BSEE Contract E16PC00002	
CONFIDENTIAL	
Raptors Design, Inc.	
Title	**Final Report for the Hampering Active Wellbore Kit (HAWK): Complementary Safety Tool For Blowout Preventers**
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"THE RESEARCH PROJECT OUTCOME DID NOT CONCLUDE AS A HIGHLY INFLUENTIAL OR INFLUENTIAL CATEGORY. THEREFORE, BSEE WOULD NOT CONDUCT A PEER REVIEW FOR THIS RESEARCH."

Outline

1. EXECUTIVE SUMMARY

The Hampering Active Wellbore Kit (HAWK) safety tool (patents pending for tool, wire, and method) was developed in response to the Deepwater Horizon Accident; and the resulting reports recommending the development of backup safety devices for use in case the Blowout Preventer (BOP) fails to properly deploy. The National Academy of Sciences report *Lessons for Improving Offshore Drilling Safety* stated that: "advances in BOP technology should be evaluated from the perspective of overall system safety" (item 3 pg. 4), and called for industry to "expand R&D efforts focused on improving the overall safety of offshore drilling" (item 10 pg. 5) [1]. The chief Counsel Report went as far as to state that "BP and its contractors had neither developed nor installed [exceedingly] sophisticated technology to guard against a blowout" [2].

The HAWK tool provides a controlled flow reduction for a loss of well control situation. The HAWK tool (Figure 1) achieves the objective to stem flow by creating a mechanical plug inside the free flowing wellbore, referred to as a Tangled Wire Mass (TWM). During a loss of well control, the HAWK tool is activated and feeds a continuous "wire" (the properties of the wire vary along its length) into the BOP wellbore via a choke/kill port. The first section of the wire is designed to not be carried by the flow until it buckles and starts to build a tangled wire mass in the wellbore. The growing TWM travels downstream and anchors on existing features of the BOP such as partially deployed shear or pipe rams. As more and more wire is fed in, the TWM grows, and the properties of the wire injected are varied to create a mechanical plug that has strength as well as the ability to stem the uncontrolled flow.

Preliminary feasibility tests conducted on a four inch diameter wellbore model demonstrated fluid flow reduction of more than 90% which led Raptors Design LLC to design and build a scale engineering prototype used to demonstrate feasibility at an 11" wellbore scale.

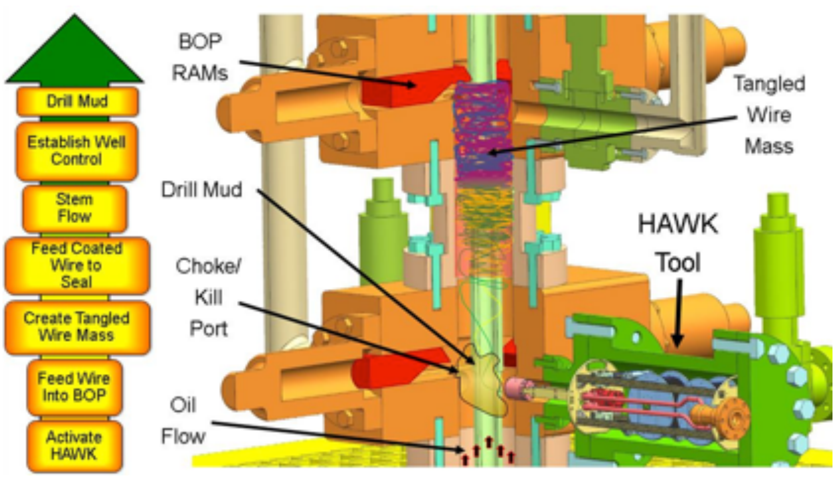


Figure 1 Cut out of HAWK tool directly connected to a BOP stack showing the mechanical plug and choke/kill port introducing drill mud.

Subsequently, Raptors Design received a contract with the Bureau of Safety and Environmental Enforcement (BSEE) Technical Assessment Program (TAP) to “demonstrate feasibility of generating a tangled wire mass inside an 11 inch free flowing stream and to measure the stemming of the flow.” This report outlines flow loop tests of the HAWK tool prototype carried out under BSEE contract E16PC00002. The flow loop tests conducted in June 2016 and Sept 2016, Figure 2, demonstrated the ability to generate a TWM inside a free flowing wellbore that can effectively be used to stem the flow and hold pressure; once deployed in a loss of well control situation, heavy mud could then be pumped through the tool and into the bore to effect a top kill of the well.

The tests conducted (Figure 2) were successful at demonstrating the ability to generate a TWM inside a free flowing wellbore, anchoring of the TWM against an obstruction that emulated a closed pipe ram, and significantly stemming the free flow; thus accomplishing our objectives. The TWM generated in both an open bore as well as a bore with a drill pipe. The TWM anchors against a rectangular or circular obstruction geometry. We also demonstrated that the flow could be reduced by as much as 91% (from 7 bpm to 0.6 bpm flow of water) in an 11 inch wellbore with an open circular aperture of 3.5 inches at 10,000 psi.

Accordingly, the next stage of HAWK tool product development would be to work with an industry partner with expertise and market presence needed to develop the commercially deployable embodiment of the tool.

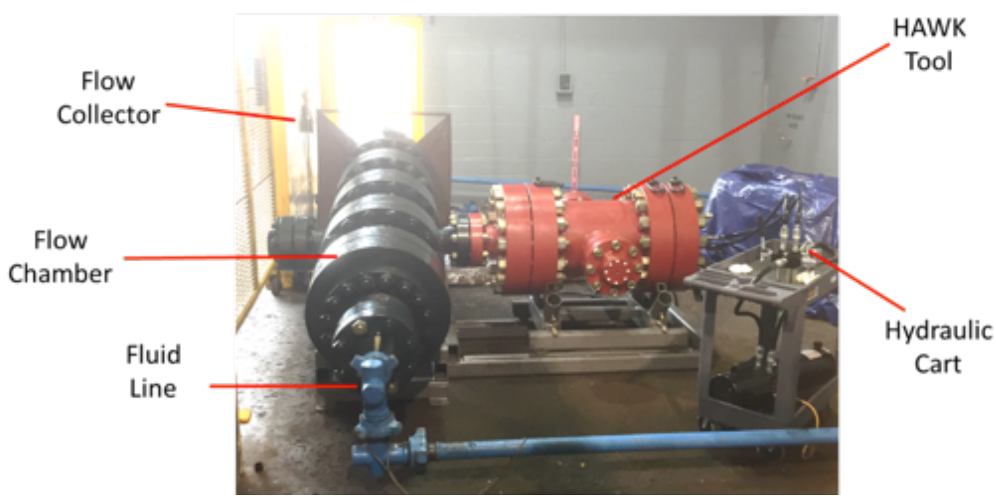


Figure 2 HAWK tool preliminary flow loop testing to validate system design at an 11 inch scale

2. HAWK TOOL Design

The HAWK tool can be deployed in two different forms: mobile (e.g., on a remote operated vehicle (ROV) or small truck that brings the HAWK to the wellhead to be connected and operated), or as independent component residing on the RAM stack to be instantly deployed should the BOP fail. The following sections describe the HAWK tool prototype design, operation methodology, and vision for how the HAWK tool could be integrated to work with a blowout preventer.

2.1. HAWK Tool Layout

The HAWK tool is divided into two modules: pressurized housing, and internal assembly. Figure 3 shows the current prototype components of the HAWK tool. The production tool would have an additional hydraulically operated gate valve (HCR valve) to allow drill mud to be introduced (after generating the TWM) via the HAWK tool into the wellbore. In addition, a valve should isolate the HAWK from the wellbore until it is needed. Figure 4 shows the 11-inch engineering prototype. The internal assembly is connected to the back flange of the pressurized housing structure.

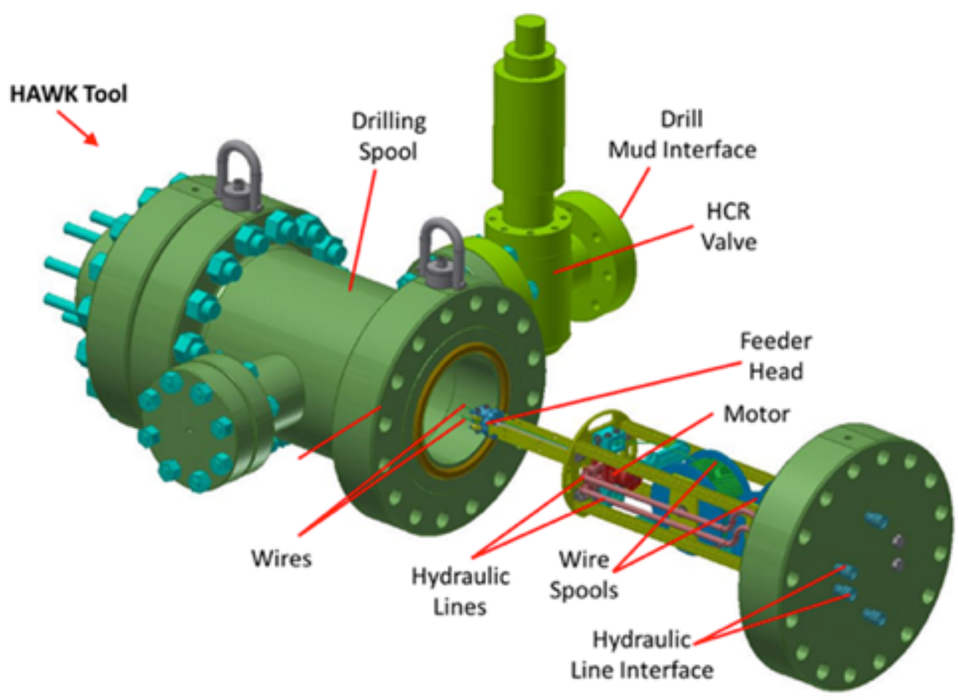


Figure 3 HAWK tool schematic layout, where the HCR valve is the hydraulically operated gate valve

The internal assembly consists of 4 components: 1) feeder head, 2) motor, 3) wire spools, and 4) sub-assembly structure. The sub-assembly structure holds all of the components in the internal assembly. The prototype uses a hydraulic motor to drive the feeder head. The wire material is pulled from the spools by the feeder head. As the wire is pushed into the free flowing well, the TWM is generated.

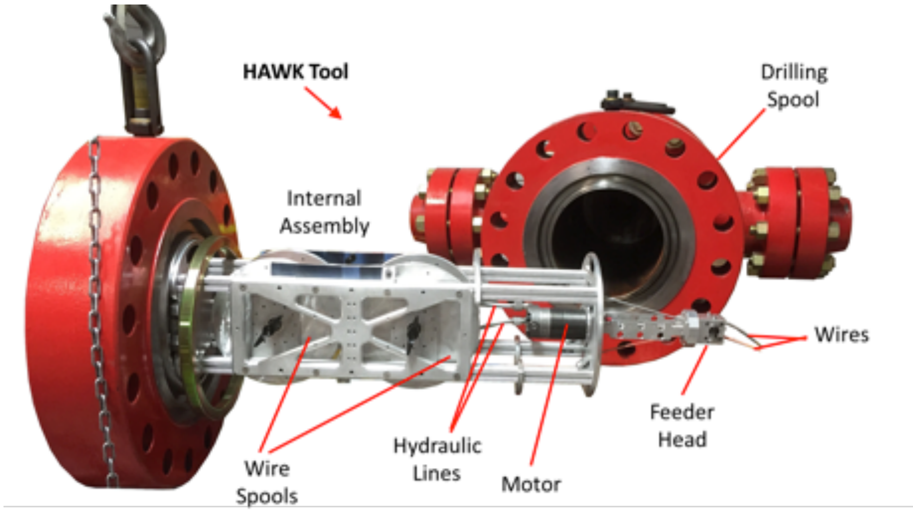


Figure 4 HAWK tool internal assembly and drilling spool

2.2. Operating Method

The wire is fed into the wellbore via the choke/kill port, and the operating method is best summarized in three steps: Generate, Anchor, and Stem (illustrated in Figure 5). During the *generate* stage the wire starts to buckle in the wellbore generating the start of the TWM. As the wire mass enlarges, its cross sectional area increases eventually leading to the flow carrying it downstream to *anchor* on an existing obstruction such as partially deployed shear or pipe rams. As more material is introduced into the wellbore, it will begin the *stem* the flow. The pressure differential across the TWM further assists flow reduction by compressing the TWM. The key parameter, as will be discussed later, is the changes in wire properties as it is fed into the wellbore.

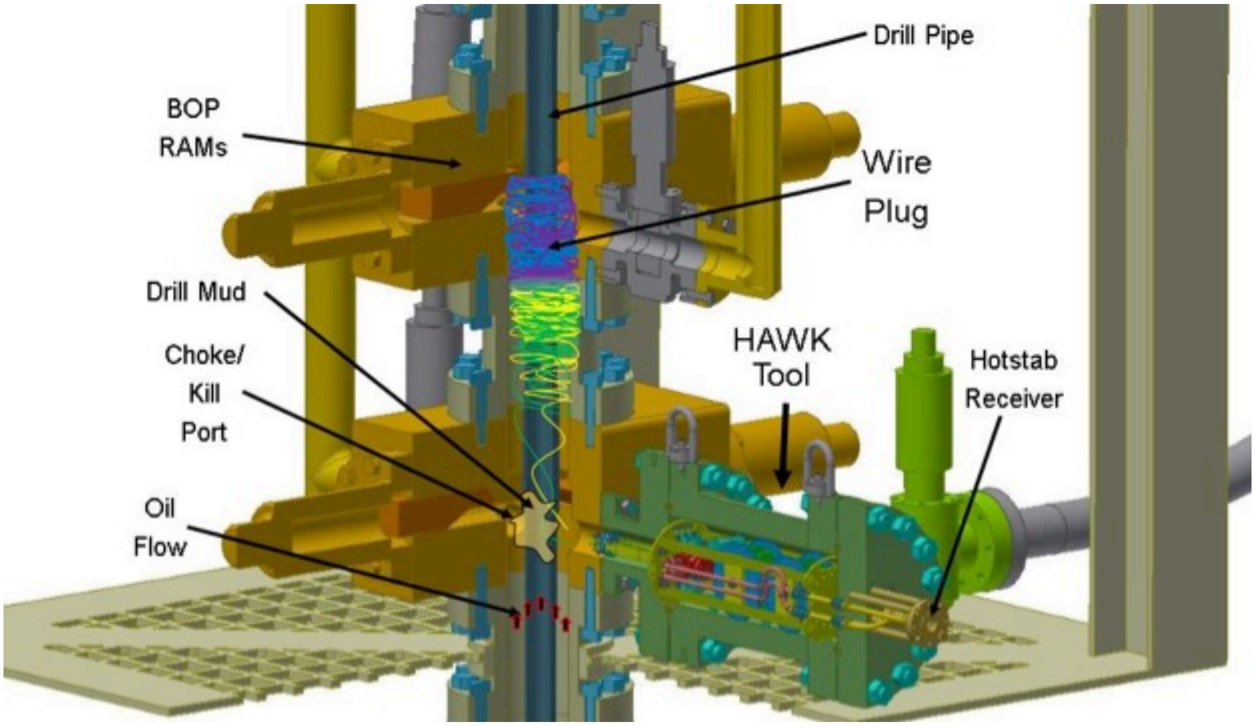


Figure 5 Method of generating a tangled wire mass to stem an uncontrolled flow.

With the flow significantly reduced, a capping stack can be more easily installed, and/or drill mud can then be introduced into the wellbore either via the HAWK tool or through a complementary choke/kill port of the BOP stack. Heavy mud can now flow downhole without being carried out of the well by an uncontrolled flow, to effect a top kill of the well. Once the top kill is affected, the failed BOP could be repaired or replaced.

In the presence of a drill pipe in the wellbore, the drill mud flows downhole and then into the interior of the drill pipe. The flow through the drill pipe interior will cease as the drill pipe interior volume is displaced by heavy drill mud.

2.3. Deployment

For immediate response the HAWK tool should be pre-installed on a BOP by connecting it to a dedicated choke/kill port (Figure 6). After a loss of well control is confirmed and the blowout preventer fails to control the well, the HAWK tool is activated. It is envisioned that the hydraulic system driving the wire feed motor can be directly integrated into the BOPs hydraulic power supply, or the HAWK tool can have its own hydraulic power reserve. As a backup, the HAWK tool can be activated via an ROV hotstab connection.

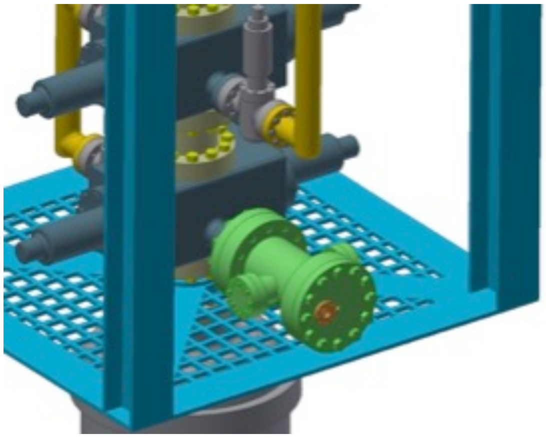


Figure 6 HAWK tool connected directly to choke/kill port

2.4. Post Deployment Operations

Once the well has been brought under control using the HAWK tool as described above, if the wellbore is clear (no drill pipe) then the BOP rams can be retracted, the capping stack valve opened, the TWM easily fished out and a cement plug can be introduced. Once set, the failed BOP can be replaced. Conventional operations can then resume.

If the drill string is still present in the wellbore, the operation is more complex because the capping stack valve needs to be opened and the drill string fished out. If this disrupts the top kill mud and the flow resumes, more top kill mud could then be injected through the choke and kill port. Once the drill string has been removed, the TWM can be fished out and a cement plug introduced.

If the BOP rams will not retract, and cannot be repaired, the TWM can still be attempted to be fished out. Else the difficult decision will have to be made to remove the BOP with just top kill mud in place.

2.5. HAWK Tool Attributes

The HAWK tool has the following attributes, which make it very attractive as a back-up safety device for BOPs:

1. **Deterministic Operation:** Feeding a continuous wire structure into a loss of well control has a predictable behavior. The flow can thus be stemmed slowly and controllably.
2. **Rapidly Deployable:** The size of the HAWK tool is relatively small (< 5 tons).
3. **Complementary:** The HAWK tool is complementary to existing safety equipment.
4. **Regulatory Incentive**: The tool is aligned with new regulations "aimed at avoiding a low-probability but high risk occurrence of a catastrophic oil spill" [3].
5. **Off-the-Shelf Components:** The pressurized housing structure of the HAWK tool is composed of commercially available components (e.g., drilling spools and slightly modified flanges) rated per API standards.
6. **Modest Cost:** The HAWK tool costs a small fraction of a capping stack, and is a very much smaller and simpler to integrate with existing BOPs.

2.6. Benefits to Stakeholders

- **Regulators**
  - Complementary safety tool
  - Onshore & offshore application
- **Operators**
  - Leasing competitive advantage
  - Provides access to well post-accident
  - Potential reduced insurance premiums
- **Drilling & service contractors**
  - Rapidly deployable
  - Provides controlled flow reduction
  - Interfaces for existing BOP infrastructure
  - Provides access port for top kill operation
- **BOP manufacturers**
  - Complements existing BOP safety systems
  - Expands safety tool market
  - Integrates into every BOP

2.7. Impact

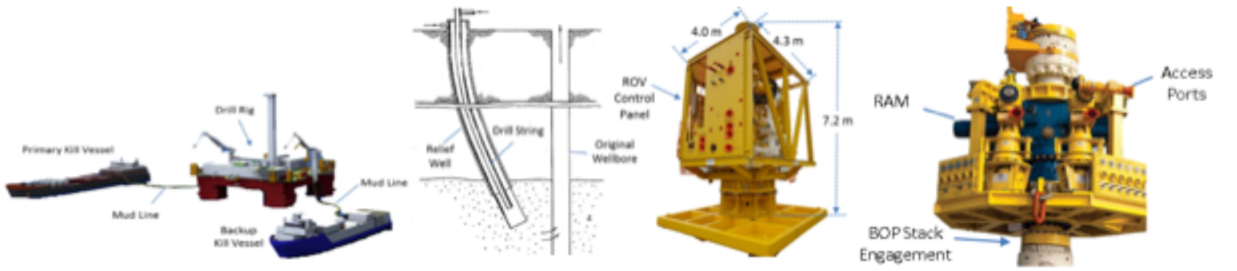
The economic ramifications of an oil spill stem from: production losses, fines, and clean-up costs. The fines depend greatly on the regulatory body for the region. In the U.S. each barrel of oil spilled carries a minimum fine of $1,100 per barrel and maximum fine of $4,300 per barrel, in accordance with the Section 311 of the Clean Water Act [4]. This means that an uncontrolled well leaking 60,000 barrels (9,540 m^3) per day [5] may cost an oil company USD $764 per second in fines alone, assuming no finding of negligence. An uncontrolled well releasing crude oil, at said rate, for 7.5 hours costs twenty million dollars in fines alone, which is on the order of the development cost of a complex tool like a deepwater ROV. Thus any tool that can close the well eight hours faster than an existing method has captured its return on investment in savings from 1/3 of a day's fines alone.

