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Physics and the Dambusters

Arthur Stinner

The story of an engineer seeing an idea come to fruition against great odds. High-grade scientific research is combined with high adventure. This provides a context that generates challenging problems for physics students.

The story of the Dambusters has captured the imagination of every generation since the Second World War. We remember the picture of the Lancaster bombers flying low above the water at night to drop barrel-shaped bombs, spinning and then bouncing on the surface, and hurtling inexorably toward their target. The successful attack on the great dams of Germany dominated the news everywhere on that day in May 1943.

Behind the extraordinary human effort of cooperation and heroism, however, there is another story. This is the story of an applied scientist seeing a plausible idea coming to fruition against seemingly insurmountable odds. It admirably illustrates the relationship between theoretical science (in this case physics) and technology and contains many of the ingredients of high-grade scientific research. It also shows that scientific research cannot be captured by a clearly specifiable 'scientific method', as science texts claim it can. Rather, it must be understood as part of a social and political context and seen as governed by human imagination, perseverance and plain good luck.

The story of the research that preceded the famous raid is briefly reconstructed here and an attempt is made to actively involve the scientifically inclined reader. In fact, this is an example of a *large context problem* that the author is using to teach physics. This type of investigation is especially suitable for GCSE and A-level students.

All information used is based on the well known 1954 movie *The Dambusters* (with Richard Todd as Guy Gibson and Michael Redgrave as Dr Barnes Wallis) *and* on the popular book of the same title written by Paul Brickhill, first published in 1951. The headings were chosen from the dialogue in the movie.

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'What can I do to shorten the war?'

Barnes Wallis had been working at Vickers–Armstrong as an aircraft structural engineer since before the First World War. In the 1920s he designed the R100, the most successful British airship, and in the 1930s he invented the geodetic form of aircraft construction, which resulted in the building of the Wellington bomber. At the outbreak of the war he decided to investigate the construction and deployment of super-bombs that could destroy large and significant targets such as the great dams of the Ruhr in Germany, with minimal damage to people. The destructiveness of such bombs, he reasoned, would be due not only to their size but also to their proximity to the dam. When they exploded close to a dam they should produce very powerful shock waves that travelled through the concrete. Wallis came to this conclusion when remembering something he read about the shattering of concrete piles driven into the bed of the Thames during the construction of Waterloo Bridge. In an engineering journal of 1935 he found the article that described the formation of shock waves in concrete. It seemed that the sudden blow produced by the large hammers sent shock waves down the piles, and part of the energy was then reflected upon encountering the ground, another solid medium. The reflected shock wave, travelling at an estimated 5000 metres per second, always reached the top before the hammer could strike again. Since the shock waves passed into an 'empty' medium the effect was one of tension on the concrete. Concrete, however, is very resistant to compression, but not to tension. The piles therefore shattered. Wallis extrapolated from these known facts to a bomb exploding under water near a large dam. He thought that a large bomb dropped from a great height could destroy the dam as long as it dropped to a depth of about 15 m close to the dam. Shockwaves would do the rest.

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'Only a question of working it out paper'

Such bombs, he calculated, would need a mass of at least 10 tonnes. Furthermore, they would have to be carried by a 50 tonne bomber at 140 m s^{-1} (320 mph) and at a height of 14 km! Wallis knew that both the bomb and the aircraft could be built with the technology of 1940, so he wrote up a proposal for the committee appointed to evaluate his idea. This proposal would have been filed under what the Air Force called 'revolutionary, complicated and crackpot theory' if it had not been for Wallis's reputation and one man, Arthur Tedder, then an air vice-marshal, who believed in the idea.

