The Physics of Tank Spillage

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1 Preamble

The physics of how a breached tank spills oil is an interesting subject on at least four grounds:[1]

1. The results can be counter-intuitive and quite surprising in certain cases.
2. A tanker crew who truly understands the process can in many damage situations significantly reduce or even eliminate spillage by properly listing and trimming the ship. Conversely, a crew or responders who do not have this understanding can materially increase the spillage by improper cargo and ballast transfers. This has happened far more often than it should. An example is the Tamano spill discussed in Section 6
3. Tanker designers need to understand how tanks lose oil in order to develop ships with attractive spillage characteristics and avoid designs with poor spillage characteristics.
4. Regulators need to understand these physics in order to draft legislation which promotes ships with good spillage characteristics and discourages ships with poor spillage characteristics. In the past, poor understanding of tanker spillage has resulted in legislation that inadvertently promoted designs with very poor spillage behavior. The Marpol single hulls are an obvious example.

Having said this, it is essential to recognize that what happens after a tank is breached can have only the most marginal impact on overall tanker spillage. Low to medium impact groundings in which the ship survives produce less than 9% of all the oil spilled by tankers.[**?**] And low and medium impact collisions are responsible for less than 3% of total tanker spillage. Differences in tank arrangement (pre-Marpol, Marpol, double side, double bottom, double hull, etc) and crew response can affect only a fraction of these small percentages. In general, in past tanker regulation, there has been far too much focus on attempting to reduce spillage after a grounding or collision has already occurred and much too little emphasis on preventing the grounding or collision in the first place. For example, far more spillage would be prevented by mandating twin screw than could ever be obtained by various tank arrangement alternatives.

Moreover, by far the single most importance cause of tanker spill volume and crew deaths is structural failure. And the most important cause of structural failure is segregated ballast tank corrosion.[**?**] Tanker designers

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[1] This paper is a modified version of Appendix C of The Tankship Tromedy for use on-board, in conjunction with CTX Mate. Automatic links to the CTX Tanker Casualty Database have been eliminated, as well as the photographs. Comments on the tanker regulatory system have been largely eliminated. Section 6 has been entirely re-written to reflect the current status of CTX Mate. The sections on vacuum have not been included. The original is available at www.c4tx.org.

and tanker regulators must be careful to avoid increasing the probability of structural failure in an attempt to make a small reduction in spillage in certain groundings and collisions.

Still more basically, the central problem in tankers is not how tanks are arranged but a regulatory system in which the key regulator, the Classification Society, is beholden to the regulatee for his existence.

In short, the contents of this CTX Technical Paper are not central to the core issues in tanker design and regulation.

Despite this, an enormous amount of effort, and even more hot air, has been expended on analyzing the pros and cons of a particular tank arrangement on the amount of oil spilled after a grounding or collision has occurred. Much of this discussion has been ridiculously politicized. In this highly charged debate, the simple, if sometimes surprising, physics of tank oil spillage has become obscured. Worse, an understanding of this process has not filtered down to either tanker operators or spill responders, despite the fact that that knowledge would do more to reduce spillage than all the paper studies of various tanker designs.

This Technical Paper is aimed primarily at those operators and responders. But it may also prove useful to tanker designers and regulators.

2 Hydrostatic Balance

In order to understand how a damaged tank spills oil, we need to understand *hydrostatic balance.* The physics is quite simple, even if the results are sometimes a little counter-intuitive.[2] Hydrostatic balance can be understood by any one who has balanced a large block of wood on a balance scale with a much smaller iron disk. It's not the volume that counts; it's the weight.

Crude oil is almost always less dense than water. An extremely dense crude oil such as Tia Juana Heavy from Venezuela has a specific gravity of 0.93; that is, a liter or gallon of this liquid weighs 93% as much as a liter or gallon of fresh water. A very light crude oil such as Zuetina from Algeria has a specific gravity of 0.80. A liter/gallon/whatever of this stuff weighs 80% as much as the same volume of water. The great majority of crudes have specific gravities which are between 0.82 and 0.87. Sea water has a specific gravity of about 1.02. It is about 2% denser than fresh water thanks to the dissolved salts it contains. More importantly, for present purposes, sea water is about 20% heavier than a typical crude oil.

With this background, let's start with the simplest situation: single bottom with the damage confined to the bottom. Figure 1 is a sketch of an old style, pre-Marpol, single hull ULCC, fully loaded. The solid line sloping downward and to the right shows the internal pressure in the tank as we move vertically downward in the tank. In Figure 1, we have assumed that the cargo has a specific gravity of 0.85, a middling density for crude oil. That is, a cubic meter of this oil weighs 85% as much as a cubic meter of fresh water. Inside the tank, the pressure head increases by 0.85 meters for each meter we move down in the tank. Thus the slope of the solid line is 0.85.

The dashed line shows the external pressure in the sea outside the tank. The seawater pressure head increases by 1.02 meters for each meter of depth. Seawater is heavier than oil; so as we move vertically downward the seawater pressure outside the tank increases more rapidly than the internal pressure in the tank. However, the pressure inside the tank has a head start since the top of the oil in a fully loaded tank is well above sea level. At some point the seawater pressure will catch up to the tank pressure.

The cross-over point is known as the *Neutral Level.* At any depth above the Neutral Level, the internal tank pressure is higher than the external sea pressure. Damage above the Neutral Level will result in a hydrostatic outflow of oil into the sea. At any depth below the Neutral Level the external sea pressure is higher than the internal tank pressure. *Damage below the Neutral Level will result in a hydrostatic inflow of seawater* ***into*** *the tank.*

In Figure 1, the Neutral Level is 2.7 meters *below* the keel. This means

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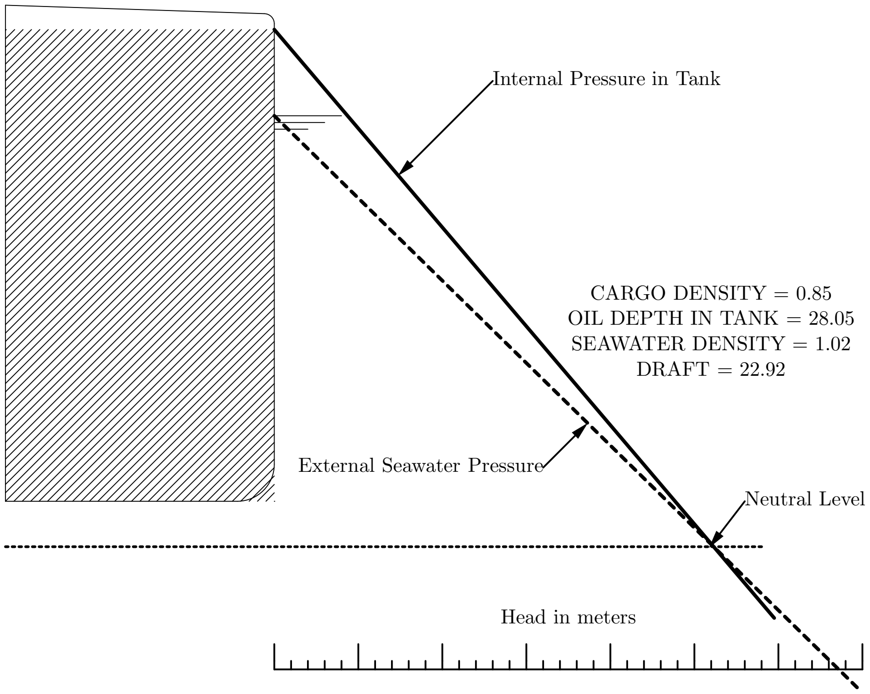
[2] Equations will be confined to footnotes. They are not really needed anyway. What is important is the sketches. All the sketches in this document are to scale. They are anatomically correct.

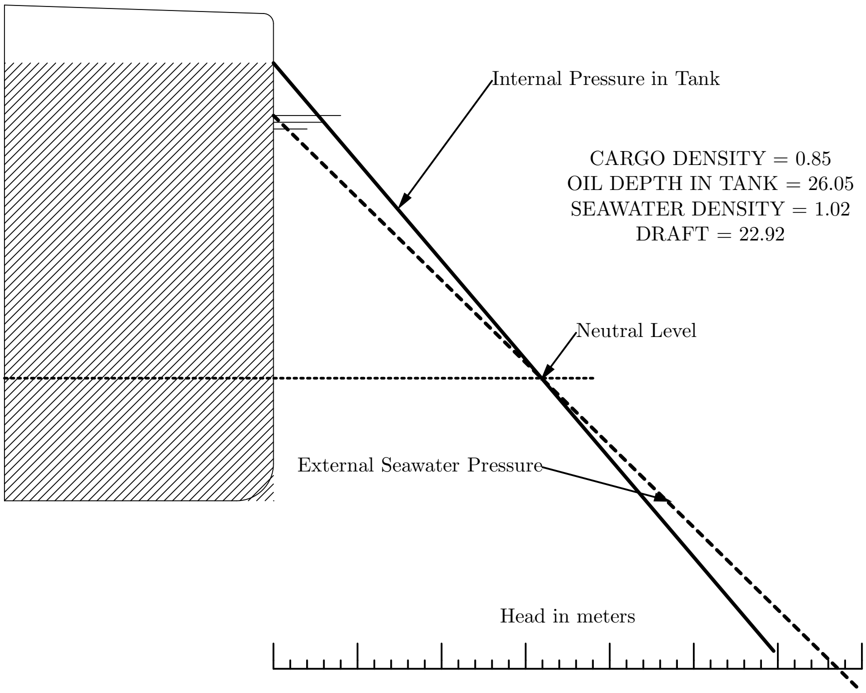


NEUTRAL LEVEL IS 2.7 M BELOW KEEL
Hydrostatic outflow from damage anywhere in the tank including flat bottom

Figure 1: Neutral Level, Fully Loaded Pre-MARPOL ULCC

that even at the very bottom of the tank the internal oil pressure is higher than the external seawater pressure. Damage anywhere in the tank, even at the very bottom, will result in a spill. Oil will flow out of the tank until the internal and external pressures at the top of the damage have equalized.

Now suppose we draw down the initial level of cargo in this tank 2 meters. Figure 2 shows the new situation, assuming the ship remains at the same draft. The oil has lost a considerable portion of its head start; and the Neutral Level, the depth at which the internal and external pressures are equal, is now 7.3 Meters *above* the keel. Drawing down the tank 2 meters has lifted the Neutral Level a surprising 10 meters.[3]



NEUTRAL LEVEL IS 7.3 M ABOVE KEEL
No hydrostatic outflow from damage below Neutral Level

Figure 2: Neutral Level for same ULCC, Tank Drawn Down 2 M

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[3] For the geeks, the equation for the Neutral Level is

$$H_{NL} = \frac{\rho_{sea} D - \rho_{oil} H_{oil}}{\rho_{sea} - \rho_{oil}}$$

where H_{NL} is the height of the Neutral Level, ρ_{sea} is the sea water density, ρ_{oil} is the cargo density, D is the ship's draft, and H_{oil} is the initial level in the tank. The fact that the denominator is generally less than 0.2 gives rise to the multiplier. Heavier cargoes have higher multipliers and vice versa.

In this case, we have a multiplier of five, every meter change in the initial cargo depth changes the Neutral Level by five meters. This multiplier results from the fact that the solid and dotted lines in Figures 1 and 2 are nearly parallel. So a slight shift upward or downward in either of these lines, makes a big difference in the cross-over point.

In Figure 2, if we have damage which is confined to the flat bottom, sea water will push into the tank lifting the oil in the tank until the internal pressure and the external pressure are equalized. When you do the calculations, you find that this will occur when the oil-water interface is 1.2 meters above the bottom. Figure 3 shows this final situation and compares it with that which would have occured if the ship had initially been loaded as in Figure 1.

