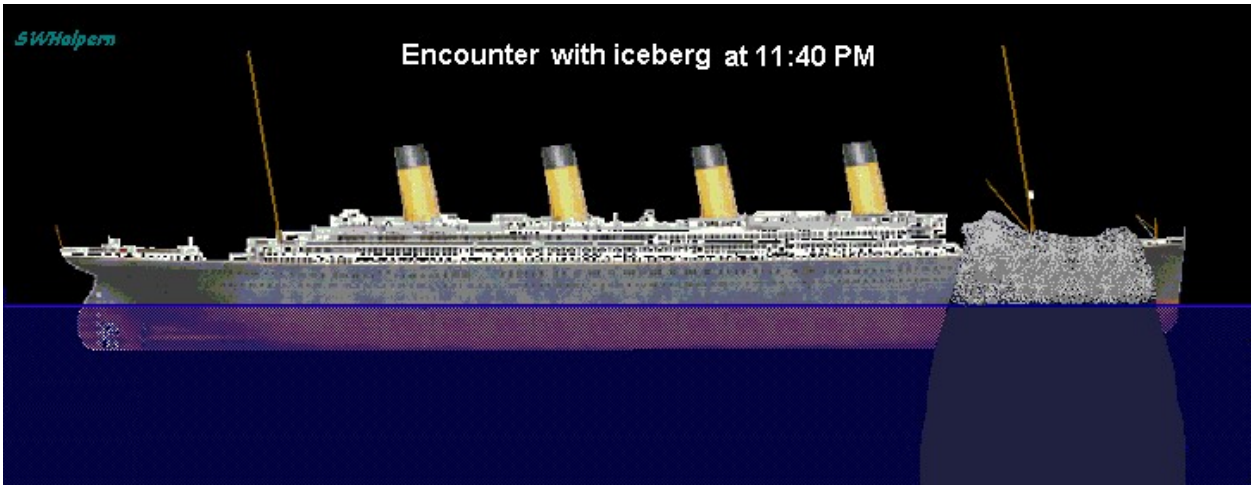
Angles of Trim and Heel

(Revised August 2017)

by Samuel Halpern

INTRODUCTION

As we all know, it was about 11:40 PM ship's time on the 14th of April 1912 that the SS *Titanic* collided with an iceberg. The iceberg itself was described as reaching a little higher than the height of the boat deck as it glided by at about 37 feet per second along her starboard side. In just under 8 seconds the major damage had been done. No less than 6 major watertight compartments suffered observable damage, from the forepeak all the way to the forward bunker in Boiler Room No. 5. Soon after the collision the ship had taken on a different appearance as water flooded into her damaged hull well below the waterline. Within 5 to 10 minutes, the ship developed a slight list to starboard as well as starting to settle down by the head.



This article considers how *Titanic*'s trim would appear in profile view as her compartments took on more and more water through the night. This article also considers the different angles of heel as the ship listed first to starboard then to port as the night wore on. The angles presented in this article were derived mostly from observations of eyewitnesses. These observations were then correlated with other events such as lifeboat launch times,[1] wireless transmission times, and other observations taken from a more comprehensive timeline of events.

To determine the flooded state of the ship from eyewitness accounts we were able to map localized observations to an angle of trim for the ship. Here we made use of a set of waterline curves that show the progressive flooding of the ship from the landmark work of Hackett and Bedford.[2] As the ship trimmed down by the head, the draught forward and aft changed over time.[3] For any given flooded condition, the draughts forward and aft define the waterline in that flooded condition. We then drew a set of these waterlines against detailed profile plans of the ship such as shown below. Then, if we have an eyewitness report that water was seen at the level of a certain deck in a certain compartment, we know that the external waterline had to be at, or somewhat above, that particular level at that particular time.

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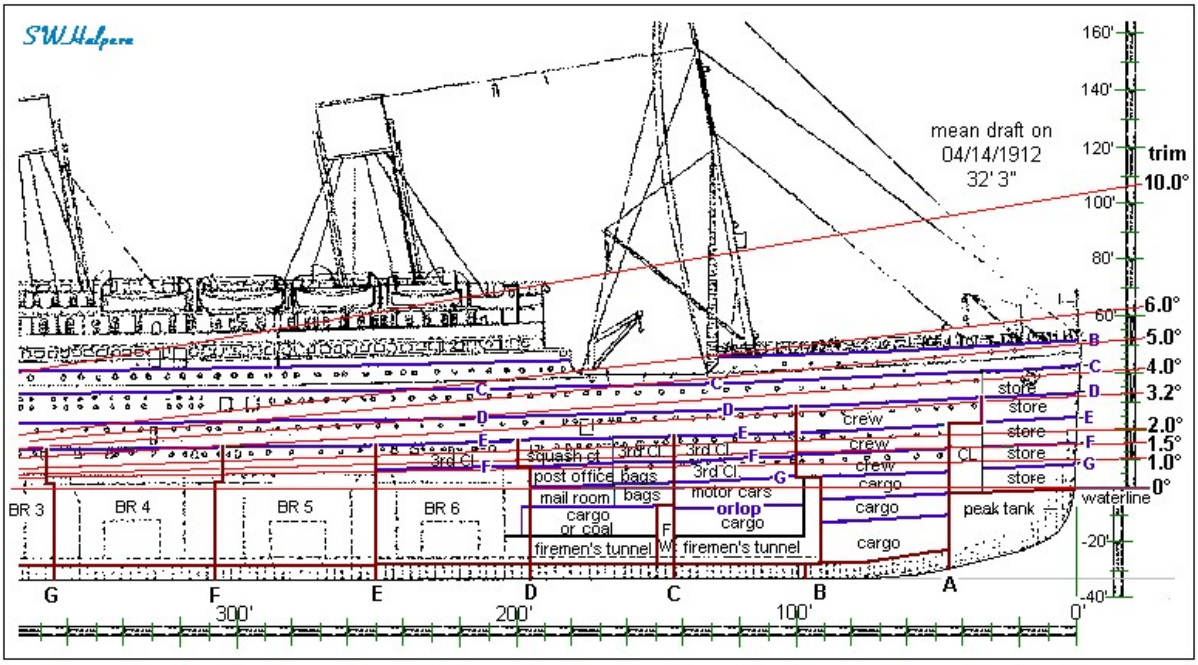
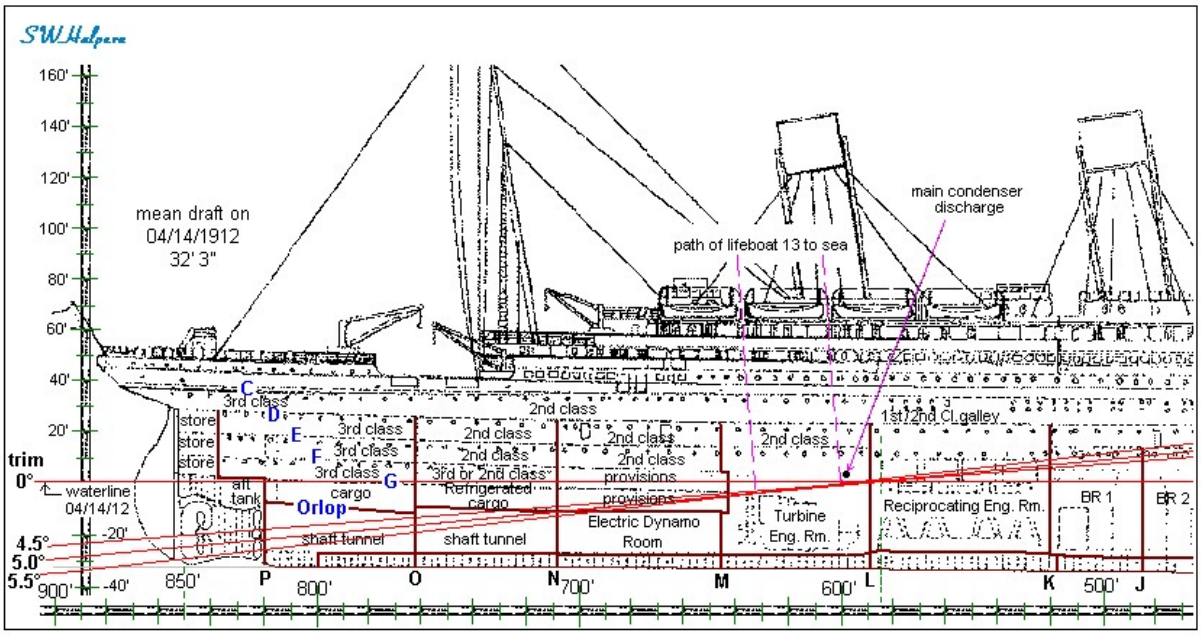
[1] Bill Wormstedt, Tad Fitch and George Behe, "Titanic: The Lifeboat Launching Sequence Re-Examined," Originally published in the THS Commutator, No. 155, 2001, updated March 2012. Available on-line at: http://wormstedt.com/Titanic/lifeboats/lifeboats.htm.

[2] Hackett and Bedford, "The Sinking of S.S. *Titanic* - Investigated by Modern Techniques," 1996 RINA Transactions.

[3] For a ship down by the head, the trim angle is given by the arctangent of the draught forward minus the draught aft divided by the ship's length between perpendiculars.