Wallis was now given the resources to build a model dam to test out his ideas. He built a scale model of one-fiftieth the size of the Möhne, the largest of the German dams, with tiny cubes of concrete, scale models of huge masonry blocks that were part of the structure of the dam. Wallis exploded a few ounces ($\sim$100 g) of gelignite under the water 1.2 m from the wall to give the effect of a 10 tonne bomb exploding about 60 m away from the real dam. The effect was less than spectacular, so he moved the explosive to 0.9 m and then 0.6 m. Still there was no damage to the wall. Then he placed the gelignite a distance of 0.3 m from the wall (equivalent to placing a 10 tonne bomb 15 m from the Möhne), but even then there were only minor cracks. He tried larger charges, and finally about 150 g of the explosive 0.3 m away breached the model dam. He calculated that in the real case a charge of 13 tonnes at a distance of 15 m from the dam would breach it. A simple calculation showed that it would require 18 tonnes of steel casing, for a total of 31 tonnes! It was clear that the next meeting with the committee would be the last one.

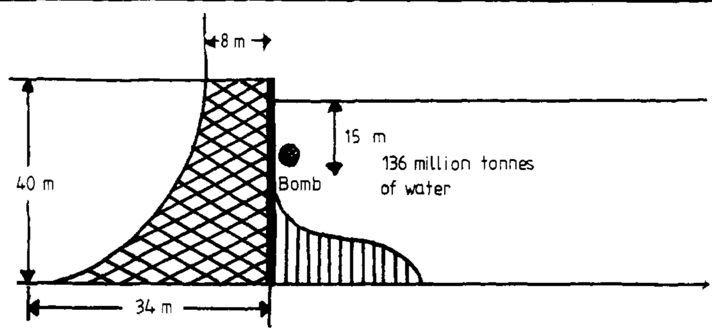


Figure 1. Möhne Dam.

Problem I

After working out many of his ideas on paper Wallis experimented on a model of the Möhne Dam. The model was scaled down to 1:50.

1. Find the dimensions of the model dam.
2. If the model had been built faithfully in all directions, how much water should it have been able to hold?
3. Compare the pressure at 15 m for the Möhne dam with the corresponding pressure for the model.
4. About 90 g of gelignite explosive under water and 1.2 m away from the model was sufficient to break the model. Based on that information alone Wallis claimed that about 10 tonnes of the same explosive under water, and at a distance of about 60 m, would breach the Möhne. Show that this is a good estimate.
5. Wallis then calculated that the steel casing for the sphere that could safely accommodate 10 tonnes of explosive should have a mass of 18 tonnes. The density of steel (iron) is about 7900 kg m^{-3} and the density of the explosive is about 800 kg m^{-3}. Now:

(*a*) determine the mean radius of the sphere;

(*b*) determine the approximate thickness of the shell;

(*c*) considering the dimensions and carrying capacity of a Lancaster bomber (see figure 2), comment on the possibility of accommodating such a bomb.

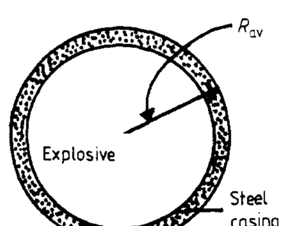


Figure 2. Initial design of the bomb.

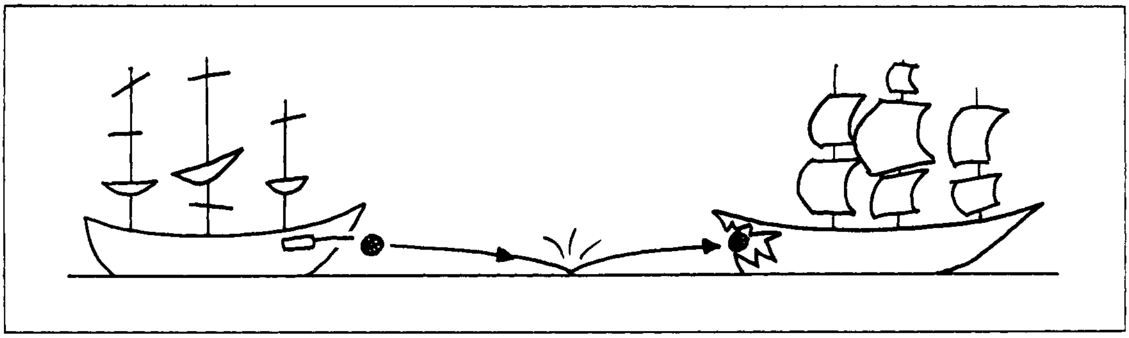


Figure 3. Nelson's skipping cannon balls.