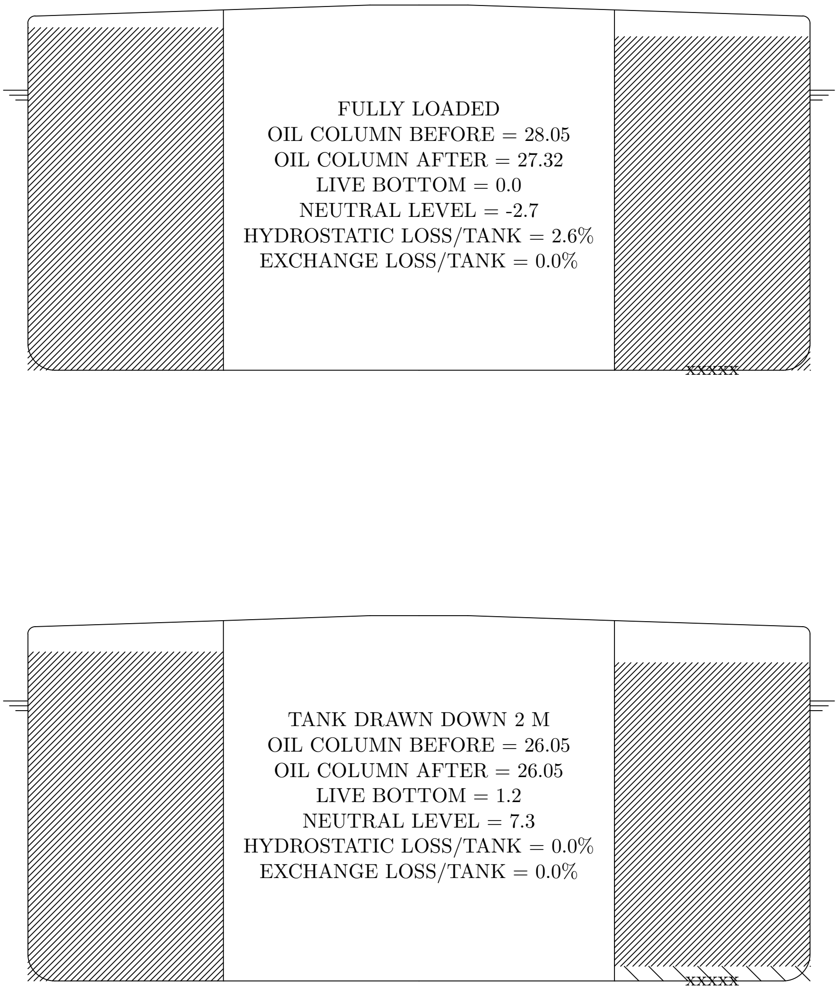

Figure 3: Final situation, Full load vs Tank Drawn Down 2 M

The top half of Figure 3 tells us that *as long as the damage is confined to the bottom*, a fully loaded pre-Marpol tanker will spill less than a few percent of the oil in each tank that was breached. Notice that the equilibrium level of oil in the tank is still well above sea level after the oil has stopped flowing out. One of the clains for double bottoms is that they are much better than the crummy old Marpol single bottoms in bottom damage. Well, the fact is that the old Marpol single hulls were pretty damn good at limiting outflow in bottom damage.

I need to make an extremely important qualification here. Figure 3 assumes the ship is at the same draft before damage and after. As long as only one or two tanks are damaged, this will be nearly true. If a lot of cargo tanks are damaged, the ship will rise in the water during the outflow and this can materially increase the outflow. The multiplier is a two-edge sword. Conversely, if some ballast tanks are damaged and flooded or a quick thinking crew ballasts the ship down, the leakage can be markedly reduced.[4]

The bottom half of Figure 3 says we only had to underload such ships by about 7%, and they would have spilled nil oil if the damage is limited to the bottom. (Once again I'm assuming the underloading was accompanied by sufficient ballast to keep the ship at the same draft.)

The bottom half of Figure 3 also tells us we must be careful to distinguish the Neutral Level from the equilibrium oil-water interface. In this situation, the Neutral Level is 7.3 meters above the bottom of the tank, but the oil-water interface after the sea water flows into the tank is only 1.2 m above the bottom of the tank. This equilibrium oil-water interface is called the *Live Bottom*.[5]

Most people have no problem accepting the fact that, if the level of oil in the tank is below that of the surrounding seawater, and we puncture the bottom of the tank, sea water will flow into the tank rather than oil flowing

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[4] Another less important, but still very significant qualification. All tanker cargo tanks are normally inerted. That is, they are pressurized with low O_2 gas from the ship's boilers. This prevents explosions. But it also increases the pressure in the top of the tank. Typically, this increase in pressure is equivalent to about a half-meter of sea water. The solid line in Figures 1 and 2 actually starts off about a half-meter higher than I have shown.

It is even a little more complicated than this. If there is outflow, the pressure in the ullage space will be drawn down, possibly as far as the P/V valves allow. If there is inflow, the pressure in the ullage space will be pushed up, possibly as far as the P/V valves allow. These effects can have a major impact on actual outflows. We will make the necessary adjustments in Section **??**.

[5] Assuming that there is a Live Bottom, the equation for the Live Bottom is

$$H_{LB} = \frac{\rho_{sea} D - \rho_{oil} H_{oil}}{\rho_{sea}}$$

where H_{LB} is the height of the Live Bottom. Notice there is no multiplier. In both the H_{NL} and H_{LB} equations, the seawater depth D at the damage is critical. It determines the external pressure. Change that depth and you change all the spillage numbers.

out.

But there are two aspects of hydrostatic balance that are much harder to swallow:

(A) One is that the water will flow in rather than oil flowing out even if the initial level of oil in the tank is above the surrounding seawater, as long as the weight of the column of oil is less than the weight of the column of sea water.[6] For a light crude and a pre-Marpol ULCC at deep draft, the level in the tank could be 4 meters higher than the sea level outside, and yet water would flow in from bottom damage rather than oil flowing out.[7] Water is heavier than oil. Think of that balance beam.

(B) The fact that a small change in the initial level of oil in the tank can make a far larger change in the position of the Neutral Level. As we have seen, thanks to the relatively small difference in density between seawater and oil, changing the initial level in the tank by 1 meter, typically changes the Neutral Level by 5 or 6 meters.

In our everyday life we don't have a lot of experience with different density liquids. If we fill up a U-tube with water, we know the level in the two ends of the tube will end up being the same. We sort of expect the same thing to happen, even if the liquids are not the same. If you have a U-tube, fill up one side with olive oil and the other with vinegar. You will see the difference. Anyway the physics couldn't be simpler or more irrefutable; and points (A) and (B) have been experimentally verified many times. I have to ask you to study Figures 1, 2 and 3 until they really make sense to you.

The term *hydrostatic balance* is used in two different contexts:

1. To refer to the equilibrium situation after the the oil water-interface has stabilized, as in "the tank had reached hydrostatic balance".
2. To refer to a tank in which the initial, undamaged cargo level is low enough so that the Neutral Level is above the bottom of the tank, as in "the tank was hydrostaticly balanced loaded". This horribly awkward phrase is usually shortened to HBL. An HBL tank in calm water will not spill oil ***if the damage is confined to the flat bottom***.[8]

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[6] It is not just laymen that have a problem with this. Many spill responders don't understand it. The report of the Diamond Grace spill in Tokyo Bay by the response commander has a sketch which shows he believes that the equilibrium level in a breached tank is the seawater level.

[7] A corollary of this fact is that hydrostatic pressure can push oil out of the tank thru P/V vents and the like if the damaged tank is low in the water and the oil column is tall enough.

[8] In a similar fashion, we will sometimes used the phrases *hydrostatically over/under-balanced* to refer to a tank in which the cargo level is above/below the HBL level.

3 Marpol versus Pre-Marpol

For our first application of hydrostatic balance, let's compare Marpol single hulls with pre-Marpol single hulls. On the right side of Figure 4 is a 215,000 ton Marpol VLCC which looks suspiciously like the Exxon Valdez. On the left side is a standard 275,000 ton pre-Marpol VLCC which has been scaled to 215,000 ton deadweight. The Marpol VLCC is a slightly bigger ship, about 2 m taller, because none of the cargo tank volume can be re-used as ballast tank volume.

Both ships are fully loaded with a 0.85 specific gravity crude. For the pre-Marpol ship loaded down to her marks, this means using up only about 94% of the available cargo cubic.[9] But for the Marpol tanker, we must use all the available cubic leaving 2 to 3% for cargo expansion. The result is that the initial oil column in the Marpol tanker is more than 2 meters taller than that for the pre-Marpol ship. But the initial drafts are almost the same.

The visual difference between the ships in Figure 4 is not all that striking. But when the tank on the right in the pre-Marpol ship is bottom damaged, a little less than 0.5 m of oil flows out before hydrostatic balance is reached. When the same tank in the Marpol tanker is bottom damaged over 2.5 m of oil flows out. ***In percentage terms, the Marpol tanker spills five times as much oil. Applied to the Exxon Valdez which ruptured 8 of 11 cargo tanks, the extra 2 meters of outflow is about 10 million liters.***

This analysis is far from complete:

1. We have not adjusted for differences in tank arrangement. The pre-Marpol VLCC will typically have 24 tanks of which two are segregated ballast. The Marpol VLCC will have something like 15 tanks of which four are segregated ballast. Normally, the Marpol tank will be considerably bigger than the pre-Marpol tank. On the other hand, the Marpol ship has a higher probability of damaging a non-cargo tank than the pre-Marpol ship.
2. We have not adjusted for change in draft, trim, and heel. As we shall see, this adjustment is critically important. In the situation in Figure 4 if the tank on the right is the only breached tank, then both ships will list away from the damage which will exacerbate spillage. However, the Marpol ship will list more (and rise more) increasing spillage more.
3. We have not adjusted for tide (if stranded), IG pressure, nor the vacuum that is created in the top of the tanks with outflow.

We will get into all these matters. However, it is obvious that the Marpol

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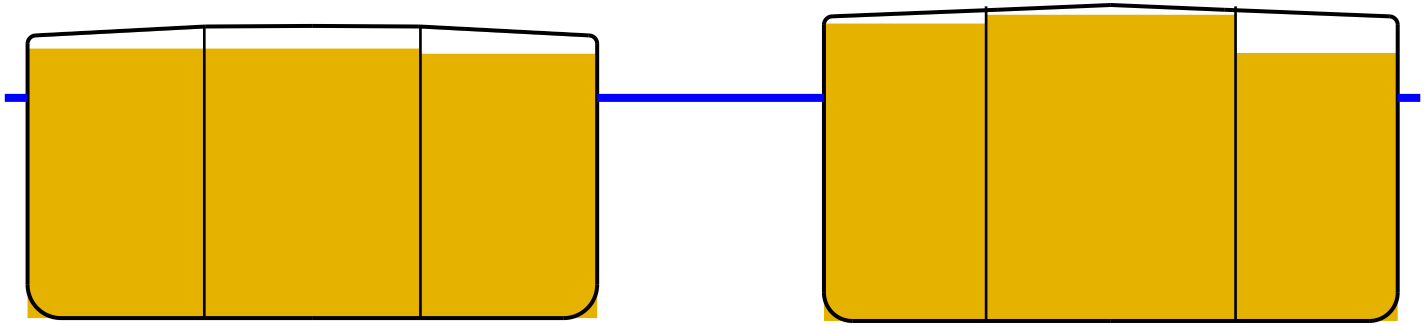
[9] A smart move in pre-Marpol days was to use up all the cubic in the center tanks in which case for most crudes the wing tanks are hydrostatically under-balanced when the ship is loaded down to her marks. This is precisely how IMO Reg 13(G) was implemented on some old ships, usually with no loss in carrying capacity. In the left side of Figure 4, this was not done.

single hulls are hydrostatically challenged.

Figure 4: Marpol vs pre-Marpol Spillage

BOTTOM DAMAGE TO TANK ON THE RIGHT



PRE-MARPOL 215,000 DWT
Depth = 24.887
Waterline = 19.400
Initial Innage = 23.735
Final Innage = 23.280
Percent Loss = 1.917

MARPOL 215,000 DWT
Depth = 26.820
Waterline = 19.660
Initial Innage = 26.190
Final Innage = 23.592
Percent Loss = 9.920

4 Yeah, but Where's the Seal

Another problem people have with hydrostatic balance is the efficacy of the seal. The Live Bottom is not really a bottom. In many situations, the oil-water interface will be quite close to the real bottom or equivalently the top of the damage. There's no barrier there; no membrane or anything similar keeping the oil in the tank. How good a seal can it be?