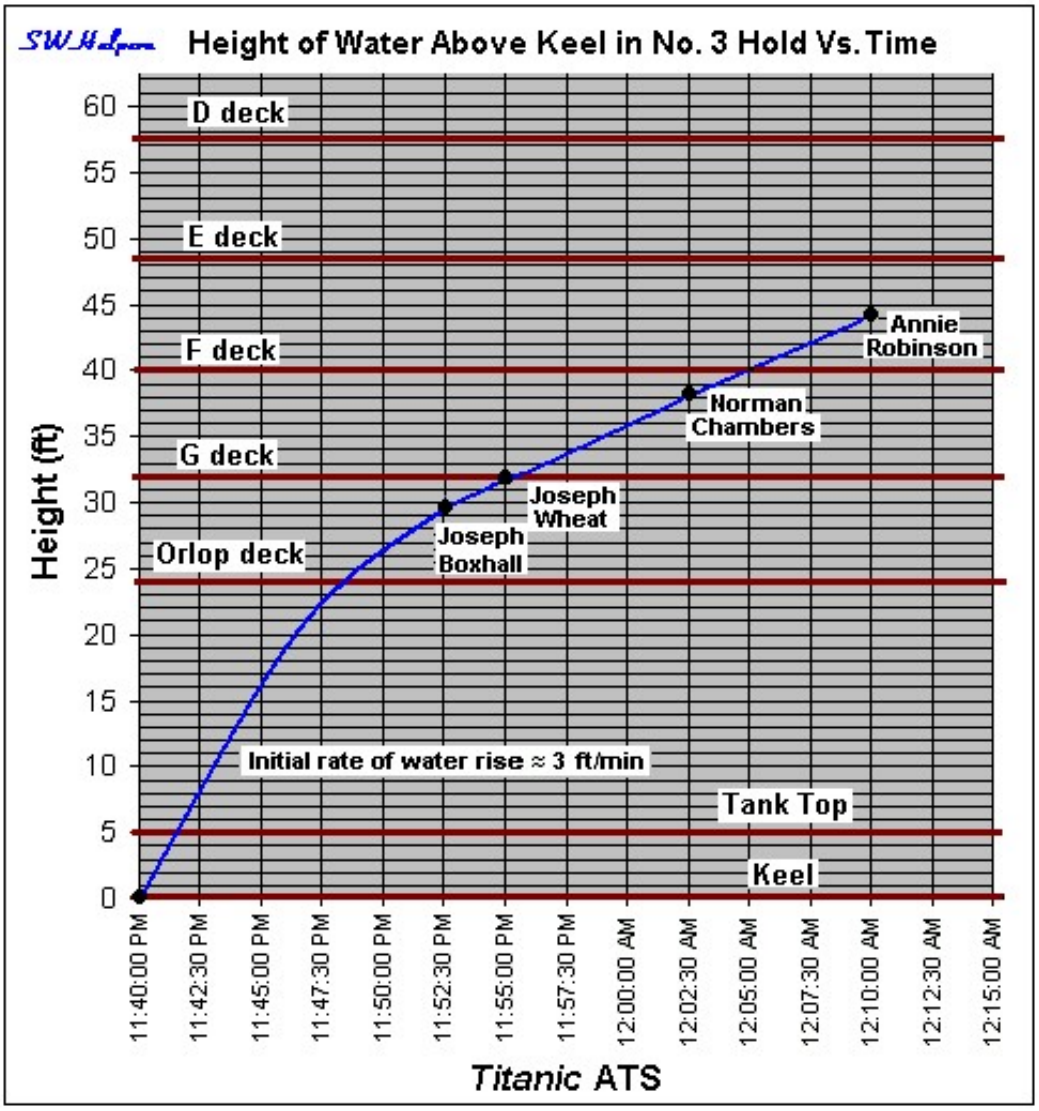
Then using a relation between trim angle for that waterline and the amount of water intake that would produce that trim angle, we can find the approximate amount of water that had flooded into the ship when that particular observation was made.



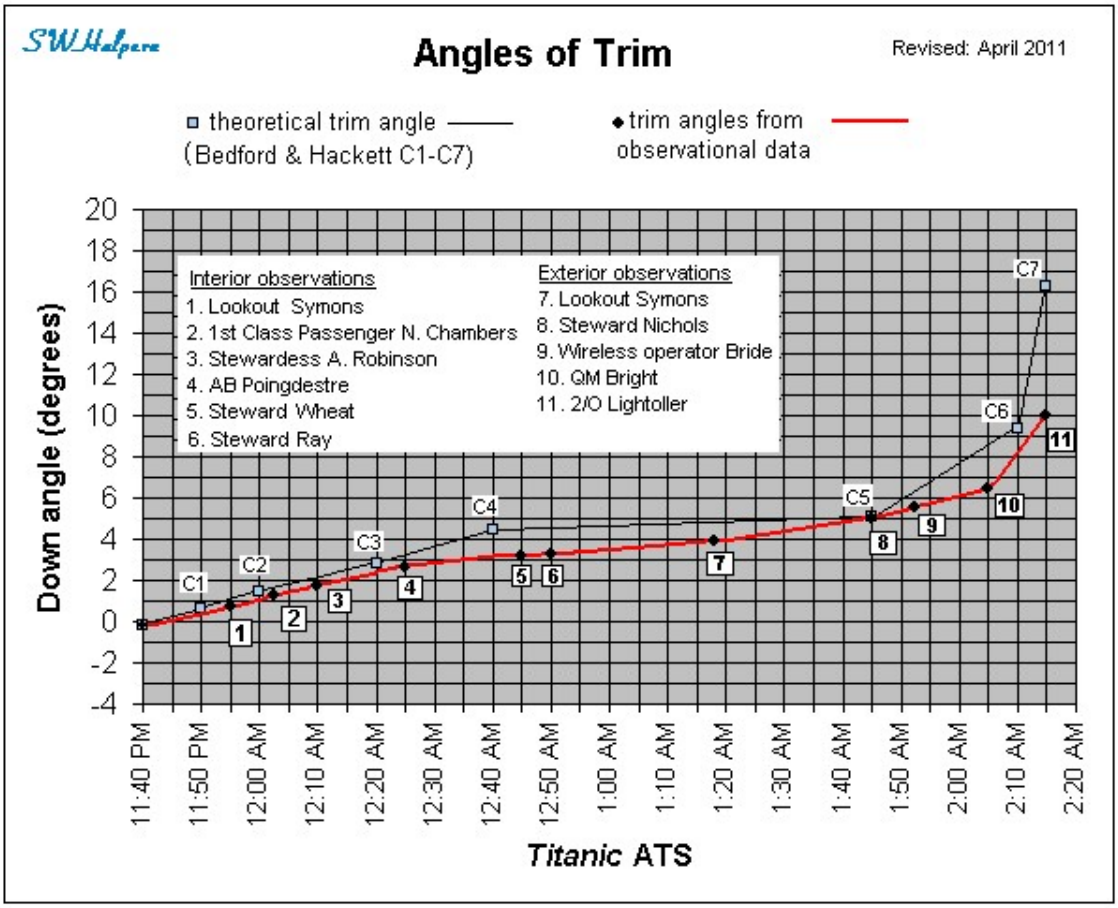


The trim of the vessel as a function of time can thus be derived from a list of key eyewitness accounts that are detailed in Appendix A. In each case the appropriate waterline was determined based on their specific observation. In doing so, the reported list of the vessel at that time was also factored in if the observation was anywhere away from the ship's centerline. The estimated times of these observations, in minutes past the collision time, is taken either directly from the testimony, or implied from some immediate action taken in relation to time taken from the testimony.

In the early stages of flooding in the vicinity of the mailroom we have a number of eyewitness accounts that allow us to plot the rise of water in No. 3 hold as a function of time. This is shown in the diagram below along with names of the witnesses involved.



From other quantifiable observations we were able to establish how far the ship had trimmed down by the head over time. These results are shown below with the specific observations identified. For comparison, we show a theoretical curve marked by conditions C1 through C7 that came from the work of Hackett and Bedford.



It should be understood that the results of theoretical work is only as good as the assumptions that went into the analysis. Although there is some close agreement along portions of the curves, the results presented here (the curve marked *observation*) were based primarily on specific observations as noted in the descriptions of events and correlating those with other documented events and time estimates. The assumptions used by Hackett and Bedford regarding flooding rates for the most part was derived from the description of flooding and time estimates that were written up in the British Inquiry report into the accident. Some of these reports may also have been a bit over estimated. For example the report said it was 5 minutes after the collision that water was seen rushing in at the bottom of the firemen's passage, yet it is more likely that this was seen about 10 to 15 minutes afterward. It was also written in the Inquiry report that water had reached a height of 8 feet over the double bottom in boiler room No. 6 just 10 minutes after the collision, yet that observation may have been the result of the list to starboard that the ship had taken on at that time.[4] In the work of Hackett and Bedford, a constant 5-degree trim angle is shown between 12:40 AM (their condition C4) and 1:45 AM (their condition C5) even though the ship continued to flood mostly from above the submerged decks. They assumed that water in the flooded compartments had reached the waterline and therefore water would no longer be entering from damage below the waterline because of the equalized internal pressure head. It is only after 1:45 AM that they assume that water starts to overflow the watertight bulkhead between boiler rooms No. 4 and No. 5; at which point the final and more rapid phase of the sinking process begins.

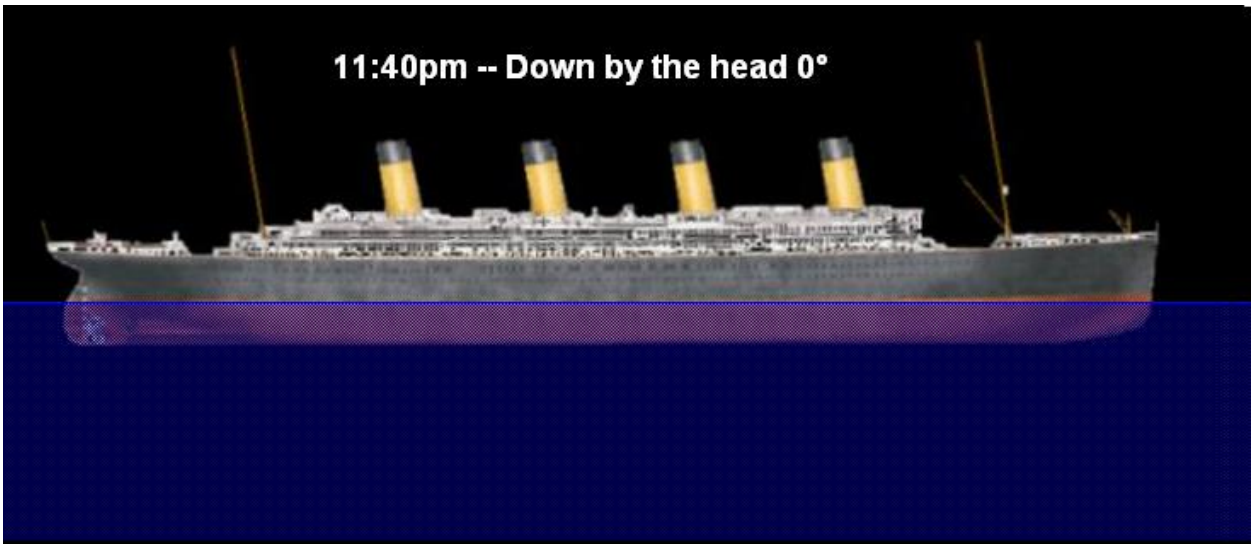
At about 2:05 AM, when Collapsible D was launched, QM Bright noted that the forecastle was just going under water. When Collapsible C (launched just a few minutes earlier) got to the water, QM Rowe noticed that the well deck was "submerged." This is very consistent with Bright's observation that

