2
Woolscouring, carbonising and effluent treatment

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2.1 Introduction

Raw or 'greasy' wool is contaminated with impurities, the type depending on the breed of sheep, the area in which the sheep are raised, and husbandry methods.

The role of woolscouring is to:

- clean the contaminants from the wool by means of an economic process
- ensure that the wool is in a physical and chemical condition to suit the intended processing route (e.g. for topmaking to minimise entanglement and retain the staple structure)
- comply with environmental requirements (this requirement has become much more important over the last 20 years).

The term 'scouring' is used here in the generic sense of a process that removes contaminants from raw wool. Thus, it includes all processes which aim to clean wool including those which use solvents other than water and those which use solids as a carrier for removing the contaminants.

Scouring clearly is a critically important step in wool processing. It must be carried out using technology that enables the wool to attain its optimum performance in further processing.

2.2 Nature of contaminants

The main contaminants are woolgrease, suint and dirt. Woolgrease, technically a wax, is produced by the sebaceous glands in the skin of sheep, while suint is produced by the sudoriferous (sweat) glands. A more precise way of defining woolgrease and suint in relation to the analysis of greasy wool relates to their solubilities in organic solvents and water respectively. Thus suint can be defined as the water-soluble fraction of the fleece and woolgrease as the solvent-soluble fraction.[1]

Woolgrease is comprised principally of high molecular weight esters formed from a mixture of sterols (including cholesterol) and aliphatic alco-

Table 2.1 Typical concentrations of non-wool contaminants (Percent by mass on greasy wool)

	Maximum	Minimum	Average
Australian (New South Wales) Merino[52]			
Grease	25.4	10.0	16.1
Suint	12.0	2.0	6.1
Dirt	43.8	6.3	19.6
New Zealand crossbred[53]			
Grease	8.5	1.6	5.2
Suint	12.1	2.2	8.0
Dirt + suint moisture	—	—	7.9

hols with straight and branched chain fatty acids. The amount present on the wool depends upon the sheep breed, with Merinos recording the highest amounts (Table 2.1). Crossbred wool usually has substantially less. For most processing routes, the requirement is to reduce the grease on the fibre to below 0.5%.

Suint is mainly potassium salts of organic acids: potassium comprises 90% of the cations present and this represents 25–27% on the weight of dry suint. In scouring liquors, at alkaline pH levels, suint has detergent properties. The amount present also depends on the breed type, with crossbreds tending to have more than merino.

The range of the levels of the contaminants is notably wide; especially for the dirt. The differences in type and level of contaminants help to explain why different hardware and processes have proven necessary in woolscouring. For example, the large amount of fine dirt on some of the fine wools from Western Australia is very difficult to remove, and low scouring throughputs are often necessary; whereas a high yielding coarse wool from New Zealand represents the other extreme of being very easy to scour.

Raw wool may also be contaminated with vegetable matter (VM). Where the wools are heavily contaminated with VM, they may have to be carbonised to remove it (Section 2.7.1). A major proportion of the wools requiring carbonising are from Australia and South Africa.[2]

2.3 Historical overview of scouring methods

Traditionally, wool was scoured in hot, aqueous solutions of soap and alkali.

Synthetic detergents have largely displaced soap, but aqueous scouring has remained the principal method. However, the use of volatile solvents to scour wool in batchwise processes was introduced about 1900.[1,3] Conventional aqueous scouring removes the woolgrease in emulsion, the suint in solution and the dirt in suspension. Solvent scouring removes the woolgrease in solution, and removes both the dirt and suint in suspension. Various dry-powder-type processes have been employed or advocated in the past, where solids are used as carriers to remove the contaminants from the wool.[1] Types of materials used have included gypsum, kieselguhr, aluminium silicate, and bran. A method currently under development in Australia uses microwave energy to heat the greasy wool while it is being contacted with a powder.[4]

Many developments in woolscouring and effluent treatment have been commercialised over the last 30 years, several of which originated in work carried out in the research laboratories of WRONZ (New Zealand) and CSIRO (Australia). Other research organisations, technical centres, machinery manufacturers and processors themselves have also contributed. More recently, with the reduction in bulk funding available for research and development laboratories, a greater proportion of the work has been commercial and has not been reported in the literature.

2.4 Unit operations

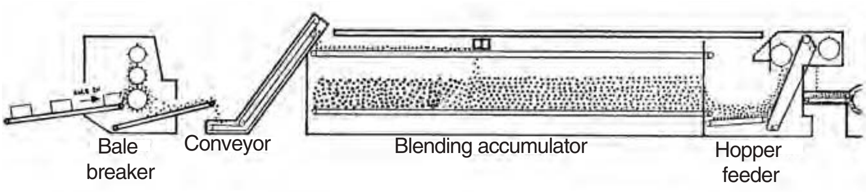
2.4.1 General overview

A woolscouring works typically includes facilities for blending and mechanically cleaning greasy wool, and drying and blending the scoured wool, as well as the scouring machine itself. The possibility of carrying out additional chemical processing may also be provided.

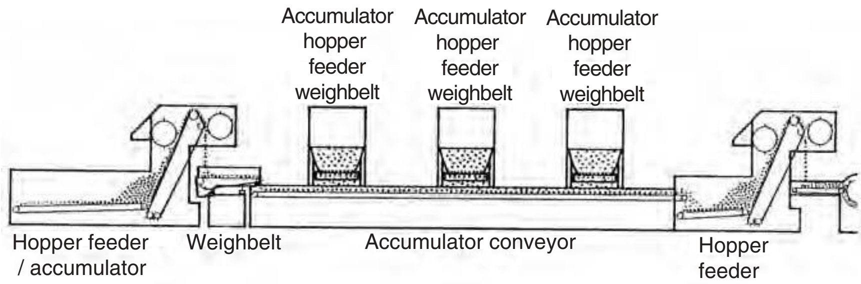
2.4.2 Blending systems for greasy wool

Two basic types of blending systems may be identified:

i) In-line blending systems (Fig. 2.1) are used where the wools being blended have similar characteristics. Partially opened wools are layered horizontally into an accumulator (blending bin) and an inclined spiked lattice empties the bin from one end, providing effective mixing. Such systems are often used by scourers of fine wools.
ii) Computerised weighbelt blending systems (Fig. 2.2) are used for blending wools that have different characteristics. Such systems include multiple weighbelt lines that deliver the wool onto a conveyor for mixing. Further opening-dusting followed by layered blending may also be included.



2.1 Typical in-line blending system.[54] [*Courtesy of ANDAR.*]



2.2 Typical computerised weighbelt blending system.[54] [*Courtesy of ANDAR.*]

Blending systems are usually built-up from standard items of equipment (e.g. hopper feeders and weighbelts), and may be customised to suit the requirements of the user. Dimensions of existing buildings often impose constraints on the layout.

2.4.3 Preheating bales of fine wool

Before densely packed fine wool is blended, preheating may be necessary to facilitate opening of the wool. Fine wools are often compressed to high densities to facilitate storage and to lower the cost of transport. Australian greasy wools are usually exported in 'tripacks', at roughly three times the density of a farm bale. Where ambient temperatures in the scouring plant are low, the packed wool remains very hard and difficult to process. It may be necessary to heat the wool to relax strains and enable efficient opening and blending; also to reduce wear and tear on the processing equipment. It has been suggested that the temperature of the greasy wool needs to be at least 15–25 °C to allow adequate opening and blending.[5]

There are three main methods of heating the bales of wool:

i) warm rooms
ii) steam injection
iii) microwave and 'dielectric' heating methods.[6]

Warm rooms have long been used to prepare farm bales for processing. With tripacks, a longer holding time is necessary and access for forklifts is necessary. The rate of heating can be increased by increasing the temperature, but mills set an upper limit of about 75 °C to avoid damage to the wool.[5] Disadvantages are the high labour costs, potentially high heating costs and the space requirements.

Injection of steam into tripacks has been practised, but yellowing of the wool at the point of injection has been a problem, especially if high temperature steam is used.[5] The Australian Wool Corporation developed the Forced Convection Bale Warmer to overcome the problems of conventional steam injection. This unit used two fluids – low temperature dry steam and warm air – which were applied to the tripack sequentially.[5] Although the unit was technically successful it has not sold in numbers.

Radio frequency heating techniques have been used in the wool industry for some time, mainly using the dielectric frequency range; typically 13.56 or 27.12 MHz. Although commercial use of bale heaters utilising dielectric heating has been reported in the literature, their use has not become widespread. Presumably, this has mainly been because of their high capital and running costs. More recently, the successful commercialisation of bale heating systems using radio frequency power in the low microwave range (915–922 MHz) has been reported.[7]

2.4.4 Opening and dusting

Wool may be opened and dusted before and after scouring, and there are generally benefits for all types of wool if both of these processes are carried out appropriately.

Greasy wool is opened to facilitate the removal of contaminants in the scour, and to assist the blending process. Opener-duster machines are also used to remove dirt and VM prior to scouring, which reduces the solids loadings in the liquors and effluent.

After scouring and drying, wool is opened to assist its transport by pneumatic conveying, to help even-out the moisture distribution in the wool mat, and to facilitate further dusting of the wool. There are results to indicate that mild opening of fine wool after drying may be beneficial to the worsted carding process[8] but further testing has indicated that such pre-opening has advantages only when the scoured wool is notably entangled.[9] Any opening of wet fine wool, even the relatively gentle action of a feed-hopper, has been shown to reduce the top length and should be avoided.[8]

Coarse wools generally can withstand quite intensive opening, both before and after washing.[1] Dag and slipe wools in particular will benefit from such treatment. It is interesting to note that the most recent commercial developments in opening equipment mainly for coarse wools – the

Short Wool Processor and the Scoured Wool Cleaner – have been high intensity machines.