If the damage is confined to the ship's bottom, the ship is floating, and nobody does anything stupid, it turns out that a Live Bottom is a pretty effective seal. Almost all crude oils hate to mix with water. The molecules repel each other. This accounts for the spreading and persistence of oil slicks, even in fairly rough water. If you do manage to mix some of the oil into the water, it will immediately tend to separate.[10]

For a floating ship, there are two natural phenomena that can generate spillage after a Live Bottom is established: current and waves. After the Exxon Valdez, the US Coast Guard decided it would be politically unwise to oppose double bottoms. This was a major change. In the 1979 post-Amoco Cadiz debate, the Coast Guard had argued for limits on tank size and against double bottoms. The main alternative to double bottoms was hydrostatic balance.

The Coast Guard knew they could not attack the basic physics of hydrostatic balance. They decided to go after the seal. In 1992, the USCG funded a series of 1/30th and 1/15th scale experiments at the David Taylor Research Center (DTRC).[**?**] These tests were an intriguing combination of crude but very interesting experimental science and blatant politics on the part of the sponsor.[**?**] But the key result is summarized in Figure 5.[11] This figure shows the Live Bottom height required to effectively halt current entrainment according to these model tests. If the Live Bottom is right at the ship's bottom, current under the ship produces a wave at the oil/water interface. When a trough in the wave reaches the down current end of the damage, the oil in the trough is clipped off and lost into the sea. As the Live Bottom rises in the tank, the amplitude of the interface wave decreases; and, for a high enough Live Bottom, even the trough in the wave is above the ship bottom, at which point current loss effectively halts. As Figure 5 indicates for a three knot current, the Live Bottom has to be about 0.7

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[10] All the witnesses to the Exxon Valdez were struck by how violently the oil emerged from the water.[**?**][p 45] The velocity that the oil had attained in its 15 to 20 m climb to the surface generated little geysers. USCG Warrant Officer Delozier, who reached the ship three hours after she grounded testified

> The oil was coming out of vessel at a very intense rate .... bubbling up into the air, sometimes up to sixteen, eighteen, twenty inches high.

[11] The DTRC experiments were actually a follow on to work done at the Tsukuba Institute in Japan which produced similar results.

meters above the real bottom.[12] For a 5 knot current, we need about a 2.2 m Live Bottom height. The required Live Bottom height goes as the square of the current velocity as would be expected from Bernoulli's Law.

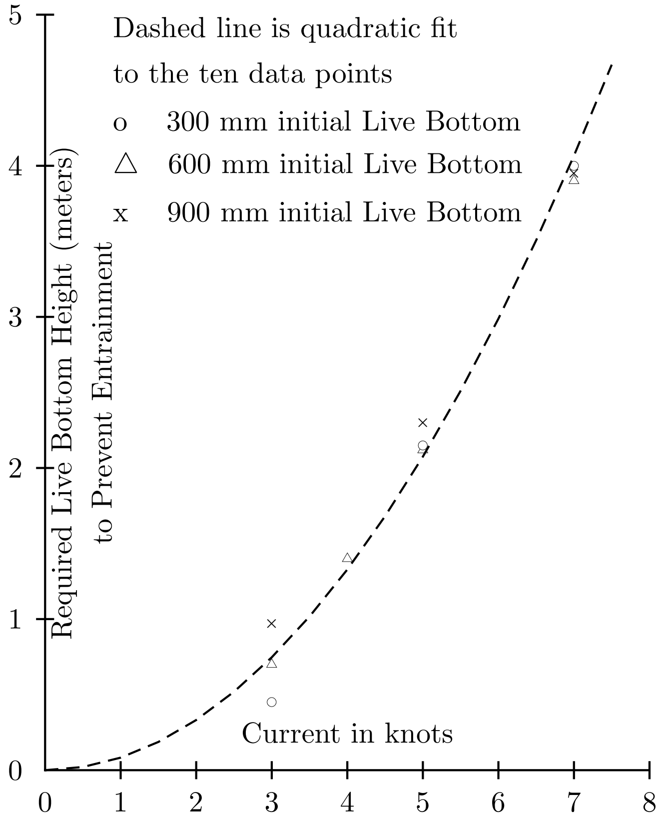

Figure 5: Required Live Bottom Height versus Current Speed

I would not make too much of Figure 5 for two reasons:

1. There is good reason to doubt the accuracy of the extrapolation of the model results to full scale. The difference between the DTRC results at 1/30th scale and 1/15th scale showed that the straightforward extrapolation used in the DTRC report and Figure 5 was of limited accuracy. DTRC was careful to point this out and call for more research; but this has never been done. The results in Figure 5 should be taken as indicative only.
2. The test procedure was to place the model tank in a circulating water tunnel and then open a hole in the bottom of the tank. This is OK experimental science but does not model a stranding.[13] Most severe groundings are strandings. In a stranding, the area around the damage

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[12] Figure 5 is not in the DTRC report. It is my interpretation of the results in Figure 9 of that report. It is the level of the Live Bottom in the tank 2 hours (ship time) after the start of the experiment at which point the oil loss rate is nil.

[13] Nor does it model the initial grounding process. Some have argued that during impact

is partially blocked by the sea bottom. Moveover, even if the surface current is say 3 knots, the current next to the sea bottom will be much smaller.

In any event, currents much in excess of 3 knots are reasonably rare and Figure 5 gives us considerable comfort that, as long as the Live Bottom is a meter or more above the top of the damage, current will almost never be a factor. In extraordinarily high current environments, you may need as much as a 2 m Live Bottom height.

A real world example of the power of hydrostatic balance in the face of large current was the OCEANIC GRANDEUR spill. On March 3rd, 1970, the Oceanic Grandeur hit an uncharted rock in the Torres Strait. The 61,000 tonner was nearly fully loaded with 55,000 tons of crude. When she hit the rock, 8 of 15 cargo tanks were breached. However, the ship flooded in a manner that resulted in her sinking 2 or 3 meters with a slight list to port, putting the port gunnel just underwater. This sinkage improved the hydrostatic balance considerably. The ship lost considerably less than 1% of her cargo as a result of the initial damage.

The weather was calm throughout but the currents in the Torres Strait can be extremely strong. Despite this, the Australian investigation report explicitly says nil oil was lost during the subsequent three days *despite tidal currents of up to 6 knots* [emphasis mine].[**?**] This was not a stranding; the ship was at anchor during this period. Most of the 1100 kiloliters spilled was lost on the 7th day of lightering as the ship rose out of the water, reducing the external hydrostatic pressure. If they had done a really careful job of lightering and ballasting, this latter spillage could have been prevented; but probably, at the cost of a longer lightering, which would have entailed its own risks. Even so the Oceanic Grandeur, with over half her cargo tanks breached, lost just 2% of her cargo. And we can be sure that the damage was not confined to just the flat bottom. In the real world, there is no such thing as a flat bottom only grounding.[14]

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the damaged tanks are momentarily exposed to the very high "current" produced by the ship's forward motion, and attempted to apply the DTRC results to this process. But they are forgetting that not only will the damage be largely blocked by the sea bottom during that period, but sea bottom material will be penetrating into the tank volume. This was dramatically illustrated in the Exxon Valdez where the crew reported that the P/V valves of the damaged tanks vented violently as the ship rode onto the rocks. The first thing that happens is the liquid in the tank is forced upward.

[14] A critically important factor in this casualty was the strength of the ship. The Oceanic Grandeur was able to withstand the over-design sagging moment associated with flooding the midships segregated ballast tanks while loaded *with her bottom all torn up*. The fact that this 61,000 tonner was built in 1965 meant that she had more strength than the later 1970's built pre-Marpol ships, not to mention far more strength than the tankers built in the 1980's and later. If the hull had failed — and a modern hull probably would have — the Grandeur would have spilled the better part of 50,000 kiloliters on the Great Barrier Reef, making this one of the most famous spills of all time. As it was, you almost certainly have never heard of this ship.

A more effective way of breaking a Live Bottom seal is wave pumping. Waves can disturb the Live Bottom two ways:

1. If the waves are small relative to the ship, almost always the case for big tankers near shore, or the ship is hard aground, we can ignore ship motion. In this case the local wave height in way of the damage becomes the key. In this situation, a conservative upper bound on oil lost to wave pumping is to assume the "real" sea level is the calm water sea level less one-half the wave height. In practice, wave pumping becomes quite slow as the Live Bottom rises to this "equilibrium" level. In the Thuntank 5 grounding, the Swedes found that several days of 4 to 5 meter waves was equivalent to an effective calm water sea level, about 1.4 meters below the actual water level.[15]

   A far more graphic example of waves having little effect on a stranded tanker — at least until they break the ship up — is the Nino grounding. On July 18, 2002, thanks to equipment failures and some truly sloppy navigation, the loaded product tanker, Nino, ran aground on exposed South African coast near East London. The ship grounded hard on sand just a few hundred yards off a beach, in the surf zone. As soon as the master realized he could not get the ship off using his own power, he did a very smart thing. He ballasted down. He did this to prevent the ship pounding in the surf. But he also improved his hydrostatic balance dramatically. The fact that the ship had already part discharged also helped matters.

   On July 31st, the ship was refloated after lightering about 2000 tons of cargo, one of the very few successful refloats off the South African coast. The ship's bottom was badly damaged, requiring 925 tons of steel repair. The official investigation report says "there is no report of any spillage". This was a single hull ship stranded for two weeks in the surf zone where wave heights are at their maximum.

2. If the ship is afloat and the waves are large enough to produce significant pitch, heave or roll, then the tank will continue to leak until the oil-water interface is in equilibrium when the tank at its highest point in the ship motion. However, as the DTMB report points out, the purely wave induced leakage rate will usually be quite slow. In fact, there have been any number of cases in which a loaded tanker has experienced bottom damage, sometimes serious damage, and then after hydrostatic balance plus a margin has been achieved has proceeded to its final destination over long distances with nil additional spillage. See for example, Embiricos, page 23.

we must get ship and date

Groundings usually occur in protected or semi-protected waters. They never occur in the open sea. The sad fact is that, if a grounding occurs in a situation where the waves are so large that wave pumping is really impor-

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[15] In this spill, the quick thinking master used vacuum to his advantage.

tant to spillage, the ship is unlikely to survive. Witness TORREY CANYON, ARGO MERCHANT, AMOCO CADIZ, (and just about all the other groundings on the coast of Brittany), BRAER, TASMAN SPIRIT and many others.

If current and wave pumping are not all that good at breaking the Live Bottom seal, there are two very effective ways of clobbering hydrostatic balance.

1. Pumping out intact tanks before pumping out damaged tanks. This lifts the ship out of the water and turns the multiplier against us. Since responders either don't really understand hydrostatic balance or are responding to other pressures, this is not that uncommon. It happened in the Oceanic Grandeur, and in at least two other major spills, that I know about (the TAMANO, and the IMPERIAL SARNIA). In each case, more than doubling the size of the spill. More on this later.
2. Put your ship aground at high tide, and then have the tide go out 2 or 3 meters, dropping the Neutral Level by 10 to 15 meters. This is what happened to the EXXON VALDEZ, Tidal height is crucial to grounded spillage, and must be allowed for in any realistic analysis of groundings. But before we address this issue we need to worry about side damage.

5 Side Damage and Exchange Flow

So far we have talked only about bottom damage. If the damage extends up the side of the tank and any real world damage will, the situation becomes a bit more complicated.

If we have side shell damage which is entirely below the waterline, two things happen:

1. First, we will have a hydrostatic outflow of oil or inflow of sea water depending on whether or not the Neutral Level is below or above the topmost point of the damage. This is the same as for the bottom damage case and follows exactly the same rules. As long as the top of the damage is below the waterline, the key point is the vertical height of the top of the damage. For damage that is entirely below the waterline, the topmost point of the damage plays almost exactly the same role at the lowest point in damage that is entirely above the waterline. You have to think upside down.
2. Second, if the resulting oil water interface after the hydrostatic flows have taken place is below the top of the damage, the lighter density oil will flow out the top of the damage while the heavier seawater flows in thru the bottom of the damage. When you do this at lab scale, the outflowing oil looks almost like a snake or a rope, emanating from the top of the damage. This *exchange flow* will continue until the oil water interface in the tank rises to the top of the damage.