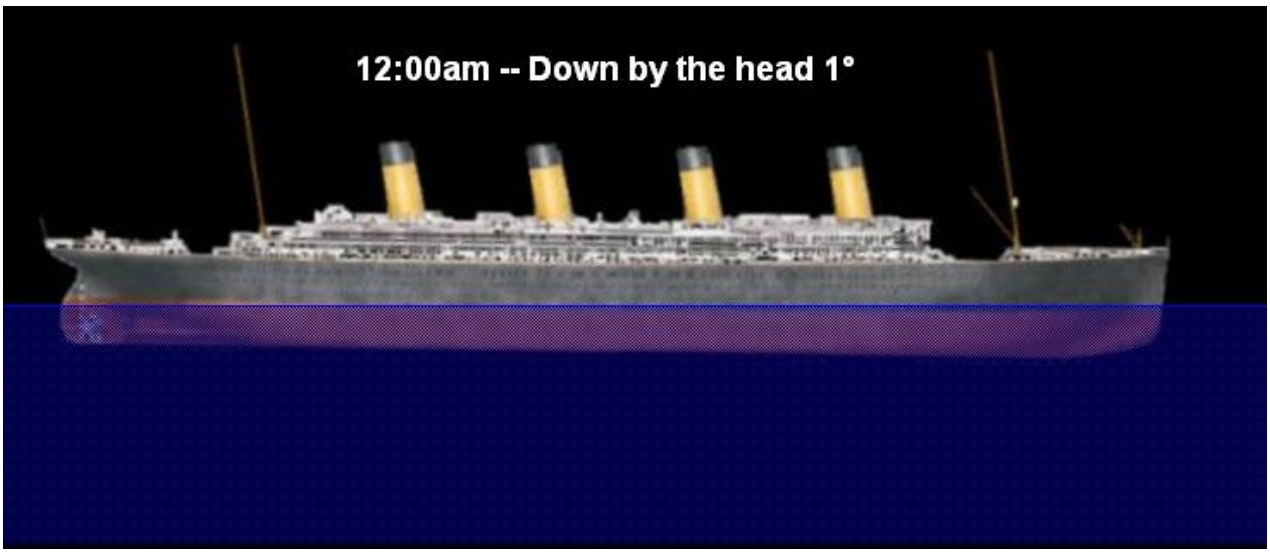
[4] See the section on Angles of Heel in this article for an explanation of how the reported depth of 8 feet of water in BR 6 after 10 minutes may have come about.

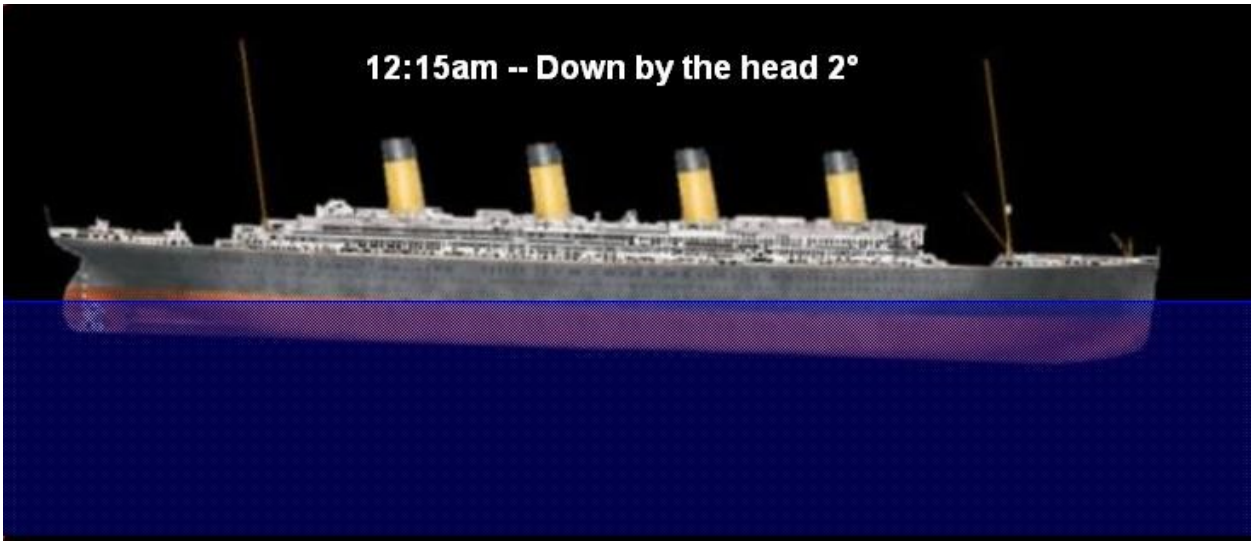
the forecastle had just gone under about the same time. As QM Bright had noted, the forecastle was about 20 feet below the level of the bridge. All this points to a down angle of about 7 degrees by 2:05 AM. At about 2:15 AM, just before Second Officer Lightoller jumped into the water, he observed that the crow's nest was level with the water as the bridge was going under. This corresponds to a down angle of 10 degrees at that time. The theoretical results of Hackett and Bedford show a much more severe down angle of 17 degrees for the same point in time. These differences presented here are not meant to be critical of their theoretical work, but only to show the difference between theoretical results and results based on more comprehensive observations.

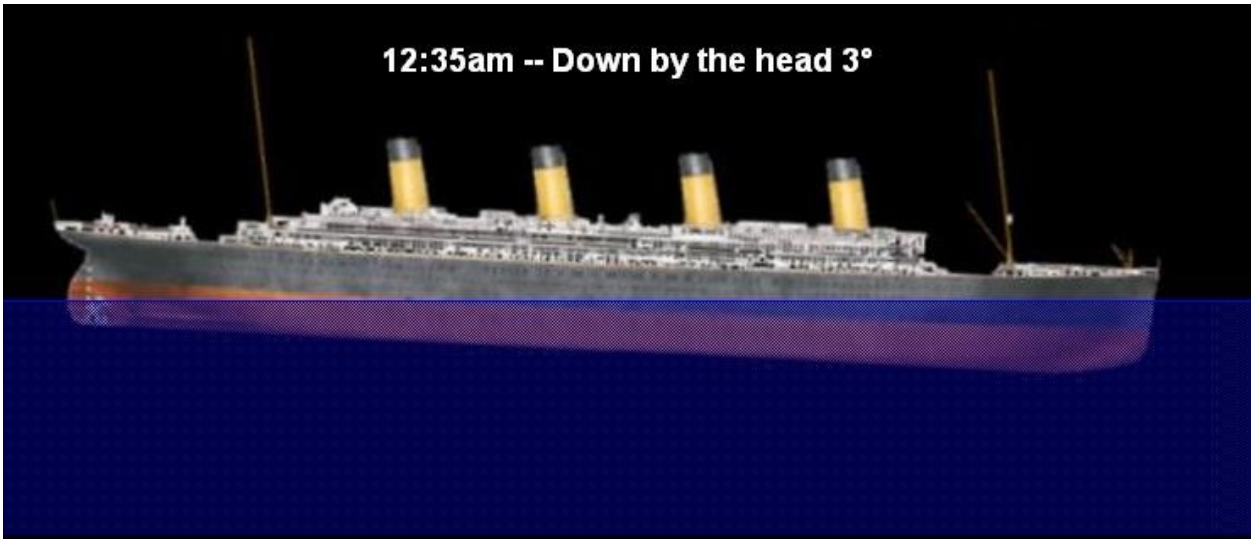
TRIM ANGLE VIEWS

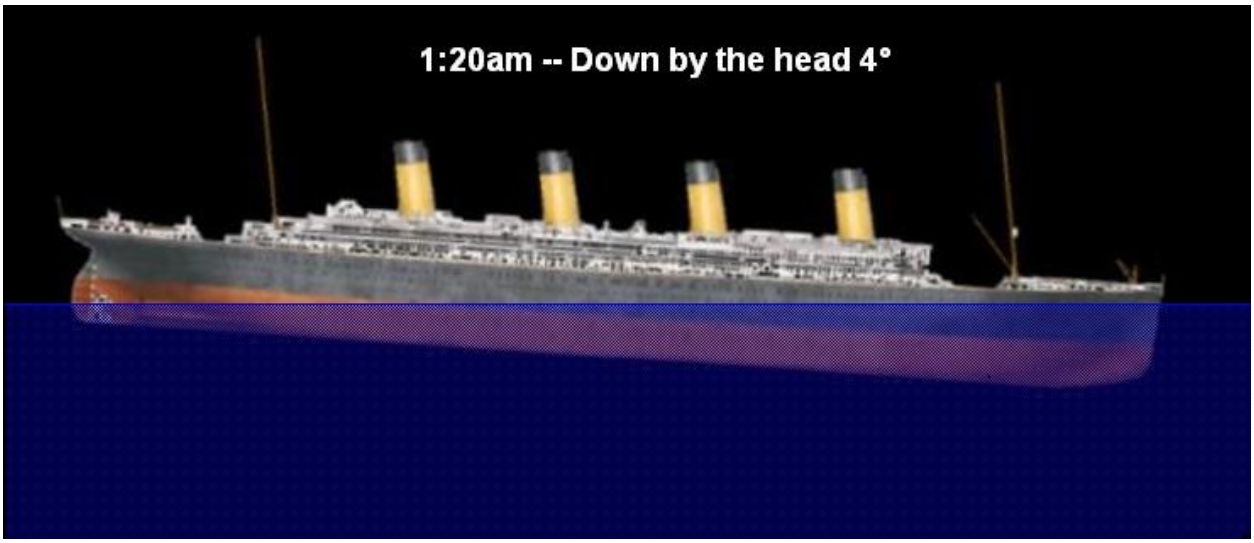
The following views show *Titanic* in profile as it settled down by the head. The effect of any angle of list is not included in these views, and therefore represents a profile view taken at the ship's centerline. (Angles of list are discussed in the next section.) A few key events correlated to each of these views are also presented.