While determining true oil spill cleanup costs is complex, the estimated US clean-up cost for offshore averages $3,490/barrel (1999 US $) which is equivalent to $5,000 in 2015 [6]. The European Commission (EC) estimated the annual cost for all major offshore incidents between $150 million and $900 million per year ("average annual cost of blowout incidents, estimated to be between €140 million and €850 million") [7]. The unit cost (per ton) of oil spilled based on the European Commission report is $25,614/ton (1999 US$) which is ~$36,500/ton in 2015 [7]; of course, the cost is dependent on location, duration of loss of well control, size of spill, amongst other factors.

The total cost of the Deepwater Horizon accident, as of February 2013, was $42.2 billion [8]. With the court ruling finding BP negligent, the total cost burden to BP is estimated at $54 billion [9]. BP's net cost per barrel, assuming the courts estimated value of 4.2 million barrels, results in approximately $12,900 per barrel of oil spilled.

2.8. Technology Comparision

The primary existing technology to address a deepwater loss of well control is summarized in Figure 7 and compared to the HAWK tool projected performance. Capping stacks and containment domes weigh on the order of 40 to 100 tons, thus requiring a significant infrastructure to deploy. The main advantage of the HAWK tool is the modest cost and small size, which allow for the pre-installation and integration with the BOP stack.



	Response Time	Cost	Support Equipment	Weight & Transportation	Reliability	Applicability	Risk
HAWK	< 1 week	Low	VOF	< 2/3 T Airplane/Ship	Medium	Medium	Low
Junk Shot	2 – 4 weeks	High ($1M/d)	Ship w/ Drill Mud	N/A Ship	Low	Medium	Med
Relief Well	4 – 10 weeks	High ($1M/d)	VOF	N/A Drill Rig	High	High	Low
Capping	2 – 4 weeks	High	VOF	40/100 T Ship	Medium	High	Med
Containment	4 – 6 weeks	High	VOF	500 T Ship	High	High	Med

Figure 7 Evaluation of competing technology for addressing a deepwater failed blowout preventer

3. HAWK TESTING

3.1. Testing Phases

The HAWK tool testing can be divided into three phases: 1) TWM scaled testing, 2) high pressure (10k psi) and flow rate (~20 kbpd) testing, and 3) BOP integrated tests. The BSEE contract only covers Phase 1 testing. Phase 2 and 3 will require evolution of the current prototype test unit into a production ready device and hence partnering with an industry stakeholder. To improve the successful accomplishment of our testing plan we are continually assessing risks and creating countermeasures.

- Phase 1: Scale testing
    - Testing: September 2016
    - Flow loop
        - 11” Wellbore
        - Flow rate
            - 315 gpm (7.5 bbl/min = 10,800 bbl/day)
            - Reynolds number 90k
        - Withstand pressure to at least 3,500 psi
- Phase 2: High pressure testing
    - Projected time: June 2017
    - Flow loop:
        - 11” Wellbore
        - Flow rate
            - Max: 600 gpm (14.3 bbl/min = 20,570 bbl/day)
            - Reynolds number range 20k to 30k
        - Withstand pressure to at least 10,000 psi
- Phase 3: BOP integrated test
    - Projected time: November 2017

At each phase the collected results are to be compared to the calculated performance based on prior experiments. The results from phase 1 will serve to corroborate and adjust the calculated performance as subsequent phases are started.

3.2. Data Collection

For each testing phase the following data is to be collected for corroborating sealing efficiency and progressing to the next phase.

- Data collection
  - Flow rate (before and after TWM introduced)
  - Pressure
    - Flow chamber
    - HAWK tool
  - Wire feed speed
    - HAWK tool
  - TWM Geometry
    - Length of TWM (post test)
- Analysis of permeability
    - Calculate permeability
    - Plot pressure vs. permeability
    - Plot permeability vs. % flow reduction
- Documentation
  - Photos
  - Videos

The deliverables at each phase include: 1) risk analysis, 2) material permeability, 3) back pressure vs. compression fill factor, and 4) permeability vs. flow stemming efficiency. By comparing the measured flow before and after introducing the TWM we can determine the sealing efficiency.

3.3. Experiment Components

At each experimental phase all of the elements can be divided into three components: 1) people & resources, 2) infrastructure, and 3) hardware.

1. People & resources
    a. Testing facility
        i. Technicians
    b. Auxiliary elements
        i. Machine shop, welding
    c. Safety protocols
2. Infrastructure
    a. Fluid supply
    b. Flow Chamber
    c. Monitoring station
        i. Sensors
        ii. Data recording
        iii. Digital recording
            1. Video of tests
3. Hardware
    a. Obstruction configuration
        i. Clear wellbore chamber
        ii. Cap with partially closed ram geometry
    b. Hydraulic power unit
    c. HAWK tool

The wellbore model also has several test parameters to vary:

1. Configuration
    a. Wellbore
        i. Size
            1. 11” (Phase 1), 13.625”, 18.75”
        ii. Obstruction
            1. Unobstructed
            2. Drill string present
        iii. Flow rate
    b. Obstruction
        i. Type
            1. Pipe ram
            2. Shear ram

    ii. Obstruction area coverage
        1. Discrete based on obstruction flanges
  c. Fluid Medium
    i. Water
    ii. Heavy Mud
    iii. Oil
    iv. 2 Phase flow
2. TWM Medium
  a. Size of wire
  b. Geometry
  c. Covering

Phase I testing focused on the ability to generate a TWM inside a full scale flow chamber subject to 7 bbl/min flow, and study how it will travel, anchor, and stem the flow. The tests enabled us to determine the wire material, geometry, and properties to form the TWM and stem the flow. The wellbore diameter was selected to be 11 inches as this was a reasonable full size representative of many existing wells, and it is not so expensive as would be an 18 inch system to test. The fluid medium was water for environmental reasons. The real flowing well releases a thicker viscosity fluid, which actually helps with the TWM generation. Simulated wellbore obstructions (partially deployed rams) were made from flanges with holes sized to represent partially deployed shear and pipe rams. A flow chamber was assembled from rental equipment.

3.4. Flow Loop Sizing

Non-dimensional numbers are used to compare the experiments at different scales in order to determine the performance projection at different sizes. The flow is scaled using a Reynolds number comparison.

3.4.1 Reynolds Number Comparison

The flow loop is scaled using Reynolds number. The flow from Deepwater horizon was turbulent ranging Reynolds values between 25,000 and 30,000 according to independent studies [5]. Figure 8 shows a flow chart to calculate the Reynolds number.

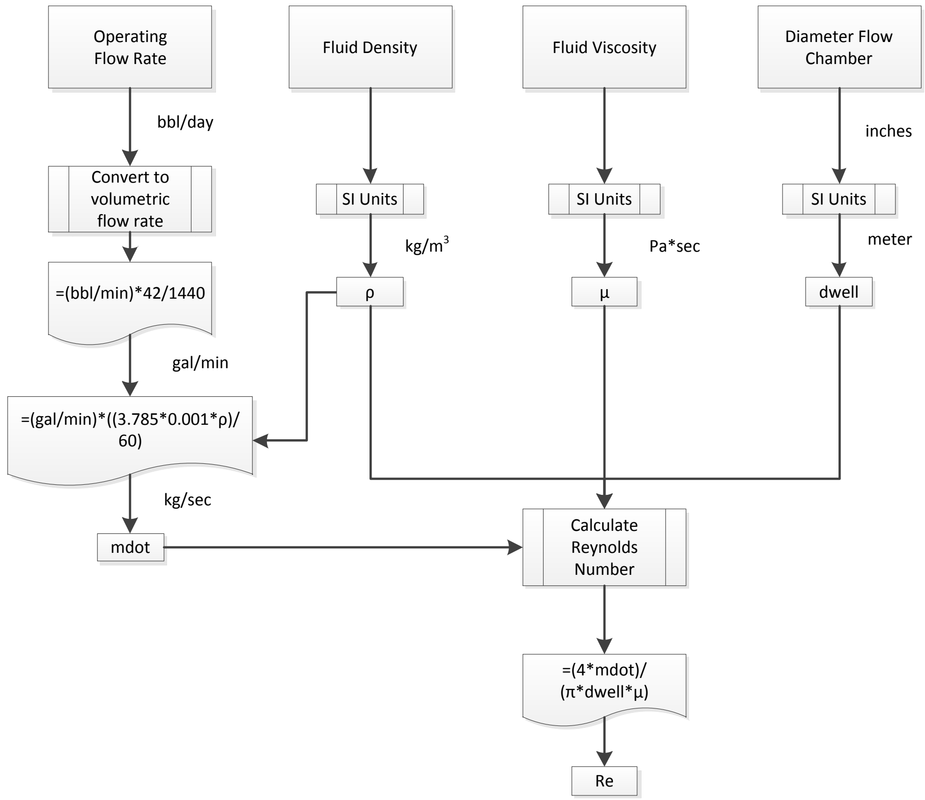


Figure 8 Reynolds number calculation flow diagram

Table 1 shows a non-dimensional comparison of the Deepwater Horizon uncontrolled flow used to calculate the minimum testing parameters of the HAWK tool in an 11 inch flow chamber operating with water, as well as outlining the HAWK tool actual testing parameters with the implications for a full scale loss of well control. The Deepwater Horizon was flowing at 60,000 bbl/day (~ 42 bbl/min) through an 18.75 inch wellbore [5]. Thus the minimum flow rate with water in an 11 inch wellbore to maintaining the same Reynolds number is 2.4 bbl/min. However, we decided to run most of our test at 7.5 bbl/min to make ensure operating at least at half the mean velocity of the full scale, given the lower viscosity of water. If we were to extrapolate our testing conditions to a full size oil well it would mean that the well would have to flow at 183,000 bbl/day which is unforeseen as the worst case discharge (WCD) is 100,000 bbl/day according International Association of Oil & Gas Producers [10]. In addition, our estimates are conservative since the viscosity of the Deepwater Horizon flow was higher than that of water. A flow viscosity greater than water, improves the TWM forming process.

The non-dimensional comparison implies that the HAWK tool technology may also possibly be used for gas loss of well control in the future.

Table 1 Comparison of non-dimensional numbers of the minimum testing parameters, and actual testing parameters for phase 1.

	Minimum Testing		Scaling	
Parameter	**Deepwater Horizon**	**HAWK Tool Minimum Testing**	**HAWK Tool Actual Testing**	**Equivalent Scale Loss of Well Control**
Wellbore Diameter	18.75”	11”	11”	18.75”
Flow Rate	~60,000 bbl/day 42 bbl/min	3,456 bbl/day 2.4 bbl/min	10,080 bbl/day 7.0 bbl/min	183,000 bbl/day 127 bbl/min
Fluid (Pa*sec)	Oil (~0.01)	Water (0.001)	Water (0.001)	Oil (~0.01)
Density (kg/m^3)	~950	1,000	1,000	~950
Reynolds Number	28,300	28,900	84,500	85,500
Mean Vel. (m/s)	0.63	0.10	0.302	1.89

3.5. Entanglement Parameter

The non-dimensional Flow Entanglement Region (FER) was derived as a force balance between the stiffness of the wire to the imparted drag loading, Equation 1. Since the wire is constantly being fed into wellbore, it was decided to use the rigidity of a wire per unit area where the exposed area is equivalent to the diameter of the wire multiplied by the diameter of the wellbore.

$$FER = \frac{\dfrac{E \cdot I}{2 \cdot r_w \cdot D_{bore}}}{\dfrac{1}{2} \cdot \rho_f \cdot C_d \cdot D_{bore} \cdot 2 \cdot r_w \cdot V_{flow}^2} \qquad (1)$$

The form of the flow entanglement number reduces to the form shown in Equation 2.

$$FER = \frac{\pi \cdot E \cdot r_w^2}{8 \cdot \rho_f \cdot C_d \cdot D_{bore}^2 \cdot V_{flow}^2} \qquad (2)$$

Where E is the Young’s modulus, C_d is the drag coefficient, r_w is the wire diameter, ρ_f if the density of the fluid, D_{bore} is the wellbore diameter, and V_{flow} is the mean flow rate velocity.

FER values approximating zero means that the dynamics of the wire is primarily governed by the fluid dynamics; whereas significantly large FER values imply that the behavior is dictated by the stiffness of the wire. Thus it is logical to assume that there is a middle ground where both the fluid dynamics and wire stiffness play a significant role to create the TWM.

The entanglement regions, identified experimentally, where entanglement occurs lies between 500 and 10,000. The FER values were used to size the properties of the wire necessary to generate the TWM inside the free flowing conduit.

3.6. Permeability Calculation

A linear permeability model is used based on the Darcy equation. The parameters are rearranged to solve for the permeability of the porous plug as a function of the measured values as shown in Equation 3. All of the factors in the equation can be quantified (viscosity) or measured (pressure, flow rate, plug length, area).

$$K = \frac{\cancel{V} \cdot L \cdot \mu}{\Delta P \cdot A_c} \quad (3)$$

Where the main sources of error for the permeability k are from the following measurements: flow rate $\cancel{V}$, plug length L, circular area A_c, and pressure ΔP.

4. AUXILIARY COMPONENTS

The TWM anchors on an existing obstruction created by partially deployed shear or pipe rams. For Phase 1 testing, these obstructions are simulated with flanges that have features machined in them.

4.1. Obstruction flanges

For the planned tests, six obstruction flanges (rated 11" 10M) were design and manufactured to mimic the obstruction geometry of a blowout preventer in different configurations (Figure 9). The shear ram geometry consist of an opening the width of the wellbore (11") and the height of the designated drill pipe size. There are three drill pipe sizes, outer diameters 3.5 inches, 4.5 inches, and 5.5 inches. The pipe ram geometry consist of 11" 10M flanges with a concentric holes in the center with varying diameter.

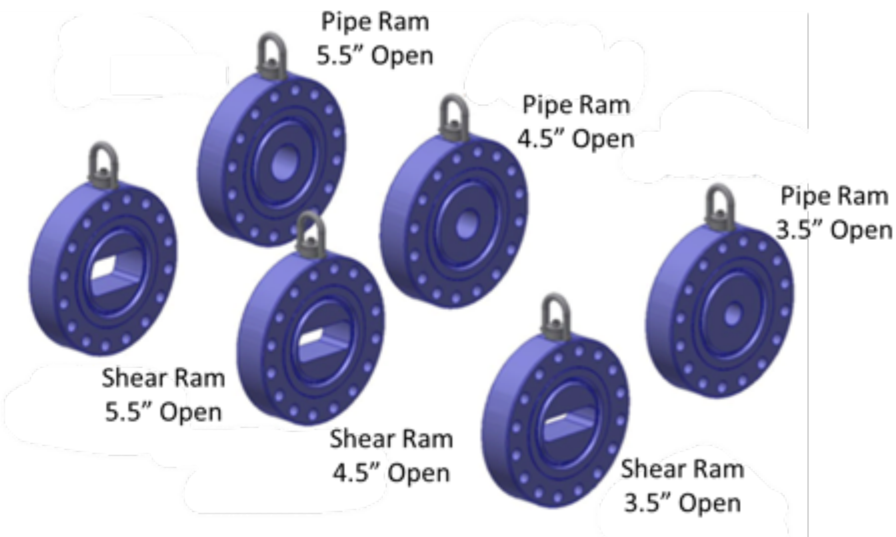


Figure 9 Obstruction flanges 11" 10M three pipe rams and three shear ram configurations

To demonstrate the ability generating a TWM around a drill pipe, sections of drill pipe were welded to flanges that mount of the obstruction flanges shown in Figure 10. Threaded holes on the face of the obstruction flanges serve to anchor the drill pipe relative to the wellbore chamber. The threaded holes allows for shifting the six foot long assembly in different configuration inside the wellbore. All of the shear ram flanges have threaded holes for three configurations, one centered and two at the extremes of the aperture.

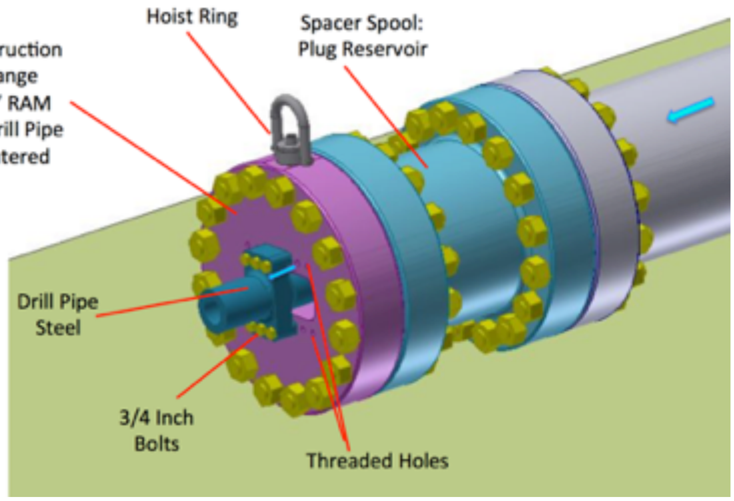


Figure 10 Drill pipe bolted onto ram obstruction flange

As shown in Figure 11, the drill pipe was welded to the mounting flange. Clearence holes on the flange serve to align an anchor the structure to the obstruction flanges. The cross section of the drill pipe shows that the end inside the wellbore was capped, preventing fluid from traveling through the interior of the drill pipe chamber.

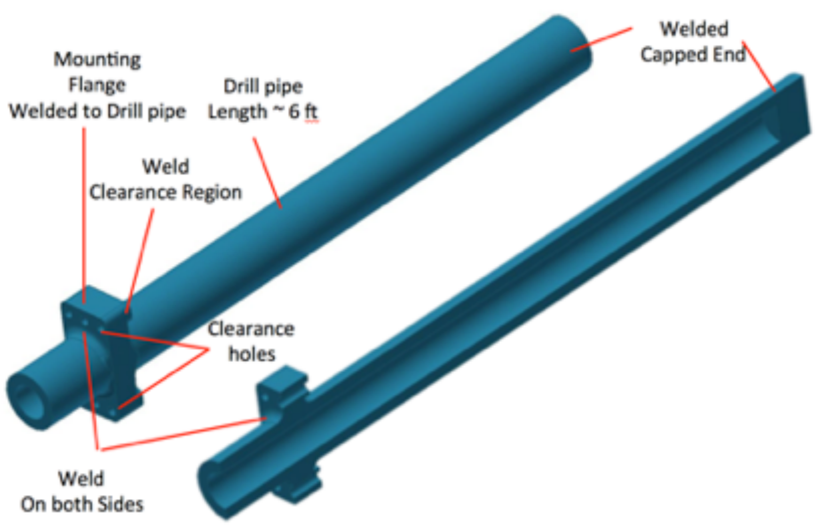


Figure 11 Drill pipe with mounting flange welded and capped end for the 4.5 inch OD drill pipe

5. PRELIMINARY PHASE 1 TESTS

5.1. TWM Generation & Feeding Parameters

From June 13th to 16th 2016, Raptors Design carried out a Phase 1 preliminary hardware test at Case Hole Snubbing Inc. in Houma Louisiana. The tests were designed to identify TWM parameters in a real flow environment. The objective of the preliminary testing was to 1) determine where to locate feeder head, 2) generate TWM in flow environment, 3) determine the efficiency of rubber cord to obstruct the flow, 4) validate wire winged design, and 5) identify the testing structure for the Phase I testing. To manage all of the aspects of the pre-test we used the organization chart in Figure 12 below.