'You can't hurry this kind of research'

The next time Wallis met his committee (now more appropriately called 'The Air Attack on Dams Committee', focusing the aim of the enterprise more definitely) he wanted to present them with a solution to the problem of placing a 5 tonne bomb under water close to the dam. The inspiration that led to a solution seems to have come from two sources: his experience as a father skipping stones with his children on water and remembering that Admiral Nelson occasionally had cannon balls ricochet on water for greater accuracy when engaged in a naval battle (figure 3). He now envisaged bombs skipping on water over torpedo nets, slithering to stop as they reached the wall of the dam. The bombs then would sink to a preset depth determined by a hydrostatic trigger that would set off a fuse.

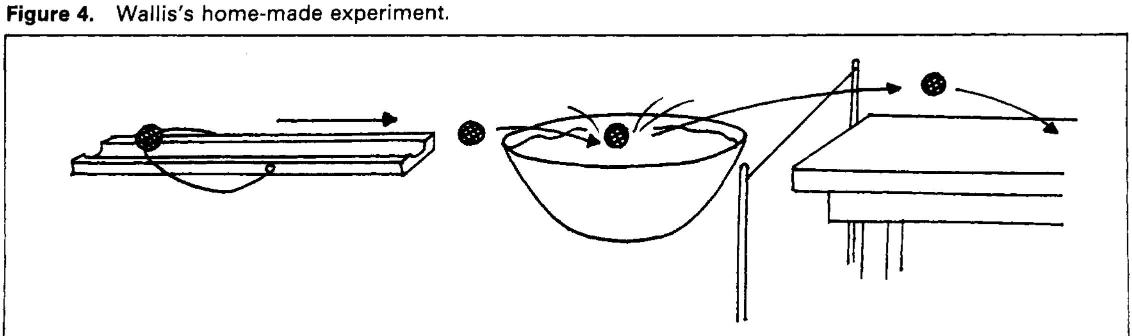
When pressed for the details of his 'theory', however, Wallis was reluctant to disclose how he thought the bombs should be released. One member of the committee spoke up for him, saving him the embarrassment of having to explain his not yet well formed idea: 'If I had a partly formed theory I certainly should not want to talk about it until it was clearly established in my own mind.'

In his garden in Dorset, Wallis promptly built a makeshift apparatus to test out his ideas of skipping a bomb on water. The simple apparatus consisted of a rubber catapult, placed a metre or so away from a tub full of water, just a few centimetres above the water level. He stretched a string (attached to two sticks) about a metre on the other side of the tub so that the string was also just above the level of the water (figure 4).

Wallis borrowed a marble from his daughter and shot it from the catapult at the water. His children assisted him in making measurements and generally amused themselves with this strange game. He decided that, indeed, it was possible to control one skip, but could one control many skips?

In order to answer that question, clearly a larger tank was needed with more facilities, including an underwater camera. Before 'The Air Attack on Dams Committee' granted him permission to use the huge ship-testing tank at Teddington, however, he had to convince the members that small charges of gelignite placed under water *against* the wall would breach it. A new model dam was built for him and he convinced the members of the feasibility of his plan when only a hundred grams or so of the explosive so placed breached the wall time after time. With this new knowledge he was able to cut down the required theoretical mass of the bomb to a manageable 4.3 tonnes consisting of 2.7 tonnes of

Figure 4. Wallis's home-made experiment.



Problem II

1. When Wallis discovered that he needed only about 2.7 tonnes of explosives to do the job, the prospects of building a spherical bomb that could be accommodated brightened. Calculate the average radius of the bomb.

