Somewhere About 12 Square Feet

By Samuel Halpern

Would you believe that a simple experiment using a milk container can lead to a result that enables us to estimate the overall damage produced by a ship striking an iceberg? This short article will show that to be the case. We will first look at how that famous 12 square feet of aggregate opening which described the extent of damage done to the *S.S. Titanic* came about. We will also see how a simple milk container can be used to visualize and quantify the flooding on the ship. We then will see how the equations and curves that describe the flooding of a simple milk container can be used to derive the same result obtained by naval architects from Harland and Wolff back in 1912. For those interested in seeing the details of the solution, an appendix is included that involves a little bit of high school algebra. This paper also considers the affect on the overall flooding rate of a ship steaming ahead slowly for a short period of time after sustaining initial damage to the bow. The results show that at low speed and short duration the additional flooding and imparted pressure might not be as severe as some people have suggested.

The Testimony of Edward Wilding

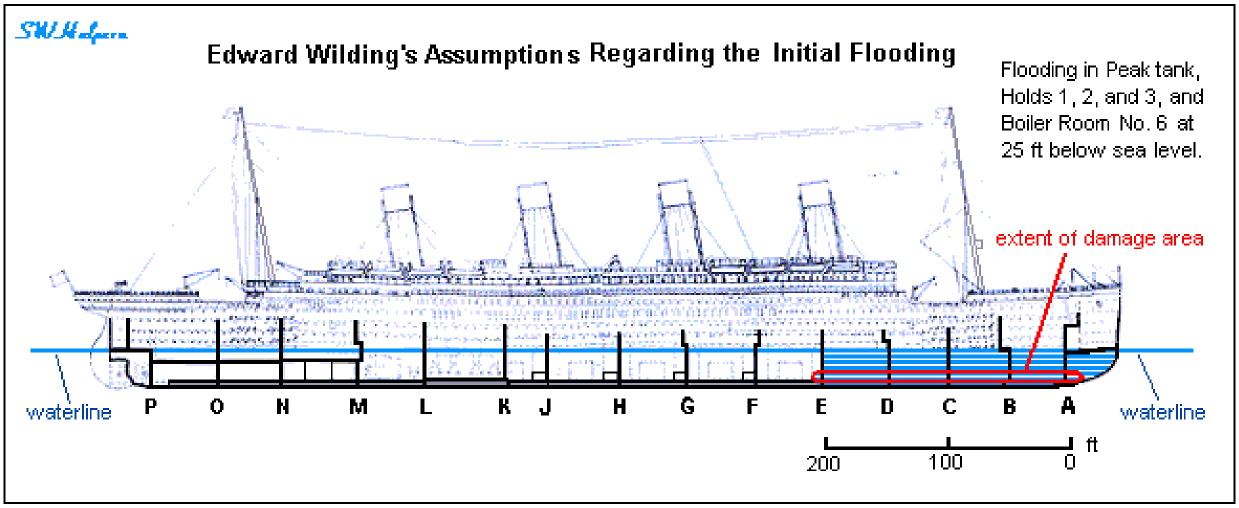
Edward Wilding, chief naval architect for Harland and Wolff, builders of the *Olympic* and *Titanic*, was called to testify as an expert witness on the 18th, 19th, and 20th days into the British Inquiry concerning the loss of the *RMS Titanic*. He was also recalled to testify as well on the 27th day. As an expert witness Wilding was questioned about various aspects related to the design, construction, and performance characteristics of the *Titanic*, as well as the effects of damage and flooding on the ship sinking. During his testimony the question came regarding the extent of damage caused by the collision with the iceberg. Based on calculations and diagrams made within the limits of hand calculations available to them, Wilding estimated that the iceberg produced an equivalent opening along the starboard side of 12 square feet that was spread across 5 major watertight compartments. It was as if the ship's side was cut open with a gash of only ¾ inches in width but extending for about 200 feet from just ahead of the collision bulkhead at the back of the peak tank forward to just abaft the bulkhead separating Boiler Room No. 6 from No. 5, the two most forward of *Titanic's* six boiler rooms. As Wilding explained to the at the Inquiry, the *Titanic* was designed to stay afloat with any two of her 16 watertight compartments open to the sea. She could even stay afloat with any three of the first 5 compartments open to the sea. Even if the first four compartments were open to the sea, it would remain afloat. However, it could not stay afloat with the first five watertight compartments opened to the sea. And in two hours and 40 minutes in the early morning hours of April 15, 1912, the *Titanic* had disappeared beneath the surface of the Atlantic.

So just how did Edward Wilding get to that famous 12 square feet of opening? Let's look at what he said before the British Inquiry (question 20422).

> *I referred this to this condition B on the plan I put in, and corresponding very nearly to condition D on the third plan. Assuming the forepeak and Nos. 1, 2 and 3 holds and No. 6 boiler room flooded, and that the water has risen to the waterline which is shown on those diagrams, it would mean that about 16,000 tons of water had found their way into the vessel. That is the volume of the water which would have to come in. As far as I can follow from the evidence, the water was up to that level in about 40 minutes. It may be a few minutes more or less, but that was the best estimate I could make. When the inflow started the evidence we have as to the vertical position of the damage indicated that the head would be about 25 feet. Of course, as the water rose inside, that head would be reduced and the rate of inflow would be reduced somewhat. Making allowance for those, my estimate for the size of the hole required (and making some allowance for the obstruction due to the presence of decks and other things), is that the total area through which water was entering the ship, was somewhere about 12 square feet. The extent of the damage fore and aft, that is from the foremost puncture to the aftermost puncture in the cross bunker at the forward end of No. 5 boiler room, is about 500* [SIC] *feet, and the average width of the hole extending the whole way is only about three-quarters of an inch. That was my reason for stating this morning that I believe it must have been in places, that is, not a continuous rip. A hole*

three-quarters of an inch wide and 200 feet long does not seem to describe to me the probable damage, but it must have averaged about that amount.

