

Modern diaper technology

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THE MODERN DISPOSABLE DIAPER is a common household product. A user is generally unaware of the sophisticated and elegant technologies in the product. This paper explores many technological features affecting performance of adult and infant diapers. These properties include absorbent materials retaining over 50 times their weight in fluid (1), multiple elastic elements in leg openings (2–4), upright barrier cuffs adding a third dimension to diaper design (5, 6), pressure-sensitive fastening tabs (7), spiral glue patterns allowing elastics to perform better (8, 9), tailor-made elastic elements providing containment without excessive pressure (2, 3, 10–12), materials contacting the skin (13, 14), and other techniques. Much technology in a modern disposable diaper can also apply to other products dealing with fluid management.

Before the 1960s, the reusable cotton diaper was the usual product to contain baby waste. These diapers have undergone little change. They are essentially square products approximately 50 cm on a side made of a thick weave of cotton fabric. A diaper wrap rather than safety pins usually holds them close to a baby. These diapers have the following problems:

1. Leakage of body fluids especially during the night and with older children
2. Significant incidence of diaper rash caused partly by skin hydration from constant contact with fluid
3. Frequent washing and drying.

Buell (15) received a patent in 1975 for the first disposable diaper to gain a significant market share. Shortly after his invention, disposable diapers became the norm rather than the exception. The absorbent material in early disposable diapers was cotton wadding. By 1975, wood pulp fibers were the absorbents. Buell's innovation was the addition of elastic in the leg openings. This elastic created a seal to reduce leakage of body fluids and improve fit.

This paper does not focus on a chronology of diaper inventions, but examines the technology currently employed in a modern disposable diaper. A generic discussion of diaper construction and performance shows that the modern disposable diaper is only a distant relative of the cloth diaper fastened with safety pins. Note also that modern diaper manufacture consists of raw materials fed to a production line. The packaged product—compressed diapers—emerges at 300 diapers per minute (4). Disposable diaper manufacturing machinery operates with no manual operations. Diaper features, therefore, must be compatible with a high production rate, fully automatic line that produces diapers with essentially zero defects (16).

CONSTRUCTION OF A MODERN DIAPER

Figure 1 shows the standard features of a disposable diaper:

- Hourglass shape for good fit and containment
- Elasticized waist
- Erect barrier cuffs and multiple elastic elements in the leg openings, barrier cuff, or both for improved containment

ABSTRACT

Modern technology makes state-of-the-art disposable diapers more functional than reusable cloth diapers. The authors discuss the critical operative properties of the topsheet, hydrophilic surge or wicking layer, absorbent core containing superabsorbent, backsheet, multiple elastic elements, barrier cuffs, and pressure sensitive adhesives. The discussion provides a comprehensive examination of the fundamental issues and technological solutions in modern disposable diapers.

- Multiple layers of materials throughout the diaper, especially in the absorbent pad area.

Over the area of the thick absorbent pad, a diaper has an outer cover. This is usually a moisture impervious polyethylene film or barrier sheet. Embossing of this sheet provides texture and reduces the bending stiffness. The outer cover may have a covering of cloth-like material for tactile and visual aesthetics. Closer to the skin than the outer cover is the absorbent core that absorbs the bulk of the fluid insult. Above the absorbent core in most ultrathin diapers is a wicking or surge layer. Contacting the user's body is the topsheet or coverstock.

Fusion technology bonds the thermoplastic polypropylene non-woven fabric topsheet, barrier cuffs, and polyethylene film outer cover. Thick constructions usually use ultrasonic bonding and thin constructions use pattern calender bonding. In some locations, glue secures diaper parts together. For example, spiral gluing using pressure sensitive adhesives commonly secures the elastics. Fastening tabs attach to the barrier sheet, and landing strips are at appropriate sites on the barrier sheet.

