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MECHANICAL EVOLUTION OF THE ROTATING BIOLOGICAL CONTACTOR INTO THE 21ST CENTURY

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Abstract:- This paper presents a review on the evolution of the mechanical design of Rotating Biological Contactors (RBC) within the United Kingdom. The findings documented have been taken from the biggest mechanical survey on RBCs ever undertaken worldwide and focuses on 300 operational units. The paper looks at the main components of the RBC and discusses the evolution of each member. Mechanical deficiencies associated with each design are briefly presented, giving an insight into reasons for improvements. This is the only known document that details changes in design philosophy employed over the last 30 years, with illustrative examples.

For the purpose of this review, the mechanical evolution of the RBC is focused on three primary sections; media panel designs, media support structures and auxiliary support systems including bearings, power units and transmission systems. It is shown that the evolution of media panels has largely been directed by economies of manufacture and operational requirements. However, the advances in the mechanical design of the RBC supporting structure, whilst dependent on the media type, is largely influenced by overcoming known mechanical deficiencies as well as increasing operational life. This paper depicts the current technology and practice of UK based manufacturers and details reasons for mechanical deficiencies.

Key words- Auxiliary support systems, bearings, biomass, mechanical design, mechanical evolution, mechanical survey, media panels, media support structure, RBC, rotating biological contactor, transmission systems.

1. INTRODUCTION

The principal of the Rotating Biological Contactor (RBC) was first developed in the late 1920's [1], however, it was not until the 1960's that the first commercial system was installed in West Germany [2,3]. Thereafter, the popularity of RBCs grew and they are currently operated across the globe. The RBC is primarily used for sewage treatment in small communities, though it is now being used for larger treatment operations. They consist of discs attached together to form a media pack as illustrated in figure 1. An operational unit can be seen in figure 2.

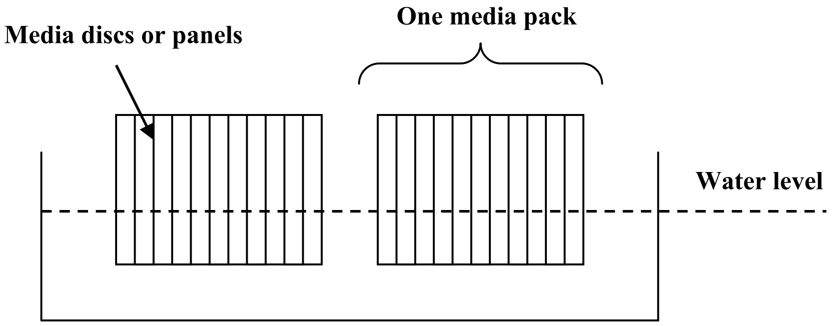


Figure 1 Schematic diagram of the Rotating Biological Contactor

The discs, also referred to as media panels, are held within an enclosed basin and submerged by approximately 35 to 40% of the height. Wastewater passes through the basin as the disks slowly rotate, exposing the biological growth (biomass) on the media panels alternately to the wastewater, and to the surrounding air [4]. Typically, a media pack consisting of a collection of media panels represents one stage of the treatment process. The RBC can consist of up to four or six separate media packs depending upon the population served and mechanical design. Media panels are fixed onto a main central shaft, either directly or with the aid of a support structure. The shaft is in turn supported by bearings and connected to a power unit. RBC units can range from 1.0 to 4.0 meters in diameter, with shaft lengths of up to 10 meters.

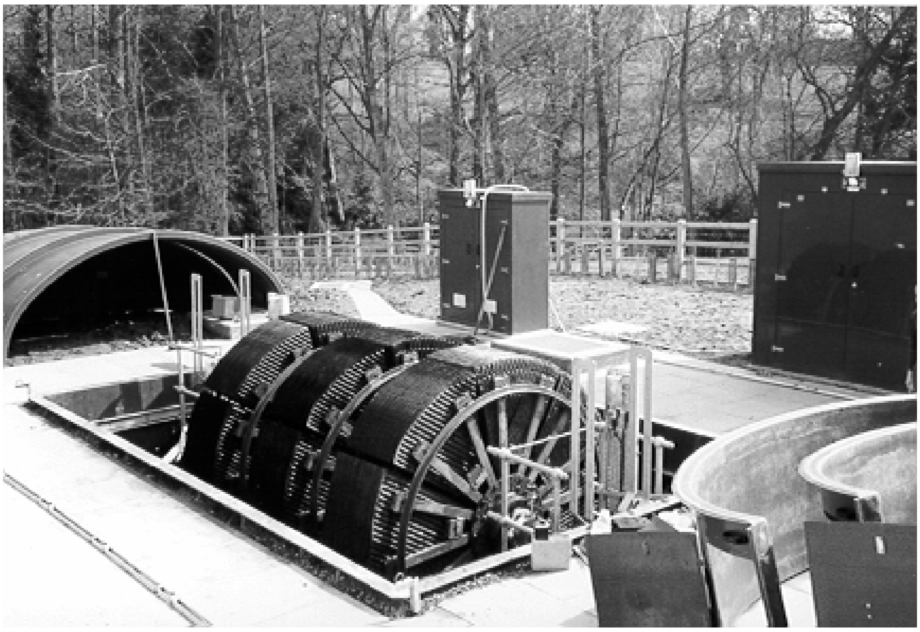


Figure 2 **Rotating Biological Contactor (RBC)**

In operation biomass attach to the surfaces of the media panels forming a slime layer. Rotation ensures aerobic conditions are maintained for the survival of the biomass. Organisms in the developed biomass remove both dissolved oxygen and organic materials from the wastewater, effectively cleaning the settled sewage. The depth to which the biomass can grow is controlled by the shearing action on the biomass as it passes through the wastewater. In a well-operated system there exists a continual cycle of film growth followed by biomass stripping [2].

The commercial viability of RBC units in the 1960's and early 70's was deemed to be very poor as flat expanded polystyrene sheets were being used for the media panels. With the development of polymers came the introduction of thin, corrugated sheets of high-density polyethylene in 1970's. This meant that the available surface area over a given length of shaft was increased dramatically, improving the performance of the RBC and its relative cost effectiveness. As a result, installations of RBC's increased considerably, but wider applications were limited due to mechanical breakdowns. Suggestions for overcoming such mechanical deficiencies have been detailed [4].

2. EVOLUTION OF THE MEDIA

The media panels on RBC units are designed to:

i) provide as much surface area for biomass growth
ii) allow drainage of the sewage liquor as the panels emerge during rotation
iii) reduce drag and impact on the panels by ensuring easy entry into the liquor

In addition to these performance-related requirements, the media design can reduce power unit requirements by reducing the drag within the liquor and the hydraulic lift. Over the last 30 years designers have continually increased the available surface area on the media panels, thereby improving the operational performance of the unit over a given shaft length. All RBC media designs fall under two categories; Glass Reinforced Polymer (GRP) and high-density polypropylene media panels.

The earliest RBC units in the United Kingdom employed flat Glass Reinforced Polymer (GRP) circular disc panels, see figure 3. The design arrangement consisted of a GRP lay-up on the main shaft, thereby allowing the media panels to be cemented directly onto the shaft. Furthermore, adjacent panels were separated by plastic circular pieces placed on axial through-rods or stud, thereby fixing the distance between individual media panels, insert figure 3. The through rods run along the length of the media pack.

Figure 3 Straight GRP media panels: Layout

The earliest known application of high-density polymer media panels was a wire mesh design, see figure 4. This particular media arrangement employed a steel support arrangement. Adjacent media panels were separated with plastic circular pieces placed on several axially located support through rods. The two media type configurations discussed above are the earliest known panels still operational today and is the starting point as we trace the evolution of the media panel designs.

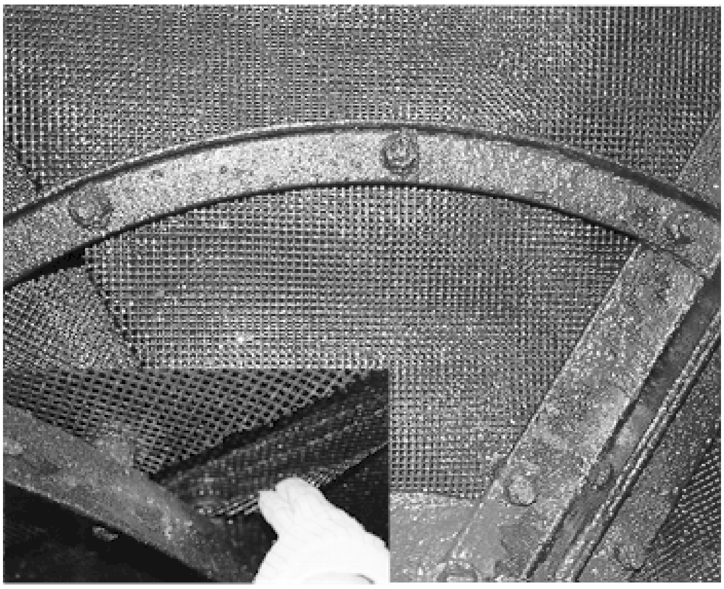


Figure 4 Plastic wire mesh media panel

2.1 GRP media panels

The evolution of GRP media designs was based on increasing the available surface area for a fixed diameter and length, and, at a reduced cost. The earliest attempts to increase the media panel surface area on GRP panels involved molding fan shaped GRP discs media panels, see figure 5. This increased the available surface area relative to the flat disc GRP panels. Adjacent panels were separated with plastic circular studs located on through rods that ran along the length of the media panel, see insert of figure 5. The distance between the panels is set to ensure adequate space for growth and development of the biomass, and drainage of the liquor.

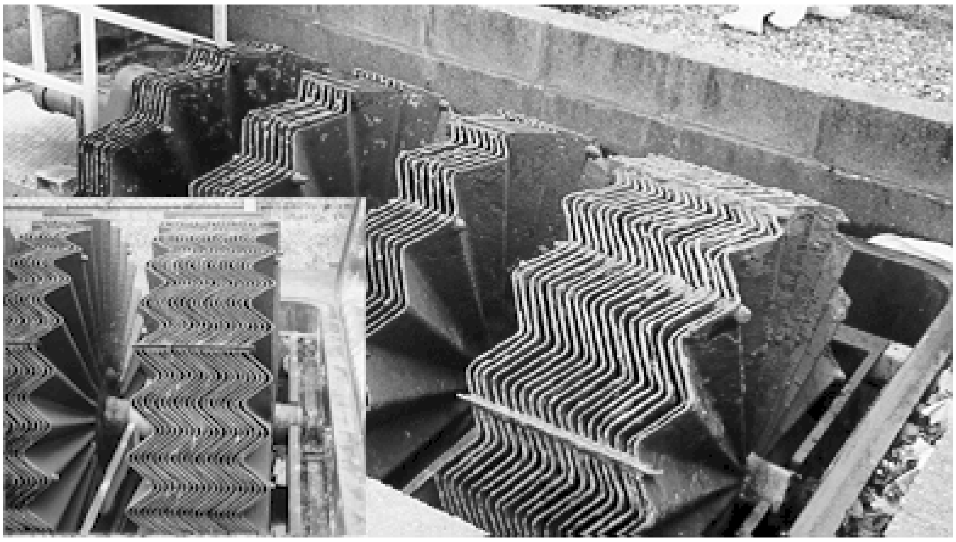


Figure 5 Fan shaped GRP media panels

To further increase available surface area, corrugations of GRP disc panels were designed see figure 6. This increased available surface area relative to the flat and fan shaped disc media panels. Adjacent media panels were separated by placing corrugations of adjacent panels at 90 degrees to each other, see insert of figure 6. This eliminated the need for through rods with circular studs that had been previous used for this purpose. This new approach resulted in a reduction of manufacturing and assembly time, and costs. However, the design is restricted to RBC's with diameters of 2 meters or less.

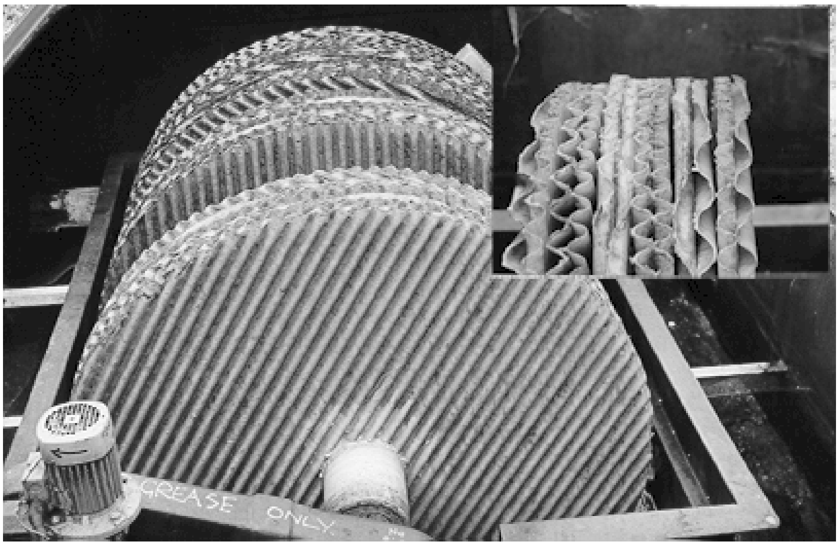


Figure 6 Corrugated GRP media panels: Layout

A distinct feature of GRP disc media panels is that it can be cemented directly onto the main shaft. The manufacture of GRP RBC's has ceased in the United Kingdom due to cost implications. Whilst GRP media panels were popular, they were expensive to manufacture, and with the development of polymers came a cheaper alternative. Furthermore, GRP media panels loose mechanical strength due to water absorption. Regrettably, this type of degradation cannot be avoided; moreover, it is not possible to improve the mechanical strength of these media panels. It is perhaps interesting to note that those RBC's employing this type of media panel have shown evidence of what can only be described as brittleness of the media, no doubt caused by water absorption. As these panels cannot be strengthened, the only solution to their mechanical deficiencies is to replace the entire defective pack, or in some instances, the complete rotor. These are high cost solutions.

2.1.1 Mechanical deficiencies of GRP media panels

Degradation of GRP media panels results in disintegration and breakage. The former is the most severe form of damage and leads to loss of available surface area and a reduction in operational performance. A severe case of disintegration caused by hydrolysis is shown in figures 7 and 8. Early 'tell-tale' signs of media disintegration and breakage are depicted in figures 9 and 10 respectively. These units cannot be repaired; ultimately they must be replaced.

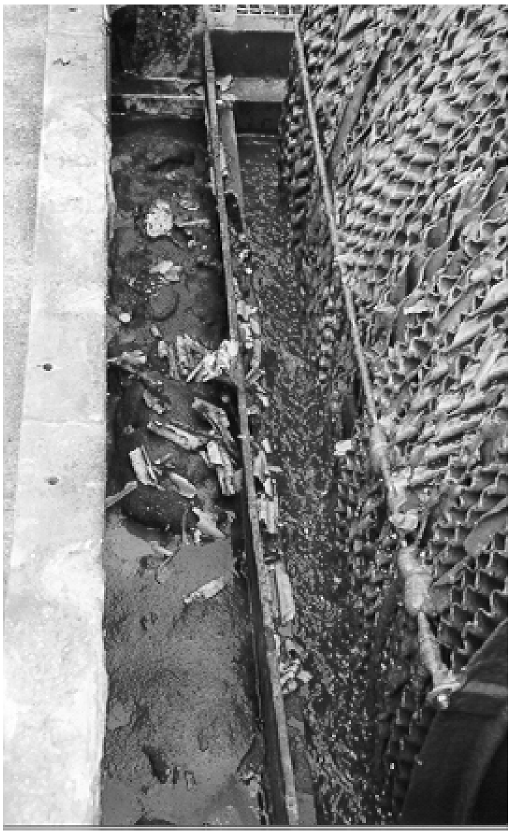


Figure 7 GRP media disintegration

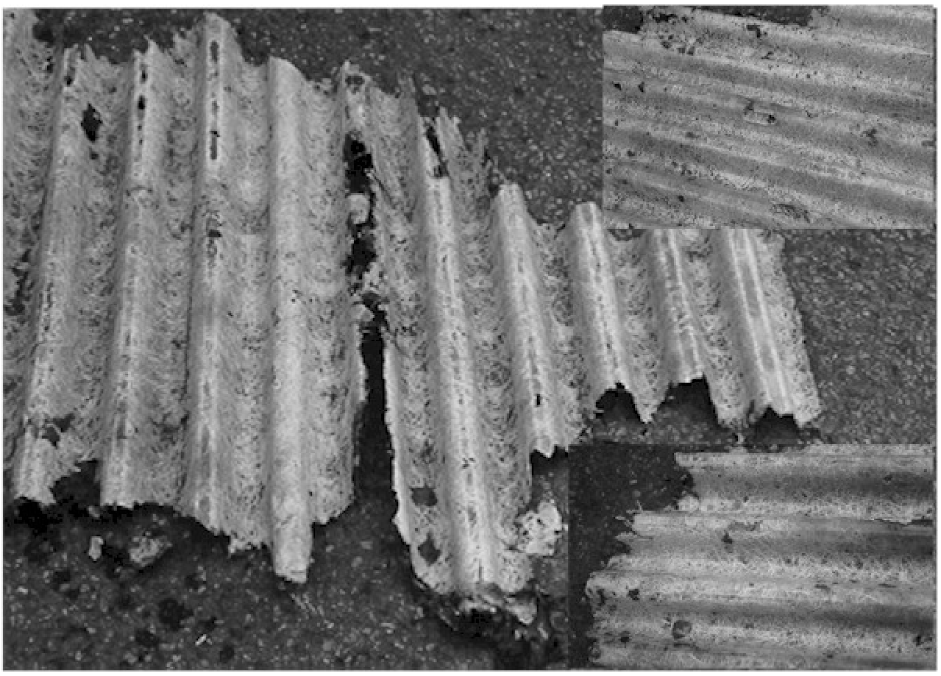


Figure 8 GRP media disintegration

Figure 9 Early signs of GRP media disintegration

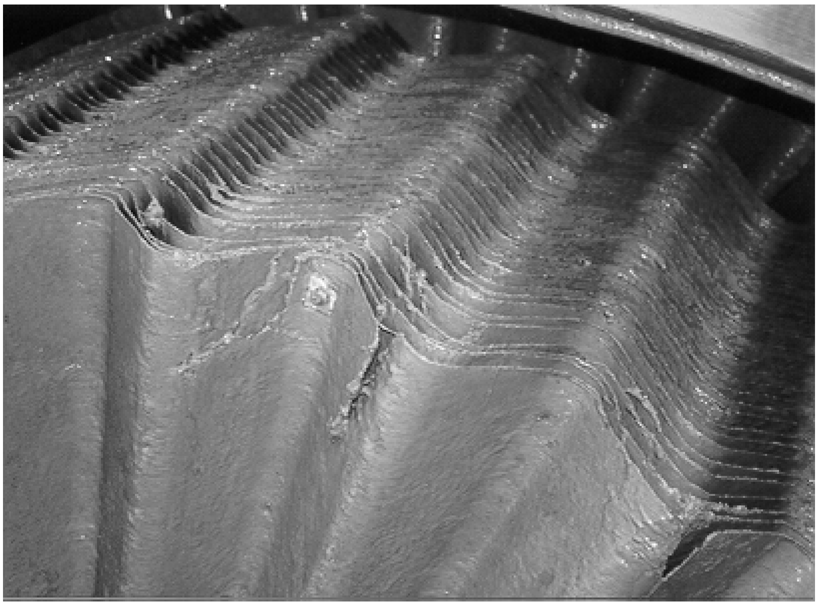


Figure 10 Early signs of GRP media disintegration

A design inadequacy with all GRP media panels is its inability to avoid biomass bridging. No attempts to overcome this problem have been discovered by the author. Typical examples of bridging for two types of GRP panels are shown in figures 11 and 12. Bridging has the effect of reducing the effective treatment area of the RBC unit, reducing operational performance efficiency.