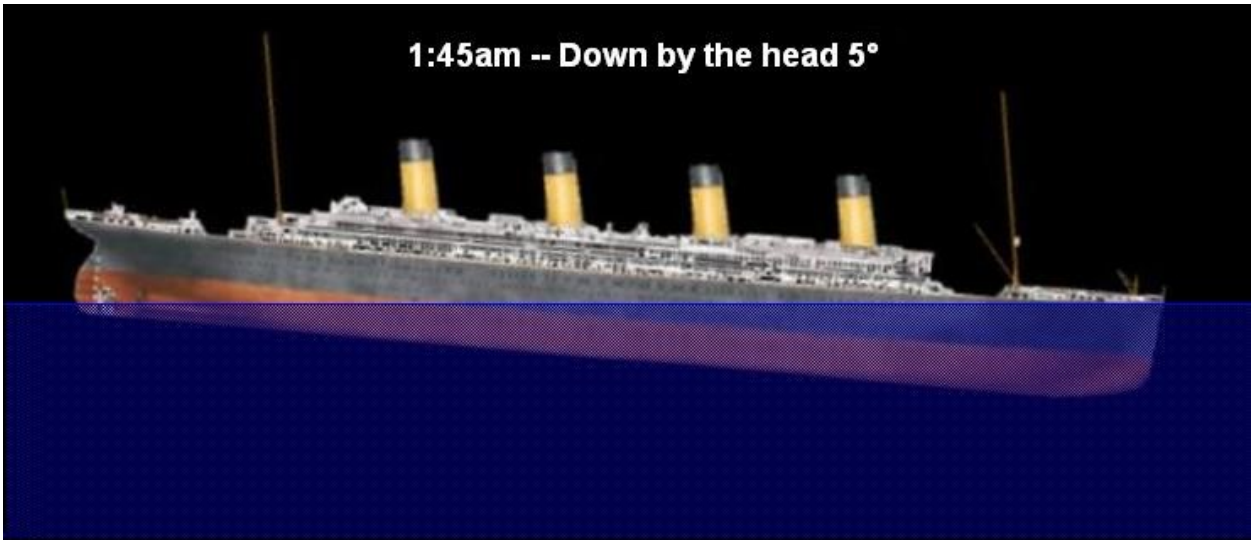


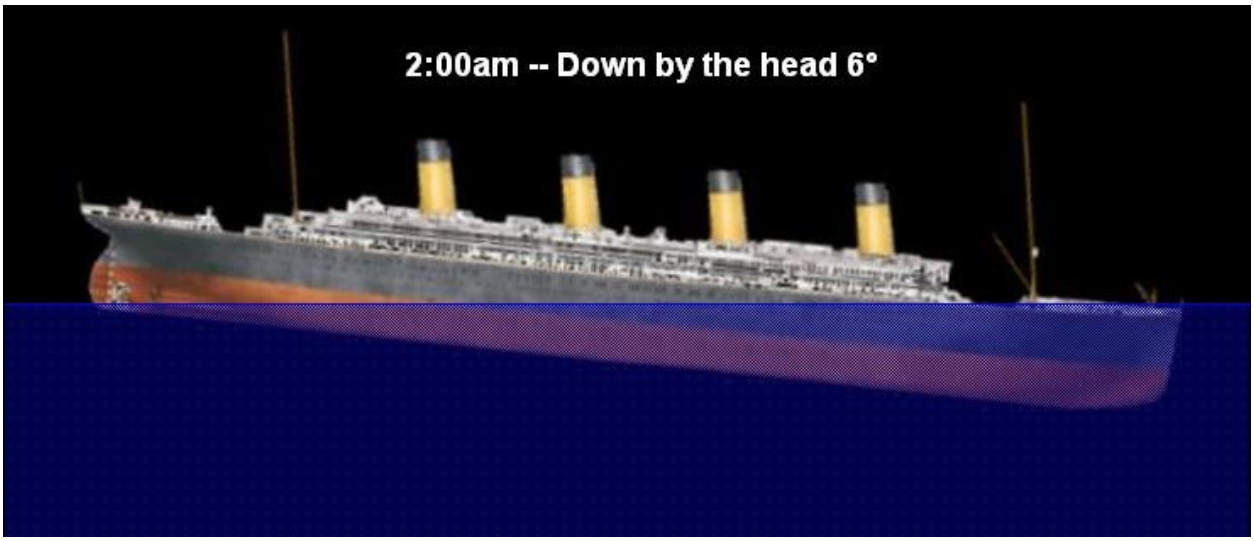


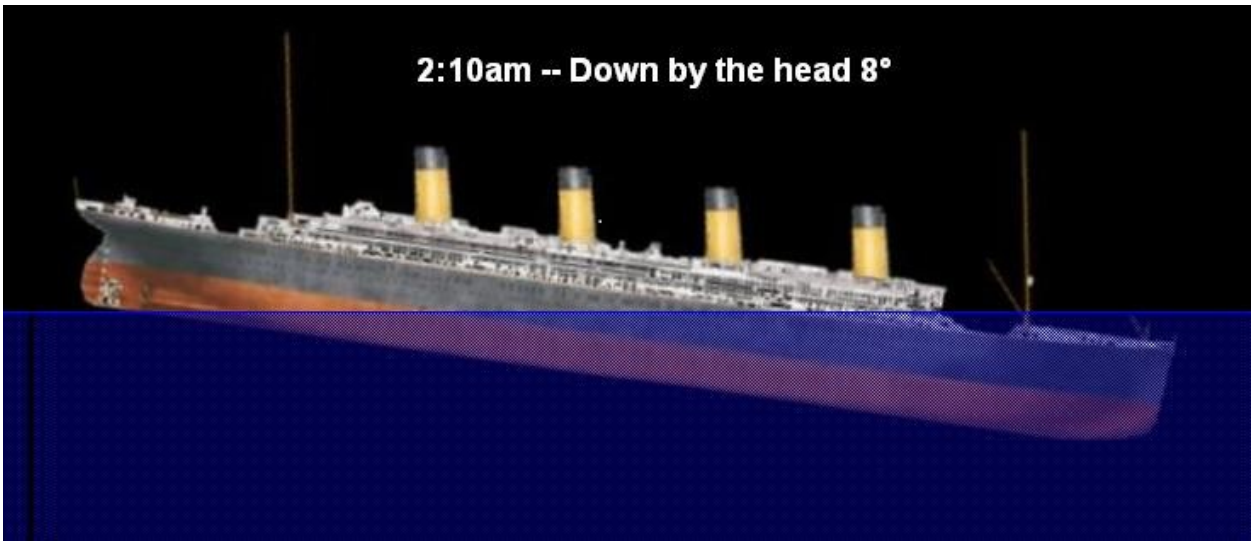

12:15am -- Down by the head 2°

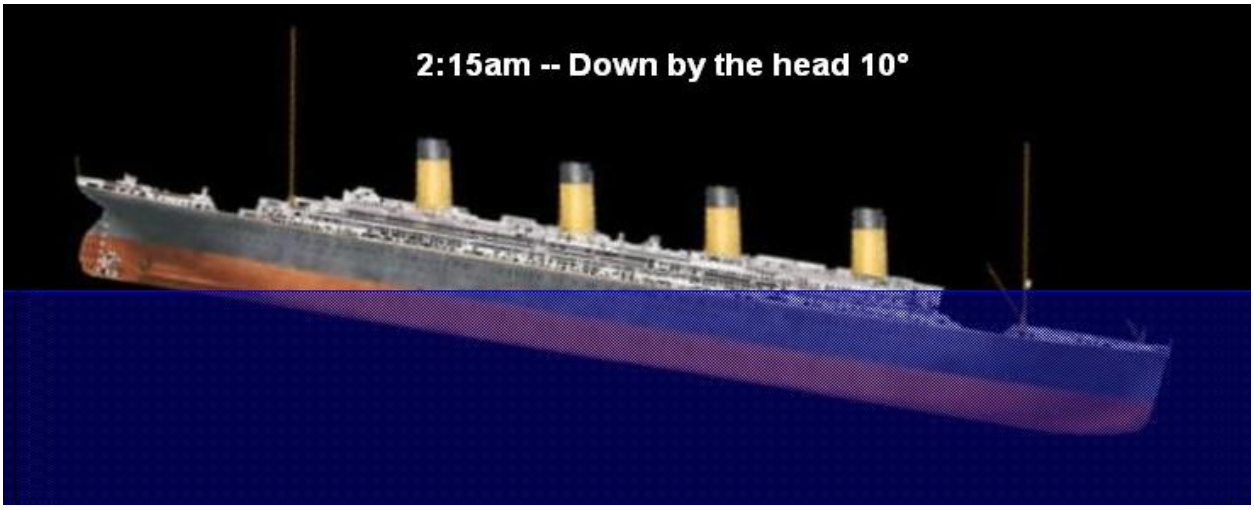

12:35am -- Down by the head 3°


1:20am -- Down by the head 4°


1:45am -- Down by the head 5°


2:00am -- Down by the head 6°


2:10am -- Down by the head 8°

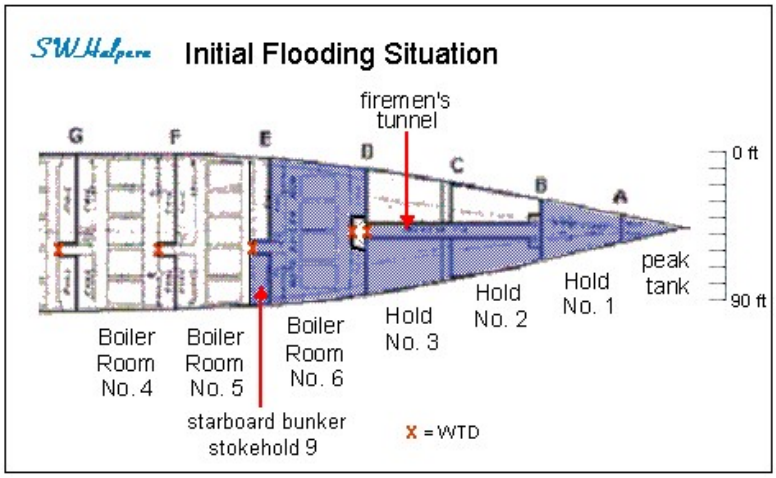


ANGLES OF HEEL

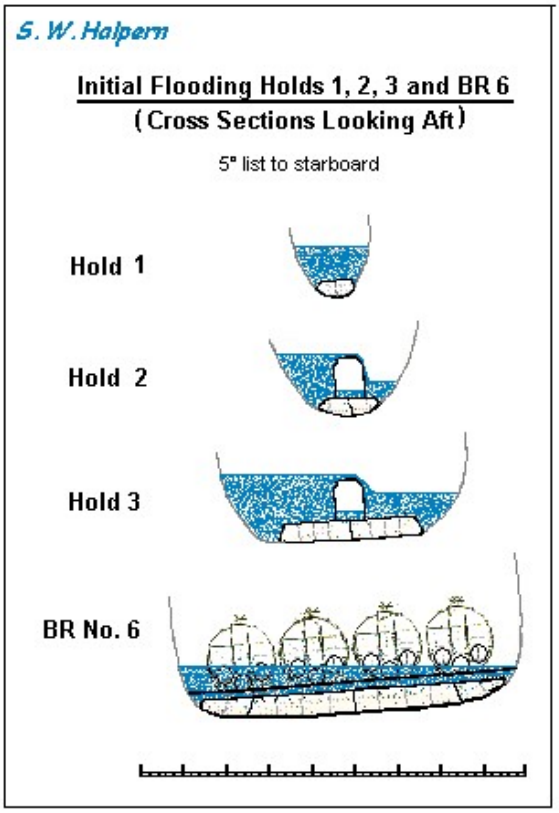
During the night the *Titanic* took on various angles of heel in addition to trimming down by the bow. Shortly after the collision it was reported that a list to starboard of about 5 degrees developed.

