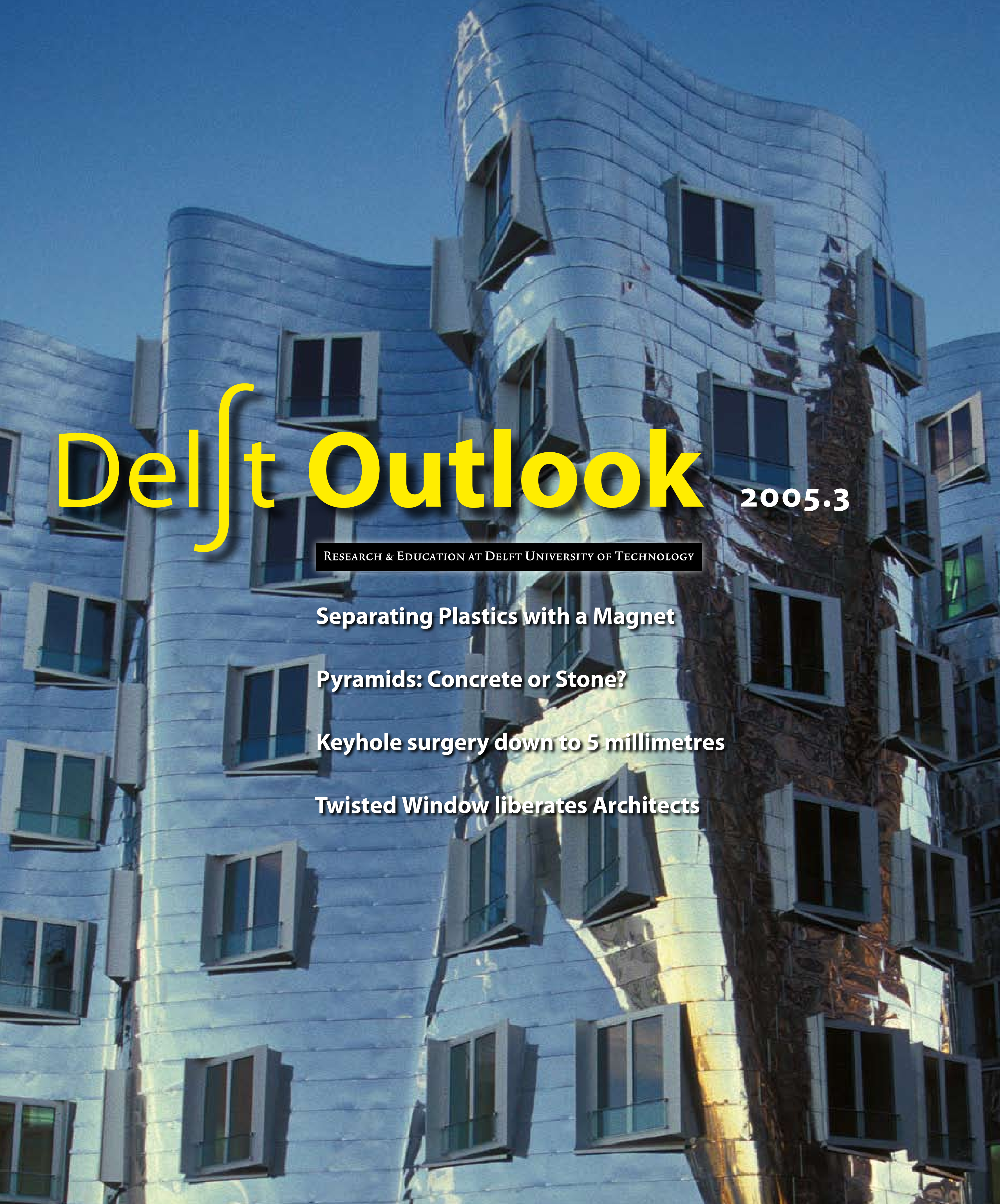


Delft Outlook

2005.3

RESEARCH & EDUCATION AT DELFT UNIVERSITY OF TECHNOLOGY

Separating Plastics with a Magnet

Pyramids: Concrete or Stone?

Keyhole surgery down to 5 millimetres

Twisted Window liberates Architects

TU Delft

Delft University of Technology

CONTENTS

3
Using a magnet to separate plastics

Separation and raw materials go hand in hand. Whereas fifty years ago the engineers at the then Faculty of Mining in Delft focussed on mining in far away places around the globe for raw materials, nowadays the gain is in the reuse of recycled materials. This is where quality and the money come in. The difference in usability of a recycled product with a purity of 95% or 99, 9% is enormous and hence its economic value too. So raw material technologist Dr Peter Rem decided to take a closer look at a field where fundamental research began more than thirty years ago: magnetic fluids.

Magnetic fluids become heavier when exposed to a magnetic field and can thus be used to separate materials of different densities, with lighter materials floating to the surface. However, since practical fluids took a long time to appear on the scene, development was faltering. Dr Rem discovered a new approach, in which separation becomes a viable option for the recycling of plastics and metals, and for refining diamonds.

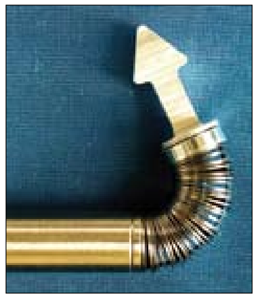
8
The Cheops mystery targeted with neutrons

Indeed, a mystery it still is, the way the Egyptians build their pyramids. Where they strong, numerous and well disciplined? Did they have a good management team? But even though: how did the ancient Egyptians managed to drag 2.5 million blocks of stone each weighing several tons to a level of up to 140 metres? Did they cut these blocks? How and where? That has been the 64-millon dollars question for many years. Nobody has been able to pinpoint a trace of a used technique. Some say that the ancient Egyptians were brilliant engineers who poured broken up limestone and cement into moulds to form made-to-measure.

So: cut or cast? That is the question which Dr. Menno Blaauw, head of Facilities & Services at the Reactor Institute Delft, subjected to the latest analysis techniques.

13
Movable tool tip for keyhole surgery

Keyhole surgery is becoming more and more common place for operations in the abdomen, such as laparoscopic surgery. However, a major problem when performing operations through small incisions, is the complex manoeuvring of small instruments. Researchers at Research Group for Medical Technology at TU Delft have built an entirely new tool tip control system, based on the tentacles of squid. This will enable surgeons to manoeuvre a camera or instrument in any direction during keyhole surgery. Whereas most medical instruments are hugely expensive, the newly designed instrument of Dr Paul Breedveld uses nothing but standard parts like cables, springs, washers and tubes, so the cost is less than one percent of the cost of the currently available tool tip system. The mechanism is easy to miniaturise. A worldwide patent has already been applied for, and the design is now ready for commercial application. Surgeons can't wait to start using the new invention, in particular because it will enable them to use minute instruments during keyhole surgery.



18
Tordos &Twisters: Windows for Curved Buildings

Is square out and are smooth curves in? It seems that an increasing number of architects are being inspired by different shapes than boxes or trianglesw. In a way it seems like going back to old times when curved glass panes in society shop windows was not uncommon. But now we are talking about curves in the entire building façades. Designing them is one thing, but actually building them is quite another. When flat windowpanes protrude from the façade, they rudely interrupt the free flow of the design, according to Dr Ir Karel Vollers of the Faculty of Architecture of Delft University. Reason for him to launch a worldwide first: a prototype of a freely curving, convex window, complete with frame, courtesy of intensive collaboration with leading glass and aluminium manufacturers. As a bonus the new design offers easy connections to existing building structures, an aspect that used to be a considerable problem.

COVER PHOTOGRAPH:
The Neue Zollhof in Düsseldorf by the American architect Frank O. Gehry.
(photograph: Thomas Mayer Archive, www. thomasmayerarchive.de)

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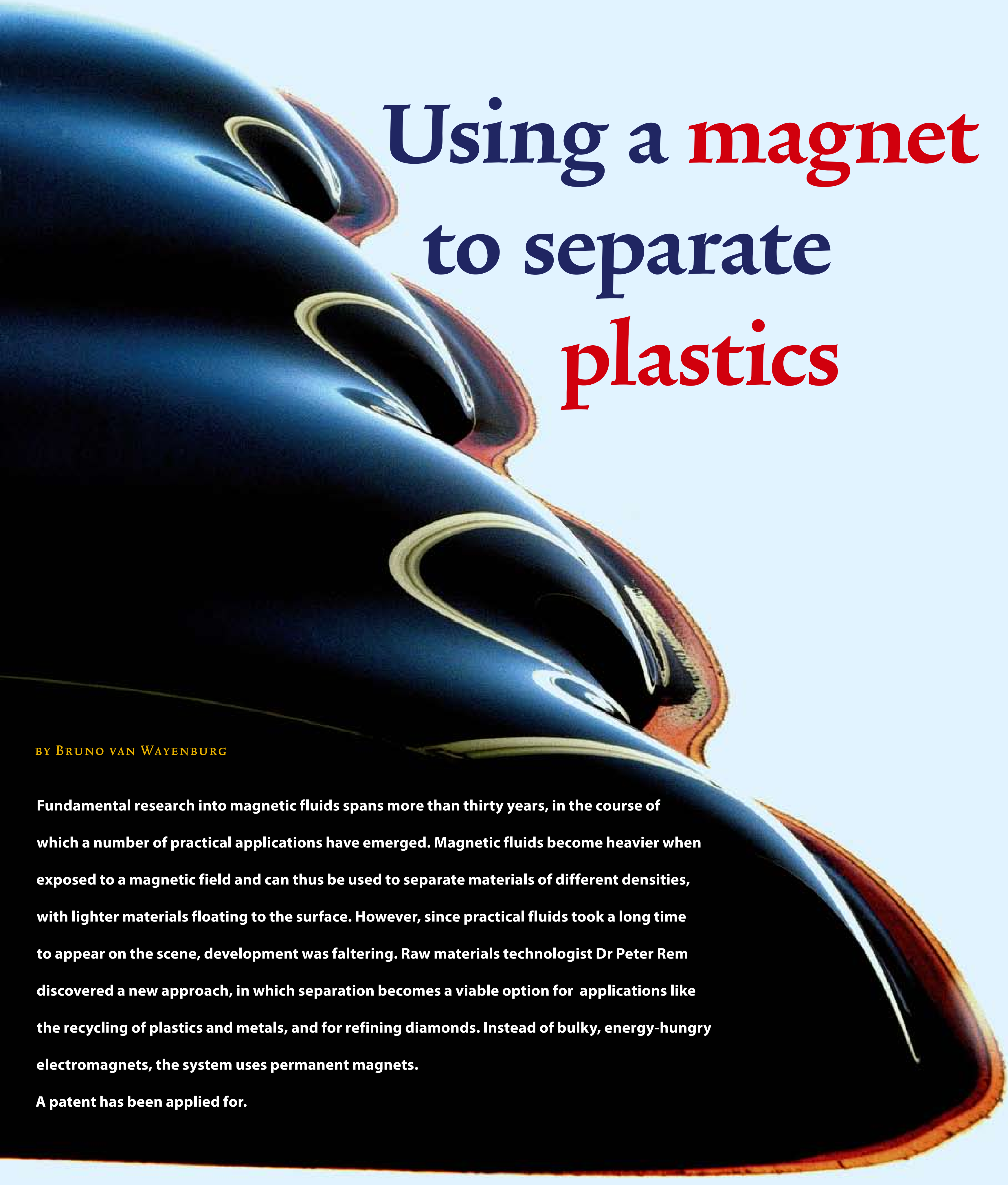
Variable-density fluid accurately separates plastics in a single process



Using a magnet to separate plastics

BY BRUNO VAN WAYENBURG

Fundamental research into magnetic fluids spans more than thirty years, in the course of which a number of practical applications have emerged. Magnetic fluids become heavier when exposed to a magnetic field and can thus be used to separate materials of different densities, with lighter materials floating to the surface. However, since practical fluids took a long time to appear on the scene, development was faltering. Raw materials technologist Dr Peter Rem discovered a new approach, in which separation becomes a viable option for applications like the recycling of plastics and metals, and for refining diamonds. Instead of bulky, energy-hungry electromagnets, the system uses permanent magnets.

A patent has been applied for.

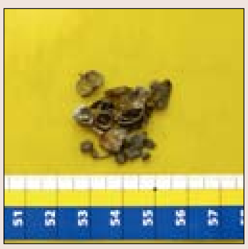
(Photo: Reko BV, Geleen)

In the Netherlands alone, 15,000 tonnes of PET waste gets recycled every year. The total quantity of waste plastics is far greater, which is where part of the problem lies, since separating different types of plastics remains a commercially unattractive proposition. Also, if the separated plastic cannot be made pure enough, the product's value plummets.

In order to process recycled PET bottles, they are shredded and any dirt and other unwanted materials such as bottle caps, labels, and whatever consumers have left behind, are removed.