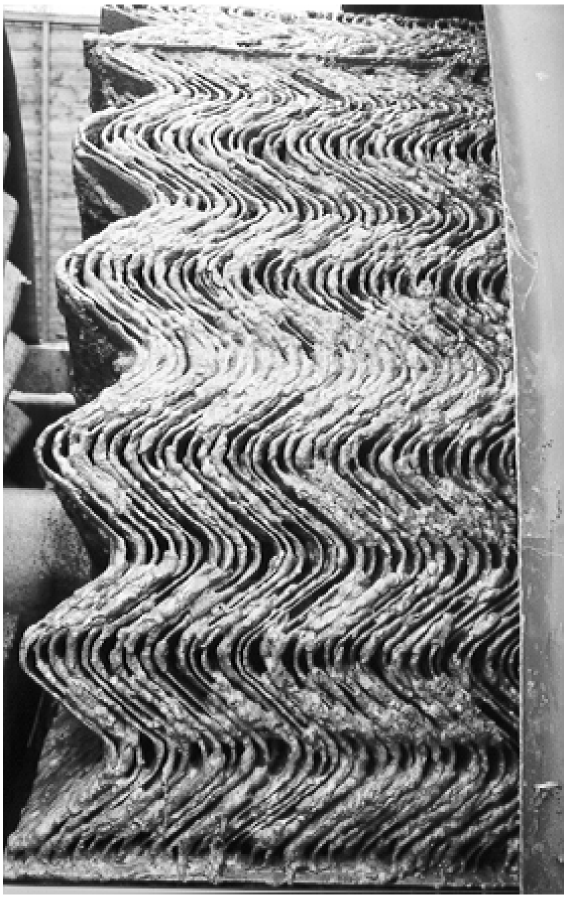


Figure 11 (left) Biomass bridging on GRP media panels

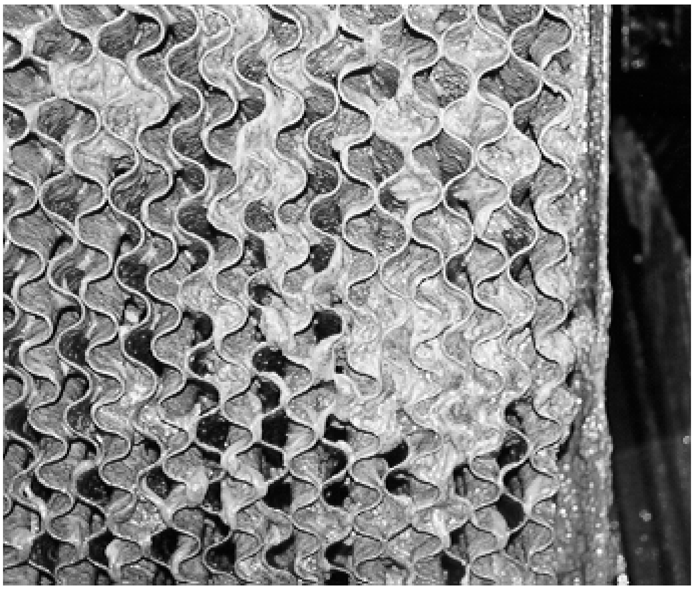


Figure 12 (above) Biomass bridging on GRP media panels

2.2 Polymer media panels

One of the earliest uses of polymers as media panels was the plastic wire mesh design. It is interesting to note that this arrangement employed media segmentation arrangement or pie section. This was a marked change from the use of circular media panels, as with the GRP configuration. To improve the available surface area various designs have been developed. One of which is the circular coil/wire type, see figures 13 and 14. These panels were cemented together at the ends of the media pack, see insert of figure 13, however the process of assembly is time consuming and expensive. The length of these polymer coils can be in excess of 1 meter.

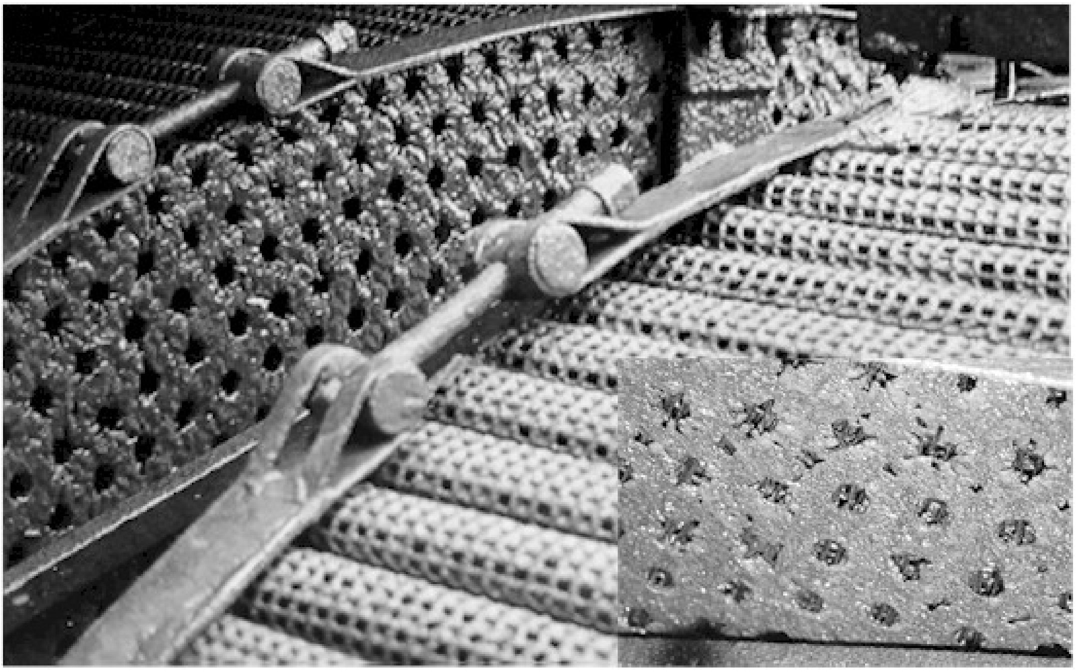


Figure 13 Coil and wire polymer media panel configuration

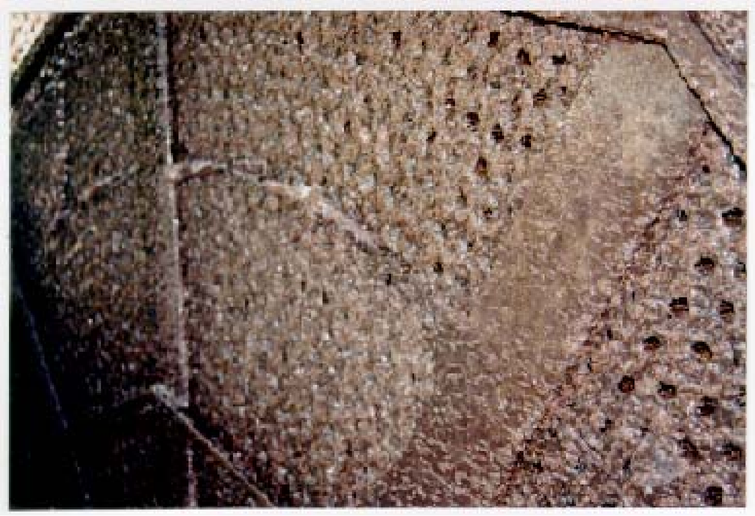


Figure 14 Coil and wire polymer media panel configuration

A similar arrangement of media assembly was a ‘trapezium type’ media configuration of a polymer material (PVC). In this instance the corrugations are inclined at approximately 10 degrees across the width of the media strip. The media strip is wound onto a the steel hub as ‘pairs’ of continuous strip, where the one strip has the corrugations inclined in the one direction, whilst the second strip has the corrugations inclined in the opposite direction, thereby producing a honeycomb effect. Before the media strip is wound on to the hub, an adhesive is applied to the hub thereby bonding the media onto the hub. Furthermore the media strips are also intermittently glued to each other during winding. The final construction should provide a solid media disc pack 3.6 meters diameter by 0.5 meters long, see figure 15. A further advance on this type of media panel design was the triangular corrugation arrangement, however, this new design required a flat polymer sheet to separate adjacent panels, see figure 16.

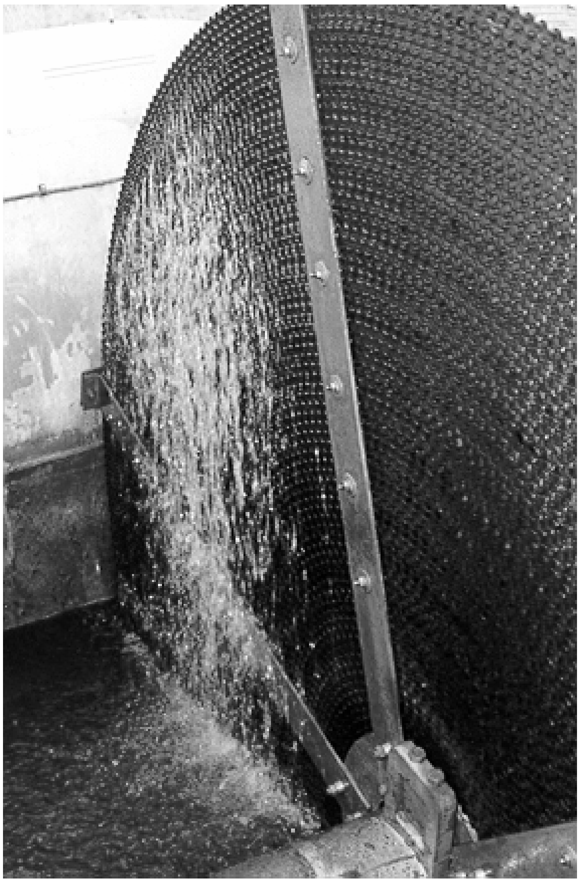


Figure 15 Trapezium type media configuration

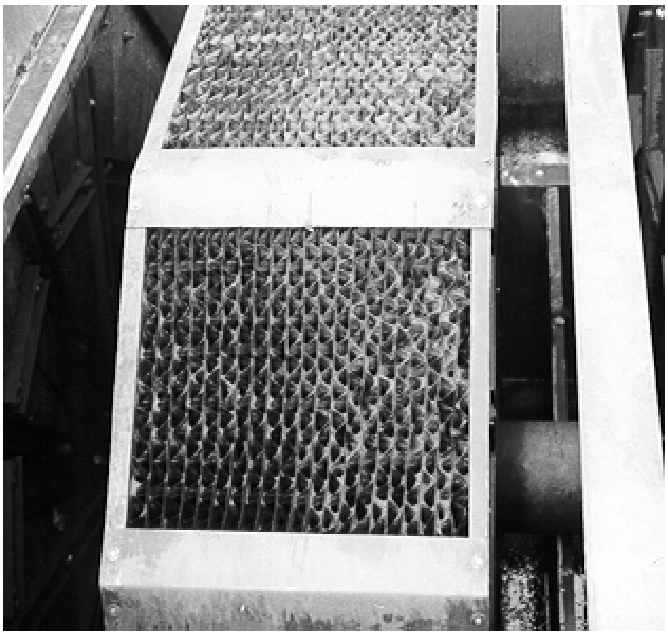


Figure 16 Triangular polymer media panel configuration

These encouraging designs lead to further improvements in available surface area on polymer media corrugations. The three most popular corrugations used to date on polymer media panels can be seen in figures 17 to 19 and were of black high-density polypropylene. The distinct corrugation designs are to ensure drainage of sewage liquor, avoiding bridging.

Figure 17 Polymer media panel, type 1: Layout

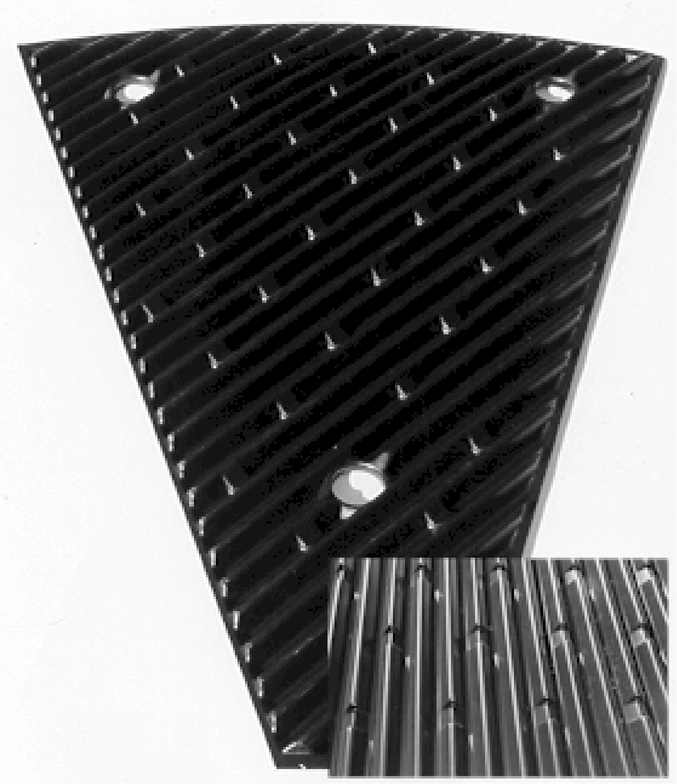


Figure 18 Polymer media panel, type 2: Close view of corrugation

Figure 19 Polymer media panel, type 3: Layout

These new designs originated in the late 1970's and were of distinct segmented arrangement. This had the advantage of ensuring a faster and more economical manufacturing process. The drawback with polymer panels in respect to GRP panels is that they cannot be cemented directly onto the main shaft; consequently they require a supporting structure. Separation of adjacent panels is achieved by placing adjacent corrugations at 90 degrees to each other, see figure 20. Furthermore, the media panels were supported by through rods that ran along the length of the pack. These were passed through circular cutout sections in the media panels and generally three to four through rods are used to support each segment.

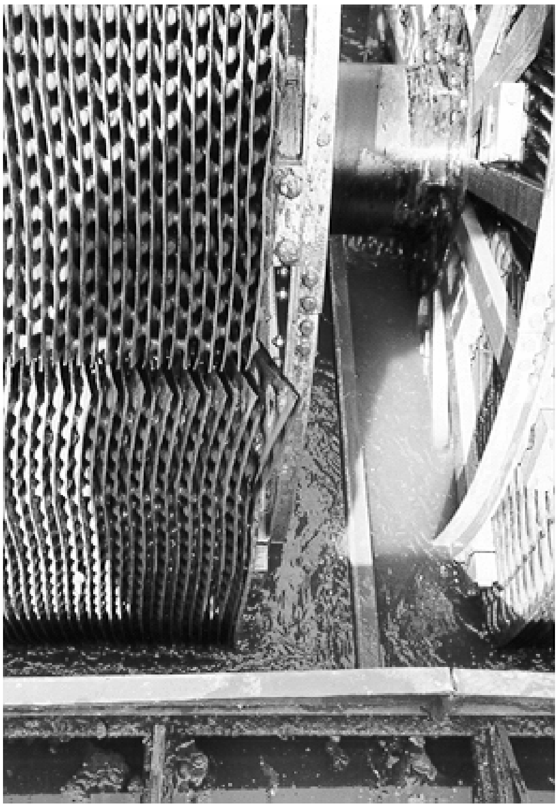


Figure 20 **Separation of adjacent polymer media panels: type 2 panels (see figure 18) separated by their corrugations.**

2.2.1 Mechanical deficiencies of polymer media panels

As this material type is a polymer, creep is a common mechanical deficiency that has been noted. Figure 21 shows the effect of creep on the cross-section of the polymer media coil design, and can be compared with figure 13. This has the effect of reducing the overall diameter of the unit, see figure 22, consequently loosing effective treatment area. The two packs depicted in figure 22 show the comparative effect of creep on the inlet pack diameter.

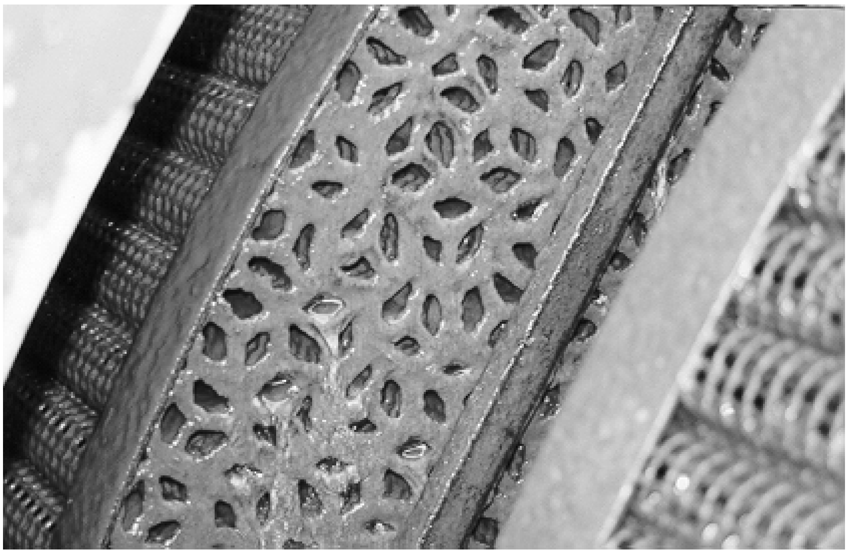


Figure 21 Evidence of creep in 'coil' type media design

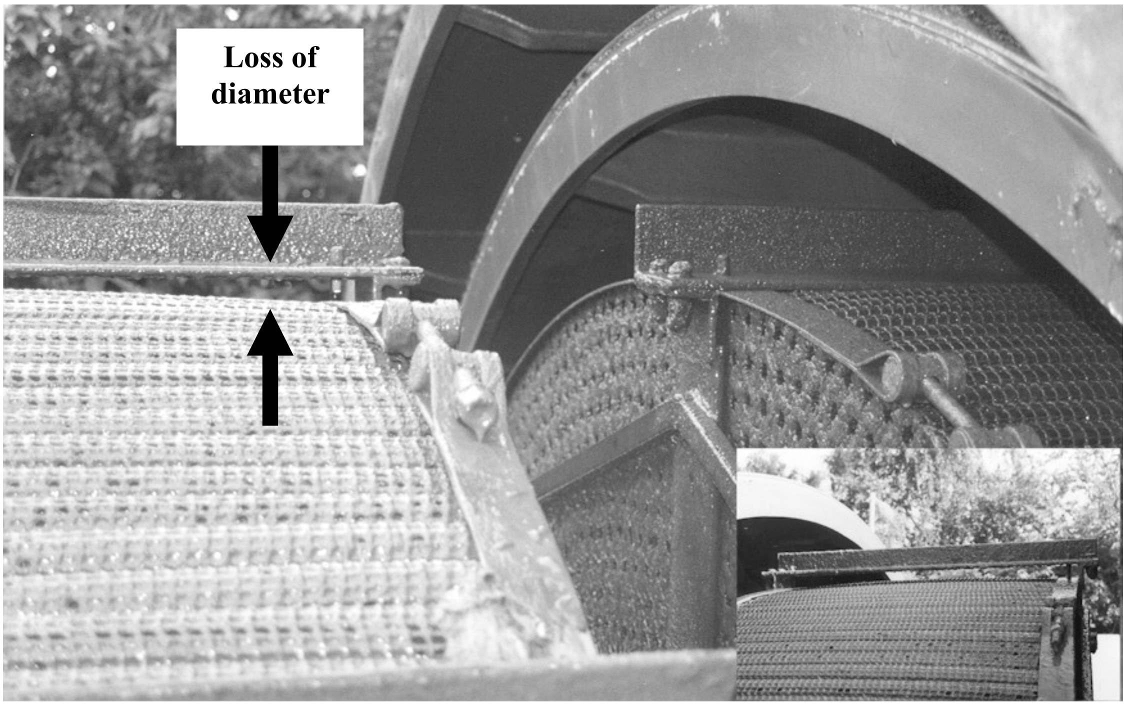


Figure 22 Effect of creep on the overall diameter of the media pack

Tearing, loss of rigidity and crumbling of high density polypropylene media panels are highlighted in figures 23 to 26, and depict mechanical inadequacies in design. Tearing of the media panels generally occurs in the region through which the support/through rods pass.

