Water-cooled spacecraft

DART to be launched by Russian Volna (Stingray) rocket

For many years, satellites were launched into orbit in the nose cone of a dispensable rocket. This is a very costly procedure with limited possibilities, which is why the Space Shuttle project was launched. Since this did not yield the expected savings, the new solution is thought to be a fully reusable launcher that looks a bit like an aircraft. Delft researchers are working on an experimental spacecraft that can be reused upon returning to earth after re-entry through the atmosphere. The capsule is to be launched in 2003 from a Russian submarine, and will be carried aloft by a Volna (Stingray) missile.
In a matter of seconds, a 35-ton SS-N-18 Stingray missile will start its ballistic flight.

In its nose it carries a projectile weighing 150 kilogrammes, the DART. Its target is over 5000 km away, and will be reached in 30 minutes.

Fourteen metres of missile break away from the Mstislav, cutting through the waves of the Barents Sea and shooting high into the sky. Nothing can stop the mission now.

A fragment from a new Tom Clancy novel? The sequel to Hunt for Red October? No, neither of those. This is the culmination of a project that was started over three years ago by ten third-year students at the Delft University of Technology faculty of Aerospace Engineering.

The object of a re-entry vehicle is to land safely, so it has to be able to survive the return journey through the Earth’s atmosphere. Although the Russian Soyuz space capsules are capable of safe re-entry, the amount of damage they sustain during the descent renders them unfit for further use. Like the American Apollo capsules, they are in fact large bullets with a protective layer that prevents them from burning up in the atmosphere. Until recently, the re-entry problem received little attention in the Netherlands and elsewhere in Europe. The escalating costs of the American Space Shuttle project — the only successful reusable space vehicle so far — caused the aerospace industry to sit back and wait. The maintenance of the ceramic tiles that make up the Space Shuttle’s heat shield alone takes up some 40,000 man-hours for one flight, contributing to the cost of approximately 500 million US dollars per flight.

Third-year project

In April 1999, ten of Ir. Tom van Baten’s students were given the assignment of designing a small re-entry vehicle that could be built by the faculty itself. It was a project for students at the end of their third year as part of a ten-week design/synthesis study. Van Baten is Professor of Aerospace Materials — one of the nine chairs at the Aerospace Engineering faculty. He specialises in thermostructural problems and high-temperature materials, one of the main technological obstacle courses in re-entry technology.

‘At TU Delft the aim has always been to take on projects with practical applications that will be of interest to the industry,’ Van Baten says, ‘and that allow us to involve different faculties. For a technology institute like ours it is also important that the project be of major scientific interest, and of course it has to be inexpensive to execute. Students are immediately attracted by subjects like this one because they present them with a real challenge.’

For some years, the U.S. Space Shuttle had a Russian sister ship, Buran. The Russian shuttle flew only once, in 1988. The absence of any visible activity since then is probably due to lack of funds. The space shuttles are protected from the extreme temperatures by a heat shield of ceramic tiles and lagging.

The many thousands of ceramic tiles that make up the heat shield of (in this case) the U.S. Space Shuttle have to be inspected and serviced, at a cost of millions of dollars.

The ceramic tiles are very fragile. Consequently, most of the damage is sustained from impacting particles coming from space, pieces of ice that break loose from the fuel tanks during launch, and unobserved minor incidents during maintenance work.
DART is an acronym for Delft Aerospace Re-entry Test demonstrator. Such a complex project involves all aspects of aerospace engineering, and practically automatically results in a broad collaboration between the various scientific fields. The focus lies in the fields of Aerodynamics, Control & Simulation, Structures, and Materials. In addition there are groups involved with flight performance, industrial organisation, production technology, and with satellite systems and navigation. All in all it is a textbook example of what is known as a «horizontal project» within TU Delft. The results of the students’ project were so good that it was decided to continue and develop a prototype that would actually be launched. Fokker Space (rechristened Dutch Space) and estec (part of the European Space Agency) both showed interest, and these companies are now participating in the DART project, together with the Dutch National Aerospace Laboratory (nlr). Van Baten: ‘As it turns out, the vehicle we had in mind fills a niche the industry had overlooked. This is pure coincidence, since our aim was to come up with a design to demonstrate our knowledge and skills, including our ability to solve any complex scientific problems we might encounter.’ Ir. Jeroen Buursink was asked to join because of his experience in the field of aerospace system integration. Together they now run the DART project, spending a lot of time trying to second the required manpower from the various departments. Fortunately there is widespread and keen support for the project.