What Wilding was saying is that the average of the sum of all the openings to the sea was the *equivalent* of a gash about ¾ inch that extended for about 200 feet from just ahead of the watertight collision bulkhead at the aft end of the peak tank (bulkhead A) to just across the watertight bulkhead that separated Boiler Room No. 5 from Boiler Room No. 6 (bulkhead E). He was quite clear that the actual damage to the ship was not one continuous rip, but was made up of various punctures along the starboard side that totaled to about 12 square feet. As he was quick to clarify, the individual punctures along the side "can only have been a comparatively short length, the aggregate of the holes must have been somewhere about 12 square feet."

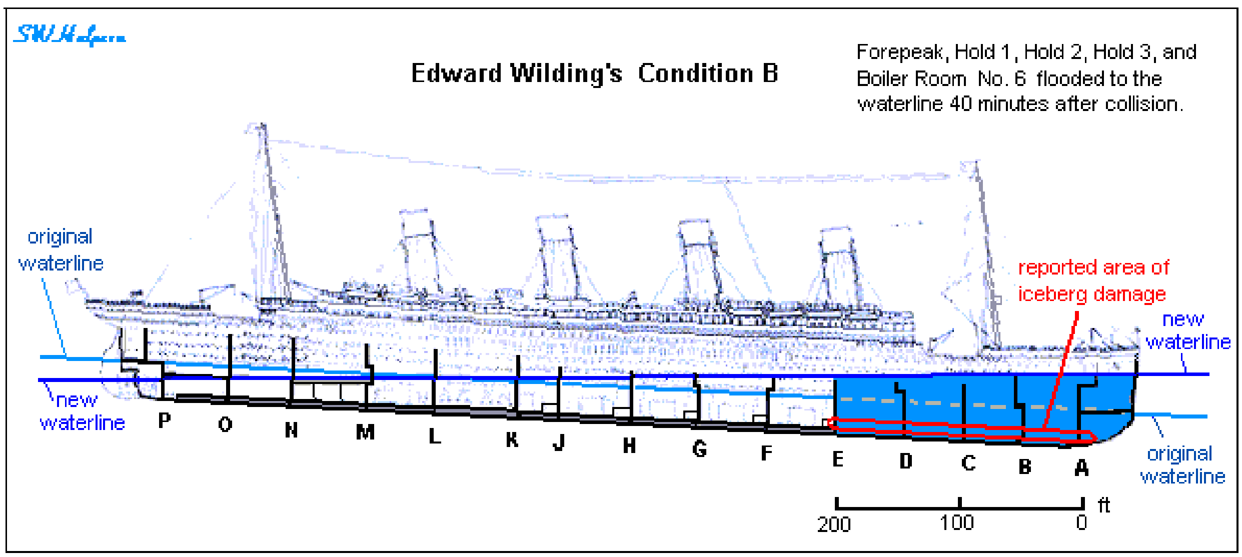


From his account we see that that several assumptions had gone into this estimate. The first is that the forepeak, cargo holds No. 1, 2, and 3, and the Boiler room No. 6 were flooding.[1] The second assumption is that water had risen to the waterline in about 40 minutes in all those 5 compartments. In this case Wilding knew that the flooding rate in each compartment was not the same. However, based on the what he had heard in evidence presented to that point, he assumed that the water would have reached the waterline in all of those compartments by about 40 minutes after the collision with some compartments having filled faster than others. Knowing the volumes of those compartments, and allowing for how much space was taken up by various obstructions in them, Wilding estimated that 16,000 long tons of sea water must have flooded into the ship by that time.

The other information needed to estimate the size of the aggregate opening is the pressure of the water at the depth that the damage took place. This information he obtained from the testimony of fireman Frederick Barrett who said that water came through the side of the ship about 2 feet above the stokehold plates in Boiler Room No. 6 and in the forward bunker space of Boiler Room No. 5.[2] The stokehold plates, the flooring that the firemen and trimmers walked on within the stokeholds, was a little over 2 feet above the ship's tank top, the top of *Titanic's* double bottom. The tank top itself was 5 feet above the keel, which in turn, was about 34 feet below the load waterline. So if we take 5 feet for the tank top, add 2 more feet for the stokehold plates, and then add 2 feet above that for where the water was seen coming into the ship, we find that the damage seen was 9 feet above the keel. Nine feet above a keel that itself was about 34 feet below the waterline means that the openings in the ship's hull were 25 feet below the surface of the sea. Thus Wilding assumed a 25 foot pressure head for the initial water inflow.

Now it should be pointed out that precision is not the objective in this particular exercise. By time the ship reached the region where the accident took place its draft had been reduced to a little over 32 feet because of the consumption of coal, water and stores on board. However, for this particular problem, which is only an estimate anyway, it appears that Wilding was not too concerned with being very precise in calculating the pressure head given the uncertainty in some of the other parameters involved. So working off a draft of about 34 feet to get to a pressure head of 25 feet is good enough. The other assumption that was taken is that the damage to the other compartments took place at the same height above the keel as that seen in the boiler rooms. Since there was no other visual evidence to say otherwise, this was a reasonable assumption for him to make as he had stated.