Contaminants that currently get left behind in the cleaned PET:

Aluminium, stainless steel, and other non-magnetic metals



Iron

Stone and glass

Electrostatic separator for removing PVC particles from shredded PET waste. Intensive stirring of the mixture imparts different electrostatic charges to the PET and PVC particles. The mixture is then dropped between the two vertical electrodes, across which a 60,000 volts electrostatic field is maintained. As they drop past the electrodes, the PET and PVC flows become separated.

Recycling materials like plastics, glass and metal has really taken off over the past decades. Even so, many of the recycled materials, like plastics for instance, cannot be used for their original purpose, because they are not pure enough. They are contaminated with wood chips (car shredding), textile, domestic waste, metals (shredded electronics) and other types of plastics. The 15,000 tons of PET bottles collected every year in the Netherlands alone are mostly for the manufacture of plastic straps and synthetic fleece material. Reusing the plastic to make new PET bottles is difficult because the maximum level of impurity arising from non-PET material must not exceed 50 parts per million. Even minor impurities could result in weak spots, and a bottle manufacturer cannot afford to supply leaking or exploding bottles.

Bollards The current separating techniques, based on the difference in flotation properties in water, can be used to separate lighter types of plastic such as polypropylene (PP) and polyethylene (PE) from the heavier types such as PET and PVC. Even so, PP and PE together are both difficult to separate and chemically incompatible, making low-quality objects such as traffic bollards the most common recycling application. The combination of PVC and PET, which used to be common when PET bottles were fitted with PVC screw caps, is even worse. The components cannot be separated, and PVC burns at PET processing temperatures.

"Fortunately the PET recycling market has managed to persuade the manufacturers to stop using that particular combination of materials," says Dr Peter Rem, associate professor of raw materials technology, at the sub faculty of Applied Earth Sciences, "but even so, we're still not very good at separating different types of plastics."

Rem and his doctoral student, Erwin Bakker are working on a separation technology that should be able to produce the required levels of purity. In addition their technology, density separation by means of magnetic fluids, is capable of separating several other types of materials in a single process. Such fluids change their density when subjected to a magnetic field.

Pink liquid If Archimedes had ever got round to publishing his bathtub eureka moment in a scientific journal, Rem and Bakker would now be including a reference to his work. As part of an assignment by a king who suspected fraud, the famous Greek scientist measured the exact difference in density between silver and gold by means of weighing and immersion in water to determine volume. The Delft team uses a related method.

"Just look at this," says Rem in the laboratory of the research group in the former Mining Institute of TU Delft. He drops a lump of metal into a cup containing a transparent pink liquid, a solution of manganese chloride. The metal sinks straight to the bottom of the cup, but when Rem places the cup on a specially prepared surface over a powerful magnet ("mind you keep pens and watches out of harm's way"), the metal rises from the bottom to remain suspended halfway to the surface.

"That's all there is about it," Rem says concluding the demonstration.

The manganese chloride solution is paramagnetic, which means that the magnet attracts the liquid. As a result, the liquid immediately above the magnet increases in density and so effectively becomes heavier. The lump of metal, which is not paramagnetic and so remains unaffected, suddenly becomes lighter in weight than the liquid, and so rises. As the effect of the magnetic field diminishes away from the magnet, the effective density of the liquid decreases with it. At the point where the density corresponds with that of the metal, the lump remains suspended. The net effect of this phenomenon is to produce a strict horizontal separation of particles of different densities, which is ideal for separating a mixed flow into its weight components in a single process.

Ditch water Even so, manganese chloride will not be the solution used in separation plants. Its only purpose here is to serve as a demonstration liquid, because it is so nice and clear. To make a solution like this, about 400 kilograms of salt have to be added to a cubic metre of water, Rem explains. Therefore, the density of the solution is 1400 kilograms per cubic metre.

"The effect of the magnetic field we're using is to add another 300 kilograms per cubic metre to the density," Rem says. Nice, but not nearly enough for full-range separation, and in addition the solution contains a lot of salt, all of which would have to be processed in a regeneration plant after use.

The real separator fluid Rem plans to use is a suspension of iron oxide particles in water, a brownish black liquid reminiscent of very dirty ditch water. Due to the small size of 20 nanometres of the particles, their thermal motion at room temperature is sufficient to keep them suspended. A special coating prevents them from locking together magnetically.

The particles, and with them the fluid, are ferromagnetic, i.e. each of the particles is a minute magnet, which greatly enhances the attraction effect. As a result, the quantity of iron oxide particles mixed with the water can be far less while achieving the same effect: only about 10 kilograms per cubic metre, i.e. 1 per cent.

"On top of that, iron oxide is cheap and harmless," Rem says, "look in any sewer and you're bound to find it."

A number of plastic balls in four different colours can just be made out in the glass beaker of murky liquid which he places on the magnetic plate. Each ball remains suspended at its own level determined by the type of plastic it is made of, and consequently its density.

"This is the separating principle in a nutshell," Rem says.

Copper, gold, and other metals

Over thirty years of research into density separation by means of magnetic fluids, with particular emphasis on separating metals and metal ores, seems like a long time to have come up with such a simple solution.

Rem: "The thing is that research has always focused on finding a magnetic field in which the liquid would have a constant effective density, just like any normal fluid."

This would make the extractable material float on the surface, like wood on water. Since no normal fluids exist that have the high densities of copper, gold, and many other metals, magnetic fluids would be just the thing for the job, or so it was thought.

If only more physicists had been involved in the research, it might have emerged earlier on that the idea in itself is literally a physical impossibility, Rem thinks. To obtain a uniform effective density, you need a magnetic field with a linear strength gradient (i.e. the plot of the magnetic field strength is a straight line). However, according to Maxwell's equations, which describe the behaviour of electrical and magnetic fields, a linear magnetic field cannot be created inside a volume.

The closest approach, a linear gradient field in a single plane, is the field that exists between the poles of an annular magnet with a specially formed cavity. Rem: "To create a magnetic field of any reasonable dimensions with such an instrument would require a set of electromagnets several metres in size."

Rem himself was actually working with just such a device some eight years ago, when he realised that there was no need for a continuous density, in fact it created an obstacle for an effective separation technique. The only reason for the preference had been that a homogeneous density came closest to classical fluids such as the water Archimedes had in his bath."

Frustrated

Unlike his Greek colleague, Rem never had his eureka moment, but in 2004 he realised there was another way. Rem calculated a magnetic field with a strength that decreases exponentially as the distance from the magnet increases. This results in an exponential decrease in the attractive force and consequently, a change in effective density, so that each type of material can find its own level of equilibrium in the magnetic liquid. This has the advantage that a large number of components of different densities can be accurately separated from each other in a single process.

Rem calculated a configuration of magnets that would produce such a field. Magnet manufacturers Bakker Magnetics, who specialise in the manufacture of complex magnet systems, then produced the configuration for the research group. Creating the experimental magnet plate was not a simple task. Its main ingredient is a set of extremely powerful permanent iron-neodymium-borium magnets.

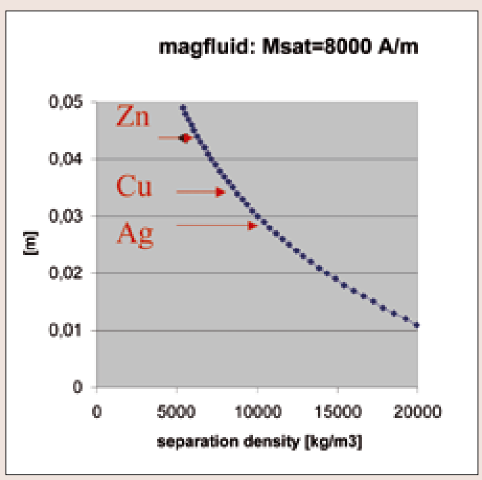
"The field strength just above the magnets is 1 tesla, which is pretty strong for a permanent magnet," Rem says. The magnets are mounted in a 'frustrated' configuration, which means that they are out of balance and subject to large forces acting between them. It is a good thing that the whole assembly is covered by a steel plate to protect researchers from being hit by any magnet fragments that may become detached from the main mass.

In addition the plate screens the assembly from curious gazes, as the magnet

Eddy current separator used for separating aluminium from PET waste. It uses a rapidly changing magnetic field to eject the aluminium particles from the mixture.

If a lump of magnesium (density approx. 1700 kg/m³) is dropped into a manganese chloride solution (density approx. 1400 kg/m³), it sinks to the bottom. If the container holding the solution and the metal is then placed on a magnet, the metal will rise in the solution (picture on the right) because of the increased density of the fluid.

By making use of the decreasing effect of the magnetic field at higher level in the liquid, balls made of different types of plastics will float at different levels according to their specific gravity, with the heavy balls sitting lowest in the liquid, and the lightest ones at the top.



Relation between the specific gravity of a material and the level at which a particle of the material will float in the magnetic liquid.

Test set-up of an inclined conveyor belt carrying a large blob of magnetic fluid, used for separating different types of metal.

The 2 litre blob is held in place by a heavy permanent magnet located directly below the belt. The magnet consists of nine poles and weighs about 120 kilograms.

As the conveyor belt carries the metal particles into the blob of magnetic fluid, the lighter particles will start to float, while heavier particles will remain lying on the belt.

configuration calculated by Rem is a secret.

"Our patent application mentions something like 'any person trained in the art is capable of creating such a field', but in practice it is not quite that simple," Rem admits with a smile.

The researchers are still in discussion with Bakker Magnetics and SenterNovem, who are funding the innovation research, to trade the patent rights for a single doctoral research grant to support Erwin Bakker. Erwin is a mining engineer who has been working for the department as an assistant researcher ever since he graduated.

Rem: "The purpose of our research is not to get rich, but rather to continue the research, and this would be one way of doing that."

Test rigs The only thing left to do at this stage is to construct a working separation plant.

Rem: "The separation principle itself works all right, but the trick is to get the materials into the separator in an orderly and effective fashion, allow them just enough time to get separated, and then extract them without disturbing the separation process."

The speed and size of the machine, and consequently, the cost of the separating process, are crucial elements in an industry processing tonnes of material for just a handful of euros, and having to do it quickly and with the smallest possible plant.

Two test rigs have now been set up. One of these is used to separate metal particles and consists of a conveyor belt running across the magnetic plate. The magnetic liquid (which in this case is pitch black due to the much higher concentration of iron oxide particles) sits stationary over the magnetic plate, like some weird outsize blob of ink, while below it the conveyor belt moves along, bringing in the metal particles.

Once inside the liquid, the various metal particles float at different levels, so horizontal separator louvres can lift them out.

"This demonstrates the viability of the principle," Rem says, "but we don't believe it is suitable for large-scale or high-speed applications."

Contaminants Erwin Bakker recently tested a different configuration that might serve as the basis of a continuous process for separating plastics. This time the liquid runs across the magnet in a continuous flow containing shreds of plastic to which contaminants in the form of glass, grit, and metal have been added. The contaminants sink to the bottom, whereas the particles of plastic are carried away by the magnetic liquid to be strained off later. The liquid is reused, and in a future version the extracted plastic particles as well as the contaminant sediment could be collected by a conveyor belt in a fully continuous process.

"I have run this set-up for up to ten minutes, and it worked perfectly," Bakker says. He has undertaken a little market research to assess the economic possibilities of his technique. Including the 15,000 tonnes collected in the

A separator vane inserted into the fluid down to 2 cm above the belt is used to separate the floating particles from those lying on the belt. The heavier particles move under the vane and drop off the end of the belt. The lighter particles float over the vane to hit a V-shaped ridge that carries them away to the side of the belt.

Netherlands, the worldwide annual PET recycling figure comes to 750,000 tonnes, which in view of the current typical processing cost of a few dozen euros per tonne would be a useful market.

Another sector appealing to the researchers is recycling the many different kinds of plastics used in motorcars (8,000 tonnes each year in the Netherlands alone; 400,000 tonnes worldwide).

"A typical car contains six different types of plastic, apart from rubber and fabrics. For all the different makes together, the number of plastics is about twenty," Rem says.

Density separation by means of magnetic fluids can provide the required resolution to separate all these different types of plastic in a single process step. Most current techniques use a separate step for each different component.

As for separating (non-ferromagnetic) metal ores or recycled metals, the outlook is less favourable. These materials are heavier and would require a magnetic liquid of much higher concentration, which in a pure form would be rather expensive. Since a small portion of the liquid will inevitably be lost, the cost will also be higher.

Diamond A possible niche application might be the refining of diamonds. A South African colleague of Rem, who also worked for the De Beers diamond company, asked the Delft team whether they knew of a separating method for the final stages of the company's production process, in which the diamonds are separated from the extracted ore.

Rem: "In this case, the economic as well as the physical prerequisites are very different from those of plastics. This is a process in which you want to end up with the full 100 percent of the diamonds, and the collected material has to be 100 per cent pure."

