ACCIDENT ANALYSIS

Superior Offshore International Project on BP Marlin Platform

Description of accident:

CaviDyne, LLC ("CaviDyne") has not been furnished with enough detailed information to be able to fully reconstruct the precise conditions that were present when this accident occurred. The following is the most accurate representation of the accident scenario as determined from information provided by Mr. Jack Vilas from Jack Vilas & Associates and Mr. Dave Gilbert, BP's Project Manager, who have spoken with representatives of Superior Offshore International ("Superior"). The diver/operator, an employee of Superior, was using CaviDyne's Model YC-2040 CaviBlaster™ operating at a pressure of 255-bar (3,700-psi) to clean marine growth from the underwater surfaces on the Marlin Platform. At the time of the accident, the reverse-thrust nozzle of the lance was in very close proximity to the operator's arm. The operator pulled the trigger on the lance, opening the valve in the lance and starting the flow of water out of both nozzles. The initial stream of water from the reverse nozzle hit the operator's arm, resulting in water being injected under the operator's skin (Attachment 2 - Photo 4). The medic on the Marlin Platform administered first aid and the injured operator was transferred to a landside hospital for further examination and observation for infection.

Cause of accident:

The primary cause of this accident appears to be the unintended slippage of approximately 1.3 cm (1/2") of the reverse-thrust nozzle guard, which allowed the nozzle to come in very close proximity to the operator's arm.

CaviDyne designed and fabricated the reverse-thrust nozzle to generate maximum thrust while being safe at the same time. Without going into the detailed mechanics of turbulent round water jets, maximum thrust is generated when the water jet flows into an ambient or surrounding fluid that is at rest. The greater thrust is a result of the greater difference in velocities between the jet and the ambient liquid. When the jet is inside of a tube or guard, the ambient water inside of the guard is affected by the water jet and attains a velocity in the same direction as the jet. This decreases the velocity differential and, thus, the thrust. CaviDyne designed the reverse-thrust system (nozzle and guard) to maximize thrust while incorporating a guard to provide safety to the operator. This strategy required minimizing the distance between the tip of the nozzle and the end of the guard, while maintaining a safe distance within the guard for the water jet to decelerate so that it would not harm the operator. CaviDyne designed and constructed the CaviBlaster™ lance used on the subject project with a guard that extended 4 cm (1-1/2") past the tip of the nozzle; a distance that our calculations indicated was safe.

CaviDyne has observed that the safety guard for the reverse-thrust nozzle could slide toward the front or cleaning end of the lance. This slippage decreased the distance between the tip of the nozzle and the nozzle guard. The combination of water flow through the reverse-thrust nozzle and the vibration of the lance when water was moving through the nozzles could cause the guard to slip. Some divers also use the tip of the CaviBlaster™ lance as a hammer. This was another factor that could have caused the guard clamp to loosen and the guard to slip.

It is CaviDyne's opinion that the injury was most likely caused by the initial flow of water out of the reverse-thrust nozzle on the lance when it was activated. In the initial instant that the valve in the lance handle is opened and water flow through the lance is initiated, a combination of physical factors act on the water coming out of both jets. The CaviBlaster™ bypass system operates by trapping water under high pressure in the hose between the pressure-regulating unloader on the power unit and the valve in the lance handle. This water is trapped at a pressure approximately 35-bar (500-psi) higher than the operating pressure of the system. In this case, the water trapped in the hose would have been at a pressure of approximately 290-bar (4,200-psi). In the instant that the lance trigger was pulled and water began to flow, the opening of the valve generated a pressure shock wave that flowed through the water and out of both of the nozzles. These two factors combined to create a condition where the water coming out of the nozzles in the instant that the trigger was pulled was at a significantly higher pressure and therefore had a higher exit velocity compared to the normal operating conditions.

At the time of the accident, the reverse-thrust nozzle was most likely in very close proximity (approximately 2.7 cm or 1") to the operator's arm and the high-velocity and high-pressure created a condition where water was injected under the operator's skin.