The other references he talked about in his statement above were conditions B and D that he had submitted earlier to the Inquiry. Condition B was a profile view of the ship which showed the effect of flooding the fore peak, the 3 cargo holds forward, and Boiler Room No. 6, the condition on which his calculation was based on. In this case the water level in the second compartment, Hold No. 1, would be over the top of the collision bulkhead A (which was watertight up to Saloon deck D) thus flooding the entire first compartment, the forepeak, even though the initial damage in that compartment was constrained to the forepeak tank just below the original waterline. In addition, the water level aft would rise to slightly above the top of watertight bulkhead E which separated boiler room No. 5 from No. 6. Even if no other damage was sustained, such as stress induced opens in hull plates and bulkheads, the loss of the ship was now inevitable. It should be pointed out that the height of bulkhead E was carried up to the Upper deck E which was about 11 feet above the load waterline in the undamaged condition.



In condition D, Wilding showed what the situation would be with respect to the waterline if not only the first five compartments were flooded but also if there were some significant flooding in Boiler Room No. 5 and some minor flooding in Boiler Room No. 4 as reported later on by several eye witnesses. He presented this to at the Inquiry only to show that even if the watertight bulkheads had been extended up to the Saloon deck D, the ship would still be lost even with no flooding in Boiler Room No. 4. If the watertight bulkheads were carried up to the Shelter deck C, and if the pumps could not keep ahead of the flooding that developed in Boiler Room No. 4, the ship would still be lost.

Some addition insight as to how Wilding came up with 12 square feet of aggregate damage came out in his disposition taken at the Limitation of Liability Hearings in New York on May 13 and 14, 1915.

> *It was known that certain spaces were filled up in a certain number of minutes, approximately. You couldn't say to a stop watch, but in about 40 minutes certain compartments forward were filled up to a certain level. The capacity of those compartments was known, and therefore the amount of water which got in, in the 40 minutes was known. The approximate depth of the position of the damage was known and it was then possible to calculate the rate of inflow per square foot of opening. I have the total inflow and I can divide that by the number of minutes and get the total inflow per minute. I can get the inflow per square foot per minute, and by dividing the one by the other I can get the square feet…My memory is 12 square feet; 4 feet by 3...For your*

information, the accuracy of that is probably one quarter either way; that is, it is more than 9 and less than 15, and 12 is the most probable.

Wilding was further questioned concerning the various assumptions and method used in the flooding analysis.

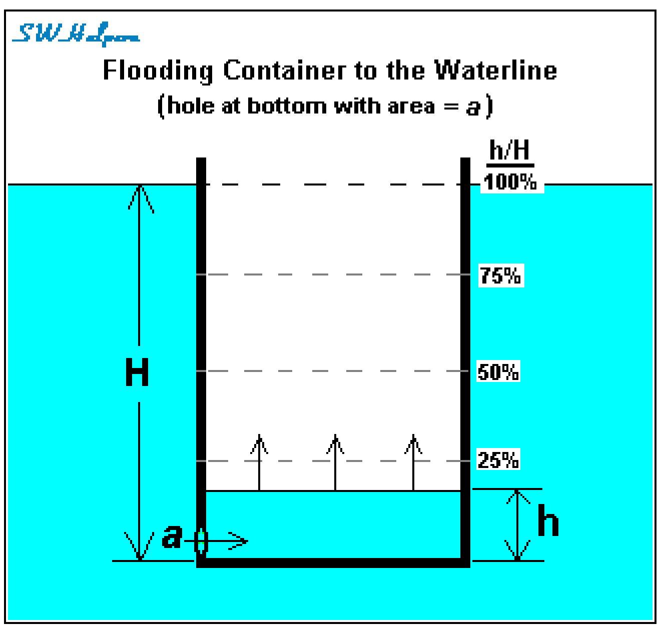
Q. In making that calculation as to the flooding plan, what factor of permeability did you allow?
A. A factor in the coal bunkers of 50 per cent and in the cargo holds of 75 per cent; in the mail and baggage rooms of 83-1/3 per cent; in the engine and boiler spaces 80 per cent; in the passenger accommodation 95 per cent.

Q. Was due consideration given to the loss of water plane?
A. Certainly; the calculations were made by what is known as the Bonjean Curve method, the direct method; he, Bonjean was a French mathematician of about 1790.