In addition, De Beers intends to fully automate the process, since the number of people working in the diamond production facilities is kept to a bare minimum to reduce the risk of theft.

Rem: "On the other hand, cost is not a primary issue."

The separation technique developed by the Delft team appeared to be the most promising, both regarding separating effectiveness and suitability for automation, but even so there was no response when Rem asked his colleague for a test sample of diamonds.

"We never heard again from them," Rem says, laughing, "but we still needed something to experiment with."

Air bubbles The plastics and recycling industries on the other hand showed much more interest.

"One manufacturer even asked us how many square metres of his factory floor he would have to keep free for installing a separator unit this summer. Mind you, not as a test unit, but for full production use," Rem recalls.

Unfortunately, things are not that simple. Before a separating process can be standardised and left to run routinely, a lot of things have to be done. The flow properties of the fluid need to be better understood, and Rem plans to bring in his colleagues at the TU Delft Fluid Dynamics department at the faculty of Applied Physics.

Rem: "The fluid cannot remain stationary, since you want to separate any particles that are stuck together. On the other hand, you want to prevent turbulence, as that might jeopardize the separating process."

Even air bubbles, which can easily remain attached to the flat shreds of plastic, would upset the apple cart, but stirring or heating the mixture might offer a solution there.

The group intends to set up standard procedures for as many applications as possible, and document what the losses are in terms of raw materials and magnetic fluid, as well as how pure the end product is.

"We intend to keep the physics as simple as possible in order to better understand why our optimisation cannot be improved upon," Rem outlines the programme, "and we would be very happy indeed if we were to have a prototype in a year's time."

For more information please contact Dr Peter C. Rem, phone +31 (0) 15 278 3617, e-mail p.c.rem@citg. tudelft. nl.

See also www.bakkermagnetics.com.

The metal particles are extracted in two flows, one in the centre, and one along the edge.

Separated particles of aluminium and copper.

This test set-up devised by doctoral student Erwin Bakker was used for separating shredded PET from contaminants such as grit, glass, and metals. This test set-up also uses a magnetic fluid, but this time the fluid moves along with the PET particles. The contaminants remain behind at the bottom of the container. The PET particles are extracted by a screen.

Courtesy Royal Asscher Diamond Company, Amsterdam

Kimberlite diamond ore

Looking into the distant past with neutrons from TU Delft's nuclear reactor

The Cheops mystery targeted

(foto: Alfred Molon, Unterhaching)

Panorama of the pyramids at Giza, which were built around 2600 B.C.

by Astrid van de Graaf

How the ancient Egyptians managed to raise a seven million tonne pyramid in a time span of only twenty years remains a mystery. Every now and then discussions flare up as to how exactly the pyramids at Giza in Egypt were constructed. How could they cut stone without the necessary chisels? How did they manage to drag 2.5 million blocks of stone, each weighing several tons, as high as 140 metres above the desert? Or did they? Perhaps the ancient Egyptians were brilliant engineers who poured broken up limestone and cement into moulds to form made-to-measure? Cut or cast? That is the question which Dr Menno Blaauw, head of Facilities & Services at the Reactor Institute Delft, subjected to the latest analysis techniques.

The pyramids were built using blocks of limestone varying in weight from 3 to 30 tonnes. The main pyramid at Giza stands 140 metres high.

(Photo: Institut Géopolymère, Paris)

French professor Joseph Davidovits is convinced that the pyramids were built using blocks of cast stone made in much the same way as concrete.

with neutrons

Six years ago Menno Blaauw came into possession of a piece of stone from Cheops' pyramid. At the time he was still working as a researcher investigating neutron scattering at the TU Delft Interfaculty Reactor Institute (IRI). He found the fragment among the effects of his late father, with whom he had visited Egypt in 1995. Egyptology had come to fascinate Blaauw senior, a chemical researcher by profession, upon his retirement.

"He felt that he was nearing the end of his days, and the Egyptian culture being so highly focused on the afterlife, this was his way of coping with the concept of death," his son says. "Having visited the country on a number of previous occasions, he was able to give me a tour of the most interesting places."

One of the places they managed to see was the Queen's chamber inside Cheops' pyramid, which is seldom opened to the public. Inside the chamber Blaauw senior, demonstrating the inquisitiveness of a true researcher, crawled into a crack at the back of an alcove, where he reached as high and as far as he could, and dislodged a piece of stone which he slipped into his pocket.

"Just to be on the safe side, he kept the fragment in his pocket to guide it safely through customs, since suitcases are all routinely scanned for artefacts," Blaauw admits with a slightly guilty look on his face.

Inexplicable Infected by his father's fascination with all things Egyptian, Blaauw junior also became interested in the mystery of the pyramids.

"In 2500 BC there were no chisels harder than stone. You simply cannot use copper to cut or break away limestone. So how did they manage to cut those

Dr Oebele Blaauw with his regular taxi driver. In the background is the pyramid of Chefren, the tip of which is still clad in alabaster.

The sample retrieved by Dr Oebele Blaauw from the crack in an alcove in the Queen's chamber of the Cheops' pyramid.

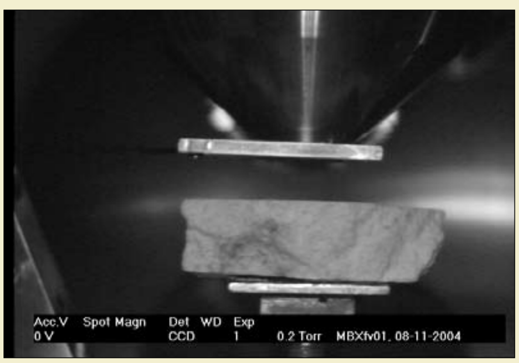
A section through the Cheops limestone sample used for tests using electron microscopy and thin section techniques.

Close-up view of the pyramid fragments in which the fossils are clearly visible.

If we zoom in on the sectional plane, several small cavities can be seen which give the impression that the stone might have been cast, since such a process could easily trap air bubbles inside the material.

This crack divides a fossil in half and is reminiscent of shrinkage.

The optically active minerals can be made visible using a pair of polarising filters at cross angles in what is known as the thin-section technique.. There is no layered structure, which there would be in a natural sedimentary rock according to Professor J. Davidovits' theory.



At the Microlab of the Civil Engineering faculty, the ESEM (environmental scanning electron microscope) was used to scan the elementary composition of the Cheops stone. A special feature of this device is that it can be used to measure the composition of a very small local part of the surface area.

blocks so accurately to size? Limestone is a relatively brittle type of stone, and it contains faults that can develop into cracks. Producing a large, solid block of limestone will inevitably leave you with an identical volume of rubble. No such mountains of rubble have ever been found."

What we did manage to find was the quarries where the stone came from. At least ten quarries all over Egypt have been traced as the suppliers using trace element analysis. Apart from cutting and stacking the blocks, transporting each 3 to 30 tonne block on sleds must have been a vast logistical operation. All in all the pyramids are still veiled in mystery.

The Blaauws have also dug up calculations on the subject. One human being can provide a certain power to drag a block of stone up an incline. We know that a pyramid took about twenty years to build. Construction commenced as soon as a new pharaoh came to the throne, because the building had to be ready when he died. This means that 20,000 to 250,000 workers had to spend each and every day dragging blocks of stone.

"The resulting construction yard would have been the size of a city, and that's just including the dragging teams, without any of the other activities. It is almost impossible to imagine," says Blaauw junior.

Cast stone In his insatiable thirst for knowledge about the pyramids Blaauw senior picked up a book by the French geochemical engineer, Joseph Davidovits. According to this scientist, the building theory of cut blocks of stone being dragged up inclines is cracking at the seams. He proposes that instead the giant pyramid stones were artificially made by pouring limestone granulate into moulds and allowing it to set, much in the way that we make concrete today.

The cast stone theory appeared plausible to Menno Blaauw.

"It is much easier to imagine. Limestone is made up mostly of calcium carbonate, a perfect basis for cement. You would leave part of the extracted limestone in granule form, grind down the other part, fire it up in a kiln, and then add water. According to Davidovits the pyramid as a whole should contain 15% water, although he makes a secret of the actual recipe for the artificial stone, since he holds a patent on the geopolymer, as it is known. After some time you end up with artificial stone that cannot be distinguished from the real thing. The treatment does not affect the trace element pattern. A simple test will not help you determine whether you are dealing with artificial stone or not. At the time when the accepted hypothesis on the construction of the pyramid was postulated, the late nineteenth century, concrete was not the common construction material we know today. So it is hardly surprising that the archeologists back then never considered the option. Today we can look at things in a different light. Who knows, we may have overlooked something," Blaauw says. His new job as head of Facilities & Services at the Reactor Institute Delft (as the facility half of the IRI is known since 1 January 2005) gave him the idea of taking a closer look at the fragment that was now his.

Searching for water At the RID, Blaauw has an instrument at his disposal that will let him take a closer look at the Cheops stone. It is a neutron scattering device, the rotating crystal spectrometer (RCS). It can be used to investigate the water content of cement stone. Concrete sets as the result of a slow chemical reaction with water that changes the cement powder into a stone-like solid material. Concrete therefore contains crystal water that is firmly bonded to the cement by hydrogen bridges. Just as astronomers scan the surface of Mars for water to detect possible signs of life, so can Blaauw use his neutron scatterer to look for signs of engineering in the age of the pharaohs.

Neutrons are uncharged particles with a mass identical to that of a hydrogen nucleus. When a neutron collides with a hydrogen nucleus head-on, it can transfer all its kinetic energy to the nucleus. But if the neutron strikes a water molecule, the latter will only absorb certain portions of energy to match the vibration frequencies of the molecule itself. The largest part of these portions will be equivalent to 70 meV. If the difference in energy between the incoming and the reflected neutrons does not peak in the 70 meV region, there are almost certainly no water molecules in the material.

Blaauw: "Lots of experiments on cement have been done in this way, so we know all we need to know about these analyses. After a full week's measuring we had still not found any sign of water. Of course, this is hardly conclusive evidence, but it gives an indication that the Cheops sample was not manufactured with a water-binding cement as we know it. If it contains any water, it is certainly rigidly locked away."

Pore structures Cement is usually made with a slight excess of water to make it easier to pour and spread. The water eventually evaporates, leaving a specific type of pore structure. A highly ingenious method that can measure such pore structures with sizes ranging from 30 nanometres to 10 micrometres is known as small angle scattering. The device used at TU Delft is of the spin echo variety, and it is used to measure the size and arrangement of the pores. Blaauw: "This device is the brainchild of Dr Theo Rekveldt, at what was then the department of Neutrons and Mössbauer Spectrometry. The smaller the angle at which the device can see, the larger the components and structures that you can observe. Our small angle scattering device is the only one in the world that can measure structures up to 10 microns. Standard equipment cannot handle anything over one tenth of a micron. In addition, our spin echo technique speeds up measurements 10,000 times, so experiments that would otherwise take a whole day can now be finished in ten seconds."

Just like the rotating crystal spectrometer, the spin echo system employs neutrons, but in a slightly different way. This device uses not only the scattering properties of the particles, but also takes advantage of the fact that neutrons in a magnetic field behave like compass needles. Although neutrons do not carry an electric charge, they do have a magnetic moment, or spin. As the neutrons come flying out of the nuclear reactor, their spins all face in different directions. A polariser is used to straighten out the neutrons so they all spin in the same direction, the orientation of which is controlled by four magnetic fields of identical strength. In Rekveldt's small scattering angle spectrometer, this is used to translate scattering into depolarisation, which is easy to detect.

To assess the pore structure of the Cheops stone, the team of Prof. Dr Ir. Klaas van Breugel of the faculty of Civil Engineering and Geosciences supplied two types of reference cement, Portland cement and blast-furnace cement. The experiments were a success according to Blaauw.

The only thing was that the distribution of the pore size in the fragment from the pyramid was nothing like that of the two modern cement types. But Blaauw has some more neutron tricks up his sleeve.

Trace elements Neutrons can cause reactions in which the nuclei become unstable when struck. The radioactive nuclei thus produced show a specific pattern for each different element.

"Activating a sample with neutrons makes practically the whole thing radioactive, so we can use a high-resolution gamma spectrometer to determine which elements, and how much of each, the sample contains," Blaauw explains. "This method made it fairly simple for us to carry out a trace element analysis on the stone sample."

Blaauw found that the sample contained mostly calcium carbonate ($CaCO_3$) with traces of other elements. This makes it no different from natural limestone.

"It did contain 1% common salt (NaCl), but this is pretty normal for sedimentary rock. And, as my father discovered to his horror, the crack in the alcove was used for exactly the purpose that secluded corners in tourist attractions tend to be used for when nature calls."