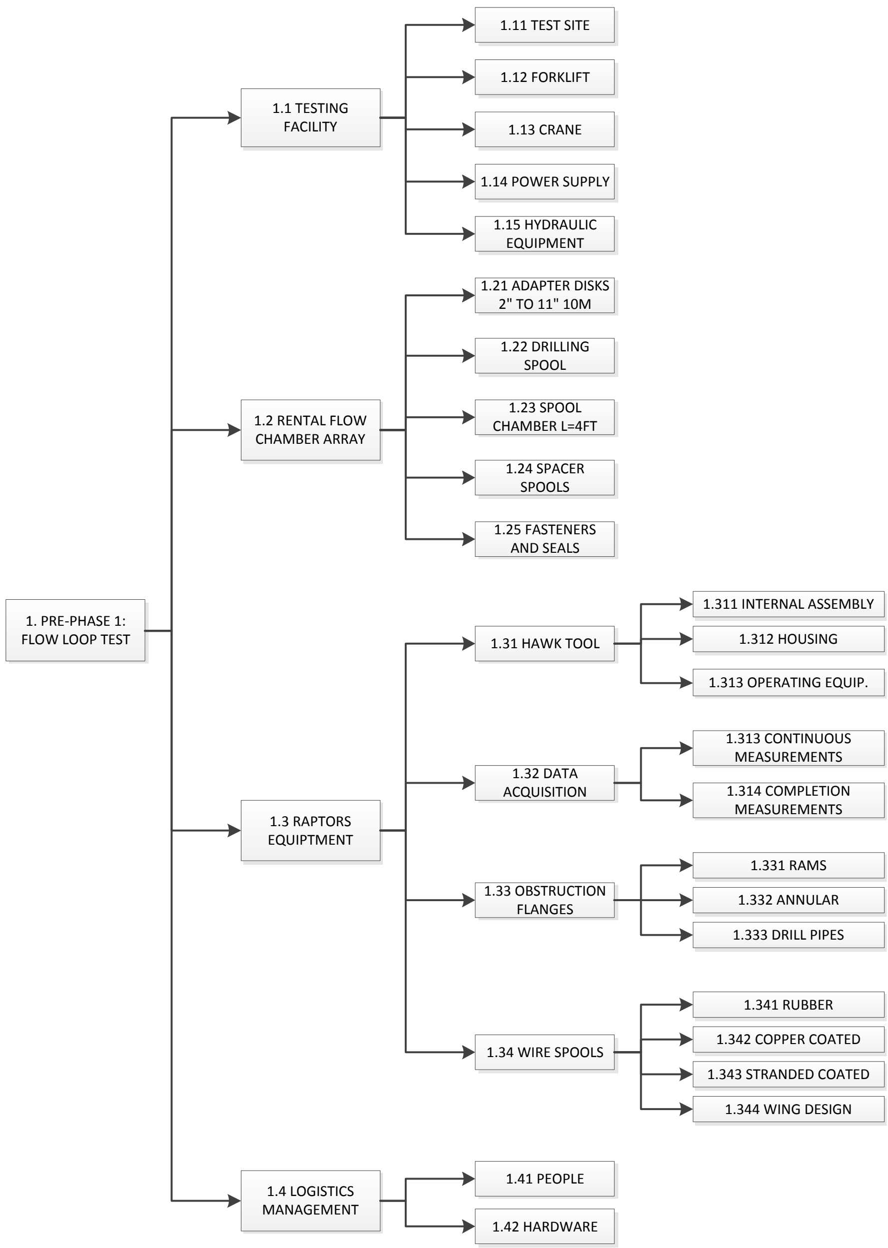


Figure 12 Organization chart for conducting preliminary flow loop testing

5.1.1 Experiment Layout

The test consisted of a flow chamber comprised of an 11" 10M drilling spool with interchangeable spacer spools. The flow chamber was mounted on a brace stand designed to hold the equipment and align the HAWK tool to the 4-1/16" 10M port of the drilling spool element as shown in Figure 13. The HAWK tool was also mounted on the brace with adjustable alignment features. The flow was provided by a Gardner Dever 600 well service pump, with a maximum 450 rpm. The pump was configured with a 3.5" plunger with the potential to generate a max flow rate of 337 gpm (~8.02 bbl/min). The water was delivered to the flow chamber via a series of 2" pup joints shown in light blue in Figure 14.

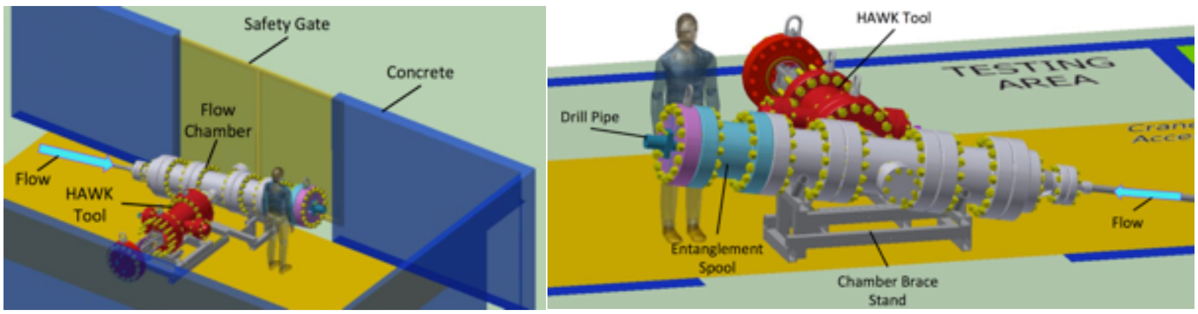


Figure 13 Test configuration showing rental flow chamber mounted on brace stand. The HAWK tool is connected to a 4-1/16" side port on the chamber where it introduces the wire.

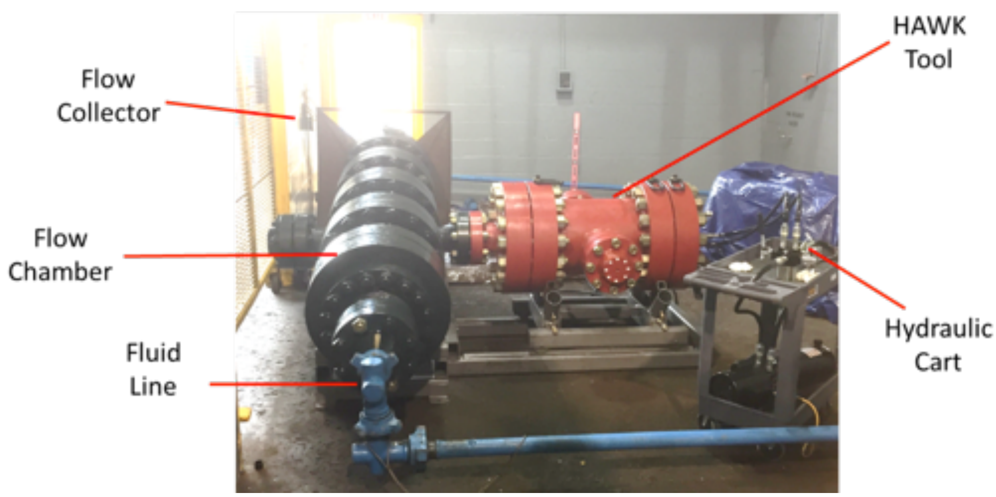


Figure 14 Test setup showing HAWK tool connected to flow chamber

5.1.2 Flow loop

The fluid pump can supply ~7.5 bbl/min (315 gal/min or 10,800 bbl/day) in the configuration shown in Figure 15. The 11" wellbore (drilling spool) flowing with water results in a Reynolds number of ~90,000 that is highly turbulent and a factor of 3 times that of the Deepwater Horizon. At 2.4 bbl/min the flow has a Reynolds number of ~29,000 consistent with the flow profile of Deepwater horizon, but the flow velocity, which is a stronger indicator of TWM movement, is much lower.

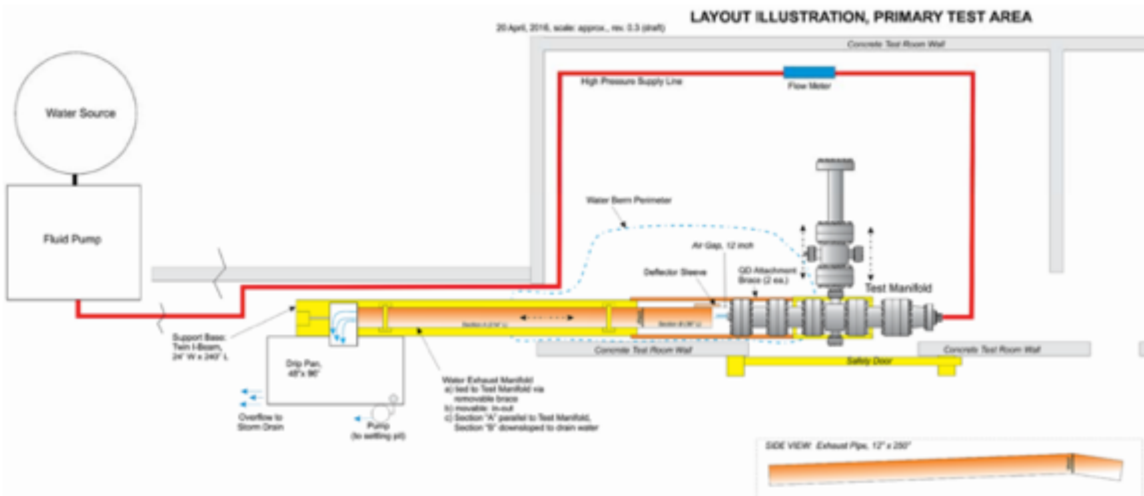


Figure 15 Flow loop test layout

5.1.2.1 Safety Components

Figure 16 shows a schematic diagram of the flow loop setup. The Gardner Denver 600 well service pump was configured with 3.5 inch plungers. The pump pressure was monitored at the exit of the pump and the pump flow rate is calculated from the stroke displacement of the pump. For safety reasons two pop off valves, one preset to (3,700 psi) and the other preset to (3,500 psi), were used. The pop off valves start to leak 300 psi below their setting therefore under this configuration the HAWK tool will not be subject to an internal pressure of 4,000 psi. A flow accumulator is also added to the flow line to dampen out any pulsation and pressure spikes coming from the pump. The HAWK tool pressure sensor is used to measure the flow chamber internal pressure; thus allowing us to determine the impact of the TWM flow resistance.

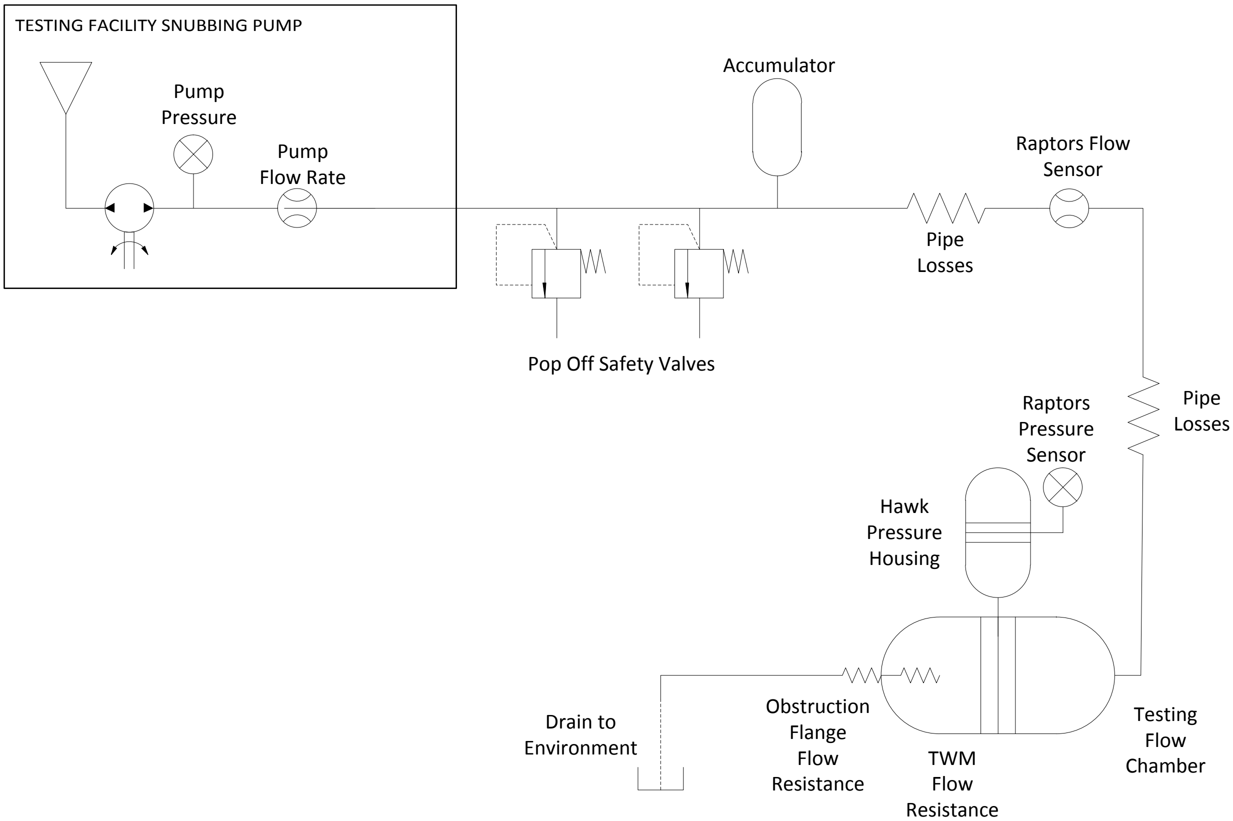
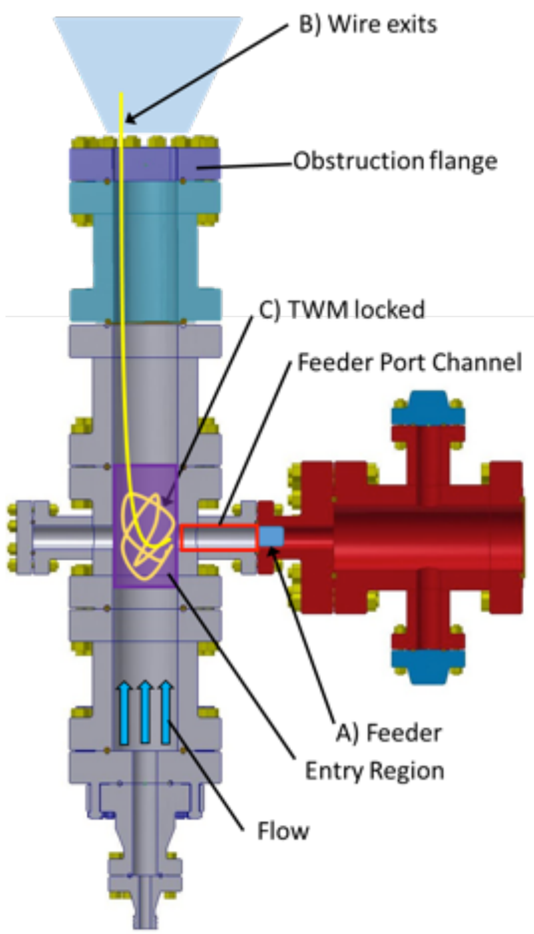


Figure 16 Flow loop schematic diagram

5.1.3 Nomenclature

Three nomenclatures were created to categorize the results of a test run. In the event that equipment malfunctions, a series of troubleshooting codes were been developed (section 5.1.3.1). As the TWM was generated and underwent the hypothesized process, TWM success level codes were setup (section 5.1.3.2). Test termination codes were also set in place (section 5.1.3.3).

5.1.3.1 Troubleshooting Codes



a. **Feeder**: The wire feeder fails to introduce the wire into the wellbore due to jam, damage, or friction
b. **Wire Exits**: The water carries the wire upstream towards the obstruction flange and exits the flow chamber without generating a TWM.
c. **TWM locked**: The TWM is generated at the entry region. The friction between the TWM and interior wellbore is high or the fluid drag is too low either resulting in a locked TWM. When the TWM is locked the wire can start to buckle in the feed port channel, thus preventing additional wire from being introduced.

Figure 17 Troubleshooting nomenclature

5.1.3.2 TWM Success Level

To quantify the level of success for a test run we use the nomenclature shown in Figure 18. The levels coincide with the progression of the plug making process. The first step consists of generating a TWM near the feeding region. As the TWM builds up enough cross sectional area it travels downstream towards the obstruction (level 2). Upon reaching the obstruction flange the TWM anchors (level 3) leading to more material to build behind to stem the flow (level 4).

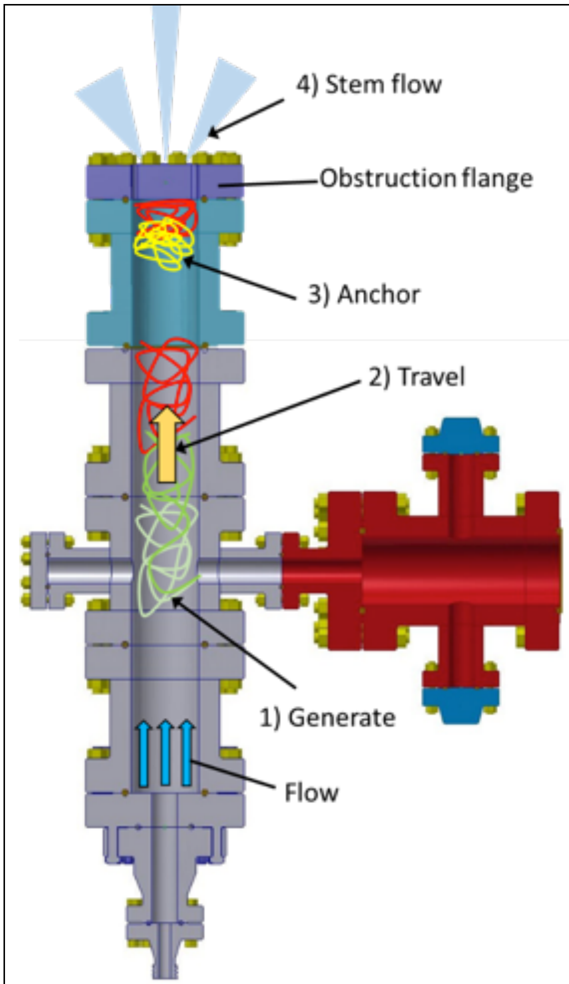
	0. **Exits:** The wire has too high of a cross sectional area or it is too low in stiffness thus the fluid takes the wire preventing any TWM from generating. 1. **Generate**: The wire interacts with the wellbore to generate the TWM in the entry region 2. **Travel**: As the wire builds cohesion the TWM drag load pushes the TWM downstream towards the obstruction flange 3. **Anchor**: The TWM catches on the obstruction flange (partially deployed ram or annular) allowing for additional material to be introduced and compacted 4. **Stem flow**: Measurable flow reduction

Figure 18 TWM success level

5.1.3.3 Termination Modes

The test can be terminated for several reasons, summarized in Figure 19 . The most often reason is a steady state (α) is reached for the test run. As the pressure increases the TWM can be extruded (β) around the open region of the obstruction flange. When the pressure load increases beyond the material strength of the TWM materials then the TWM is sheared (γ), effectively cutting a section of the TWM.

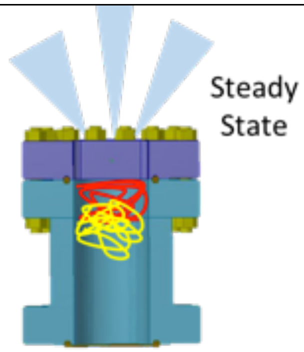
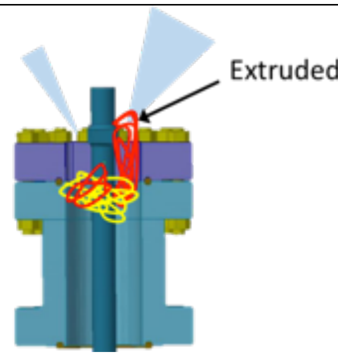
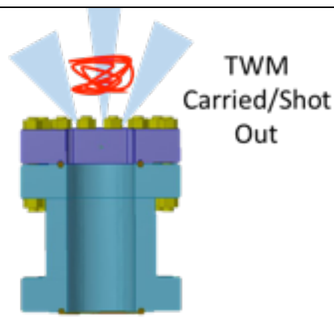
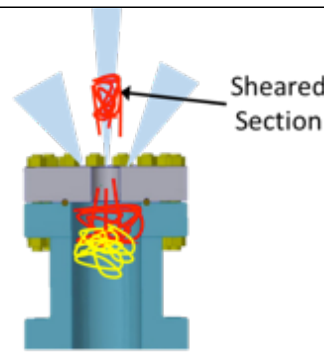
	
α) Steady state: The pressure and flow reach a plateau	**β) Extrusion**: The TWM is deformed due to the pressure load and is pushed out of the anchoring region of the obstruction flange.
	
з) TWM carried/shot out: The TWM cross section is too high at the beginning and is carried out of the flow chamber by the flow.	**γ) Shearing**: A section of the TWM material is sheared and ejected due to the significant applied load.

Figure 19 Termination modes for tests

5.1.4 Data Acquisition

Data is acquired using digital cameras, video recorders, and digital measurement devices for pressure and flow rate.