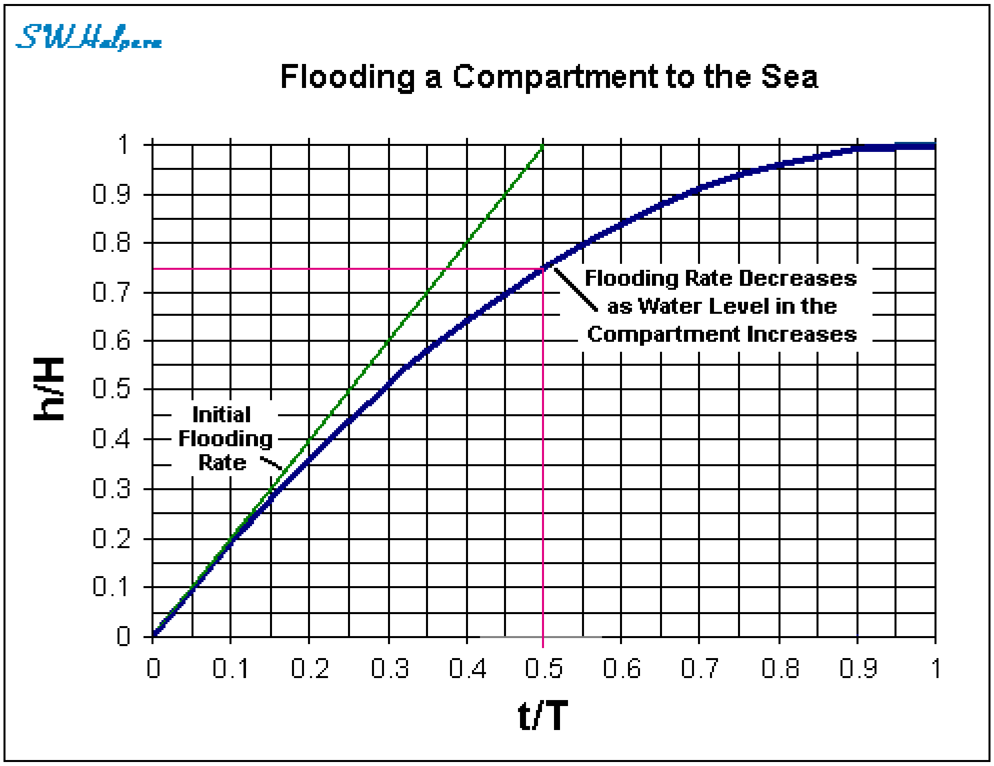
So with all of this information is there some way we can easily derive an approximation for the total equivalent area of all the openings based on the information that was given without resorting to Bonjean curves, specific compartment permeability, or other such specific details? The answer to this question is yes.

Flooding a Milk Container

To derive the answer we are looking for we need to do a little experiment with a tall container of constant horizontal cross-section.[3] What we do is take the container and puncture a small hole on its side near the bottom. We will then hold the container near its top and quickly push it down into a large basin filled with water with only the very top held above the waterline level of the basin. We now will watch as the container floods with water through the hole we made, and note the time it takes for the container to flood to certain levels as it floods up to the waterline of the basin. The picture of this simple experiment is shown below.



What we will find is that the rate at which the container fills with water is not linear. At first is fills quite rapidly. But as the water rises higher in the flooding container the rate at which it is rising starts to slow down. In fact we can quantify this by noting the time it takes to fill the container to certain levels. If we then plot out our results we will get a curve that matches the following diagram.



This diagram is what is called a normalized plot. The vertical height axis is a measure of the height of water in the container (h) divided by the depth of the hole at the bottom of the container (H) below the waterline. The time axis is also a normalized value. It is a measure of the time (t) to reach a certain normalized height (h/H) divided by the time (T) for the water to finally reach the water line. What we see is that the container will flood half way to the waterline in just under 30% of the time it takes to flood all the way to the top. We also see that the water in the container will flood to a height of 75% of the waterline in exactly one-half the time it takes to flood up to the top.

For example, suppose you had a rectangular milk container and punched a hole near its bottom with a pencil and then quickly placed it in a large, deep basin filled with water such that the bottom of the container was 20 cm below the waterline. And suppose that when the container filled to that waterline it held 1 liter of water. If you then measure the time it takes to flood the container to certain levels, you should see results that follow the curve above. So suppose in your experiment you measure the time it takes the water to reach the 10 cm mark at just under 12 seconds. What you will then see is that the water will reach the 15 cm mark by 20 seconds, and then reach the 20 cm waterline mark at 40 seconds. Of course the actual time that you yourself will measure will depend on two things, the first is the size of the hole that is punctured at the bottom, and the second is the cross-sectional area of the container that you actually use. The larger the hole, the faster the container will fill. The larger the cross-sectional area, the larger its volume, and the longer the container will take to fill.

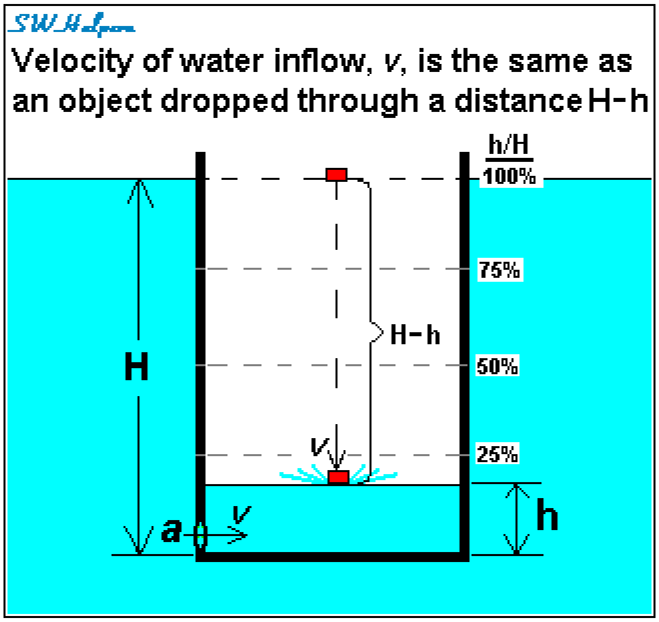
So how we go from here to get the size of the aggregate opening that damaged the *Titanic?* As it turns out we need to find the flooding rate. The equation that gives us the flooding rate for a milk container also works for a flooding compartment in a ship. When you first put the container into the basin there was no water inside. But on the outside of the container there was water under a pressure of say 20 cm at the depth of the hole. Thus the container starts to flood at time 0 with water pouring in under that pressure though the area of the hole that we punched. It is rising at its maximum rate at that point. At some time *T*, the water level inside the container is no longer because it has reached the waterline of the basin and there is no tendency for water to flow in or out. In the example we used above, where *H* was 20 cm and *T* was 40 seconds, the initial rate of water rising in the container turns out to be 1 cm/sec. (See Appendix-A for details.)

