Why B/S RAMS May Not Have Sealed on ROV Deadman Command

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1. Conclusions

In the presence of the control system leak at the blind shear (B/S) ram T-lock, and with no replenishment of power fluid from surface, there was probably insufficient subsea accumulator capacity to both overcome the leak and to close the B/S rams and stop the blowout flow past it. The analysis shown in the BP investigative report is faulty and not in accordance with current American Petroleum Institute (API) standards (and probably Minerals Management Service (MMS) rules based on API) for a deepwater subsea blowout preventer (BOP) control system. To be sure, the as-built design of the system was probably in accordance with API standards in the year 2000 time frame in which it was commissioned, but the API standard revision in year 2004 should have prompted a subsea upgrade soon thereafter, for sure not later than the 5-year recertification of the stack had that been carried out.

2. General Observation

It must be noted that to execute the "deadman", also called the Automatic Mode Function (AMF) command to close the B/S rams, the hydraulic conduit from surface must be dead or disconnected and the multiplex cables to the pods both inoperable. While this condition was probably satisfied early in the explosion and fire from the blowout, defects in both Blue and Yellow pods on the BOP would have prevented it from being triggering then. So the commentary here pertains to when the triggering was later supplied by Remotely Operated Vehicle (ROV) operation at the stack of a special function which bypasses the pods. The important point here is that regardless of how triggered, all the power fluid to execute the command must come from the subsea stack-mounted accumulators.

3. Analysis Offered by BP to September 8, 2010

Appendix Z of BP's "Bly" report dated September 8, 2010,[1] contains an analysis by Agito subsidiary Ultra Deep of the control system hydraulics for the Deepwater Horizon subsea BOP stack. Therein[1] they state that it was not possible with 1500 psi bore pressure to find a leak rate at the T-lock that would prevent the B/S ram from shearing the pipe and closing. So they increased the bore pressure to 4200 psi and with a leak rate approximated by a sharp-edged orifice of Cv = 3, the pipe could not be sheared. Under the same conditions of bore pressure, but with a Cv = 1, they say that the shearing and closure would be accomplished, and with only 3000 psi bore pressure and a Cv=3 simulated leak, the shearing a closure could be accomplished.[2]

4. Defects in the BP (Ultra Deep's) Analyses

The usable fluid from the 640-gallon total volume of subsea accumulators at full subsea charge and with 5500 psi initial N_2 charge at surface is grossly overestimated by Ultra Deep. They say at full charge (7165 psia), the "available volume" is 126.8 gallons.[3] This is approximately correct for the stored volume, but the usable volume is somewhat less than the stored volume with slow (isothermal) discharge, and less than half of that for a rapid (adiabatic) discharge. Author's calculations (See Appendix) using adiabatic expansion of the N_2 when actuation occurs show only 53.5 gallons usable volume to a discharge pressure of 3000 psi—the residual pressure value needed to shear and seal.

Adiabatic expansion is cited as the correct calculation method by API Standard 16D for deep subsea systems where rapid, high energy discharge is needed. Quoting from McAdams,[4]--"API Example 7 involves a rapid discharge system located subsea. This must be solved for an adiabatic discharge according to API requirements."

In a perfectly sealed control system (no leak at T-lock, no leaks at check and dump valves) that 53.5 gallons would be enough to shear the pipe and seal, which requires about 31.4 gallons.[5]

However, the system was NOT perfectly sealed. There was a significant leak at the B/S ram T-lock. Ultra Deep modeled that leak minimally at 35.5 gpm at 1280 psi differential (Cv=1)[6] and maximum of 87 gpm at 850 psi differential with Cv=3.[7] It is patently unclear from the Ultra Deep presentation how they arrived at the differentials used since there was always higher differential between control pressure at the B/S ram and sea pressure than they cite, about 1500 psi for the first six seconds of flow and increasing to about an average of 2700 psi for the balance of the total closing time of about 26 seconds.[8] It seems very likely that the total leaked volume during the closing time would exceed the narrow margin between available fluid (53.5 gallons) and the necessary closing volume (31.4 gallons). Under the circumstances, the accumulators may have sheared the drill pipe, but run out of sufficient fluid energy before finishing the strokes on the blocks after the shear and applying sealing stresses to the rubber seals.

In a no-leak situation, the N_2 in the bottles would have slowly warmed up and the available volume (and pressure) would have approached that predicted by isothermal expansion, which is about 102 gallons by the author's calculations. But it is doubtful that the warming effect would be rapid enough to make up for a continuous T-lock leak which would prevail as long as the function was triggered, and hence the B/S ram seals would never hold pressure tightly. Under blowout conditions, erosion would set in, much of it focused on the softer material of the B/S ram body and on the rubber seals themselves as evidenced by preliminary videos of the bore of the recovered BOP stack.[9]

Other leaks in the system might also have robbed the accumulators of capacity to close the B/S rams. If three of the eight 80-gallon stack-mounted bottles had lost their nitrogen pre-charge, the usable volume (adiabatic) would be only 34 gallons. If check valves that isolate these dedicated accumulators from the rest of the system or the dump valve that enables bleeding them down to sea before a stack recovery had leaked during the intervening time between loss of the rigid conduit and triggering of the AMF function by the ROV, the fluid thus lost could have meant there was just not enough left to perform that function fully.