5.1.4.1 Camera Layout

A Lorex camera system was used to video the entire process from assembly, thru testing. The cameras where placed as shown in Figure 20 .

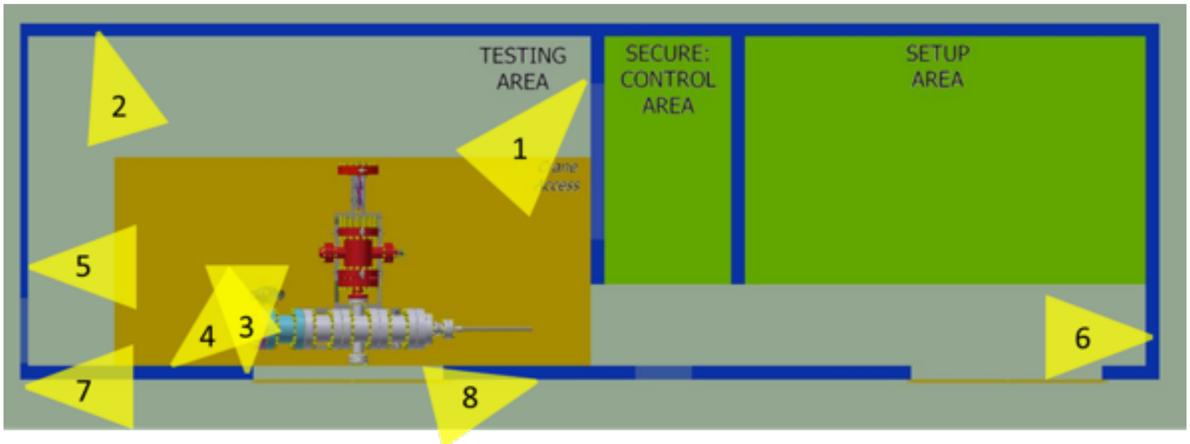


Figure 20 Preliminary testing camera setup

5.1.4.2 Pressure Measurement

The pressure is measured at the HAWK tool using an Omega pressure sensor (Model DPG409-5.0KG-W serial number 454387). The gauge pressure range of the instrument is from 0-5000 psi, with an accuracy of ± 0.08% BSL (Best Straight Line). The absolute pressure of the sensor is 7250 psi max. The sensor has an external digital display showing the internal pressure of the HAWK tool, and also transmits the value to an Omega wireless receiver (UWTC-REC2-D-V2-NEMA serial 15510297). The wireless transmitter feature of the sensor has a sample rate of 1 sample every two seconds. The UWTC series wireless transceiver communicated via a USB interface to a windows laptop running a proprietary data acquisition program, TC Central. In the event of sensor failure, video recording of the dial gauges on the pump is used.

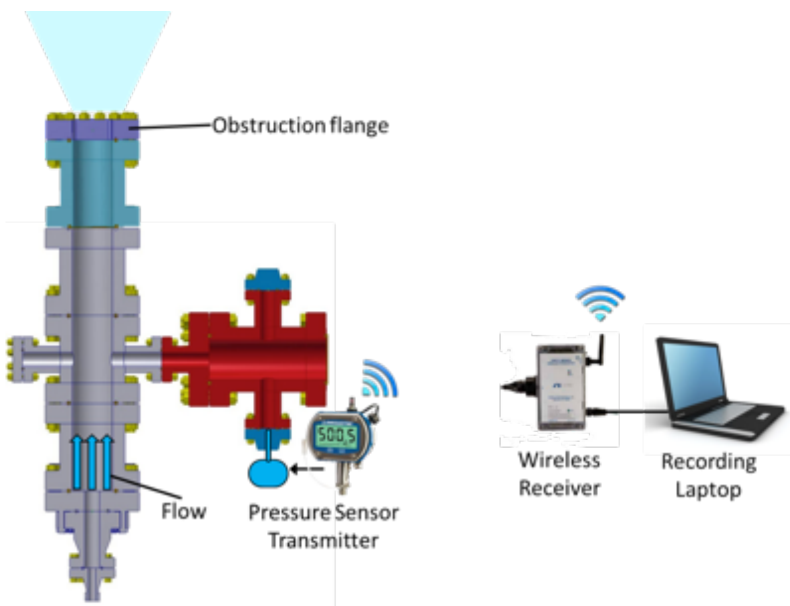


Figure 21 Pressure measurement configuration

5.1.4.3 Flow Rate Measurements

A hybrid ultrasonic flow meter (FDH-1 purchased from Omega) was used to measure the flow rate across a two inch pup joint. The pup joint selected for measurements was a new unit with minimal wall corrosion. The velocity range of the sensor is between 0.07 to 9.14 m (0.25 to 30') per second. The measurable flow rate limit of the sensor is 5.3 bbl/min. At higher flow rates the flow rate is measured at the pump.

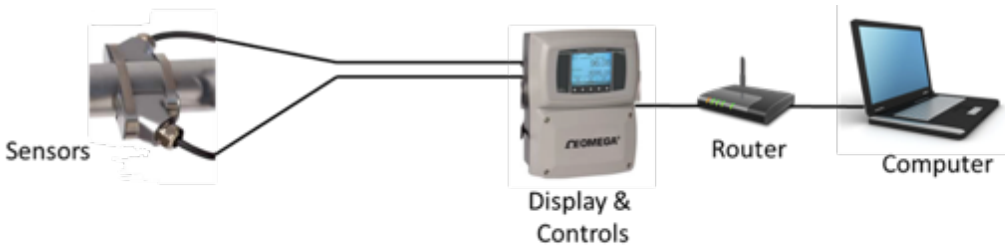


Figure 22 Flow measurement configuration

5.1.5 Test Protocols

5.1.5.1 Testing Area

The testing area was marked with caution tape to limit entry of non-essential personnel. All of the personnel at the facility were notified of limited access to the test area. All individuals in the testing area had personal protection equipment, which included steel toe shoes, safety glasses, and hardhat. Impact resistant gloves were worn when handling large equipment.

5.1.5.2 Organization Structure

The testing facility assigned a team leader. Raptors Design's Dr. Rojas was assigned to general logistic management and contingency plan. Raptors Design's Dr. Slocum was assigned to coordinating the sequence of experiments to be performed and guiding the assembly of the large components.

5.1.5.3 Start Test Procedure

1. Pretest start communication:
    a. Prior to starting each test, Raptors personnel inform the pump operator what the plan for the test will be.
2. Signal to initiate test**.**
    a. Given that the pump operator has a limited line of sigh to the control room and the test setup. Radio communication via walkie talkies is used to communicate with the pump operator. Due to the noise level of pump during operation, hand signals were also agreed upon to notify the pump operator to start and terminate the test.
3. Start signal received.
4. Pump operator starts fluid flow

    a. The flow begins the fluid flow at ~0.5 bbl/min until water begins to flow out pass the obstruction flange. With a visual confirmation of water flow, the pump is slowly ramped up to the desired flow rate ~7.5 bbl/min.

5. Control room confirmation
    a. The control room will have a visual camera on the dials at the pump. When the flow reaches the desired value, a signal is given to Dr. Slocum to initiate the wire feeding process.
6. HAWK tool activate
    a. The hydraulic motors are activated manually from the testing area. Dr. Slocum slowly opens the valve on the hydraulic cart, leaves the test area and enters the control room.
7. Monitor System
    a. From the test room we can monitor the pressure of the pump, pressure inside the HAWK tool, flow rate of the pump, and measured flow rate. (The flow meter installed on the pipe is susceptible to vibrations.
    b. The pressure is recorded throughout the test.
    c. Video is recorded throughout the entire testing period.
8. HAWK tool deactivated
    a. From the control room power is turned off to the HAWK tool.
9. Test Duration
    a. Depending on the measured pressure and flow rates the test duration will vary.
10. Interim check
    a. If we suspect that the TWM has minimal development, or the wire has jammed the flow will be stopped, the capture cone at the exit region is moved out of the way to look into the flow chamber. In addition the view window (opposite to the HAWK tool port) may be opened to check on the feeder.
11. Conclusion of the test
    a. The pump operator is notified to reduce the flow to a stop.
    b. View window is opened to take photos of the inside of the chamber. The HAWK internal assemble is checked to determine amount of wire introduced into the flow chamber. The photos are taken of the TWM for documentation.

5.1.6 TWM Media

Four types of wire were tested for the TWM generation phase:

1) THN copper wire 14 gauge
    a. Solid wire copper
2) Stranded copper wire 12 gauge
    a. Stranded wire
3) Silicone cord
    a. 4mm silicone 80 durometer
4) Stranded copper wire covered for wing design with a 1” wide dual layer of tape

5.1.7 Experimental Results

Table 2 shows the results from the preliminary test of the HAWK tool in a flow loop configuration.

Table 2 Preliminary testing setup and (DF = Danfoss OMM20 hydraulic motor)

#	Mount	Motor	Obstruction	Drill Pipe	Proboscis	Feeder Head	Feed Rate	Flow Rate (bbl/min)	Spool A	Spool B	Post Wing Design	HAWK Pressured Measured (Calc.)	Max Pump Pressure (psi)	Troubleshooting	Success Level	Termination
1	2	DF	RAM 3.5”	Yes Ct	9”	Z3	Full	2.5	Si 4mm	Cu 14awg	N	0	-	A	1	α
2	2	DF	RAM 3.5”	Yes Ct	9”	Z3	Full	4.5	Si 4mm	Cu 14awg	N	0	-	A	1	α
3	2	DF	RAM 3.5”	NO	9”	Z3	R. S.T.	7.5	Si 4mm	Cu 14awg	N	0	-	C	1	α
4	2	DF	RAM 3.5”	NO	9”	Z3	R. S.T.	7.5	Cu 14awg	Cu 14awg	N	0	-	C	1	α
5	2	DF	RAM 3.5”	NO	9”	Z4	R. S.T.	7.5	Cu St. 12awg	Cu St. 12awg	N	0	-	AC	1	α
6	2	DF	RAM 3.5”	NO	9”	Z4	R. S.T.	7.5	Cu St. 12awg	Cu St. 12awg	N	0	-	AC	1	α
7	2	DF	RAM 3.5”	NO	18”	Z4	R. S.T.	7.5	Cu St. 12awg	Cu St. 12awg	N	0	-	AC	1	α
8	2	DF	RAM 3.5”	NO	25”	Z4	R. S.T.	7.5	Cu&Si 14awg	Cu St. 12awg	Yes	100 psi	-	C*	4	α
9	2	DF	ANN 3.5”	Yes	25”	Z4	R. S.T.	7.5	Si 4mm	Cu 14awg	Yes	0	-	C*	1	α
10	2	DF	ANN 3.5”	NO	25”	Z4	R. S.T.	7.5	Cu 14awg	Cu 14awg	Yes	700 (1500)	2250	C*	4	γ
11	2	DF	RAM 3.5”	Yes Ct	25”	Z4	R. S.T.	7.5	Cu 14awg	Cu 14awg	Yes	21	-	C*	4	β

5.1.7.1 Feeder head location & TWM generation

5.1.7.1.1 Test 1

The obstruction configuration was set to a 3.5 Ram with a drill pipe. The wire feeder (the proboscis) was configured to be 16” (setting 9” from internal assembly) behind the wellbore interior diameter. The solid copper 14 awg entered the wellbore and started to generate the TWM. The Si 4mm wire was stuck to the choke/kill feed port channel leading to the flow chamber. Thus as more wire was fed port channel was closed of preventing more wire from being introduced into the flow chamber.

5.1.7.1.2 Test 2

To mitigate the effects of the first test, the silicone wire was tied at the tip to the solid copper 14 awg wire to induce a pulling effect by the stiffer wire. Once again the silicone wire was stuck to the port channel thus preventing more wire from being introduced into the flow chamber. It was also noticed that the TWM generated from Cu 14awg was getting stuck behind the drill pipe. Thus the drill pipe was removed for subsequent tests and sent to the welding shop to be extended.

5.1.7.1.3 Test 3

With the ram 3.5 obstruction (drill pipe removed) the next test was run at the max flow rate (7.5 bbl/min) that could be delivered by the pump. It was also suspected that the transition from turning the hydraulic motor on could be inversely affecting the feeding process thus a slow transition (S.T.) was adopted where Dr. Slocum slowly turns on the hydraulic motor and leaves the designated testing area. The silicone wire continued to fill the port channel.

5.1.7.1.4 Test 4

Two spools were loaded with Cu 14 awg and introduced into the flow chamber to generate the TWM. The TWM composed of the stiff wire stayed near the feeding region. It was hypothesized that the buckling of the Cu 14 awg wire was radially anchoring to the walls of the flow chamber, which inhibits its ability to travel upstream.

5.1.7.1.5 Test 5

Two spools were loaded with Cu 12 awg stranded and introduced into the wellbore. A protective sheath designed to limit the friction between the wire and the walls of the port channel setup in front of the feeder head. During the feeding process the sheath was dragged by the wire and taken into the flow chamber.

5.1.7.1.6 Test 6

The test 5 was repeated without the protective sheath. The stranded wire being less stiff than the solid copper behaved similarly to the copper wire at the beginning and as the entry region was occupied it proceeded to entangle inside the port channel preventing the feeder from introducing the entire wire spool into the wellbore.

5.1.7.1.7 Test 7

With the full range of wire stiffness tested, the feeder was placed 7 inches from the wellbore interior diameter (18" from the internal assembly). The hypothesis was that by limiting the feed port length the wire can be introduced directly into the wellbore. Two spools of stranded Cu 12 awg wire were introduced into the wellbore. The TWM remained in the entry region.

5.1.7.1.8 Test 8

Test 8 was used to determine how effective the silicone cord alone would be to stem the flow. Two spools of blue wire were fed into the flow chamber equipped with a 3.5" Ram obstruction (more than 1500 ft.). The HAWK tool was reloaded 3 times with two spools each to introduce Silicone cord. Even with all of that material the flow remained only marginally obstructed. Therefore the round wire and cord combination needs to a wing geometry.

5.1.7.1.9 Test 9

With the feeder head at the wellbore interior wall the obstruction was set to a 3.5 annular with a drill pipe. The diametrical gap is 0.040 inches. The objective was to determine if the corded silicone would serve to stem a small gap that would be similar to a failed seal inside a blowout preventer. The test demonstrated that the TWM will be generated and that the cross sectional area of the wires is such that the flow is too low to take the wire towards the area of interest. Therefore, for all of the design configuration a winged wire design is required.

5.1.7.2 Generate TWM in Flow

5.1.7.2.1 Test 10: Annular Obstruction 3.5" diameter

The obstruction flange was configured to a 3.5 annular flange. The flow rate was set to 7.5 bbl/min. Two Cu 14 awg wire where loaded onto the HAWK tool. After the TWM was generated the flow was turned off. A covered wire wing prototype was introduced manually via the view port to validate the hypothesis of wing design at scale for stemming the flow. The covered wire wing design proved ideal for being carried forward by the flow and for stemming the flow. The pressure increased to ~1500 psi in the chamber prior to shearing of the TWM (pressure at pump 2,250 psi), see Figure 23.

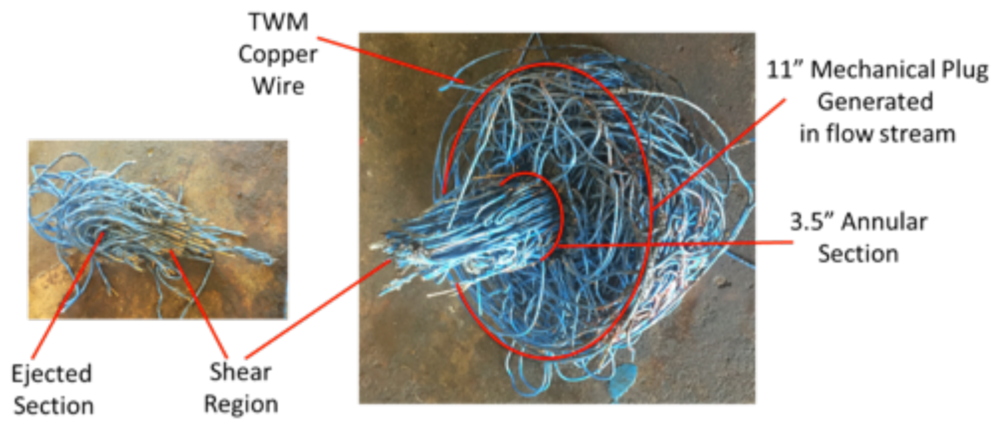


Figure 23 Tangled wire mass made from copper wire using a 3.5" open annular obstruction. The TWM sheared at a differential pressure of ~1,500 psi (2,250 observed at the pump).

5.1.7.2.2 Test 11: Ram Aperture 3.5" with Drill pipe

The feeder head was placed at the interior diameter of the wellbore. The obstruction was set to a 3.5 ram with a drill pipe in the center. Two Cu 14 awg were loaded into the HAWK tool to generate the initial entanglement. Figure 24 shows a TWM generated around a 3.5" drill pipe backed by the prototype wire wing design. The TWM was generated with a 7.5 bbl/min flow rate. Figure 25 shows the front of the obstruction ram flange with the wire wing design bulged due to the low strength of the core wire.

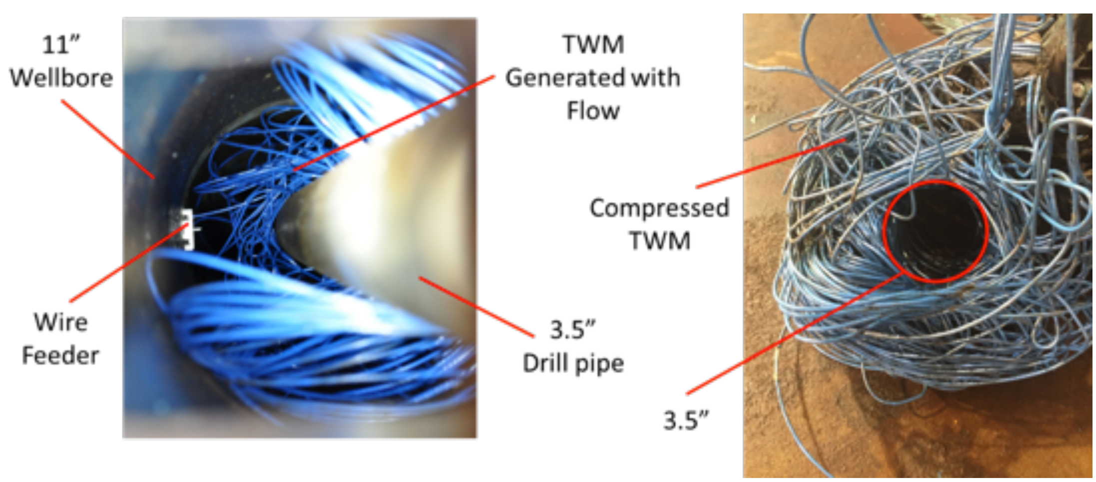


Figure 24 Tangled wire mass made from copper wire using a 3.5" ram obstruction with drill pipe. The TWM was created around the drill pipe.

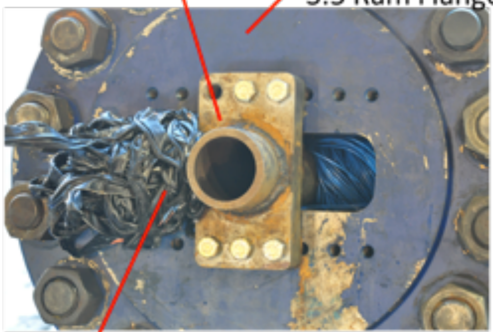


Figure 25 Experimental setup showing drill pipe connected to obstruction flange

5.1.8 Observations and Results

5.1.8.1 Instrumentation

The transmission rate of the pressure sensor generated a delay in the measured pressure. Changing the pressure sensor to a wired system will result in added complexity and is a source for tripping or catching hazard. Thus the simplest solution is to set a camera to view the pressure dials of the pump to capture the instantaneous pressure of the pump.

When the pump changes from low gear to high gear the vibration in the pup joints cause a misalignment in the flow transducers resulting in loss of signal. Given that the flow sensor at the pump is in agreement with the flow meter, it is thus also best to use the same camera at the pump to also record the flow rate at the pump.