> Mr. HICHENS. …The captain sent then for the carpenter to sound the ship. He also came back to the wheelhouse and looked at the commutator [sic] in front of the compass, which is a little instrument like a clock to tell you how the ship is listing. The ship had a list of 5° to the starboard.
> Senator SMITH. How long after the impact, or collision?
> Mr. HICHENS. I could hardly tell you, sir. Judging roughly, about 5 minutes; about 5 to 10 minutes…

Asymmetrical flooding in the first 6 compartments caused this initial list to starboard. The major contributors to the initial list were in Holds 2 and 3 as water was initially confined to the starboard side by the watertight firemen's tunnel on the ship's centerline that acted as a longitudinal bulkhead. This tunnel was taken to a height of 10.5 feet over the tank top. Water was also filling the empty coalbunker in stokehold 9 located on the forward starboard side of Boiler Room No. 5 (BR 5). Although water was also entering the forepeak, Hold 1, the firemen's tunnel, and Boiler Room No. 6 (BR 6), it would be the flooding in Holds 2, 3, and the bunker in BR 5 that contributed the most to the initial list as can be seen below.



The 5 degrees of initial list was confirmed by an analysis of the heeling moments that would be set up due to water entering these areas. This analysis is presented in Appendix B. Cross sectional views of the initial flooding in the first few minutes in Holds 1, 2, and 3, and Boiler Room No. 6 with the ship listing 5° to starboard are shown in the diagram below.



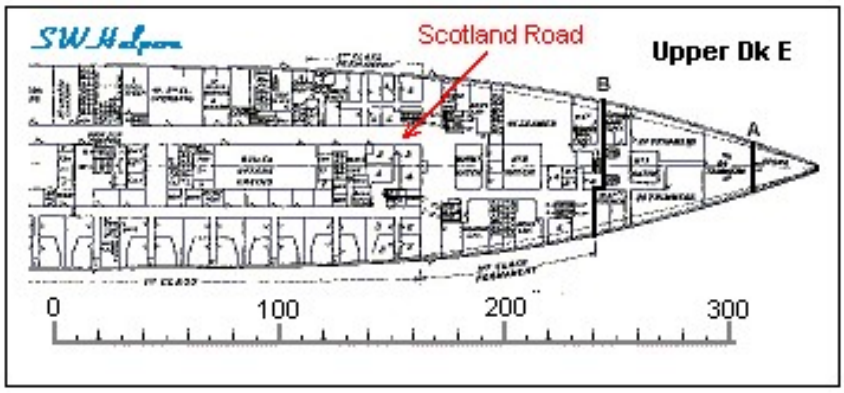
Notice that there is a difference in the depth of water on the two sides of the compartment for BR 6 when the ship had a list of 5 degrees. The boilers were 15 feet, 9 inches in diameter. The difference in water height between the low starboard side of the room and the high port side of the room with a 5-degree list is about 7 feet. In addition, a trim of 1-degree down by the head would make the flooding at the forward end of the boiler room about 1 foot deeper overall compared to the aft end of the room. If water on the low side reached about halfway up the height of a boiler that means it would be at a level of about 8 feet above the stokehold plates there. On the high side it would be only 1 foot above the plates. It is easy to understand the conclusion that BR 6 was flooded to 8 ft over the stokehold plates about 10 to 15 minutes after the collision if fireman Fred Barrett noticed that water was reaching up to about half the height of the low side boilers when he came down the escape trying to get back into BR 6. What all this says is that the reported depth of flooding may have been somewhat overestimated.

This initial list to starboard was to correct itself as water started to fill the port sides of Holds 2 and 3. Later on, a list developed to port. The most likely reason for this is the large open areas on E deck in way of the wide working passage known as Scotland Road. This was explained by Edward Wilding, Naval Architect from the design office of Harland & Wolff, the builders of the *Titanic*:

> Then, later on, the water got above E deck; we have heard of it in the working alleyway. When the water got above E deck, the broad passage we know as Scotland Road, the third class alleyway leading aft on the port side offers a much easier road for the water, and there is a much larger flow into it on that port side, because the only way the water could

> get into the first class alleyway on the starboard side is up the stair which comes from the Post Office; whereas there are several stairways and hatches at the former end of the deck, all of which could pour water, or enable water coming up through them to get along the working passage on the port side.

The forward E deck plan showing the large open spaces is shown below.

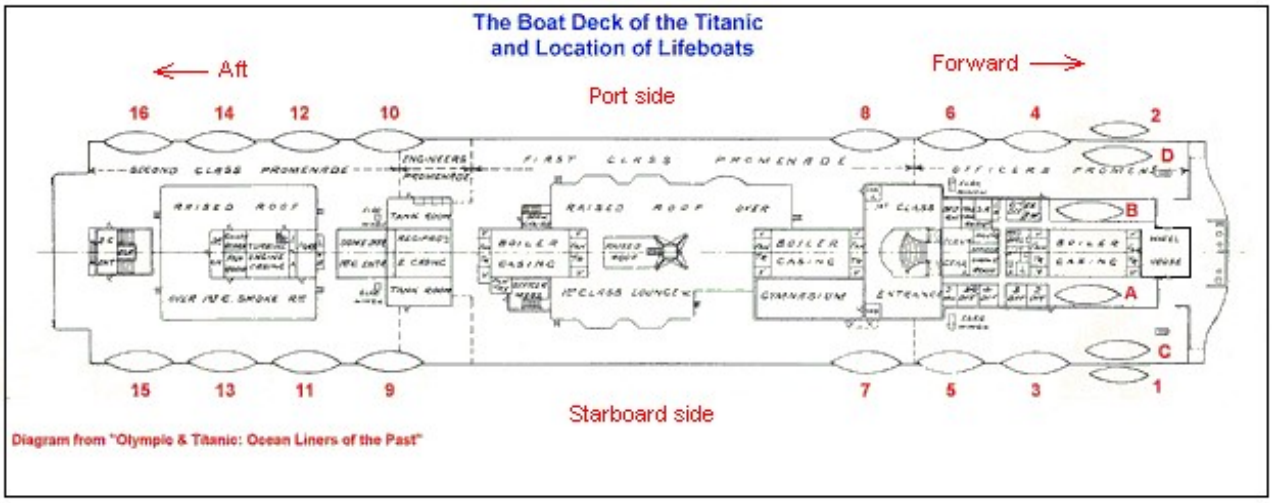


The amount of list that the ship took to port later on in the sinking process can be estimated based on eyewitness observations. AB Frank Evans was helping load lifeboats on the port side of the ship.

> Mr. EVANS. ... After we got them into that, I sung out to the seaman: "How many have you got in that boat?" I said: "Ginger, how many have you got?" He said: "There is only me here." I lowered that boat, sir, and she went away from the ship. I then went next to No. 10, sir, to that boat, and the chief officer, Mr. Murdoch, was standing there, and I lowered the boat with the assistance of a steward. The chief officer said, "What are you, Evans?" I said "A seaman, sir." He said "All right; get into that boat with the other seamen." He said, "Get into that boat," and I got into the bows of this boat, and a young ship's baker was getting the children and chucking them into the boat, and the women were jumping. Mr. Murdoch made them jump across into the boat.
> Senator SMITH. How far?
> Mr. EVANS. It was about two feet and a half, sir. He was making the women jump across, and the children he was chucking across, along with this baker. He throwed them onto the women, and he was catching the children by their dresses and chucking them in.

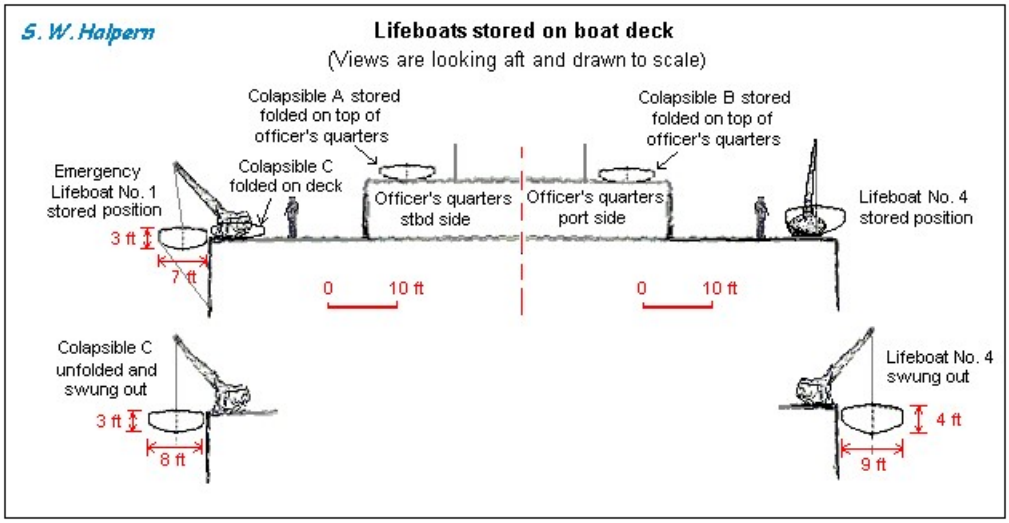
Lifeboat No. 10 was launched about 1:50 AM.[5] Based on what was reported we could get an estimate of the list from considering the dimensions of the lifeboats and davits. The location and identification of *Titanic*'s lifeboats are shown in the figure below.

[5] See http://wormstedt.com/Titanic/lifeboats/lifeboats.htm for a revised posting of lifeboat launch times.