2. The force of impact (average force) of such a bomb on water after falling from a height of 75 m is enormous.

(*a*) First, find the speed of impact, assuming that air resistance is negligible.

(*b*) Then calculate the average force of impact of the sphere if it sinks to a depth of 3/4 of its diameter.

3. What is the buoyant force on the sphere at the moment of maximum immersion?

4. Now find the impact force for a drop from 18 m. Assume that in this case the bomb sinks to a depth of 3/8 of the diameter. How do the forces compare? Comment.

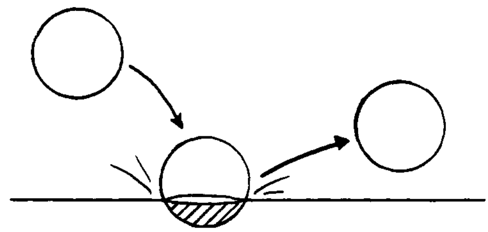


Figure 5. Spherical bombs skipping over water.

Problem III

1. All of us have tried skipping stones on water. What is surprising is that the physics of a skipping stone is not well understood. In the August 1968 issue of the *Scientific American*, for example, a large section of the regular feature 'The Amateur Scientist' was devoted to convincing the reader of just that. It showed, among other unexpected findings, that the stone does not bounce along the water in a series of successively shorter leaps until it finally stops, as one would expect. Rather, the stone may skip a short distance first and then skip a much longer distance. Wallis discovered that even with a perfectly spherical object like a golfball you do not get this expected trajectory of successively diminishing bounces because of the spin imparted to the ball on contact with the water. Look up the article in the *Scientific American* and study it—you may be the first one to find a solution to this puzzling problem. If you do, please contact the author of this article!

2. Using a tennis ball we can investigate the trajectory of a ball bouncing at a high horizontal speed. Ideally one should have access to a 'gun' like those tennis coaches use. Failing that, rig up a simple sling shot (or catapult) of the type Wallis put together. You could, of course, simply throw the ball horizontally. Use a large area (like the floor of a school gymnasium) and observe the motion of the tennis ball. With the aid of several friends you could mark the places where the ball bounces. Note, for example, what kind of spin is imparted to the ball on contact.

Now consider the following problems.

3. A tennis ball is projected horizontally from a catapult at a height of 1.00 m. The first contact is made at a distance of 5.25 m. Assume that the ball bounces back to 50% of its previous height upon each impact.

(*a*) Predict the bouncing distances d_1, d_2, d_3 . . . .

(*b*) What should be the speed of the ball so that it would land at a spot 20 m away?

(*c*) Write down an equation that relates total distance d, number of bounces n and the initial speed v_{in} for this ideal situation.

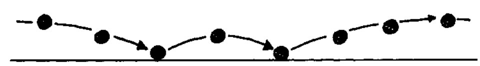


Figure 6. A skipping stone.

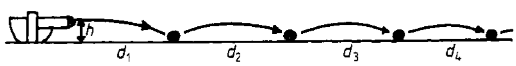


Figure 7. Idealised trajectory of a tennis ball.

4. According to this simple model of a ball projected horizontally over a level surface the horizontal component of the velocity stays constant. The bouncing ball's velocity must, of course, also diminish. Now account for a progressive reduction of velocity as well. Consider the above problem if the reduction of the horizontal velocity is to 80% after each contact point.

In reality, however, one should also try to account for the spin of the ball, a difficult problem to solve. Jearl Walker (1985), for example, claims that a ball projected without spin will bounce as shown in figure 8. Test this claim. How would you give this kind of trajectory a mathematical description?

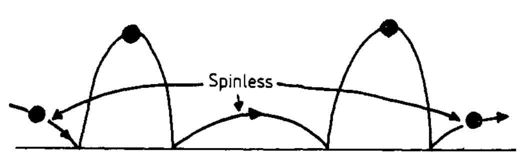


Figure 8. Trajectory of a tennis ball?