5.1.8.2 Lessons Learned

The preliminary flow tests showed the following:

1. Rubber (silicone) cord wire alone is insufficient for stemming the flow
2. A coated wire wing design works good for flow reduction, but simple duct tape on copper wire is not strong enough and eventually extrudes and shears
3. High strength wire (Copper and aluminum are too weak) is needed, with fiberglass filament reinforced tape (strapping tape) to form the wings
4. TWM generates well around a drill pipe as well as across an open hole

5.2. Wing Design Farm Pond Test

The concept of the winged "coated wire" was tested with low pressure flow tests in a 6 inch diameter clear chamber. The tube was connected to a 4" hose connected to a 290 gpm 80 psi max pressure irrigation pump. Water from a pond on Dr. Slocum's farm was used as the source, and the flow out simply drained back into the pond. The tests demonstrated that a wire with a small hydrodynamic cross section (nominally bare or equivalent) must first be fed in to generate the scaffolding/bridging material with then forms a TWM. The scaffolding wire should have a propensity to plastically buckle, such as happens with copper or aluminum wire. The coated wire then uses the scaffolding to build a cohesive TWM. The TWM anchors against the scaffolding wire's TWM and carries it forward to the partial opening and starts to stem the flow.

6. PHASE I TESTS: ANCHOR & STEM

Phase 1 tests were also conducted at Case Hole Snubbing Inc. in Houma Louisiana from September 27th to Oct 1st 2016. The objective of the phase I tests was to validate the method behind the HAWK tool to generate, anchor, and stem a free flow through an 11 inch chamber, in particular, test new configurations of "wire" which resulted from earlier preliminary tests. To achieve higher ultimate TWM strength, instead of just copper wire, a high strength stranded wire and fiber reinforced tape were used. For example, the 3/32 aircraft cable used has a minimum breaking strength of 1000 lbs. To provide flow resistance, and additional strength, "strapping tape"-fiberglass reinforced High Strength Tape (HST), was used: The 3M Corp high strength strapping tape used has a minimum breaking strength of 600 lbs/inch width. Compare this to soft copper or aluminum 12 gauge wire with a strength of 20ksi which would correspond to a tensile strength of about 190 pounds. Thus we expected we would be able to withstand pressures to about 10k psi for a similarly sized TWM.

6.1. HAWK Tool Test Feeder

In order to test wire designs with various coating widths, a dedicated HAWK tool test feeder (TF) was designed and manufactured that bolts directly to the flow chamber choke/kill port, allowing for rapid changeover. The wire spool is placed outside and the wire fed in through a small slit into the TF with some leakage. Once the ideal coating width (tape width) was determined, a dedicated feeder would be designed for the HAWK tool proboscis for use with later Phase 2 and 3 tests should funding for them be obtained.

6.2. Organization Structure

The safety and progression of the test was administered by the individuals from Table 3. The Houma team has an assigned team leader; whereas Raptors has divided the leadership role by topic. Dr. Rojas was responsible for the logistics planning of the tests, determine safety procedures, as well as make changes to the protocol. Dr. Slocum was responsible for directing the sequence of conducting the tests.

Table 3 Key individuals responsible for safety and tests

Equipment & Testing Personnel	Test Sequence Director	Logistics & Safety
Houma Leader	Dr. Slocum	Dr. Rojas

6.3. Experiment Layout

6.3.1 Flow Loop

To enable a flow rate above 8.0bbl/min, two pumps needed to be connected. The start-up pressure and flow showed that 500 psi of back pressure is needed to generate a flow of 7 bbl/min. Most of the tests were conducted at 7 bbl/min. One test was done above 8.5 bbl/min to demonstrate that the TWM scaffolding can withstand a significantly high flow rate.

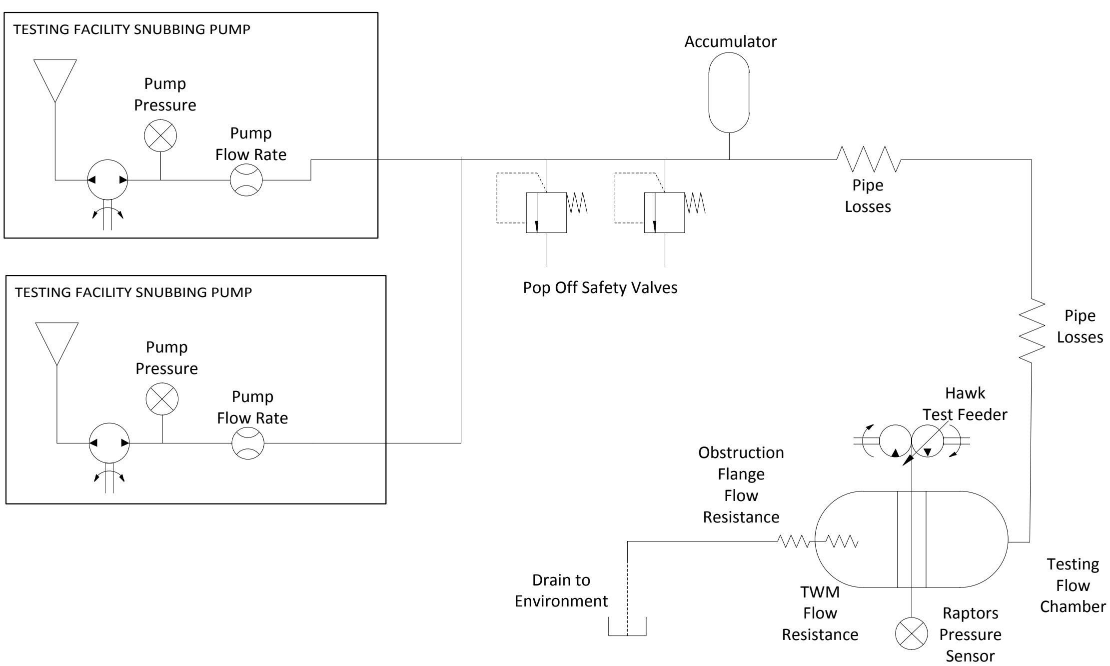


Figure 26 Flow measurement configuration

The pop off safety valves were set to 4,000 psi and 4,300 psi. Accounting for the pressure losses, the pressure in the chamber should not exceed 3,500 psi before both of the pop off safety valves are triggered. Table 4 shows the working pressure ratings of the main elements. The two limiting components are the npt threaded connections of the pressure sensor and the bolts/threads that connect the drill pipes to the obstruction flanges.

Table 4 Pressure rating of elements (The HAWK tool Test Feeder is an open design that allows for some leakage during the feeding process. After the wire is introduced the unit is disconnected and a flange is placed which is rated to a working pressure of 10k psi)

Family	Component	Working Pressure Rating
Flow Loop	Pump	10M+
	Pup Joints	15M
Flow Chamber	Connections	10M+
	Flow Chamber	10M
	Interface	10M
HAWK Tool Test Feeder	Open Housing	0
Obstruction	Flanges	10M
	Drill pipes & Bolts	4M

6.3.2 Data Acquisition

The sensors and instrumentation used for the preliminary testing used to conduct the phase 1 test are described below.

6.3.2.1 Camera Layout

The camera configuration was similar to the setup in the preliminary test, and is shown in Figure 27.

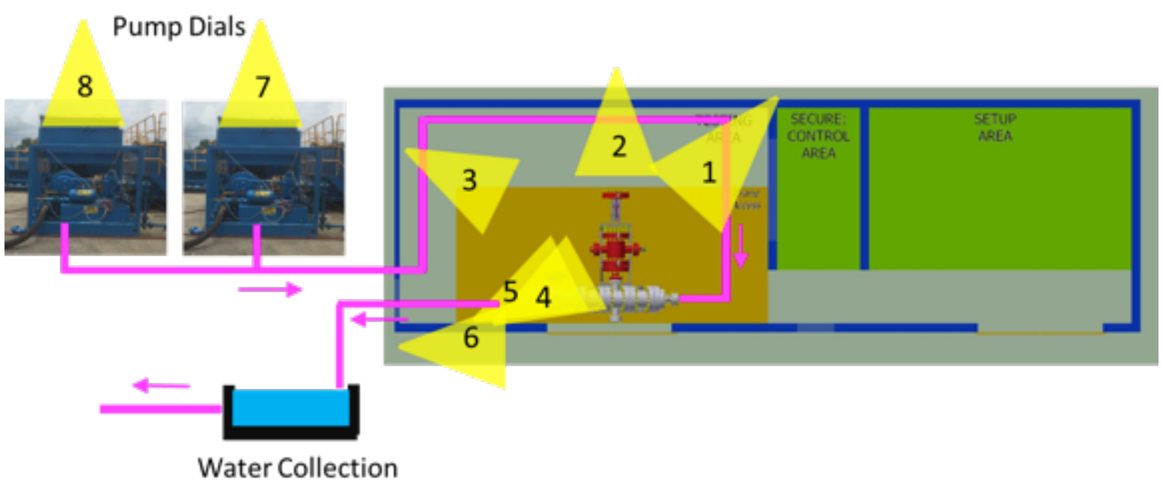


Figure 27 Lorex camera configuration for phase 1 test

6.3.2.2 Pressure Measurement

The pressure measurements were recorded via an Omega pressure sensor (Model DPG409-5.0KG-W serial number 454387) in conjunction to the Omega wireless receiver (UWTC-REC2-D-V2-NEMA serial 15510297) as described in Section 5.1.4.2. Since the wireless transmitter feature of the sensor has a sample rate of 1 sample every two seconds. Two cameras were placed at the pumps to record the pressure and flow rate at the pump throughout the testing process. Thus throughout the testing period we could monitor the pump pressure and flow rate.

6.3.2.3 Flow Loop Measurements

The flow rate was measured at the pumps using a camera to record the results. Based on the preliminary experiments, the measured values at the gauges where the same as the flow sensor. Thus we proceeded to use the pump gauges to measure the flow rates before and after.

6.3.3 Test Protocols

6.3.3.1 Method Tests: Start Test Procedure

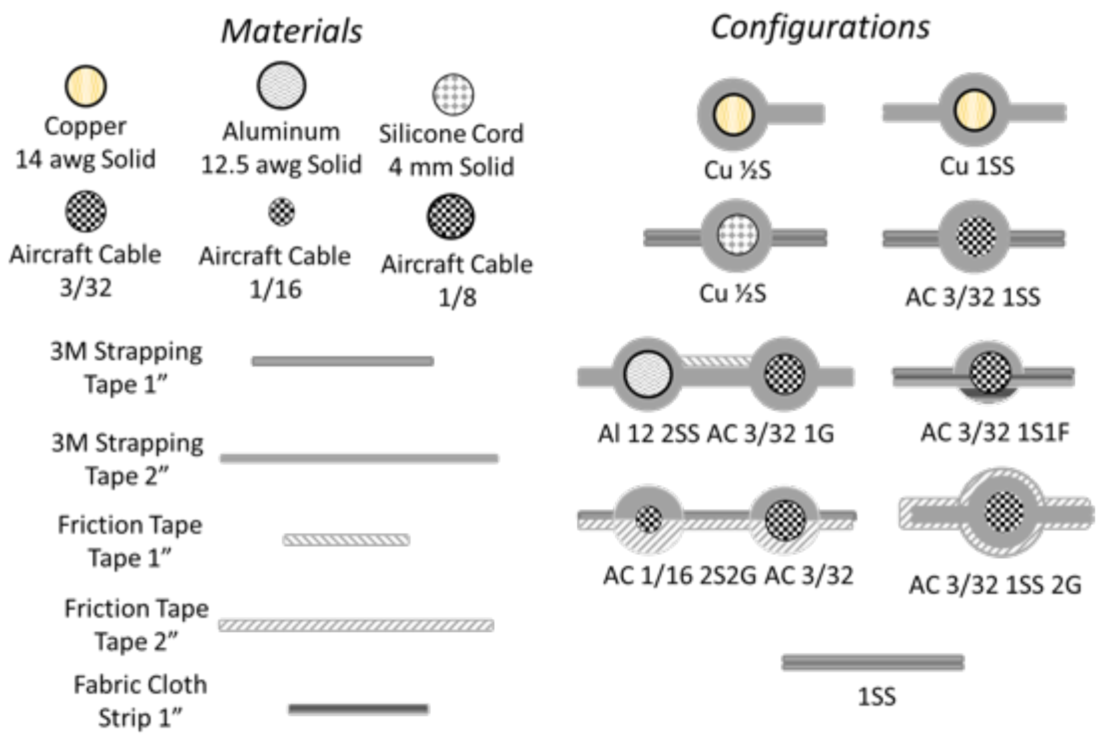
1. Pretest start communication:
    a. The pump operator is told the goal of the test.
    b. Turn on integrated testing lights from facility.
2. Signal to initiate test**.**
    a. Begin fluid flow at ~0.5 bbl/min until water begins to ooze out pass the obstruction flange.
3. Pump operator starts fluid flow
    a. With a visual confirmation of water flow, ramp the pump up slowly to the desired flow rate.
4. Control room confirmation
    a. The control room has a video camera on the dials at the pumps: when the flow reaches the desired value, a signal is given to Dr. Slocum to initiate the feeding process.
5. HAWK tool test feeder activated
    a. The hydraulic motors are activated manually from the testing area.
6. HAWK tool test feeder deactivated
    a. The power to the hydraulic cart is unplugged, locking out the pump and motor.
7. Close Flow Chamber
    a. A 4-1/16" 10M flange replaces the HAWK tool test feeder and the chamber is exposed to full flow.
8. Test Duration
    a. The test is allowed to continue until Dr. Slocum decides based on the steady state pressure and the water reservoir allowance.

6.3.3.2 High Pressure Tests

If a generated TWM plug holds 3,500 psi of pressure, the pop up valves trigger. At that point, in concultation with the Houma facility manager, the intent is to isolate the pop up valves and incrementally increase the pressure to 10k psi to test the ability of the TWM to hold high pressure and stem the flow.

6.3.4 TWM Materials

Reels of pre-made cable formed on a custom wire/tape making fixture were prepared beforehand, and the fixture was brought to the experiments in anticipation of observations of test results leading to new configurations that would be needed to be made in situ. As shown in **Error! Reference source not found.** four different core materials and three coating materials were used throughout the testing sequence. In addition to feeding uncoated materials, nine configurations were tested of the core and covering materials.



6.4. Testing

Testing was carried out in incremental steps to better understand the dynamic behavior of the system. In a fully closed system the entire process will be continuous. The tests were designed for rapid change over and to incrementally achieve the objective of stemming the uncontrolled from.

6.4.1 Experimental Results Detailed Summary

The experimental results are separated into the 1) mechanics/behavior development (Table 5), and 2) TWM strength and stemming (Table 6, Table 7, and Table 8).

Table 5 Mechanics and behavior development. All of the obstructions have been set up for a 3.5" annular. (H = horizontal feeding, Cu = copper , S = strapping tape, R = silicone rubber, AC = Aircraft cable, M = measured pressure using Omega sensor)

Setup			Scaffolding			Strength			Stem	Scaffolding				Scaffolding		
Test #	Objective	Feed Orientation	Wire Core	Wing Width	Length (ft.)	Wire Core	Wing Width	Length (ft.)		Flow Rate Initial (bbl/min)	Steady State Pressure (psi)	Flow Rate Final (bbl/min)	Chamber Pressure Max/Final (psi)	Troubleshooting	Success Level	Termination
1	1	H	Cu 14awg	½S	50	-	-	-	-	5.0	500	5.0	~0	C	1	α
	2	-	Cu 14awg	½S	50	-	-	-	-	5.12	500	5.12	~0	-	1	α
2	1	H	Cu 14awg	1 SS	185	-	-	-	-	5.0	500	5.0	~0	C	1	α
	2	-	Cu 14awg	1 SS	185	-	-	-	-	5.3	500	5.3	~0	-	1	α
	2	-	Cu 14awg	1 SS	185	-	-	-	-	7.1	600	7.1	~0	-	2	3
3	1	H	Cu 14awg	1 SS	25	AC 3/32	1SS	150	-	5.0	500	5.0	~0	C	1	α
	2	-	Cu 14awg	1 SS	25	AC 3/32	1SS	150	-	7.0	600	7.0	~0	-	2	3
4	1	V	Cu 14awg	1 SS	336	-	-	-	-	7.1	600	7.1	~0	C	1	α
	2	-	Cu 14awg	1 SS	336	-	-	-	-	7.0	800	7.0	~0	-	2	α
	1	V	Cu 14awg	1 SS	336	AC 3/32	1SS	140	-	7.0	800	7.0	M5.2	C	1	α
	3	-	Cu 14awg	1 SS	336	AC 3/32	1SS	140	-	7.0	700	7.0	M5.5	-	3	α
	1	V	Cu 14awg	1 SS	336	AC 3/32	1SS	140+ 171	-	7.0	800	7.0	M5.3	C	1	α
	4	-	Cu 14awg	1 SS	336	AC 3/32	1SS	321	-	7.0	800	7.0	M81 M13	C	4	β
	2	V	Cu 14awg	1 SS	336	AC 3/32	1SS	~0 + 197	-	7.0	600	7.0	M24	-	2	β

Table 6 Mechanics and behavior development. All of the obstructions have been set up for a 3.5" annular. *Travel induced via fabric material ~ 6 sq.ft (H = horizontal feeding, Cu = copper , S = strapping tape, R = silicone rubber, AC = Aircraft cable, M = measured pressure using Omega sensor)

Setup			Scaffolding			Strength			Stem	Scaffolding				Scaffolding		
#	Objective	Feed Orientation	Wire Core	Wing Width	Length (ft.)	Wire Core	Wing Width	Length (ft.)		Flow Rate Initial (bbl/min)	Steady State Pressure (psi)	Flow Rate Final (bbl/min)	Chamber Pressure Max/Final (psi)	Troubleshooting	Success Level	Termination
5	**1**	V	Al12awg AC3/32	2SS 1G	141	-	-	-	-	7.0	600	7.0	~0	C	**1**	**α**
	2	-	Al12awg AC3/32	2SS 1G	141	-	-	-	-	7.0	600	7.0	~0	C	**1**	**α**
	2*	-	Al12 AC3/32	2SS 1G	141	-	-	-	-	7.0	700	7.0	M5.3	C	**1**	**α**
	1	V	Al12 AC3/32	2SS 1G	141	AC 3/32	1 SS	70	-	7.0	700	7.0	M5.5	C	**1**	**α**
	2	-	Al12 AC3/32	2SS 1G	141	AC 3/32	1 SS	70	-	7.0	700	7.0	M17	-	**2**	**α**
	1	V	Al12 AC3/32	2SS 1G	141	AC 3/32	1 SS	70	R 1SS - 167	7.0	700	7.0	N.A.	C	**1**	**α**
	4	-	Al12 AC3/32	2SS 1G	141	AC 3/32	1 SS	70	R 1SS - 167	7.0	900	7.0	N.A	-	**4**	**β**
6	**1**	V	AC1/16 AC3/32	2S 2G	50	-	-	-	-	7.0	600	7.0	M3.2	C	**1**	**α**
	2	-	AC1/16 AC3/32	2S 2G	50	-	-	-	-	7.0	600	7.0	~0	B	**0**	**з**

The lessons learned from the first six tests allowed for the fundamental understanding that allowed us to reach 10,000 psi in test 7 summarized in Table 7 and 6,600 psi in test 8 summarized in Table 8.