If we were to fill the same container from the top (with no hole at the bottom) at the same initial flooding rate as when the flooding started, we would find that the container would fill in one-half the time (or 20 seconds in our example). This can be seen by the curve marked ‘Initial Flooding Rate’ in the diagram above. The reason why the flooding rate slows down for a container flooding from the bottom up is because the water inside the container is creating a pressure that works against the outside pressure as the water level inside the container gets higher and higher. Of course when the inside water level reaches the waterline, the inside pressure must equal the outside pressure and therefore no more water can enter the container. In other words the flooding stops when the container is full to the waterline.

To get to the size of the area, *a*, of the hole at the bottom of the container we still need a little more help. This comes from a Dutch-born member of a Swiss mathematical family, Daniel Bernoulli, who’s most important work considered the basic properties of fluid flow, pressure, density and velocity. In his famous contribution known as the Bernoulli principle, he shows that the total pressure in a fluid must be a constant. It is the sum of what is called the static pressure plus the dynamic pressure. The static pressure is the pressure of water that is not moving. Dynamic pressure is the pressure due to movement, the same pressure that is felt if you put your hand outside the window of a fast moving vehicle. Outside our small container at the depth of the hole and some distance away we have only the static pressure of the water at a depth 20 cm below the surface. The dynamic pressure is 0 because there is essentially no water movement. On the inside of our container there is only the pressure of the atmosphere when the flooding first starts at $t=0$ because there is no water inside the container to offset the pressure on the outside. However, we do have dynamic pressure on the inside caused by water rushing into the vessel through the hole. As the water level inside rises we will get both static pressure and dynamic pressure. The rising water inside the container creates an offsetting pressure to that on the outside, at the same time that we have dynamic pressure caused by the continued inflow of water through the hole.

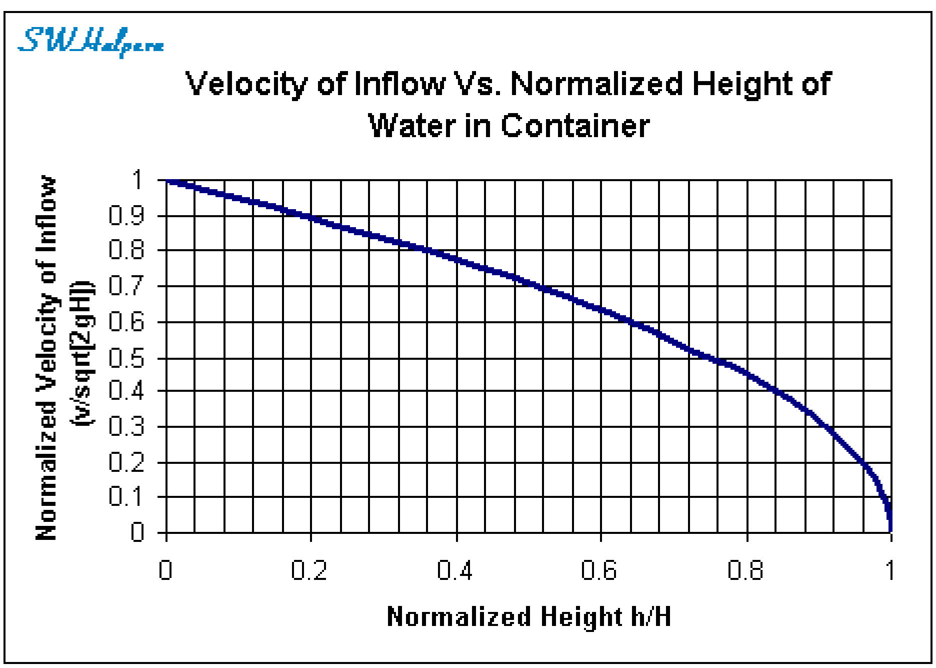
So what is the speed of that rushing water entering our container? To get that answer we apply Bernoulli’s equation which equates total pressure outside to total pressure inside. What we find is that at any point in time the outside pressure due to the depth of water beneath the surface, the static pressure, must equal the sum of the inside static pressure due to the depth of water in the container ***plus*** the dynamic pressure caused by the inflow. We can then solve Bernoulli’s equation to find the inflow velocity of the water coming through the opening.

The surprising result of solving Bernoulli’s equation is that the inflow velocity at any point in time turns out to be exactly the same as that reached by an object that is dropped from the level of the waterline to the level of the water surface inside the container at that point in time. This is seen in the following diagram.



Now at *t=0*, the inside height of water, *h*, is zero, and the inflow velocity must be at its maximum since there is nothing to oppose the inflow rate. This velocity is exactly the same as dropping an object into the empty container from a height of H above the bottom. As the container fills with water the inflow velocity depends only on the height of the remaining unflooded portion of the container. When the water inside finally reaches the waterline of the basin, the velocity of inflow becomes zero. In other words, the container is full and flooding ceases.

This variation of inflow velocity with the height of water inside the container can be seen in the diagram below. This diagram plots the inflow velocity as a function of the normalized height of water inside the container (h/H). The inflow velocity is normalized by dividing by the maximum inflow velocity which occurs when the flooding started with no water in the container.