RDX explosive and a case 1.6 tonnes. Permission was now granted to use the large tank at Teddington.

The experiments at Teddington were begun and continued for five months, much to the displeasure of the committee. The objective was to control a skipping missile, to find out how speed, height of launching, number of bounces and the desired distance were related. Wallis first thought that the missile should be spherical so that identical contact-area hits would be guaranteed. But it soon became obvious that the bounces were too often unpredictable, even though he used larger spheres, first golf balls and then 1 kg spheres of steel. It took some time but he found the answer: the first bounce gave the sphere a top-spin and that is why the golf balls tended to dig themselves into the water. Would flat discs be preferable? The answer was a clear no, as anyone who has carefully observed the skipping of stones on water or sand would agree. Wallis now rigged up a cradle for the spring-loaded catapult that would give the missiles a pronounced back-spin. The back-spin not only allowed him to control the distance but provided him with a serendipitous effect: the residual back-spin toward the end of the run made the sphere go under the water at the far end. This was exactly what he wanted! At this point in the movie we hear him say to one committee member: 'There is a fine dividing line between inspiration and obsession . . . it is sometimes very hard to know which side you are on'. And a little later he says: 'One goes on and on . . . as if against a brick wall, then suddenly a light flashes.'

'Just when you think you have solved a problem . . .'

The size of the sphere required to carry the RDX explosive, however, turned out to be unmanageably large. The steel case had to be strong enough to withstand the impact with water at well over $90\,\mathrm{m\,s^{-1}}$ (200 mph). It was evident that even if the monstrous spherical bomb could be attached to the Lancaster, the aircraft could not be moved without the danger of risking collapse before take-off! What he needed was a different shape that would be large enough and make contact with water on identical surface areas. A large cylinder would do it, providing that it did not tilt during the trajectory. How do you prevent a cylinder from tilting? By making it spin, of course! He knew, for example, that it took a considerable force to tilt a spinning bicycle wheel. The same gyroscopic principles must apply to a spinning cylinder. The answer was now clear: shape a missile like a portly barrel with sufficient back-spin to keep it gyroscopically on a level axis all the way to the end of the trajectory.

The theory was tested with model barrels using various weight/size ratios to make sure that the real bomb could be carried under a Lancaster. By trial and error he found the speed necessary for each model to traverse the required distance. The spin of the barrel was also found by trial and error and was shown to be between 450 and 500 revolutions per minute backwards. Would a full-size bomb behave as the theory and the scaled-down experiments predicted? Wallis was convinced it would work. However, only after weeks of anxious waiting and arguing with various members of the Ministry of Supplies did he receive the services of one Wellington bomber.

The new bomb was tested as soon as the

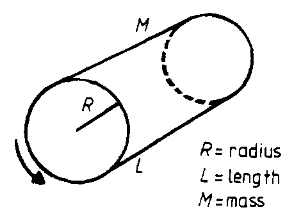


Figure 9. Cylindrical bombs.

Problem IV

A spinning top, a bicycle wheel and a spinning cylindrical barrel are very stable. Wallis designed the barrel so that it could withstand a spin of up to 500 revolutions per minute. The high rotation was used to fulfil two requirements: to give the bomb stability throughout the trajectory, and to make sure that a little spin was left over when it hit the dam. The length of the cylindrical bomb was about 2.1 m, the mass of the RDX explosive 2.7 tonnes and the mass of the case 1.6 tonnes.

1. Find the approximate diameter of the cylindrical bomb.

2. You probably know what happens when, sitting on a rotating piano stool, you attempt to twist a spinning bicycle wheel.

(*a*) From this knowledge extrapolate to the stability (the bomb's tendency to maintain its direction) of a rapidly spinning cylindrical bomb.

(*b*) Speculate on how carrying a spinning cylinder of this size must have affected the stability of the aircraft in flight.