Even though the cavitation system is very safe during operation, there are still safety precautions that must be observed when using the system. The reverse-thrust nozzle that was in use during this incident has a working pressure of 255-bar (3,700-psi) with a volume of seven gallons per minute. CaviDyne has calculated the velocities of water at different distances from the nozzles of CaviBlasters™ and other conventional water jets (Attachment 1 and Table 1). Water exits the CaviBlaster™ nozzle through an orifice with a diameter of 0.178 cm (0.07") at a speed of approximately 178 meters (585 feet) per second. The water begins to decelerate rapidly soon after it leaves the orifice; however, as is explained in the enclosed calculations, the zone within two inches of the nozzle is turbulent and the velocity of the water jet is high. At a distance of 5 cm (2") from the nozzle, the centerline velocity of the water has decelerated to approximately 36 meters (120 feet) per second, which is unlikely to cause harm to the operator. Please note; however, that these calculations are based on normal operating conditions and velocities will be higher during the initial instant that the trigger is pulled. For example, the water velocity just inside of the nozzle when the trigger is pulled is approximately 195 meters (640 feet) per second. The pressure shockwave that is generated by the opening of the valve also creates a different energy distribution and discontinuities at the interface of the two bodies of water. These two factors and the higher water jet velocity create conditions that are more damaging than normal operating conditions.

Future precautions / engineering solutions:

CaviDyne has redesigned the guard so that it cannot slip. This will eliminate the scenario that appears to have been encountered in this instance where the guard was initially at a safe length but, after use, slipped and exposed the operator's arm to high water velocities near the tip of the nozzle. The redesign incorporates a slot in the guard through which the reverse-thrust nozzle is inserted (Figure 1). This prevents the guard from slipping in the event that the black polycarbonate clamp becomes loose.

CaviDyne has also redesigned the length of the nozzle to provide a greater safety factor. The guard extends 16 cm (6.35") past the tip of the redesigned reverse-thrust nozzle. At this distance, the centerline velocity of the water jet is approximately 12 meters (40 feet) per second. That velocity is lower than the velocity of water in a garden hose discharging through a 3.75 mm (0.15") diameter nozzle (Table 1). Modifications to existing nozzles have also been made to provide this greater safety factor.

In order to maintain the effectiveness of the nozzle, the ambient water velocity inside of the guard must be minimized. Because CaviDyne has moved the nozzle away from the end of the guard, longer slots (Figures 1 and 2) are machined into the revised guard. These longer slots will inhibit the ambient water inside of the guard from obtaining significant velocity in the direction of the water jet and will maintain the effectiveness of the reverse-thrust jet.

Photos 1-3 in the Diving Safety Alert (Attachment 2) show that the end of the guard had been crushed prior to the accident. Photo 2 also shows that the guard was broken and part of the guard was missing. It is likely that this was at least one cause of the guard slippage and was a possible additional factor in the injury. CaviDyne has increased the wall thickness of the stainless steel guard to 3.2 mm (1/8") (Figure 2). This will make it more difficult to damage or deform the guard as well as compensate for the strength lost by lengthening the slots.

It is also the responsibility of the operator to inspect the equipment on a regular basis. If the lance had been inspected prior to the dive on which the accident took place, the apparent damage to and slippage of the nozzle guard may have been observed and corrected. This may have prevented the accident. CaviDyne has incorporated information describing the inspection of the nozzle guard into its CaviBlaster™ O&M Manuals and has provided updated manuals to all CaviBlaster™ owners.

Conclusion:

This accident was caused by the operator inadvertently contacting the high-velocity reverse-thrust water jet while his arm was in very close proximity to the nozzle. The operator was able to contact the water jet because the guard slipped forward, reducing the distance between the tip of the nozzle and the end of the guard. The initial high-velocity flow of water and pressure shockwave out of the nozzle when the operator pulled the lance trigger injected water under the operator's skin.

Under normal operating conditions, the velocity of both water jets will push objects away from the nozzles. It would be very difficult for a diver to get their hand close enough to the nozzles to cause an injury. However, as we have seen, if the lance is not operating and a diver's skin is placed directly in front of **either** nozzle prior to activating the water flow, or if the lance is passed over a diver's skin at a very close distance **(typically less than 3 – 5 cm or 1 – 2")**, the conditions described above are capable of causing an injury.

It is important that the diver/operator wear protective gloves and keep clear of the tip of the CaviBlaster™ lance when operating the equipment.

For additional information please contact John Fulkerson with Cavidyne at 352-505-7840.

Figure 1

Figure 2

ATTACHMENT 1

Turbulent Round Water Jet

Basic theory and assumptions:

Assumptions and considerations:

- Newtonian fluid steadily flows through a nozzle of diameter d, which produces (approximately) a flat-topped velocity profile with velocity $\mathrm{U_j}$ and forms a high-Reynolds number turbulent jet ($Re = \frac{d\, U_J}{\nu} > 10^4$), which flows into an ambient of the same fluid, which is at rest.