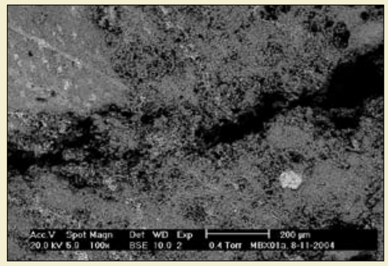
The trace of iridium they found, a material that must have come from outer space, he dismisses as the result of meteor impacts at the end of the Cretaceous Period. He does not believe in visiting aliens.

Although an element analysis can never provide conclusive evidence to show whether a stone was cut or cast, Blaauw did get other useful information, in the form of traces of uranium, thorium, and potassium.

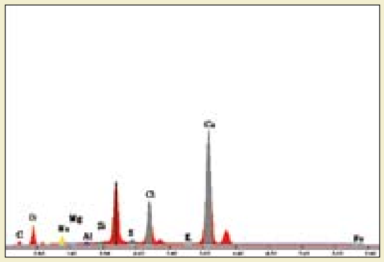
"It is quite normal to find these elements, as they are found throughout the Earth's crust. In addition to cosmic radiation, these traces form a major source of our daily dose of radiation. However, they also form an interesting source of radioactive information for dating the pyramid fragment."

Luminescence dating Practically every type of rock contains bits of feldspar or quartz. When a piece of rock is subjected to ionising (radioactive) radiation, the tension in the crystal structure of these minerals increases. The Cheops stone contained mostly feldspar. The increased tension resulting from the ionising radiation is recorded as if by a photographic film. This enables us to determine the age of the stone.

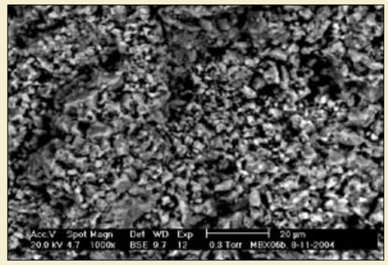
Blaauw and his team were very interested in the composition of the red colour in this crack.



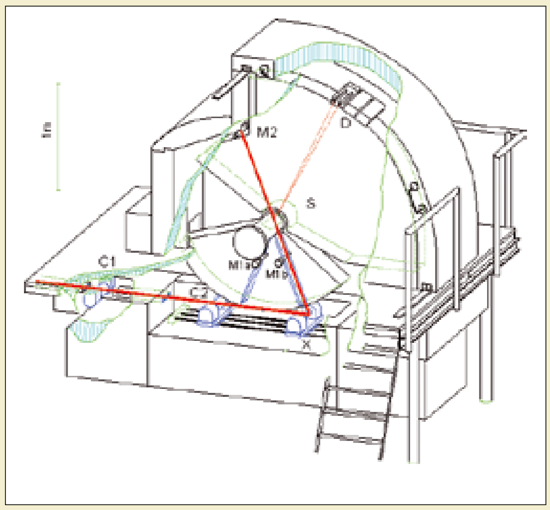
The area of the red crack as seen by the ESEM.



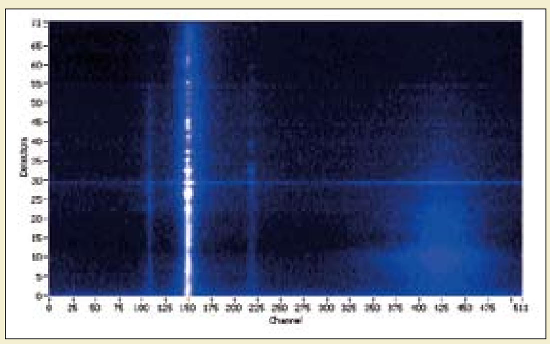
The X-ray spectrum of an ESEM measurement shows the composition of the various elements making up the stone. As was expected, calcium has a dominating presence. By comparing two readings, the red pigment is shown to be iron chloride.



Zooming in even further on the Cheops stone yields no new information.

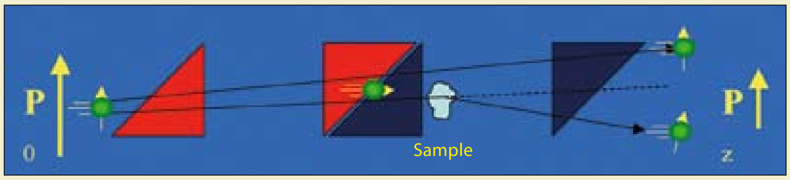


Using the rotating crystal spectrometer (RCS) developed by IRI, Blaauw was unable to prove the presence of water in the Cheops stone (S). The operating principle of the RCS is as follows. Neutrons from the reactor enter the device at the lower left. Two choppers (C1 and C2) chop up the neutron flow into pulses of an approximately known wavelength. When the pulses strike the crystal (X), only the neutrons with an exactly known wavelength are registered. The orientation of the crystal determines the wavelength. By rotating the crystal, neutrons with a wide spectrum of wavelengths in time are reflected. The purpose of the system is to measure the fractions of neutrons that the sample scatters in a certain direction and with a certain velocity. Any neutrons that fly straight on are counted by monitor M2, while the scattered neutrons are detected by hundreds of detectors (D). The exact time of detection is also recorded to enable the flight time to be measured. The detectors are all based on the absorption of neutrons by 3He.



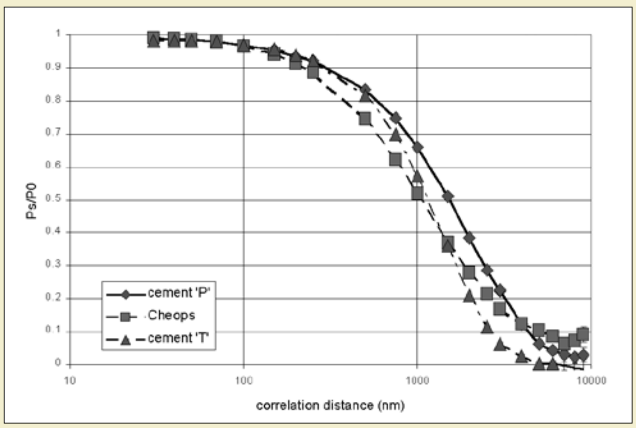
Result of the RCS test: the X axis plots the neutron velocity, and the Y axis plots the scattering angle. The colour indicates which fraction of the neutrons arrived at which angle and at which velocity.

Blaauw used the SESANS to determine the pore structure and the arrangement of the pores.. This device was developed at IRI in recent years by the team of Dr Wim Bouwman. The set-up consists of a monochromator, a polariser, four electromagnets, an analyser, and a detector.



The operating principle of SESANS is as follows. Neutrons passing through the monochromator (a crystal) all have the same wavelength. A mirror selects neutrons of identical spin (polarisation). Four electromagnets turn the spin directions clockwise or anticlockwise. When the neutrons have passed through the sample, the distribution of the spin direction of the scattered neutrons is measured using the detector and analyser.

These two samples of fundamentally different types of cement were prepared at the Microlab of the Civil Engineering faculty. The sample on the left was made using Portland cement, while the one on the right was made with blast-furnace cement.



The results of the SESANS experiments. The X axis plots the distances within the material, while the Y axis plots the probability of finding solid material at a distance X from any point within the solid material. The plots indicate that the two types of cement differ only in the coarseness of the pore structure, whereas the Cheops sample plot shows markedly different properties around 10 µm, so the plots intersect.

Feldspar and quartz are minerals that store energy when exposed to ionising radiation. Daylight frees the stored energy in the form of visible light. The Cheops stone contained no quartz, only feldspar, which was read using infrared light at the National Centre for Luminescence Dating, which shares the premises with the Reactor Institute Delft.

Blaauw: “It is like a film that has been exposed, but not yet developed. To free the feldspar, the stone is pulverised in darkroom conditions and dissolved, leaving the feldspar, which is insoluble. The darkroom conditions are necessary because normal daylight is sufficient to relax the crystal tension. We then shine an infrared beam onto the feldspar and get visible light in return. The level of the returned light provides a measure of the tension and therefore of the radiation dose the rock has received since it last saw daylight. Since reading the stone in this way will simultaneously relax the crystal tension, this is an experiment that you can do only once.”

The strength of the radiation source (uranium, thorium, potassium) being known, and thus the speed at which ‘the damage is done’, by measuring the damage, the time at which the Cheops stone last saw daylight can be calculated. Unfortunately the experiment showed this to be 400,000 years ago.

“This is a minimum value by the way. The material could be older, as the tension slowly relaxes of its own accord, and the feldspar moves back a bit to its former state. If the stone had been made from pulverised limestone, the counter would have read 2600 BC. Even if the feldspar had not been subjected to daylight during the pulverisation stage, it would most certainly have resettled during the production of cement from limestone, most of which takes place in kilns at high temperatures. Even Davidovits assumes that the ancient Egyptians used this method to prepare their cement.”

Conclusive Even though Blaauw couldn’t prove the theory favoured by his father, which he would have loved to do, he is certain of his findings.

“Additional research will of course be necessary if we are to have unambiguous results for the stone used in Cheops’ pyramid, for example comparative tests with other materials such as the artificial stones created by Davidovits. However, our particular stone is a normal, natural limestone, not a manufactured cast. To my mind the luminescence dating has provided conclusive evidence.”

The halved piece of stone from Cheops’ pyramid and its many fragments have now been stored in a plastic sample bag. Blaauw will be sending his findings to Davidovits to disprove the cast stone theory. Recently a new advocate of the theory appeared on the scene in the person of Belgian physicist Guy Demortier, who takes the presence of arsenic and unusual silicon oxide compounds as indications for the cast stone theory. However, using his activation analysis, Blaauw managed to find only 1 mg arsenic per kg of material, and hardly any silicon. So the theory proposed by Demortier is not supported by Blaauw’s results either. He does not think much of Davidovits’ claim that the fossils in artificial stone are arranged in a haphazard fashion either.

“The same applies to the material I experimented on, but petrologists can see nothing wrong with it. It just indicates that we are talking about the same type of material. According to Demortier and Davidovits, the cement should contain sodium hydroxide (NaOH), but sodium is present in the same molar concentration as Cl, in other words, as common salt, which is nothing unusual in sedimentary rock.”

Of course, Blaauw used only a very small fragment from an enormous pyramid, so how representative can his results be?

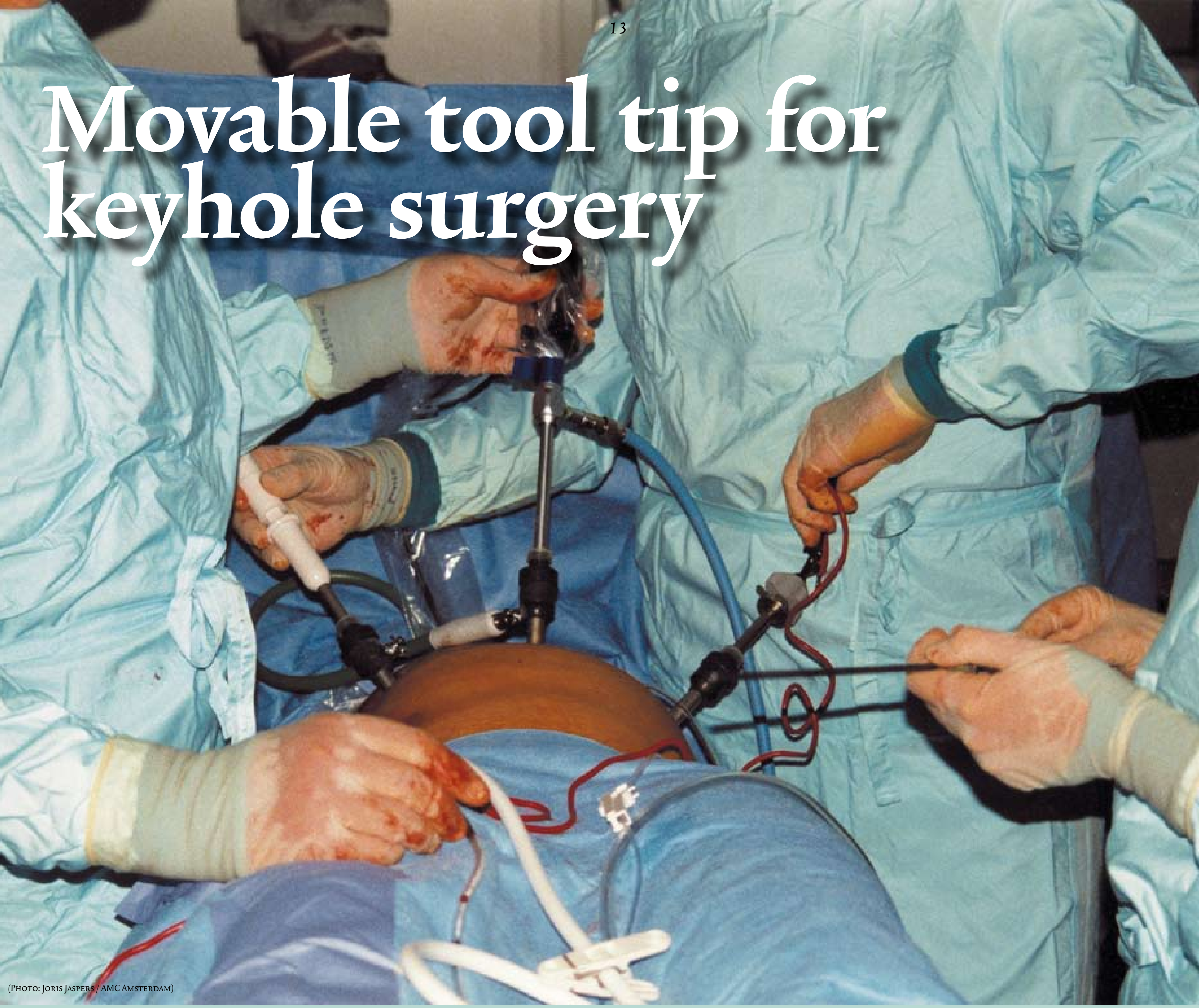
“That question is difficult to answer. In Davidovits’ book there is a drawing of a fossil structure that is identical to what we see in our fragment, so that makes it more plausible. Also, the fragment came from the core of the pyramid. I would not have thought there would be much chance of taking a 50 gram sample of natural limestone from 7 million tons of artificial stone, but it must be said that we used only a very small piece of stone from a giant pyramid, so the last word on the subject has yet to be said.”