So how do we get the area of the hole opening through which this water is flowing? We all know that length multiplied by area is volume. So a change in length per unit of time, which is velocity, when multiplied by area must be the change in volume per unit of time. If we therefore multiply the initial entry velocity of the water, *v*, by the *equivalent* cross-sectional area of the opening, *a*, we get the initial volume of water per second entering the container at *t=0*. But this *initial* entry volume rate is equal to the volume of the container divided by one-half the time it takes for the container to flood to the waterline as we have seen in the diagram that showed ‘Flooding a Compartment to the Sea.’ From this we can get a relatively simple expression (see Appendix-A) that gives us the area size of the opening in terms of other known quantities such as the volume of the compartment flooded to the waterline, the total time for the compartment to flood to the waterline, and the depth of the opening below the waterline. If we use our example of a milk container that holds 1 liter of liquid that flooded from an opening 20 cm below the surface of the water in 40 seconds, we find that the size of the hole needed to do that is 25.2 square mm, or a hole about 5.7 mm in diameter.[4]

Flooding the *Titanic*

Let us now apply the same technique to derive the aggregate damage to the *Titanic*. To restate, the known assumptions regarding the flooding situation as presented by Edward Wilding:

- The forward compartments flooded to the waterline in about 40 minutes after the collision.
- A pressure head of 25 feet was taken at the level of the openings along the starboard side.
- The amount of water in all 5 flooded compartments was taken at 16,000 long tons of sea water.

Since we will be using the English system of measurement we first have to convert everything to feet and seconds. To begin with we know the ship took on 16,000 long tons of sea water in 40 minutes. To get the flooded volume in cubic feet we must multiply the 16,000 tons by 35 cubic feet per ton of sea water. This gives us a volume $V = 560{,}000$ cubic feet. The time to flood to the waterline, 40 minutes, must be multiplied by 60 seconds per minute to get $T = 2400$ seconds. The outside static pressure head was given to us by Wilding at $H = 25$ ft. We now have everything we need to get the area of the hole opening we are looking for.

When we take these values and plug them into the equation given in Appendix-A, the same used for our little milk container, we find that the equivalent aggregate area of the hole opening is ***11.67* square feet**, a value that is in good agreement with Wilding. With that size of aggregate opening, the ship would be taking in 13.3 long tons of sea water per second immediately following the collision. Of course, as the level of water in the flooding compartments rise toward the level of the sea, the inflow rate will slow down. Unfortunately, as we all know, the flooding was not able to be contained to just the 5 forward compartments, and the ship eventually foundered after 2 hours and 40 minutes.

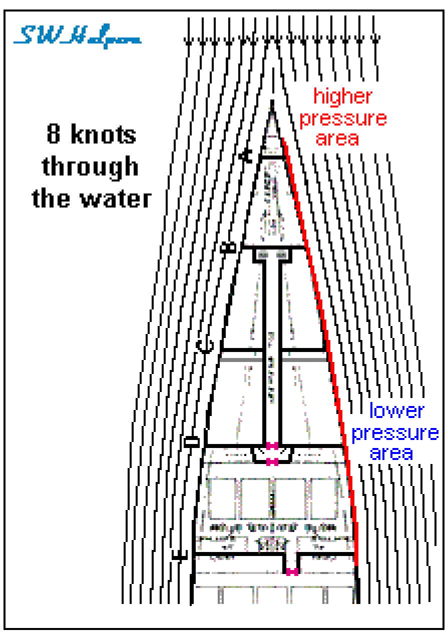
In 1996 two naval architects from Harland and Wolff, C. Hackett and J. G. Bedford, conducted a computerized analysis of the sinking of the *Titanic*. In their work they also addressed Edward Wilding’s estimate for the aggregate area of openings in the hull.[5] What they used was an equation for initial flooding rate which did *not* include the decrease in flow velocity as the inside elevation head increased as we have done here. They also used a multiplication factor called the coefficient of discharge, C, which takes into account the convergence of streamlines for water flowing through an actual opening into a vessel. In order for them to get the same result as Wilding, they had to arbitrarily reduced their coefficient of discharge from a value of 0.61 (used for a clean round opening) to a value of 0.485. Before changing this parameter, they were only able to obtain a result of 9.53 square feet. As we have seen, our result is expressed as an equivalent area opening from the very beginning, and it includes the reduction in inflow rate as the container fills toward the waterline.

Forward Movement

There is quite a bit evidence that the *Titanic* was moved ahead again after first coming to a stop after the accident happened. Evidence is provided from trimmer Thomas Dillon[6] and greaser Frederick Scott[7] down in the engine rooms, QM Alfred Olliver[8] up on bridge, and several passengers including a documented visual observation of the ship moving by 2nd class passenger Lawrence Beesely.[9] There has been much speculation as to why the ship would be moved ahead again after the collision, including the possibility that they needed to get clear of some nearby ice so that lifeboats could be launched safely. But it has also been suggested that this forward movement contributed to some significant additional flooding, if not the main contributor to the loss of the ship.[10] It has been hypothesized that moving the ship in a damaged condition created enormous hydraulic forces which might have caused weakened seams and other damage to open wider, increasing the flood of water through missing rivet holes and between the deck plates.

