Conventional multi-interval/zone stimulation approaches generally fall into one of two categories: (1) the placement of individual treatments via a single pumping event and the deployment of tools and equipment into a wellbore to facilitate selective isolation and tailored stimulation of each individual zone; or (2) multiple treatments placed during a single stimulation pumping event using various flow control or fluid diversion approaches to coerce fluids into each of the available reservoir intervals.

While approach (1) provides high-quality stimulations that maximize production from each reservoir interval, the approach is generally costly due to the time and equipment required for implementation. As a result, cost control is generally achieved by stimulating only the highest quality reservoir intervals (bypassing smaller or less attractive intervals).

Approach (2) minimizes the cost per stimulated interval by reducing the time that equipment is mobilized. However, the stimulation treatments placed using this approach are generally poorer in quality because treatment fluid delivery to each individual reservoir interval is not assured or directly controlled. More specifically, when multiple reservoir intervals are simultaneously exposed to a stimulation pumping event, some reservoir intervals may not be stimulated, thus reducing the total number of treated intervals. The remaining intervals may receive disproportionate volumes of treatment fluids that deviate appreciably from the optimized single interval treatment design. The end result is a larger number of intervals treated per unit stimulation cost but with generally poorer stimulation effectiveness.

To capture the optimized production benefits associated with approach (1), and the cost reduction benefits associated with approach (2), ExxonMobil has developed and patented two new stimulation technologies that enable the rapid placement of a large number of high-quality treatments. These technologies are expected to improve the recovery from multi-zone conventional resources and "enable" economic recovery of multi-zone unconventional resources.

The two new technologies are referred to as "Just-in-Time Perforating" (JITP) and "Annular Coiled Tubing Fracturing" (ACT-Frac). These technologies enable: (1) the delivery of a large number of stimulation treatments (e.g., 40+ treatments)
in a single well over an extended pay interval in a timely manner; (2) effective diversion between treatments to improve placement of treatments specifically designed for each target zone; and (3) the ability to pump treatments at high flow rates to ensure efficient and effective stimulation.

To date, the development, deployment, and commercialization of these novel technologies has generally focused on enabling the economic development of a large tight gas resource located in the Western United States of America. This undeveloped tight gas resource has been known to industry for well over 50 years and presents a challenging test for any fracture stimulation technology. The formation is characterized by a thick reservoir section (up to 5,000 feet) that is comprised of numerous vertically stacked lenticular sands with effective permeabilities on the order of 1 microdarcy.

**New Multi-Zone Stimulation Technologies**

**Just-in-Time Perforating (JITP).** JITP involves pumping high flow rate treatments down the casing with a perforating gun assembly in the well to selectively perforate one interval at a time. Diversion between treated intervals is promoted through the deployment of ball sealers.

**JITP Bottom Hole Assembly (BHA)** - A typical JITP bottom hole assembly is deployed via monoconductor wireline and is comprised of a magnetic decentralizer, Casing Collar Locator (CCL), select-fire perforating gun assembly with stand-offs, and a mechanical decentralizer, as shown in Figure 1.

![Figure 1. JITP Bottom-Hole Assembly](Image)

**JITP Stimulation Method** - A well is stimulated using the JITP method by sequentially treating individual zones via the combination of selectively perforating single intervals and promoting the isolation of these intervals through the deployment of ball sealers. A single continuous pumping operation allows un-interrupted operations as well as positive pressure on the ball sealers to facilitate effective fluid diversion.

Figure 2 summarizes the typical JITP stimulation process. The gun assembly is positioned at the first zone to be treated (using the CCL for depth control) and the first gun is fired. The gun assembly is then raised to the next zone of interest and the first treatment is pumped. At the tail-end of the first treatment, ball sealers are added to the flow, with at least one ball sealer for each perforation. When the ball sealers arrive downhole and seat on the perforations, as evidenced by a sharp rise in wellbore pressure, the next gun is fired and the second treatment is initiated (without shutting down the pumps). While the second stimulation is being pumped, the BHA is pulled off of the perforations, moved uphole, and positioned at the third zone to be treated. This process is repeated for up to six zones per deployment of the gun assembly. Once the set of treatments is completed, the gun assembly is retrieved. If more zones are to be treated, a frac or bridge plug is set above the stimulated zones to provide isolation from the next set of treatments.

![Figure 2. JITP Stimulation Process](Image)

The JITP process relies on success in several key technical areas: 1) ball sealers must reliably flow past the BHA during pumping operations; 2) the BHA must not become differentially "stuck" to perforations while a treatment is being pumped (caused by the radial pressure gradient that drives the treating fluid into the perforations); 3) balls must tightly seat against perforations to mitigate leakage and ball sealer erosion; 4) if a pumping operation is interrupted, balls should be capable of re-seating when pumping is re-initiated; 5) the perforating operation must be properly timed to ensure that the balls have passed the BHA before the next gun is fired; and 6) if the stimulation treatment fluids are staged (e.g., varying fluids and/or proppant concentration), then proper arrival of the ball sealers is important. These key technical areas are discussed in more detail below.

Because ball sealers must reliably flow past the BHA during pumping operations the JITP BHA is designed to include decentralization. Decentralization maximizes the unrestricted cross-sectional area available in the wellbore to facilitate
unhindered ball sealer passage. The diameter of the gun barrels are also sized to maximize the available unrestricted cross-sectional area while still providing sufficient perforation charge to ensure reliable and effective communication with the formation.