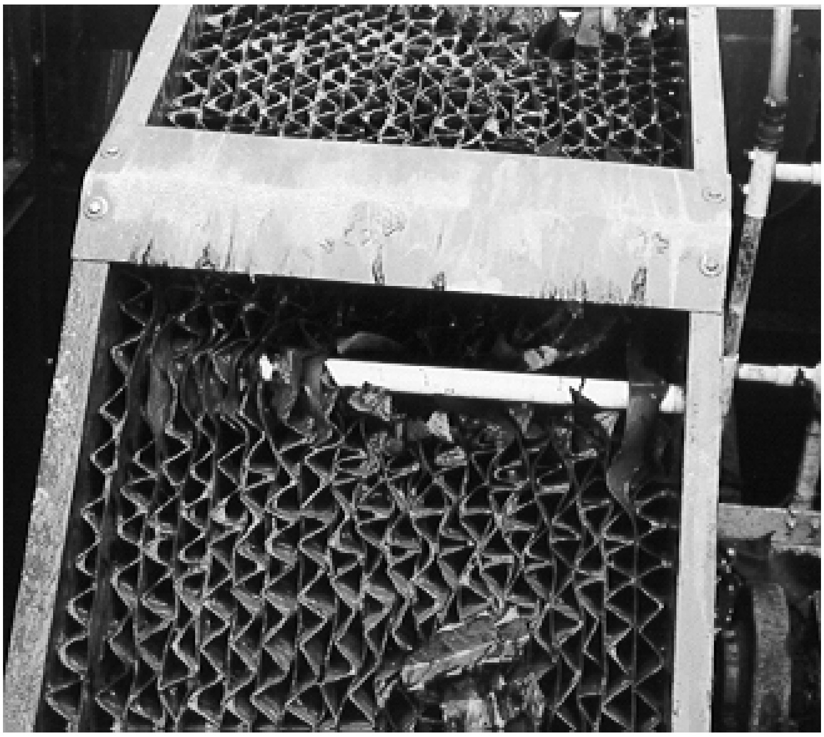


Figure 23 Tearing of High density polypropylene media panels

Figure 24 Tearing of High density polypropylene media panels in the vicinity of the support through rod

Figure 25 Loss of rigidity on an end media panel

Figure 26 Crumbling of High density polypropylene media panels

Similar to the GRP panels, bridging on polymer media panel is very evidently and the authors are unaware of any attempts to overcome this problem in the design of RBC's, see figures 27.

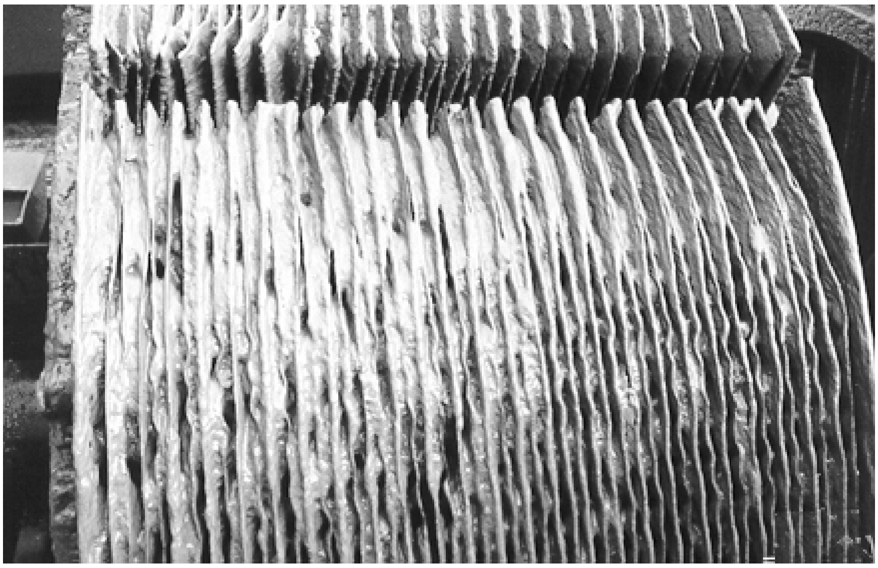


Figure 27 Biomass bridging of High density polypropylene media panels

3. DESIGN EVOLUTION OF MEDIA PANELS

3.1 GRP media panels

As these panels cannot be strengthened, or replaced without physically removing the unit from its operational position, this type of media design is no longer employed in the United Kingdom. The last known manufactured RBC unit that employed GRP media panels was in the late 1980's.

3.2 High Density polymer media panels

Designs that employed the ‘coil type’ media panels could have evolved from the net type design, as the underlying media structure is identical. They are very few RBC units employing this type of media configuration and its manufacture is not employed today.

The most common media designs employ high density polypropylene materials. The various design configurations employing this material have common mechanical deficiencies, particularly strength and rigidity. Tearing of panels generally occurs in the region through which the support rods pass, see figure 28. The reason is attributed to inadequate strength of the hole/ring circumference and poor quality finishes in cutting/manufacture these holes. The jagged edges give rise to stress concentrations, which eventually lead to crack growth and tearing in this vicinity. Current designs have improved the strength in this particular region and more stringent finishing requirements are in place, see figure 29.

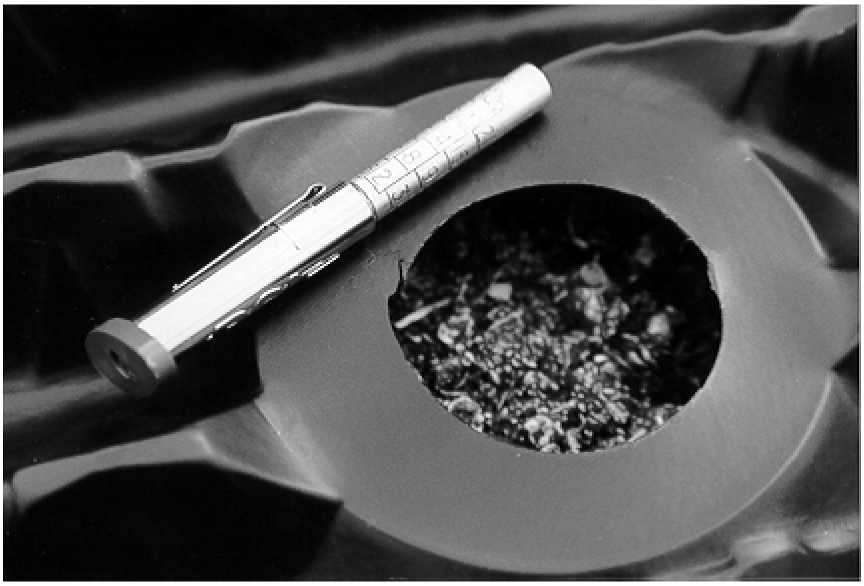


Figure 28 Tearing of media panel in the vicinity of the through rod

Figure 29 Improved strength of hole in media panel

Following a mechanical design audit on RBC's [4] it was noted that the thickness of high-density polypropylene media panels employed (0.5mm) was insufficient to avoid tearing, improve operational life and to retain rigidity. Whilst an increased thickness is currently employed, 0.9mm, it has meant that capital costs have increased whilst whole life costs have reduced.

The problem of rigidity, particularly on the end media panels was initially addressed by cementing the first five media panels together. Whilst this increased the rigidity, problems of this nature were still observed. More recently, particularly on the larger RBC units, supports have been designed to maintaining rigidity, see figure 30. Furthermore, to overcome crumbling of the end panels, a thick polypropylene panel, in the order of 5mm, has replaced the end media panel, see figure 31. In this particular instance, the design also overcomes loss of rigidity.

Figure 30 Design to overcome loss of rigidity

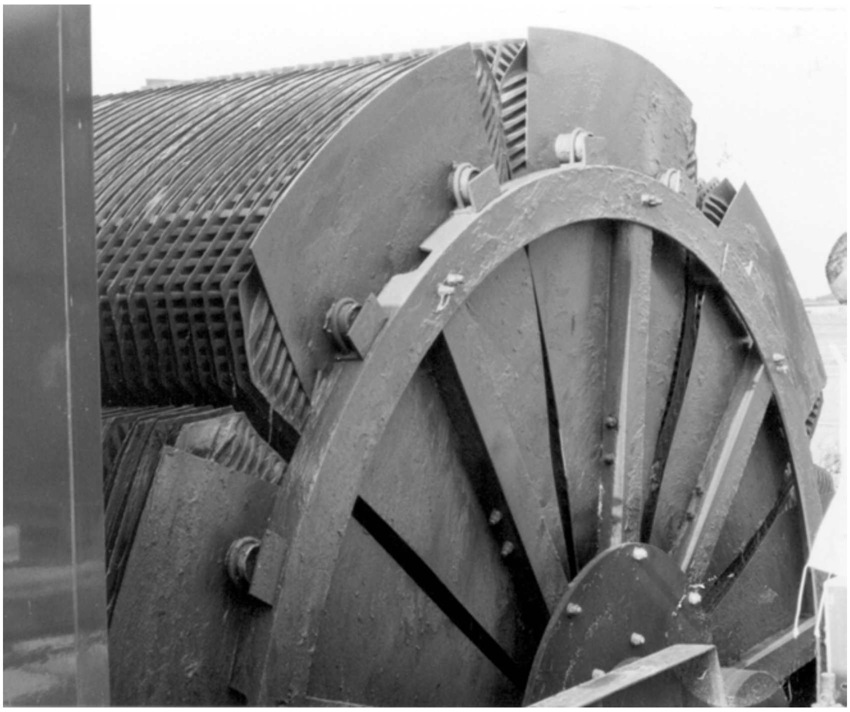


Figure 31 Design to overcome loss of rigidity and crumbling

It is interesting to note that all manufacturers now employ segmented media designs. There is potential to further reduce manufacturing costs, particularly in relation to the process of manufacture/assembly of each segment, as currently, the panels are placed onto a jig to locate the through/support rods. This is a very laborious execerise and a costly manufacturing process; however, it is an improvement on the ‘coil’ type configuration that required circular separators to be positioned between each media panel. The advantage of a segmented approach also portrays manufacturer’s interest in replacing damaged or fatigued polymers segments rapidly. Thus the new support structure arrangements allow for easy removal of media segments, two design types are shown in figure 32.

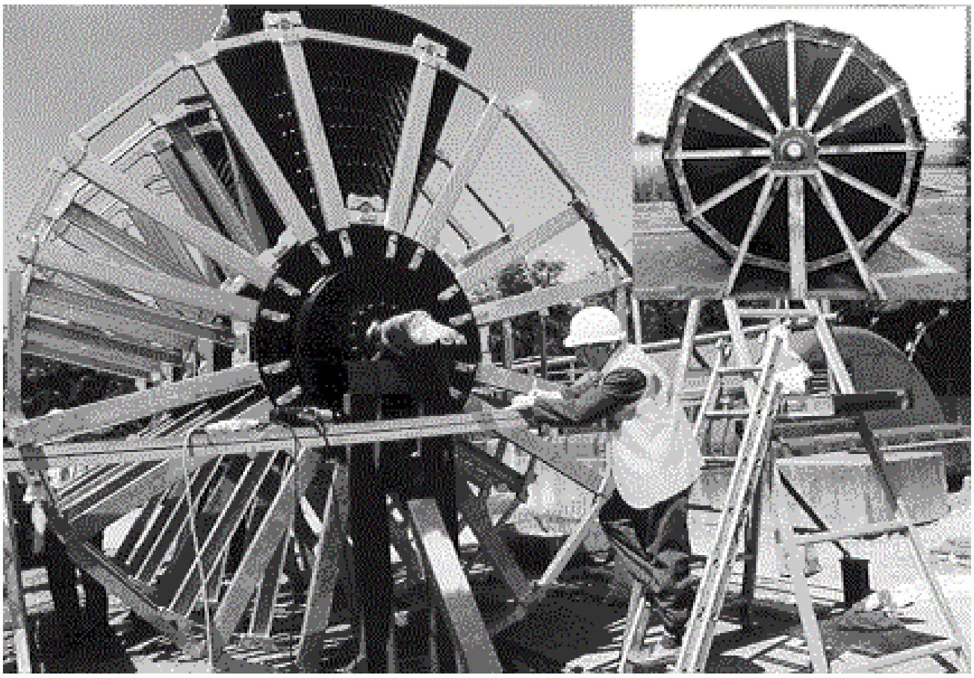


Figure 32 Media segment design

The newest media designs, introduced in 1995, overcomes the problem of water drainage, implying less hydraulic lift and a reduction in motor unit power requirements, see figure 33 and this is a direct cost saving.

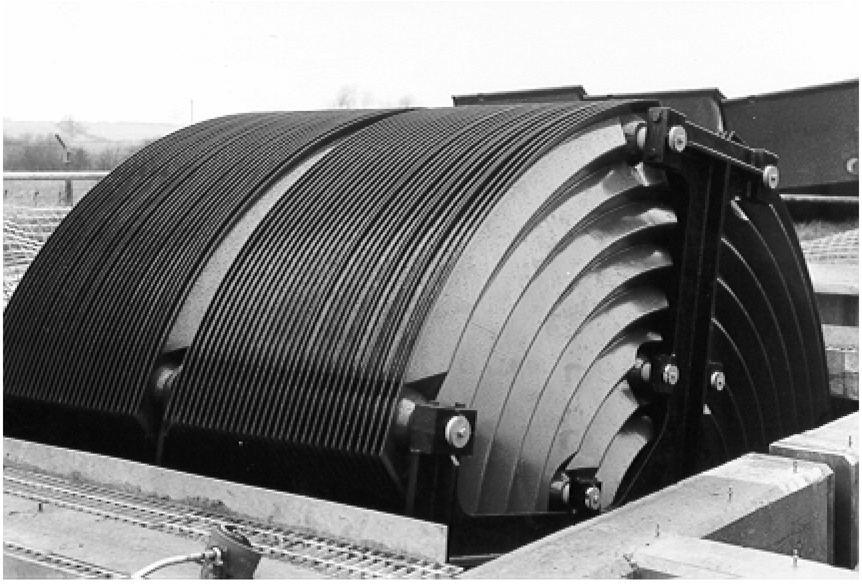


Figure 33 Most recent polymer media design

Furthermore, to avoid bridging the spacing between media panels was set at 26mm. The spacing is achieved by placing circular rings between adjacent panels. There have been no reported cases of bridging to dates, 7 years into its use.

4. TYPES OF MEDIA SUPPORT STRUCTURES

As detailed in the previous sections, there are two types of media panels employed on RBC's; GRP and polymer types. By the nature of their design only polymer panels require a media support structure. The typical weight of a fully functional RBC unit of (diameter 3.0 meters) is approximately 23,000kg for a typical four pack RBC unit having 30% immersion. Of this weight over 70% is attributed to biomass growth and entrapped sewage liquor.

Different RBC support structure designs have evolved over the last 30 years with the aim of producing a functional system at low capital cost. The earliest known RBC unit still operational to date is illustrated in figure 34. The media panels on this unit were of ‘wire mesh configuration’ (see figure 4) and held in position by longitudinal steel through rods which run along the length of the media pack. The through rods are in turn supported by a frame consisting of coated steel angles and plates. The steel angle sections are joined to form radial arms which are in turn bolted onto a plate that is welded to the shaft, see bottom left of figure 35. The through rod ends are bolted onto a circumferential angle rim, see bottom right of figure 35. Each media pack employed three circumferential rims. A steel angle ran along the length of the extreme outer diameter of each media pack and was held by opposite circumferential rims; this is illustrated in the top right corner of figure 35. The steel angle restricts media panel movement and provides extra structural support. To date this design is still operational with no reported faults, though it must be stated that assembly of such a unit will be laborious and expensive due to its intricate construction.

Figure 34 **Design arrangement of oldest known operational unit in the UK**

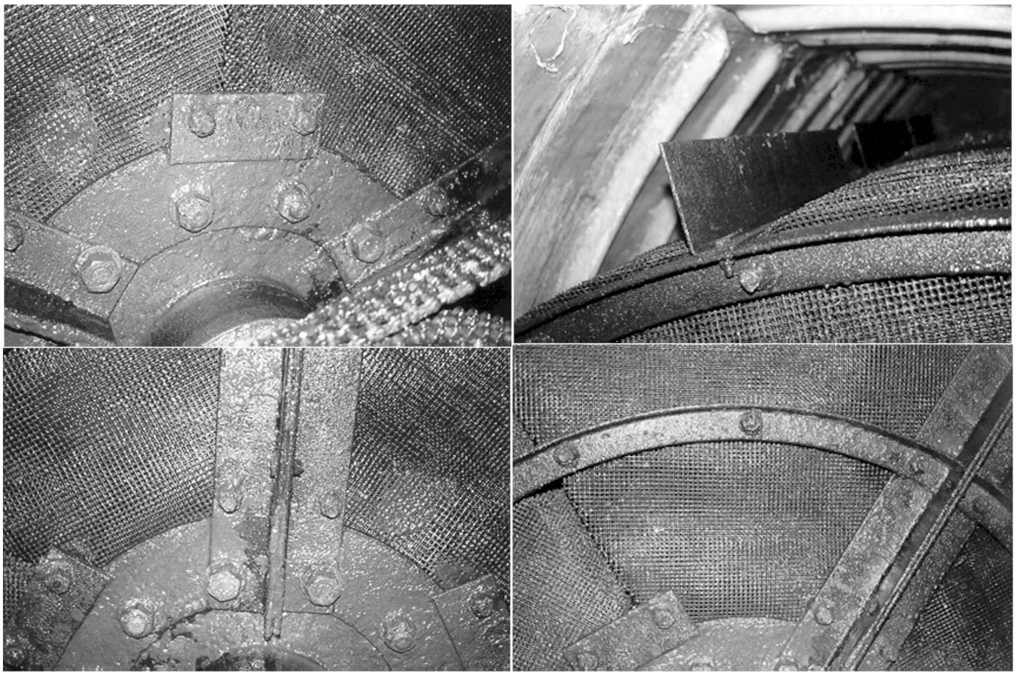


Figure 35 **Design arrangement of RBC unit showing details of the media support frame**

Another design configuration employed for supporting ‘wire mesh type’ media panels is shown in figure 36. The support structure consisted of segmented steel plates bents at its extreme periphery. Adjacent segments were bolted together. The distal ends of the media supporting through rods were bolted to the steel frame. The through rods extend along the full length of each media pack and provided support for the media panels. A total of five through rods are employed per segment. The cost of manufacture of this design is considerably less than that detailed earlier. These are the only two designs known to the author employed for supporting the particular media configuration.

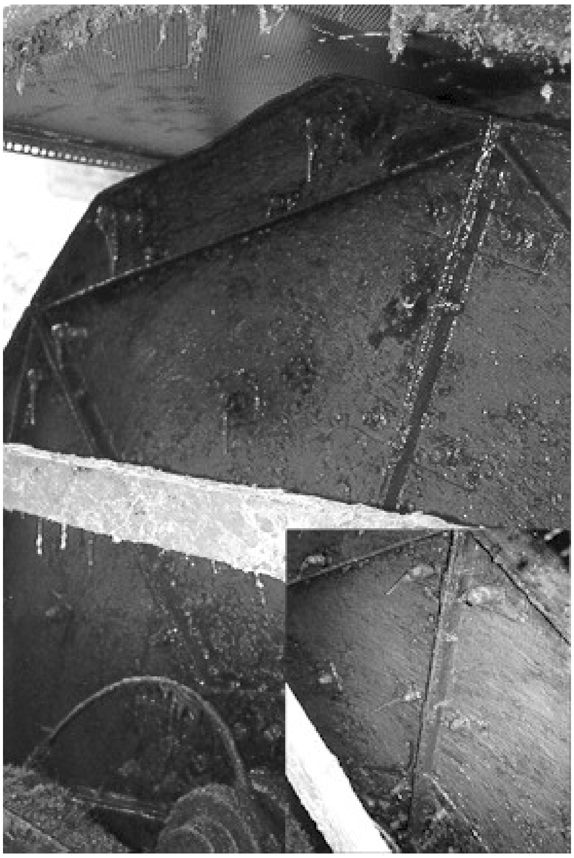


Figure 36 RBC unit with segmented steel plate support frame design arrangement

A more recent design of similar support frame arrangement is illustrated in figure 37. This unit employed circular ‘coils’ (∅20mm) as its media extending along the length of the media pack (see figure 13). The coils were held in position by outer circumferential straps located at each end of the media pack, see insert in figure 37. During assembly the circumferential straps are tightened to aid positioning and locating the media. A steel angle ran along the length of the extreme outer diameter of each media pack and was held by opposite radial spider arms. This particular type of design is submerged by approximately 60% of its total height, consequently the bearings were submerged. However by increasing the submerged area the load on the support structure is reduced. The amount by which a unit can be submerged is governed by operational requirements of the treatment process.