Exchange flow is quite different from hydrostatic flow:

1. It is an order of magnitude slower. Since the outgoing oil has to be replaced by incoming water, the effective flow area is halved. When the flow area is halved, the flow velocity is reduced by more than half because of viscous effects around the perimeter of the flow. More importantly, the forces driving exchange flow tend to be much weaker than the forces driving hydrostatic flow. A typical hydrostatic flow will start out with a net driving head of 2 or 3 meters of oil. If the layer of oil below the top of the damage after hydrostatic flow is say 3 meters deep, the driving head is about 0.15 (the difference in the densities between oil and water) times this depth.[16]

   The “fact” that exchange flow is much slower than hydrostatic flow is the reason we can assume that hydrostatic flow happens first, then

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[16] To my knowledge, there has been no real quantitative study of exchange flow, neither experimental nor theoretical. Playing around at lab scale, it is obvious that exchange flow is far slower than hydrostatic. Embiricos[**?**] talks about a grounding of an unidentified 90,000 tonner in the Suez Canal, in which the master noted that after 42 minutes, the spillage rate was greatly reduced. The log data indicates the tank emptied at 0.40 ft/min prior to that time and 0.05 ft/min after that time. Embiricos associates the earlier period with hydrostatic flow and the latter with exchange flow. This is plausible but not proven. To say more, we would need the ship draft, the cargo density, the initial level in the tank, and the location of the top of the damage.

exchange flow. In reality, exchange flow begins before hydrostatic flow is finished. But, in most real world cases, the hydrostatic flow is so much faster that this assumption is close enough.

2. The pressure drop across the hole is in your favor. Once you get into exchange flow, below the very top of the hole, there is more pressure on the outside than on the inside. Therefore it is much easier to make some sort of repair. If you can cover the hole with almost anything from the outside, even some kind of canvas, it will tend to stay there. In hydrostatic flow, the flow pushes any attempt to plug the hole away from the hole.
3. The tube of outflowing oil climbs upward immediately. In the case of a double sided tanker, this means that all the oil will climb into the top of the double sides; and, if the double sides are still intact down to below the waterline, at least some of this oil will be captured there by hydrostatic balance. Much the same thing happens with hydrostatic flow but in this case, the outflow velocity can be large enough so that a good bit of the oil is carried outside the outer shell, before it turns vertically upward. You don't want either; but if you are faced with a choice of 100 cubic meters of hydrostatic flow or a 100 cubic meters of exchange flow, you would much prefer the latter.

This most definitely does not mean that side damage is preferred to bottom damage. Figure 6 makes the point that side damage is much worse than bottom damage, and, if you must have underwater side damage, you want it as low as possible.

In Figure 6, we start out with the same situation as in Figure 1, a fully loaded pre-Marpol ULCC. We then damage the side shell with the highest point of damage 4 meters above the keel. Since the Live Bottom is well below the keel, the first thing that happens is hydrostatic outflow. We lose 5.3% of the tanks contents before hydrostatic flow stops.[17] In the top half of Figure 1, when the damage was confined to the bottom, we lost only 2.6% of the tank to hydrostatic flow.

And our troubles are not over. The situation after hydrostatic flow looks like the middle sketch in Figure 6. The oil in the bottom 4 meters of the tank is below the top of the damage. This situation is unstable. The seawater pressure at the bottom of the damage is higher than the pressure inside the tank at the bottom of the damage. Sea water will pushes its way into the bottom of the damage forcing oil out the top. Unless we do something, this exchange flow will continue until we have lost all the oil in the bottom 4 meters of the tank, over 14% of the original cargo, for a total loss of about 20%.

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[17] The problem is that oil will flow out until the external pressure at the top of the damage is the same as the internal pressure at this point. For every meter the damage extends up the side shell, the outside head drops by ρ_{sea} but the inside pressure drops only by ρ_{oil}.

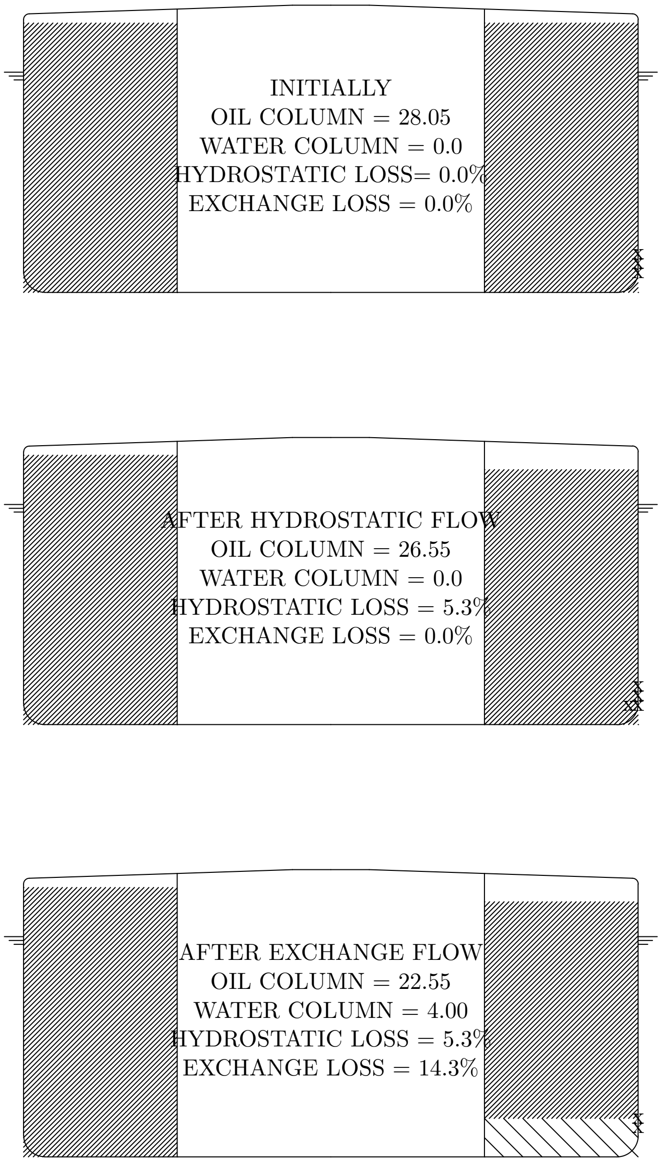

Figure 6: Fully Loaded, Pre-MARPOL, Side damage up 4 M

If we initially underload the tank, so that the Live Bottom is 4 m above the keel, — this requires an initial oil column of 26.7 m or about 5% underloading, we will have no hydrostatic loss but we will still face a 14% loss in exchange flow.

In order to stop the exchange flow via hydrostatic balance, we would have to underload the tank to the point where the incoming hydrostatic flow of sea water will push all the oil in the tank above the top of the damage. This would require an initial oil column of 22.5 m or 20% underloading. The further up the tank the damage extends, the worse it gets. ***The real problem with hydrostatic balance is that it is not very effective against side damage.*** Of course, the same thing is true of double bottoms.

In general, you want to keep side shell damage as far away from the waterline as possible. If the damage is completely above the water line, you would prefer the bottom of the damage to be as high as possible, for in this case the low point of the damage determines how much of the tanks contents will drain out. But if the damage in entirely below the waterline, you want the highest point of the damage to be as low as possible, for in this case the high point of the damage determines how much outflow there will be. Worst of all is damage that straddles the waterline.[18] Collisions usually result in this kind of damage to the hittee. In this case, if we do nothing, we will eventually lose all the cargo in the tank.

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[18] Despite the fact, that the single most important number for damage below the waterline is the highest point of the damage, it is almost never recorded in the spill investigations. You will see something like “6 foot gash in forward starboard tank”. But unless we know the highest point of the gash (lowest if damage is all above the waterline), we can’t do anything with this information.

6 Ballasting Down: the Tamano Spill

Hydrostatic balance has a number of implications, some of which people find surprising at first glance.

6.1 Ballast Down

If you have damage low in the ship, it almost always pays to sink the ship lower in the water. A little study of Figures 1 and 2 will reveal that, if we were in the full load situation, Figure 1, and we sank the ship 2 meters lower, it would have more or less the same effect as having drawn the tank down 2 meters. In fact, it will have a bit more effect. For a medium density crude with a specific gravity of 0.85 and sea water with a density of 1.02, the equation for the height of the Neutral Level, H_{NL} is

$$H_{NL} = \frac{1.02D - 0.85H_{oil}}{1.02 - 0.85}$$

where H_{oil} is the height of the oil in the tank, and D is the ship's draft in way of the damage. Pressing the ship down into the water an extra meter is worth more than removing a meter of oil from the tank because a meter of seawater weighs more than a meter of cargo.

Figure 7 shows the Figure 1 situation if we are able to get the ship 2 meters deeper in the water. The Neutral Level has gone from 2.7 meters below the keel to 9.3 meters above. Generally, the most effective thing a crew can do if the ship has bottom damage is to get the damaged tank(s) lower in the water.[19] That's what the crew of the Nino did. One of the good things about a double bottom is that, when it is damaged, it automatically ballasts the ship down. The same thing is true of an HBL-loaded single hull, but, unless a segregated ballast tank is breached as in the Oceanic Grandeur, the amount of automatic ballasting down will be much less. Unfortunately, the way we build ships these days, it also automatically over-stresses the ship.

6.2 Do not discharge non-damaged tanks

Conversely, the dumbest thing you can do is to lighten the ship and bring it further out of the water.

I should know. The first spill I ever attended was the TAMANO in July of 1970 in Casco Bay outside Portland, Maine. At that time, there was a pipeline from Portland to Eastern Canada. The Tamano, a 100,000 ton, four year old, pre-Marpol single hull, fully loaded with heavy fuel oil, hit a ledge in-bound to the pipeline at about 0120 in the morning. The weather was clear. She had just picked up a pilot. This was probably a navigation

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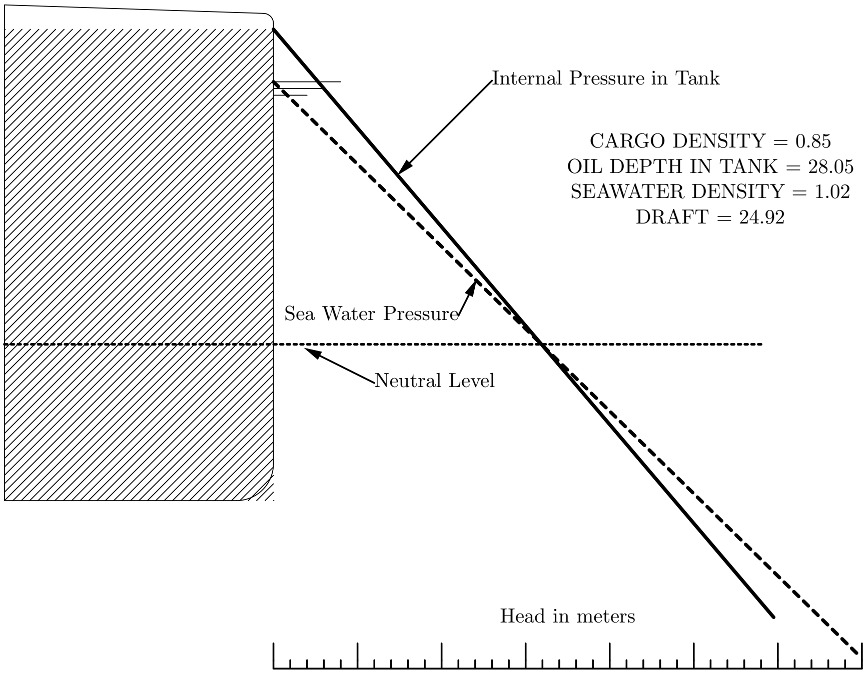
[19] In doing so, we must be careful not to exceed the ship's structural limits. This is the subject of Section 7.