(*c*) How, do you think, did the releasing of the spinning bomb affect the stability of the flight?

3. The centripetal forces are very large at these high rotational speeds and they must be known to ensure the safety of the structure of the casing. Calculate the maximum centripetal force on the rim of the spinning cylinder. Express this value in terms of *g*, *the acceleration due to gravity*.

4. The energy required to make the large cylinder rotate at 480 revolutions per minute is very large. Calculate this energy. Consider the mass of the cylinder to be evenly distributed.

Wellington was converted. The impact, however, damaged the bomb and the trajectory went array. The casing was strengthened, but from a height of 45 m the bombs still shattered. Finally, in desperation he asked Wing Commander Guy Gibson, the leader of Squadron 617 (later called the 'Dambusters') to try flying at an altitude of 18 m. He was sure that at that height the bomb would not shatter. After weeks of practising flying at that altitude Gibson was satisfied that it was safe (at least during the day) and they made a trial drop. The bomb performed perfectly. Wallis was happy.

Plywood bombsights and steel spotlights

There were still two small problems to be solved before an actual attack could be made. One had to do with keeping the aircraft at the correct height to within a metre. The other problem was connected with the need to drop the bomb at a certain distance in front of the dam. Gibson suggested that they dangle a wire with a weight on it from the aircraft so that it would touch the water at the correct height. They tried it, but at the required speed the line was trailing behind almost horizontally!

The solution came a little later, an idea attributed to the 'back-room' boys. It was a simple idea but very effective: put a spotlight under the nose and another one under the belly of the aircraft, both pointing down, adjusted so that the lights would meet in a figure 8 at the preset height (figure 10).

The solution to the second problem was equally simple. It seems that a carpenter put it together in minutes out of bits of spare wood (figure 11). The base was a triangle made of plywood with a small opening to look through and two nails hammered partially in the other corners. The idea was to look through the small opening and when the two towers on the dams were in line with the nails the bomber would press the release button. Assuming that both the speed and the height were correct the bomb should follow the expected trajectory.

Wallis's last task was to work out the final speed, altitude and dropping-range. He decided on $100\ \mathrm{m\ s^{-1}}$ (230 mph), 18 m and 550 m, respectively. Practice runs were made by Gibson and his crew on nearby lakes, during the day and at night, using the plywood bombsights and the steel spotlights. Their accuracy improved until they were able to drop the bombs consistently within metres of the target. Squadron 617 was ready for the raid on the dams of the Ruhr. On 17 May 1943 the mission was carried out successfully, inflicting a significant blow to the German war machine.

The successful raid on the dams of Germany is

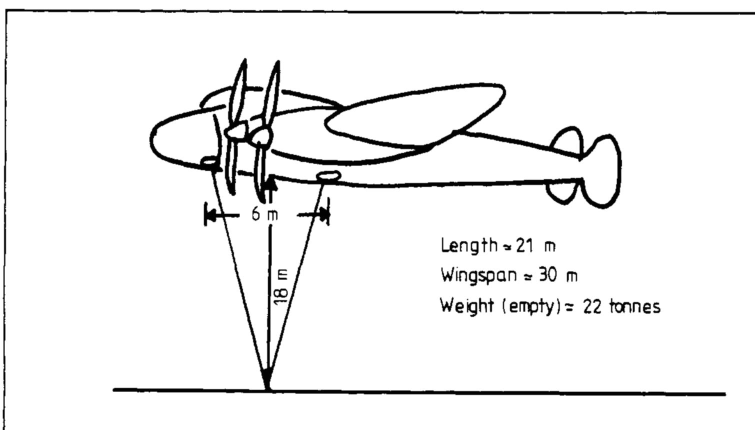


Figure 10. Lancaster bomber.