X-33
Initial fears were that the Americans would fly their X-33 before DART could be completed. This would kill DART’s news value, turning it into just another variation on a theme. X-33 was to be a prototype for a large, reusable launch vehicle, a possible successor to the Space Shuttle. The project was cancelled due to insurmountable technical problems and their financial ramifications. The Americans were on the verge of overshooting their original 1,000 million U.S. dollar budget by at least 50%. The aims of DART are fairly modest. It is to be a flying laboratory for aerodynamic measurements of phenomena that occur during re-entry in to the atmosphere. Chemical processes also play a role in high-altitude, high-speed aerodynamics in rarefied gases, but little is known about them. For example, oxygen and nitrogen molecules will dissociate, draining heat away from the vehicle. However, this positive effect is subsequently undone when the atoms recombine and produce heat. The idea is to design a vehicle that will prevent the dissociated molecules from striking the surface as much as possible. On top of that, atomic oxygen can seriously corrode the vehicle’s skin.

Van Baten: ‘These measurements are extremely important. Although we can perform all sorts of calculations down here on the ground to predict the behaviour of the air up there, and how the vehicle will behave in those airflows, we cannot confirm the results using wind tunnel tests. There simply isn’t a wind tunnel on earth capable of simulating the conditions up there, with extremely high speeds and a rarefied
atmosphere without the effects of gravity. So since calculations alone cannot tell us what is going to happen, we plan to use DART as a test bed.’

Wind tunnel
A wind tunnel is incapable of simulating all the required conditions simultaneously. The gas is expanded to give it sufficient velocity, which causes it to cool rapidly. Although this allows the simulation of high-speed airflows, there is no temperature increase. The reverse is also possible, gas with the right temperatures at the surface of the vehicle, but at low speeds, resulting in airflows around the vehicle that differ from reality. It is either one or the other, as well as a further constraint. Buursink: ‘As the maximum speed increases, the size of the wind tunnel decreases. At Mach 10 or 20, the diameter of most wind tunnels is no more than a few centimetres.’

This necessitates the use of a scale model, which introduces new problems because different physical phenomena scale differently. If you double the diameter of a sphere, its surface area increases fourfold, and its volume becomes eight times as much. Inversely, a down-sized scale model of DART will have a surface area that is too big for the volume it encloses. This makes it difficult to obtain representative measurements of temperature effects on the vehicle.

Calibrating the results of calculations, computer simulations and wind tunnel experiments requires real-world flight data.

Van Baten: ‘Being a university project, the cost has to be kept as low as possible. On the one hand we have the scientific requirements of high accuracy and reliability of measurements, and the need to ensure the vehicle’s safe return, while on the other hand all the work has to be done within our faculty’s budget, which is all but gobbled up by the launch, which alone costs half a million euro.’

This is cheap at the price, since the normal figure is ten to one hundred times as much. And you don’t even get a dedicated mission, since the vehicle is taken up as one of several different payloads.