As it turns out, this scenario can be analyzed by extending the what we have done to include a dynamic pressure component as well as a static pressure component on the outside of the hull. Again we turn to Bernoulli's equation to quantify the effect. What Bernoulli's equation states is the total inside pressure must equal the total outside pressure across the opening. What we now find is an additional term in the equation due to dynamic pressure on the outside of the hull that was not there before. Taking this into account we can again solve Bernoulli's equation to get the velocity of the inflow rate. (See Appendix-A.) Like before we find that the highest rate of inflow takes place at the initial stage of flooding, at *t=0*.

Let us now take the case of the *Titanic*. Assuming the ship was moved forward at slow speed ahead which corresponded to about 8 knots (about 30 revolutions on her reciprocating engines with the turbine *disengaged*). Eight knots is 13.5 feet per second. The added pressure due to forward motion is turns out to be equivalent to a pressure head of 2.85 feet, an increase of only 11.4% over the elevation pressure head of 25 feet. This is the ram affect caused by forward movement of the ship. The initial rate of flooding at *t=0* would increase by only 5.5%, or 14 tons per second instead of 13.3 tons per second. And all this assumes that our 12 square feet of damage was straight across the bow and not along the side of the ship.[11] For damage along the side the situation is much more complex because of the changing streamlines of the water flow past the hull. Near the bow there would be an increased pressure where the streamlines curve away from the centerline of the ship. Further back the pressure will decrease as the streamlines bend the other way trying to parallel the ships centerline again. It becomes a very complex problem to solve analytically. But what we can say is that the flooding will be far less than the case which we have considered where the damage is directly across the bow.



The bottom line in all of this is that the forward movement of the *Titanic* that took place after the initial stopping of the vessel could *not* have significantly contributed very much to the overall flooding situation if the movement did not continue for any significant length of time at any appreciable speed.

Summary

We have shown that a simple milk container can be used to estimate the area of openings in the hull of the *Titanic* that resulted from a collision with an iceberg. Using the assumptions presented by Edward Wilding before the British Inquiry, we were able to derive the same 12 square feet of aggregate opening that he obtained back in 1912. We also were able to show that any forward movement of the ship after the collision took place would not result in any significant increase to the flooding rate in the ship's compartments given the reported location of where the damage took place, and the relatively slow speed of movement.

Appendix-A

The equation that govern the flooding of a container is derived from the Bernoulli's Equation which is really a statement of the conservation of energy. In simple terms, Bernoulli states that the total pressure in a fluid is the same everywhere in the fluid. But what is total pressure? The total pressure is the sum the static pressure (which can be measured by moving with the fluid at a given point) plus the dynamic pressure (which is a measure of the pressure needed to stop the movement of the fluid at a given point). In equation form:

$$P_T = P_S + P_D$$

For our application, the static pressure is given by,

$$P_S = \rho\, g\, h$$

where ρ is the density of the fluid, g is the acceleration of gravity, and h is the height of the surface of the fluid directly above the point of measurement.

The dynamic pressure is given by,

$$P_D = \tfrac{1}{2} \rho\, v^2$$

where as before ρ is the density of the fluid, and v is the velocity of the fluid at the point.

Since the total pressure, static plus dynamic, is the same everywhere for any two points in our system, we can write:

$$\rho\, g\, h_1 + \tfrac{1}{2} \rho\, v_1^2 = \rho\, g\, h_2 + \tfrac{1}{2} \rho\, v_2^2$$

To simplify we can divide both sides by ρ to get,

$$g\, h_1 + \tfrac{1}{2}\, v_1^2 = g\, h_2 + \tfrac{1}{2}\, v_2^2$$

For our example of a container submerged in a large basin of water, let $h_1 = h,$ the height of water inside the container above the opening at the bottom. Let $v_1 = v,$ the velocity of the water flowing into the container at the level of the opening. Let $h_2 = H$, the height of water above the level of the opening outside the container. And finally, let $v_2 =$ s, the speed of the container moving through the water in the direction that the opening is facing.

So for our particular application we get,

$$g\,h + \tfrac{1}{2} v^2 = g\,H + \tfrac{1}{2} s^2$$

Solving this for v we get,

$$v = \text{square-root } [2g\,(H - h) + s^2]$$

If the container is not moving, our starting case, $s=0$, and

$$v = \text{square-root } [2g\,(H - h)]$$

Now the rate of flooding inside the container is the rate of change in flooded volume per unit of time. The flooded volume is the cross-sectional area of the container times the height of water in the container. If A is the cross-sectional area, then $h\,A$ is the flooded volume. So the flooding rate must therefore equal the rate of change in height per unit time, $\Delta h/\Delta t$, multiplied by A, or $A\,\Delta h/\Delta t$.

However, this flooding rate must also equal the volume of water coming into the container through the opening per unit time. That volume per unit time equals the entry velocity of the water, v, times the cross-sectional area of the opening, a. Therefore we have,

$$a\,v = A\,\Delta h/\Delta t$$

Since we have derived an expression for v, we can solve the above for $\Delta h/\Delta t$, the rate at which the water level inside the container is rising per unit of time. The result is:

$$\Delta h/\Delta t = a/A \text{ square-root } [2\,g\,(H - h) + s^2]$$

This is a differential equation that can be integrated to get h as a function of time, t. The solution is:

$$h = a/A \text{ square-root } [2gH + s^2]\,t - \tfrac{1}{2}\,(a/A)^2\,g\,t^2$$

Say that at $t=T$ the height of water inside the container reaches the waterline level of the basin, $h=H$. Solving the equation for T, we find

$$T = A/(a\,g)\ \{ \text{square-root } [2gH + s^2] - s \}$$

For the case of a non-moving container, $s=0$, and we find

$$h = a/A \text{ square-root } [2\,g\,H]\,t - \tfrac{1}{2}\,(a/A)^2\,g\,t^2$$

$$H = a/A \text{ square-root } [2gH]\,T - \tfrac{1}{2}\,(a/A)^2\,g\,T^2$$

and

$$T = A/(a\,g) \text{ square-root } [2gH]$$

We can easily normalize the equation for h above to get,

$$h/H = (2 - t/T)\,t/T$$

where, as before, t is the time for water reach a level h inside the container, H is the depth of hole at the bottom of the container, and T is time it takes to flood the non-moving container to the waterline.