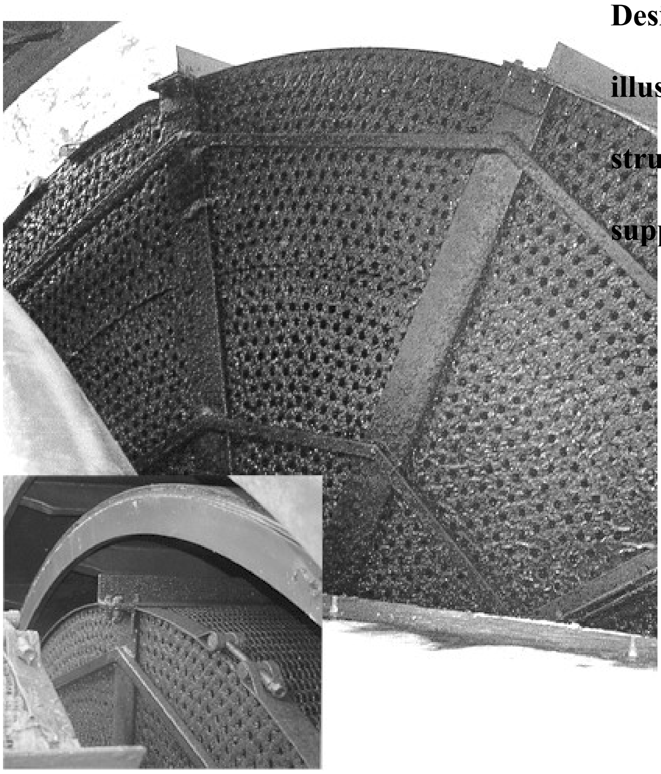
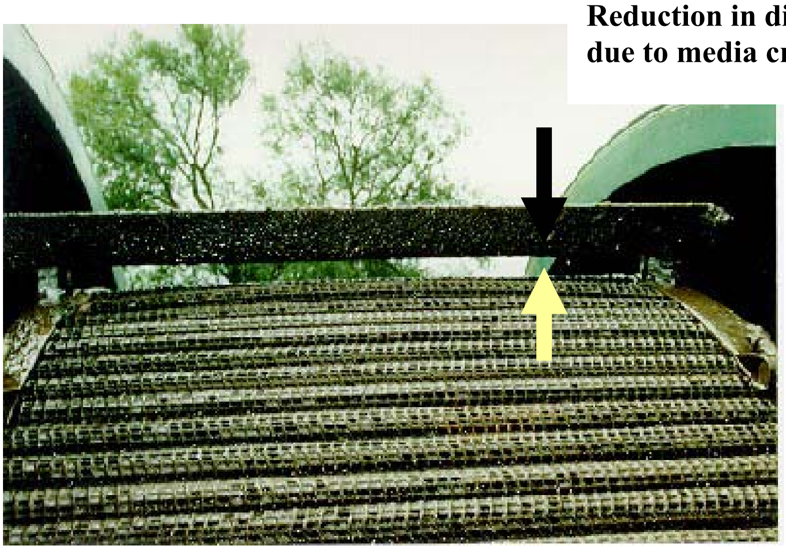


Figure 37 (left)

Design arrangements of RBC unit illustrating coil-type media support structure and outer circumferential support straps

A draw back with this particular design is that the circumferential straps, used to located the media coils can become loose, see figure 38. With the passage of time and under heavy biomass growth, creep of the circular coils results in compression of the media sections. Consequently, the entire media section looses its rigidity and initial size, and the circumferential straps become ineffective in positioning the media sections. The amount by which the media sections can creep is illustrated in figure 39. Furthermore, the flow of sewage liquor through the media sections affected by creep becomes impeded, consequently, the affected media pack carries excessive liquor during its rotation. A direct result of loose straps is media movement, which in turn results in additional impact forces on the support structure causing acceleration forces to be reacted back to the gear drive unit. These reactive forces have caused the foundation bolts, securing the drive unit to the foundation, to work loose. Figure 40 illustrates the consequence of such a mechanism.

Figure 38 Loose outer circumferential strap



Reduction in diameter due to media creep

Figure 39 Gap between structure and media coils caused by media creep

Figure 40 Fracture of foundation bolts due to transient torque produced by loose media pack

The Unit illustrated in figure 41 was designed in the mid 1980's. The support structure is bolted to the shaft, see left picture of figure 42, and this results in increased stress concentrations on the shaft. It is not surprising that this design has experienced early shaft fracture. At the end of the media support structure locating pins fitted into the ends of the through rods, are used to prevent axial movement, see figure 42 (right). However, rotation of the through rods about it location is not restricted and results in grooves being cut at the ends of the through rods, finally cumulating in failure of the through rod.

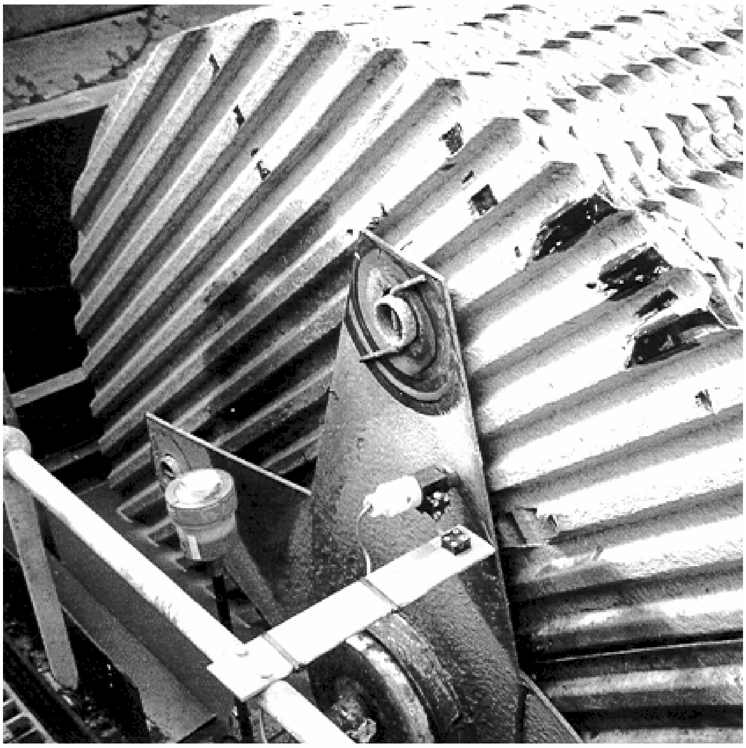


Figure 41 **Design arrangement of RBC unit**

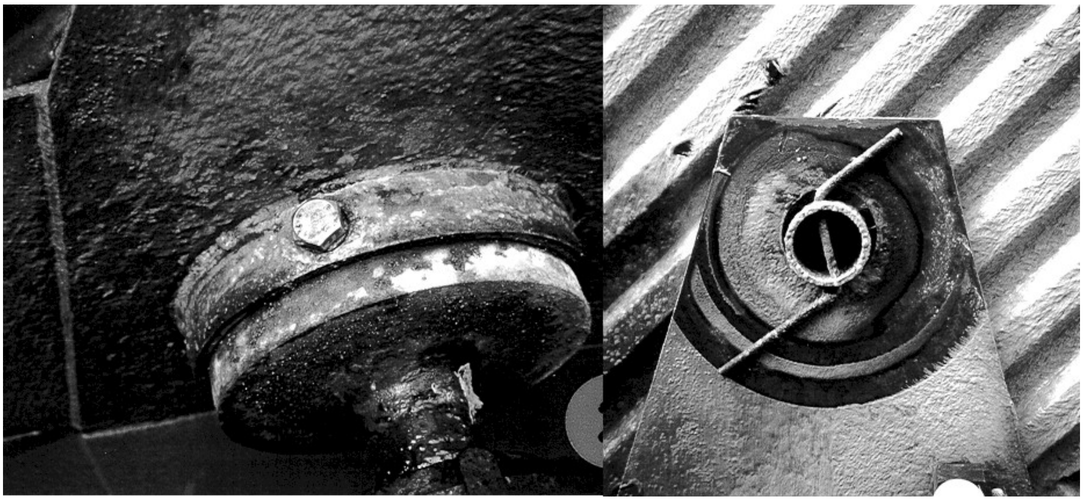


Figure 42 **Design features showing method of clamping support frame to the main shaft and restricting axial movement of the through rod**

The unit illustrated in figure 43 is restricted to RBC sizes with diameters of less than 1.5meters. This design arrangement consisted of black high-density polypropylene media panels held in position by longitudinal through rods, which were in turn supported by a steel support frame.

Figure 43 Design arrangement of RBC unit

In total, four longitudinal through rods supported each media pack. ‘U’ shaped straps clamped the longitudinal through rods onto a flat steel plate, which was in turn welded to an angle steel radial arm, see figure 44. Additional structural support was provided by a flat bar that was bolted to adjacent radial arms, illustrated in figures 43 and 44.

Figure 44 'U' shaped straps clamping the media support through rods to the support frame

The radial angle structure was clamped to a shaft plate. Two designs of shaft plates were employed, the first was welded directly to the shaft, see figure 45, whilst the second was a clamp mechanism that was bolted into position, see figure 46.

Figure 45 Welded shaft plate

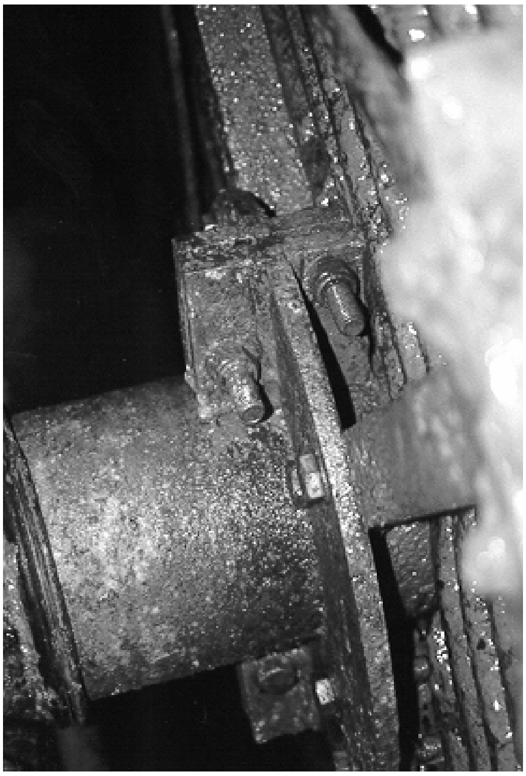


Figure 46 Bolted shaft plate

Materials used for the support structure were of mild steel while the longitudinal through rods and 'U' shaped straps were of stainless steel. It was noted that polymer sheeting was used to prevent direct contact between the stainless steel through rod and 'U shaped strap from the steel plate onto which the rod rested, see figure 47. The purpose of this sheeting is to eliminate galvanic corrosion. It is not clear if over the passage of time, creep of the polymer will result in loss of clamping efficiency of the 'U' strap. Furthermore, no attempt had been made to prevent contact between the steel supporting structure and the stainless steel nuts and bolts and consequently these units experience galvanic corrosion. This type of RBC is only ideal for low load requirements.

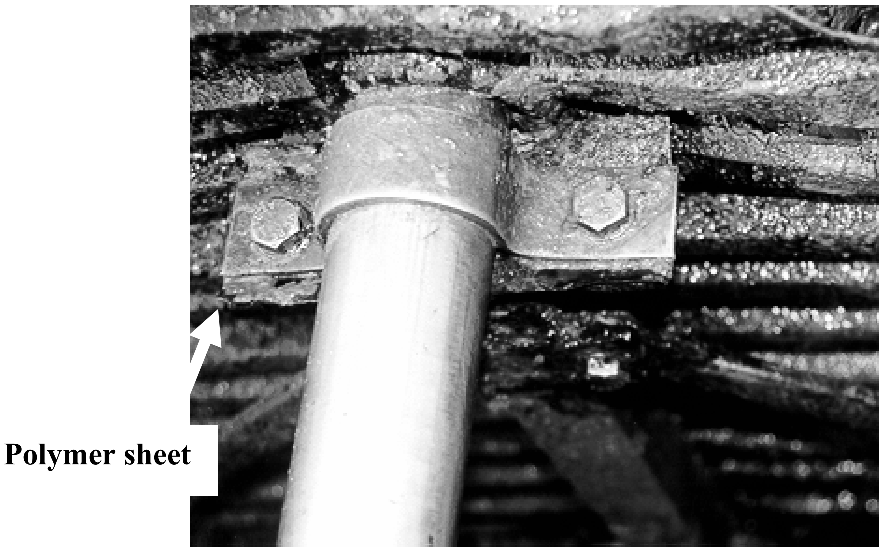


Figure 47 Plastic sheet to prevent contact between different materials

Another design employed for low load requirements illustrated in figure 48 and employed black high-density polypropylene media panels. This unit is restricted to diameters of 1.0 meters or less and its panels are held in position by longitudinal through rods, which were in turn supported by a steel frame.

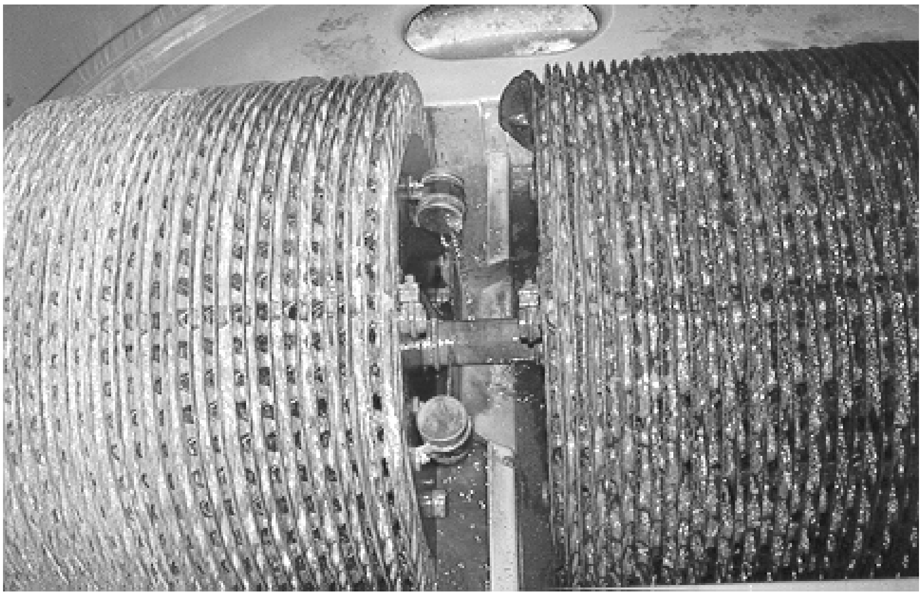


Figure 48 RBC unit layout

Similar to the previous design each media pack was supported by a total of four longitudinal through rods. Two of the through rods were clamped onto an angle structure, which was in turned clamped to the main hollow shaft, see figure 49. The other rods were not supported and simply rested on the media panels.

Figure 49 Media pack support structure and clamping arrangement

'U' bolts were used to secure the steel angle to the main hollow shaft and clamp the through rods to the angle steel, see figure 49. Flat plates were used to make up dimensional discrepancies between the 'U' bolts and the longitudinal through rods, see insert of figure 49. A circular plastic disc was positioned between the angle steel and the media panels and was intended to provide lateral support to the panels. Improvements of the ‘coil type’ media panels have lead to the ‘trapezium type’ (PVC) media corrugations. The support structure for such a configuration is illustrated in figure 50.

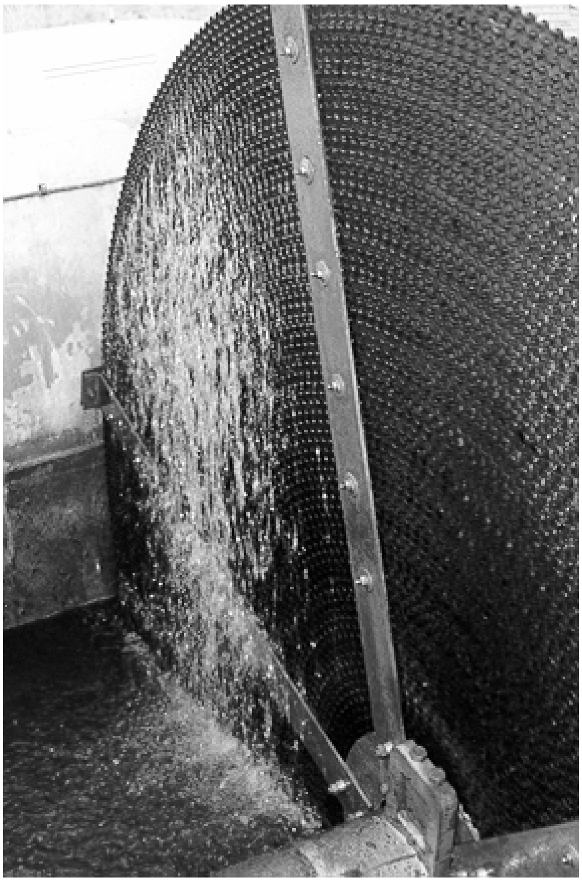


Figure 50 Support structure design arrangement for trapezium type media corrugations

In order to provide a positive drive between the media pack and shaft, twelve radial spider arms (six per side) are clamped to the media pack using six through rods per pair of spiders, the spiders are in turn bolted to the shaft hub. Moreover, to ensure a good transference of torque between the spiders and media pack, two strips of neoprene are sandwiched between the media pack and spider arm, see figure 51. In addition to the spider arms, two circumferential stainless steel banding strips are employed to offer further strength.

A weakness with this design is that the action of clamping the neoprene strips between the media pack and the radial spiders produces a compressive stress into the side walls of the PVC media corrugations. Moreover, because both the neoprene and the PVC media pack are viscoelastic materials, creep will most certainly occur, or even crushing, resulting in loss of clamping force between the media pack and spiders. The consequences of loosing the clamping force between the spiders and media pack, is that the weight of the media pack is transferred directly onto the shaft hub causing crushing of the PVC corrugations. Figure 52 clearly illustrates the effect of crushing which has taken place under one of the radial spiders.