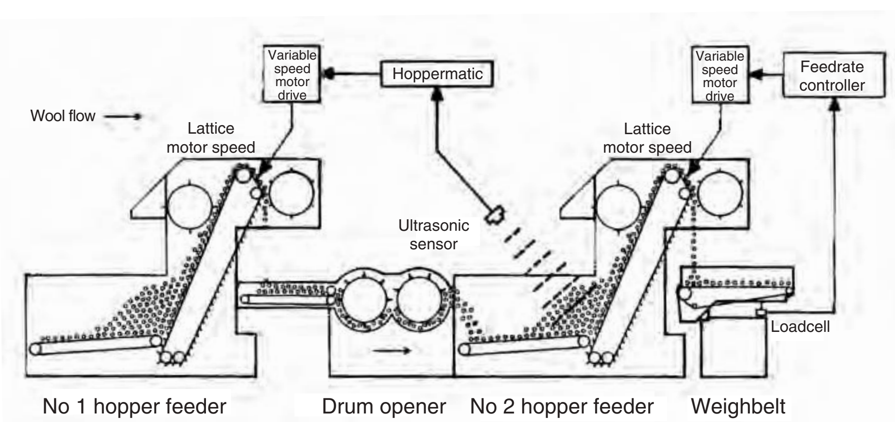
The following types of machine are commonly used, listed approximately in order of increasing intensity of opening:

Bale-breakers are strongly-built, large machines for breaking open bales prior to opening/dusting in a drum opener. The mechanical action may be derived from drums with teeth (see Fig. 2.1) or from large flails rigidly attached to shafts. The former types are often used by scourers of fine wools, while the latter are favoured by the commission scourers in the UK for handling rolled fleeces.

Feed-hoppers are machines with multiple roles of feed-rate regulation, opening and wool containment. They have a spiked lattice which carries the wool out of the hopper for delivery to the next stage of the process (see Fig. 2.3).

Drum openers most commonly have two drums (Fig. 2.3), but configurations have ranged from one to four drums (Fig. 2.4). New Zealand scourers have recently favoured three-drum units for their flexibility and additional cleaning capacity. Many of these openers are now supplied with screens that are cleaned automatically as they slide sideways out of the machine under the power of hydraulic rams. There are also various options available for handling the waste from openers, including straightforward gravity discharge into waste containers, pneumatic conveying, and mechanical systems such as augers and belt conveyors.

Measurements by WRONZ on the performance of multi-drum openers in industry showed that they removed 5 to 16% of the dirt on the wool, depending on the wool type, provided the screens were cleaned regularly.[10] These measurements were carried out on New Zealand wools and a



2.3 Opening and feeding system.[54] [*Courtesy of ANDAR.*]

2.4 Three-drum greasy wool opener. [*Courtesy of Kaputone Wool Scour (1994) Ltd.*]

lesser performance would be expected on fine wools, which contain more grease.

The opening process carried out by rotating drum openers appears to occur in three main ways.[10] Intense opening takes place firstly at the feed or 'nip' rollers at the entry to the opener, as the teeth on the drum tear or 'pick' at the constrained wool mat. Secondly, fixed teeth on the screens will break up the wool flow with a strong effect since they are normally designed to intersect with the rotating teeth on the drums. An important innovation from WRONZ was the development of a self-cleaning-teeth assembly, which provides a self-cleaning capability and a means to adjust the number of rows of fixed teeth in the 'up' position while the opener is in operation.[11] Thirdly, there is less severe opening as the wool changes direction on transferring from one section of the opener to the next.

One of the outcomes of the considerable amount of work carried out at WRONZ on the opening and dusting of greasy wool was the design of a self-cleaning machine, the WRONZ *Autoclean*, which reached the commercial prototype stage.[12] Although its opening and dusting performance was up to expectation, it has not achieved commercial success.

Stepped opener-dusters use a smaller diameter rotor than drum openers (Fig. 2.5). Their usage at the greasy end of the scour has much reduced during the last 20 years, mainly because the dusting screens became rapidly blocked with dirt, and they essentially become an expensive inclined conveyor. They are better suited to the cleaning of scoured wool.

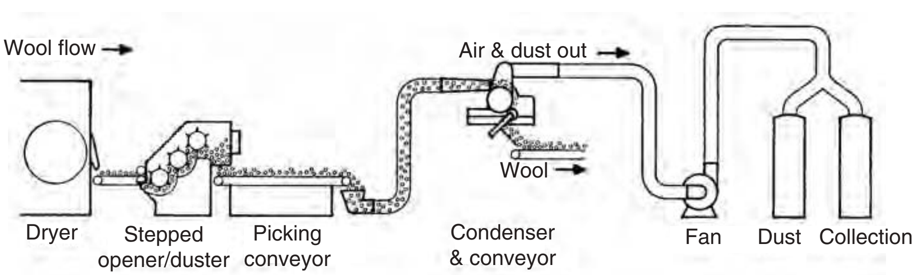
The *Short Wool Processor* is based on the principle of hinged flails (as in a dag crusher) attached to a rotor. It may be used in continuous or batch processing modes. The Short Wool Processor is used off-line mainly to pre-open and dust dag wools and slipe wools.

Cott Openers are used for breaking apart cotted fleeces. The main working part is usually a rotor fitted with angled teeth or pins which combs a fringe away from the fleece as it is fed at a controlled rate.[1] The feeding system is usually a conveyor belt that delivers the fleece to a pair of restraining spiked rollers, or to a spiked roller working in combination with a 'piano key' set-up.

Cyclic Openers have a large diameter drum fitted with teeth, with intersecting workers located above it. It is fed via conveyor and feed rollers. In New Zealand, it was used mainly on slipe and dag wools; elsewhere it was also used to open wools prior to carbonising. It may be used in batch or continuous mode.[1] In New Zealand, the Short Wool Processor has largely superseded the Cyclic Opener.

The less demanding duty on scoured rather than greasy wool suits the Stepped Opener-Duster machine. The degree of opening is determined at the design stage by the selection of the number of drums, their speed, and whether feed rollers are required. Figure 2.5 shows a scoured wool dedusting system that includes a three-drum stepped opener-duster. In this example, the wool is delivered onto a picking conveyor before it is transported by pneumatic conveying to its destination for discharge by a condensor. The air from the condensor is exhausted to atmosphere via filter bags or cyclones.

Scoured Wool Cleaners are a WRONZ development commercialised by Mentec.[13] Unlike most opener-dusters for wool, which have multiple drums or rotors with the wool being fed from one drum to the next, the Scoured Wool Cleaner is a single-rotor machine, with the wool being fed near one end and discharged at the other end. Thus, the wool has an axial flow



2.5 Scoured wool finishing system.[54] [*Courtesy of ANDAR.*]

component as well as a rotational component. In this respect, the Scoured Wool Cleaner is similar to the willows or 'beater-scutchers' used for dedusting in the carbonising process.[14] It achieved rapid penetration into the New Zealand scouring industry, owing to its proven wool cleaning capability. A smaller machine operating on a similar principle is available for recovering fibre from the waste of the main unit.

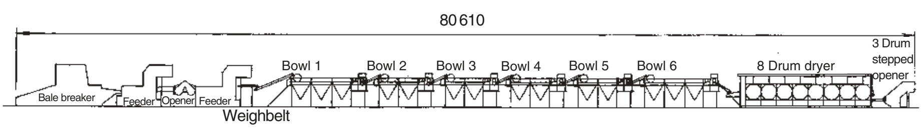
Fearnought machines operate like a card with swift, workers, and strippers. They are mainly used by scourers in the UK for opening and blending.

2.4.5 Washing wool in scouring trains

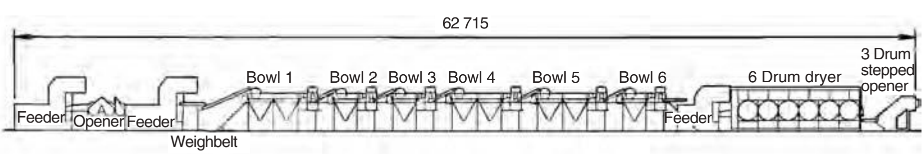
A scouring train comprises a number of wash bowls and squeeze heads, and is usually linked to an in-line dryer and a woolgrease recovery system. Figure 2.6 shows a typical plant layout for a scour for fine (e.g. Merino) wools; while Fig. 2.7 shows a typical plant layout for coarse (e.g. NZ crossbred) wools.

Older conventional scouring lines typically include four bowls having rake or harrow mechanisms that dunk and transport the wool. The scoured product from such designs is satisfactory for most purposes so that the basic mechanical motions of aqueous scour bowl design have not changed greatly over the last 100 years. Most of the greasy wool processed throughout the world is still scoured in aqueous systems using rake and harrow machines.[15] Details of the bowls have, however, changed significantly.