Table 7 TWM incremental generation for holding pressure and stemming flow. The obstruction was set for a 3.5" annular. *Travel induced via fabric material ~ 6 sq.ft. (F = Fabric, H = horizontal feeding, Cu = copper , S = strapping tape, R = silicone rubber, AC = Aircraft cable, M = measured pressure using Omega sensor)

Setup			Scaffolding			Strength			Stem	Scaffolding				Scaffolding		
#	Objective Level	Feed Orientation	Wire Core	Wing Width	Length (ft.)	Wire Core	Wing Width	Length (ft.)		Flow Rate Initial (bbl/min)	Steady State Pressure (psi)	Flow Rate Final (bbl/min)	Chamber Pressure Max/Final (psi)	Troubleshooting	Success Level	Termination
7_2	**1**	V	Al12	-	328	-	-	-	-	7.0	700	7.0	M3.1	C	**1**	α
	2	-	Al12	-	328	-	-	-	-	7.0	700	7.0	N.A.	-	**2**	α
	1	V	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 15	-	-	-	-	7.0	700	7.0	N.A.	C	**1**	α
	2	-	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 15	-	-	-	-	7.0	700	7.0	N.A.	-	**2**	α
	1	V	Al12 + AC1/16 AC3/32	- 2S 2G	328 +15 +115	-	-	-	-	7.0	700	7.0	N.A.	C	**1**	α
	2	-	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	-	-	-	-	7.0	700	7.0	N.A.	C	**1**	α
	2 *	-	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	-	-	-	-	7.0	800	7.0	N.A.	C	**2**	α
	1	V	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	128	-	7.0	700	7.0	N.A.	C	**1**	α
	2	-	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	128	-	7.0	700	7.0	N.A.	C	**2**	α
7_3	**1**	V	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	128 + 159	-	7.0	700	7.0	M6.9	C	**1**	α
	3	-	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	287	-	7.0	700	7.0	M8.8	-	**3**	α
	4	M	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	287	180 1SS	7.0	800	7.0	M16	-	**4**	α
	4	M	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	287 + 150	180 1SS+ 180 1SS	7.0	1000	7.0	M 672	-	**4**	α
	4	M	Al12 + AC1/16 AC3/32	- 2S 2G	328 + 130	AC 3/32	1 SS	387	360 1SS + 140 AC3/32 1S1F	-	-	-	M 6187	-	**4**	α
	Complete TWM High Pressure Hold and Limit Test									7.0	10200	0.64	10200		**4**	γ
	Complete TWM High Pressure Limit Test									-	-	-	11000		**4**	

Table 8 Test 8 TWM incremental generation for holding pressure and stemming flow. The obstruction was set for a 3.5” annular. *Travel induced via fabric material ~ 8 sq.ft (R = Silicone Cord 4mm diameter) (P Stands for Pulsing Sequence and impact on system)

Setup			Scaffolding			Strength			Stem	Scaffolding				Scaffolding		
#	Objective Level	Feed Orientation	Wire Core	Wing Width	Length (ft.)	Wire Core	Wing Width	Length (ft.)		Flow Rate Initial (bbl/min)	Steady State Pressure (psi)	Flow Rate Final (bbl/min)	Chamber Pressure Max/Final (psi)	Troubleshooting	Success Level	Termination
	1	V	AC1/8	-	300 ?	-	-	-	-	7	500	7	~0	-	1	α
	2	-	AC1/8	-	300 ?	-	-	-	-	7	500	7	~0	-	1	α
	2	M	AC1/8	-	300 ?	-	-	-	1SS 180	7	500	7	~0	-	0	з
	1	V M	AC1/8 + Al12awg	-	300 + 399	-	-	-	-	7	500	7	~0	C	1	α
	2*	-	AC1/8 + Al12awg	-	300 + 399	-	-	-	-	7	600	7	~0	-	3	α
	2	V	AC1/8 + Al12awg	-	300 + 399	AC 3/32	1SS 2G	140	-	7	600	7	~0	-	1	α
	2*	M	AC1/8 + Al12awg	-	300 + 399	AC 3/32	1SS 2G	140	-	9.1 11.7	1500	11.7	N.A.	-	2	α
8	3	M	AC1/8 + Al12awg	-	300 + 399	AC 3/32 + AC 3/32	1SS 2G + 1SS	140 + 647	-	11	1400	11	N.A	-	3	α
	4	M	AC1/8 + Al12awg	-	300 + 399	AC 3/32 + AC 3/32	1SS 2G + 1SS	140 + 647	1SS 180	7	700	7	M69 M63	-	4	α
	4	M	AC1/8 + Al12awg	-	300 + 399	AC 3/32 + AC 3/32	1SS 2G + 1SS	140 + 647	1SS 180 + 1SS 180	7	-	7	3491	-	4	α
	4 P	-	AC1/8 + Al12awg	-	300 + 399	AC 3/32 + AC 3/32	1SS 2G + 1SS	140 + 647	1SS 180 + 1SS 180	7	4200	7	4200	-	4	α
	4	-	AC1/8 + Al12awg	-	300 + 399	AC 3/32 + AC 3/32	1SS 2G + 1SS	140 + 647	1SS 480 + R 1SS 312	7	6600	-	6600	-	4	γ

6.4.2 Experimental Results Description & Discussion

6.4.2.1 TEST 1

Objective: Generate TWM scaffolding & get it to travel

Fifty feet of Cu 14 awg winged ½" was introduced into the wellbore flowing at 5.0 bbl/min. The feeding process was stopped since the TWM locked in the entry region thus preventing more wire from being introduced. The test feeder was removed. The feeder port was closed off with a blind 4-1/16" flange. The flow was reinitiated to see the effect of the flow on the TWM (note that this is performed since the test feeder is open to the environment). At a flow rate of 5.1 bbl/min the TWM only slightly travelled forward, as shown in Figure 28.

Figure 28 Image from inside the flow chamber

6.4.2.2 TEST 2:

Objective: Generate TWM scaffolding & get it to travel

The cross section of wire was increased from ½" to 1". A total of 185 ft of Cu 14 awg wire was introduced into the flow chamber flowing at 5.0 bbl/min. The test feeder was removed and the flow chamber was closed. The pumps were turned on to 5.3 bbl/min to force the TWM scaffolding to travel downstream. The chamber was opened and the TWM had yet to travel, Figure 29.

Figure 29 Image from view port showing TWM still remains in place at 5.3 bbl/min.

The flow chamber was again closed and a flow rate of 7.0 bbl/min was established. The TWM material was carried/shot out pass the obstruction flange. Thus, demonstrating that when the drag force overcomes friction it has the ability to force the TWM to travel downstream. Less winged wire is thus needed to have the TWM travel.

6.4.2.3 TEST 3

Objective: Generate TWM scaffolding, travel & add strengthening

The TWM scaffolding material was reduced to a length of 25' Cu 14 awg winged design (strapping tape) followed by strengthening material 3/32" aircraft cable with 1" winged (strapping tape). The 25' of the scaffolding material was followed by 150' of the strengthening material. The material was fed with the flow rate at 5 bbl/min. After completing the feeding process, the test feeder was removed and the blind flange added. The flow rate was slowly brought back up to 7 bbl/min, where the TWM material was carried/shot out of the flow chamber Figure 30.

Figure 30 TWM material that shot out

6.4.2.4 TEST 4

Objective: Generate scaffolding, travel, strengthen, & anchor

To assist the TWM generation and travel process the feed orientation of the wing wire design was set to vertical, thus a exposing a higher initial cross sectional area. A total of 336 ft of Cu 14awg winged (1" strapping tape) was introduced into the flow chamber with a flow rate of 7.1 bbl/min. The test feeder was removed and the blind flanged added. The flow rate was restored to 7.3 bbl/min to get the TWM to travel. The pump pressure increased to 800 psi. The TWM travelled downstream to the obstruction flange, Figure 31.

Figure 31 Scaffolding material at the obstruction flange. Thus showing that the TWM has travelled to the obstruction and started the anchoring process.

The test feeder was remounted and the strengthening material was added, 3/32 AC 1" winged (strapping tape). A total of 140 ft. was introduced of strengthening material was introduced into the wellbore before the TWM locked in the entry region. The blind flange was then added and the flow restored to 7bbl/min. The pressure at the pump ramped up to 800 psi. The test feeder was reinstalled to continue feeding more strengthening material. As mentioned earlier, in a fully closed system the entire process will be continuous. These tests are designed for rapid TWM material exchange.

At this stage the TWM has started to build volume and still needs to be compacted. As shown in Figure 32, the TWM strengthening region is still loose packed in the chamber.

Figure 32 Strengthening material still loos in the flow chamber

The flow chamber was closed again and the flow restored for to 7.0 bbl/min for 4 minutes to allow time for the TWM to compact. The test feeder was once again mounted on the flow chamber and used to feed 171 ft. of strengthening material 3/32 AC winged 1". The flow chamber was closed again and the flow rate was gradually restored to 7.0 bbl/min.

The pressure inside the flow chamber started to rapidly rise from the 6 psi at steady state to 19 psi then to 50 psi within a matter of 12 seconds. The spray pattern at the exit of the obstruction changed as well. The Houma team reduced the flow rate at the marked time (Figure 33) in order to minimize the overspray and then gradually increased it again to 7.0 bbl/min. The flow is maintained at 7.0 bbl/min and the pressure inside the flow chamber continued to gradually increase. The pressure inside the flow chamber rose to 81 psi then suddenly dropped to 13 psi and pray eliminated. Thus a section of the TWM either moved or was carried out by the flow.

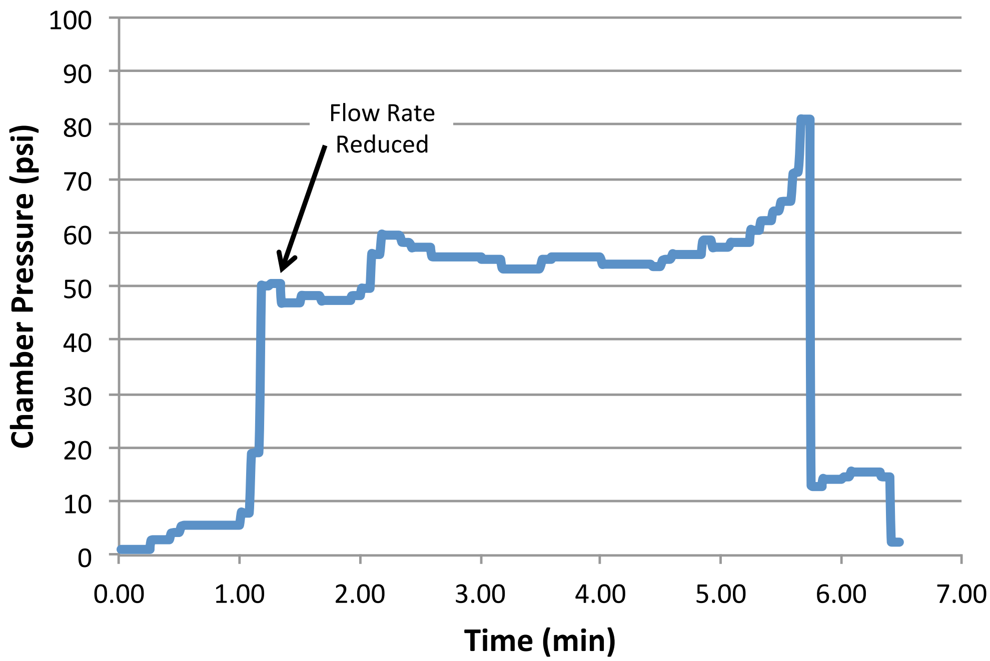


Figure 33 Chamber pressure versus time

The photos from inside the flow chamber, Figure 34, reveal that most of the TWM AC material was carried out by the flow.

Figure 34 Image from inside the flow chamber showing that most of the TWM material was extruded by the flow under 81 psi of back pressure.

The front of the obstruction flange shows that the structural wire was squeezed through the open region of the obstruction flange allowing for the structural material to be carried out as shown in Figure 35.

Figure 35 Obstruction cap showing the copper coated wing wire slipping through the opening

Since there was very little material left, it was decided to add additional material behind the existing structure to determine if it would allow for more strengthening material to be carried out or if it would anchor.

A total of 197 ft. of strengthening material was fed into the flow chamber with the test feeder. A maximum pressure of 24 psi was reached in the flow chamber. The test feeder was removed, the blind flange installed, and the flow restored. As the flow was restored the newly introduced TWM material was also carried out by the flow. The TWM material slid out and remained intact. Thus it was concluded that although very strong, the strapping tape's smooth surface was preventing it from creating a coherent plug: the friction between the scaffolding material of the TWM needs to be increased in order to hold pressure.

6.4.2.5 TEST 5

Objective: Focus on anchoring to hold pressure

A new wire design was created using 2" wide strapping tape. It consists of a sandwich of 2" wide strapping tape covering a 12 gauge aluminum wire and 3/32 AC separated by 1". The groove created between the wires has a 1" ribbon of friction tape (effectively 80 grit sandpaper, this tape is typically applied to walking surfaces to help prevent people from slipping. The brand used was "Gator Grip" tape)

The test feeder was again installed and 141 ft. of the 2" wide double core tape was fed into the flow chamber. The blind flange was installed on the flow chamber and the flow restored to 7 bbl/min for a period of 3 minutes to get the TWM to travel downstream towards the obstruction cap. The view port was opened to determine travel along the flow chamber. The TWM was anchored in the entry region preventing additional material from being introduced into the flow chamber.

To force the TWM to travel, fabric material was placed behind the TWM. The flow chamber was closed and the flow set to 7 bbl/min for an additional 3 minutes, with a max chamber pressure of 5 psi. The scaffolding TWM only minimally travelled downstream. Seventy feet of strengthening material 3/32 AC winged was fed into the flow chamber. The blind flange was re-installed and the flow restored to 7 bbl/min and allowed to flow for three minutes. The TWM travelled downstream onto the second spacer spool. The TWM was barely present near the obstruction flange.

To further compress the initial TWM a silicone core 4mm winged (1" strapping tape) is introduced as a stemming material. The test feeder was able to feed 169' into the flow chamber. The flow chamber was closed and the flow set to 7 bbl/min. The TWM started to push against the obstruction flange and as the pressure increased eventually it gave way and was carried/shot out of the flow chamber, Figure 36. The sensor data is not available for details. The pump pressure increased from 700 psi to roughly 1000 psi according to the operator.

Figure 36 Material carried/shot out by the flow

6.4.2.6 TEST 6

Objective: Focus on Anchoring

Since the scaffolding material from test 5 proved to be too stiff for the fluid drag to make it travel downstream a new type of wing design was fabricated. It consists of a layer of 2" strapping tape with both a 3/32" AC and 1/16" AC separated by an inch and a two-inch friction tape. Fifty feet of the 2" double AC wire was fed into the flow chamber.

The flow chamber was closed and the flow established to 7 bbl/min to get the TWM to travel downstream. As the flow ramped up to the designated 7 bbl/min the TWM was carried/shot out by the flow.

6.4.2.7 TEST 7

Objective: Focus on Anchoring to hold pressure

The early tests have shown that a coated scaffolding allows for slipping between the layers and leads to the TWM being carried/shot out as the pressure increases. Thus the scaffolding material has been chosen to be a 12.5 gauge aluminum wire. The test feeder was used to feed 328 ft. of aluminum wire into the flow chamber to create the initial scaffolding, Figure 37. The flow chamber was closed and the flow rate set to 7 bbl/min for 3 minutes to allow the aluminum TWM to travel downstream.

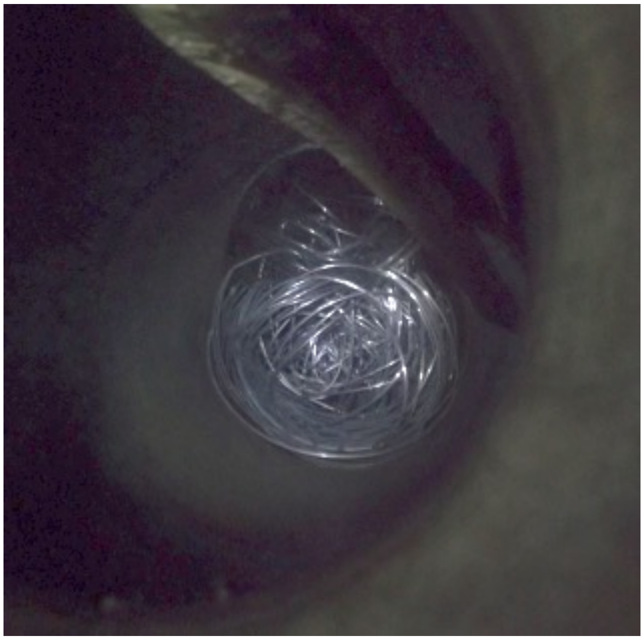


Figure 37 Aluminum inside the flow chamber as seen from the aperture of the obstruction flange.

To assist generating friction and to force the existing TWM to travel, 2” winged tape from Test 6 was fed in using the test feeder. About 15 ft. of the 2” winged design fed before the TWM locked in the entry region preventing additional material from entering. Once again flow chamber was closed and the flow set of 7.0 bbl/min for 3 minutes.

With the scaffolding TWM in place and initial travel secured, an additional 59 ft. of the 2” winged tape was introduced into the flow chamber. The flow chamber was closed and the flow set to 7 bbl/min for 3 minutes to force the TWM to travel downstream. The TWM was still locked in the entry region, therefore, fabric material was placed behind the TWM and with a flow rate of 7 bbl/min the entire TWM moved downstream to the obstruction flange.

The next step was to introduce the strengthening material, 3/32 AC 1” wing design. 128 ft. of strengthening material was introduced into the flow chamber. The flow chamber was closed and the flow set to 7 bbl/min for another 3 minutes. Figure 38 shows that the TWM has moved downstream.

Figure 38 TWM from inside the flow chamber

An additional 159 ft. of strengthening material was fed into the flow chamber. During the feeding process the internal pressure of the flow chamber measured to 6.9 psi. The flow chamber feed port was closed and the flow rate set to 7 bbl/min for 3 minutes. The max flow chamber pressure measured was 8.8 psi.

With the scaffolding material and the strengthening material packed against the obstruction flange, the stemming material is introduced. The stemming material is two 1" strapping tapes stuck to each other in a ribbon. 180 ft. of stemming material was introduced manually into the flow chamber with the flow off. The production unit can have features allowing for feeding into the chamber. The flow chamber feed port was closed and the flow was slowly raised to 7 bbl/min. The flow chamber pressure increased to 16 psi.

An attempt was made to feed 3/32 AC 1" winged into the 16psi chamber with the test feeder and due to the pressure build up the test feeder had limited success. Thus 150 ft. of 3/32 AC 1" winged was introduced manually into the flow chamber. A second 180 ft. of ribbon material was also introduced into the flow chamber manually. The flow chamber feed port was once again closed and the flow rate set to 7 bbl/min. The flow chamber was open to introduce a third 180 ft. of ribbon material. As shown in Figure 39 the TWM is packed in the front 24" of the first spacer spool and the TWM is anchored (Figure 40) on the obstruction flange.

Figure 39 Internal flow chamber photo showing the TWM is 24” in length unpressurized.

The TWM at the obstruction flange shows limited bulging.

Figure 40 Figure showing the TWM at the obstruction flange from the 3.5” port.

The flow chamber was closed the flow rate set to 7 bbl/min. The pressure quickly rose inside the chamber to 560 psi and then levelled off at around 670 psi Figure 41, so the test was stopped and the final stemming material was added.

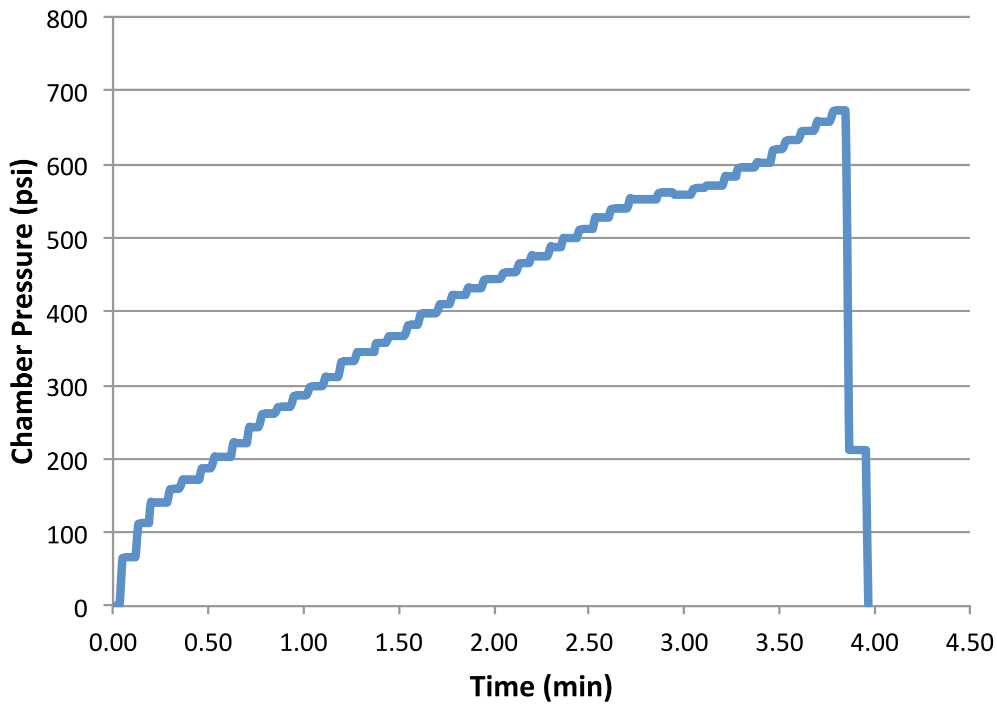


Figure 41 Chamber pressure versus time as the TWM starts to compact

To further compact the TWM and stem a new wire type was created consisting of 1” strapping tape, 3/32 AC, and 1” fabric ribbon. A length of 140 ft. of this stemming material was manually introduced into the flow chamber.

The pressure increased dramatically from 0 to 452 psi in 1 second and within 20 seconds passed 6,000 psi as shown in Figure 42.