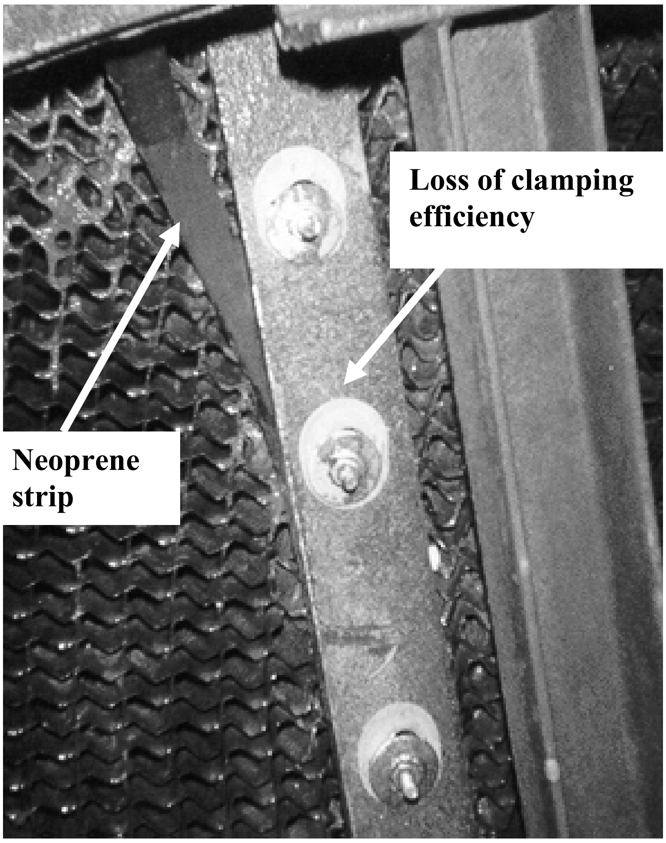


Figure 51 Evidence of loss of clamping efficiency

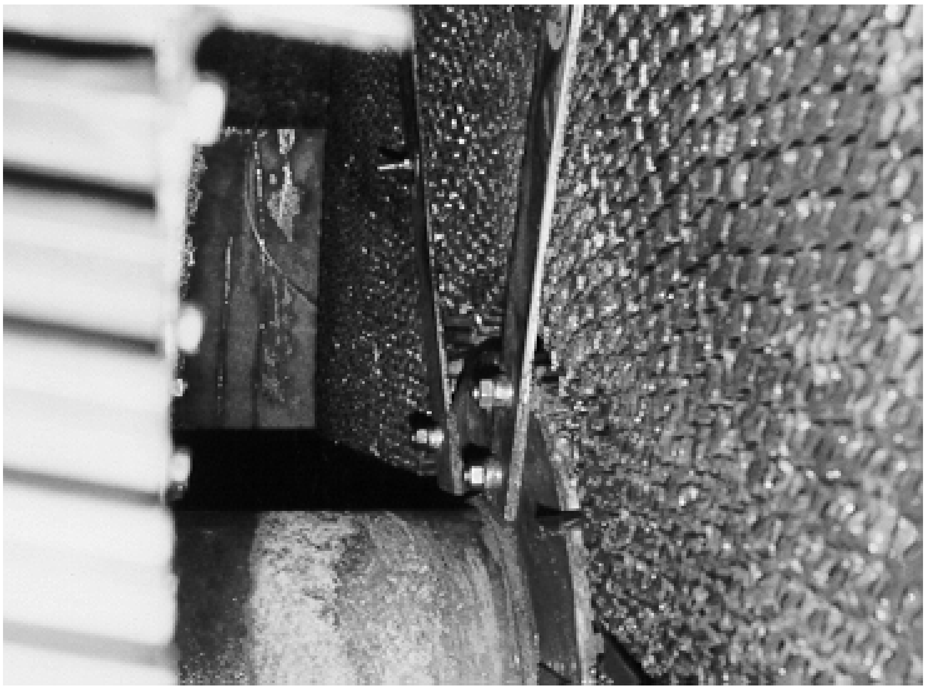


Figure 52 Evidence of crushing of media

A widely employed design of RBC used for high load conditions with diameters of up to 3 meters can be seen in figure 53 and consists of one radial spider per media segment, manufactured from rolled channel or angle, and three through rods per disc segment. There are 8 segments per pack with a total of 24 through rods. The spider (radial arm) is secured to the shaft plate with bolts and the plate is welded to the shaft. The supporting structure consisted of stainless steel angles or channels, plates, ‘U’ bolt clamps and through rods. The ‘U’ bolts were used to clamp both the inner and outer through rods onto the support frame, see figure 55 (left). For the older designs, illustrated in figure 20, the circumferential angle frame is welded to the radial arm whilst for recent designs a metal plate is used to circumferentially locate the individual segment frames, the plate was bolted to the outer-rim of adjacent support frame segments, see figure 54 and 55 (right). Furthermore, the arrangement of the steel angle circumferential rim in figures 54 and 55 allowed for axial restriction and location of the through rods, not provided by older designs. In more recent designs of this latter configuration (figure 21), steel plates have been welded onto the end frame to improve the strength and stiffness of the media support structure, see figure 56. This development is a direct consequence of failure on the support structure due to the inability to support high bending stresses. In addition, diameters of RBC units employing this modification increased to 3.6 meters. It is interesting to note that the method of welding the shaft plate to the shaft was not as illustrated in figure 46 where the weld was completely circumferential. In this instance the weld was at four positions on the shaft, see figure 56. This is an attempt to reduce stress concentrations in the vicinity of the weld.

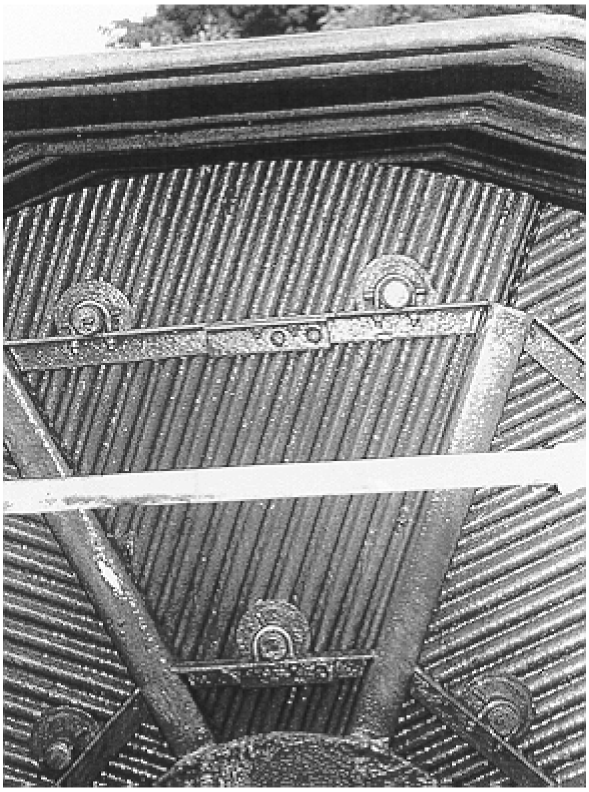


Figure 53 RBC design arrangement employed for large units

Figure 54 RBC design arrangement showing double radial spider arms per media segment

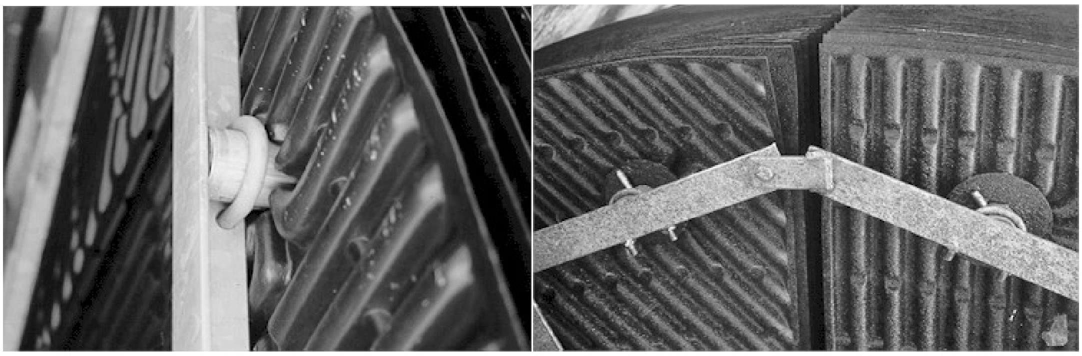


Figure 55 Methods of retaining through rods to the support structure

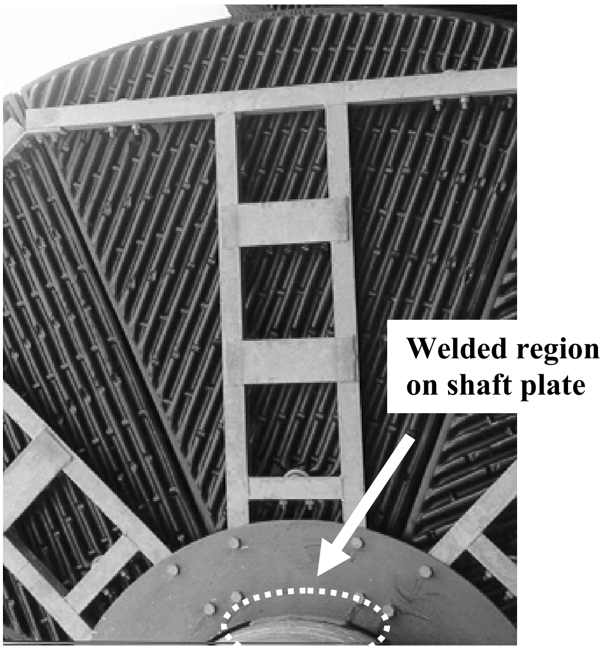


Figure 56 RBC design arrangement to improve bending resistance

On these designs, clamps supporting the through rods onto the support frame have experienced serious loss of clamping efficiency due to their poor design. The ‘U’ bolt or clamp does not have sufficient strength to adequately withstand the bending couples produced by the through rod, particularly when the media segment is in the horizontal position [4]. Moreover, the clamping mechanism is not sufficient to prevent localised fretting, which would ultimately result in loss of tightening torque of the securing nut. The deeper implications of the above, is that the ‘U’ bolt would either come free, or experience fatigue fracture within a few months of operation, see figure 57. The reason for failure is attributed to the effect of low frequency corrosion fatigued coupled with possibly excessive tightening torques on the ‘U’ bolts [1]. Therefore any improved design must be sufficiently robust to withstand the very large bending couples produced by the through rods, furthermore, cognisance should be given to the reaction load when the media panel is in any circumferential position as the RBC rotates.

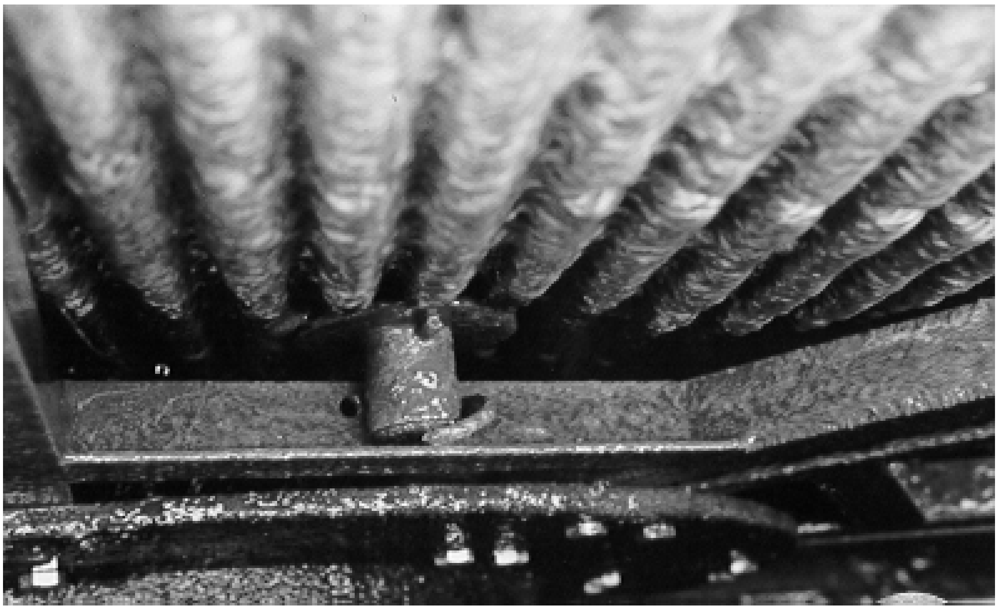


Figure 57 Fractured 'U' bolt

Furthermore, a number of these RBC designs have suffered from support frame failure. It is perhaps interesting to note that this design employs structural steelwork having the lowest cross-sectional dimensions compared with other similar size RBC examined. Whilst it could be argued that this design offer low capital costs they hide the high whole life cost. In addition, due to the low fatigue limits of a lighter frame, fatigue fracture is common, see figures 58 and 59.

Figure 58 Fracture support structure; Insert shows fracture at different rotational position.

Figure 59 Fractured support structure

Another common design of RBC with a diameter ranging from 2 to 3 meters is illustrated in figure 60. It consists of channel radial spider arms and an angle circumferential rim. The design consists of between 4 to 8 segment sections with three supporting through rods are employed per segment. During manufacture, the segments are lowered into the support structure frame. For this reason a section in the region where the radial spider arm was clamped to the outer circumferential rim was cut away in the circumferential rim, see figure 65. Whilst the reasons for the cut away section is understood, it does pose the problem of introducing localised stresses. Two of the through rods are retained by 'U' shaped straps on the outer circumferential rim, as illustrated in figure 61. The third through rod, referred to as the inner through rod is rested onto a plate within the radial channel arm, see figure 62. A bolt is used to retain the inner through rod in this position, see figures 60 (insert) and 62. As the inner through rod was not secured to the radial arms they have been known to work loose with costly consequences, see figure 63.

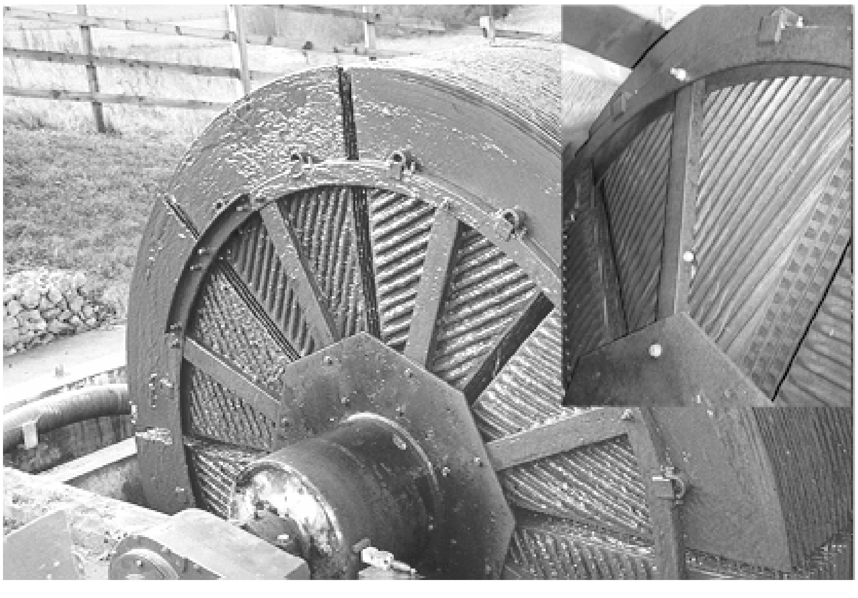


Figure 60 Design arrangement illustrating channel section radial arms

Figure 61 'U' strap for retaining through rod to support structure

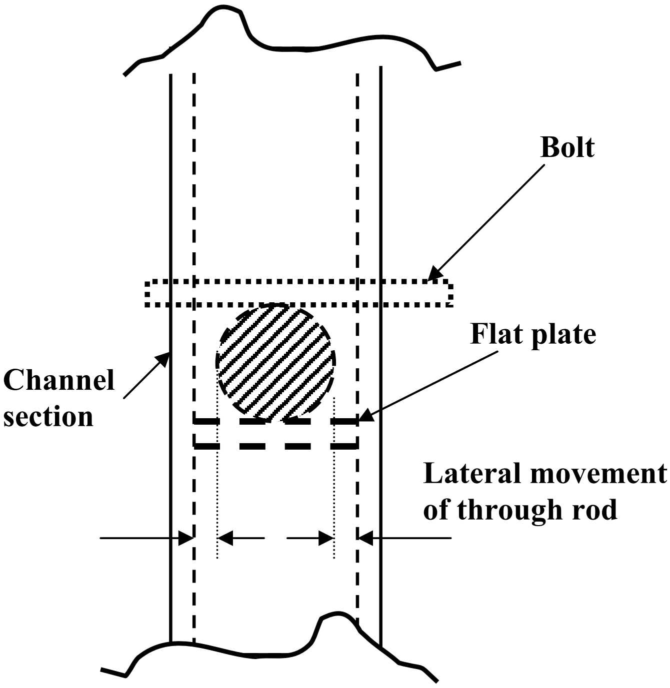


Figure 62 Position of inner through rod on support structure

Figure 63 Loose inner through rod

In addition, due to the lack of restriction of the inner rod, media segment movement has been observed on numerous sites, see figure 64, which will result in additional impact forces being placed on the media support structure and can accelerate the process of fatigue failure and loss of bolt tightening torque. The former has been experienced on ‘U’ straps, see figure 65. It is interesting to note that the fracture occurred in the region of maximum stress.

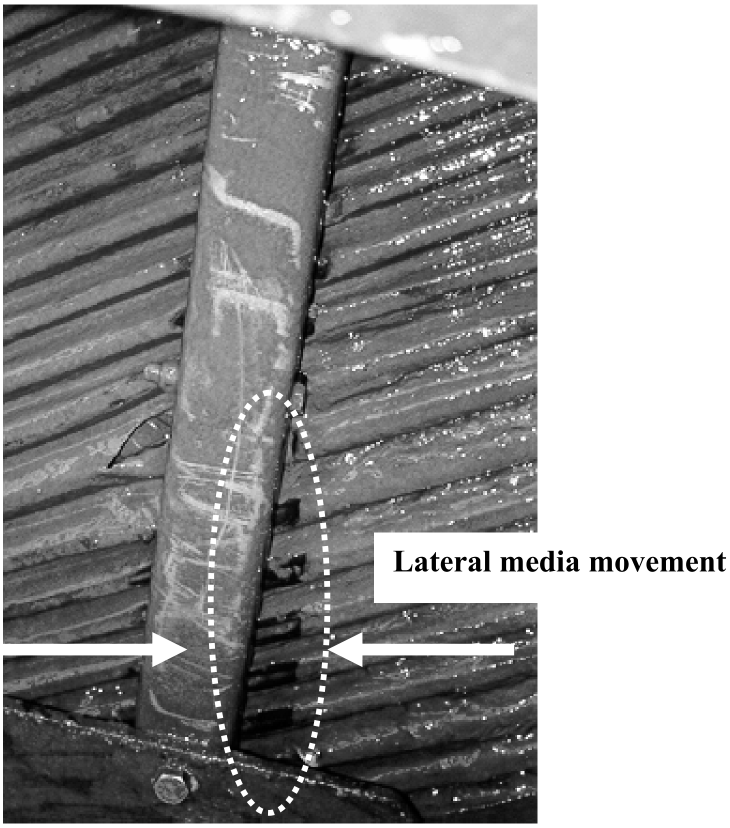


Figure 64 Media segment movement

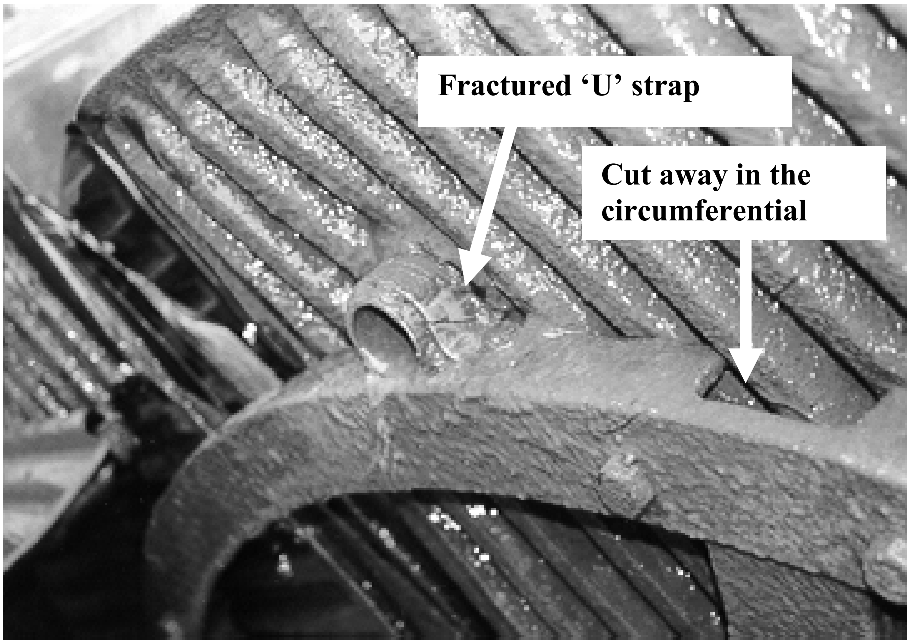


Figure 65 Fractured 'U' strap

Successful attempts to restrict movement of the inner through rod have been made by positioning a hollow circular piece over the through rod end in an attempt to restrict its lateral movement. Other attempts include the use of 'V' shaped plates, see figure 66.