NEUTRAL LEVEL IS 9.3 M ABOVE KEEL

Figure 7: Full load but ballasted down 2 M

error, although the ship alleged that a buoy was out of position. The ship proceeded to the terminal, where it was discovered she was leaking.

I was a junior faculty member at MIT at the time, and had made a very modest name for myself in New England by pontificating on the impact of oil drilling on Georges Bank. But I had never actually seen a real world oil spill of any size. The locals invited me and some of my students to see for ourselves. I jumped at the chance.

By the time we got there, the leakage had stopped. No one was quite sure why including me, although after the fact it was clear that the damaged tanks had gone to hydrostatic balance. (Later it was learned that only 1S was damaged, a 20 foot gash 8" wide — but the all important highest point of the damage was not reported — it was somewhere low in the tank).

The decision was made to off-load the cargo so that the ship could go to the yard for repairs. (Besides the Canadian charterers were desperate for the oil.) But the damaged tank could not be pumped out with the ship's pumps since the oil-water interface in this tank was above the tank suctions. Pumping this tank out would merely pump out sea water which would be replaced by more seawater. This is the normal situation when a tank is breached. The suctions for the ship's pumps are at the very bottom of each tank. Otherwise, you would never be able to completely empty the tank. But this means that as soon as the oil water interface in a seriously damaged tank is above the bottom, the ship's pumps can't pump cargo out of that tank.

So they started pumping out the intact cargo tanks. Immediately the ship began leaking again. Before we stopped we had more than doubled the size of the overall spill. At the time, neither I nor apparently anyone else had thought through the hydrostatic balance thing. In retrospect the situation could not have been handled any worse. By pumping out the intact cargo tanks, we lifted the ship out of the water and destroyed the hydrostatic balance. The damaged tank probably had a plan area of about 300 m^2. The heavy fuel oil cargo had a density of around 0.95. For every centimeter we raised that tank, we spilled roughly an extra 3,200 liters. The final spill volume was put at 378,000 liters. It took only a half meter reduction in draft to double the spill.

As soon as the spill was discovered, the ship should have been moved into deeper water and ballasted down as far as possible, listing and trimming the ship in the direction of the damage. At that point, we should have put submersible salvage pumps on-board and pumped out the damaged tank from the top down.[20] Only after we had removed the oil from the damaged tank should we even have thought about discharging the other cargo tanks. Preposterously stupid.[21]

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[20] These pumps can be lowered into the tank to a point above the oil water interface.

[21] I have not found any reference to the hydrostatic screw up nor the secondary spill

Many years later, a Coast Guard veteran told me that the same thing had happened at the IMPERIAL SARNIA spill in the St.Lawrence Seaway in 1974 but I was never able to get any details. The TAMANO is the only major spill at which I have been physically present. One wonders how often this silly mistake is made.

The power of Hydrostatic Balance is a two-edged sword. Here are two obvious things NOT to do to avoid lowering the Neutral Level.

1. ***Don't discharge intact tanks*** which will raise the ship in the water massively increasing hydrostatic flow from the breached tanks.
2. Similarly, ***Don't deballast the ship.***

The only exception to these two rules is: you have grounded at high tide and by deballasting/discharging/jettisoning you may be able to get the ship off before the tide goes out with horrible effect on hydrostatic balance — this is what happened to the EXXON VALDEZ — and/or the ship's structural integrity — see the SEA EMPRESS spill below.[22] Conversely, if you have grounded on soft, flat bottom at low tide and the situation is safe and stable, ballast down, stay put, and let the rising tide improve your Neutral Level markedly.

As soon as you get in trouble, call for submersible pumps.[23]

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in any of the official Tamano documentation. It shows up only obliquely as a sudden "failure" of the containment equipment well after the initial leak had stopped. I don't know whether this omission was intentional, or simply due to complete ignorance of what was happening.

[22] The common salvage process of overpressuring, "blowing a tank", is an obvious example of Hydrostatic Balance in reverse. It should be employed only if the benefits outweigh the additional oil outflow and there is no feasible alternative.

[23] One can make a strong argument that all tankers should be required to carry a submersible pump and a means for driving it. Further the successful use of the system should be periodically demonstrated to port state inspectors.

7 The Right Response

Hopefully by now you are convinced that the right response in terms of ballasting and cargo transfers can be crucial in determining the final amount spilled. The question on the table is: how do you get the right response, and how do you get it quickly enough?

This is where CTX Mate comes in. Every tanker has software on-board which takes as input an actual or potential tank loading pattern, and computes the corresponding draft and trim, estimates the stresses imposed on the ship by this loading pattern, and checks that these stresses are within legally allowable values. This program is called the *Loading Instrument*.

It is not difficult to endow the Loading Instrument with the capabilities of handling damage and spillage. The Center for Tanker Excellence has developed such a program. It's called CTX Mate (Mate). The Center for Tanker Excellence has made this program available under the Gnu Public License, which means that anyone can download the program without cost. More importantly, the program is Open Source, which means any one can examine the inner working of the program.

CTX_Mate serves at least three purposes:

1. It's a normal loading program in every day use. This is crucial. It means that the program has been thoroughly tested on this particular ship for a wide range of loading conditions. It means the crew is intimately familiar with the program's operation and facile in its use. Turning to basically untested, rarely used, unfamiliar software in the middle of a crisis is a prescription for disaster. Finally, it means that the tank loading pattern at the time of the casualty is already in the program. With Mate, if a ship experiences damage, the crew can flip the program to Damage Mode with a single click, and type in six numbers for each damaged tank. (The six numbers tell Mate the location of the damage in that tank.) Click again and all the damage calculations are done. No multi-hour delay in getting up and running.
2. It's a salvage program capable of computing flooding, damage stability, and strength for any given loading pattern. The crew will immediately know if the ship is in danger of sinking, capsizing, or being over-stressed. In most middle sized spills, this will not be the case; but, if they are in danger of losing the ship, the crew needs to know right away.
3. It's a spill reduction tool. In order to properly compute the equilibrium draft, trim and heel for a damaged tanker, you must compute how much cargo is lost from the damaged tanks, and the extent of seawater flooding in all the damaged compartments. In other words, do all the hydrostatic balance calculations for each damaged tank, both the hydrostatic outflow/inflow and the exchange flow, properly accounting for the change in draft, trim, and heel as a result of the outflow and

flooding.

And this bring us to the neat part. As soon as the crew determines that they are not in danger of losing the ship, they can start trying out possible ways to minimize spillage. If the damage is low on the hull, as is often the case, you want to get the damaged area as deep into the water as possible, in other words you want to trim and heel the ship toward the damage.

Figure 8 is a simplified screen shot of Mate for a typical full load departure condition for a double hull ULCC. Mate is in Normal mode and the screen is full with the usual mostly commercially oriented information, one row per tank. The cargo consists of a single parcel whose density is 0.8502. All cargo tanks are loaded to 98% full. The ship has a midship draft of about 24.4 m, about 1 meter trim aft, and a very slight heel to port. Figure 9 shows a transverse section in way of the number 1 tanks, looking aft. The local draft at this section is about 24 m. Life is good.

Then disaster. The empty forward port ballast tank, 1B_P, is damaged from the baseline up the side 10 meters, and the damage extends well into the fully loaded 1P cargo tank. The internal damage is such that 1B_P and the adjoining 1P cargo tank are effectively a single tank. The Chief Officer flips to Damage mode with a single click, and enters the location of the damage in 1B_P. He "groups" 1P with 1B_P. And rebalances the ship. Figure 10 shows the CTX Mate Mainscreen at this point. Many of the commercially important columns are gone, replaced by columns dealing with the damage and spillage.[24] The damage extent in 1B_P is in the six rightmost columns in the 1B_P row. The combination of 1P with 1B_P was done by putting 1B_P into 1P's GROUP column.

Already Mate has told us a great deal. With this damage, if the crew does nothing, the ship will end up with a draft at the FP of 25.5 m, a trim of 1.4 m by the bow and a heel of 2.7 degrees to port. The maximum bending moment and shear force are only 50% of the allowables. So structural strength is probably OK. The metacentric height after flooding is a robust 8.6 m, so stability is not a problem. The ship's low point will be 26.6 m below sea level, so as long as we have 30 m or more water depth, we can concentrate on reducing spillage.[25]

Figure 11 shows the equilibrium situation in way of the damage in 1B_P if the crew does nothing. The red box shows the extent of the damage as entered by the crew. The flooding will trim the ship by the bow and list her to port, pushing the top of the damage 3 meters deeper into the water than it was in the intact situation. This will reduce the spillage markedly from what would have occured if the ship has somehow remained at the

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[24] Cargo volumes in barrels (the reprehensible commercial practice) are now displayed in cubic meters.

[25] Mate is careful to distinguish between draft and depth. Draft is measured in a direction parallel to the ship's aft perpendicular. Depth is measured in the direction of gravity. If the ship has large trim and heel, draft can be much larger than depth.

pre-damage numbers. Of course, we need to get the ship into deep enough water quickly, so that it can flood without re-grounding.

Despite the favorable trim and list and the fact that the wing ballast tank has captured some 7,000 cubic meters of oil, if the crew does nothing, the ship will still lose 1,500 cubic meters of oil to the sea, all by Exchange loss. After flooding, the top of the damage in 1B_P will be 16.7 m below sea level. There will be a column of oil in the combined 1P/1B_P almost 20 m high above the top of the damage. But the volume of this column is less than the 40,316 cubic meters that was originally in the tank, so we lose a million and a half liters of oil, a major oil spill.

However, our CTX Mate equipped crew is on the ball. They realize the need to trim and heel the ship further in the direction of the damage. One obvious possibility is to ballast 2B_P. So the Chief Officer asks Mate what will happen if they do that, which takes a total of about 5 keystrokes. Figure 12 shows the Mate results. Filling 2B_P increases the trim by about 3 meters and the heel by about 5 degrees. Bending moment and shear force are still fairly low, despite the fact that the deadweight is well above normal limits. Stability has actually improved. New hull low point is 30.6 m below sea level, fine if we have enough water.

Figure 13 is a better view of the equilibrium with 2B_P 98% full. The new top of the damage is 21.5 m below sea level, the total height of the liquid column in 1P/1B_P above the top of the damage is nearly 25 meters, enough to not only hold all the oil that was in 1P but to put the Live Bottom 4 meters above the top of the damage. ***The crew can turn a 1500 cubic meter spill into no spill, provided they can trim and heel the ship quickly enough.***[26]

How much of this reduction they will actually achieve will be determined by how rapidly they can ballast the ship relative to the outflow rate. But if the size of the hole(s) is not too large and they react quickly, they will get most of this reduction. In this case, the fact that they only have to deal with exchange flow will be a big help. [27]

I repeat all the crew had to do to get all this information is to enter

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[26] Figure 13 makes another point. Hydrostatic balance has almost completely filled 1B_P. If the crew were to list the ship further, or the oil column were taller, oil would be forced out the ballast tank vents. You can go too far.

[27] If you are really with me, you are asking yourself how can ballasting down affect exchange flow. There are two ways. First, remember that hydrostatic flow takes place before exchange flow (more or less). Ballasting down can increase the hydrostatic inflow pushing a portion of the oil in the tank that was below the top of the damage above the top of the damage where it is no longer subject to exchange flow. Second, trim and heel can lower the volume of the tank that is below the top of the damage. You can see by taking the bottom picture in Figure 3 and rotating it clockwise. Put a ruler across the sketch at the top point of the damage, but keep the ruler level (un-rotated). Note that the area below the ruler is a triangle (or at least a trapezoid) which is smaller than the original rectangle. In Figure 13, this is happening in both the transverse and longitudinal directions.

the six numbers in the rightmost columns in Figure 12 (the location of the damage), enter a new group code for 1P, and click on REDO. And then enter one number (%FULL for 2B_P) and click on REDO.[28]

This little vignette hints at the fourth role of a program like CTX Mate: a training tool. Most crews, owners, and responders are unaware of the power of properly trimming and listing the ship. The calculations are far too tedious to do by hand, so nobody does them. Whenever I show something like Figures 10 and 12 to even experienced tankermen or governmental authorities, I invariably get a "Wow!" or at least an "I don't believe it!". By running through a series of drills with a program like CTX Mate, everybody learns about the true power of hydrostatic balance in a very concrete context. For the first time, they really understand that in many cases by simply trimming and listing the ship, they can cut the spillage in half or more, or in some cases eliminate it entirely.[29]

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[28] In the real world, the Chief Officer should also look at flooding FP and maybe 3B_P. Speed is of the essence and, if he can use gravity to flood three tanks, he will get to the zero spill drafts and heel sooner. But as noted in the second last footnote, he may not want to ballast all these tanks fully. Go the point where the Live Bottom is comfortably above the top of the damage, and then stop.