- The flow is statistically stationary and axisymmetric.

- The velocity components in the x, r and θ coordinate directions are denoted by U, V and W accordingly.

- The mean velocity is predominantly in axial direction ($r = 0$ is the axis around which the profile of $\langle U \rangle$ is symmetric).

- The mean circumferential velocity $\langle W \rangle = 0$ and the mean radial velocity $\langle V \rangle$ are smaller than $\langle U \rangle$ by an order of magnitude.

- The mean velocity profile beyond the developing region ($\frac{x}{d} > 30$) is self-similar. See Pope, 2001 for details and explanations.

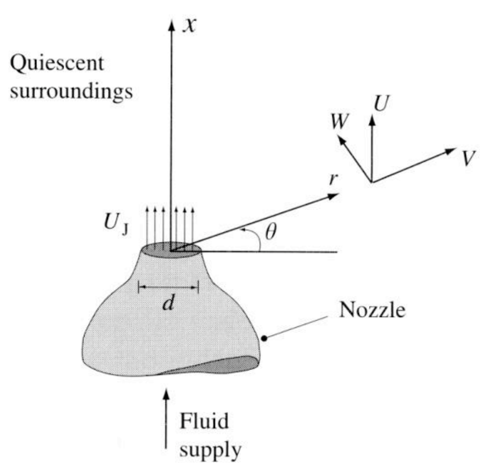

Figure 1 - Sketch of a round jet from a nozzle (Image from Pope, 2001)

Empirical derivations:

Definitions:

The centerline velocity of the jet as $U_0(x) = \langle U(x,0,0)\rangle$

The jet's half width as $r_{1/2}$, where $\langle U\left(x, r_{1/2}(x), 0\right)\rangle = \frac{1}{2}U_0(x)$

After Hussein et al., 1994 we can define two constants:

$\frac{U_0(x)}{U_J} = \frac{B}{(x-x_0)/d}$ where B is the velocity-decay constant and

$S \stackrel{\text{def}}{=} \frac{dr_{1/2}(x)}{dx}$ where S is the spreading rate, which is also a constant.

Table 1 shows the results of measurements by different researchers in liquids with Reynolds numbers different by an order of magnitude. The results show that B and S are indeed independent of Re (within experimental uncertainties). For further calculations we will employ B=5.8 and S=0.094 from Table 1.

	Panchapakesan and Lumley, 1993	Hussein et al., 1994 Hot-wire data	Hussein et al., 1994 Laser-doppler data
Re	11,000	95,500	95,500
S	0.096	0.102	0.094
B	6.06	5.9	5.8

Table 1 - Empirical estimates of spreading rate and velocity-decay constant for round jets

Typical Caviblaster™ unit calculations

Let us consider a typical "zero-thrust" nozzle on a Caviblaster™ unit with the following parameters:

- "Zero-thrust" nozzle diameter = 0.07" = 0.1778 cm
- "Zero-thrust" nozzle flow rate = $7\ gpm = 0.0265\ m^3/min = 441.631\ cm^3/s$

$Q = 441.631\ cm^3/s$ $d(0.07) = 0.1778\text{cm}$

This translates into $U_J = Q\Big/\frac{\pi d^2}{4} = 17{,}770\,\frac{cm}{s} = 178\ m/s$

$x/d = 30 \Rightarrow x = 6\ cm$ is the region where flow is fully developed (6 cm from the nozzle) and we can apply the above principles to it. Using (1) at the distance $x = 6\ cm$ from the nozzle-centerline velocity $U(x) \approx 30.6 \frac{m}{s}$.

Also, based on (1) we can build a curve for centerline velocity (Figure 2).