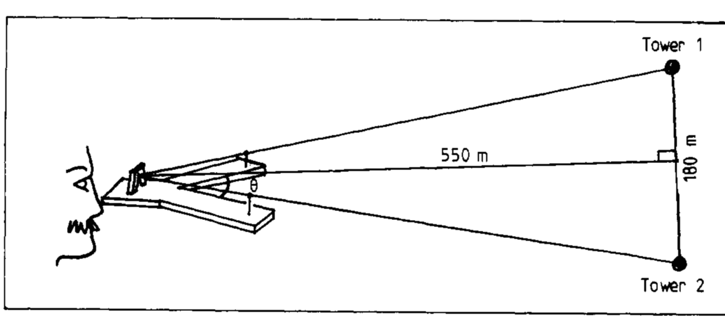


Figure 11. Plywood bombsights.

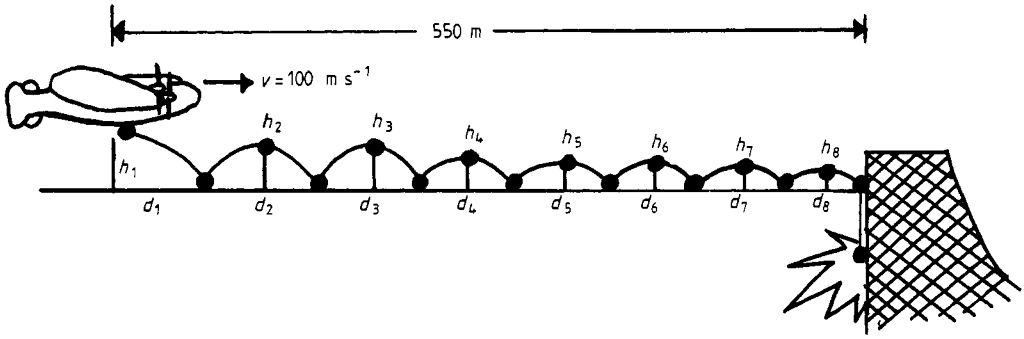


Figure 12. Idealised bomb trajectory.

Problem V

Just before the raid Wallis gave the following crucial data to Squadron 617: horizontal velocity 100 m s^{-1}; height, 18 m; dropping-range, 550 m. He had faith in the reliability of the hand-made bombsight to establish the dropping-range of 550 m and in the spotlights to guide the pilot at the height of 18 m.

The author has made some calculations on the assumption that about eight bounces were required to hit the dam. This assumption was based on the requirement that the speed of the bouncing bomb must be reduced to about 5 m s^{-1}. (At higher speeds we would risk the bomb's skipping over the dam.) By developing an equation on this assumption, it was found that if the height diminishes to about 90% of the previous height at each impact, and if the horizontal velocity decreases to about 70% of its previous value at each impact, then the bomb makes contact just before hitting the dam with a velocity of about 5 m s^{-1}. Remember, however, that our problem is still 'idealised'. We did not account for the effect of the spin on the cylindrical bombs.

1. Calculate the angle required for the bombsight to establish the range of 550 m.
2. Now decide at what angle of separation the spotlights must be placed if they are to come together at an altitude of 18 m. Consider them to be separated by 6 m.
3. Use all this information given and calculate, as for the case of the tennis ball, the last contact point and the speed of the bomb just before it hits the wall and submerges to the preset depth.
4. Now show that the equation that describes the above situation is as follows

$$R = 2(2hv_0/g)^{1/2}(\tfrac{1}{2} + a^{1/2}b + ab^2 + a^{3/2}b^3 + a^2b^4 + a^{5/2}b^5 + a^3b^6 + \ldots a^{7/2}b^7 + a^4b^8 + \ldots)$$

where a is the successive diminishing factor for height, $0<a<1$, b is the successive diminishing factor for the horizontal velocity, $0<b<1$, h is the height of launching, v_0 is the launching velocity (assumed not to diminish appreciably before first impact) and g is the acceleration due to gravity, taken as 10 m s^{-2}.