Over the years, various major innovations in scour bowl design have reached commercial prototype stage but only a few have gained ultimate commercial acceptance. Of particular note were the different designs of aqueous jet scours during the 1960s by CSIRO and the University of New



2.6 Scour plant for fine wools.[54] [*Courtesy of ANDAR.*]



2.7 Scour plant for coarse wools.[54] [*Courtesy of ANDAR.*]

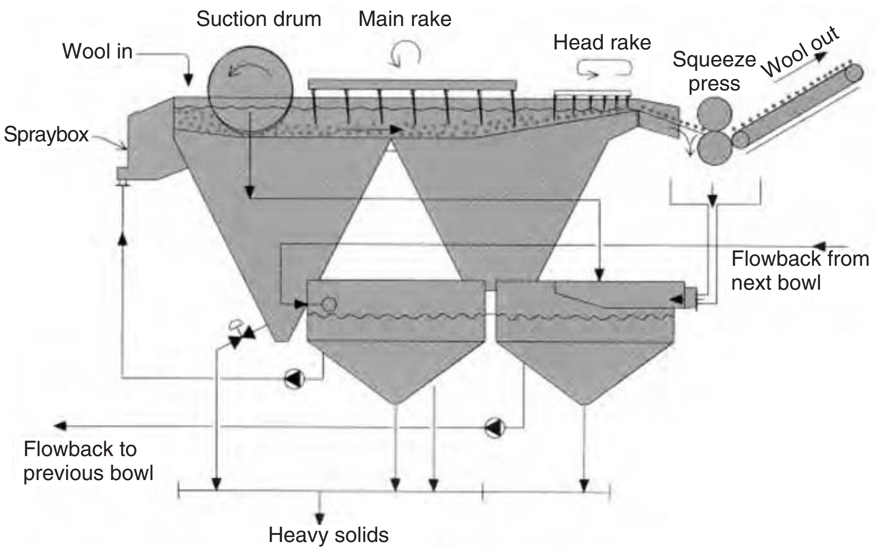
South Wales.[1] These designs were aimed at improving the combing results when compared with scouring on conventional machinery and while they achieved that aim, it was also shown that conventional scouring mechanisms could be developed to achieve a similar improvement in processing performance (e.g. in the *Petrie-Wira Improved Scour*).[16]

An important scouring development commercialised during the 1960s was the Fleissner suction drum scouring bowl.[17] Perforated suction drums are used to transport the wool and also to wash it by means of liquor flow from outside to the inside of the drums. In the original design, the liquor circulation pumps were located inside the drums. In later designs, an axial flow pump was installed in a side space of the bowl. It is interesting that the original design allowed for flexibility in bowl length, ranging from one to three suction drums long.[17] During the late 1980s, a 3 m-wide suction drum scour was installed in Uruguay,[15] which remains the largest working width of woolscour available from any manufacturer.

The suction drum design has been successful mainly for high yielding fine wools; on dirtier wools, product cleanliness becomes an issue. The wool mat acts as a filter for fine dirt, some of which may remain in the wool mat at the exit of the final suction drum bowl. For this reason, a 'hybrid' scour has been installed by some mills with a selection of suction drum and rake bowls being fitted into the scour train. Hence, the particular bowls are chosen depending on their prime function: grease and suint removal or dirt removal.

Rake and harrow bowls fulfil most of the requirements for the washing of fine and coarse wools. Rake systems using three-throw crank drives have proven most popular, since they can be set up to have a lesser felting effect than a square action single harrow, and their compact dimensions makes the bowl easier to cover. A small number of machines have used swing-rake mechanisms, which simulate the movement of a hand-held fork,[1] to move the wool through the bowls, but they are only suitable for blends that demand a particularly strong mechanical action.

A hopper-bottomed scour bowl of recent design (ANDAR) is shown in Fig. 2.8. The wool is fed into the bowl and is submerged and wet-out by means of the suction drum, which is mechanically driven at the required speed. Liquor within the scour bowl is circulated from the spraybox to the squeeze press by means of the flow-around pump. A heat exchanger may be installed within the spraybox or installed separately to heat the liquor flow between the flow-around pump and the spraybox. The main rake moves the wool through the bowl where it is picked up by the head rake, which in turn delivers the wool to the drain tray. The squeeze press removes liquor from the wool and then transfers it to the outfeed conveyor for delivery to the next step in the process.



2.8 ANDAR bowl flow diagram.[54] [*Courtesy of ANDAR.*]

During early 1978, two 'mini-bowls' designed by WRONZ were installed by ANDAR as a replacement for the first scouring bowl at the original installation of the WRONZ Comprehensive Scouring System (see Scouring Systems) in Timaru, New Zealand. The impetus for this development was the general trend towards shorter scouring bowls, the knowledge that many raw wools are easy to wash, and the stimulus given to the industry in New Zealand by the demonstration of the *Lo-Flo* wash-plate process to the trade at Geelong in 1977.[18] Comparative trials showed that the scouring efficiency of two mini-bowls was comparable with that of two bowls of conventional length (the mini-bowl was 2.7 m long, while the conventional bowls were 6.7 m and 5.8 m long).[19] The benefits due to mini-bowls were several including: space savings, reduction in energy losses, reduced volume, reduced capital cost, reduced maintenance, and ease of operation.[18] Commercialisation was successful, with ANDAR/WRONZ mini-bowls installed in New Zealand and overseas soon afterwards. Subsequent experience showed that mini-bowls were not ideal for washing low yielding fine wools, mainly because dirt removal could be a limiting factor. However, they were still chosen by some processors for scouring and rinsing applications of high yielding fine wools on the basis of their own experience, and they are widely installed for the processing of New Zealand coarse wools, often in combinations with long conventional bowls. The mini-bowl hopper design, with its hopper of full scour working width, became the basis for the ANDAR multi-hopper designs to follow. Scour lines comprising bowls of one, two, three, and sometimes four hoppers long were installed, mainly in Australia, Asia, and the USA.

2.4.6 Squeeze heads

The action of the squeeze rollers (Fig. 2.9) is critical to the efficiency of removal of contaminants from the wool. As the wool mat enters the nip of the squeeze rollers, it is subjected to intense hydrodynamic forces which are particularly efficient at removing woolgrease and suint from the wool fibres, but less efficient at removing dirt. Efficient squeeze rolling also minimises the carryover of contaminants entrained in the wool mat to the next bowl in the scouring line. The efficiency of the squeeze rollers of the last bowl in the scouring line is also very important. By reducing the regain of the wool entering the dryer, the energy usage of the dryer is reduced while its wool throughput capacity is increased. The squeezing efficiency of rollers in a scouring line increases with temperature and with the applied downforce on the top roller.

Typical industrial squeeze rollers are designed for a maximum downforce in the range of 5 to 10 tonnes per metre of scour width. Thus, a 2 m-wide

2.9 Squeeze press. [*Courtesy of Jandakot Wool Washing Pty Ltd.*]

scour line will normally have a squeeze roller set capable of 20 tonnes total downforce at the exit of the final scouring bowl. Other bowls in the line may be equipped with so-called '10 tonne' presses.

Most modern squeeze rollers are pressurised via pneumatic systems. The bottom rollers are commonly of solid steel with a stainless steel coating. The top rollers are also commonly made of steel with a lapping of polyamide rope of square cross section.

Where acid conditions are expected (e.g. in the final bowl, where insect resist treatments may be applied, or in the acid bowl of the carbonising process), the lapping should consist of polyester rope owing to its superior acid resistance. Historically, the top rollers were lapped with wool top or nylon tow but such lapping has been largely superseded due to the superior durability of square rope. A few scourers, mainly in Europe, have chosen to use polyurethane coatings for the top squeeze rollers.

The regain of wool from squeeze rollers is between 50 and 100% depending on the efficiency of squeezing.[1] The main factors affecting the result are the liquor temperature, the downforce on the top roller, the type and condition of the lapping on the top roller, and the evenness of wool flow through the rollers. It is useful to consider what results might be expected for some specific processing conditions. Wool regains in the range 60–70% should be achieved with 10 tonne squeeze rollers with top roller lapping of nylon rope on 2 m-wide scouring lines with bowl temperature of about 60 °C. Figures in the range 50–60% should be achieved for 20 tonne presses with similar operating conditions.

2.5 Scouring chemistry

2.5.1 Detergents and builders

Before the 1950s, the main detergent used to scour wool was soap, which was used with an alkaline builder, usually soda ash.[20] The propensity of soaps to form insoluble salts with calcium and magnesium ions in hard water areas prompted the development of synthetic detergents and the most common ones used in the scouring industry today are non-ionic types.[15] Until recently, nonyl or octylphenol ethoxylates have been most popular. However, they are not readily biodegradable and concerns regarding the environmental effects of such detergents and their breakdown products has resulted in voluntary and legislative restrictions on their use in several countries. As a result, the usage of the more biodegradable fatty alcohol ethoxylates is increasing.

Soda ash (sodium carbonate) remains the most common builder used, although sodium chloride or sodium sulphate are sometimes used. The action of the builder is to stabilise the emulsified woolgrease and dirt, and prevent redeposition back onto the wool.[15]

Suint has soap-like detergent properties when either natural alkalinity is present in the fleece or alkali is added to the washing liquors.[1] Greasy crossbred wools contain more suint than fine wools and, unlike such wools, are naturally alkaline, as well as containing much less woolgrease. This explains why crossbred wools are usually scoured with a hot first bowl without any addition of soda ash. In contrast, soda ash may sometimes be added to the early bowls of fine wool scours.

Table 2.2 shows typical bowl operating temperatures for scouring with neutral non-ionic detergent. The optimum temperature depends on the actual detergent used, but is usually within the range 50–65 °C.[15] Where alkaline scouring conditions are employed, temperatures less than 55 °C should be used.