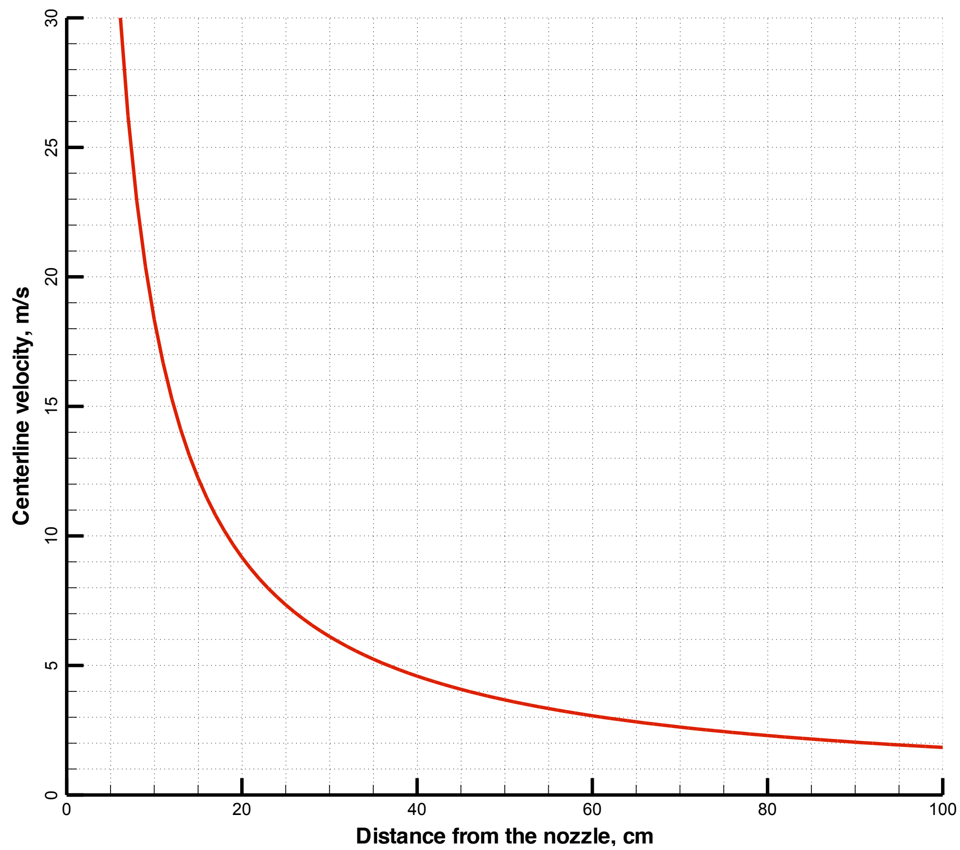

Figure 2 - Changes in jet centerline velocity with distance from the nozzle

As illustrated by Figure 2, the centerline velocity of the jet rapidly decreases with distance from the nozzle. While the exit velocity of the jet was calculated to be at almost 180 m/s it slows down to about 5.5 m/s after traveling 30 cm.

References

1. Pope, S.B.: Turbulent Flows. University Press Cambridge, 2001.
2. Panchapakesan, N.R., Lumley, J.L.: Turbulence measurements in axisymmetric jets of air and helium. Part 1. Air jet. Journal of Fluid Mechanics 246, 197-223.
3. Hussein, H.J., Capp, S., George, W.K.: Velocity measurements in a high Reynolds number, momentum-conserving, axisymmetric, turbulent jet. Journal of Fluid Mechanics 258, 31-75.

TABLE 1

CENTERLINE WATER VELOCITIES AT DIFFERENT DISTANCES FROM NOZZLES

Distance from nozzle (inches)	Centerline Velocity (mph) Caviblaster™ 6 gpm @ 1,900-psi	Caviblaster™ 7 gpm @ 3,700-psi	Caviblaster™ 7 gpm @ 4,200-psi	Water blaster 10 gpm @ 10,000-psi	Water blaster 10 gpm @ 20,000-psi	Garden hose 4.3 gpm @ 65-psi
0	288	398	438	658	929	51
2	63	81	89	124	147	
3	42	54	59	82	98	
4	32	40	44	62	73	
6	21	**27**	**30**	41	49	
12	11	13	15	21	24	

Notes:

1) Caviblaster™ and water blaster velocities have been calculated discharging into water. Garden hose velocity has only been calculated at the nozzle because it is assumed to discharge into the air and is used as a reference.

2) Garden hose velocity calculated discharging through a 0.150" diameter nozzle.

3) Velocities at 0" are not centerline velocities; they are velocities inside of the nozzle. Velocities just outside of the nozzle will be much higher and cannot be accurately calculated.

4) The YC-2040 Caviblaster™ zero-thrust nozzle guard extends 6.35" past the end of the nozzle. At this distance from the nozzle, the centerline velocity is approximately 26 mph under operating conditions and 29 mph in the instant that the trigger is pulled.

DIVING SAFETY ALERT

May 2007

Diver Injury using Cavitation Blaster

A new type of HP Water Blasting system has been introduced to GoM divers.