Buursink: ‘Apart from the fact that we simply can’t find this kind of money in our budget, this type of launching does not fit our requirements in terms of velocity range and re-entry angle. Only the right conditions will do for studying the aerodynamics involved, after all, that is what it is all about. We have deliberately opted for a ballistic flight, as simple as possible. The vehicle will simply drop back to earth like a bullet, following a highly predictable track. I searched the Internet for a launcher to meet our two most important requirements: the right track at the lowest possible cost. That’s how I ended up at the Russian Makeyev State Rocket Centre. After exchanging a couple of e-mail messages, this proved to be the perfect solution for our purpose. A little later we visited Jean Muylaert, head of the Aerothermodynamics department at estec, where we met the Russian professor, Mikhail Ivanov, who is the head of the Computational Aerodynamics Laboratory at Novosibirsk in Siberia. Ivanov showed great interest in...
our project and offered to help us in establishing the right contacts and handling the various procedures in Russia. Ivanov also lent us the use of his institute to meet the people of the State Rocket Centre. When we were there, Ivanov also told us that we could use his laboratory to carry out measurements.

SS-N-18 missile
The start treaties between the former Soviet Union and the U.S. included the decision to destroy a large number of SS-N-18 missiles. The easiest way of getting rid of them is to remove their nuclear payload and launch them. To get something in return, the rockets have been adapted for civilian use and have had their names changed to Volna (Wave). The U.S. has embarked on a comparable programme for their Minuteman missiles. However, these are available only for use by NASA, the U.S. Air Force, and U.S. universities. Other users and commercial applications are not allowed. The Russian programme has already seen a number of flights for scientific purposes, including microgravitation experiments. The Volna missiles are launched from a submarine in the Barents Sea, near Murmansk. The initial plan was for a DART mission across the entire north of Russia (i.e. Siberia), with a parachute descent into Kamchatka.

Lifting power
The main problem to be overcome is the heat resulting from air friction.

Van Baten: ‘Upon re-entry into the earth’s atmosphere, vehicles like this one are subjected to extreme thermal loading. The temperatures can rise to as much as 1800 °C. These temperatures can be avoided to some degree if you do not allow the vehicle to follow a ballistic track, but fly it instead. This will induce lift, and will allow the vehicle to glide down into the atmosphere, and so bring down the temperature load. The downside is that the vehicle will be heated over a longer period of time, albeit at a lower temperature. During that time, the heat will penetrate further into the vehicle’s interior, so you will have to take extensive thermal insulation precautions.’

DART however, is a ballistic vehicle and as such incapable of controlled flight, so a different solution to the heat problem is required. The vehicle’s velocity in orbit is about 8 km/s, or Mach 25. To reduce speed, the vehicle has to lose its kinetic energy in some way. The only way to do so is in the form of heat (through friction with air molecules) and by generating shockwaves. The shape of the vehicle must be such that these shockwaves do not curve back onto its own surface, which would cause the skin to heat up after all. The heat load calculated for the nose of the vehicle is so high that there is no material currently available that would survive the onslaught, not even such advanced and costly materials as Carbon-SiC or Carbon-Carbon, which consist of carbon fibres in a carbon or silicon carbide matrix. Although capable of withstanding extremely high temperatures, the problem is that it will burn away during re-entry. It simply oxidises, and it is very difficult to find protective coatings that can survive...
such high temperatures and corrosion. Another requirement for a coating is that it must have the same thermal expansion coefficient as the substrate, or it will simply flake off.

Buurssink: ‘The only way to make these materials reusable is by keeping the temperature below 1600 °C. The temperatures we are dealing with are a few hundred degrees over that, and that would simply burn of these materials. They may be useful for controlled flights, but even so they remain extremely expensive and require a lot of maintenance. Therefore we are trying to find a metal solution, which will be much cheaper to produce and requires little maintenance in comparison.’