The rate at which the initial flooding takes place in normalized form for a non-moving container is given by another simple equation:

$$\Delta h/\Delta t = 2H/T\,(1 - t/T)$$

where $\Delta h/\Delta t$ represents the change in water level inside the container per unit of time; e.g., in cm per second. At time $t=0$, we see that the water level inside is rising at a rate equal to twice the depth of the hole divided by the time for the water to reach the waterline level of the basin, or $2H/T$. This is the initial flooding rate of the container.

At time $t=T$, the water level inside is rising at a rate of zero having reached the level of the waterline for non-moving container.

We have shown before that,

$$v = \text{square-root } [2g\,(H - h) + s^2\,]$$

where v is the velocity of the inflow, g is the acceleration of gravity (980.7 cm/sec/sec or 32 ft/sec/sec), and H is the outside pressure head (the depth of the opening below the waterline), and h the inside pressure head (the height of water in the flooding container). For the case of a non-moving container, s=0, we find:

$$v = \text{square-root } [2g(H - h)\,]$$

This equation turns out to be exactly the same as what you would get by dropping a free falling object through a distance of $H - h$.

The initial inflow velocity is a maximum at $t=0$ when $h=0$. At that time,

$$v = \text{square-root } [2gH]$$

for a non-moving container.

Now we have already seen that initial rate at which the volume of water inside the container is rising at $t=0$ is equal to $2H/T$. We also said this must equal the inflow velocity times the equivalent area opening, or

$$a\,v = 2AH/T$$

Looking at this expression we notice that the product of A times H is nothing more than the volume of the inside of the container taken to the waterline. Let us call that volume V. We then have,

$$a\,v = 2V/T$$

which we can easily solve for a, the area of the opening, after substituting the expression derived for v at t=0 given above. What we get is:

$$a = (2V/T)\,/\,\text{square-root } (2gH)$$

the equivalent area of the opening expressed in terms of known parameters.

If we now consider the case where the container is moving at a speed of s in the direction that opening faces, we find the initial inflow velocity at $t=0$ is

$$v = \text{square-root } [2gH + s^2\,]$$

or

$$v = \text{square-root } [\,2gH\,(1 + s^2/2gH)\,]$$

The maximum height of water that is reached inside the moving container is when the inflow velocity becomes zero. In that case the inside pressure at the level of the opening must equal the outside static pressure plus the outside dynamic pressure due to the movement of the container through the water. In equation form,

$$\rho g h = \rho g H + \tfrac{1}{2} \rho s^2$$

which simply reduces to,

$$h = H [1 + s^2 /(2gH)]$$

the height of the water that is reached in the flooded container.

---

[1] Wilding also knew that the forward starboard-side coal bunker in Boiler room No. 5 was also flooding, but this was from a small gash that was no worse than what would be produced from an ordinary fire hose (British Inquiry, 2255). He therefore did not consider this significant in his initial estimate.

[2] British Inquiry, 1888, 2096-2099.

[3] The individual watertight compartments of the ship up front were more trapezoidal in shape, both in their horizontal cross sections and in their transverse cross sections, rather than rectangular. The affect of this would be a more rapid rise in the level of water in a given compartment initially and a much slower rise in water later on compared to a compartment of rectangular transverse cross section of the same total volume.

[4] In reality the size of the actual hole punched would be about 28% larger in diameter than this value assuming a sharp-edged circular opening. What we are calculating here is the *equivalent area of the opening* called the “vena contracta” which results from the convergence of the streamline flow past the orifice.

[5] C. Hackett and J. G. Bedford, “The Sinking of the S.S. Titanic – Investigated by Modern Techniques,” presented at a joint meeting of RINA and IESIS, December 10, 1996, Section 4.5.

[6] Dillon reported seeing the engines go ahead slow for about 2 minutes at some point in time after the collision. British Inquiry, 3715-3729.

[7] Scott said he saw the engine telegraphs call for slow ahead several minutes after the collision. British Inquiry, 5565-5568, 5609-5620.

[8] Olliver said he saw Capt. Smith ring down half-ahead on the engine telegraphs at some point following the collision. American Inquiry, p. 531-532.

[9] Beesley noticed two white streaks of foam streaming along the ship’s side on his 2nd trip up to the boat deck following the collision. Lawrence Beesley, “The Loss of the S.S. Titanic,” Chapter 3, originally published by Houghton Mifflin Co., 1912.

[10] David G. Brown, “The Last Log of the Titanic,” International Marine/McGraw-Hill, 2001.

[11] If the ship was moved at twice this speed, say 15 knots (corresponding to a little over 50 revolutions on her reciprocating engines with the central turbine now engaged), then the ram effect becomes much more significant. The increased pressure head becomes 11.4 feet, or 46% above the elevation pressure head, and the increase in initial flooding rate becomes 21%, or 16.0 tons per second instead of 13.3 tons per second. Again, we are assuming the worst case where those 12 square feet of damage is straight across the bow and not along the side.