It is instructive to vary the values of a and b using a commonly available computer (the author used a Commodore 64) and see how you can fit the assigned range for a given number of bounces. You should find that if you let $a=0.9$ and $b=0.7$ you will get just about the right answer. Of course, we do not know what the correct values for a and b are. Only an actual scaled-down experiment would provide us with a clue as to what these should be for the real case.

Problem VI

The Möhne Dam had a capacity of 136 million tonnes of water. Assume that the dam was full before impact and that the surrounding area was flooded to an average height of about half a metre. Approximately what area did the flood cover?

one of the most celebrated military adventures of the Second World War. The idea and its implementation that led to the destruction of the dams came from the imagination and the determined effort of a gentle engineering genius. In the words of one of the committee members: 'He conceived something absolutely unheard-of and carried it through with flying colours.' The story of the Dambusters has been celebrated as a military adventure for a long time. It is time we celebrated with equal enthusiasm the story as an imaginative scientific adventure.

There is a sad postlude to this story. When Wallis heard of those who died as a result of this raid he was supposed to have said, with tears in his eyes: 'Oh, if I'd only known, I'd never have started this!'

Let us conclude with the following compilation of pithy statements made in the movie *The Dambusters*. Each of these relates to scientific research. Their thoughtful discussion in a classroom, for example after viewing the movie, can yield information and much clarification about the nature and the social impact of scientific research in general.

1. 'It is only a question of working it out on paper.'
2. 'You can't hurry this kind of research.'
3. 'There is a very thin dividing line between inspiration and obsession.'
4. He thought constantly about it.
5. That is exactly how a full-sized bomb would behave.
6. 'The idea came from Nelson.'
7. 'Everything depends on secrecy.'
8. It was absurd to think how simple it was.
9. 'Looks clever on paper but can you make it work?'
10. 'Did you invent this thing in your own head?'
11. 'One goes on and on . . . as if against a brick wall, then suddenly a light flashes.'
12. 'Do you mean that a 5 tonne bomb can bounce along like a ping-pong ball?'
13. 'If I'd only known, I'd never had started this!'

Acknowledgments

I wish to thank my wife Ann for preparing the sketches, my colleague John Gooderham for his helpful suggestions, and Scott Crawford, a student at Leaside High School, for assisting me with the solutions to the problems.

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ANSWERS TO PROBLEMS

Problem I

1. 80 cm, 16 cm, 68 cm.
2. about 1000 tonnes.
3. 1/ 50.
4. 1:50, $(50)^3 \times 90$ g $\simeq$ 10 tonnes.
5. (*a*) 1.45 m; (*b*) 9 cm;
   (*c*) bomb is too large and heavy.

Problem II

1. 93 cm.
2. (*a*) 38 m s^{-1}; (*b*) 6.5×10^6 N.
3. 35 900 N.
4. about the same as 2(*b*) above.

Problem III

3. (*a*) 5.25 m, 7.43 m, 5.25 m.
   (*b*) 10.5 m s^{-1}
   (*c*)

$$d = 5.25 + 2\,v_{in}\left(\sqrt{\frac{1}{2\times 5}} + \sqrt{\frac{1}{2^2\times 5}} + \ldots \sqrt{\frac{1}{2^n\times 5}}\right)$$

   until equality is reached.

4.

$$d = 5.25 + 2\,v_{in}\left(0.8\sqrt{\frac{1}{2\times 5}} + 0.8^2\sqrt{\frac{1}{2^2\times 5}} + \ldots 0.8^n\sqrt{\frac{1}{2^n\times 5}}\right)$$

   until equality is reached.

Problem IV

1. 1.4 m.
2. (*a*) very stable;
   (*b*) very stable, as long as straight flight is maintained;
   (*c*) less stable.
3. ~200 *g*.
4. 3×10^6 J.

Problem V

1. 19°.
2. 19°.
3. ~5 m s^{-1}, shortly after the eighth bounce.

Problem VI

272 km^2.