Desuinting is favoured by many scourers in Europe, in part because the contaminants removed in Bowl 1 are thereby eliminated from the woolgrease recovery system connected to the following bowl(s). This has potential benefits in terms of reduced wear on pumps and centrifuges in the woolgrease recovery system. *Siroscour* in 3-stage mode uses a modified desuinting bowl (see Section 2.6 for details).

The rate of detergent usage depends on the type of wool being scoured, but should be less than 9 litres/tonne greasy weight for merino wools and less than 3 litres/tonne greasy weight for crossbred wools. More of the detergent should be added to the second and third hot scouring bowls to enable the countercurrent flowback system to have greatest effect. However, when scouring merino wools this approach may have to be tempered if the detergent foams excessively in the later scouring bowls.

The rate at which wool can be scoured depends greatly on the type of wool. Thus, a relatively clean crossbred wool from NZ usually can be scoured at more than twice the throughput of a low-yielding Merino type

Table 2.2 Typical bowl temperatures for aqueous woolscouring (°C)

Bowl No.	1	2	3	4	5	6
Desuinting	<35	60	60	55	50	50
(fine wool)	D	S	S	S	R	R
Conventional	60	60	60	50	50	50
(fine wool)	S	S	S	R	R	R
Conventional	65	60	60	cold	cold	60
(NZ crossbred)	S	S	S	R	R	R

Where D = desuint, S = scour (with detergent addition to bowl), R = rinse.

from Western Australia. The latter wools have a greater surface area to clean owing to the smaller fibre diameter, have more woolgrease, and commonly have much more fine dirt which is difficult to remove.

Wool throughputs have increased markedly over the last 30 years owing to improvements in scour and dryer design, process control, and increase in scour working width. Thus, a 3 m-wide scour is capable of washing good quality NZ crossbred wools at a rate of 5.5 tonnes/h. It is of interest to note that, as the working width of woolscour increases, the throughput per metre of width also increases, probably because edge effects are less important for wider scours.

2.5.2 Water quality

There are two main sources of problems associated with water quality: hardness and the presence of multivalent metal ions.[20] While hardness, in the form of calcium and magnesium ions in the water, does not interfere directly with the action of non-ionic detergents, their presence could cause redeposition of fibre contaminants and dyeing problems. It has been suggested that it is possible to scour greasy wool satisfactorily in water of total hardness up to 70 mg $CaCO_3$/litre, while unsatisfactory scouring is likely to occur over 100 mg/litre.[15] In hard water areas it may be necessary to install a softening plant in order to prevent such problems.

Apart from calcium and magnesium, the presence of metal ions such as iron can cause severe dyeing problems by interacting with dyestuffs.[20]

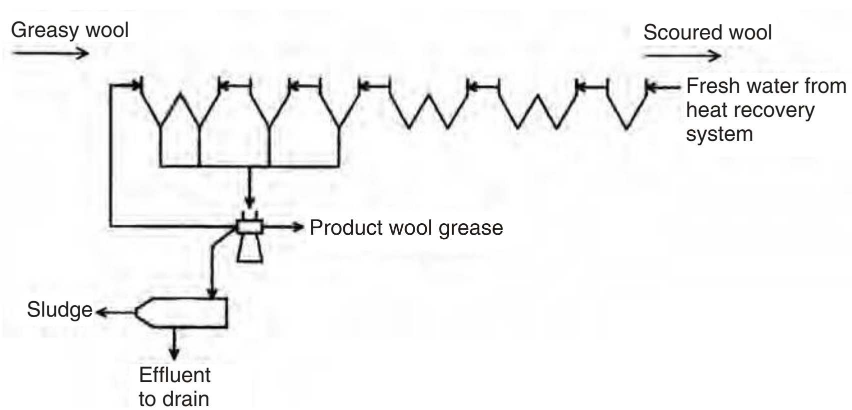
2.6 Development of scouring systems

For many years, woolscouring of the wide range of wools available was viewed as an art rather than a science. Even wools of the same breed and micron range vary widely in their scouring properties, depending on where the sheep were raised and the methods of husbandry. An early system of note was the *Duhamel* process, which was introduced in France during the 1920s.[1] The system included several elements that were to become cornerstones of woolscouring in the future, e.g. bowls with conical shaped bottoms and the use of decanter and nozzle-disc centrifuges to remove dirt and woolgrease from the liquors, respectively. The process never received universal acceptance, perhaps because poor scouring could have been expected under the liquor conditions used;[1] but it is also likely that maintenance problems on many items of equipment would have been severe. Even today, with the major advances in materials and design, the selection of pumps, fibre screens, solids removal systems and centrifuges must be approached warily.

During the 1960s, research and development on scouring machinery concentrated on the design of individual scour bowls. During the 1970s, while such developments continued, they became viewed in the context of a systems approach to woolscouring. This was necessary as energy and pollution discharge costs soared,[21] while there was also new environmental awareness. This process probably began with the WRONZ Comprehensive Scouring System (see Fig. 2.10), which was first installed at a new woolscour in Timaru, New Zealand in 1972.[1,22] The system was designed after the main deficiencies of typical plant design and operation had been identified.[1]

The major outcomes were to integrate the contaminant removal systems into the operation of the scour so that all heavy effluent (i.e. that originating from the hot scouring bowls rather than from the rinsing bowls) received treatment before discharge. Such treatment included removal of fibre and heavy solids, and recovery of woolgrease. Batchwise operation, where the scour bowls were 'dumped' to drain from time to time, was replaced by a fully continuous process. Liquor management was 'tight', with avoidance of bowl overflows and use of bowl-to-bowl 'flowback' running countercurrent to the wool flow. The 'flowdown' of heavy liquor to drain was at a controlled rate that could be set manually or automatically via measurement of a particular property of the liquor (e.g. density or turbidity). Heat was recovered from the flowdown and used to preheat fresh water being fed to the scour.

During 1977, CSIRO released the *Lo-Flo* process to industry.[23] This had a high level of effluent treatment integrated into the scour process. The *Lo-Flo* process relied on the phenomenon of 'concentration destabilisation'. When this liquor condition was reached, all of the suspended solids were



2.10 Simplified flow diagram of WRONZ comprehensive scouring system.[54] [*Courtesy of ANDAR.*]

able to be removed by centrifuging, and the liquor was then able to be re-used indefinitely.

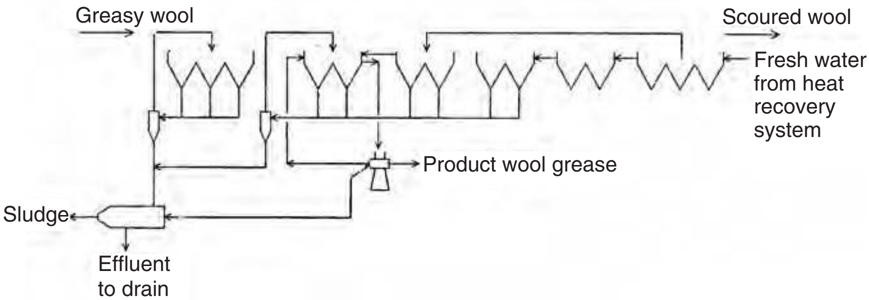
It was considered that several substances were involved in causing the destabilisation of the liquor. One was suint, another was the detergent added to scour the wool and the builders such as soda ash that were added to the liquors.[23] Destabilisation was said to be enhanced by high temperatures, and the liquors were heated almost to boiling point before centrifuging. During equilibrium operation, a mass balance for soluble substances (suint, builder, and detergent) was said to be achieved where the mass of such substances discharged with the sludge from the decanter and with the cream from the disc separator(s) equalled their rate of introduction to the machine.[23] There would also be a significant mass of soluble substances carried forward from the *Lo-Flo* unit to the next washing stage.

The *Lo-Flo* process was trialled by IWS at full-scale in a mill in the UK. To facilitate the transport of wet wool through squeeze rollers at very high liquor concentrations, wash plate systems were used both in the CSIRO laboratory machine and in the IWS full-scale machine. Wash plates include a perforated metal sheet down which the wool is caused to slide by a jet of liquor into the nip of the squeeze rollers.[21] In practice, IWS found that it was necessary to maintain a small flowdown from the *Lo-Flo* unit.[21] For dirty wools, the decanter sludge production increased and the suint removal was improved so that the flowdown could be eliminated.

Guided by experience in operating their full-scale *Lo-Flo* installation for two years, the *Mini-Flo* process was introduced by the IWS, mainly to address the low rates of dirt removal of the wash-plates.[21] Their *Lo-Flo* installation was modified to trial the process, and achieved 65% recovery of woolgrease and 59% recovery of dirt.[21] The *Mini-Flo* prototype used conventional bowls to remove dirt from the wool after the wash plates, while the commercial design used mini-bowls for the purpose. While the results from the commercial prototype were promising, neither *Mini-Flo* nor *Lo-Flo* achieved continued commercial success.

An early reference to *Siroscour* (Fig. 2.11) highlighted the need for cleaner wool and better dirt recovery, both of which had been problems with *Lo-Flo*.[24] Residual contaminants could affect processing performance in several ways, including contributing to dust and fly in the mill, affecting the performance of processing additives, leading to increased wear and tear on machines, and visual effects on both topmaking and subsequent processing (e.g. in spinning and dyeing).[25] Studies by CSIRO scientists had also shown that each of the usual wool contaminants, i.e. grease, dirt and suint, had easy-to-remove and hard-to-remove fractions.