For more information please contact Dr Menno Blaauw, phone +31 (0) 15 278 3528, e-mail m.blaauw@tnw.tudelft.nl.

More information about the theory of Prof. Joseph Davidovits can be found in:

- La Nouvelle Histoire des Pyramides d’Egypte, ed. Jean-Cyrille Godefroy, Paris, 2004, ISBN 2-86553-175-9.
- Ils ont bâti les pyramides, ed. Jean-Cyrille Godefroy, Paris, 2002, ISBN 2-86553-157-0.
- The pyramids: an enigma solved, Hippocrene Books, New York, 1988, ISBN 0-87052-559-X

Movable tool tip for keyhole surgery

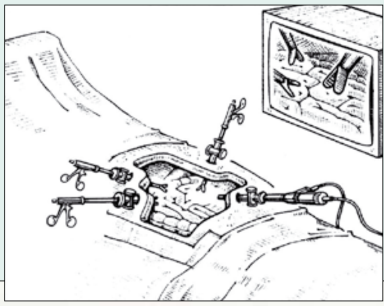


(Photo: Joris Jaspers / AMC Amsterdam)

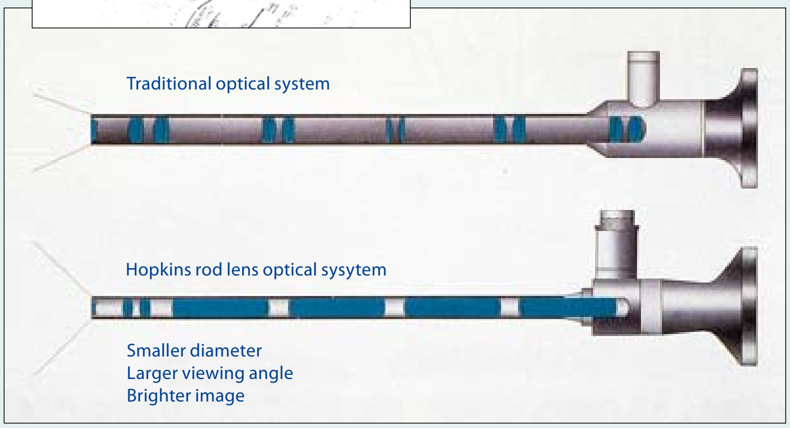
A major problem in keyhole surgery, which involves surgeons performing operations through small incisions, is the complex manoeuvring of small instruments. Researchers at TU Delft have built an entirely new tool tip control system, based on the tentacles of squid that will enable surgeons to manoeuvre a camera or instrument in any direction during keyhole surgery. The concept uses nothing but standard parts like cables, springs, washers and tubes, so the cost is less than one percent of the cost of the currently available tool tip systems. The mechanism is easy to miniaturise. A worldwide patent has already been applied for, and the design is now ready for commercial application. Surgeons can't wait to start using the new invention, in particular because it will enable them to use minute instruments during keyhole surgery.

A laparoscopic operation, during which the abdomen is inflated with CO_2 to create more room to work. Three cannulae (tubes containing valves) have been inserted. The surgeon uses the endoscope (in the middle) to look inside the cavity. The other cannulae are used to insert surgical instruments.

by Bennie Mols

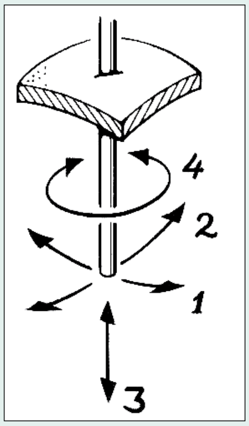


Cutaway view of the abdomen with three laparoscopic instruments, and, on the right, an endoscope. The surgeon operates looking at the camera image from the endoscope, which is displayed on a monitor.

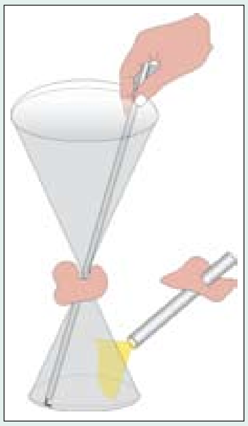


(Photo: Karl Storz)

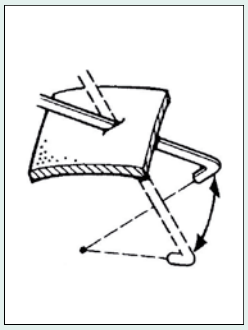
Current rigid endoscopes for laparoscopic surgery.



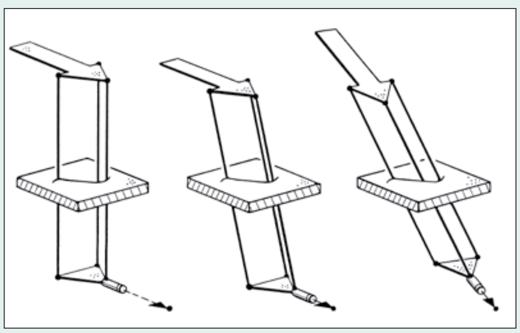
The cut in the abdominal wall restricts the motion of current rigid endoscopes to one translational and three rotational degrees of freedom.



The incision acts as a fulcrum for the movements of endoscopes and instruments. As a result, movements of the hand are both mirrored and scaled.



A rigid 90° endoscope can be used to view organs from several sides. One drawback is that the image will be tilted, resulting in a slight orientation error. This calls for another solution, i.e. a steerable tip.



The principle of the Endo-Periscope is based on parallograms. The camera (at the bottom) accurately follows every movement of the grip.

Breedveld first tested his ideas in a model made of wood and aluminium. Once he knew how everything worked, he started refining the mechanism and reducing its size.

The aim of the surgeon in minimally invasive surgery is to damage as little healthy tissue as possible and still be able to perform all the necessary surgical actions. In abdominal surgery, for example, a small incision is made in the abdominal wall through which the surgeon first inserts a laparoscope, an endoscope adapted for use in abdominal surgery (laparos being Greek for belly). The laparoscope consists of a tubular instrument with a light source and a camera fitted to one end, which surgeons can use to see inside the abdomen.
But a traditional laparoscope (a straight tube without a flexible tip) severely restricts movement. The surgeon can rotate the laparoscope a little bit in three directions, but that is all. Looking at a feature from several directions is simply not an option, even though this is exactly what surgeons want to do. Ideally, surgeons should be able to rotate a small camera or an instrument inserted through a small cut, in the abdomen for instance, in any direction, since that would enable them to see tissue structures from any angle, and operate on them, without having to make a new incision. This requires a movable tip which surgeons can manipulate in a simple way by hand.
Dr Ir Paul Breedveld has been working on designing and building an endoscope tip that can move in any direction at the Department of BioMechanical Engineering of the Mechanical, Maritime & Materials Engineering faculty of Delft University of Technology ever since 1997. After several innovative prototypes the most recent one has just been completed for commercial application.
“I am not just trying to come up with fundamentally new mechanical engineering principles,” Breedveld says. “I also want to make sure that they get used rather than disappear in some drawer to gather dust.”

Too expensive

On a table in his office at the university, Breedveld sets out a display of movable tip controls to show their historical development. The standard laparoscope used by surgeons has a diameter of ten to twelve millimetres, although five millimetres is now slowly becoming the standard. Breedveld’s first prototype had a diameter of fifteen millimetres, whereas the latest prototype only measures five millimetres in diameter. And now the new Delft Cable Ring Mechanism will allow it to become even smaller, down to one millimetre. However, the development involves much more than simply making things smaller; the entire mechanism that bends the tip has undergone a radical change.
Moveable endoscopes were initially developed for gastro-intestinal examinations, with the express purpose of being able to negotiate the twists and bends of the oesophagus, stomach, and intestinal tract. At their business end, these endoscopes feature a movable tip that can be remotely controlled by the surgeon. Breedveld demonstrates how the mechanism of such a classic tip works. It is a complicated system of rings connected to hinges and riveted joints. The tip can twist in any direction and is controlled by means of four thin cables running through guide tubes soldered to the rings. The guide tubes are necessary to make sure the cables can move only along their length.
Breedveld: “A number of companies in Japan manufacture these flexible endoscopes. However, the mechanism is so complicated that even in a country where practically everything has been automated, the things still have to be manufactured by hand.”
This makes the tips expensive: they come at anything from € 300 to € 500 each.

Gastro-intestinal examinations have one big advantage over abdominal surgery, for one. Since the gastro-intestinal tract itself is not sterile (it is a bit like the world outside which has been pushed inside the body), there is no need for the endoscope to be sterilised after use to kill all the bacteria it carries. It does get disinfected, of course, but for use in abdominal surgery anything the surgeon inserts into the body must be meticulously sterile. This means that endoscopes for abdominal use have to pass extreme requirements. The current standard practice for hospitals is to sterilise instruments for twenty minutes in steam at 120° Celsius. Of course, a movable tip system has to be able to cope with that. There is a movable tip system that is suitable for sterilising, but it requires a different, more expensive sterilisation technique, which is something that hospitals would rather avoid. Another company builds a complicated robot system costing well over a million euros that uses remotely controllable instruments. This system also uses a standard, rigid endoscope. For many hospitals however, this option again is too expensive. The challenge lies in finding a new mechanism for a controllable tip that is much cheaper to manufacture. It must be a mechanism capable of doing many different things, and it must use a simple construction."

The tip must be small (preferably no wider than five millimetres, but less is always better), hollow – the surgeon has to able to look through it using an optical system – and it must be capable of bending through a wide angle in any direction, preferably with a small radius.

New spring type During the very first stages, Breedveld used a technical Lego construction set to build a parallelogram mechanism that enabled him to convert the movements of the grip held by the surgeon into a rotary movement of the tip. If the surgeon rotates his hand in a certain direction, the tip rotates in the same direction. Although some translations occur in mirror image, the grip is always parallel with the viewing direction of the camera. The principle worked, so Breedveld knocked together a wooden model with a real camera on the end. The control mechanism worked very intuitively, but it was clear that this mechanism could not be scaled down to anything near five millimetres. Even if it could be done, the mechanism would become too expensive and too fragile to make it useful in the medical world.

During a six-month stay in Japan from 1999 to 2000, Breedveld, constructed a metal prototype together with Japanese colleagues at the Tokyo Institute or Technology that worked just like the wooden prototype, even though is was of a very different construction and no longer used two interconnected parallelograms.

"We came up with a novel type of spring," Breedveld recalls. "Nothing like your classic, helical spring, because you cannot thread a tension cable through it without it slipping out of place. To improve cable guidance, we made a number of rings made of spring steel and spot-welded them together, with the welds alternating at right angles. Each ring has two small holes in it through which the cables are threaded. The resulting 'Ring Spring' is easy to compress, but hard to twist."

The design received an award at the most prestigious European conference on endoscopic surgery. The design was called an Endo-Periscope, because the tip was now free to twist in any direction. The first prototype of the Endo-Periscope had a diameter of fifteen millimetres. Surgeons loved it, but immediately saw a few drawbacks. The grip on one end was an unwieldy big lump, and in its neutral position, the tip curved through 180°. And then of course, the Endo-Periscope had to be slimmed down.

Twenty minutes So, something else was needed. Breedveld and his colleagues set to work and in 2001/2002 designed a variant of the 'Ring Spring' and a much improved grip for the surgeon. The new tip can twist through 120 in any direction, uses four cables running though the spring, and uses a clever compensation spring inside the grip. The freedom of use of the tip has been increased dramatically. At twelve millimetres, this second prototype of the Endo-Periscope was also a bit slimmer.