Steam film
Some years ago, Fokker Space conducted a study into the use of a water-filled metal nose. Water will absorb vast quantities of heat. You will be hard put to to find any other material with a higher evaporation heat. ‘You just have to make use of what nature provides’, Van Baten jokes. DART’s nose will contain a water-filled metal sphere. The friction heat is transferred to the water, causing it to boil. The amount of heat this technology will help absorb is at least two megawatts per square metre. At too high heat fluxes the well-known «drop on a hot stove» effect will occur, in which a film of steam forms between the metal and the water. This reduces the heat transfer rate, and so reduces the system’s efficiency. However, as the vehicle is slowed down during its descent, the negative acceleration of 10 to 15 g presses the water into the nose, improving the transfer of heat to the water, and suppressing the formation of a steam film. Using the water cooling system, the temperature of the metal surface will be limited to approximately 250 °C. The heat transfer may perhaps be further improved by roughening the inner surface of the sphere.

The outer skin of the nose will be made of the «oxide-dispersion-strengthened» alloy, PM1000, which contains nickel and chrome with small quantities of iron, titanium, aluminium, and yttrium oxide. As the alloy melts, the material properties change. So, the metal is mixed as a powder and sintered under high pressure and temperature. At high temperatures in an oxygen environment, the outside of the metal forms a chromium oxide layer which is highly corrosion-resistant because it prevents further interaction of the metal with the oxygen atoms. Should any damage occur, for instance by a meteorite striking the surface, the layer repairs itself because the underlying chrome immediately oxidises. The material also has a high emission coefficient, causing the surface to act almost as a black body. And the higher the efficiency with which a surface radiates heat, the greater the cooling effect. In addition, PM1000 has a low catalytic effect, therefore recombination is limited. Most metals have some kind of catalytic effect on the recombination process, so the recombination will tend to occur at the metal skin surface, transferring the recombination energy back into the vehicle.

Plasma tunnel

In April 1999, ten students at the Delft faculty of Aerospace Engineering were given the assignment of designing an experimental spacecraft/re-entry vehicle. The project formed the basis for the current DART project. After several design evaluations, two models remain, Volan (named after a Russian spacecraft of the nineteen-sixties) and Revolution.
Since the idea had already been published, Fokker Space was unable to obtain a patent for the principle of the water-filled nose cone. Even so, the knowledge being gained from experiments is at least as important as the idea itself, and that is how TU Delft hopes to gain its position within the European space field. With the support of esa the principle will probably soon be tested at the German Aerospace Laboratory, Cologne or maybe in a wind tunnel near Naples, Italy. In view of the extreme conditions it simulates, «wind tunnel» is a bit of a misnomer, so those involved prefer to call it a «plasma tunnel». In the plasma tunnel, a water-filled, thin-walled PM1000 sphere with a diameter of 10 cm will be subjected to hot flows. The effects will be measured using pressure and temperature sensors. A small camera inside the sphere will record how the vapour bubbles are formed as the water starts to boil. The energy absorbed by the water will be carried off by releasing the resulting steam into the environment. According to Buursink these tests are important to create confidence in the Delft theories. TU Delft has another ace up its sleeve, since it holds the patent for a method to cool the surface behind the nose cone as well. Although this part of the skin is not subjected to the same heat load as the nose itself, it can reach temperatures up to 1400 °C. In the past, Russian engineers proposed making small holes in the skin, with water behind it. The water will evaporate, cooling the surface.

Van Baten: ‘In itself it is a good idea, but we cannot use it because it would disturb our aerodynamics measurements. On the spot I came up with the idea of placing a water-saturated porous layer at a small distance behind the skin. This doubles the radiation cooling capacity of the skin, which now radiates in two directions. On the inside, the heat is transferred to the water in the porous plate. As in the nose, the evaporating water provides efficient cooling, enough to lower the skin temperature by a few hundred degrees — sufficient to keep it from melting.’

The skin of the vehicle will be subjected to this vast heat flux for only a few seconds, so the cooling system requires only a few litres of water. The porous material, called «zal», consists of aluminium oxide fibres with a silicon oxide bonding agent. It is a relatively cheap and widely used insulation material in the aerospace industry, and it is able to absorb enormous quantities of water. zal-15 for example (the number refers to its density) will hold 370% of its own weight in water. Subjected to an acceleration of 26 g in a centrifuge, it did not spill a single drop of water.