The model of contaminant removal was as follows:[25]



2.11 Simplified flow diagram of *Siroscour*.[54] [*Courtesy of ANDAR.*]

1) the contaminant mass is penetrated by water and detergent;
2) the contaminants begin to swell as the water penetrates the mass (the rates of penetration and swelling vary considerably for different contaminants);
3) wool grease globules are formed within the swollen mass;
4) the complexed and uncomplexed easy-to-remove contaminants are removed from the surface of the wool;
5) the hard-to-remove contaminants, which may either be only partially swollen or adhering strongly to the fibre surface, are partially removed.

Easy-to-remove contaminants comprised the unoxidised woolgrease, readily soluble suint and loosely held minerals, together with organic and proteinaceous dirt. The remaining hard-to-remove contaminants comprised a small fraction of the total oxidised grease, slowly soluble suint, sub-micron mineral dirt and flakes of protein contaminant.[26] To facilitate the scouring of most of the contaminants, and to assist in the removal of the contaminants from the liquors, 'two-stage' and 'three-stage' scouring was promoted. Three-stage scouring was the preferred mode of operation.[25]

The first stage (Bowl 1) removed dirt without removing woolgrease by using a modified suint bowl. Small additions of detergent and soda ash were made and the temperature was kept below 35 °C. This improved the recovery of dirt via settling tanks or hydrocyclones in the liquor treatment loop connected to Bowl 1, since there was less chance that non-settleable grease-dirt complexes could be formed. In the second stage (Bowls 2–4), the easy-to-remove contaminants were removed.

Bowls 2 and 3 were scouring bowls containing hot detergent liquor while Bowl 4 acted as both a rinsing bowl to remove the easy-to-remove contaminants entrained in the wool mass and as a soaking bowl to encourage further swelling and hydration of the hard-to-remove contaminants. The third and final stage (Bowls 5 and 6) removed the hard-to-remove contaminants.

Siroscour provided a system which will effectively wash the full range of fine wools, much in the same way that the WRONZ System provided a similar outcome for New Zealand wools. While the WRONZ System with mini-bowls was indeed capable of efficiently and effectively washing the better types of fine wool, it was not capable of washing all types. A happy marriage of CSIRO and WRONZ technologies took place in the first ANDAR *Siroscour*, where Bowls 3 and 4 were mini-bowls, as there were space constraints at that particular site.

A comprehensive series of trials comparing the performances of different woolscours in industry was reported by the IWS in 1993.[27] This was actually the second series of such trials, carried out because there were a number of weaknesses in the first series of trials.[25] They were carried out by running four-tonne (greasy) batches each of fleece and skirtings through five different scours: a conventional rake/harrow scour, a suction drum scour (Fleissner), a *Siroscour*, a short-bowl (mini-bowl) scour, and a solvent scour (de Smet). The results showed strong relationships between specific opening energy and top length (hauteur), and between specific opening energy and noil.

Specific opening energy has proven to be a useful measure of the degree of entanglement of wool presented to the card. This measurement technique was developed and used at CSIRO, Geelong. By suitably instrumenting their card, they were able to determine the work done per kilogram of wool carded, i.e. 'the specific opening energy'.[9]

Since there are so many variables at play in any particular scour, only a proportion of which can be measured and reported, it is difficult to confirm causal relationships. The method of changing only one or a few variables on a particular scour is therefore preferable, and such tests were carried out on a *Siroscour* in Asia.[25] These tests confirmed the better performance of 3-stage scouring, compared with conventional scouring, both in terms of increased top length *and* better whiteness (Table 2.3). This is the type of result that scourers have always aimed for and disproves the proposition that better colour can only be achieved at the expense of a more felted product (e.g. via increased mechanical energy input through the scouring process) and hence reduced top length. A subsidiary trial using three-stage scouring was carried out where the degree of mechanical action both in greasy wool opening and in agitation in the bowls was reduced. This had the expected effect of improving the top length but with a small reduction in whiteness (Table 2.3).

2.7 Chemical treatments in woolscours

2.7.1 Carbonising

Raw wools are contaminated with amounts of vegetable matter (VM) depending on the environment in which the sheep were raised. The VM

Table 2.3 Comparison between conventional and three-stage scouring for wool scoured at a commercial topmaking plant (Mill A)[25]

Topmaking	Hauteur (mm)		Whiteness of tops (Y)	
	Conventional	3-stage	Conventional	3-stage
Mill A	65.6	67.3	65.1	65.5
CSIRO	68.7	69.1 (70.6)	66.4	67.0 (66.2)

includes burrs, seeds, twigs, and straw.[28] While the woolscouring process is very efficient at removing grease, dirt and suint from the raw wool, it is not effective at removing much vegetable matter. Pre- and post-scour opening and dusting machines can be specified or customised to remove small amounts of VM, but its removal is usually regarded as one of the functions of the card.[2]

Where the level of VM contamination is high, or where a VM-free product is required, a chemical treatment known as carbonising is necessary. A recent estimate puts the total volume of raw wool carbonised at more than 100 million kg per annum.[2] The carbonising process takes advantage of the difference in chemical stability of wool keratin and VM (mainly cellulose and lignin) towards mineral acids.

The carbonising process comprises conventional scouring, acidising, drying, crushing, beating, neutralising and final drying of the product. If alkaline scouring conditions are employed by means of additions of sodium carbonate, it is necessary to rinse the wool well before it is acidified.[2]

Sulphuric acid is the usual choice, applied at a concentration in the treatment bowl in the range 4.5–7.5%,depending on the bowl temperature and on the residence time of the wool in the bowl.[2,28] A wetting agent effective under acid conditions is selected to obtain maximum penetration of acid into the VM, while minimising the acid content of the wool. Materials of construction are selected to resist damage by the acidic liquors. The acid concentration in the bowl is best measured by acid-base titration: Knott showed that the densitometric method overestimated the acid concentration by more than 20 g/l for most of a trial week.

Moisture removal prior to drying traditionally used squeeze rollers. More recently, it has become accepted practice to install a continuous centrifuge after the acid squeeze roller and before the dryer feed-hopper. Centrifugal moisture removal provides a lower and more even regain distribution in the acidified wool, reducing the loss of fibre strength.

Modern high-throughput plants use a separate dryer and baker rather than an integrated unit. Thus, the dryer is designed for rapid drying at low temperature but with significant heat inputs, while the baker is designed for higher temperatures but with lower heat inputs. This provides improved flexibility in control, including an opportunity to redistribute the wool mat by means of a feed-hopper prior to the baker. The drying stage is critical in the process,[2,28] since acid hydrolysis of the protein chains may occur. Damage can be minimised by drying at low temperatures (60–70 °C) with high air flow rates through the wool mat.

After drying, the wool is baked at a temperature in the range 105–130 °C. Baking times in industry are typically 3–10 minutes depending on factors including openness of the wool mat, wool mat thickness, through-flow air velocity, and the amount of acid on the VM.[28] Under the influence of the concentrated sulphuric acid, the VM becomes brittle and charred, which facilitates its removal in the crushing and beating stages.

During baking, some acid may react with the wool to form covalently bound sulphate, which can cause problems in subsequent dyeing processes. The amount increases with temperature, baking time and acid concentration on the wool.[2]

It is necessary to crush the VM directly after baking because its crushability decreases when moisture is reabsorbed.[2] Crushing is carried out by passing the wool between sets of pressurised rollers arranged in series, and there is a trade-off between efficient crushing and length reduction in the wool fibre.

Beating (dedusting) of the wool entails mechanical action in willows or stepped opener-dusters.[2,14,28] Much of the now friable vegetable matter is removed at this stage.

After beating, the carbonised wool retains an acid content that can cause damage to the fibre if it is not properly neutralised. Neutralisation is usually carried out in a scouring train comprising 4 to 5 bowls.[2] The first bowl contains water, in order to remove free acid and to allow hydration of the wool. The next 2 bowls usually contain sodium carbonate solution to neutralise the wool. Nonionic detergents may also be added to the neutralising bowls.[28] The fourth and sometimes the fifth bowls contain rinse water to remove residual sodium carbonate.

2.7.2 Bleaching, insect-proofing and control of photo bleaching

Certain chemical processes normally carried out in textile and carpet mills can be applied within the constraints of a continuous scouring regime. Bleaching with sodium metabisulphite or peroxide, insect-resist treatments and a photobleaching control process are those most commonly applied. The chemistry and treatment conditions are described in detail in Chapter 7.