[29] The column labeled HBL shows how far each tank would have to be drawn down in order to become hydrostatically balanced. A negative number means that the tank is already under-balanced. These tanks cannot be leaking from a bottom pit. This can be very useful information when a ship has a bottom leak but doesn't know which tank it is.

Figure 8: Pre-damage, full load departure condition

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CTX MATE 0.48.0-BASE.  Ship is DEMO ULCC.  Load pattern is lf_al98dep. Last modified at 2006-12-16T15-43-42
USING API/SG .01/.0001, F/C .1/.01, VCF_4, O_INN/WEDGE, AT SEA ALLOWABLES,
all tanks 98 pct full arab lite
based on /tfs/u/NLOAD/1.92/LF.al98dep. but NLOAD did not have 5 ton crew wt

  TANK  |O|PT|CGO| API | TEMP|  SG  |ULLAGE|INNAGE|%FULL | VOLUME | WEIGHT |FREEWTR|NONLIQ|  GSV   |  LCG   | TCG_xs | VCG_xs | MOI_m4 | WL_ze  | GROUP  |

1C      |P|UL|AL| 34.56| 60.0|0.8502| 1.404|31.440| 98.00|  253583| 34276.8|    0.0|   0.0|  253583| 135.185|   0.004|  19.004|   60247|  10.617|1C      |
2C      |P|UL|AL| 34.56| 60.0|0.8502| 1.404|31.445| 98.00|  299519| 40485.9|    0.0|   0.0|  299519|  80.077|   0.004|  18.995|   85977|  10.462|2C      |
3C      |P|UL|AL| 34.56| 60.0|0.8502| 1.397|31.445| 98.00|  299518| 40485.9|    0.0|   0.0|  299518|  21.377|   0.004|  18.995|   85977|  10.316|3C      |
4C      |P|UL|AL| 34.56| 60.0|0.8502| 1.411|31.445| 98.00|  299518| 40485.9|    0.0|   0.0|  299518| -37.323|   0.004|  18.995|   85977|  10.170|4C      |
5C      |P|UL|AL| 34.56| 60.0|0.8502| 1.405|31.450| 98.00|  271983| 36764.0|    0.0|   0.0|  271983| -93.821|   0.004|  19.001|   68842|  10.043|5C      |
1P      |P|UL|AL| 34.56| 60.0|0.8502| 1.447|30.953| 98.00|  137464| 18581.0|    0.0|   0.0|  137464| 134.669|  18.053|  19.294|   19428|  10.081|1P      |
1S      |P|UL|AL| 34.56| 60.0|0.8502| 1.436|30.957| 98.00|  137464| 18581.0|    0.0|   0.0|  137464| 134.678| -18.048|  19.294|   20653|  10.168|1S      |
2F_P    |P|UL|AL| 34.56| 60.0|0.8502| 1.652|30.745| 98.00|   93801| 12679.1|    0.0|   0.0|   93801|  94.769|  21.348|  19.058|   12230|   9.795|2F_P    |
2F_S    |P|UL|AL| 34.56| 60.0|0.8502| 1.537|30.766| 98.00|   93801| 12679.1|    0.0|   0.0|   93801|  94.769| -21.344|  19.058|   12230|   9.899|2F_S    |
2A_P    |P|UL|AL| 34.56| 60.0|0.8502| 1.710|30.740| 98.00|   93801| 12679.1|    0.0|   0.0|   93801|  65.419|  21.348|  19.058|   12230|   9.722|2A_P    |
2A_S    |P|UL|AL| 34.56| 60.0|0.8502| 1.620|30.768| 98.00|   93801| 12679.1|    0.0|   0.0|   93801|  65.419| -21.344|  19.058|   12230|   9.827|2A_S    |
3P      |P|UL|AL| 34.56| 60.0|0.8502| 1.627|30.763| 98.00|  187601| 25358.0|    0.0|   0.0|  187601|  21.376|  21.348|  19.058|   24460|   9.613|3P      |
3S      |P|UL|AL| 34.56| 60.0|0.8502| 1.615|30.788| 98.00|  187601| 25358.0|    0.0|   0.0|  187601|  21.376| -21.344|  19.058|   24460|   9.717|3S      |
4F_P    |P|UL|AL| 34.56| 60.0|0.8502| 1.644|30.745| 98.00|   93801| 12679.1|    0.0|   0.0|   93801| -22.631|  21.348|  19.058|   12230|   9.503|4F_P    |
4F_S    |P|UL|AL| 34.56| 60.0|0.8502| 1.618|30.770| 98.00|   93801| 12679.1|    0.0|   0.0|   93801| -22.631| -21.344|  19.058|   12230|   9.608|4F_S    |
4A_P    |P|UL|AL| 34.56| 60.0|0.8502| 1.646|30.741| 98.00|   93801| 12679.1|    0.0|   0.0|   93801| -51.981|  21.348|  19.058|   12230|   9.430|4A_P    |
4A_S    |P|UL|AL| 34.56| 60.0|0.8502| 1.627|30.766| 98.00|   93801| 12679.1|    0.0|   0.0|   93801| -51.981| -21.344|  19.058|   12230|   9.535|4A_S    |
5P      |P|UL|AL| 34.56| 60.0|0.8502| 1.620|30.827| 98.00|  130263| 17607.6|    0.0|   0.0|  130263| -88.858|  20.428|  20.704|   20813|   9.437|5P      |
5S      |P|UL|AL| 34.56| 60.0|0.8502| 1.582|30.856| 98.00|  130263| 17607.6|    0.0|   0.0|  130263| -88.859| -20.423|  20.704|   20813|   9.540|5S      |
SLOP_P  |P|UL|AL| 34.56| 60.0|0.8502| 1.526|31.097| 98.00|   41112|  5557.1|    0.0|   0.0|   41112|-121.718|  16.248|  23.315|    8581|   9.655|SLOP_P  |
SLOP_S  |P|UL|AL| 34.56| 60.0|0.8502| 1.483|31.144| 98.00|   40061|  5415.0|    0.0|   0.0|   40061|-121.550| -16.279|  23.362|    9580|   9.750|SLOP_S  |
FP      |E|UL|sw|1.0250|     |      |35.689|-0.063|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        | -24.015|FP      |
1B_P    |E|UL|sw|1.0250|     |      |35.496| 0.005|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        | -24.218|1B_P    |
1B_S    |E|UL|sw|1.0250|     |      |35.583|-0.082|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        | -24.155|1B_S    |
2B_P    |E|UL|sw|1.0250|     |      |35.514|-0.014|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        | -24.377|2B_P    |
2B_S    |E|UL|sw|1.0250|     |      |35.588|-0.088|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        | -24.301|2B_S    |
1FO_P   |P|UL|f1|0.9876|15.00|0.9876| 2.473|23.649| 90.92|  3458.2|  3415.4|    0.0|   0.0|  3458.2|-137.992|  21.577|  24.982|    5944|   8.544|1FO_P   |
1FO_S   |P|UL|f1|0.9876|15.00|0.9876| 2.689|23.342| 90.92|  4150.8|  4099.3|    0.0|   0.0|  4150.8|-137.804| -20.718|  24.292|    5944|   8.301|1FO_S   |

...... more bfo, do, etc tanks, point loads .....

FW_S    |E|UL|sw|1.0250|     |      |10.438|-0.038|  0.00|     0.0|     0.0|    0.0|   0.0|        |        |        |        |        |   0.761|FW_S    |
CREW    | |  |  |      |     |      |      |      |      |        |     5.0|       |      |        |-148.000|   0.000|  40.000|        |

DWT     439411    2150 LT Sdwt DRAFTMID  24.427  AL   3166356 TOV   3166356 GSV   427996 MT BLINDZONE     196 Pitch RG  86.5 LOWxs-163.150  Draftmarks
CARGO   427996  TPC      230.3 DRAFT AP  24.882                                             MANI_HT_S  11.204 Roll RG   19.3 LOWys   0.000 Aft-P  24.890
BLLST        0  MTC       5959 DRAFT FP  23.972                                             MANI_HT_P  11.062 LCB     10.950 LCG    10.966 Aft-S  24.799
BFO      11409  WETTED   37238 TRIM      -0.910                                             DISPLCMENT 507333 TCB      0.038 TCG     0.022 Mid-P  24.531
OTHER        5  SEA_SG  1.0250 HEEL      -0.139                                             MAX SHEAR  -10917 VCB     12.765 VCG    19.155 Mid-S  24.366
MAX %SHEAR  -47.8% at    FR040 PROP IMM  13.114                                             MAX BEND  -830654 LOW PT  -24.84 DEPTH  100.00 Fwd-P  24.054
MAX %BEND   -76.2% at    FR087 GM corr    8.168                                             MAX HOG    -0.233 MIN FLOOD  7.11@   3FOP_VENT Fwd-S  23.970
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Figure 9: Section in way of 1S/1C/1P, pre-damage