Van Baten: ‘If you tell this story to people from the aerospace industry, they will stare at you in disbelief. It is so simple, so natural, that nobody is prepared to believe it actually works.’

Cockpits
In the large building behind the offices of Delft Aerospace, two groups are competing for the available space. At the back there is the «museum», a collection of discarded aircraft and spacecraft components. At the front is the laboratory, filled with all sorts of machines.

The model consists of a number of interchangeable elements and is packed with sensors. In spite of the fact that its shape is very different from that of DART, the assembled model provides useful data for the Delft researchers.
that pull, push, twist, and use many other ways to fatigue and stress materials in order to test their durability and strength. Every year, the boundary between the two neighbours shifts a little, to the museum’s disadvantage. Every year, the aircraft, undercarriages, wings, tailplanes and satellite parts are forced to huddle closer together. There is even a dismantled racing car that survived a crash. The traces of the crash are unmistakable, but the structural integrity has been retained. Between a number of showpieces from the inheritance of the Fokker works we find the laboratory’s greatest asset: one half of an experimental aircraft fuselage made using glare. Following an extensive test programme at Hamburg in Germany, the Airbus company has decided that part of the fuselage of the new generation of Airbus 380 aircraft will be constructed from this glued aluminium laminate material. It is lightweight, strong, and fire-resistant, but above all it was invented at Delft University of Technology.

Right at the front of the building is screened-off room in which Buursink and Van Baten have built their test rig. This is where they test the effect of high temperatures on the skin of DART. Fourteen quartz lamps, each with a power consumption of 2500 W, are suspended only one centimetre above the material being tested. Under the lamps are two sample sheets of zal. One is dry, the other has been saturated with water. A few millimetres above the zal, the PM1000 outer skin is suspended. The temperature on the surface of the dry sample increases up to about 1200 °C, a realistic temperature for a space vehicle re-entering the earth’s atmosphere. The electric power to generate this heat is one megawatt per square metre, enough to require the construction of a special power supply. As the water evaporates from the wet sample, the surface temperature remains a few hundred degrees cooler than that of the dry sheet, exactly as predicted, and just the amount needed to ensure survival of the vehicle’s skin. The test samples measure only 10 x 10 cm. Because of the power consumption involved, experiments on a larger scale will have to wait until the building has been rewired.

On top of a filing cabinet inside the office, we find the model of DART (which was still called REVolution at the time) made during the student project. It looks a bit like a nineteen-twenties cloche hat. Under the cloche is the lightweight carbon-fibre spaceframe, with the water-filled sphere on top, much like a high-tech water tower. The real DART will be about 1.30 metres in diameter and height, and will weigh about 150 kg. In its nose it will hold 10 litres of water, with another two litres in the porous panels.

Pure coincidence
A few years ago, esa launched a project for the development of a new generation of launch vehicles for Ariane 5. The emphasis of this Future Launches Technology Program (fltp) is on improved efficiency and cost reduction. It will be like a Space Shuttle, but without the excessively expensive heat shield maintenance.

Computer simulation of the temperatures without taking into account the chemical reactions that will occur in reality. The omission of the chemical reactions results in substantially higher temperatures (3 times as high).

Computer simulation of the chemical reaction around the capsule upon re-entry into the atmosphere. Chemical reactions occur where atomic nitrogen is present.

The cooling water tank and the porous, water-absorbent layer can be seen under the outer (metal) skin of Revolution.
Van Baten: ‘That programme lacks exactly the step we have defined with DART. It’s pure coincidence — we weren’t to know. Until then we thought of it purely as a demonstration model.’

