountered when switching fuels, which is a likely occurrence in practice, and should be anticipated by pilot trials.

A conclusion from the Tidd Demonstration Program was that for the practical protection of the gas turbine it was essential to develop instrumentation to indicate when cyclone blockages occur, and to develop devices that can clear the blockage with the unit on line. If this could be achieved it was believed that turbine internals would have a two-year life. Available erosion-resistant coatings are expected to be capable of providing protection over this period, so that it appeared likely that the gas turbine hot gas path components would require refurbishing on a two-year cycle, which is not unreasonable. There is insufficient information available from the operating units to confirm the validity of this proposal, or whether the operating interval is longer or shorter than two years.

The fact that when the cyclone ash outlet systems performed properly, long-term operation has been achieved with acceptable wastage of the gas turbine components suggests that the original goal of removing ash particles larger than four microns to avoid erosion damage could be achieved with further relatively straightforward improvements to the hot gas clean-up components. This would require that the ash that passes through the cyclone systems is not abnormally erosive, and that cyclone upsets can be avoided. However, other experience from these plants suggests that cyclones alone will not be sufficient to provide assurance that gas turbine component life will meet expectations. However, it does not appear to be sufficient to remove the larger ash particles; the fine dust appears also to be a major problem, since it permeates mechanisms such as those associated with the variable nozzle guide vanes and causes them to malfunction or fail. These observations provide a powerful argument for the use of positive filtration on PFBCs. Fortunately, ceramic filters of various configurations appear capable of fulfilling this need. While it might even be possible to eliminate the cyclones, it is likely that they will be useful in reducing the particle loading on the ceramic filters, and they also may be desired as safety back-ups.

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