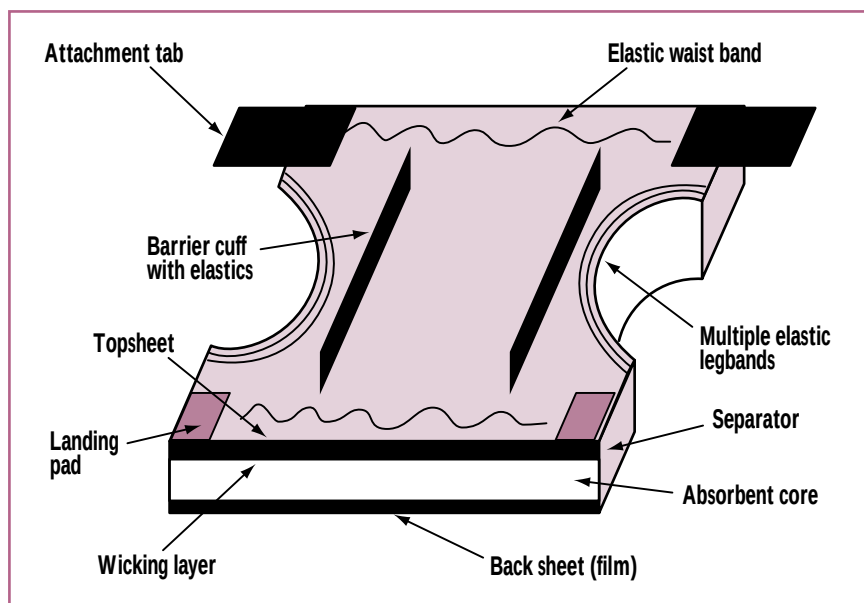
The ideal diaper is thin and flexible to fit each individual perfectly. The popular hourglass shape design allows the top and bottom to unite, forming the waist. Sides form the leg bands. With a proper cut, the diaper can fit snugly. An ideal diaper can withstand multiple insults and still feel dry to the touch. It has zero leakage and does not allow diaper rash to develop. Within the last decade, diaper manufacturers have approached ideality in function, but continue to work to develop environmentally friendly products (17–19).

TECHNOLOGICAL FEATURES OF STATE-OF-THE-ART DIAPERS

Diaper and barrier cuff technology uses such terms as hydrophilic, hydrophobic, and impermeable. Although the difference between hydrophobic and impermeable may initially seem subtle, it can lead to significant performance differences in some applications. Hydrophilic is literally water-loving. Hydrophobic means that fluid does not wet the material. Certain vapors can pass readily through breathable hydrophobic fabrics. A high pressure or driving force can force fluid through the small pores of a hydrophobic fabric. Impermeable means fluid cannot pass at a significant rate even with pressure. Fabrics are breathable, but impermeable materials such as solid films are generally not. Breathable fabrics offer more comfort during use.

Topsheet

The only layer of the diaper to contact the body of the user directly is the topsheet or coverstock. Used with the absorbent core, this layer allows all the fluid expelled by the body to pass through and enter the diaper. It does not allow fluid to rewet. The skin is therefore always dry, even when the diaper has partial loading. Cloth diapers and the coverstock and absorbent combinations used on early diapers were not effective



1. Schematic construction of a modern disposable diaper

in eliminating surface wetness on liquid insult. Studies have shown that continued exposure of skin to local dampness causes skin hydration—a precondition to diaper rash.

Current infant diaper topsheet usually uses hydrophobic fibers of polypropylene that offer the desired performance. The polypropylene is a spun bonded fabric or a thermally bonded, carded web (BCW) (20). The spun bonded fibers are continuous, and the other option uses staple fibers. The advantage of spun bond technology is the inexpensive web. BCW technology allows fiber crimping. The resulting advantage is that the fabrics are soft and flexible. Treatment with surfactants can alter the surface properties of any fibrous web. Surfactants can lower or raise the contact angle of fluids on the fiber.

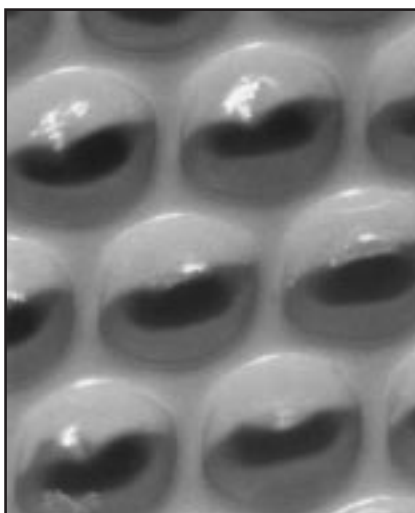
Some diapers use apertured hydrophobic film treated with surfactant to provide a hydrophilic surface (14, 21, 22). Construction of these diapers requires placement with the wide end of the cone against the wearer's body. Figure 2 shows the narrow end of the cone

faces the absorbent core. The surfactant allows the fluid to wet the otherwise hydrophobic topsheet. The apertured structure is effective because capillary forces allow body fluids attracted by the surfactant to pass into the diaper. The apertures act as one-way valves and do not allow fluid to rewet the skin. The inherent hydrophobicity of the backside of the topsheet further inhibits the return flow of liquid.

The result of these constructions is dryness of the topsheet even on liquid insult. This minimizes the incidence of diaper rash (23). Using materials in the absorbent core that have high affinity for fluids—super-absorbents—aids the dryness.