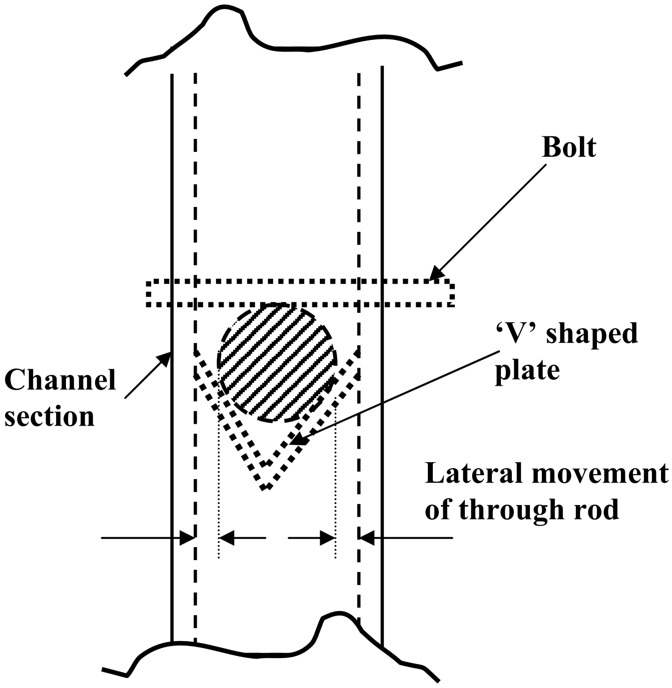


Figure 66 'V' shaped plate to restrict inner rod movement

Whilst earlier designs did not restrict axial movement of the outer through rods, see figure 67, this has been overcome by welding end plates onto the circumferential angle rim, see figure 60, 61 and 68. Figure 67 shows axial movement of an outer through rod and bending of the circumferential rim. The latter is a direct consequence of the large bending moments the structure is subject to.

Figure 67 Bend support structure

In addition due to the inadequate clamping efficiency of the ‘U’ strap the outer through rod has been known to rotate within its strap and cut into the support structure, see figure 68 and 69.

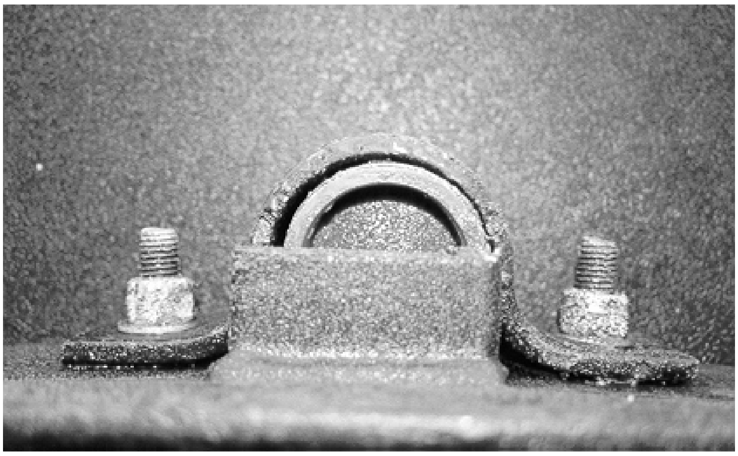


Figure 68 Inadequate clamping of through rods plus axial end stop

Cut in end plate due to rotation of through rod

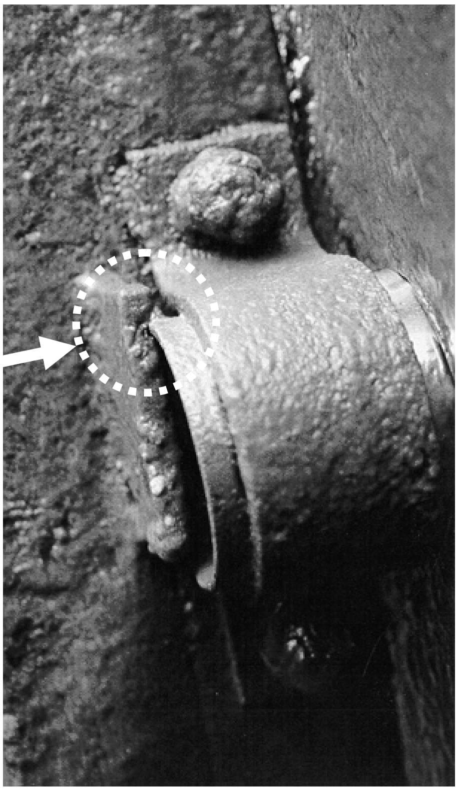


Figure 69 Rotation of through rod within its clamp

Of the designs already detailed it has been observed on numerous units that a mixture of materials were employed giving rise to galvanic corrosion. For instance whilst, the through rods employed were of stainless steel, the ‘U’ straps used to secure these through rods to the support structure were a mixture of stainless and galvanised steel. Furthermore, stainless steel bolts had been used to clamp components onto a steel structure. It must be noted that the main hollow shaft on RBC’s detailed was always of mild steel. To assist in separation of stainless steel bolts from the steel structure plastic washers have been employed, see figure 70. Over the passage of time, these plastic washers will creep with the net result of loss of bolt tightening torque, see figure 71.

Figure 70 Plastic washer

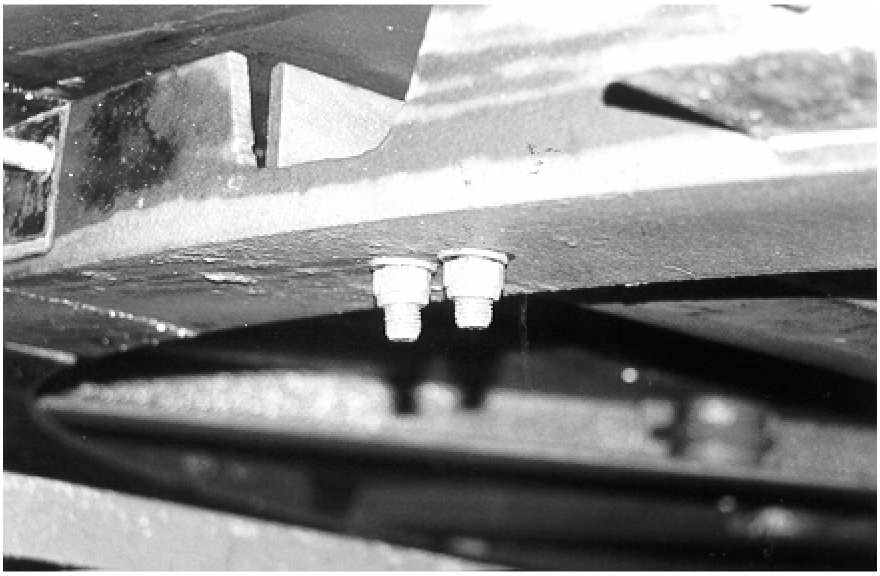


Figure 71 Loss of bolt tightening torque due to plastic washer creep

This will result in movement of components creating additional impact forces on the structure.

Other direct consequences of mixing materials include corrosion of the ‘U’ bolts and ‘U’ straps, see figure 72. In these instances there is a direct loss of cross-sectional area of the bolts resulting in a reduction of load carrying capability and eventual fatigue fracture. It is interesting to note that on the ‘U’ bolts corrosion begins in the regions experiencing the highest stresses, see insert of figure 72. This phenomenon is referred to as stress corrosion fatigue.

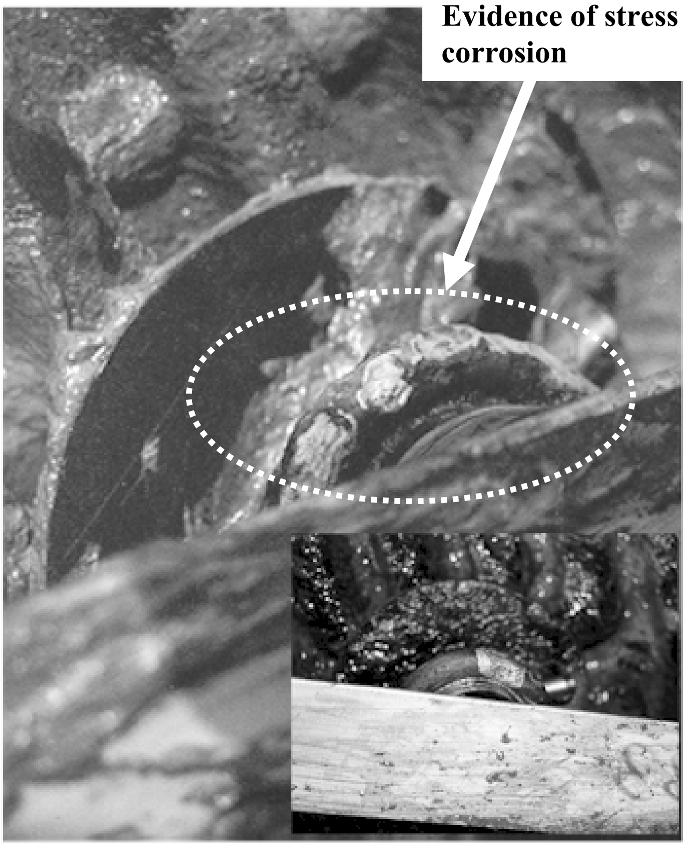


Figure 72 Stress corrosion of ‘U’ bolt

Another design configuration employed in the United Kingdom for heavy load requirements is illustrated in figure 73 and consists of one radial spider per disc segment manufactured from rolled channel. However, only two through rods on each segment were used to support the polypropylene media panels onto the support structure. A further two through rods were used to hold the media panels in position and plastic washers were employed for this purpose. This provides inadequate support of the panes and it is not surprising that the media panels at the inlet end, where the biomass growth is heaviest, has collapsed, see figure 74. Each media pack consisted of 12 segments.

**Figure 73	Design arrangement of RBC unit**

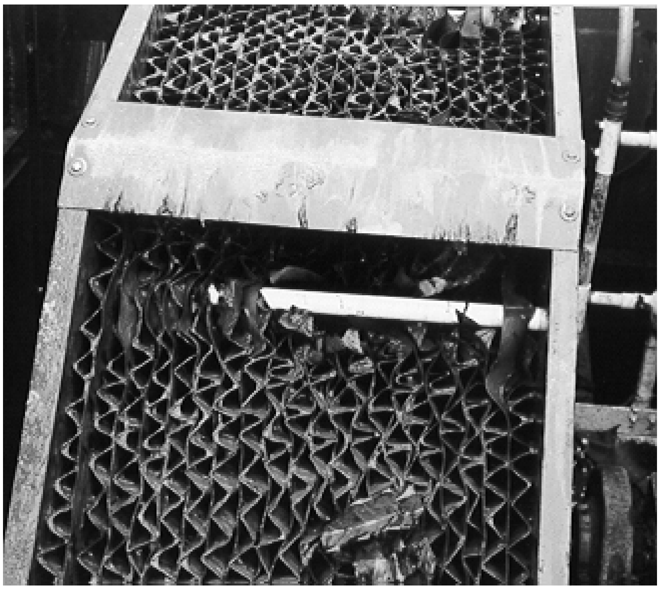


**Figure 74	Inadequate support for media panels**

The spider is bolted to a shaft split hub and are mechanically locked by the use of lock nuts, see figure 75 for a typical arrangement. The types of positive locking employed include nylon lock nuts or double lock nuts, dependent on RBC unit, the latter can be seen in figure 76. The drawback with nylon lock nuts exposed to sewage liquor over a passage of time is that they have been known to work loose. Traditionally manufacturers employing double lock nuts (sometimes referred to as ‘Jam’ nuts) have placed the smaller nut on top of the bigger nut. Double lock nuts have the advantage of requiring minimum skill provided certain basic rules are applied. Historically the nuts are of different thickness, one standard nut and the other half the thickness of the standard nut. In assembly the thinner nut should be fastened first and the large nut fastened on top on the thinner nut [5].

Figure 75 Split hub arrangement

Figure 76 **Improper bolting of double lock nuts**

The distal end of the radial spider is secured to the outer circumferential rib via a weld cruciform plate onto which is bolted a further rolled channel using, figure 77 illustrates this technique.

Figure 77 **Circumferential design arrangement**

The design arrangement illustrated in figures 78 and 79 are restricted to RBC's with a diameter of 2.0m and employs four segments, each segment had a total of three through rods. Four radial steel channel spiders were employed which were welded at the distal end to steel angle sections. These were in turn bolted to steel channel sections acting as circumferential rims, see figure 79 (left). The spider is secured to a shaft split hub, as describer earlier (see figure 75) bolts which are mechanically locked by the use of lock nuts. The through rods are secured to the media pack support frame using a single bolt, locking is achieved by making use of a spring washer.

Figure 78 Design arrangement of RBC

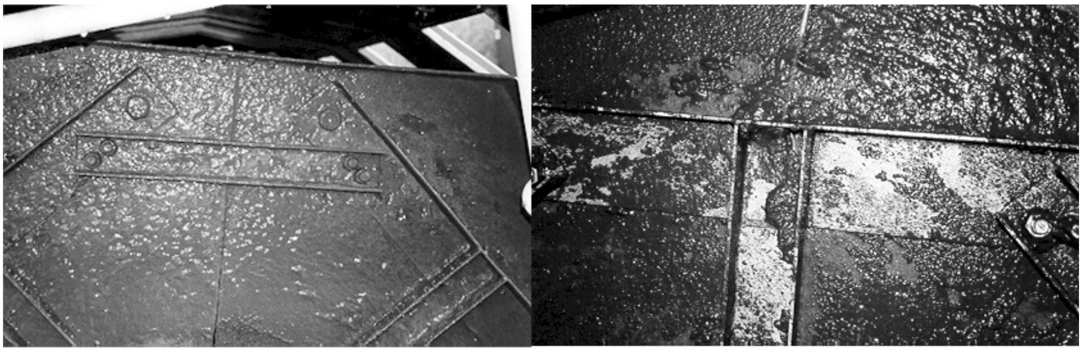


Figure 79 Close view of design configuration employed in figure 78

One of the most common RBC designs is illustrated in figure 80 and ranges in size from 3 to 4 meters in diameter. The support structure consists of one radial spider, manufactured from rolled channel, and four through rods per disc segment. All four through rods are secured to the support structure and a total of 12 segments were employed per media pack. This is a marked improvement on the earlier design in which only two through rods were attached to the support structure (figure 73). This improvement offers more support for the media panels.

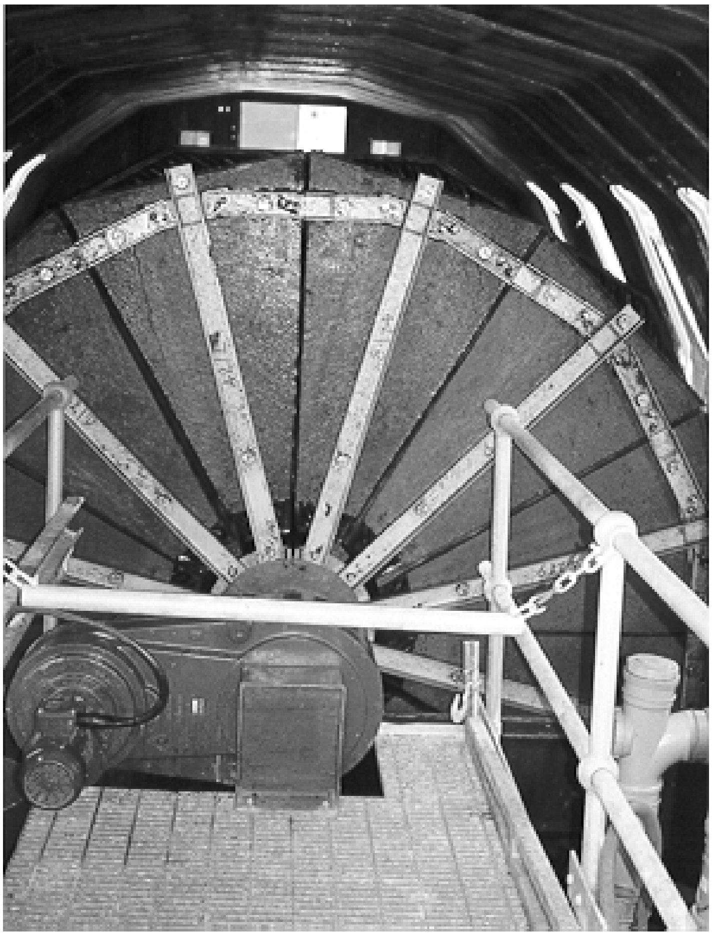


Figure 80 Segmented design arrangement of RBC

The spider is bolted to a shaft split hub as with previous designs described earlier. Other features of this design are identical to those reported in figures 75, 76 and 77. The through rods are secured to the media pack support frame using a single bolt and locking is achieved by making use of a spring washer, however, on a number of RBC's this through rod securing bolt has become loose, see figure 81.

Figure 81 Loose bolt employing spring washer

A concern with these designs that employ a split hub for clamping the radial spider arms to the shaft is that the clamps are seated on a GRP overlay and it is impossible to estimate how long the GRP overlay will maintain its integral shape. Should hydrolysis of GRP overlay result in loss of rigidity, it is possible for the clamping plate to slide and rotate about the main shaft. However, a few RBC's of this design have been in operation for many years and the split shaft clamp has not shown mechanical distress.

5. EVOLUTION OF MEDIA SUPPORT STRUCTURES

Over the last thirty years the evolution of mechanical design was firstly governed by economies of manufacture. This is illustrated by the change from detailed intricate designs to segment less robust support structures. However, the newer designs of RBC units have been plagued with mechanical deficiencies and this has governed more recent design changes. The mechanical design of an RBC is not simply selecting the best material to perform a particular function based on stress levels, but is more concerned with the corrosion and fatigue behavior of the various materials chosen at low speeds of loading

Before attempting to design any machine component, it is most important to understand the mechanism by which the component is subject to force loading, and whether the loading is static or cyclic. For example, on most medium size RBC's the media segment is supported by three through rods, whereby each rod is reacted back onto the media support frame and held in position by some form of end clamp. When establishing the magnitude of loading applied to each of through rods per media segment, it is a common misconception to assume that each through rod supports the same load and that the loading is constant. The actual load value is dependent on the type, size and orientation of the media corrugations; moreover, the loading is "dynamic" resulting from rotation. For example, as the media emerges from the liquor, draining off water has to be considered in addition to the biomass loading. Furthermore, as the media segment re-enters the liquor the loading has now changed both in magnitude and direction, thereby causing reversed cycle loading, which is an important factor when selecting the size of through rod and rod end clamp design. This is probably why tearing of the media in the vicinity of the through rod hole always occurs at the one hole before progressing onto the next [4].

Three design strategies have been considered in designing the new generation of RBC media pack support structure and through rod. The first investigated the possibility of rigidly clamping the ends of the through rods to the support structure, this has the effect of lowering the bending stress in the centre of the rod, thereby allowing a small cross sectional dimension to be employed. Unfortunately this particular design would call for a more robust support structure with associated high capital costs. The second option was to consider the attachment of the through rods to the support frame as ‘simply supported’ (pin-jointed). However, this method would introduce larger bending stresses inn the centre of the through rod and can also introduce fretting at the point of attachment to the pin-joint resulting in premature failure.

A more palliative design solution is to allow small elastic distortions within the structure. Employing this design allows the through rods to be rigidly clamped to the structure, however flexing of the support structure results in lowering the reactional bending stresses thereby alleviating much of the stress intensity at the point of attachment. This strategy has resulted in a new method of clamping the through rods to the support structure as illustrated in figure 82.

Figure 82 **Four-point line contact 'vee' block**

This clamping arrangement is accomplished by bolting the top 'V' section onto the lower part. Specific tightening torques are calculated. This arrangement ensures contact between the clamp and the through rod.

Best practice relating to the design of through rod end clamps is governed by the design of the media pack support frame, moreover, most manufacturers acknowledge the loading pattern described above will give rise to bolt loosing. To combat loss of bolt tightening torque use is made of positive locking for both nuts and bolts, see figure 83. Initial difficulties of properly aligning tab washers have been over come by pre-forming the washer on a jig there by ensuring the "upturned" section always aligns with the flat of the nut or bolt. The design arrangement illustrated in figures 80 and 83 offers structural flexibility for this rigid method of securing the through rod to the supporting structure.

Figure 83 Use of positive locking plates on nuts and bolts

Current RBC designs have taken cognisance of axial and rotational through rod movement. The method of circumferentially welding the shaft plate to the main hollow shaft has been improved by placing a sacrificial plate between the shaft and the shaft plate, see figure 84. This serves to reduce the stress concentration in the welded vicinity.