"We then used this prototype to carry out a number of experiments," Breedveld says. "These show that even persons who have never handled an endoscope before can master the controls of the movable tip within twenty minutes. Another experiment that used a hook instead of a camera also yielded very positive results. The test subjects were able to twist the tip just like their wrist, and could easily go through complicated stitching routines with it. When they managed to do that, we saw for the first time that our research, which from the very start had been focused on using a camera for viewing, could also be very useful for the manufacture of small remotely controllable instruments."

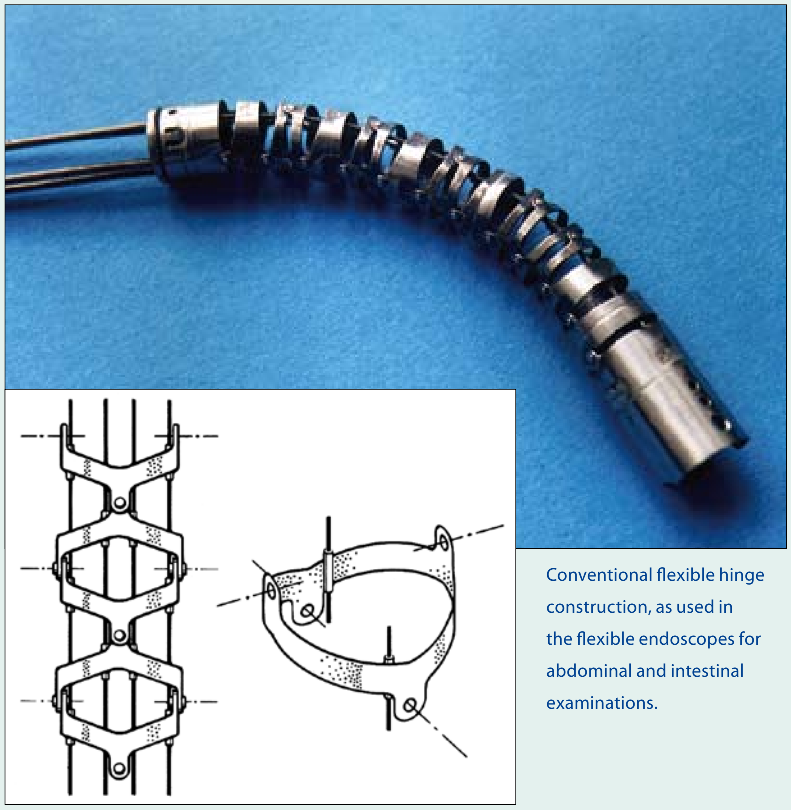
"Unfortunately, we cannot make the Ring Spring much smaller in diameter without raising the cost quite a bit. All in all, it meant that we had to go in search of a completely different mechanism – again."

Squid arm A second line of Breedveld's work was the search for mechanisms that can propel themselves through the intestinal tract. Breedveld and some students under his supervision went to look at mechanisms to be found in the natural world around us that might possibly be used in an artificial mechanism.

"This eventually brought us to the tentacles of a squid. A squid does not bend its tentacles with four strings of muscles; instead, it uses a whole ring of muscle

(Photo: Olympus Nederland, Leiden)

For intestinal examinations flexible endoscopes are used like these two colonoscopes made by the Japanese firm Olympus.



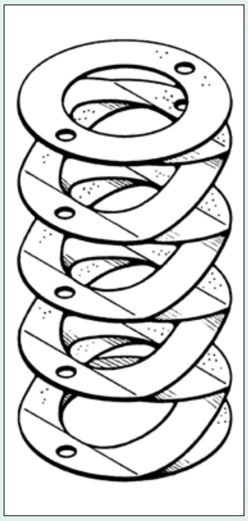
Conventional flexible hinge construction, as used in the flexible endoscopes for abdominal and intestinal examinations.

(Photo: Intuitive Surgical Inc.

Modern telemanipulators, such as the Da Vinci by the American firm Intuitive Surgical, use remotely controlled steerable instruments. Such instruments are fairly complex and difficult to miniaturise.

PHOTO: INTUITIVE SURGICAL INC.

The tools of the robot made by Intuitive Surgical Inc. are fairly complex and require an expensive sterilisation technique.



Dr Ir. Paul Breedveld and Professor Shigeo Hirose of the Tokyo Institute of Technology, invented the Ring Spring consisting of spring steel discs spot-welded together. The Ring Spring has an asymmetrical bending stiffness and a very high torsion stiffness. The holes conduct the wires that control the tip.

First prototype of Breedveld's Endo-Periscope, developed in 1999-2000 during his sabbatical at the Tokyo Institute of Technology.

The endoscope tip can be rotated sideways from –60° to +60° (left), and up and down between 0 and 180° (right).

strings. At one point I was on my way from our coffee machine, which had broken down, to get coffee elsewhere, and the idea hit me of fitting the Endo-Periscope with two normal springs, one inside the other and with a slightly smaller diameter. The annular space between them could then be filled with cables, just like the ring of muscle strings in the squid tentacle. This is going to be the big one, I'm sure. It means that we will no longer need specially designed rings with holes in them, or soldered tubes."

Traffic light "None of my major inventions were ever conceived in this office of mine," Breedveld adds with a laugh.

"I got the idea that resulted in the Ring Spring when I woke up once at three o'clock in the morning, and the idea for the second prototype suddenly presented itself while I was waiting for the light to change at a pedestrian crossing somewhere in Holland."

He has named his latest invention the Cable Ring Mechanism, and has applied for a worldwide patent on the idea. Since the annular gap is completely filled with cables, they can only move along their own length, so they can no longer slip sideways to the inside of the curve. The second spring holds them in place. By tensioning and relaxing the cables the tip can be curved in any direction.

Although the Cable Ring Mechanism was inspired by a squid tentacle, the mechanism works along slightly different lines. A squid tentacle probably has a whole ring of muscle strings to make it less vulnerable. If one or two of the muscle strings get damaged, the remainder of the ring will still be perfectly capable of moving the tentacle in all directions. The tip with the Cable Ring Mechanism uses the ring of cables to prevent them slipping out of place along the curvature of the spring.

Breedveld again places the prototypes produced so far next to each other.

"You can see how each design is slightly thinner than the last, and also how the bending mechanism gradually moved away from the existing mechanism using joints. We started with a special spring with a zigzag structure in one direction, but without any joints. Next we had a special spring that could move both ways, with a double zigzag structure, and now we have two normal springs, one inside the other, with cables filling the gap in between. The funny thing is that the special springs we used made it increasingly difficult to scale down the mechanism, whereas the Cable Ring Mechanism makes it easier, since it takes fewer cables to fill up the gap between the springs. In fact, a diameter of one millimetre would be ideal."

Complexity According to Breedveld, the complexity of the mechanism has also been considerably reduced.

"The current design uses only standard components: cables, helical springs, washers and tubes. Even the springs can be bought off the shelf in small diameters. This means that the design will be very cheap to produce, a couple of euros for each tip, as opposed to the couple of hundred euros which current tip models cost. This is just what we set out to achieve. What we now have is a disposable tip rather than an expensive tip that has to be sterilised after every use and at great cost.'

The latest prototype was completed last year and measures only five millimetres in diameter, with an internal diameter of two millimetres. Between the two springs run 22 thin steel cables, each only 0.45 millimetre thick. Cable friction is practically a non-issue, and the tip will easily flex through 120 degrees. At the end of the tip the cables have been compressed between two rings.

Breedveld: "Some people who see the Cable Ring Mechanism for the first time wonder why the Ancient Greeks never thought of it, since it looks so simple. As is often the case with good design, with hindsight it appears so simple, but it's a long and winding road getting there."

For continued development of the tip, Breedveld and Jules Scheltes founded DEAM BV, a recent TU Delft spin-off company. DEAM BV, that collaborates with other manufacturing companies to develop instruments, aims to market the tip in 2006.

Instrument control In a slightly different form a tip using the Cable Ring Mechanism can also be used to remotely control instruments fitted to the end of the tip.

"For this purpose, the assembly no longer needs to be hollow down the centre, as for use in endoscopy," Breedveld says.

"We can dispose with the internal spring, and replace it with a cable that can be moved along the length of the tip to operate an instrument, which can be anything from a pair of pincers, a hook, or a gripper, to an ultrasound instrument. For certain applications it might also be useful to replace a cable in the Cable Ring with a flexible tube or fibre-optics, who knows. In any case, we have covered every angle in a patent."

The researchers at Delft University now have a basic technique that is suitable for an entire range of medical applications. There is no reason why the tip could not be only one millimetre in diameter, which would open up the way for cheap remotely-controlled micro-instruments and catheters.

"Micro-instruments are not a major issue in abdominal surgery, in which a five-millimetre cut is small enough, but I can imagine there being interest from the eye, ear, or brain surgery disciplines."

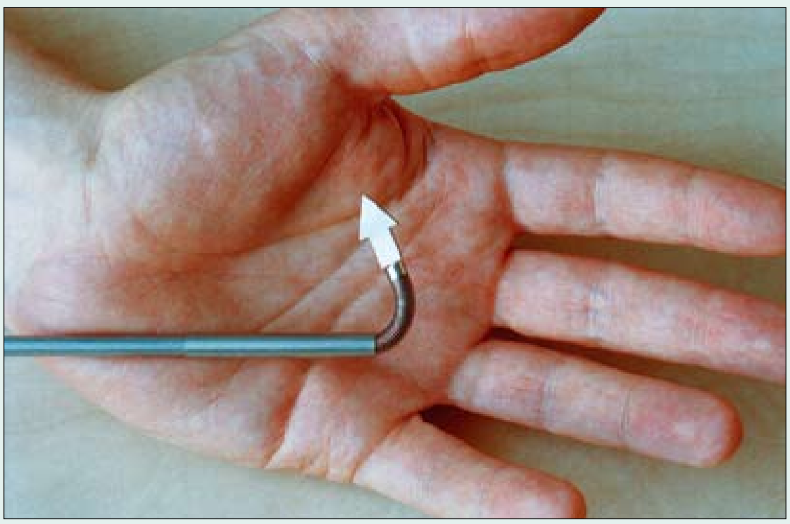
Breedveld can see possible applications in an industrial context in addition to medical applications.

"Internal inspections of complex engines and fuel tanks spring to mind, or being able to fasten screws around corners. This is now being done using rigid endoscopes and instruments, but freely controllable tools can be very efficient. In any case, the industrial market is a lot smaller than the market for medical applications, if only because the sterility of the instrument is not an issue in industrial use, where the tip can be used again and again, whereas for medical use, it would simply become a disposable tip."

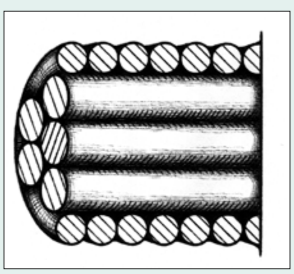
Breedveld already had many contacts among surgeons, but through DEAM BV he has now been in contact with a lot of industrial representatives. In the last few months he has been visited by practically every major medical industry in the world.

"For a number of companies we are now preparing prototypes to their exact specifications," Breedveld explains "and surgeons are already asking us when they will be able to buy a movable tip control system using the Cable Ring Mechanism. According to them, they would really like the system for instrument applications. The complex manoeuvring of small instruments remains a major problem in keyhole surgery, which involves surgeons performing operations through small incisions."

For more information, please contact Dr Ir Paul Breedveld, phone +31 15 278 5232, e-mail p.breedveld@wbmt.tudelft.nl, or Dr Ir. Jules Scheltes, tel. +31 6 150 75341, e-mail jss@deamcorporation.com

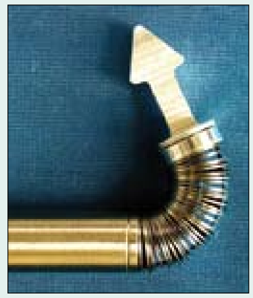


The third prototype has an outer diameter of just 5 millimetres. Breedveld is currently working on the next generation endoscope, with a diameter of as little as 1.3 millimetres.

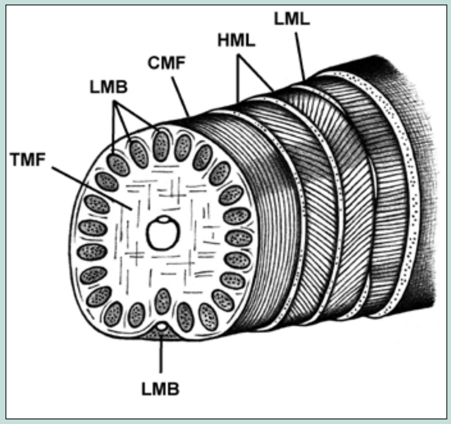


Replacing the inner spring by a cable enables Breedveld to miniaturise a number of steerable instruments and catheters, ready for low-cost mass production.