2.8 Drying

2.8.1 General

The clean, wet wool from the final squeeze roller set of the woolscouring line carries 50–100% of its bone dry mass as water, depending mainly on the temperature of the water in the bowl, the squeeze pressure and the type and condition of the covering ('lapping') on the top roller. The percentage of moisture based on the wool base is termed 'regain', and this parameter must be reduced to a typical target value of 16% at the exit of the dryer. Drying is responsible for 30–60% of the heat usage of a typical woolscour[1] and ways of reducing the usage of heat have constantly been sought.[29]

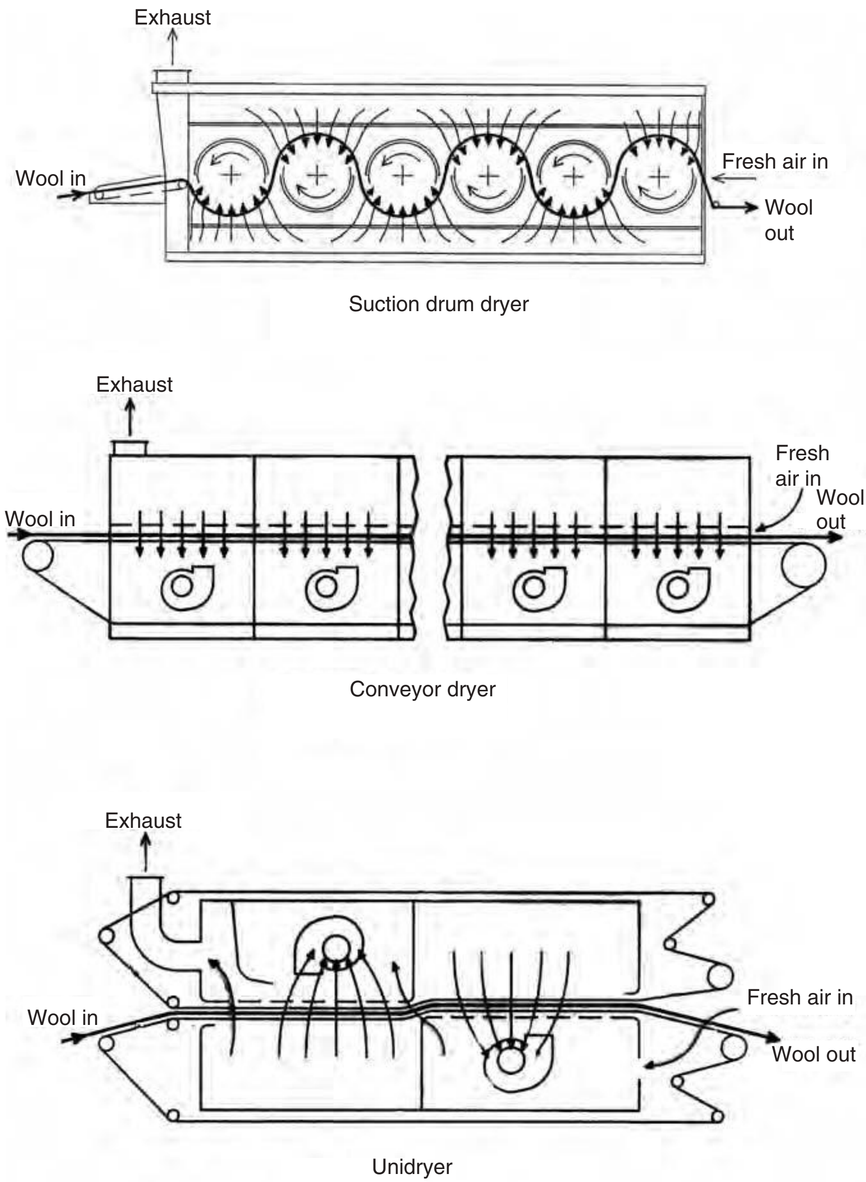
A future approach to energy conservation is 'airless' drying, where the material is dried in an atmosphere of superheated steam rather than in hot humid air.[30] Energy usage may be much reduced by recompressing and reusing the water vapour,[29] or by merely using the recovered heat in wet processing.[30] It was found that colour changes on drying should not be a problem but that only thin layers of wool could be handled by the technology. The latter requirement is likely to limit the applications, particularly in the drying of loose fine wool. Applications of superheated steam drying have been hindered by lack of suitable equipment and the corrosive conditions encountered.[29]

2.8.2 Commercial dryers

The dryers used in the scouring and carbonising industry are of the continuous throughput type with throughflow air circulation. The air and material flows within a wool dryer are normally worked in counterflow to maximise the thermal efficiency and drying capacity. Dryers are classified according to the mode of transport of the wool.

A *suction drum dryer* (Fig. 2.12) is fed by means of a belt and the wool is conveyed through it by perforated suction drums. Fixed baffles located inside the drums restrict the air flow to the upper or lower half of each drum alternately. The air circulation may be heated by steam or hot water coils located above and below fans mounted at the ends of the drums. Alternatively, the air circulation heating may be via direct gas firing. Suction drum dryers are compact, are easily controlled and have reasonable capital cost.

Conveyor dryers carry wool through the dryer on a perforated slat conveyor through which hot air is circulated downwards (Fig. 2.12). Heating may be via steam or hot water coils or via direct gas firing. Such dryers occupy a larger floor area than drum dryers of the same production capacity since the rate of air circulation through the wool is lower. Upwards air



2.12 Types of wool dryer, not drawn to scale.[54] [*Courtesy of ANDAR.*]

flow has the aim of improving the evenness of drying but only very low airflow rates can be used before the wool is lifted off the conveyor. Capital costs of conveyor dryers are higher than for drum dryers and they usually have a slower response in temperature control. Fig. 2.13 shows a conveyor dryer of recent design, where the wool is conveyed by means of porous sandwich belts.

The *Unidryer* (Fig. 2.12) is a more recent introduction, and was originally intended to be a rapid ('high intensity') dryer for carbonising loose wool.[31] The wool is carried through the dryer between two woven polyester conveyors while being subjected to reversing airflows in alternate sections of the dryer. The original design used air temperatures up to 150 °C, and relatively heavy bed weights of wool. Lower operating temperatures were used in later designs mainly due to industry concerns about wool yellowing. Because the wool mat is totally contained, throughflow air velocities may be adjusted without the wool drop-off problems that might occur in a suction drum dryer. This means that control of air velocity with possible energy savings is a viable means of regain control. Cleaning requirements should be less frequent because it is less likely that fugitive wool will accumulate in the dryer.

It was originally commercialised in the UK on loose wool and then hanks, but achieved little market penetration. Early applications of the *Unidryer* included the drying of hanks, coils of yarn in the WRONZ Twistset process, and loose stock in dyehouses.[1] The *Unidryer* was succesfully installed in a

2.13 Modern sandwich-conveyor dryer. [*Courtesy of Jandakot Wool Washing Pty Ltd.*]

woolscour of 3 m working width in New Zealand during 1996 and further sales followed.

Historically, most of the dryers in the wool industry have been heated by means of steam coils. More recently there has been a trend towards heating by means of direct firing with natural gas where it is available. This trend has been driven by improvements in dryer capacity, speed of response in control, and savings in process heat owing to the elimination of transmission and boiler losses that characterise steam systems. Heating by means of radio frequency power has a theoretical advantage in that the energy should be preferentially absorbed by the moisture in the wool, which should result in a more evenly dried product. However, suitably controlled and well maintained hot air dryers produce wool that is sufficiently uniform for baling directly, with lower capital and running costs than radio frequency drying.

2.9 Solvent scouring

There are several major advantages of solvent scouring. Felting and entanglement associated with aqueous scouring are largely eliminated, woolgrease recovery is much increased, suint recovery may be designed into the process, and aqueous effluent problems are avoided. At first sight then, there are several clear cut advantages to be gained from solvent scouring, with only minor disadvantages – the necessity for solvent recovery, possible toxicity and fire hazards to be set against it.[32]

Several different processes reached commercial prototype status during the 1950s–1970s without achieving significant commercial success. These included a process developed at the Swedish Institute for Textile Research,[33] the CSIRO solvent jet process,[32] and a process developed in Yorkshire at the West Riding Woollen and Worsted Mills Ltd.[34] The Swedish and CSIRO processes both used a relatively high boiling point petroleum fraction, while the Yorkshire process used tetrachloroethylene.

The most successful solvent scouring technology has been the de Smet process, with seven plants in commercial operation in 1990.[35] It uses a combination of non-polar (hexane) and polar (isopropyl alcohol) solvents to target woolgrease and suint removal from the wool respectively. However, despite the acceptable results obtained for the de Smet plant in comparative testing of woolscour performance,[27] there has been little further market success for this technology in the 1990s. A contributing factor is the high capital cost for such plant compared to conventional aqueous plant, during a time of low profitability in the wool industry generally.

A new type of solvent scour was commissioned in Japan during 1983. This was the Toa-Asahi process and the solvent used was 1,1,1 trichloroethane. The wool was solvent degreased, dedusted and then given a conventional soap/soda scour to remove residual suint and dirt. Only one plant was ever installed, and it has ceased operation. Part of the problem with this process was that the chosen solvent both depletes ozone and is a greenhouse gas.[36]

Historically, high capital costs have militated against the installation of solvent scouring systems. Additionally, because many of the investments in scouring during the 1990s have been for plant upgrades or plant relocations rather than for 'greenfield' installations, the opportunities for a step-change in technology have been limited. An exception is the solvent scouring technology from Wooltech Ltd, of Brisbane, Australia,[37] who have developed a system using a formulation of 1,1,2 trichloroethylene (TCE). This solvent is non-flammable and does not deplete ozone, since it chemically degrades before reaching the ozone layer. However, TCE is toxic to humans and requires appropriate handling, as described in material safety data sheets (MSDSs) which are available on-line.[38] A full-scale topmaking plant including a complete *Wooltech* solvent scouring system was installed in Trieste, Italy in time for the *ITMA* Exhibition of 1995 in Milan.

Enhancements of fibre properties have been claimed by the treatment using TCE, including increased tenacity, elongation and resilience.[37] It has also been claimed that such enhancements combined with the very low residual grease content of the scoured product enables good quality yarns to be spun using the rotor system. When compared with conventional aqueous scouring equipment, which is simple, robust, and has a long working life, solvent scouring equipment is much more sophisticated, and requires a chemical process engineering approach to its operation. However, if the aqueous scouring plant has a comprehensive effluent treatment system added to comply with strict environmental regulations, the levels of engineering sophistication are similar.

It will always be difficult to remove the suint and to a lesser extent the dirt, from the raw wool by means of TCE. However, subsequent processing may be arranged to include further cleaning and obtain a satisfactory product (e.g. by backwashing). Capital and operating costs, as well as processing performance, will ultimately determine the success of this technology. At the time of writing, there have been no further installations of the Wooltech system.