5. References

1. BP, "Deepwater Horizon Accident Investigation, Appendix Z. Hydraulic Analyses of BOP Control System (from Ultra Deep)," September 8, 2010, 121, http://www.bp.com/sectiongenericarticle.do?categoryId=9034902&contentId=7064891.
2. BP, op. cit, 129
3. BP, op. cit., 114.

4. James McAdams, "Using NIST Tables for Accumulator Sizing," http://mcadamsengineering.com/NIST_by_Hand.pdf. A reinforcing reference is http://www.pngis.net/standards/details.asp?StandardID=API+Spec+16D-S%3A2004.
5. BP, op. cit., at end of Appendix Z, "Parameter List - Deepwater Horizon BOP Control System - Ultra Deep," 18.
6. BP, op. cit., 125.
7. BP, op. cit., 129.
8. BP, op. cit., 131.
9. Video clip of BOP stack interior after recovery, http://www.youtube.com/watch?v=LBCIIw3m39M&feature=channel.

6. Appendix – Calculations of Usable Fluid from Subsea Accumulators

McAdams[A-1] provides an excellent guide for calculation of usable fluid volumes from subsea accumulators and exposition of the need to do so in a particular manner. Access to API Specification 16D was not available, but McAdams makes the following observation: "API Example 7 involves a rapid discharge system located subsea. This must be solved for an adiabatic discharge according to API requirements." And McAdams provided the particulars of using the NIST tables to do so. The tables themselves are available on line.[A-2]

Stepwise, the calculations involve assessment of N_2 volumes, pressures, temperatures, and N_2 densities at:

1. Surface conditions where the N_2 pre-charge is applied.
2. Subsea conditions before power fluid charge is applied.
3. Subsea conditions after power fluid charge is applied.
4. Subsea conditions after the power fluid is used, in this case, without any replenishment from surface:
    a. Considering adiabatic expansion of the N_2 when power fluid is used rapidly.
    b. Considering isothermal expansion of the N_2 when power fluid is used slowly.

These cases were calculated using a Microsoft Excel spreadsheet for convenience, but a number of the values needed to be picked from the NIST tables and manually input to the spreadsheet with appropriate input to that valuable aid. The spreadsheet elements are reproduced below.

SURFACE CONDITION FOR PRE-CHARGING:				
PRECHARGE PRESSURE	5515	psia		
PRECHARGE TEMPERATURE	80	°F		
VOLUME of BOTTLE(S)	640	gal	85.5615	ft^3
DENSITY OF N_2 from NIST	21.746	lb_m/ft^3		
MASS OF N_2 CONTAINED	1860.620	lb_m		
ONTO SEA FLOOR W/BOP:				
WATER DEPTH	5000	ft		
SEA PRESSURE at SEA FLOOR	2239.67	psia		
TEMP at SEA FLOOR	40	°F		
DENSITY of N_2 from NIST	21.746	(Full of N_2)		

ACC N_2 PRESS at SEAFLOOR	4885	psia, from NIST @ Sea Temp		
WITH CHARGE PRESSURE APPLIED:				
N_2 CHARGE PRESSURE SURF	5000	psia		
N_2 CHG PRESSURE SUBSEA	7165	psia		
N_2 DENSITY from NIST TABLES	27.334	lb_m/ft^3		
N_2 VOL W/ CHG APPLIED	68.0698	ft^3		
[PWR FLUID CALC VOL= BOTTLE VOL MINUS N_2 VOLUME:]				
PWR FLUID CALC VOLUME	17.4917	ft^3	133.8008	gal
ENTROPY from NIST IS:	1.1278			
DISCH TO 3000 PSIG (ADIABATIC)				
ACTUAL DISCH MINIMUM	5239.67	psia		
DENSITY from NIST TABLES	24.736	lb_m/ft^3, Temp Falls to 0.8 °F !!		
N_2 VOL W/ DISCH APPLIED=	75.219	ft^3 →		
PWR FLUID SUPPLIED=	7.149	ft^3 →	**53.48**	**gal**
FRACTION of TOTAL VOL=	0.084			
DISCH TO 3000 PSIG (ISOTHERMAL)				
DIFF PRESS at FUNCT-MIN	3000	psi		
DISCH ABS PRESS=	5239.67	psia		
DENSITY from NIST TABLES=	22.768	lb_m/ft^3		
N_2 VOL W/ DISCH APPLIED=	81.7208	ft^3		
PWR FLUID SUPPLIED=	13.65	ft^3 →	**102.11**	**gal**
VOL SUPPLIED/TOTAL VOL=	0.160			

The reduction in usable volume from isothermal to adiabatic was so marked that this author questioned the validity (or his usage) of the NIST tables and checked some cases using N_2 compressibility factors picked from other sources.[A-3] Within the expected error from picking Z values from graphics, the densities, etc, tracked exactly.

7. Appendix References

A-1. McAdams, James P., PE, "Using the NIST Tables for Accumulator Sizing," http://mcadamsengineering.com/NIST_by_Hand.pdf.

A-2. NIST, "Thermophysical Properties of Fluid Systems," http://webbook.nist.gov/chemistry/fluid/.

A-3. Michael J. Mombourquette, "Gas Laws and Stoichiometry Involving Gases," Graphic for "Compressibility Factor for Nitrogen Gas," (z-factors for N_2), http://www.chem.queensu.ca/people/faculty/mombourquette/FirstYrChem/GasLaws/index.htm.