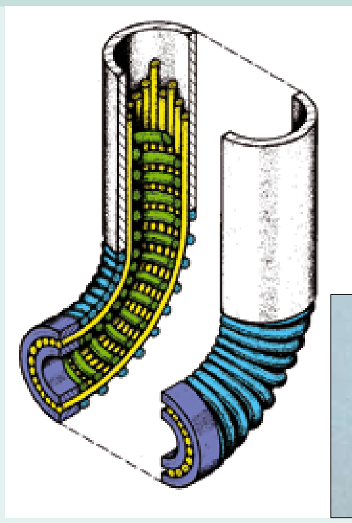
Breedveld's second prototype of the Endo-Periscope, developed in 2001-2002 had a diameter of 12 millimetres. The significant features of this model are the simplified construction of the grip and the parallologram mechanism.



The tip of the second prototype can be steered over 120° in all directions.

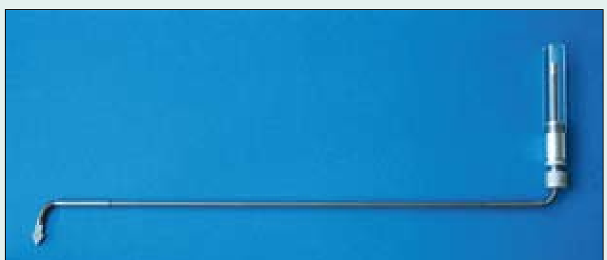


Cross-section of a tentacle of a squid. Belonging to the family of Cephalopods, squids have no hard skeleton for support. Yet they manage to move their tentacles and arms in a great many directions. The tentacle is surrounded by longitudinal and helical muscle layers (LML & HML). The cross-section contains a ring of longitudinal muscle bundles (LMB) enclosed by transverse and circular muscle fibres (TMF & CMF). The tentacle functions as a muscular hydrostat: since the volume of the tentacle remains equal, its stiffness, curvature and length can be changed by the interaction between the longitudinal retractor muscles (LML and LMB) and the circular and transversal extensor muscles (CMF and TMF). The longitudinal muscle bundles (LMB) play a role in retracting as well as bending the tentacle in a certain direction. The ring of muscle bundles inspired Breedveld to create the Cable Ring Mechanism.

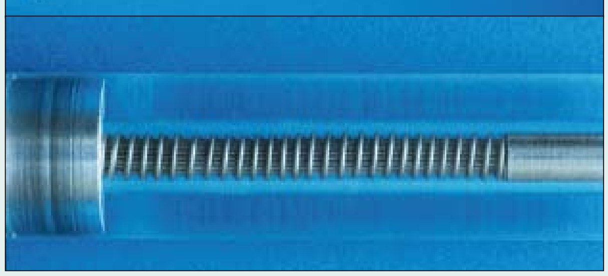


Cross-section of the tip of the recently developed third prototype of the Endo-Periscope, showing the ring of cables, surrounded by two helical springs and fixed at the tip between two rings.

Close-up of a model to test the fixation of the 22 cables between the two rings.



Overall view of the third prototype of the Endo-Periscope.



Close-up of the transparent grip showing the Cable Ring Mechanism.

The 'Ginger and Fred' office building of the Nationale Nederlanden Insurance Company in Prague, Czech Republic (1996) by the American architect Frank O. Gehry. The nickname, referring to the dancing couple Ginger Rogers and Fred Astaire, was inspired by the two elegantly curved intimate volumes in the façade. The transparent one resembles a tailored ballroom gown. It is facetted with flat quadrangular sheets of glass. Fred is formed from precast concrete panels. No freely curved window panes were available at the time, so Gehry reverted to rectangular window frames that protrude at varying distances from the rendering over the concrete elements.

Curved windows offer architects more freedom

Tordos *and* Twisters

BY MARION DE BOO

An increasing number of architects are being inspired by smooth curves and surfaces. Drawing them is one thing, but actually building them is quite another. When flat window panes protrude from the facade, they rudely interrupt the free flow of the design, according to Dr Ir Karel Vollers of the Faculty of Architecture of Delft University. That is why he is launching a worldwide first: a prototype of a freely curving, convex window, complete with frame, courtesy of intensive collaboration with leading glass and aluminium manufacturers. As a bonus the new design offers easy connections to existing building structures, an aspect that used to be a considerable problem. On top of that, Vollers has taken into consideration the feasibility of producing such high-tech windows at an affordable price. His design has been patented.

"Ever since the nineteen eighties, architects in Holland and abroad felt dissatisfied with the ubiquitous rectangular blocks of buildings, more often than not clad in a plate-glass curtain wall," says Vollers, who is an architect as well as a building technologist. "So they started experimenting with cylindrically rounded buildings, and eventually started sketching voluptuous curves inspired by images from nature such as dunes, beaches, waves, and the images of information streams flowing around the Web."

Having graduated as an architect from TU Delft, Vollers worked for various architects' firms as a project manager. Following an intermezzo as a designer and wholesaler of light-emitting jewellery, he embarked on an eight-year doctorate research project. In 2001 he was awarded his doctorate at TU Delft with a cum laude distinction for his thesis, Twist & Build, creating non-orthogonal architecture. He has since been working as a lecturer at TU Delft, and in addition runs his own architect's firm in Amsterdam.

Freedom of Form

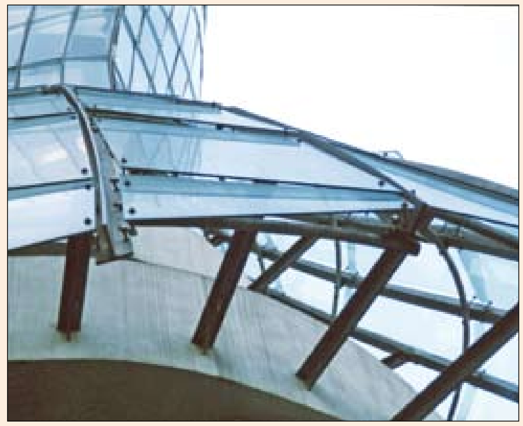
"Of course, rectangular buildings are less complex to produce, measure, and assemble," Vollers says, "which is why they are cheaper. These days however, architects like to take inspiration from flowing lines; they are searching for much more freedom of form." For this reason Vollers is collaborating with glass and aluminium manufacturers to produce a freely curving façade system.

"However, their production must be financially feasible," Vollers says. "We're not simply looking at one-off prestige objects like exhibition pavilions or upmarket company office lobbies. We want it to be a commercially viable system. You could build council houses with nicely curving bay windows or skylights! With an equal outer surface it can offer much more extra space and volume than a rectangular box ever could!"

During his research Vollers had to translate architectural designs with curved lines, twisted surfaces, and flowing shapes into structurally feasible models. He developed a sample sheet of different building shapes with curved façades. The freely curved ones are classified as BLOBs, a reference to the shapeless, man-eating, gelatinous monster in the film of the same name (USA 1958, directed by Irvin S. Yeaworth, with a remake in 1988). In mathematics, BLOB also stands for Binary Large Object, i.e. a cloud of data. At the Delft Faculty of Architecture, Vollers heads the BLOB group, which, supervised by Prof. Dr Ir. Mick Eekhout, looks at how these challenging buildings can materialise.

"Non-standard architecture covers about the same field," Vollers says, "with different parts all being different shapes. Non-standard emphasises the lack of repetition of parts; as yet they usually are straight or flat; BLOB underlines the free-flowing nature of these shapes and their components."

When building a BLOB, the major technological challenge is to create highly twisted window frames in extreme structures, not to mention the glass that goes in them.



Ginger consists of two layers of steel-supported glass curtain wall. The interior layer, the underskirt, is the actual wall of the building, while the outer layer acts as a screen for the office spaces underneath. Ginger's vertical steel T-members curve in two directions and also twist. To follow the curves, flat panes of glass overlap at varying distances.

Sectional Aluminium

To fit the curved glass, the glazing supports must be twisted. This can be done in a number of different ways. Vollers, together with the Alcoa Architectuursystemen company, aluminium facade system designers, opted for a simple and cheap solution, which was to redesign an existing framing system. The design has been exhibited at international conferences from Helsinki to Seoul, and the researcher has taken out a patent on it. In 2001 Vollers was awarded the Dutch Aluminium Award for Architecture. The Alcoa AA100Q-Twist facade system has been developed specifically for the creation of free-form curved facades. The use of new techniques has made it possible to simultaneously bend and twist the framing profiles and so achieve the variable curvature of the design's surface. The system includes a window that opens smoothly and that features a multi-point latching system. The axes of the hinges (halfway along the top and bottom bars of the window) are exactly in line.

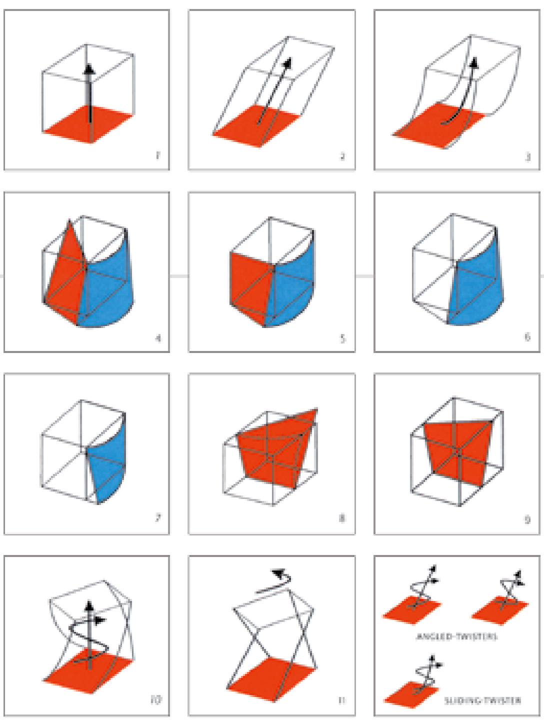
A major advantage of starting out with existing components such as glazing bars, joints, metal strips, and rubber seals for the Twist facade system, is that the current certificates can be used.

Vollers: "The system is unique because it enables us to make curved surfaces that are much more complex than simple cylinders and cones. Once a glass facade can be curved, the industry will be quick to transform other elements accordingly. There is a whole new field of components waiting to be developed by the industry."

Vollers himself will now focus on the development of freely double-curved toughened glass.

"For continued innovation it is essential that glass producers and window frame manufacturers work in concert, because the one cannot exist without the other. So far we have been unable to produce the curved glass cheap enough, and as long as that does not succeed, the suppliers of building components that connect with the window frame will not develop their product. In other words, stalemate."

So, different industries will have to start investing in the new technology at the same time. Vollers: "There is no market demand yet, since the product is still completely new, and still at the development stage. The computer-controlled mould system has not yet been built either. Now that a few builders have spent a lot of their energy on complex, labour-intensive projects, the industry is sitting back to watch what comes next. Developments don't wait however, and building processes are becoming more rational, and will soon fit building practice. I expect our new facade system to be used on a large scale within five years. We will soon be flooded by new construction projects."



Vollers classified various (building) volumes according to their geometric features.

Extruders:
1 Ortho drawn by shifting ground plans along a vertical line
2 Angler ditto, along an inclined straight line
3 Slider ditto, along a 2D curve

Rulers:
4 Free ruler with ruled surfaces (conoid and hypar)
5 Ortho-ruler ditto, of which some connect with their rules to an orthogonal grid
6 Free-conoid one or more conoids, of which at least one doesn't connect with rules to an orthogonal grid
7 Ortho-conoid ditto, of which all connect with rules to an orthogonal grid
8 Free hypar one or more hypars of which at least one does not connect with rules to an orthogonal grid
9 Tordo one or more hypars, of which all connect with rules to an orthogonal grid
10 Twisters a repetition of twisted façade elements in vertical direction
11 Roto-Twisters a repetition of twisted façade elements in horizontal direction, while floor plans differ on each level

Bendable Vollers is now making headway with an improved prototype of the façade system which he developed together with aluminium manufacturer Alcoa Architectuursystemen BV. The system can seamlessly attach any shape of freely curving glass surface to buildings with any structural grid. Usually this is a rectangular structure, in other words, vertical walls, horizontal floors, and rectangular floor plans.

Vollers: "If you design a freely curving curtain wall around such an orthogonal building, you run into the problem that the window frames do not meet the floors and the interior walls at right angles. The angle changes constantly, and the glazing supports must be capable of accommodating the change. With the façade bending forwards and backwards, it has to support structural forces, show and wind loading. These window frames are subject to considerable stresses."

The frame consists of two parts. The rear, rigid support profile can be fixed parallel with or at right angles to a flat wall or floor, and absorbs all the forces. A specially designed glazing strip is used to fit the curved glass. It rotates around the cylindrical edge of the rear support.