Surge layer

Most ultrathin diapers now consist of two layers: the wicking or surge layer and the absorbent core. As recently as ten years ago, a state-of-the-art diaper body used only wood pulp. At approximately 10 times its weight in fluid, this has low absorbency. The capillaries—the spaces between the fibers—trap the fluid. By adjusting the density of the pulp fiber layers using various pro-



2. Photomicrograph of apertured film from an adult diaper



3. Photomicrograph of iodine stained spiral glue pattern from a diaper

cessing techniques, manufacturers control the capillary size. This controls the volume of wetting fluid absorbed and the binding strength between fiber and fluid. The fundamentals of absorbency teach that small capillaries bind fluid tightly and large capillaries have high capacity (24). Soon after the introduction of superabsorbent polymers, their use became popular in the body of a diaper. While the superabsorbents offered tremendous advantages, such as total fluid retention and tenacity of binding, they have certain limitations in a total diaper design. This led to the incorporation of layers in the bulk of a diaper to include a surge layer.

The surge layer of the diaper consists mainly of hydrophilic fiber. The fluid impinges on this layer as it passes through the topsheet. The fibrous assembly absorbs the liquid virtually instantaneously by capillary forces. The fibrous structure thus wicks away the localized insult, distributes it into an area larger than the direct insult, and temporarily holds the fluid until it is captured by the absorbent core. Total pore size in the surge layer is sufficiently large to pro-

vide the required capacity and mobility of the fluid. Fluid in the small pores will be the final material to drain to the superabsorbent.

The most important characteristics of the wicking layer are wettability, pore size, and pore size distribution. Weak acids such as citric can crosslink the fluff or wood pulp fiber commonly used in wicking layers. This modifies the characteristics of the fibrous web (25–27). The acid crosslinking imparts a three-dimensional character to each fiber. This gives the assembly more bulk or lower density with concomitantly greater fluid distribution and absorption capacity. The surge layer may also use appropriate constructions of surfactant treated, bicomponent, synthetic fibers (28).

Absorbent core

The absorbent core is the heart of the diaper because it is responsible for retention of body wastes. Practically all modern diapers use wood pulp fiber and superabsorbent particles. The wood pulp fiber is an inexpensive hydrophilic fiber that can trap approximately 10 times its weight in fluid in the capillaries among fibers. Superabsorbent can

absorb 40–60 times its weight in body fluid (1, 29), but it is considerably more expensive albeit more effective than wood pulp. Thin diapers contain superabsorbent as small particles trapped in the fibrous network. It is possible to shake them out. To prevent their movement into the surge layer, there is a layer of tissue sandwiched between the surge layer and the absorbent core.

The superabsorbent in diapers is usually a partially neutralized sodium or potassium polyacrylate (29). It is a lightly crosslinked polymer that swells enormously upon exposure to water. This growth of the superabsorbent with fluid uptake is a phenomenon that requires consideration in diaper design and construction. Incorporation of superabsorbent into a diaper is not a simple matter, as the elapsed time between invention of superabsorbent and their presence in diapers suggests (30, 31).

Because superabsorbents are ionic materials, their performance depends on the ionic character of the fluid used. Urine is a saline solution containing approximately 0.8–0.9% salt (1, 13). It varies from person to person and from day to day. Most superabsorbents in diapers absorb more than 100 times their weight in water, but only about 50 times their weight in urine.

The substitution of superabsorbent for some wood pulp in a diaper allowed diapers to become thin, flexible, and conform well to body contours. Better conformation has led to less leakage. Older diapers had absorbent cores that were essentially 100% wood pulp fiber. These diapers were quite thick, bulky, and ill fitting. In addition, the larger capillaries did not bind with water as tightly as the superabsorbent particles do. The older diapers, therefore, had a predisposition to leak.

Note, however, that use of 100% particulate superabsorbent would

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not be as effective as the combination of superabsorbent in a fibrous assembly. Two problems with superabsorbents cause this:

1. Superabsorbents do not absorb fluid as quickly as do the capillaries in wood pulp.
2. Superabsorbents can gel block.

Gel blocking occurs when a superabsorbent particle swells upon exposure to fluid. The partially swollen mass only allows fluid to pass into the unswollen regions slowly. In addition, partially swollen particles that come in contact coalesce and greatly reduce the rate of penetration of additional fluid. By dispersing the superabsorbent in wood pulp fiber and distributing the fluid using a surge layer, manufacturers have a construction with isolated particles. The particles can then achieve nearly their limit in fluid capacity. The pulp can distribute and hold the fluid until the superabsorbent tenaciously binds and wicks the fluid away from the capillaries. In this way, the superabsorbent also helps prevent rewetting of the topsheet (13). Most current work on superabsorbents focuses on developing superabsorbent fibers to replace the particles currently used in diapers (32).