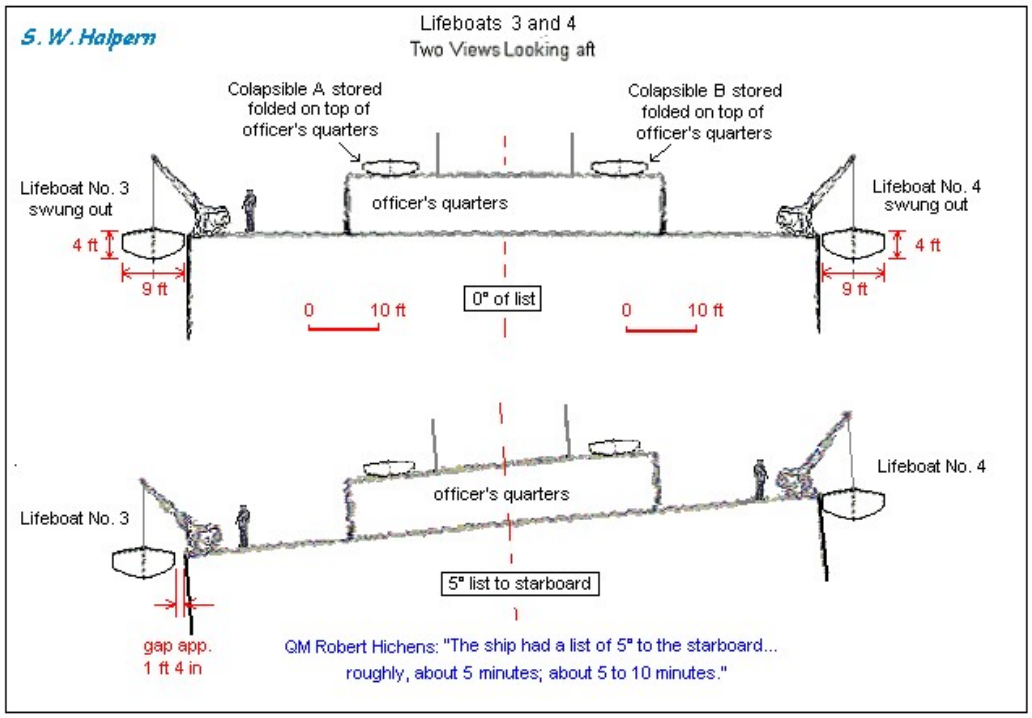


The *Titanic* carried a total 20 lifeboats. Two of them, boats No. 1 and No. 2, were emergency boats that can be launched relatively quickly if need be. They were wooden cutters 25 ft long, 7 ft broad, and 3 ft deep, with a capacity of 326.6 cubic ft, constructed to carry 40 persons. Fourteen regular lifeboats were also wooden boats, No. 3 through No. 16, each 30 ft long, 9 ft broad, and 4 ft deep, with a capacity of 655.2 cubic ft, constructed to carry 65 persons each. And four boats were Englehardt collapsible lifeboats, No. A through D, each 27.5 ft long, 8 ft broad, and 3 ft deep, with a capacity of 376.6 cubic ft, constructed to carry 47 persons each. Two of these, A and B, were stored on top of the officer's quarters, while C and D were stored alongside the davits for boats No. 1 and 2, respectively.

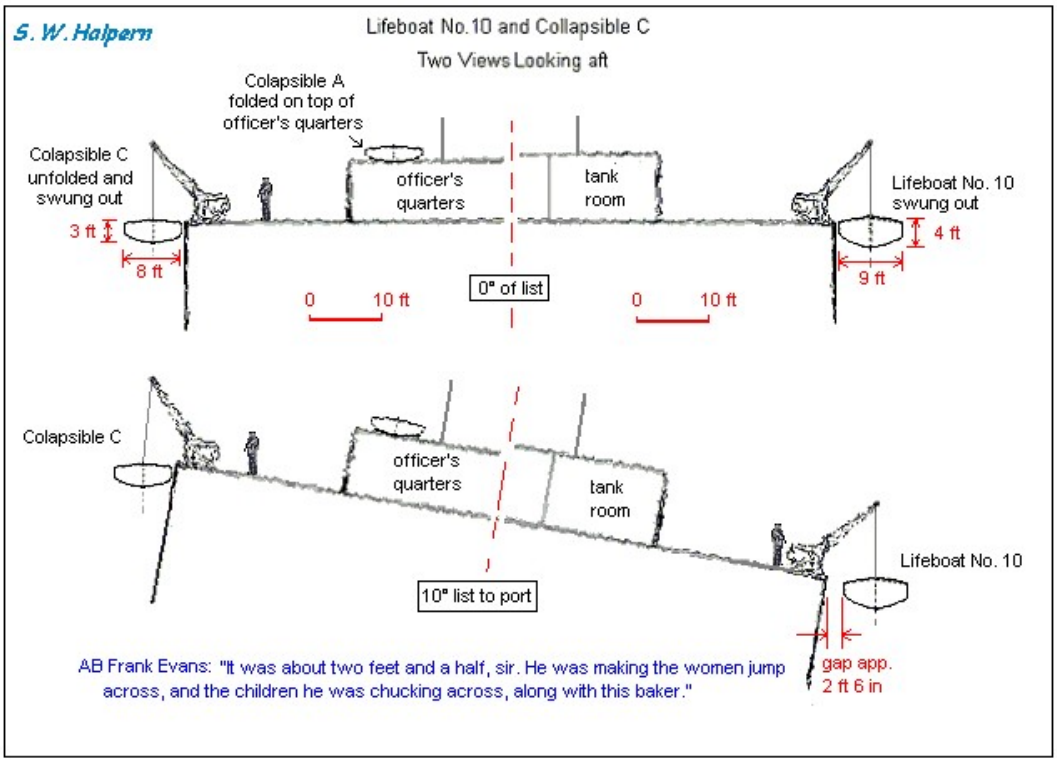
The diagrams below, drawn to scale, show cross sectional views of the boat deck looking aft so we can get an idea of what things looked like under various conditions. The first diagram shows two views, the starboard side near emergency lifeboat No. 1 (which was always swung out), and the port side near lifeboat No. 4 just aft of emergency boat No. 2. These views are for normal conditions; i.e., no list and all the boats stored on deck. For reference, people figures (5 ft. 7 in. tall) are included to show relative size. Also for reference, a view with Collapsible C unfolded and swung out in the davits that held lifeboat No. 1 on the starboard side, and boat No. 4 swung out on the port side, are also included under zero list conditions.



The next diagram shows what the view would be of the second set of boats, lifeboat 3 (starboard) and lifeboat 4 (port), both swung out shown with zero list, and with a 5° list to starboard.



The next diagram shows what the view would be with Collapsible C (starboard) and lifeboat 10 (port) swung out with zero list, and with a 10° list to port. Notice that with a 10° list to port Collapsible C would be well up against the side of the ship as it was lowered, just as QM Rowe had reported. Also notice the resulting 2.5 ft gap between the ship's side and lifeboat No. 10 over on the port side as reported by AB Frank Evans. A gap of 2.5 ft results if the ship had taken on a list to port of about 10° as shown.

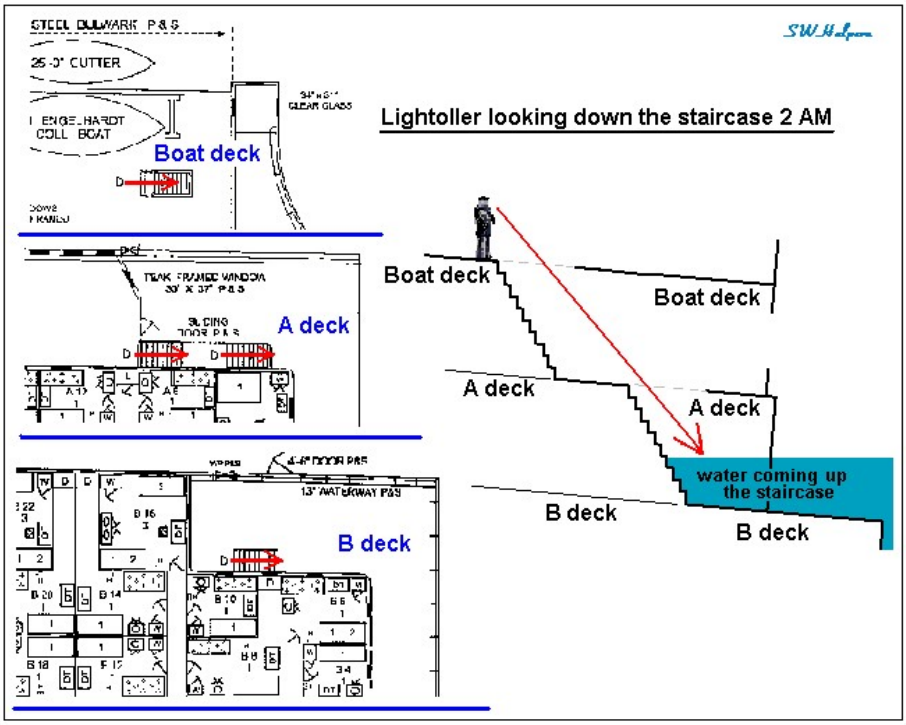


Some additional insights to the trim/list situation near 2 AM can be obtained from the observations of Second Officer Lightoller. From testimony before the British Inquiry:

> 14018. You did order this collapsible boat [D] on the port side to be lowered down from the davits? – (Lightoller) Yes.
> 14019. Did you notice how far she had to drop to get to the water? - Yes.
> 14020. Now how far had she to drop? - Ten feet.
> 14021. Is that ten feet from the rail of the boat deck? - Ten feet from where that emergency boat is hanging now (pointing on the model).
> 14022. And there she met the water? - Yes.
> 14023. (The Commissioner.) The fore part of the ship must have been under water? – 'A' deck was under water.
> 14024. And the bridge must have been under water? - Almost immediately afterwards the water came from the stairway. There is a little stairway goes down here just abaft the bridge, which goes right down here and comes out on this deck for the use of the crew only and it was almost immediately after that the water came up that stairway on to the boat deck.
> 14025. (The Solicitor-General.) When you were filling that collapsible boat and preparing it to go, had you noticed that the water was over the bows of the ship? - I could not say the bows of the ship but I could see it coming up the stairway.
> 14026. You noticed that? - Yes.
> 14027. And the other people on the boat deck could see that too? - If they looked down the stairway, yes.

Lightoller said before boat D was lowered he could see the water coming up the stairway. He also said the boat had only to drop 10 feet to reach the water, but we know 'A' deck was 9' 6" below the boat deck, so the water level would have been close to the level of 'A' deck as they started to lower boat D. When the boat was finally in the water, 'A' deck was awash. Then "almost immediately afterwards" Lightoller sees the water coming up the stairway onto the boat deck.

The stairway that Lightoller was referring to went from the boat deck down to a small landing on 'A' deck where they had a sliding door so you can go outside. It then continued down in the same direction to 'B' deck. Attached is diagram that shows this stairway and what Lightoller was looking at. Partial deck plans for all 3 relevant decks (boat deck, 'A' deck and 'B' deck) are also shown on the left side of the diagram for reference. While loading boat D with passengers, water would be seen coming up the stairway from 'B' deck below. At the time they started to lower boat D, the water would be close to that 'A' deck landing 9' 6" below. By time boat D was in the water and they were removing the falls the water would have started to come up the stairs from 'A' deck toward the boat deck.



