Summary Preliminary Report from the Flow Rate Technical Group
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Three independent methods considered by the FRTG place the minimum oil flow rate at greater than 12,000 barrels per day. Two of the methods determine that the flow rate could be as high as 20,000 barrels per day. The team using video to analyze the plume believes that the flow rate could be at least 12,000 to 25,000 barrels per day. Therefore, the area of overlap of all three methods ranges between **12,000 to 19,000 barrels per day**. These are all preliminary estimates.

In arriving at this preliminary range of values, the FRTG pursued entirely independent strategies, each of which yielded it own range of values. The values from the independent methods were combined to find the mostly likely flow rate for the well from the intersection of different methods. The Plume Team pursued the approach of observing video of the oil/gas mixture escaping from the kinks in the riser and the end of the riser pipe, using particle image velocimetry analysis to estimate fluid velocity and flow volume. The Mass Balance Team used remote sensing data from deployment of the Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) and satellite to calculate the amount of oil on the ocean surface on a certain day. The team then corrected the value for oil evaporated, skimmed, burned, and dispersed up to that day and divided by time to produce an average rate. Each method has its own limitations and biases as described below.

Mass Balance: 12,000 to 19,000 barrels per day

The mass balance team used data from the AVIRIS airborne sensor flown over the Gulf of Mexico on May 17, 2010. The sensor can map both the aerial extent and thickness of oil by observing changes in reflectance that occur in the near infrared because oil absorption is less in that waveband. AVIRIS can only observe a portion of the total spill area in one day, and there is some uncertainty in estimating what proportion of the total spill area is represented in the scene that is imaged. On May 17, the mass balance team calculates that they observed 15% of the total spill, and assumes that the portion they observed is representative of the total spill. An adjustment is made for additional dull oil and sheen that coat the surface in fairly uniform layers too thin to be sensed by AVIRIS but from other sensors have been shown to persist in known ratios to the area of the thick oil (88:10:2 for sheen to dull oil to thick oil). On May 17, the amount of thick oil was 70,000 to 150,000 barrels. Bounds on the contribution of sheen and dull oil that need to be added to those totals are 60,000 to 120,000 barrels depending on reasonable thicknesses chosen for sheen and dull oil. Therefore, lower and upper bounds on the oil spill on May 17 are between 130,000 and 270,000 barrels of oil. This is the amount of oil that poses the largest threat to the coastal environment, and a large proportion of the oil released after this date was either disperser subsea or collected with the riser insertion tube tool (RITT).

Corrections are then made for the amount of oil that was evaporated, skimmed, burned, and dispersed either subsea or on the sea surface. These corrections nearly double the total amount of oil as of May 17th. The total oil is then divided by the number of days to get an average rate. This method is not without its biases that might not be captured by formal uncertainty bounds as well. For example, all of the corrections made to the surface oil were to add in losses of oil to the system. To the extent that there are other unknown processes that remove oil naturally from the system that are unaccounted for, there may be “unknown unknowns” in this analysis as well. Therefore, further scientific investigation could push these estimates higher. For example, a correction was made for anthropogenic dispersion of oil subsea (assuming that none of it arrived at the surface), but current expeditions underway may determine that there is more oil in the subsurface than can be accounted for from surface and subsea dispersion. Note that while the plume team's analysis yields an "instantaneous" rate for flow of the well at that time that the video was taken, the calculation based on mass balance is an average rate for the first 27 days of the spill, assuming that the 5 days that sea-bottom dispersants were being applied did not contribute to the observable spill.

Plume Modeling: at least 12,000 to 25,000 barrels per day (range of lower bounds)

The plume modeling team observed video from both the end of the riser where the majority of the flow is escaping and from the kink in the riser where a smaller amount exits through small slits in the top of the riser. The main method employed to make their estimates was through a common fluid dynamic technique called particle image velocimetry (PIV). While difficult in practice, it is simple in principle. In this method a flow event, e.g. an eddy or other identifiable item, is observed at two consecutive video frames. Distance moved per time between frames gives a velocity, after adjustment for viewing angle and other factors. Repeated measurement over time and space give an estimated mean flow. Flow multiplied by cross-section area of the plume gives a volume flux.

The challenges this team faced in getting reliable results were many. First, they only had a limited window of data in time to choose from. They had to select data from before the RITT was inserted into the riser as that tool captured a variable amount of flow. They needed a time window when application of subsea dispersant was not perturbing the flow. They required footage from after the period when a trench was excavated at the end of the riser to better expose the end of the plume. Most challenging was getting good lighting and unobstructed views of the plumes from work-class ROV's not intended to capture research-quality footage and occupied doing other tasks at the time.

Second, perfecting the methodology for calculating multiphase flow (oil, water, gas, hydrate in poorly known ratios) under very high pressure is worthy of a research effort. This is not a turn-key project, and yet the team did not have the luxury of time to explore many alternative approaches or calibrate methods with deep-sea tests using known fluxes of fluids in prescribed ratios. A key parameter was the average ratio of gas to liquid. This term seemed to vary over the time period of the spill. Increasing gas increased the velocity of the plume but decreased the mass flow. Lacking independent estimates, the group took the average values provided by BP at face value. Analysis of the available short movies of the raiser flow shows the existence periods when the flow oscillates from pure gas to seemingly pure oil. This appears to be an indication of Slug Flow Regime. These periods of gas-oil flow fluctuation are in the range of minutes but could also be in the range of hours or even as long as days. In order to properly determine the effect of the intermittency of the gas/oil composition in the total estimate of the oil discharged from the riser leak, the analysis should be extended to long video records spanning several days.

Not all of the experts engaged in PIV analysis. Some simply reviewed the work of those that did, while still others provided additional verification by checking the PIV answers with their calculations using other techniques. Given the challenges in applying the methods in to this particular problem, team members concluded that formal statistical error bounds on upper and lower limits on flow volume derived from a rigorous estimation of the uncertainty in model parameters would fail to capture all possible sources of error in this approach to recovering the true flow rate. It would only account for the known unknowns, but not the unknown unknowns that might be revealed if one could actually calibrate these methods against a known flow rate given the complex multiphase and flow behaviors at high pressure. The experts concluded that the effect of the unknown unknowns made it more difficult to produce a reliable upper bound on the flow rate. Therefore, they chose to simply produce a range of lower bounds from their independent analyses, all of which they thought were defendable. A formal error analysis by one member of the plume team estimated that the uncertainty in any one estimate (e.g., from the "known unknowns") would be ±40%.

Reality Check: at least 11,000 barrels per day

To these independent estimates, a lower bound on the flow rate can be provided as a reality check by observing the behavior of the plume as a function of how much oil can be pulled up the RITT (Riser Insertion Tube Tool) from the leaking riser. On May 25, 2010, at approximately 1630 CDT, the RITT was yielding oil at the rate of 8000 barrels per day. The flow meter on the *Enterprise* vessel has been independently calibrated by a third party and thus this value is deemed reliable. We can revise that lower bound upwards by noting that a trickle of oil was still escaping out the end of the riser. If we assume that flow represents 15% of the original flow, then the lower bound on the flow rate rises to about 9000 barrels per day. At the same time, flow was moving through holes near the kink in the riser. It is difficult to estimate the proportion of oil versus gas escaping from the slits in the riser at this position. If the slits in the kink represent 1/6th of the flow, a lower threshold on the flow from observing changes in flow after insertion of the RITT is about 11,000 barrels per day of oil. Note that this lower bound alone is more than twice the earlier flux estimate of 5000 barrels per day. We consider this lower bound close enough to the 12,000 barrels per day determined from the other two methods to be consistent with those lowest low bounds.

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