Backsheet and fastening mechanisms and adhesives

Externally viewed in use, a diaper shows its profile and backsheet. Backsheets employed today are impervious to liquids, although breathable backsheets are under consideration (19, 33). The film used in most diapers is a low-density, opaque, polyethylene film. The surface may have texture to give a cloth-

like feel, reduce glare, and decrease stiffness of the diaper. Unisex diapers often use an all-white backsheet, and sex specific products use colored sheets. Premium products may have a fabric backing covering the film.

Attached to the backsheet are the fastening tabs and the landing pad for the tabs. The landing pad is a high-density polyethylene strip (34) that allows detaching and reattaching the fastening tabs without damaging the integrity of backsheet and defacing the diaper. Modern diapers usually use pressure-sensitive adhesive tabs on the backsheet to provide the best fit to the baby or adult. Alternate adhesives employ microencapsulation for release on application of pressure. Premium diapers may use Velcro® attachments.

Various bonding techniques conducive to high-speed processing join or consolidate the different layers in the diaper. We have already mentioned the two types of thermal bonding. Pattern calender bonding of a diaper unifies the fibers in the topsheet. Ultrasonic bonding joins the thick sections of a diaper. A common adhesive is a low molecular weight, viscosity controlled, styrene-isoprene-styrene triblock thermoplastic elastomer (2, 3). Spiral gluing techniques allow attaching the stretched elastics to the fabrics using pressure sensitive adhesives. The spiral pattern shown in Fig. 3 helps high elastic recovery after removing the stretching force. Spiral gluing is rapid and uses minimum glue (35). Spiral gluing is a component of almost all commercial diaper manufacturing equipment.

Elastics and barrier cuffs

Many industry experts consider Buell a pioneer in modern disposable diaper technology. He patented the addition of elastic leg bands to a disposable diaper (15). Incorporation of elastic leg bands reduced leakage so much that the disposable

diaper industry changed from a small business to the containment means of choice. The structure and composition of elastic members have undergone several changes.

The modern disposable diapers today often contain multiple strands in a side-by-side configuration rather than Buell's single strand (2, 3). Since the fabric gathers at the leg openings, the original single strand seals needed to be tight to contain the fluids effectively. When they are too tight, they "red mark" the skin and abrade. Using multiple elastics forms several gasketing lines. Although each line may leak, the net result is low pressure, no "red marking," and a satisfactory seal. The wearer is more comfortable and confident.

Introduction of erect barrier cuffs added a third dimension to the diaper and improved containment (5, 6). The outer leg elastics may consequently not need seal as well, but they do need to continue providing a snug fit to prevent leakage. When the diaper body separates from the human body, for example, leakage may occur because the absorbent material is not in position to do its job (36).

Polybutadiene rubber strands continue to have wide use in diapers, although spandex also finds use. Spandex has the advantage that one can precisely engineer its properties to suit the purpose. Since diaper use is on the unloading curve of the elastic, tailoring to control the unloading characteristics of elastic elements may be important.

Introduction of elastic to the waist occurred shortly after the introduction of leg elastic (4). The elastomers are thermoplastic block copolymers (2, 3, 10). Their forms may be films adhesively or ultrasonically bonded in place (37), foamed polyurethanes (10), hot melt adhesives, or fibrous assemblies such as melt-blown webs (38, 39). Some

new "stretch" diapers and training pants use elasticized side panels or elasticized ears (27).

SUMMARY

Modern disposable diapers use several clever technologies including barrier cuffs that give the diaper a surprising three-dimensional character and tremendous containment properties. Absorbent technology includes use of isolated superabsorbent particles that can absorb approximately 50 times their weight in body fluids and wicking or surge layers designed to spread and temporarily hold released body fluids. Multiple elastics provide a good net seal by placing several leaky seals in series. This technique ensures low pressure with minimal irritation under the elastic elements. Diaper consolidation technology includes thermal bonding—ultrasonic and pattern calender bonding—and adhesive bonding. Thermoplastic pressure-sensitive adhesives spun as fine filaments and laid on the diaper in spiral patterns minimize the use of adhesive and facilitate excellent recovery of the stretched elastic elements. The special design of the material against the skin of the diaper wearer keeps the skin dry. Construction of surfactant-treated apertured films and nonwoven polypropylene fabrics achieve this result. The design of these technologies has been for the disposable diaper industry—a multibillion dollar industry after only a quarter century. TJ

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