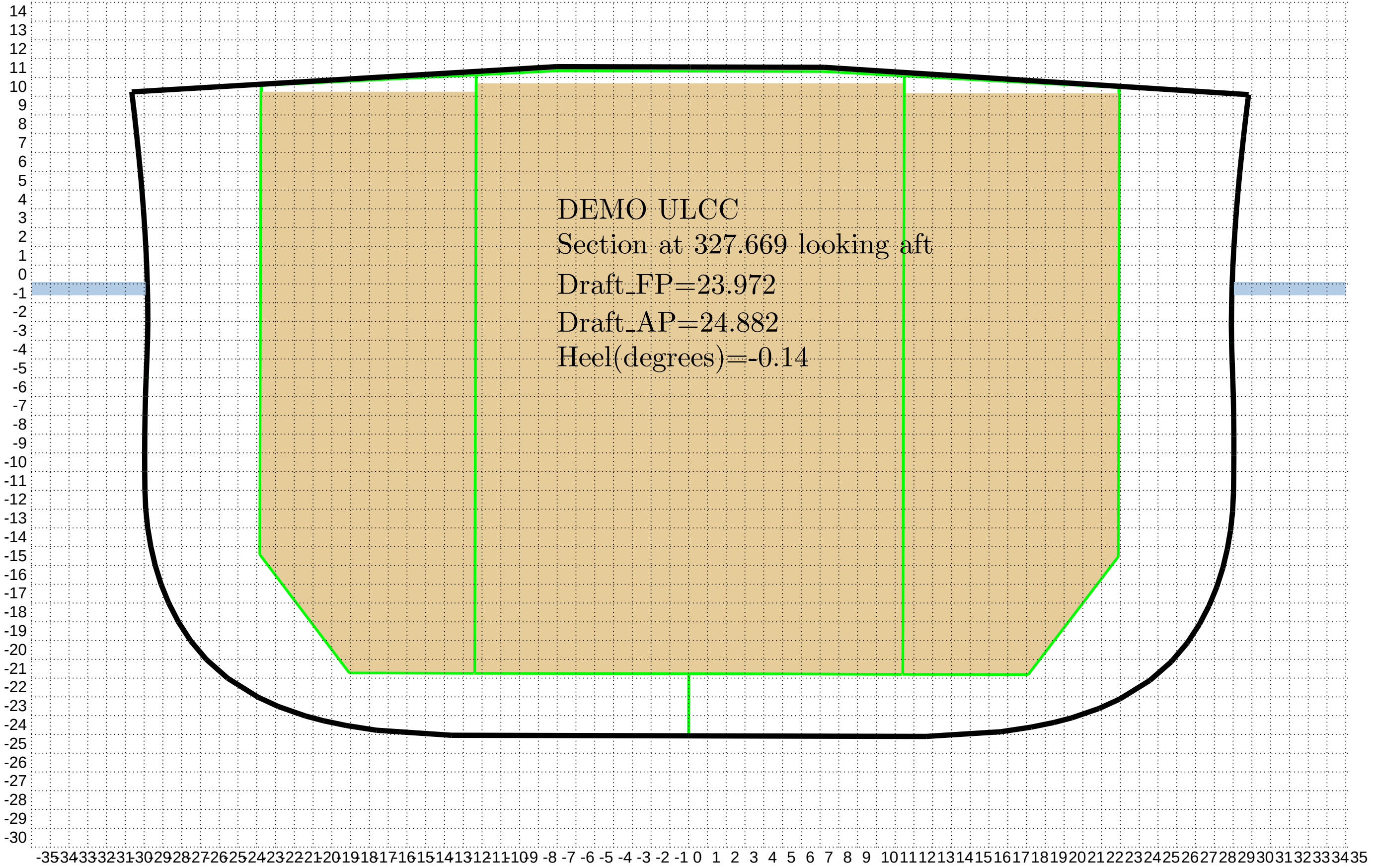

Figure 10: Damage 1B_P/1P up 10 m. Crew does nothing

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CTX MATE 0.48.0-BASE.  Ship is DEMO ULCC.  Load pattern is lf_al98_dam1P. Last modified at 2006-12-16T16-58-11
USING API/SG .01/.0001, F/C .1/.01, VCF_4, O_INN/WEDGE, AT SEA ALLOWABLES,
lf_al98dep with 1B_P damaged from 0 to 10 m, 1P grouped with 1B_P
19 m col of oil in 1B_P/1P abv damage, still lose 1500 m3 exchange loss

  TANK  |O|PT|CGO| API | TEMP|  SG  |ULLAGE|INNAGE|%FULL | VOLUME | WEIGHT |IGS_mm| HBL_m |TANK_WL|OIL/SW |HYDROOUT|EXCHGOUT|KEY_ze | GROUP  |high_xs|high_ys|high_zs|low_xs |low_ys |low_zs |

1C      |P|UL|AL| 34.56|15.56|0.8502| 1.103|31.776| 98.00| 40316.4| 34276.8|   510|  4.698|  9.353|       |        |        |       |1C      |       |       |       |       |       |       |
2C      |P|UL|AL| 34.56|15.56|0.8502| 1.158|31.727| 98.00| 47619.7| 40485.9|   510|  4.915|  9.547|       |        |        |       |2C      |       |       |       |       |       |       |
3C      |P|UL|AL| 34.56|15.56|0.8502| 1.150|31.728| 98.00| 47619.6| 40485.9|   510|  5.182|  9.768|       |        |        |       |3C      |       |       |       |       |       |       |
4C      |P|UL|AL| 34.56|15.56|0.8502| 1.165|31.727| 98.00| 47619.6| 40485.9|   510|  5.448|  9.989|       |        |        |       |4C      |       |       |       |       |       |       |
5C      |P|UL|AL| 34.56|15.56|0.8502| 1.135|31.755| 98.00| 43241.9| 36764.0|   510|  5.719| 10.215|       |        |        |       |5C      |       |       |       |       |       |       |
1P      |G|UL|AL| 34.56|15.56|      |      |      | 98.00|        |        |      |       |       |       |        |        |       |1B_P    |       |       |       |       |       |       |
1S      |P|UL|AL| 34.56|15.56|0.8502| 1.540|30.888| 98.00| 21855.0| 18581.0|   510|  5.194|  9.700|       |        |        |       |1S      |       |       |       |       |       |       |
2F_P    |P|UL|AL| 34.56|15.56|0.8502| 1.908|30.524| 98.00| 14913.1| 12679.1|   510|  3.104|  7.854|       |        |        |       |2F_P    |       |       |       |       |       |       |
2F_S    |P|UL|AL| 34.56|15.56|0.8502| 1.436|30.901| 98.00| 14913.1| 12679.1|   510|  5.445|  9.830|       |        |        |       |2F_S    |       |       |       |       |       |       |
2A_P    |P|UL|AL| 34.56|15.56|0.8502| 2.001|30.484| 98.00| 14913.1| 12679.1|   510|  3.238|  7.965|       |        |        |       |2A_P    |       |       |       |       |       |       |
2A_S    |P|UL|AL| 34.56|15.56|0.8502| 1.429|30.993| 98.00| 14913.1| 12679.1|   510|  5.578|  9.940|       |        |        |       |2A_S    |       |       |       |       |       |       |
3P      |P|UL|AL| 34.56|15.56|0.8502| 1.926|30.498| 98.00| 29826.2| 25358.0|   510|  3.427|  8.132|       |        |        |       |3P      |       |       |       |       |       |       |
3S      |P|UL|AL| 34.56|15.56|0.8502| 1.476|30.962| 98.00| 29826.2| 25358.0|   510|  5.766| 10.106|       |        |        |       |3S      |       |       |       |       |       |       |
4F_P    |P|UL|AL| 34.56|15.56|0.8502| 1.900|30.524| 98.00| 14913.1| 12679.1|   510|  3.637|  8.296|       |        |        |       |4F_P    |       |       |       |       |       |       |
4F_S    |P|UL|AL| 34.56|15.56|0.8502| 1.434|30.989| 98.00| 14913.1| 12679.1|   510|  5.978| 10.272|       |        |        |       |4F_S    |       |       |       |       |       |       |
4A_P    |P|UL|AL| 34.56|15.56|0.8502| 1.892|30.530| 98.00| 14913.1| 12679.1|   510|  3.771|  8.407|       |        |        |       |4A_P    |       |       |       |       |       |       |
4A_S    |P|UL|AL| 34.56|15.56|0.8502| 1.433|30.995| 98.00| 14913.1| 12679.1|   510|  6.111| 10.382|       |        |        |       |4A_S    |       |       |       |       |       |       |
5P      |P|UL|AL| 34.56|15.56|0.8502| 1.837|30.645| 98.00| 20710.1| 17607.6|   510|  4.076|  8.689|       |        |        |       |5P      |       |       |       |       |       |       |
5S      |P|UL|AL| 34.56|15.56|0.8502| 1.323|31.150| 98.00| 20710.1| 17607.6|   510|  6.368| 10.617|       |        |        |       |5S      |       |       |       |       |       |       |
SLOP_P  |P|UL|AL| 34.56|15.56|0.8502| 1.730|30.927| 98.00|  6536.3|  5557.1|   510|  4.846|  9.298|       |        |        |       |SLOP_P  |       |       |       |       |       |       |
SLOP_S  |P|UL|AL| 34.56|15.56|0.8502| 1.100|31.562| 98.00|  6369.1|  5415.0|   510|  6.635| 10.896|       |        |        |       |SLOP_S  |       |       |       |       |       |       |
FP      |E|UL|sw|1.0250|     |      |35.822|-0.157|  0.00|     0.0|     0.0|   510|-25.564|-25.564|       |        |        |       |FP      |       |       |       |       |       |       |
1B_P    |D|UL|sw|1.0250|     |0.9090| 5.953|29.585|  0.00| 30664.9| 27874.6|   510|  0.000|  2.833|-16.698|     0.0|  1507.0|-16.698|1B_P    |300.000| 31.000| 10.000|330.000| 20.000|  0.000|
1B_S    |E|UL|sw|1.0250|     |      |37.110|-1.572|  0.00|     0.0|     0.0|   510|-25.446|-25.446|       |        |        |       |1B_S    |       |       |       |       |       |       |
2B_P    |E|UL|sw|1.0250|     |      |35.562|-0.024|  0.00|     0.0|     0.0|   510|-26.561|-26.561|       |        |        |       |2B_P    |       |       |       |       |       |       |
2B_S    |E|UL|sw|1.0250|     |      |37.104|-1.565|  0.00|     0.0|     0.0|   510|-25.225|-25.225|       |        |        |       |2B_S    |       |       |       |       |       |       |
1FO_P   |P|UL|f1|0.9876|15.00|0.9876| 2.708|23.443| 90.92|  3458.2|  3415.4|     0|  7.447|  8.036|       |        |        |       |1FO_P   |       |       |       |       |       |       |
   ...... more BFO, DO, etc tanks, point loads .......
FW_S    |E|UL|sw|1.0250|     |      |10.996|-0.585|  0.00|     0.0|     0.0|     0|  1.718|  1.718|       |        |        |       |FW_S    |       |       |       |       |       |       |
CREW    | |  |  |      |     |      |      |      |      |        |     5.0|      |       |       |       |        |        |       |        | 35.000|  0.000| 40.000|       |       |       |