2.10 Woolgrease and its recovery

It is useful to clarify terminology relating to woolgrease.[1] The material secreted from the sebaceous glands of sheep is 'wool wax'. The material recovered from woolscouring liquors or by solvent extraction from greasy wool is known as 'woolgrease' which, as well as wool wax, may contain pesticide residues, dirt, suint components, and detergent. When the crude woolgrease is refined, the product is known as 'lanolin'. The major components of lanolin are high-molecular-weight esters formed from a mixture of sterols, aliphatic alcohols, and diols combined with straight chain, branched chain, and hydroxy fatty acids. Minor components are free alcohols and acids.[1]

Acid cracking is a long-established process which includes woolgrease recovery, but because it is applied at 'end-of-pipe', it is described in the effluent treatment section. Centrifuging is almost universally used and is most efficiently employed by integrating the operation with the liquor circulation in the scour train as in the WRONZ System or Siroscour.

The design of the woolgrease recovery system depends on the quantity and quality of the woolgrease available on the raw wool. For coarse wools (e.g. New Zealand Romney types), two-stage recovery is used. In this type of plant, the liquor is first pumped to a nozzle/disc centrifuge set up as a concentrator to produce a cream for subsequent feeding to a disc separator set up as a purifier. This is usually a self-desludging machine rather than a nozzle machine since there is only a small quantity of dirt in the feed. For Merino wools, a three-stage recovery plant is used, where three centrifuging stages are used in series. Again, the first stage is concentration using nozzle/disc centrifuge(s) and the third stage is purification; but interposed is an additional concentration stage, typically using a self-desludging disc centrifuge. Fig. 2.14 shows a recently installed woolgrease recovery plant for Merino wools.

For practical reasons of centrifuge operation and to assist the removal of water-soluble contaminants and dirt, water at almost boiling temperature is added with the cream being fed to the purifier. The product from the purifier centrifuge should be woolgrease at less than 1% moisture.

Part only of the grease present in woolscouring liquors can be recovered by centrifuging and this fraction differs in composition from that remaining in the liquor.[39] The recovered material is relatively unoxidised while the remainder is relatively oxidised and tends to be darker and of less commercial value.

Recycling the clean phase from the separators back to the first hot scouring bowl is usually carried out as part of a system to control the level of total solids in the bowl and this favours the recovery of woolgrease.[40] Feeding the liquors to the primary centrifuges at elevated temperatures assists recovery, but there appears to be little benefit in using temperatures above about 75 °C. However, it is claimed that a feed temperature close to boiling point enhances recovery when operating in the *Lo-Flo* regime.[23] Only a minority of commercial centrifuges are suitable for use on woolscour liquor, which brings technical challenges for high-throughput (2.4–3.0 m width) scouring machines. Solvent extraction and aeration have been very rarely used for woolgrease extraction.

2.14 Woolgrease recovery plant. [*Courtesy of Jandakot Wool Washing Pty Ltd.*]

Woolgrease has an enormous diversity of uses whether as the material recovered in scouring plants, as the refined product (lanolin), or as chemical derivatives of woolgrease[1,40] and lanolin. Crude woolgrease has been used for anti-corrosive coatings or additives, leather processing aids, release agents, and tree-wound dressings. It is refined to lanolin by a process of deodorisation, bleaching, and neutralising to provide a lighter coloured product with little odour and low free fatty acid and moisture contents. Lanolin is used widely in the pharmaceutical and cosmetic industries. In pharmaceutical uses, the desired properties of lanolin and its derivatives include their general inertness and ease of emulsification. Cosmetic uses take advantage of the material's ability to absorb large quantities of water as water-in-oil emulsions or when suitably modified, to stabilise oil-in-water emulsions.

Lanolin may be saponified to the constituent acids and alcohols. Cholesterol is one of the most frequently sought after products of saponification, and is one of several that can be further transformed for cosmetic and pharmaceutical use. The wool wax acids are useful in protective surface coatings, corrosion inhibitors, and when converted to metallic soaps, as lubricants.

2.11 Effluent

2.11.1 Effluent components

It is useful to group unit operations and processes together to provide what are known as *primary, secondary, and advanced (or tertiary)* treatments of effluent.[41] In primary treatment, physical operations such as screening, sedimentation, and centrifugation, are used to remove floating and settleable solids found in the effluent. In secondary treatment, biological and chemical processes are used to remove most of the organic matter. The most widely-used measure of organic pollution in effluents is the 5-day biochemical oxygen demand (5-day BOD or BOD[5]). In advanced treatment, additional combinations of unit operations and processes are used to remove other constituents, such as nitrogen- and phosphorus-containing compounds, that are not significantly reduced by secondary treatment. Land treatment processes, now more commonly termed 'natural systems', combine physical, chemical, and biological treatment mechanisms and produce-water with quality similar to or better than that of advanced wastewater treatment.[41]

Woolgrease recovery and dirt recovery are now integrated with the operation of the scour line. However, after such primary treatment the effluent remains highly polluting and difficult to treat. The effluent from a 2 metre-wide woolscour can give a pollution load similar to that of a town with over 30 000 people.[42]

Effluent discharge from an efficient scouring plant contains these components:

i) An oxidised less biodegradable fraction of woolgrease.[43]
ii) A dissolved organic component (suint) relatively easy to biodegrade.
iii) A dirt content which varies tremendously. Fine particles associated with residual woolgrease cannot be completely removed by mechanical means.
iv) Minor components such as detergents, insect resist agents, bisulphite, peroxide, and builders (e.g. sodium carbonate).

Jamieson and Stewart identified the contributions of the main contaminants to the pollution load and summarised the results in the following formulae:[1]

$$
\begin{aligned}
\text{BOD[5]} &= 2400 \times \text{Suint} + 5100 \times \text{Oxidised grease} \\
&\quad + 11\,350 \times \text{Top grease} + 185 \\
\text{COD} &= 8267 \times \text{Suint} + 30\,980 \times \text{Oxidised grease} \\
&\quad + 28\,326 \times \text{Top grease} + 6454 \times \text{Dirt} + 1536
\end{aligned}
$$

BOD[5] and COD are given in mg/litre and the contaminant concentrations are percentages by mass in the effluent. BOD[5] is the Biochemical Oxygen Demand: it is the quantity of oxygen needed to oxidise one litre of the waste under the conditions likely to be met with in natural receiving waters; the [5] refers to the length of time for which the sample is incubated, namely 5 days. COD is the Chemical Oxygen Demand; it is the amount of oxygen in milligrams required to chemically oxidise one litre of the waste under specified conditions. The formulae illustrate that the oxidised grease is indeed more difficult to degrade by biological means than the top (or unoxidised) grease.

2.11.2 Primary methods of effluent treatment

Minimisation of water usage and production of relatively concentrated effluent streams is part of efficient scour management. A concentrated effluent is more conveniently treated than a high-volume waste stream. Primary treatment should, therefore, be integrated with scouring.

Modern scouring systems such as the WRONZ or *Siroscour* systems incorporate primary treatments. Sedimentation (settling of particles by gravity) in settling tanks is still practised industrially, but the use of settling tanks in liquor treatment loops may cause scour liquors to become anaerobic and discoloured due to microbial activity. The use of hydrocyclones has become more widespread as pump and hydrocyclone design have improved.

The *Lemar Stage 1 Process* may be used to increase the rate of woolgrease recovery and to dewater the sludges produced by a typical WRONZ System.[1] In this process, the flowdown effluent and sludges are combined and pumped via a hydrocyclone to a decanter centrifuge. The centrate from the decanter is fed to a disc centrifuge where woolgrease (an additional 8–10%) is recovered.

Dissolved air flotation has been tested at full scale as a treatment for heavy liquors. It was found that the liquors from a modern scouring system were too concentrated and the results were no better than sedimentation or thickening.[44]

2.11.3 Secondary treatments

Chemical destabilisation by acid cracking is the oldest industrial method for treating woolscour effluents, and is still used by several mills,[42] mainly in Europe. It involves adding sulphuric acid to the effluent to provide a pH of 2–3.5, and allowing the resulting sludge to settle. A low grade woolgrease is recovered from the sludge by boiling followed by filter pressing. The method works efficiently for effluents from soap/soda scouring, but is unreliable for effluents from scours which use non-ionic synthetic detergents. Acid cracking at the boil has been shown to overcome the difficulties encountered with non-ionic detergents.[42]

There have been many variations of chemical coagulation and flocculation, regarding both the chemicals used and the process details. Generally, chemical coagulation produces a voluminous sludge that requires dewatering. Simple filtration is not possible since the woolgrease in the sludge causes the filters to clog. Historically, rotary drum vacuum filters using precoats have been employed for dewatering, at considerable running cost. Recent advances in this type of process have included the additional use of polymeric flocculants in a multi-pronged chemical approach, along with decanter centrifuges for sludge dewatering.[42,45] Generally, processes using large amounts of chemicals are now considered ecologically undesirable. Alternative approaches treating wastes as a resource are coming to the fore.[46,47]

Sirolan CF is a chemical flocculation process developed to treat heavy effluent, i.e. the flowdown from hot scouring bowls combined with the sludges from the heavy solids loops. After pH adjustment with acid and flocculation with a polymer, effluent is fed to a decanter centrifuge where suspended solids are removed as a sludge with 50–70% total solids. This process removes over 95% of the solvent extractable and suspended solids, and reduces COD by about 75%. It is used commercially by several scours in the UK and Australia.