"The very bendable glazing strip can be shaped and fitted on site during construction," Vollers explains. "I think our design may be the key to a rational execution of freely curving buildings."

For the prototype the glass is shaped onto moulds that have been milled from aerated concrete. The resulting shapes are of very high quality, with a much more evenly curved surface than obtained with earlier prototypes. A new addition to the façade system is a window that opens and closes very smoothly.

"I'm looking forward to tackling the first large-scale project with the new system", Vollers continues. "It will be far from simple. With all the windows being different shapes, the panels must be very closely matched in all three dimensions, and they must be fitted together at exactly the right angles. Computers play a major role in this process, which is ten times more complicated than fitting a normal, flat curtain wall."

The power of Niemeyer The history of the project goes back a long way. One source of inspiration for Vollers is the oeuvre of Oscar Niemeyer (b. 1907), examples of whose work he first saw in 1986 during an architects' study tour through Brazil.

"Niemeyer is the main architect of the new Brazilian capital, for which he used a work force of 50,000. The power of his form language was a revelation to me. His buildings stand in the landscape like sculptures, and in some cases they connect with it. The contour of the new museum of modern arts, MAC, at Niteroi, Rio de

PHOTO: THOMAS MAYER ARCHIVE, WWW.THOMASMAYERARCHIVE.DE

The housing and office complex Der Neue Zollhof in Düsseldorf (1999) by Frank O. Gehry. The complex is divided into three buildings, each of which has a different geometry and finish. The twisted walls of the middle building are clad with stainless steel sheets. The sheets are connected to a frame; as the panes are not stretched within their surface but only bent, folds are visible. The cladding only approximates the twisting surface.

Town Hall of Alphen aan de Rijn, -2001, by EEA architects The twisted façade is triangulated to approximate the curved surface. By making a diagonal fold or seam in a twisting grid, no expensive twisted panes are needed and flat panes can be used instead. Triangulation implies more seams and more complex corner connections.

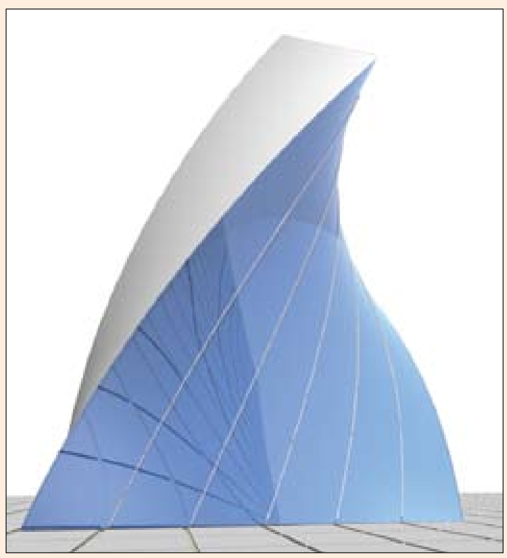
Turning Torso apartment and office tower in Malmö (Sweden) (2004) by the Spanish sculptor, painter and architect Santiago Calatrava. The outer construction with steel tubes emphasises the twisting.

The 90° twist across a 186 m height involves only a small twist per window pane. Therefore this façade was made of flat elements that meet under a slight angle.

MODELLBILD: MARKUS PILLHOFER RENDERING: STEFAN LAUB

Model of the European Central Bank in Frankfurt (2004) by the Austrian architects Coop Himmelb(l)au in Vienna. The hypar shaped façade connects with straight lines to the orthogonal superstructure. The production and measuring of building parts along straight lines connects to conventional production techniques.

Feasibility study of a 90° twisted tower (1995) by Dr Vollers. This 'twister' was made with straight horizontal and standing lines that emphasize visual qualities. Both floor plan and façade elements are repeated in vertical direction with an incremental horizontal rotation. The repetition facilitates production and assembly.



Rear side of the 90° twisted tower.

Janeiro, for example, very cunningly runs parallel with the contour of Sugar Loaf Mountain in the background. I think that is great."

Niemeyer accepted commissions from all sorts of totalitarian regimes.

"His philosophy is that as time passes, the circumstances under (?) which buildings were built, disappear in the background. What is left is the building. Good and grand designs can lift people out of the misery and poverty of their daily lives and so make them feel better. His designs manage to make people marvel, which is a very generous gift, and I like that."

Niemeyer managed to build his labour-intensive designs in South America with optimum use of low wage levels. Vollers has pinned his hope on computer power.

"A computer can make hard work light."

Systematic Description During his research, Vollers started a systematic description of the form and material properties of a twisted façade. Vollers: "You cannot bend a twisted surface from a sheet of paper, since the surface has to be stretched. Similarly, you cannot make the outer surface of a ball from a sheet of paper either."

The straight lines in a twisted surface, don't run parallel with each other, nor do they pass through a single point, as in a cone. He replaced the mathematical plane descriptions and formulae with an inventory of shapes of his own that is geared to actually constructing it rather than understanding the mathematical ins and outs. For example, he describes a twisted plane as 'a plan constructed of straight lines that are formed by copying a line and then translating and rotating the copied line. It always involves a rotation at right angles to the translation.

"There is no mathematics involved," the researcher emphasises.

He used this method to describe a whole range of complex building models, and then analysed each for its external appearance, construction, and possible façade connections. Eventually, he arrived at two main types, the 'tordo' and the 'twister. A tordo is a building that incorporates at least one twisted façade, and that has a rectangular supporting structure. A twister is a building all the façades of which twist in the same direction, like pasta twists. Each floor of a twister is slightly rotated relative to the one below. A fine example of a twister is the 180 m high Turning Torso tower at Malmö, designed by Calatrava.

Having finished his research, Vollers focussed on the construction of free-form, or freely double-curved planes.

"These basically do not feature straight lines and therefore are much more complex. This puts up the price of construction, but on the other hand an architect gets much more power of expression in return," Vollers says. "Creating a building with playful, free forms as yet requires a lot of manual labour. As a result you only see few of them. Their rarity gives the buildings an aura of luxury, if only because so few people can afford one. But these buildings will now be constructed in greater numbers, and computers will take over much of the work. Even the manufacture of exclusive glass and window frames is becoming automated. Masters such as the American architect Frank Gehry have a fantastic team of computer experts at their disposal. They know how to get the most out of the available production options when working on their dream forms."

Liberating Free-flowing shapes may be used to set a design in its urban or landscaped environment. For instance, the baseline of a façade can take on the direction of a nearby object such as a road or a canal while the top of the façade echoes a quite different direction; within the surface plane they twist towards each other.

"Architecturally speaking, a twist in a form or surface has an alienating effect," Vollers says. "The perception of the perspective is different from that of a normal rectangular building, because instead of a single vanishing point there is a whole series of them, one for each horizontal line in the façade."

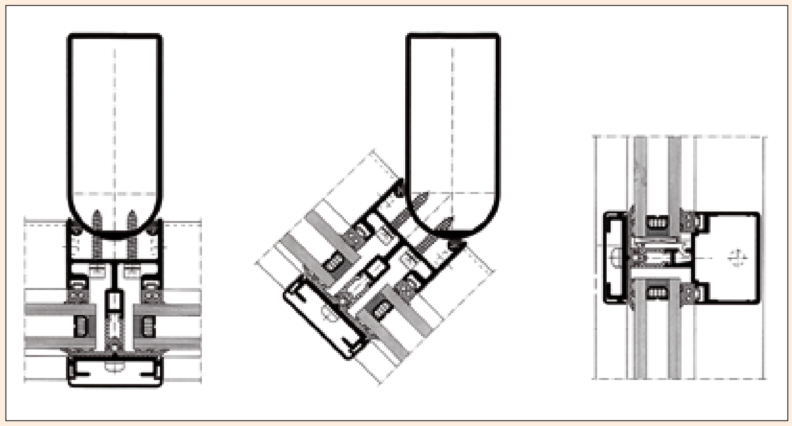
Until now, architects building such a curved shape with glass could only approximate it by faceting the surface, i.e. breaking up the façade in lots of small flat surfaces.

"A good architect manages to turn constructional limitations to his advantage," Vollers says. A faceted diamond is more attractive than a rounded one. Likewise, a façade can achieve crystalline beauty."

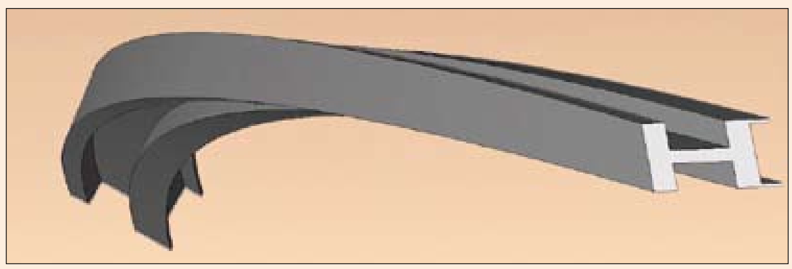
However, rather than opting for faceting, Vollers decided to go for real curved

The first prototype (2000) has straight framing profiles and twisted glass that meet under varying angles. The glass was bent on an adjustable mould made of metal bars. The irregular surface curvature sufficed to test connections and transformations between the parts, but didn't meet the quality demands of the market.

The second prototype (2005) is freely curved. The transom along the floor is straight, whereas the mullions' curve has a 4-metre radius.



Cross-section of the new profile showing a specially designed mullion with a standard glazing fixture. Because the mullion has a cylindrical end, the glazing fixture can be attached in any position between +45° and - 45°. The top and bottom of the panes are attached to the transom profile, as depicted on the right.



The special tooling that was required to bend and twist the outer profiles was developed by Van Campen Alumnium in Lelystad. Drawing twisting profiles and their connections proved complex task; it was executed by the Technical Design & Informatics Group of the Faculty of Architecture of Delft University.

The complicated task of assembling an opening window in the curved prototype was also carried by Van Campen Aluminium. The meeting of four panes requires small tolerances. The window has no hinges on the one side, but pivots in the middle of the top and bottom ends. In one movement the handle operates five closing points along the sides of the window.

glass simply because it creates different kinds of reflections and different associations of form. In order to get the glass in the required shape, he made an adjustable mould consisting of height-adjustable horizontal steel bars, on top of which a flat sheet of glass could be bent into shape. The heated sheet of glass should bend without showing the impressions of the steel bars. For the second prototype, Vollers worked with milled moulds to support the glass along its entire surface. Currently he is involved in making a computer controlled flexible mould with adjustable cylinders. The points on top of the cylinders are placed at such small intervals that it will avoid the denting of the surface. "An interesting development is the use of cold bent tempered glass panes," Vollers says. "As tempered glass can take much higher tension, it can be bent into shape to fit the window frames on site during construction. After all, the rotation is not so great for each separate sheet of glass as long as the façade is big enough."

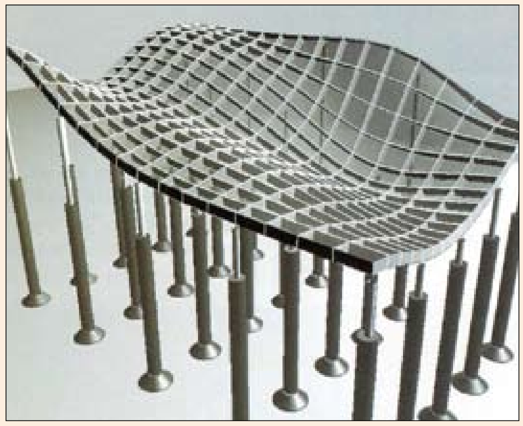
For further information about this subject, please contact Dr Karel Vollers, phone +31 15 278 4297, e-mail k.j.vollers@bk.tudelft.nl

To curve the glass panes large moulds are milled from cellular concrete and placed in the furnace of glasbending firm Bruining in the city of Dordrecht. The furnace was fired at 700°C.

Two curved panes are turned into insulating glass, following a process very similar to that with flat panes. The Glaverbel Stopsol Supersilver Ice Blue glass panes have a highly reflective ceramic coating, which withstands high bending temperatures and emphasises the curving.

The 3D curved edges of the glass panes were cut along the sides of moulds milled from polystyrene. These moulds were subsequently used for transport from the glass manufacturer to the aluminium assembler.

◀ Inner side of the Alcoa AA 100Q-Twist showroom model of the freely curved façade. As the model is composed of the same standard elements, it will seamlessly connect to façades of simpler geometry, built with the Alcoa AA 100Q-system.



The next step is the development of an adjustable mould. This one, designed by architect Lars Spuybroek. It is similar to the principle that is being studied by the BLOB group of the Building Technology department at Delft University.

The open window of the ▶ curved façade, currently shown at the BATIMAT 2005 trade fair in Paris, is quite an eye catcher.

INS & OUTS

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