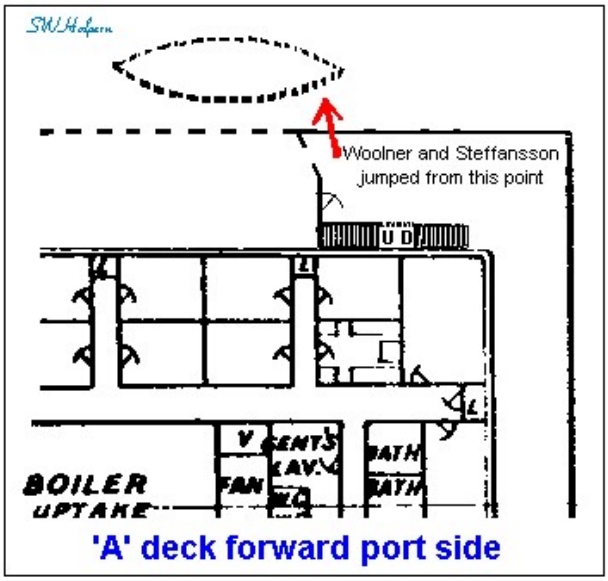
In his book, "*Titanic* and Other Ships," Lightoller wrote:[6]

> As this boat was being lowered, two men jumped into her from the deck below. This, as far as I know, was the only instance of men getting away in boats on the port side. I don't blame them, the boat wasn't full, for simple reason we couldn't find sufficient women, and there was no time to wait – the water was then actually lapping round their feet on 'A' deck, so they jumped for it and got away. Good luck to them.

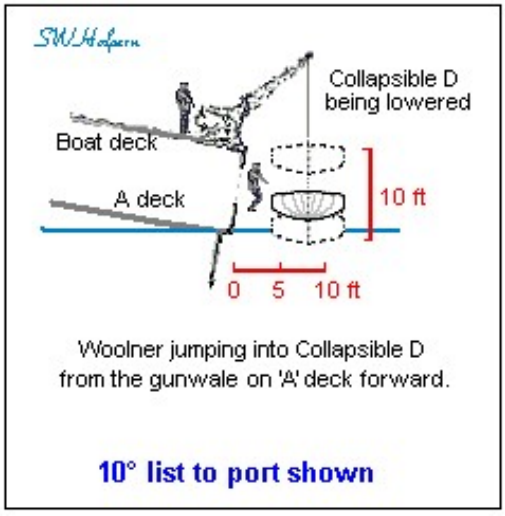
What Lightoller described was the escape of first class passenger Hugh Woolner and his friend Mauritz Håkan Björnström-Steffansson. According to Woolner's account, he and Steffansson had gone down to 'A' deck after assisting with the loading of women and children into Collapsibles C and D. There is an account written in Collier's Weekly by Mrs. Helen Churchill Candee that claimed the reason for Woolner and Steffansson going down to 'A' deck was to "to see if any stray women were there unrescued."[7] In all likelihood, as *Titanic* researcher Ben Holme suggests, it could simply have been a deliberate attempt to try and get into Collapsible D, the last boat to be lowered, without any officer around them to block their way. In his testimony before the American Inquiry, Woolner said that he noticed water just coming onto 'A' deck forward when he and Steffansson climbed onto the gunwale on the port side of 'A' deck to make a jump for boat D, which as Lightoller described, was coming down into the water. The boat deck was exactly 9 feet 6 inches above 'A' deck, the deck that Woolner and Steffansson were on. They were just ahead of the enclosed part of the 'A' deck promenade, near where the bow of collapsible D would be when it reached the water as pictured below.

[6] Commander Charles Lightoller, "Titanic and Other Ships," originally published by Ivor Nicholson and Watson in 1935, Chapters 30 to 35.

[7] Helen Churchill Candee, "Sealed Orders," Collier's Weekly, May 4, 1912. A copy of this article is available on-line at http://www.encyclopedia-titanica.org/articles/candee_02.php.



It is entirely reasonable that 'A' deck should begin to flood as boat D was reaching the water at the point where Woolner said they jumped for it. Boat D was not just dropped into the water. QM Bright, who was put in charge of boat D, had said: "When the boat was lowered the foremost fall was lowered down and the other one seemed to hang and I called out to hang on to the foremost fall and to see what was the matter and let go the after one." To get into the boat near its bow Woolner and Steffansson had to land near the centerline of the collapsible not far from where the falls would be. Woolner estimated the distance as close to 9 feet. It had to have been quite a leap to land into the boat safely. I don't know how Steffansson managed to do it, but Woolner almost missed it altogether. "I jumped too, and hit the gunwale [of the lifeboat] with my chest, which had on this life preserver, of course and I sort of bounced off the gunwale and caught the gunwale with my fingers, and slipped off backwards." Woolner then had to be pulled into the lifeboat. Below is a picture of what it would have looked like looking aft.



Could this have happened the way it was described and pictured above? Consider the following. The boat deck was 58' 0" above a 34' 7" load waterline amidships. Allowing for a mean draft of 2 feet less since the ship had completed about two-thirds of its voyage, we are talking about a boat deck that was about 60 feet above the waterline amidships under zero trim. With the forecastle head seen to be going under when they launched boat D, the water at the aft end of the forward well deck would have to be close to the level of B deck forward on the ship's centerline, or 18' 6" below the boat deck. As QM Bright had

said, “What we call the forecastle head was just going under water. That would be about 20 feet lower than the bridge, I should say.” Now a list to port of about 10 degrees, producing a 2.5 feet gap between the side rail of the Boat deck and the side of a lifeboat as seaman Frank Evans observed, would bring the port side of the boat deck down by 8 feet while raising the starboard side by 8 feet. This means the port side of the forward part of the boat deck would only be 18' 6" - 8' = 10' 6" above the water which supports Lightoller's observation of how far they had to lower Collapsible D. This then puts the port side of ‘A’ deck at its forward end about 1 foot above the water at that time lifeboat D was launched, which was about 2:05 AM. Within a couple of minutes the sea would be up to ‘A’ deck, and as Woolner said, "And as we went out through the door the sea came in onto the deck at our feet.” They then hopped up onto the gunwale to make a jump for it “because if we had waited a minute longer we should have been boxed in against the ceiling."

Between the launching of D and the time Lightoller left the ship, the water would have risen from the level of ‘A’ deck to the top of the wheelhouse on the port side. It was in the last 10 to 15 minutes or so that things started to happen very, very fast.

I hope the diagrams presented in this paper will give the reader some concept of what the angles of trim and list were like at different points in time, and how they would change during the 2 ½ hours between the time of collision and the start of the breakup of the hull.

Appendix A – A Few Eyewitness Reports

[Captain Charles Weeks and Samuel Halpern]

The following table provides a list of key eyewitness observations regarding the flooding or condition of the ship following the collision. The following abbreviations are used: AI=American Inquiry, ATS=Apparent Time Ship, BI=British Inquiry, BR=Boiler Room, NYT=New York Time, WTD=Watertight Door, WTB=Watertight Bulkhead. For lifeboat launch times, see article by Bill Wormstedt, Tad Fitch, and George Behe previously referenced.

Time Interval	*Titanic* ATS	Witness	Reference	Observation
0:00	11:40pm	multiple	AI p.450.	Collision with iceberg.
		Barrett	BI 1868, 1917.	Water pouring in 2 feet above the stokehold plates in BR 6 at No. 10 stokehold and in forward bunker in BR 5 starboard side.
0:05	11:45pm	Hemming	BI 17716, 17724.	Peak tank flooding fast but forepeak above tank was dry.
		Shiers	BI 4532-4534.	Chunks of ice seen on well deck and iceberg disappearing off starboard quarter astern.
		Hendrickson	BI 4847-4851.	
0:10	11:50pm	Buley	AI p.607.	Water heard entering Hold 1and tarp ballooning over hatch; time is estimated.
		Hendrickson	BI 4847-4854.	Water seen at bottom of firemen's tunnel coming from starboard side; time and supported by Sheir's observations on well deck.
		Poingdestre	BI 2821-2825.	Told of 7 ft of water in Hold 1 by ship's carpenter.
		Hichens	AI p.451	A 5° list to starboard noted on inclinometer in the wheelhouse.
		Barrett	BI 1935-1937.	Water seen 8 ft over stokehold plates in BR 6.
0:12	11:52	Boxhall	BI 15374, 15379.	Water seen within 2 ft of G deck in Hold 3 on his 2nd inspection forward. Time estimated between 11:50 and 11:55.
0:15	11:55pm	Johnston	BI 3395-3397.	Flooding in baggage room on G deck seen from F deck in Hold 3.
		Wheat	BI 10901-10918.	Water coming onto G deck in Hold 3 just moments after meeting up with James Johnston; Wheat estimated the time at 10-15 min after collision.
		Threlfall	Bridgewater Mercury, May 1912.	Water was seen flowing down spiral staircase from leading-firemen's quarters on G deck.
		Symons	BI 11356, 11402-11413.	Water on G deck around coamings of Hold 1 hatch; "All hands stand-by" called by boatswain; Symons estimated this was "5 min to 12".