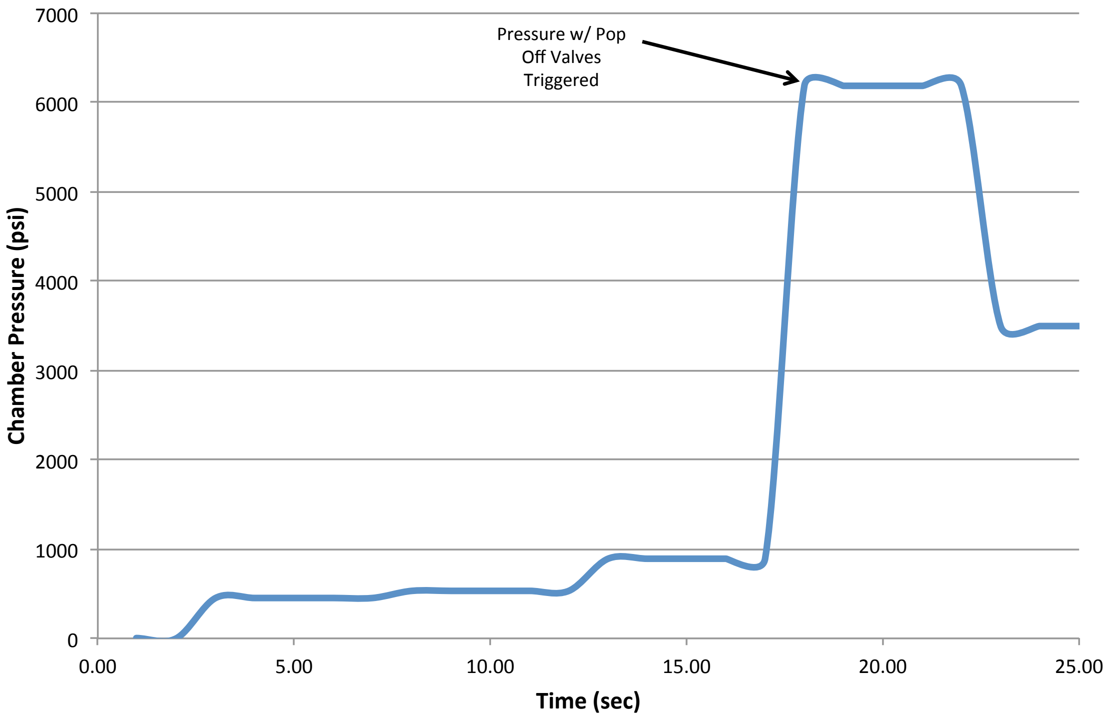


Figure 42 First 20 seconds of the experiment. The spike in the pressure is due to the pressure compressing the TWM, which further improves the ability to stem the flow. The spike is also due to the fact that this experiment is discretized. In the field the pressure will be monitored as a function of feeding in order to eliminate any pressure spikes in the wellbore.

The pop off valves were triggered by the high pressure which by itself meant that the testing goals were met; however, even greater pressure was actually held, as the pressure spiked to 6187 psi measured by the Omega pressure sensor. Even after stopping the flow, the flow chamber remained pressurized to ~3,500 psi with minimal decrease, Figure 43. After ~5 minutes the pressure was relieved by opening valves at the pumps.

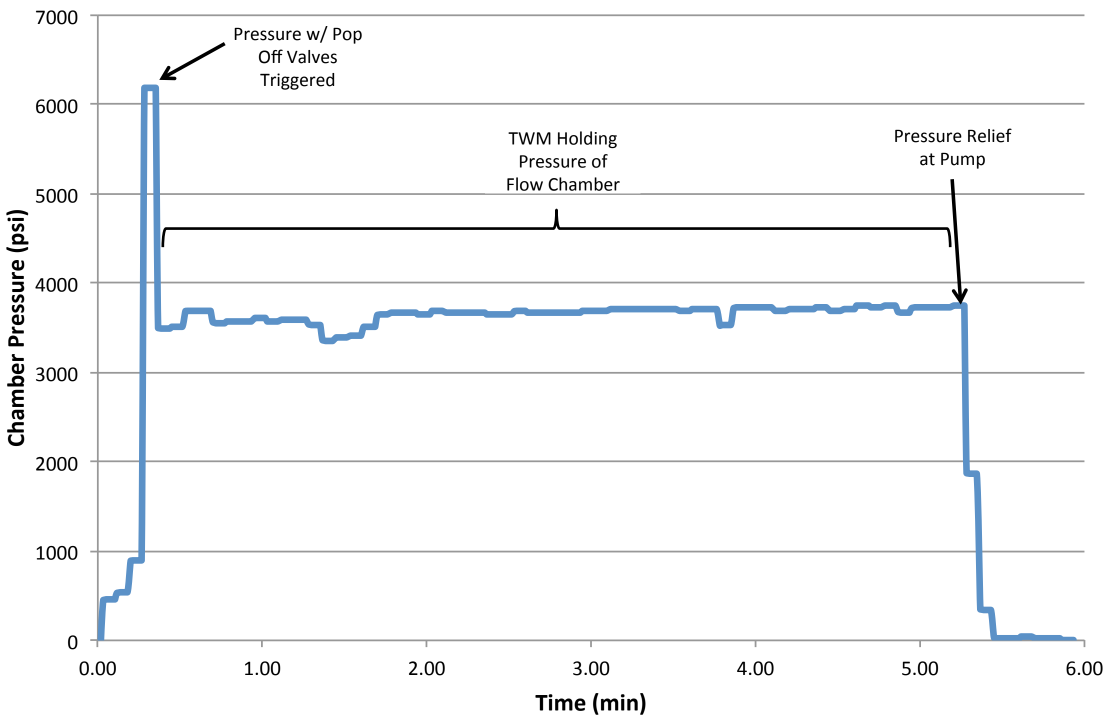


Figure 43 Chamber pressure versus time showing the ability of the TWM to hold a pressure after the flow has been turned off.

The entire flow loop was inspected to make sure it could withstand a test hold pressure of 10k psi. The TWM material was pressurized in 1,000 psi increments up to 10k psi and the pressure is shown in Figure 44. After 1 minute we started raising the pressure to perform a limit test. The TWM held to a maximum of 11,000 psi before yielding. A 91% stemming efficiency is obtained by comparing the unrestricted flow rate configured to a nominal 7 bbl/min compared to the average flow rate at hold pressure 0.64 bbl/min.

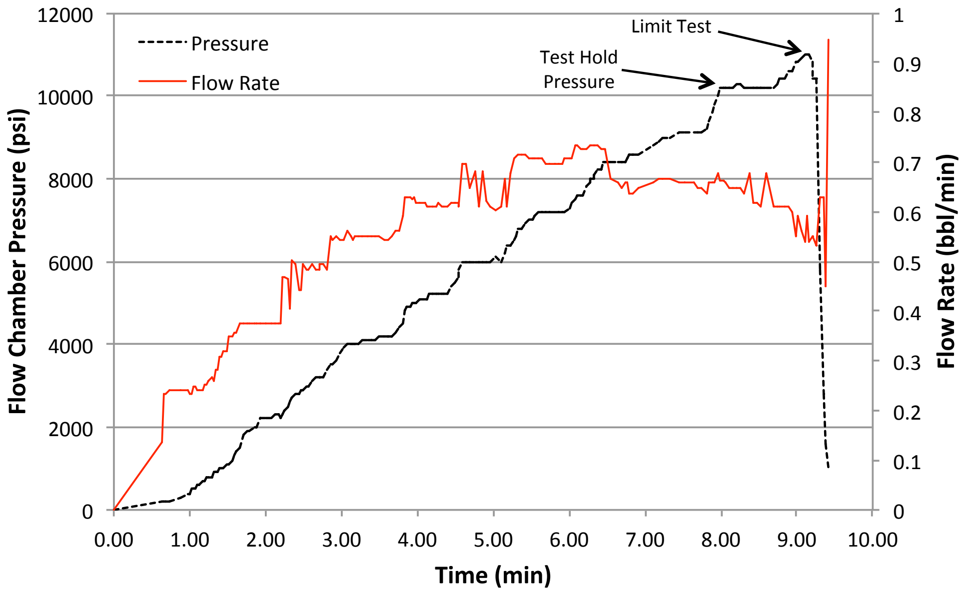


Figure 44 Test 7 flow chamber pressure and flow rate versus time showing for the 10,000 psi high pressure hold

The final sum of all of the material in test 7 is summarized in Table 9.

Table 9 Material sum for test 7

TWM Section	Length (ft.)	Material Description
Scaffolding	328	12.5 gauge aluminum wire
	130	2” Wide strapping tape, with two cores 1/16” and 3/32” aircraft cable separated by 1”, and 2” friction gator grip tape
Strength	287	1” 3/32 AC coated on each side with 1” strapping tape
	180	1” dual strapping tape
	150	1” 3/32 AC coated on each side with 1” strapping tape
Stemming	180	1” dual strapping tape
	140	1” strapping tape, 3/32 AC, and 1” Fabric cloth
TOTAL	1395 ft.	

The TWM material that remained inside the wellbore, Figure 45, was cohesive and was readily removed from the wellbore as a plug. This is a good sign that in a real application, it can be fished out once the well has been top killed.

Figure 45 TWM from test 7 material remaining inside the flow chamber after tested till 11,000 psi

6.4.2.8 TEST 8

Objective: Determine if the scaffolding TWM can be created with 1/8 AC.

The test feeder was used to feed 700 ft of 1/8" AC in a flow rate of 7 bbl/min. The flow chamber was closed and the flow rate set to 7bbl/min to get the AC TWM to travel towards the obstruction flange. The AC was pushed into the main bore and the pumps turned on to flow 7 bbl/min for 3 minutes. The port was opened and no appreciable motion of the 1/8 AC occurred, Figure 46.

Figure 46 AC 1/8 inside flow chamber viewed from the obstruction flange aperture

360 ft. of ribbon stemming material was pushed into the bore manually and the port closed and the pumps turned on. The froth blew through the OF, but not the 1/8" AC. The AC did move to the front of the OF, but was not bridging the opening.

The behaviour are indicative of earlier smaller scale results that show it is required to have a malleable wire to generate the scaffolding for the strengthening material to bridge off. The test feeder was reinstalled on the flow chamber and used to feed 399 ft. of 12.5 gauge aluminum wire. Two attempts were made to feed the solid 12 gauge wire with the test feeder; however the test feeder was too big to feed the raw aluminum wire. The test feeder is designed primarily to feed the winged wire material, and with slight modification will also feed a range of wire gauges (future prototypes). A total of 399 ft. of aluminum wire was manually introduced into the flow chamber. To get the TWM to travel, fabric material was manually introduced (equivalent of 150 ft. of 1" wide fabric). The flow chamber was closed and the flow rate set 7 bbl/min for 3 minutes to get the scaffolding to travel downstream. It was observed that the TWM reached the front of the obstruction flange.

The test feeder was used to feed 140 ft. of 3/32 AC 1" winged design in a flow rate of 7 bbl/min, Figure 47.

Figure 47 TWM inside flow chamber

The obstruction flange open aperture shows the 1/8 AC cable sliding past the sides and the aluminum wire firmly fixed behind, Figure 48.

Figure 48 Obstruction flange front showing the

2” wide GG tape had to be used: 1” wide HST with 3/32” AC core was wrapped with 2” wide GG that was folded over so both sides of the HST structure were covered. 120 ft. of this material was prepared and placed into the bore. The pumps turned on to flow 7 bbl/min for 3 minutes. The port was opened and no motion of the both sides covered with GG tape material occurred. Thus there was just too much friction from having friction tape on both sides winged wire. The equivalent to 70 ft. of fabric material 1” material was introduced to was for the high friction covered TWM to travel downstream. The flow chamber was closed and the flow rate set to 7 bbl/min.

For the strengthening material, 647 ft. of 3/32 AC 1” wing design was manually inserted into the wellbore. The flow chamber was closed and flow rate set to 11 bbl/min to move the TWM forward. The pressure in the flow chamber spiked to 30 psi and the flow rate was quickly removed. The flow rate was then restarted to 7 bbl/min for two minutes.

To start the stemming process 180 ft. of ribbon material was added. The flow chamber closed and the flow rate set to 7 bbl/min. The peak pressure reached was 69 psi and the steady state 64 psi as shown in the Figure 49 below.

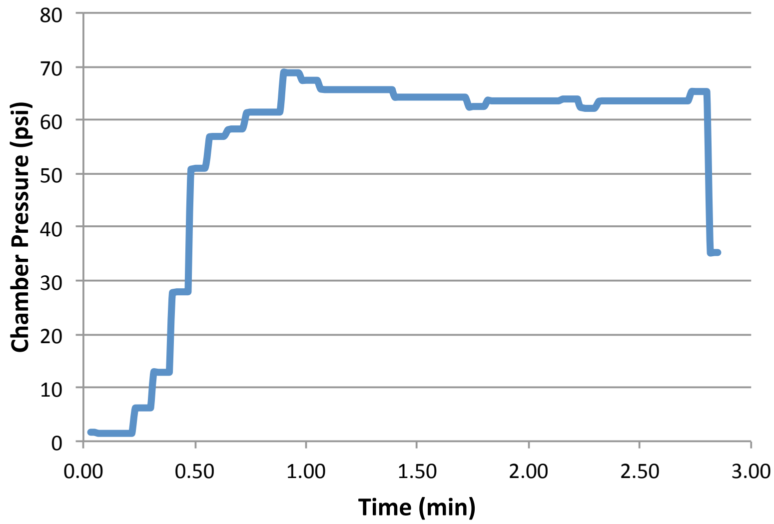


Figure 49 Chamber pressure versus time showing the beginning of the packing for stemming

The flow chamber was closed and the flow rate restored to 7 bbl/min. The pressure and flow rate are shown in Figure 50. Notice that at 8.7 min the TWM reaches a critical point where it starts to compress. As the material compress the permeability decreases and the pressure increases rapidly. The continuous feeding and pressure monitoring will take care of eliminating these unwanted pressure spikes.

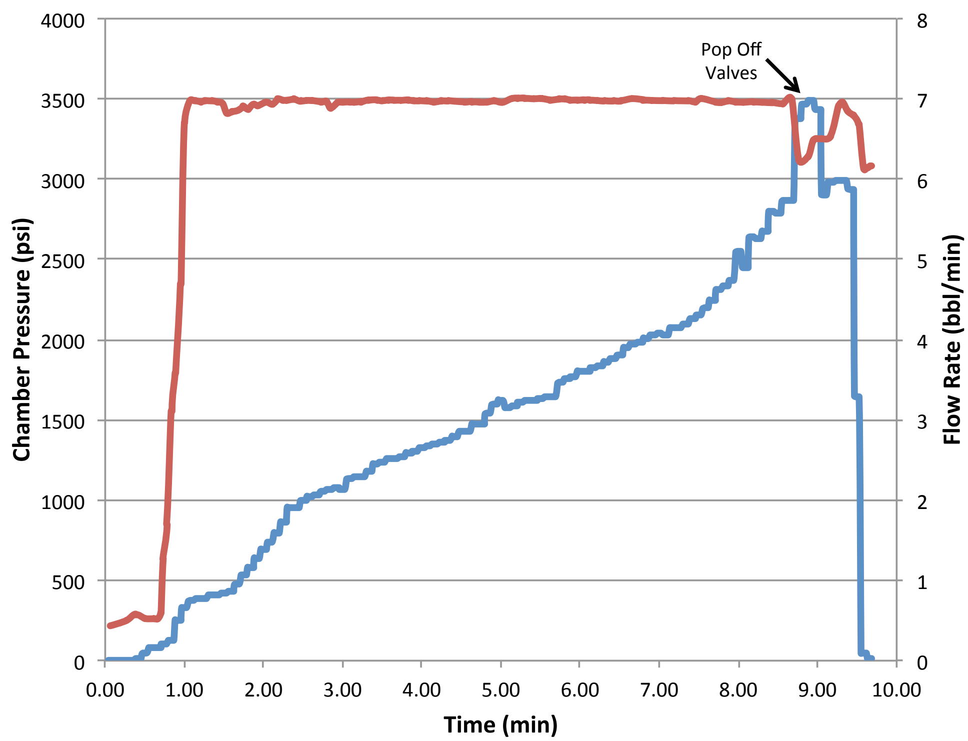


Figure 50 Chamber pressure and flow rate as a function of time showing the TWM on the onset of packing

To proceed to the higher-pressure tests, the blind flange with the digital pressure transducer (rated 5k psi) was removed to allow for the TWM to be exposed to higher pressures. To assist with the stemming of the flow, 312 ft. of silicone cord 4 mm diameter coated on both side with 1” strapping tape for wings was manually inserted into the wellbore.

The pumps were started up to flow 7 bbl/min. The pressure rose quickly to 1800 psi, but stayed there for several minutes. The flow had to be channelling. The main difference between test 8 and 7 was that test 7 had as a sealing material the 1” HST on cloth.

The pressure did not rise again to the 3600 psi when the pop off valves blew. Somehow the plug relaxed and the flow had found a channel, which was attributed to the 1/8” AC. It was decided to pulse the flow by lowering and raising flow rate as if the TWM were to take a gas pocket followed by more fluid. The pulsing brought the pressure up to 3k psi very quickly where it held for several minutes at 7 bbl/min flow. The pump operator cycled it again and this time the pressure rose quickly to 4k psi, Figure 51.

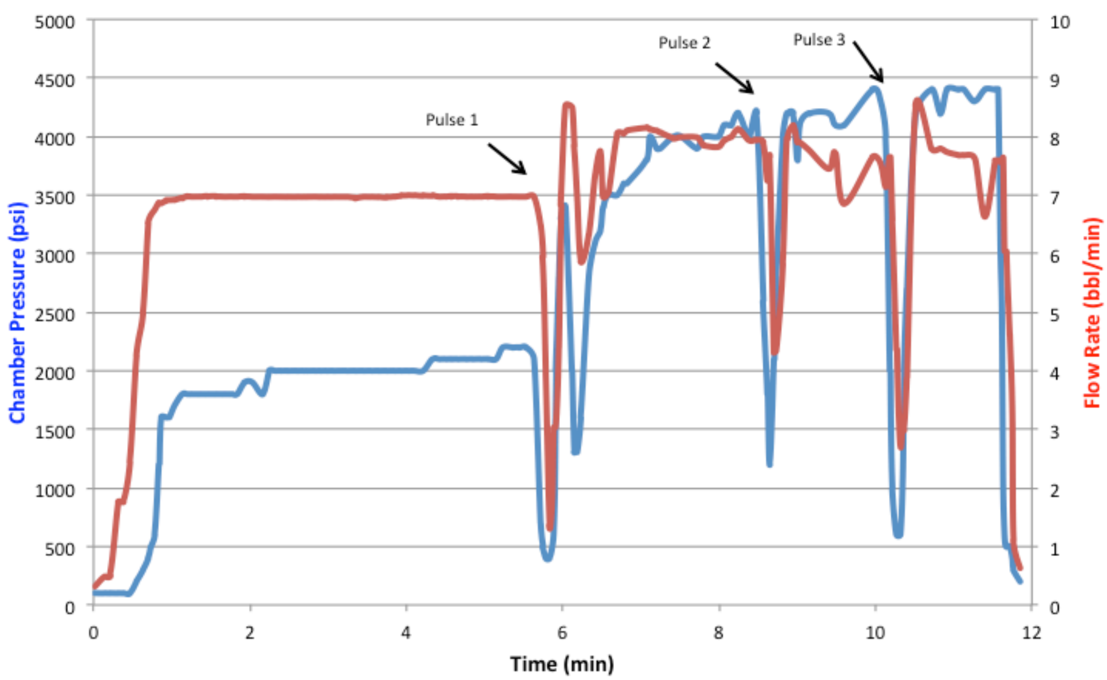


Figure 51 Pulsing sequence to determine TWM stability against a gas section intake

The flow chamber view port was opened to determine effect of pulsing. The chamber was once again closed and the testing continued. The chamber pressure steadily increased and the flow rate oscillated erratically, Figure 52. At roughly 4 minutes into the test the pressure reached almost 6k psi a section of the TWM was sheared and ejected. The pressure however quickly recovered and at 4.7 minutes another section of the TWM was ejected. There were subsequently three pressure fluctuations were shearing/ejection of material could not be confirmed. Shortly passing the 7 minute test mark a third confirmed shearing/ejection event took place after reaching a pressure of 6,600 psi.