A new underwater HP Water Blasting unit using a 4500 psi jet stream instead of 10,000 psi has been used to clean marine growth from structures and vessels, the principal is an engineered system that uses cavitation (explosive bubbles) to remove marine growth.

The system at the time of the incident was being used to clean marine growth from an offshore facility and has only recently been introduced by a couple of operators in the Gulf of Mexico. The agreement to use the tool was only considered after witnessing the unit in tank tests with the contractors and operators in attendance.

As with any HP system the divers' were briefed on the potential dangers of the unit, although it was shown by the inventor that the nozzle jet stream, due to the cavitation principal gun, would not harm a diver's body if it past over it 8 to 10 inches away. This was demonstrated time and again during the trials.

Like all HP blasting systems the gun assembly was designed that a portion of the jet stream is directed to the rear in an attempt to balance the thrust of the unit and if not balanced as in traditional HP Blasting to at least reduce the push back from the front nozzle.

What was not understood until this incident is that the retro-jet had the potential of injuring the diver.

Thus it was felt by the divers', diving contractors' and the operators' that hopefully we had at last found a diver friendly water blasting system.

It's important to emphasize that everyone involved in the familiarization, training trials and offshore utilization felt this was a better system and it may still be developed into one.

Brief account of Incident: During cleaning operations the diver released the trigger on the cavitation gun (de-activating the jet stream) to reposition his body. When the diver reapplied pressure to the trigger on the gun, the cavitation gun kicked back toward the diver, causing the retro end of the gun to come into close proximity of his wrist and forearm. Subsequently the retro-jet caused a high pressure (approx. 1000psi) seawater injection injury to the diver's forearm.

Actual Severity: Diver was recovered to the surface and immediately seen by the medic onboard the DSV. A high pressure injection injury was apparent and it was agreed that they would Medivac the injured diver to a hospital for observation. The arrangements were made by the OIM and a night flight was set-up.

On arrival at the hospital the injured person was treated by the emergency room doctor, given oral antibiotics and then released, pending a follow-up visit to a specialist. When the specialist examined the patient it was determined the wound was shallow and the small amount of seawater injected would drain without any surgery being required. Follow-up visits to observe the patient for any sign of infection were scheduled and the patient was released for active duty.

The incident could have caused permanent injury but only resulted in a first aid case.

What went wrong in this case: The inventor was on site earlier in the project and had reviewed all of the hazards associated with the unit but didn't think that the retro-jet posed a threat underwater, but did recognize it while surface testing the gun. There were written procedures with several warnings in red relating to keeping out of the path of the front jet within 2" to 3" of the nozzle, but no similar warning about the retro-jet. There were demonstrations and familiarization with all of the diving crew and project management on-site; there was also recognized safe operational experience by another operator without incident.

Original engineering of the retro-jet did not prevent diver injury, due to the end of the rear baffle being less than two inches from the retro-jet. During the HAZID and following Risk Assessment of the gun and system, the retro-jet was not identified as having a high pressure injection risk as was the front jet.

One thing that was discovered is that the diver was wearing protection that covered that area of his body but was not the 11" butyl rubber gloves recommended in the diving contractor procedures. As can be seen in photo 5 the retro-jet punched a hole through the neoprene glove, which may not have happened wearing butyl rubber gloves. But this is not a tested theory.

Immediate actions taken: A Safety Stand Down was immediately called and all work stopped on the DSV. The injured party was dispatched to the beach and an investigation was commenced. The manufacturer was notified and informed the cavitation gun was taken out of service and it was stated that the Cavitation System would not be used until redesign of the gun was undertaken and the operator's Engineering Authority has reviewed the modification and extensive testing be completed before the system can be re-considered for use.

Subsequent Actions: Manufacturer has modified the retro-jet by moving the nozzle further back inside the rear baffle. The incident report has been circulated within the company and this public notice is developed for distribution to the general public.

Pending issues: Operator Engineering Authority hasn't examined the modifications and won't be able to make recommendations until that is done. From the diver's perspective it is hoped that the retro-jet nozzle and the baffle of the gun be redesigned, so that it is physically impossible for the diver to ever be injured in the future.

Photo 1 – Cavitation gun

Photo 2 – End view of retro-jet

Photo 3 – Side view of retro-jet showing proximity of retro-jet nozzle to end of baffle. (approx 3 cm)

Photo 4 – High pressure injection injury to the diver's forearm

Photo 5 – Diver's glove showing hole at location of injection