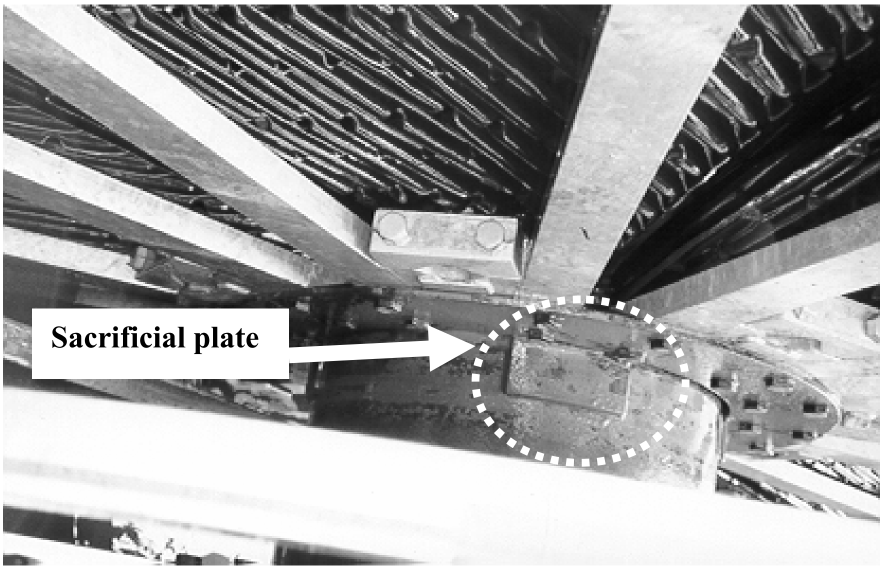


Figure 84 Sacrificial plate for welding onto main hollow shaft

6. AUXILLARY SUPPORT SYSYETMS

6.1 Power transmission

As RBC's operate at speeds of between 0.6 to 2 revolutions per minute, most power units require some form of speed reduction system. The earliest known RBC units employed chain connection for transmission of power to the RBC hollow shaft. Figure 85 illustrates this system on a unit of approximately 3 meters diameter, whilst figure 86 depicts the exact arrangement on a much smaller RBC (1.5meters diameter).

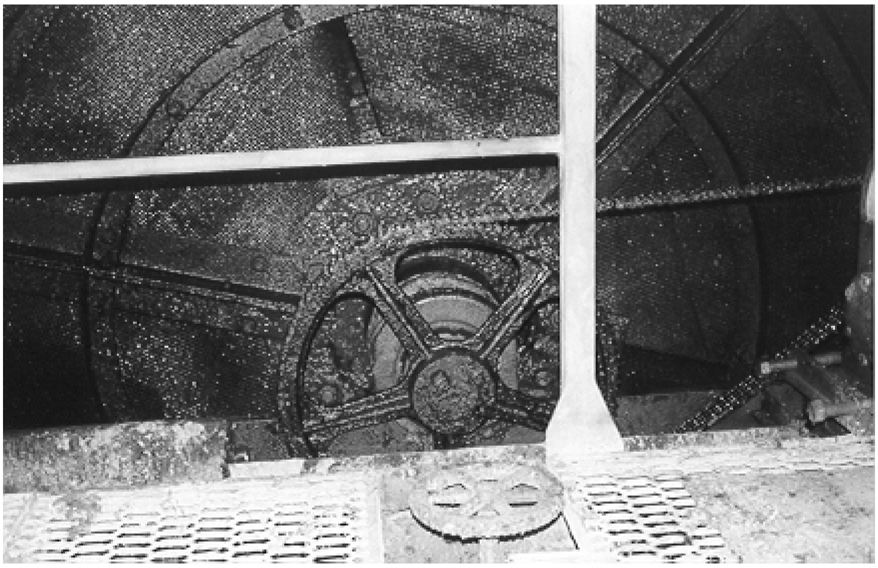


Figure 85 Chain connection between motor and main RBC shaft

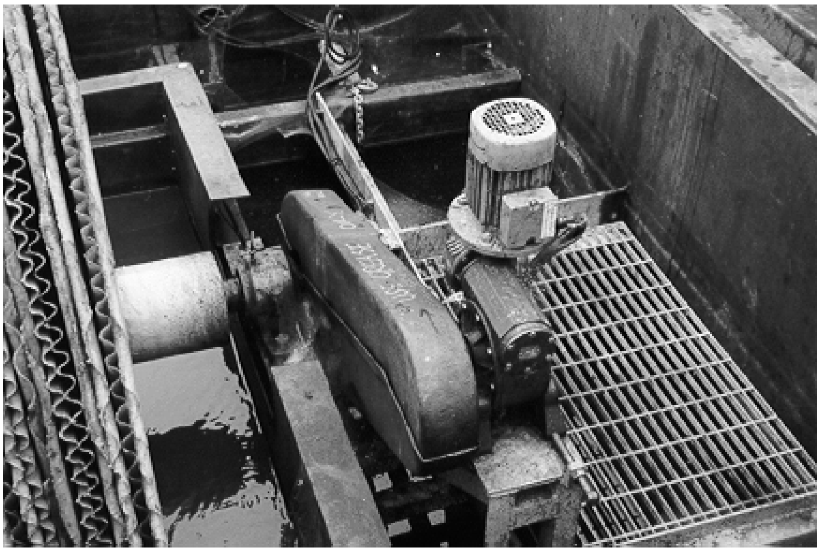
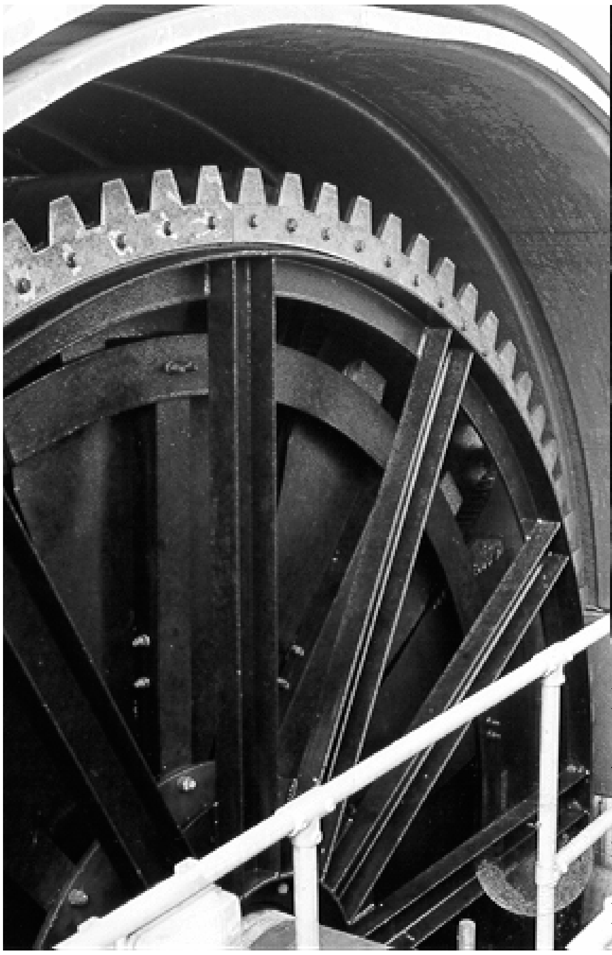


Figure 86 Chain connection between motor and main RBC shaft

The difficulties with this arrangement are that with the passage of time the chain will loose its tension and in many instances has broken. In much smaller sized RBC units (diameters of 1 meter or less) a belt connection is sometimes employed to drive the main shaft. Some RBC units employ a gear and pinion power transmission arrangement, as illustrated in figures 87 and 88. In this particular instance the pinion wheel consisted of 8 teeth driving the larger gear wheel (figure 87) consisting of 84 teeth. The larger gear wheel was of fabricated construction and therefore susceptible to alignment difficulties.



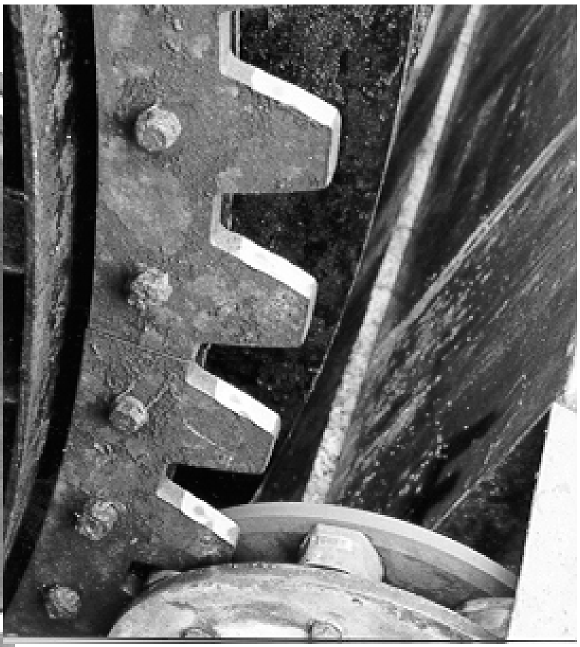


Figure 87 (left) Pinion and gear transmission arrangement; Larger gear wheel

Figure 88 (above) Pinion and gear transmission arrangement; Pinion

This susceptibility has been very evident as severe grooving has been observed on the side of the segmented gear wheel plates, see figure 89. Moreover, it has been noted on a few RBC units that severe wear had occurred on the contacting face of the gear tooth, resulting from high contact pressures and the unavoidable sliding that takes place between tooth pairs, see figure 90.

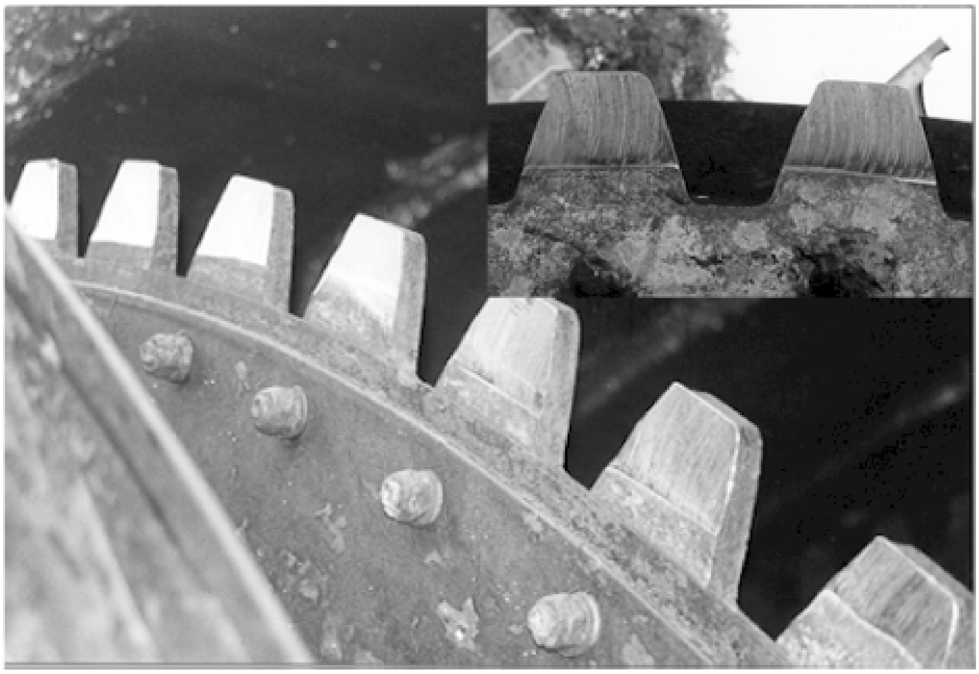


Figure 89 Wear on side of gear teeth due to misalignment

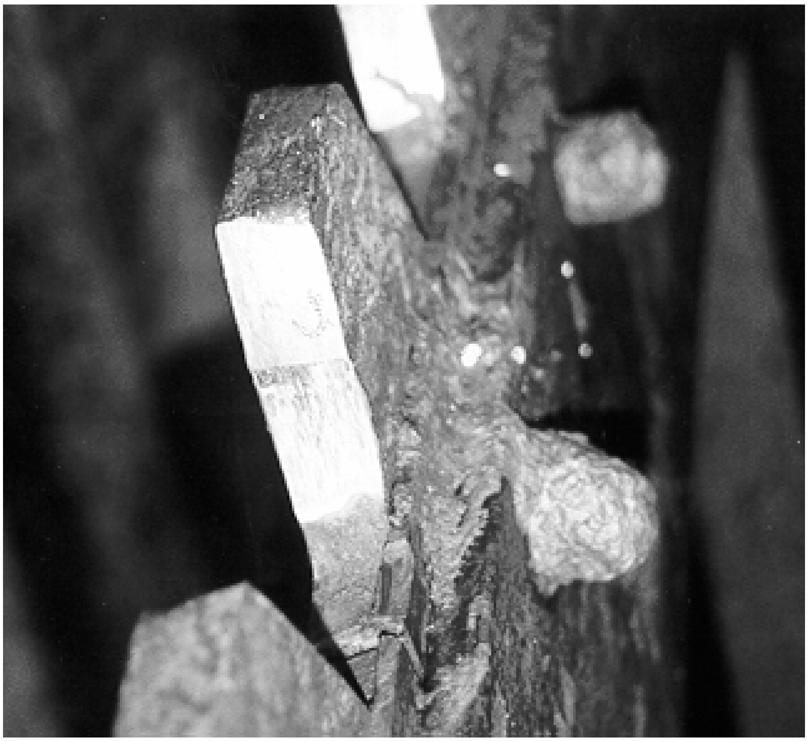


Figure 90 Wear on contact face of gear tooth

As a direct result of the described wearing action a jerking motion of the entire RBC unit was observed. This jerking action caused the rotor to be rapidly accelerated resulting in transient torque forces being reacted back onto the drive unit, resulting in foundation bolts retaining the power unit to fracture. This mechanism is similar to that reported earlier in this paper and illustrated in figure 40.

Other manufacturers have opted for polyamide ‘Tecast T’ material for the pinion drive rollers. This implied that the rollers had been designed for a limited life. The design philosophy of making the rollers as a sacrificial element could be for a number of reasons. The most likely rational, is that all gears experience a sliding motion and are therefore susceptible to wear, and that by making the pinion drive rollers from a polymer wear is confined to the rollers, therefore replacement can be achieved with minimum cost and down time.

Whilst this is a reasonable design strategy it can place an unnecessarily heavy burden on maintenance personnel as there is a need for regular site visits to inspect the entire drive system, particularly as experience to date has shown the rollers to suffer accelerated wear. Also there have been occasions where the entire gear drive has jammed precipitated by worn rollers. Furthermore, severe pitting of the roller on the outer diameter has been observed within only ten weeks of fitting new rollers, thereby giving rise for concern. Moreover, even with regular greasing, the rollers have experienced seizure caused by excessive wear debris being trapped between the roller and spindle, which in turn has promoted wear at the outer diameter of the roller. In many cases the outer surfaces of the rollers have pitted, resulting in material flaking and/or blistering, see figure 91.

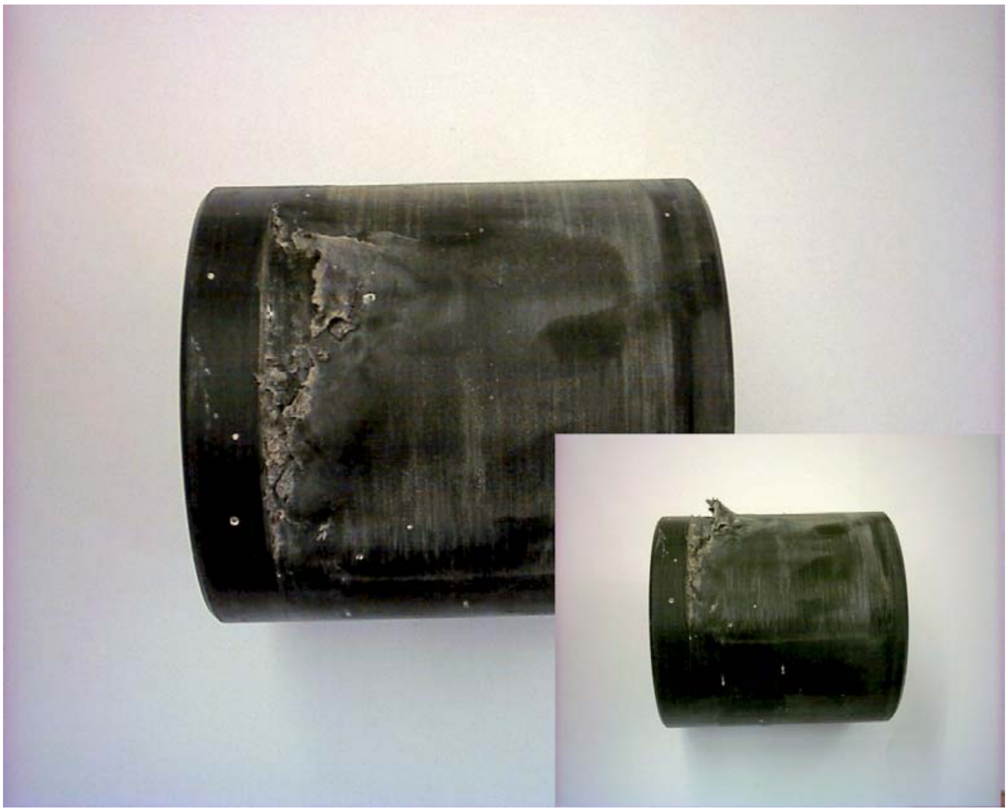


Figure 91 Material flaking on pinion roller

Fundamental design limitations include excessive Hertzian compression stress at the contact surface between the roller and the larger gear wheel, as illustrated in figure 91. Moreover this particular design requires the pinion to be perfectly aligned with the larger gear wheel; failure to comply with this fundamental requirement would most certainly result in accelerated surface flaking/blistering of the outer diameter of the roller. Figure 92 shows the wear to be unevenly distributed along the length of the roller, suggesting that correct alignment was never achieved.

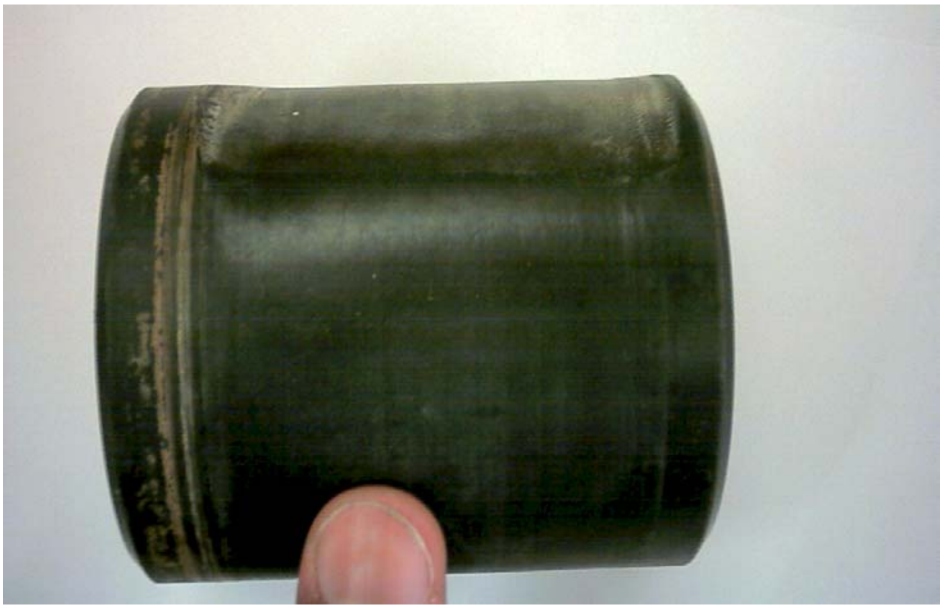


Figure 92 Evidence of uneven wear due to misalignment

The current designs today employ a much smother power transmission systems, eliminating the problems of loose connections and wear on pinion/gear arrangements. Typical units employed today include power and speed reduction units supplied by ‘David Brown’, ‘Bauer’ (see figure 93) and ‘Brevini’, all of which are shaft mounted gear drives and produce successful transmission requirements.