DWT     448705    7144 MT Sdwt DRAFTMID  24.839  AL  481555.4 TOV  481555.4 GSV   409415 MT HYDROLOSS       0 GRNDxs   0.000 LOWxs  80.100
CARGO   409415  TPC      230.2 DRAFT AP  24.150                                             EXCHGLOSS    1507 GRNDys   0.000 LOWys  31.300
BLLST    27875  MTC       5942 DRAFT FP  25.529                                             GRND FORCE     -0 LCB   13.347 LCG    13.321
BFO      11409  WETTED   37537 TRIM       1.380                                             DISPLCMENT 516627 TCB      0.710 TCG     0.439
OTHER        5  SEA_SG  1.0250 HEEL      -2.652                                             MAX SHEAR   -9415 VCB     12.996 VCG    18.859
MAX %SHEAR   47.0% at    FR115 PROP IMM  12.412                                             MAX BEND  -564802 LOW_PT  -26.57 DEPTH  100.00
MAX %BEND   -57.2% at    FR110 GM corr    8.614                                             MAX HOG    -0.165 MIN FLOOD  7.00@   2FOP_VENT
```

Figure 11: Damage 1B_P/1P up 10m. Crew does nothing

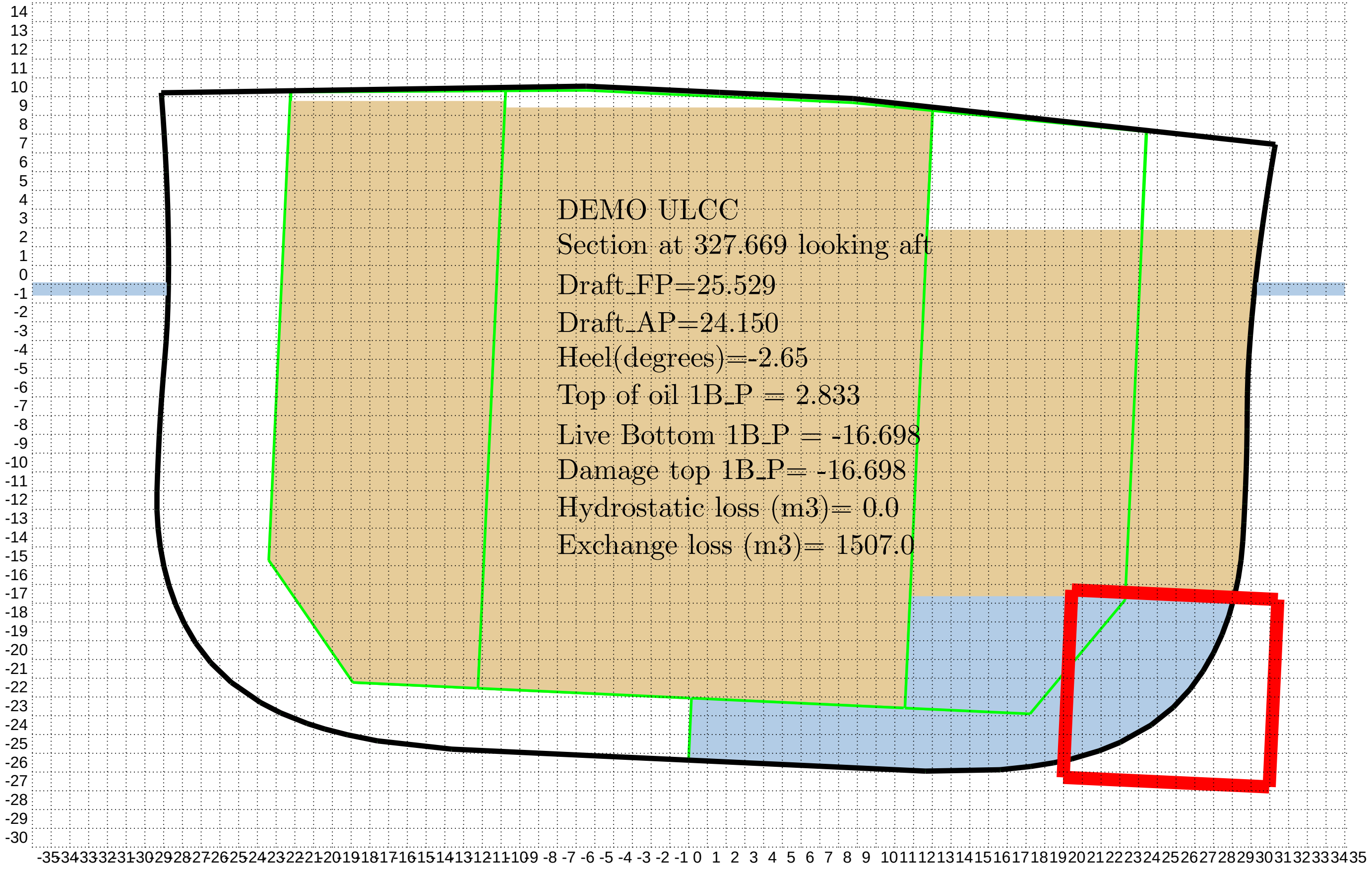

Figure 12: Damage 1B_P/1P up 10 m. Crew ballasts 2B_P 98%.

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CTX MATE 0.48.0-BASE.  Ship is DEMO ULCC.  Load pattern is lf_al98_dam1P_fl2B_P. Last modified at 2006-12-07T15-58-23
USING API/SG .01/.0001, F/C .1/.01, VCF_4, O_INN/WEDGE, AT SEA ALLOWABLES,
lf_al98dep with 1B_P damaged from 0 to 10 m, 1P grouped with 1B_P, fill 2B_P
19 m col of oil in 1B_P/1P abv damage, zero spill, 4 m seal

  TANK  |O|PT|CGO| API | TEMP|  SG  |ULLAGE|INNAGE|%FULL | VOLUME | WEIGHT |IGS_mm| HBL_m |TANK_WL|OIL/SW |HYDROOUT|EXCHGOUT|KEY_ze | GROUP  |high_xs|high_ys|high_zs|low_xs |low_ys |low_zs |

1C      |P|UL|AL| 34.56|15.56|0.8502| 0.259|32.888| 98.00| 40316.4| 34276.8|   510|  2.282|  7.543|       |        |        |       |1C      |       |       |       |       |       |       |
2C      |P|UL|AL| 34.56|15.56|0.8502| 0.322|32.831| 98.00| 47619.7| 40485.9|   510|  3.089|  8.277|       |        |        |       |2C      |       |       |       |       |       |       |
3C      |P|UL|AL| 34.56|15.56|0.8502| 0.311|32.835| 98.00| 47619.6| 40485.9|   510|  3.956|  8.997|       |        |        |       |3C      |       |       |       |       |       |       |
4C      |P|UL|AL| 34.56|15.56|0.8502| 0.328|32.832| 98.00| 47619.6| 40485.9|   510|  4.823|  9.715|       |        |        |       |4C      |       |       |       |       |       |       |
5C      |P|UL|AL| 34.56|15.56|0.8502| 0.305|32.854| 98.00| 43241.9| 36764.0|   510|  5.634| 10.379|       |        |        |       |5C      |       |       |       |       |       |       |
1P      |G|UL|AL| 34.56|15.56|      |      |      | 98.00|        |        |      |       |       |       |        |        |       |1B_P    |       |       |       |       |       |       |
1S      |P|UL|AL| 34.56|15.56|0.8502| 1.598|31.094| 98.00| 21855.0| 18581.0|   510|  4.523|  9.360|       |        |        |       |1S      |       |       |       |       |       |       |
2F_P    |P|UL|AL| 34.56|15.56|0.8502| 2.201|30.495| 98.00| 14913.1| 12679.1|   510| -1.039|  4.491|       |        |        |       |2F_P    |       |       |       |       |       |       |
2F_S    |P|UL|AL| 34.56|15.56|0.8502| 1.186|31.415| 98.00| 14913.1| 12679.1|   510|  5.593| 10.062|       |        |        |       |2F_S    |       |       |       |       |       |       |
2A_P    |P|UL|AL| 34.56|15.56|0.8502| 2.369|30.382| 98.00| 14913.1| 12679.1|   510| -0.605|  4.851|       |        |        |       |2A_P    |       |       |       |       |       |       |
2A_S    |P|UL|AL| 34.56|15.56|0.8502| 1.001|31.685| 98.00| 14913.1| 12679.1|   510|  6.027| 10.422|       |        |        |       |2A_S    |       |       |       |       |       |       |
3P      |P|UL|AL| 34.56|15.56|0.8502| 2.273|30.416| 98.00| 29826.2| 25358.0|   510|  0.016|  5.398|       |        |        |       |3P      |       |       |       |       |       |       |
3S      |P|UL|AL| 34.56|15.56|0.8502| 1.108|31.595| 98.00| 29826.2| 25358.0|   510|  6.650| 10.971|       |        |        |       |3S      |       |       |       |       |       |       |
4F_P    |P|UL|AL| 34.56|15.56|0.8502| 2.194|30.495| 98.00| 14913.1| 12679.1|   510|  0.695|  5.929|       |        |        |       |4F_P    |       |       |       |       |       |       |
4F_S    |P|UL|AL| 34.56|15.56|0.8502| 1.015|31.673| 98.00| 14913.1| 12679.1|   510|  7.327| 11.500|       |        |        |       |4F_S    |       |       |       |       |       |       |
4A_P    |P|UL|AL| 34.56|15.56|0.8502| 2.172|30.515| 98.00| 14913.1| 12679.1|   510|  1.128|  6.288|       |        |        |       |4A_P    |       |       |       |       |       |       |
4A_S    |P|UL|AL| 34.56|15.56|0.8502| 1.000|31.693| 98.00| 14913.1| 12679.1|   510|  7.760| 11.859|       |        |        |       |4A_S    |       |       |       |       |       |       |
5P      |P|UL|AL| 34.56|15.56|0.8502| 2.072|30.675| 98.00| 20710.1| 17607.6|   510|  1.892|  6.978|       |        |        |       |5P      |       |       |       |       |       |       |
5S      |P|UL|AL| 34.56|15.56|0.8502| 0.767|31.971| 98.00| 20710.1| 17607.6|   510|  8.387| 12.412|       |        |        |       |5S      |       |       |       |       |       |       |
SLOP_P  |P|UL|AL| 34.56|15.56|0.8502| 1.948|30.976| 98.00|  6536.3|  5557.1|   510|  3.653|  8.257|       |        |        |       |SLOP_P  |       |       |       |       |       |       |
SLOP_S  |P|UL|AL| 34.56|15.56|0.8502| 0.235|32.694| 98.00|  6369.1|  5415.0|   510|  8.734| 12.777|       |        |        |       |SLOP_S  |       |       |       |       |       |       |
FP      |E|UL|sw|1.0250|     |      |36.031|-0.076|  0.00|     0.0|     0.0|   510|-27.968|-27.968|       |        |        |       |FP      |       |       |       |       |       |       |
1B_P    |D|UL|sw|1.0250|     |0.9172| 0.664|35.164|  0.00| 35454.0| 32519.9|   510|  0.000|  3.536|-17.198|     0.0|     0.0|-21.472|1B_P    |300.000| 33.700| 10.000|300.000| 33.700|  0.000|
1B_S    |E|UL|sw|1.0250|     |      |40.042|-4.213|  0.00|     0.0|     0.0|   510|-27.471|-27.471|       |        |        |       |1B_S    |       |       |       |       |       |       |
2B_P    |P|UL|sw|1.0250|     |1.0250| 3.083|32.746| 98.00| 13809.8| 14155.0|   510|  1.813|  1.813|       |        |        |       |2B_P    |       |       |       |       |       |       |
2B_S    |E|UL|sw|1.0250|     |      |40.018|-4.189|  0.00|     0.0|     0.0|   510|-26.752|-26.752|       |        |        |       |2B_S    |       |       |       |       |       |       |
3B_P    |E|UL|sw|1.0250|     |      |35.614|-0.088|  0.00|     0.0|     0.0|   510|-30.273|-30.273|       |        |        |       |3B_P    |       |       |       |       |       |       |
3B_S    |E|UL|sw|1.0250|     |      |39.745|-4.219|  0.00|     0.0|     0.0|   510|-26.034|-26.034|       |        |        |       |3B_S    |       |       |       |       |       |       |
4B_P    |E|UL|sw|1.0250|     |      |34.644| 0.882|  0.00|     0.0|     0.0|   510|-29.554|-29.554|       |        |        |       |4B_P    |       |       |       |       |       |       |
4B_S    |E|UL|sw|1.0250|     |      |39.475|-3.949|  0.00|     0.0|     0.0|   510|-25.315|-25.315|       |        |        |       |4B_S    |       |       |       |       |       |       |
5B_P    |E|UL|sw|1.0250|     |      |38.486|-2.607|  0.00|     0.0|     0.0|   510|-27.451|-27.451|       |        |        |       |5B_P    |       |       |       |       |       |       |
5B_S    |E|UL|sw|1.0250|     |      |36.525|-0.627|  0.00|     0.0|     0.0|   510|-24.596|-24.596|       |        |        |       |5B_S    |       |       |       |       |       |       |
AP      |E|UL|sw|1.0250|     |      |18.210| 0.151|  0.00|     0.0|     0.0|   510|-10.108|-10.108|       |        |        |       |AP      |       |       |       |       |       |       |
1FO_P   |P|UL|f1|0.9876|15.00|0.9876| 3.171|23.193| 90.92|  3458.2|  3415.4|     0|  5.814|  6.445|       |        |        |       |1FO_P   |       |       |       |       |       |       |

..................more BFO, DO, etc tanks, point loads ..........

FW_P    |E|UL|sw|1.0250|     |      |10.231| 0.266|  0.00|     0.0|     0.0|     0| -0.583| -0.583|       |        |        |       |FW_P    |       |       |       |       |       |       |
FW_S    |E|UL|sw|1.0250|     |      |12.072|-1.576|  0.00|     0.0|     0.0|     0|  2.959|  2.959|       |        |        |       |FW_S    |       |       |       |       |       |       |
CREW    | |  |  |      |     |      |      |      |      |        |     5.0|      |       |       |       |        |        |       |        | 35.000|  0.000| 40.000|       |       |       |

DWT      467505   25944 MT Sdwt DRAFTMID  25.647   AL  481555.4 TOV  481555.4 GSV   409415 MT HYDROLOSS       0 GRNDxs   0.000 LOWxs  80.100
CARGO    409415   TPC      231.6 DRAFT AP  23.386                                             EXCHGLOSS       0 GRNDys   0.000 LOWys  31.300
BLLST     46675   MTC       5974 DRAFT FP  27.909                                             GRND FORCE     -0 LCB   16.248 LCG    16.188
BFO       11409   WETTED   38155 TRIM       4.524                                             DISPLCMENT 535427 TCB      2.006 TCG     1.308
OTHER         5   SEA_SG  1.0250 HEEL      -7.734                                             MAX SHEAR   -8183 VCB     13.574 VCG    18.711
MAX %SHEAR   51.9% at    FR115 PROP IMM  11.614                                             MAX BEND  -577322 LOW_PT  -30.61 DEPTH  100.00
MAX %BEND   -67.8% at    FR108 GM corr    9.537                                             MAX HOG    -0.154 MIN FLOOD  3.75@   1B_P_VENT
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Figure 13: Damage 1P up 10 m. Crew ballasts 2B_P