SWIMS[47] is an acronym for Scour Waste Integrated Management System. Its features are:

i) effluent treatment is closely integrated with the operation of the scouring line;
ii) each waste stream is treated separately;
iii) the wastewater treatment systems are modular; and
iv) the scouring wastes are considered as a resource.

As well as the heavy liquor flowdown from the hot scouring bowls, in three-stage Siroscour operation there are discharges from the modified desuinting bowl and from the rinsing bowls. Evaporation of the desuinting flowdown produces a potassium fertiliser, while the rinsewater is subjected to microfiltration or other membrane treatment. Suint in the effluent produced by *Sirolan CF* still has substantial COD. Laboratory and pilot plant trials have substantially removed this by aerobic treatment (*Sirolan CFB*) except for some bio-refractory material which still exerts a COD. Sludge from *Sirolan CF* has proved satisfactory as an ingredient for the making of compost when mixed with a variety of materials.[47]

Alcohol destabilisation occurs if water-soluble alcohols are added to woolscour liquor, to give three phases:[1]

i) Grease/alcohol phase saturated with water;
ii) Dirt/water phase saturated with alcohol; and
iii) Water phase containing suint and saturated with alcohol.

Alcohols including n-butanol and n-hexanol have been used in laboratory and pilot plant studies, while a full-scale plant using n-pentanol ran for 5 years before the woolscour ceased operation for reasons unrelated to the effluent process.[1]

Woolscour emulsions may also be destabilised by short-term aerobic or anaerobic treatments, and the woolgrease flocculates into a sludge.[43] A two-stage laboratory process working on Australian scouring liquors removed 70–90% of the woolgrease (without significantly biodegrading it) at a combined hydraulic retention time of 4–10 days. Such destabilisation is apparently not robust enough for commercial processes to have been developed based on it alone, but anaerobic pretreatments have been used as precursors to full scale coagulation and flocculation processes,[1,42] and there are probably opportunities for more leverage to be gained from such low cost destabilisation, perhaps incorporating chemical treatments or electrocoagulation.

By way of contrast, aerobic digestion uses free oxygen to convert wastes into carbon dioxide and water, plus biomass. Long residence times are necessary and the feedstock must generally be dilute. Process variables that need to be monitored include temperature, oxygen levels, pH, nutrient levels and degree of mixing. Scours in Germany and Australia have successfully used such treatments. A topmaking plant in Germany reported BOD reductions from 1100 to 80 mg/l and COD reductions from 2500 to 1200 mg/l.[46]

Commercial anaerobic digestion plants have been reported, but generally the process requires long treatment times and is prone to upsets in the feed.[1] A conventional sludge digestion plant has been operating in New Zealand fed with flowdown liquors in admixture with domestic effluent since the early 1980s.[1] When operated at a retention time of 20 days, 80–95% reductions in BOD and suspended solids were achieved.

Ultrafiltration is a membrane process which is used to separate suspended solids from dissolved solids. On heavy liquors, it produces a suint solution and a concentrated grease-dirt sludge (concentrate). Ultrafiltration plants have been used in the UK scouring industry on heavy liquors for some years, with the concentrate trucked away to appropriate disposal sites and the ultrafiltrate discharged for further treatment at the local sewage works.[42] Ultrafiltration and microfiltration have also been used successfully to treat rinsewaters to enable recycling of water in the scouring process. Microfiltration membranes have a larger pore size than ultrafiltration membranes, and hence exhibit higher flux rates.

Evaporation may be carried out as a stand-alone effluent treatment if suitable outlets for the sludge are available. Various commercial plants are available, and are in use in Europe, Asia and Australia (Fig. 2.15). The efficiency of energy usage may be improved by a number of means, e.g. multiple effect evaporation, use of the steam produced to heat the scour, or by mechanical or thermal vapour recompression.

2.11.4 Tertiary treatments

Several systems using biological lagoons are in operation in rural areas of Australia.[42] A typical process involves a number of pits and lagoons in series as follows:

i) A sludge pit to remove settleable solids.
ii) A deep anaerobic pond, sealed by a floating crust of woolgrease. This pond receives the heavy flowdown effluent. Retention time is approximately two to four weeks.

2.15 Effluent treatment plant incorporating an evaporation system. [*Courtesy of Jandakot Wool Washing Pty Ltd.*]

iii) An aerated lagoon, perhaps using floating aerators.
iv) A large holding lagoon, which also receives the dilute rinsewater effluent from the scour. It acts as an evaporation pond or as a holding pond for subsequent irrigation to land.

One scour in Australia combines the anaerobic pond and aerated lagoon into a facultative[41] lagoon. The dilute effluent is recycled to the scour via a trickling filter, settling and chlorination.[42] The main disadvantages with lagooning systems are occasional odour problems and the need for unpleasant cleaning out of the sludge pit and anaerobic ponds.

2.11.5 Total treatments

Evaporation and incineration eliminates all aqueous effluent. During the 1970s, over 22 mills in Japan which operated woolscours installed various evaporation and incineration plants.[1] Discharge requirements of increasing severity stimulated such expensive measures. Unlike the situation for a stand-alone woolscour plant, the capital and running costs were spread over a large operating base. At the time of writing, all of the scouring operations within Japan have been replaced by lower cost processing options outside Japan.

Today's evaporation plants are typically of the multiple effect falling film type, sometimes operating under vacuum.[42,46] Sludges are often burnt in a two-stage process, where the first stage generates a combustible gas by pyrolysis. This approach minimises problems associated with fusion of potassium compounds in the combustion zone and with deposition of particulates downstream of the combustion zone.

The performance of a very comprehensive effluent treatment plant at a topmaking mill in Germany has been described.[46] Evaporation/incineration is used to treat the heavy effluent while the rinsewaters are treated separately in an aerobic biological system. Condensate from the evaporation plant is reused in the scour rinsing process after stripping ammonia by steam and removing odours and pesticides via a fixed bed bioreactor.

Main routes for disposal have been to landfill or for more dilute sludges to be spread on land. Landfill disposal is becoming less favoured as dumping charges increase.[47] Suitably conditioned sludges have some value as a fertiliser in agriculture,[46] but there may be adverse effects in some cases of sludge disposal on land.[48]

Composting of sludges is already being carried out commercially by a topmaker in Australia, and it is likely that this method will become more widely used. It has been shown that the sludge from *Sirolan CF* may be readily composted and that the woolgrease and associated pesticide residues arising from on-farm treatments to control lice, flystrike etc are broken down in the process.[47] It has also been shown that composting of woolscour sludges and solid wastes must be carried out with care to avoid inadequate results.[48] Trials on the pelletising of sludge for use as a fuel or slow release soil improver/conditioner have also been reported.[47]

2.12 Process control and quality assurance

Over the last 30 years in particular, there has been sustained development in control and instrumentation systems in woolscouring. Often, such developments have been mainly applications of generic innovations from outside the industry (e.g. weighbelt feeding) but significant innovations have also derived from the special needs of the industry (e.g. the *Drycom* moisture meter). A brief mention of the more significant developments of both types will be given here.

Weighbelt feeding of the greasy wool to the scour is now regarded as essential, to provide an even feed-rate of wool with benefits in terms of consistent scouring and drying, increased productivity and provision of management information.

Scourcom set the standard for state-of-the-art computerised control systems for woolscours (Fig. 2.16).[1,49]

2.16 Scourcom computer monitors. [*Courtesy of Jandakot Wool Washing Pty Ltd.*]

Hoppermatic control of the level of greasy wool in feed-hoppers has allowed for improved control of the opening and feeding stages.[1,49]

Various on-line monitors have been developed to measure the regain of wool at the exit of the dryer with the most successful unit being the *Drycom* moisture meter.[1,20,49]

Control of liquor quality is now practicable by means of density or turbidity sensors.[1,20,49] Suitably rugged and reliable sensors are now available commercially for scouring and rinsing applications.

The *Trimwaste* system controls the discharge of sludge from settling tanks.[1,20,49] The potential number of applications for this system has reduced as hydrocyclones have become more widely used instead of settling tanks.

Continued development has taken place in the measurement of scoured wool properties by means of Near Infra Red Analysis (NIRA). A 'Generation III' instrument has recently been successfully installed in a woolscour.[50] This instrument has detectors operating in the visible region as well as the near infra red, which has enabled accurate measurement of the 'as is' and 'base' colour of the scoured wool. In addition, residual grease and moisture levels are monitored simultaneously, with most of the information for these measurements originating from the near infra red detectors. Since the measurement time is now down to 45 seconds, the information is valuable as a guide to the operation of the scour itself. Integrity of the wool sample has been achieved by automated sample coring, transport, loading into the instrument, measurement and sample sealing.

2.13 Energy conservation

Woolscouring is an energy intensive process. In terms of the operating costs for a woolscouring plant, energy is second only to labour. Considerable work was carried out on energy efficiency in woolscouring during the 1970s and early 1980s in response to the rapid fuel price rises of the time.[1,51] While there was little scope for reducing the electricity usage in woolscouring, there was considerable potential for savings of process heat by improved design of the heating system, improved control and by installing heat recovery systems. Taking advantage of heat recovery from heavy effluents and from rinsewater is now routine, but heat recovery from dryer exhaust air is less common due to a longer payback time and more demanding practical requirements.

Owing to the installation of new, higher productivity scours of 2.4 m and 3.0 m working width during the last 20 years, average energy costs per kilogram of wool scoured have fallen. Improved process control whereby throughputs can be maintained at higher average levels has assisted this result.

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