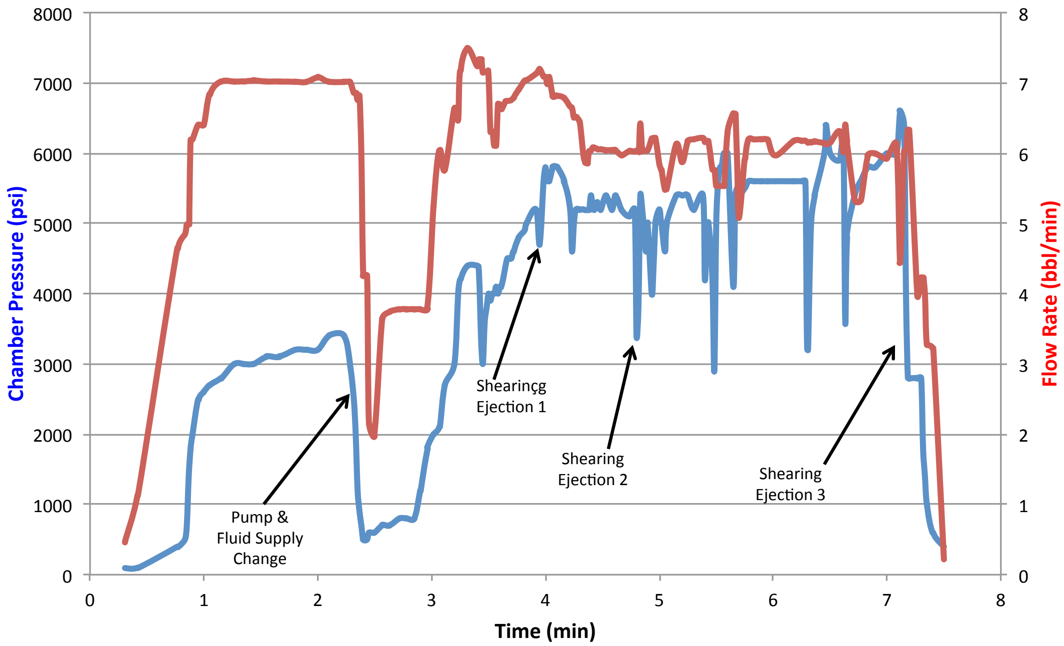


Figure 52 Test 8 chamber pressure versus time

Figure 53 TWM removed from test 8

7. DATA ANALYSIS & DISCUSSION

For those readers in industry, please note that the method/techniques and machine for generating a TWM inside a free flowing structure is patent pending technology.

7.1. Tangled Wire Mass

The TWM has at least three distinct sections along its length: scaffolding, strengthening, and stemming material all in series. The scaffolding is the material with a small cross section that buckles and bends inside the free flowing wellbore to generate a foundation for the strengthening material. In order to get the TWM to travel downstream the strengthening material is of a wing design with a higher cross section. The materials can include high strength strapping and the surfaces may be coated with grit material, or swelling material to increase the energy required for slipping. The stemming material can be also a winged wire design that is the form of a high strength ribbon. The experiments used strapping tape as the stemming material to seal the small fluid gaps within the TWM.

7.1.1 Wellbore Configuration

The tests demonstrated that a TWM can be generated in an open wellbore as well as a wellbore with a drill pipe present. The wire follows the path of least resistance and fills any open spaces. In the wellbore,

7.1.2 Obstruction Geometries

The tests also demonstrated that the TWM can anchor on both annular geometries as well as ram style geometries. The limit in each configuration remains for future testing.

7.2. Deliverables

7.2.1 Risk Analysis

A major risk of a junk shot is the sudden stemming of the flow which can cause a hydraulic hammer (“water hammer”). This can create a pressure spike that could blow out the well’s rupture disks in the casing and compromise the entire formation. Thus an important advantage of the HAWK tool is its ability to regulate the wellbore pressure based on the feed speed of the wire. As was demonstrated in earlier tests, the TWM works on a self-assist basis. As the pressure across the TWM increases, the TWM is further compacted, thus further increasing the backpressure. The testing demonstrated that after 3,000 psi the materials begin to compress rapidly. In a production-deployed tool, the pressure could thus be monitored and used to control the feed rate of the material from the HAWK tool.

7.2.2 TWM Permeability

The permeability of the TWM from Septembers Test 7 is calculated at between 1-5 Darcy (m^2) at pressures above 4000 psi, as shown in Figure 54.

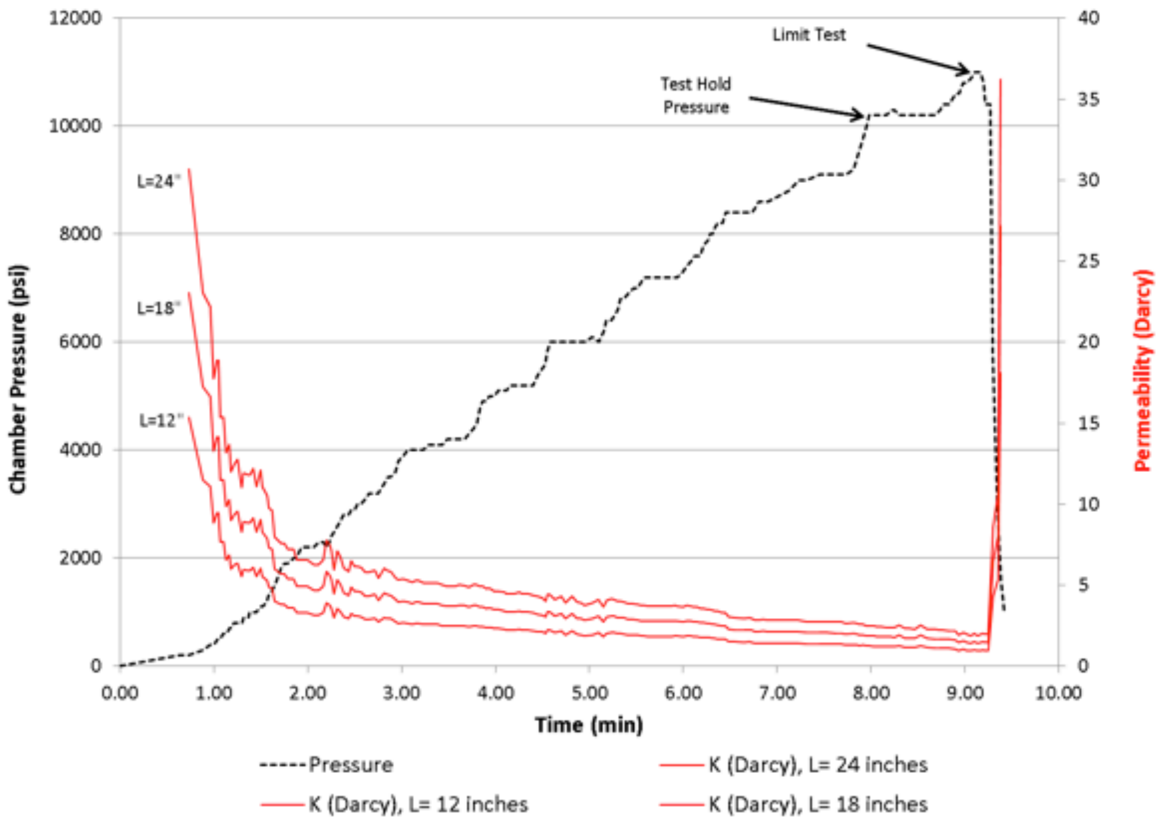


Figure 54 Test 7 Calculated permeability

The permeability of the TWM from Test 8 follows the same downward slope as that of Test 7. The modifications in the wire that created the Test 8 TWM plug resulted in a higher permeability (less stemming of the flow). Thus, as mentioned earlier, the scaffolding of the TWM needs to be a malleable material that buckles and plastically deforms. The 1/8" AC was observed to go across layers of the TWM which we believe resulted in the flow channeling, creating low resistance flow paths as shown in Figure 55.

At pressures above 5,000 psi, the TWM of Test 8 reaches a permeability below 50 Darcy. Figure 56 shows the permeability of Test 8 for the high pressure tests. The length of the TWM is estimated between 12 and 24 inches based on the photos taken from inside the flow chamber. With the flow off, the TWM almost filled the first drilling spool which was 30 inches long. After yielding and ejecting material, the core of the TWM remaining was approximately 12 inches.

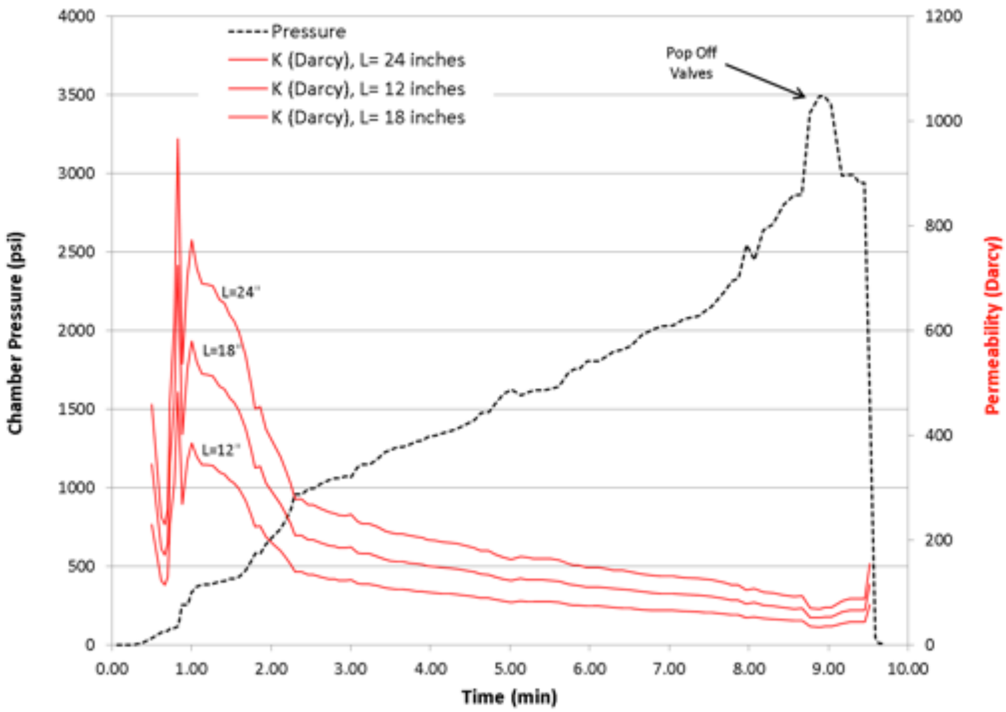


Figure 55 Test 8 Calculated permeability from low pressure tests until pop off valves are triggered

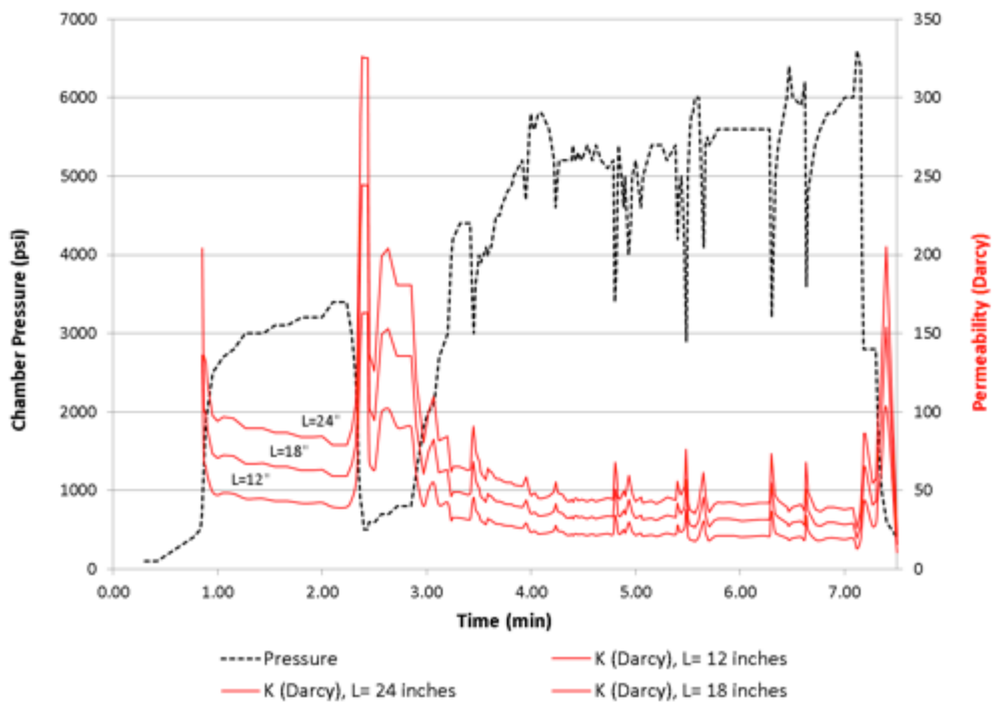


Figure 56 Test 8 Calculated permeability analysis of high pressure test

7.2.3 Back Pressure vs Fill Factor Relationship

As the back-pressure (the pressure behind the TWM) increases eventually the TWM begins to compress increasing the density of the plug thus increasing the fill factor. As shown in Figure 44, at 8,200 psi the flow rate makes a transition from an upward slope to a downward slope. At 10,200 psi the flow rate distinctly decreases again. To measure the relationship in continuous time with the flow it would be necessary to have a water proof high pressure camera embedded inside the flow chamber, which was outside of the scope of the Phase 1 testing.

7.2.4 Permeability vs Stemming efficiency Relationship

As the permeability decreases the stemming efficiency increases. Test 7 demonstrated that a permeability between 1-5 Darcy reduced the flow from the 7 bbl/min to a nominal 0.64 bbl/min.

The first order implications is that in a 18.75 inch wellbore flowing with 100,000 bbl/day (the worst case discharge pressure) with a back pressure of 15,000 psi may be stemmed between 75% (permeability of 5 Darcy) and 97% (permeability of 1 Darcy), Figure 57.

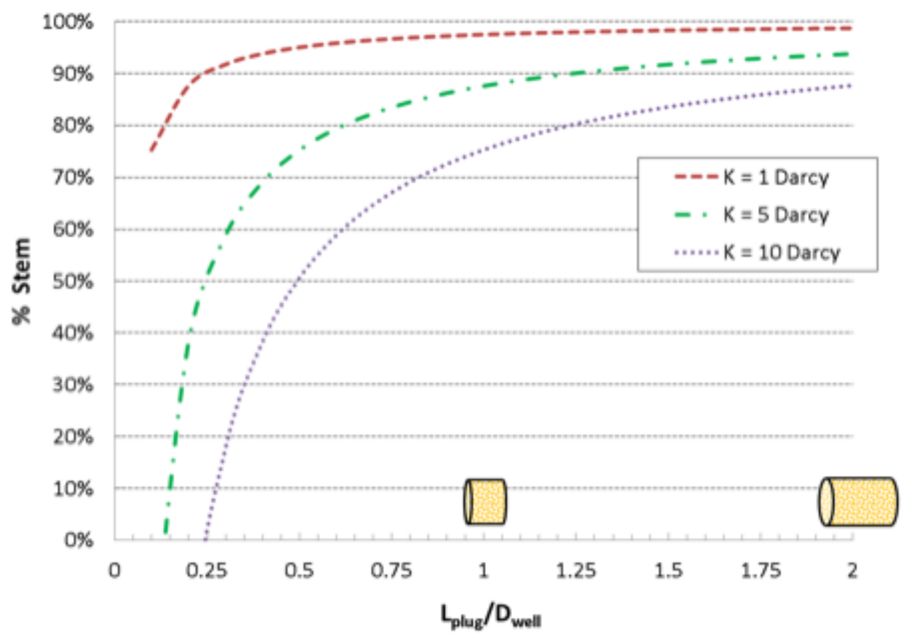


Figure 57 Theoretical percentage flow reduction versus characteristic length of the TWM for TWM with three permeability values (1, 5, and 10 Darcy) in an 18.75 in wellbore, flowing with 100,000 bbl/day, and a back pressure of 15,000 psi, and oil viscosity of 8.39×10^{-3} Pa*sec.

7.2.5 Stemming Efficiency

The stemming efficiency from the Sept test 7 calculated at 91%, coincide with the prior 4" flow tests that generated a stemming efficiency greater than 93%.

8. RECOMMENDATION FOR PRODUCT INTRODUCTION

Introducing the HAWK tool into the oil industry will require appropriate capital to complete product development and testing of the final design. This section summarizes the next steps necessary to introduce the technology into the market.

8.1. Required development resources

Transitioning from the prototype development phase to the production and deployment phase will require capital spending to deliver the HAWK tool into market. As shown in Figure 58, the production and deployment phase will require: 1) engineering personnel, 2) shop area, 3) fabrication facilities, 4) knowledge of certification processes, 5) testing facilities, 6) marketing personnel, as well as 7) sales and logistics groups who are known and trusted in the industry. The key questions and concerns related to the hardware have been addressed with the prototype development and Phase 1 test results. Raptors Design has a detailed outline of the hardware components for the HAWK tool and connectors along with a list of second order tasks to be addressed in the production phase.

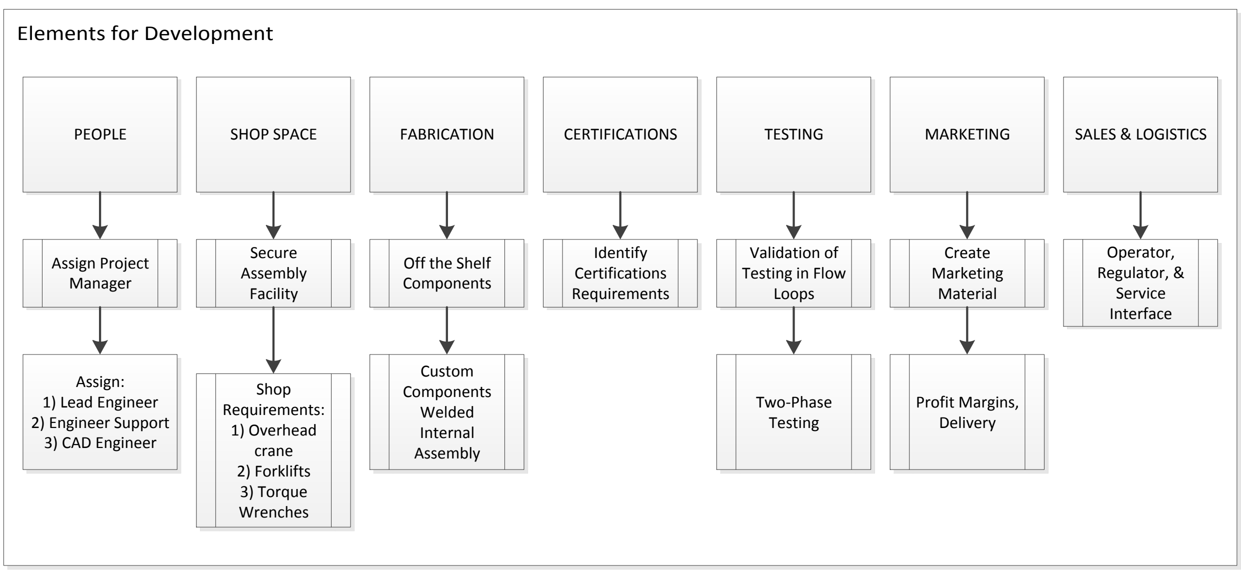


Figure 58 Elements needed for the production and deployment phase

The main challenge to introduce HAWK tool into the market is the current price of oil, which leaves very little funds for the development of safety tools.

8.2. HAWK Tool in the Field

The roadmap for development and introduction of the HAWK tool would begin with the acquisition of the technology by an established industry supplier with high-pressure product development personal and testing facilities. Development tasks include (some of these can be conducted in parallel):

1. Establish a supplier for providing wire with the varying sections needed as described above. Wire and tape can be combined using a "converter" machine.
   a. Design the wire spool to be wound and fed axially (as is common in the weaving industry) to minimize the size of the HAWK pressure chamber.
2. Design the feeder, based on above experience, for feeding both uncoated and coated wire as well as just fabric and strapping tape (the final flow stemming agent we referred to as "froth").
   a. The feed head should be extendable to be placed right at the junction of the side port and the free-flowing well bore to prevent the possibility for the wire to buckle in the port and jam the feeder.
3. Conduct Phase 2 and Phase 3 tests.
4. Coordinate with BSEE best practice guidelines for introducing the HAWK, perhaps by providing incentives for operators who use a backup device in situ with a BOP, and if proven successful, regulations for mandatory.
   a. For Arctic drilling in particular, an in situ back up safety device is especially important.

An onshore unit can be made available to complement the offshore HAWK tool.

8.3. Cost Analysis for Product Introduction

It is estimated that would cost an estimated $15M to develop the HAWK technology as an independent company; whereas it would cost an estimated ~$6M (in addition to M&A cost) for an established company with flow loop test facilities to complete the product development, rigorously test, and market the technology.

9. CONCLUSION

Given that the vast majority of the wells outside the Gulf of Mexico (85-90%) have a wellhead pressure of less than 10k psi [10], the tests done in Phase 1 show the technology is essentially ready to deploy with very little additional development. For higher pressure tests, more tests, as above for example, are needed, but the trend is clear, higher strength wire and tape are available and in addition to feeding more structural material before the flow stemming material is fed, it is envisioned that very high pressure flows can be stemmed, even up to 20k psi.

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