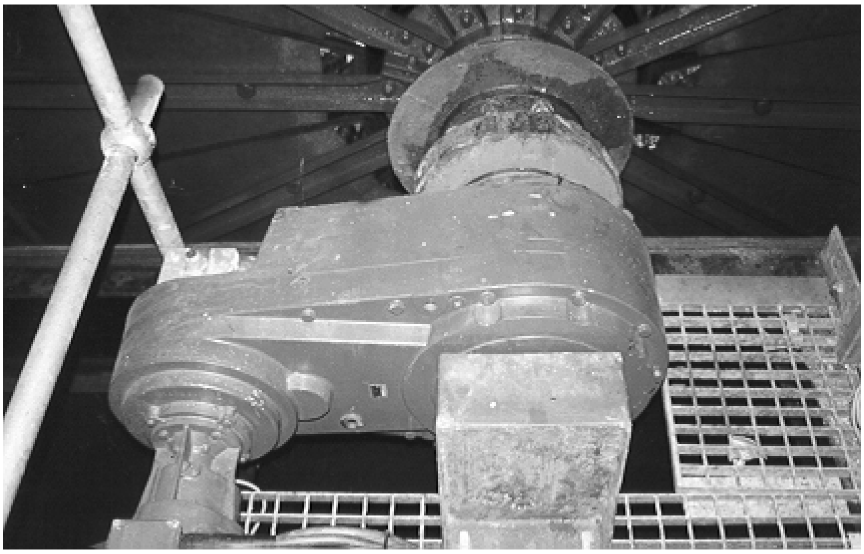


Figure 93 Typical transmission unit employed on current RBC’s

It must be mentioned that though not practiced regularly, couplings connecting two shafts have been employed. This arrangement is intended for use where otherwise the hollow shaft would be unable to support the weight of the unit. Thus, the RBC unit is essentially split into two and four bearings employed. However, to avoid the use of a second power unit, a coupling is employed between the shafts, see figure 94.

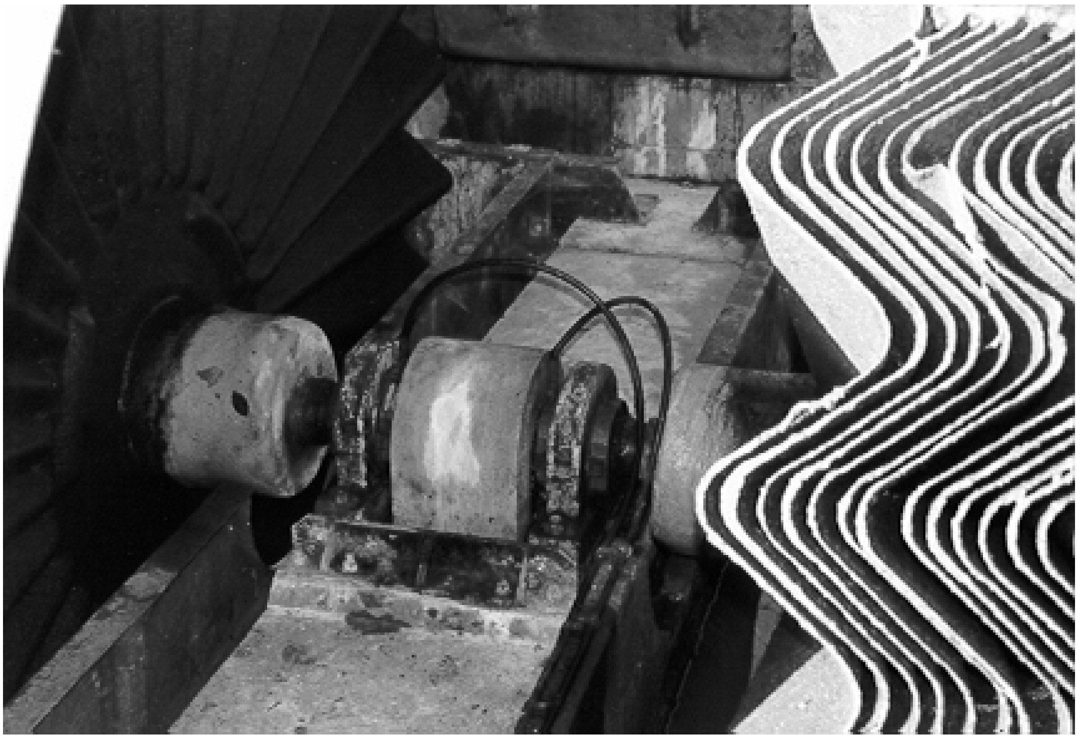


Figure 94 Coupling employed to avoid the use of two power units

6.2 Bearings

The bearings employed on RBC units are typically roller element bearings as this has the advantage of accommodating misalignment. In smaller sized units dry rubbing type bearings have been employed, see figure 95. The material used in figure 95 was an unfilled ‘polyamide’ (nylon) which has good resistance to abrasion and works well at low rubbing speeds. On very few occasions submerged bearings are employed. In this instance the entire unit is submerged by approximately 60% of its diameter.

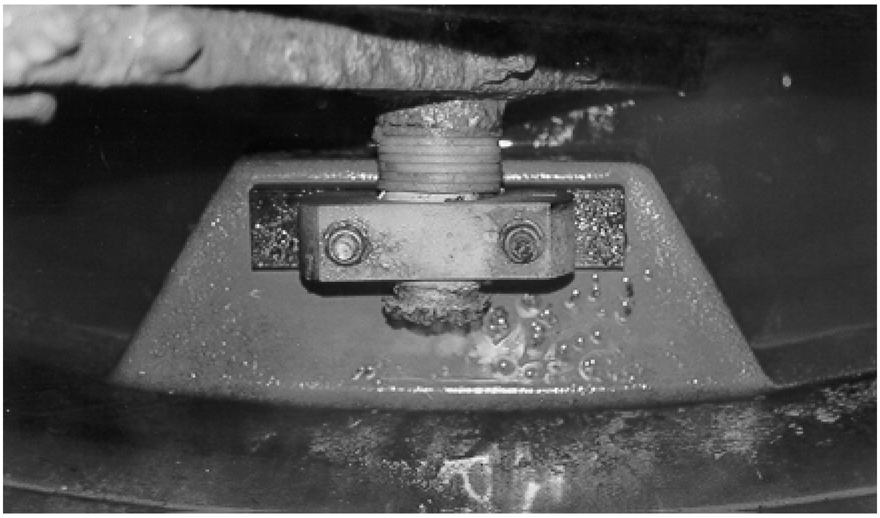


Figure 95 Dry rubbing bearings

Almost all RBC bearings employed rubber seals to retain the bearing lubricant (grease) within the housing. Furthermore, it has been observed that none of the bearings used on RBC's have grease escape or discharge values. Ideally a discharge (escape) valve should be fitted to the underside of the housing, opposite to the lubrication entry point. This has the advantage of ensuring the passage of fresh grease across the bearing and will prevent grease build up within the housing. A build up of grease will force out the bearing seals from their intended position, resulting in contamination of the lubricant and accelerating bearing failure, see figure 96. Following a recent investigation on the effectiveness of various seal types to reduce the ingress of sewage liquor and retain grease within the housing [6], Aluminium triple labyrinth (ATL) was recommended. Furthermore, care must be taken to ensure that the discharged grease does not fall into the sewage liquor.

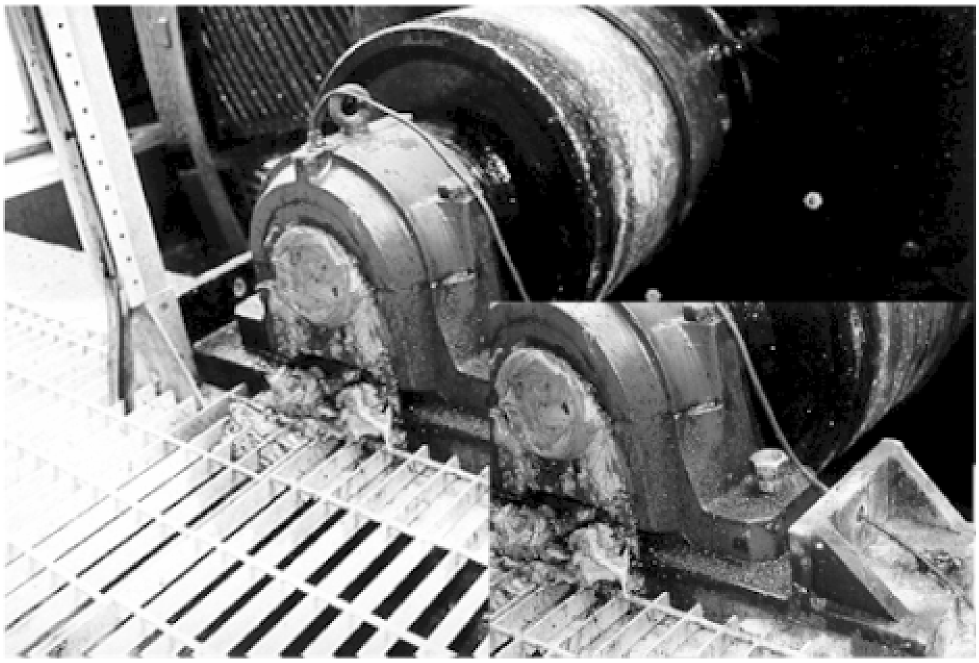


Figure 96 Loss of sealing efficiency of the bearing

In addition, analysis of failed bearings has shown them to have adequate load carrying capabilities, but poor elastohyrodynamic film thickness. An adequate elastohydrodynamic film thickness is essential in maintaining an oil film between the components in the bearing. Furthermore, because of the slow rotational speed the centrifugal force generated within the bearing, to ensure circulation of the grease is greatly reduced in comparison to medium/high speed bearings. Therefore, even if grease was continually pumped into the bearing housing, there is no guarantee that the grease would reach the critical components, i.e., the raceway and rollers. This will inevitably lead to grease starvation of the most critical bearing components. The cause of premature bearing failure on the several RBC's is attributed to lack of lubrication, either as a result of an inadequate grade of grease, grease starvation or in some instances grease contamination. The latter has been observed on numerous RBC units, see figure 97.

Figure 97 Evidence of rust in a bearing housing

All current RBC bearings employ discharge valves to ensure fresh grease reaches critical parts in the bearing. In addition, due to the low rotational speeds combined with heavy reactional loads on RBC's, all current designs now employ grease with a minimum base oil viscosity of 1200 centistokes (cSt). Other typical bearing defects observed are illustrated in figures 98 and 99.

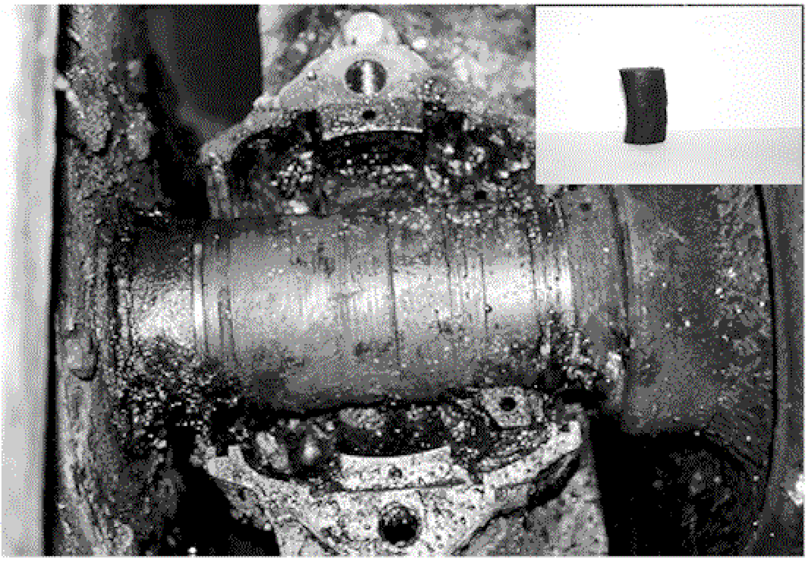


Figure 98 Scored stub shaft due to worn rolling element of bearing (see insert)

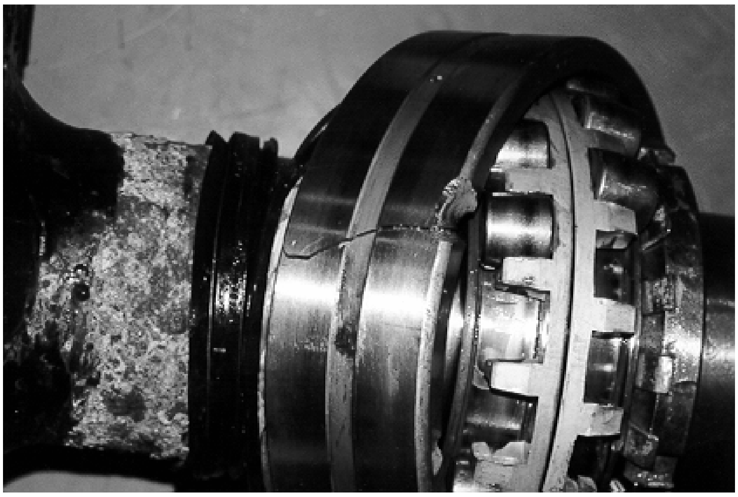


Figure 99 Fractured outer race

6.3 Stub shaft and shaft

All RBC designs employ a stub shaft for locating the entire unit onto its bearings. In some design configurations, the stub shaft is bolted onto a plate which in turn is welded to the ends of the main hollow shaft, see figure 100. Without a thorough understanding of corrosion fatigue at low rotational speeds [4] these bolts have been known to fracture with devasting consequences, see figures 101 and 102. In some instances, apart from the complete loss of operation of the RBC unit, the GRP basin tank which contains the sewage liquor has been known to get damaged. Cognizance of the lowering effects on fatigue limits due to the combined effect of corrosion and low rotational speeds can overcome this mechanical deficiency.

Figure 100 Coupling bolts used to clamp stub shaft to the main hollow shaft

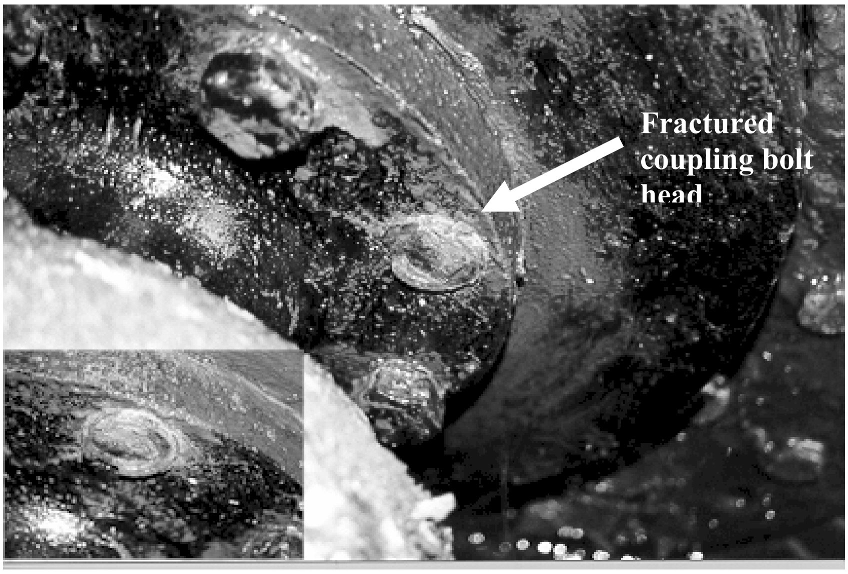


Figure 101 Fracture of coupling bolts

Figure 102 Complete collapse of RBC unit due to fracture of stub shaft coupling bolts

Another design employed for attachment of the stub shaft to the main shaft involves circumferentially welding the stub shaft directly onto the main shaft. This has the disadvantage of creating stress raises on the main hollow shaft.

Whilst the consequences of fractured coupling bolts have been detailed, it has also been observed that poor quality of manufacture and assembly of the stub shaft onto the main shaft has resulted in early fracture of the coupling bolts. In this instance, the tapped recess for the coupling bolts on the plate to be welded onto main hollow shaft were shorter that specified. As a direct consequence, the specified clamping torques could not be achieved and the rotor collapsed after less than 2 months of operation.

The effect of fractured coupling stub shaft bolts on other auxiliary systems, such as the gearbox and bearings is devasting. Even more damaging to the auxiliary systems, including the stub shaft, is complete fracture of the main hollow shaft, see figure 103. However, with a better understanding of the effects of corrosion fatigue at low rotational speeds, maximum stress levels for design of the main components of the RBC have been detailed [4].

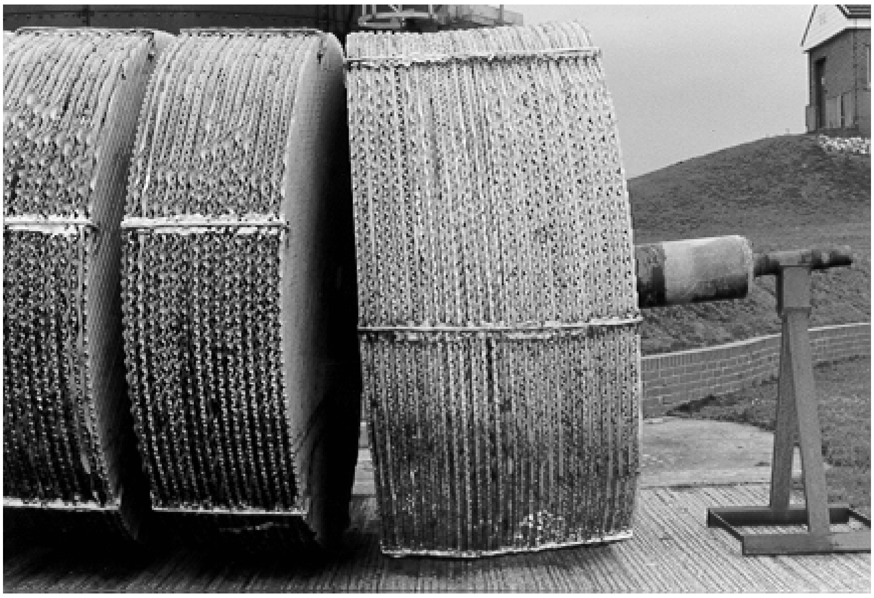


Figure 103 Shaft fracture

7. CONCLUSIONS

The mechanical evolution of the RBC over the last thirty years has been detailed. As a consequence of developments in media design glass reinforced polymer media panels are no longer manufactured due to associated high costs. The most commonly used media panels today are high-density polypropylene of which many designs have emerged. To retain operational requirements an increase in panel thickness and strength of the holes where the through rods pass is suggested. Reducing the effects of drag and hydraulic lift time serves to reduce power requirements.

The majority of mechanical deficiencies on the support structure are attributed the effect of low frequency corrosion fatigued coupled with mixture of materials, inadequate clamping arrangement of all through-rods and the use of a polymer sheeting and washers to avoid direct contact of differing materials. The economic argument in relation to the current designs is really concerned with the conflict between balancing the initial capital cost of the equipment, with the cost of maintenance over the life of the RBC. However, good design should be focused on providing equipment requiring little maintenance, at a competitive cost, whilst maintaining stringent manufacturing standards.

A recently designed unit (1996) that takes cognisance of the difficulties with media and mechanical designs is illustrated in figures 33 and 104. The unit illustrated in figure 33 employed steel ‘T’ sections for the support structure and the through rods were secured to the structure with ‘V’ shaped clamps, similar to that illustrated in figure 82. The unit illustrated in figure 104 employed steel hollow box sections for the support structure and employed ‘V’ shaped clamps. It is interesting to note that the oldest designs of RBC, illustrated in figures 34 and 36 are still operational today with no reported faults

Figure 104 New generation RBC

In relation to the RBC auxiliary systems, power and speed reduction units have evolved to produce much smoother transmission. Bearings currently employed have discharge valves to aid the movement of grease within the bearing. It would be of great benefit to use dry rubbing bearings on larger RBC units and completely eliminate the need for lubrication. This would also save on operational costs associated with maintenance teams. With a thorough understanding of the mechanisms of mechanical failure, a new approach to RBC design has resulted in more robust RBC units.

8. ACKNOWLEDGEMENT

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