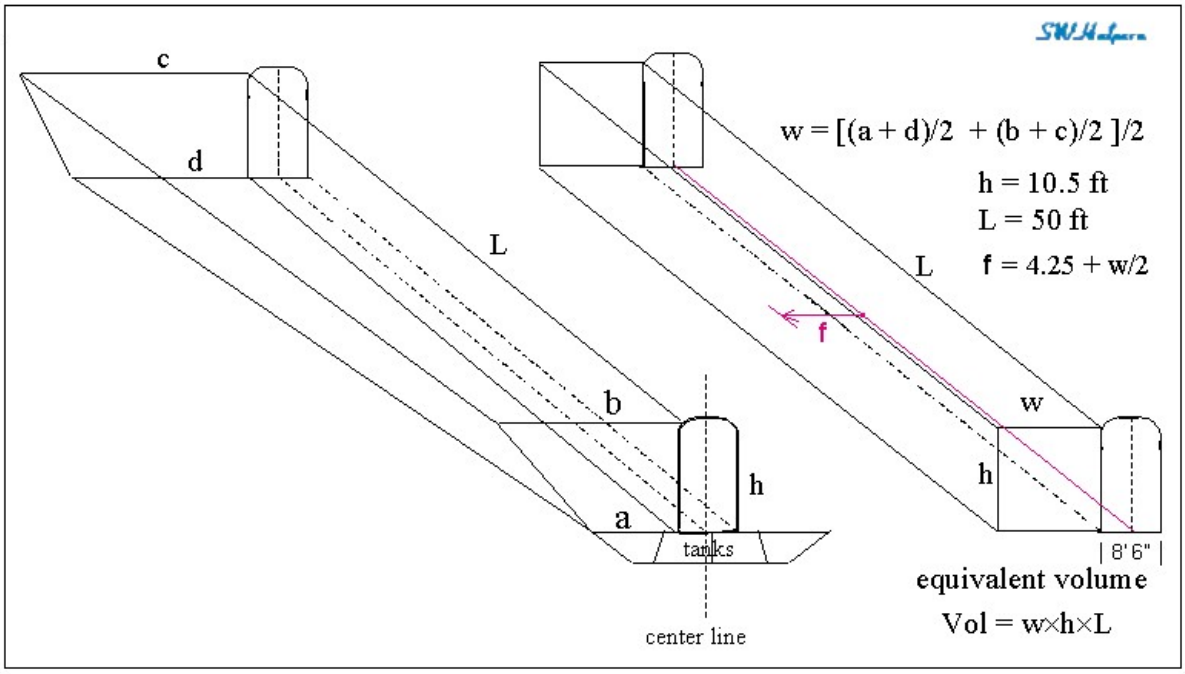
0:22	12:02am	Chambers	AI p.1042.	Saw 3 unidentified officers (engineers?) inspect flooding in post office/1st class baggage rooms. Water was within 2 ft of F deck in Hold 3 at this time and appeared not to be rising very fast according to an overheard remark coming from one of the officers; Time 1200-12:05 is estimate based on his actions and the rise of water seen in Hold 3.
0:28	12:08am	Pitman	BI 14958-14966.	Water seen coming onto G deck from starboard side by Hold 1 hatch.
0:30	12:10am	Robinson	BI 13277-13283.	Water seen within six steps of coming onto E deck (4 ft below) in Hold 3; She went to look just after seeing Capt. Smith and Thomas Andrews returning from the mail room about 1/2 hour after collision
0:45	12:25am	Poingdestre	BI 2842-2858.	Water 3 ft on E deck in crew's quarters. He estimated the time at 45 minutes after the collision.
1:05	12:45am	Wheat	BI 10956-10972.	Water was seen flowing down 1st class stairs from E deck down to F deck just aft of WTB-F. Estimated time at 12:45-12:50.
1:10	12:50am	Ray	AI p.803-804.	Water on E deck up to 2nd funnel casing by main 1st class stairway port and starboard sides.
1:30	1:10am	Barrett	BI 2348-2349.	Rush of water seen in BR 5 in pass between boilers; water on E deck seen coming from forward at location of escape from BR 5. Depth not quantified. Time was Barrett's best guess.
1:37	1:17am	Symons	BI 11490.	Water up to 2nd row of ports under ship's name at bow. [Time based on lifeboat launch time (1:05) plus 10-15 minutes to reach water and pull away due to being caught up on guy wire at B deck while lowering.]
		Cavell	BI 4248-4265.	Trimmer Cavell comes up the escape from BR 4 after seeing water coming over the stokehold plates there.
1:40	1:20am	Dillon	BI 3811, 3913.	Water coming up over stokehold plates forward in BR 4; He estimated it was 1hr 40min after collision when ordered up from engine room.
		Scott	BI 5839.	All personnel ordered up from engine rooms. Said it was 20 min past one.
		Threlfall	*Bridgewater Mercury*, May 1912.	Said that all personnel ordered up from stokeholds at 1:20am.
1:45	1:25am	Cavell	BI 4282-4294.	Went back down into BR 4 but came up again after seeing nobody there.
2:05	1:45am	Barrett	BI 2140-2142.	Notices forecastle head was not under yet from Boat No. 13.
		Nichols	private letter.	Notices *Titanic's* propellers were half out of the water from Boat No. 15.
2:10	1:50am	Evans	AI p.677.	List to port about 10° based on 2.5 ft gap between lifeboat 10 and side of rail on boat deck.
2:12	1:52am	Bride	AI p.1063; 16543-16553.	*Baltic* responds to Bride's message at 11:50 NYT. Philips returns and Bride informs him of communications with *Baltic*. Philips reported seeing well deck awash, and a list to port was very noticeable.

		Bright	AI p.837.	Forecastle head seen going under as Boat D is lowered.
2:25	2:05am	Rowe	AI p.524.	Boat C reaches water and well deck was seen completely submerged.
2:35	2:15am	Lightoller	AI p.90.	Water up to crow's nest and coming over the forebridge before he jumped in. Time is best estimate based on breakup events described below.
		Gibson	BI 7565.	Lights of steamer that fired rockets disappeared at 2:05am *Californian* ATS, 2:17am *Titanic* ATS.
2:37	2:17am	Symons	BI 11510-11525.	*Titanic's* stern came "well out" as bow pitches down suddenly as all the lights go out. Ship appeared to split in two "abaft the after expansion plate" with the stern righting itself without the bow. Time based on seeing remaining stern section go under "two or three minutes" afterward.
2:40	2:20am	multiple	AI p.294.	Remaining stern section disappears beneath the surface.

APPENDIX B – THE INITIAL LIST TO STARBOARD

The contributors to an initial list to starboard would be due to asymmetrical flooding in various compartments. When we look at all 6 forward compartments what we see is Hold 2 and Hold 3 having an effective longitudinal watertight bulkhead in the way of the firemen's tunnel. This would tend to confine the flooding initially to the starboard side until water overflowed the height of the tunnel and began to fill the port side as well. The flooding of the emptied forward bunker in BR 5 on the starboard side also contributed to the list. Since the peak tank was on the ship's centerline there would be no heeling moment there. Hold 1 and BR 6 have nothing to stop the water from moving across the compartment transversely, and so they could be ignored initially in trying to estimate the initial angle of heel due asymmetrical flooding. Water flooding into the firemen's tunnel, which was also reported early on, would not contribute to the heel since it too was on the ship's centerline. In estimating the contribution from the bunker in BR 5, I assumed that the rate of flooding was from an equivalent fire hose opening of 3 inches diameter with a pressure head of 25 ft located 4.5 ft above the tank top (2 ft above the stokehold plates) as reported by fireman Fred Barrett. I found it would take about 12 minutes to fill the bunker to that level with 41.5 tons of water in there. The center of the bunker from the centerline of the ship worked out to be about 27 ft. This contributes a heeling moment of 1120.5 ft-tons.

Now we have to look at the contributions of Holds 2 and 3. To do that I had to estimate the volume that would be flooded on the starboard side of the ship between the hull and the starboard side of the tunnel. With reference to the figure below, the firemen's tunnel reaches a height of 10.5 ft above the tank top. The next thing was to measure the distances from the starboard side of the tunnel to the starboard side of the hull in three places, first was aft of bulkhead B, then at bulkhead C, then at bulkhead D, and also at two heights, at the level of the top of double bottom, and 10.5 ft above that, the height of tunnel. For this I used detailed bulkhead plans from H&W. I then took the average distance to the side for the tank top level and for the 10.5 ft level above it. Summing these two numbers together and dividing by 2 gets the average width of the volume we are looking for. For Hold 2 this came out to be about 12 ft, and for Hold 3 it came out to be 25.2 ft. – Think of this as the average width at half the height of the firemen's tunnel in those two cargo holds. – The next thing I did was to multiply these average widths by the height of tunnel (10.5 ft) to get their mean cross sectional areas. The next step was to multiply those mean cross sectional areas by 50 ft, the approximate length of each hold, to get the volumes we are looking for. I then added 10% to these values to account for the small volume between the double bottom margin plates and hull that is below the level of the tank top that would also fill up. Finally, the next step was to divide these calculated volumes by 35 long tons per cubic ft to get the tons of seawater that would take up those spaces. The results are, Hold 2 takes on 198 tons and Hold 3 takes on 416 tons on starboard side to the height of the firemen's tunnel. Keep in mind that this is not the total quantity of water entering these compartments, but only the amount that entered that would cause the ship to take on an initial list to starboard. Any water spilling over the top of the tunnel would add to a corrective moment tending to reduce the list as these compartments continued to flood. Thus what I did was look for the worst case list which is what we are really interested in.



To get the heeling moments for Holds 2 and 3 we have to find the centers of the flooded areas from ship's centerline. That would equal 1/2 the average width of the volumes taken from above plus another 4.25 ft which is one-half the width of the tunnel (also shown in the above figure). The results were a moment arm for Hold 2 that came out to be about 10.3 ft, and for Hold 3 that came out to almost 16.9 ft. When these are multiplied by the weight of water in each volume we get 2039 ft-tons for Hold 2, and 7036 ft-tons for Hold 3. These numbers assume that those spaces were empty. If we now then take a permeability of 75% as assumed by H&W naval architect Edward Wilding for these two holds, then the two moments become 1529 ft-tons for Hold 2, and 5277 ft-tons for Hold 3. If we then add all three moments together, Hold 2, Hold 3, and the starboard bunker in BR 5, we get a total of 7926.5 ft-tons.

Now once a list starts to develop it would also cause water in the compartments that have free, unconstrained movement, to slosh towards the starboard side, thus changing the location of the water's center of mass in those compartments. The contributions of these various compartments however would differ. For example, the peak tank and Hold 1 would not be major contributors since they are relatively narrow and the moment arms would be quite short. The major contributor would of course be Boiler Room No. 6 which is quite wide. The unsymmetrical wedge that results can easily be calculated for a given angle of list. It is essentially independent of the depth of water in that compartment. If we do this we find a moment of 3492 ft-tons is produced based on the dimensions of that boiler room and a permeability of 65% for flooding that does not yet get above the height of the boilers. All of this is based on the dimensions of the boiler room, the double-ended boiler volumes, and a list of 5 degrees which was obtained through an iteration process. Thus the total heeling moment caused primarily from the flooding in Holds 2 and 3, BR 6, and the starboard bunker in BR 5 equal 11,418.5 ft-tons.

To get the angle of list in radians we divide this number by the ship’s displacement on the night of April 14, and then divide that result by the metacentric height (the GM) of the ship. Both the ship’s displacement (48300 tons) and the metacentric height (2.63 ft) come from work of Hackett and Bedford. The result that is obtained is an angle of list of 0.090 radians, which equals **5.15 degrees**, a result that agrees very well with the observation of QM Hichens.

The results in this analysis, as in any other, are subject to the approximations and assumptions that were taken. It says one would expect to see a list close to 5 degrees on an inclinometer about 10 to 15 minutes or so after contact with the iceberg. As water would start to fill the spaces on the port side of Holds 2 and 3 after going over the top of the firemen's tunnel (via the hatchways for example) one would

expect the list to starboard to begin to lessen over time despite the bunker in BR 5 continuing to fill because of the differences in flooding rates. The bunker itself would continue to fill until one of the bunker doors gives way, which is the real weak point on the bunker bulkhead. My guess is that it was a bunker door that gave way when Fred Barrett saw that rush of water come from the passage between the boilers when he was in BR 5 later on that night, and not a collapse of a watertight bulkhead as some others have assumed.

HOME