In February of this year, esa completed a preliminary study for a small reusable re-entry vehicle with exactly the same mission definition as for DART. The conclusion is that DART is a very good and feasible design, both regarding shape and ballistics. Even so, Jean Muylaert of estec already has a different shape in mind, a rounded square-section pyramid shape called kheops. It also has a spherical nose and a body partly clad with «hot metals» (PM1000). However, the vehicle’s aerodynamics are much more complex than DART’s (which is rotation-symmetrical), it costs five to ten times as much, requires more effort to develop, but will yield much more flight data. In addition, on its sides it carries (fixed) flaps that further complicate the flow patterns, the aerodynamics of which Muylaert is keen to study. The different shape doesn’t bother the Delft researchers as much as the fact that for the time being, estec are planning to fly the vehicle without their novel cooling technology. Van Baten is convinced that kheops too will need the extra safety margin afforded by the water cooling system. During the first test, kheops will even fly at reduced speed — less friction so less heat — to see how the spacecraft stands up to the treatment. This can be done by selecting a launch pattern that will limit the re-entry velocity. If all goes well the first time, the speed can be increased with the second launch.

**Threat**

The Dutch government has currently pledged 3 million euro for the first year.

Van Baten: ‘I’m hoping that TU Delft will receive one half to one million of that to fund our activities, i.e. the hot-metal tests and thermal structure calculations. Our aerodynamics group is also participating, verifying simulation codes against the flight data of a real flight, and Control & Simulation will probably be involved as well.’

Although the money is not to be spurned, the real point is to keep the faculty involved in such an innovative project, to showcase the available know-how and to demonstrate its practical application.

‘I still have a strong preference for DART,’ Van Baten says, ‘not just because of our cooling system, but also because of its simpler shape. DART is much cheaper to manufacture, and that leaves less opportunity for errors. The behaviour of kheops is extremely difficult to predict, particularly since the pyramid shape is more prone to instability. Whatever happens, we will continue our research on DART, although I doubt that DART will actually be launched.’

In fact, the original Delft project is about to be scuppered by the European plans. After all, it will be very difficult to find funding for DART if the Netherlands are already putting up money for kheops. This makes it all the more important to ensure that the head start Delft has in this field is shown to full advantage in a European context. esa are planning to

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*Sketch showing the water cooling concept for the DART capsule. The heat load on the nose of the vehicle brings the water to the boil. The resulting water vapour (carrying the heat) is drained off. In this way, the boiling water holds down the temperature of the metal skin. The original idea came from Fokker Space.*

*Section through the setup used to test the DART cooling system. These tests, to be carried out at the German aerospace laboratory in Cologne, will have to demonstrate the feasibility of the method.*
launch at least three test flights. The tests may well result in a decision to use water cooling after all. Deep in his heart, Van Baten cannot help hoping that kheops will not be able to do without the Delft cooling system.

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A second cooling concept (patented by TU Delft) uses a porous, water-saturated layer. The water-saturated layer is placed a small distance from the outer skin. The outer skin radiates heat to the porous layer, where the heat evaporates the water into water vapour, which is drained off, carrying the heat with it, thus lowering the temperature of the outer skin.

Holder with 2 PM1000 test samples, one of which is cooled.
Setup used to test the effect of the porous and water-carrying ZAL15 material at high temperatures. Using fourteen quartz lamps with a total power consumption of 35 kW, it simulates the temperatures that occur during re-entry into the earth’s atmosphere as the result of heat generated by friction as air flows along the skin.

The test are done up to a temperature of about 1300 degree Celsius.

Simulated temperature progress during re-entry of DART. The lower plot represents the water-cooled option. The results closely match the expectations of Buursink and Van Baten.
X-33 is a scale model (approximately 60–70% of actual size) of a proposed reusable launcher that was to combine a large number of technologies to carry out test flights at hypersonic speeds (Mach 10–15). A large part of the outer skin is clad with a metal heat shield, like the DART vehicle. Technical complications resulted in long delays, and the X-33 project was cancelled early in 2001.