Stand-offs are included in the JITP BHA as a means of mitigating differential sticking issues that can arise from firing perforating guns in over-balanced and continuous pumping conditions. The radial gap provided by the stand-offs prevent the guns from covering the perforations and provide a flow path for treatment fluids to enter the perforations, thus minimizing the "sticking" effect and allowing the gun assembly to be pulled up-hole. Of course this standoff, and the associated restriction in the wellbore flow passage, has to be balanced with the first requirement of reliable ball sealer passage.

To promote effective fluid diversion, and robust response during upset conditions, the ball sealers used for JITP are an ExxonMobil-patented design made of a rubber-coated syntactic foam that is designed to maintain buoyancy under high pressure/high temperature conditions. Buoyancy is necessary to ensure that balls migrate up-hole during temporary interruptions to pumping operations (upset conditions) thus enabling balls to re-seat once pumping operations are re-initiated.

Qualification of JITP was focused primarily on laboratory testing of the specially-designed ball sealers. The ball sealers were tested at the maximum loads and temperatures anticipated in field application to verify that they would maintain their integrity and buoyancy during the expected exposure time. Additional studies included perforation burr height/profile characterization and its impact on ball sealer seatability as well as computational studies supporting the design of the radial gap size provided by the stand-off subs (for a given gun length). In addition, the JITP gun assembly underwent field qualification to determine the maximum pump rate that could be achieved without exceeding the maximum working load of the wireline.

Figure 3 shows a typical pressure response during a five zone JITP treatment. Note that the pump rate is maintained throughout the process, even when the pressure rises during "ball-out". The ball-out pressure rise requirements are specified to predetermined levels prior to firing the next gun as an indicator of when the perforated interval has been sufficiently plugged by ball sealers. However, it may occasionally be difficult to achieve the desired ball-out pressure response in latter treatments due to ball sealers on lower zones leaking as a result of erosion, poor seating, or other upsets. In this case, the stimulation process is terminated, the JITP BHA is removed from the well, and a frac or bridge plug is set. The next set of treatments is then placed above the frac or bridge plug.

Generally, 4 to 6 zones are stimulated during a single pumping operation as determined by the ball-out pressure response. Bridge or frac plugs are deployed between pumping events to isolate the previously placed set of treatments. After all the desired zones in a well have been treated, the bridge/frac plugs are drilled out and the well is placed on commingled production.

Annular Coiled Tubing Fracturing (ACT-Frac). ACT-Frac was developed after JITP with the objective of capturing potential enhancements to the JITP multi-zone stimulation process.

The ACT-Frac approach relies on the deployment of a BHA that permits multiple perforation and wellbore isolation events during a single deployment into a well. Typically the assembly is conveyed via coiled tubing, isolation between treatments is achieved using an inflatable packer, and perforation is provided via select-fire perforating guns. The treatment is pumped down the tubing-casing annulus to achieve the high flow rates necessary for efficient and effective stimulation.

ACT-Frac Bottom-Hole Assembly - A typical ACT-Frac bottom-hole assembly is shown in Figure 4 and consists of the following key components:

Coiled Tubing (CT) - Coiled tubing is used as the BHA deployment means and is connected to the BHA via a CT connector and a tension-release shear sub. Monoconductor wireline is contained within the coiled tubing to facilitate actuation of the BHA's select-fire perforating guns and to enable communication with the BHA's CCL.

Wash Tool and RILV - The Remote Intervention Logic Valve (RILV) is the "brain" of the ACT-Frac tool. It consists of a series of hydraulically-actuated valves to selectively: 1) inflate/deflate the packer; 2) enable circulation down the coiled tubing and into the tubing-casing annulus via a wash tool; and 3) enable pressure equalization across the packer, so that downhole operations can be performed at the proper time and in the proper sequence.

Packer - An inflatable packer is included in the BHA to provide isolation between the current zone and the previously treated zones. An equalization path allows selective pressure equalization across the inflatable element before, during, and
after activation. The opening and closing of this equalization path is regulated by the RILV.

Slips - The slips anchor the BHA to the casing walls in a single direction and are used to prevent downhole axial movement of the BHA. The slips are resettable and operate on a 'J' latch mechanism, i.e., the slips are toggled between the "set" position and "run-in-hole" position via one ~12 inch movement of the coiled tubing uphole.

Perforating Gun Assembly - Similar to JITP, select-fire guns are used for perforating. However, ACT-Frac select-fire guns are typically larger and deployed with 60-degree phasing. The gun barrels are sized to permit the use of large perforating charges while still providing sufficient flow area past the guns in the event that the ACT-Frac tool must be pulled past treatment fluids (e.g., proppant-laden cross-linked gel).

![ACT-Frac Bottom-Hole Assembly](image)

**ACT-Frac Stimulation Method** - A well is stimulated using the ACT-Frac method by sequentially treating individual zones starting from the bottom of a well and moving uphole. Each zone is treated separately using a single pumping event and bridge/frac plugs are not used. Positive isolation is achieved using multi-set downhole equipment that is moved uphole from zone-to-zone to facilitate multiple treatments via a single deployment of wellbore equipment into a well.

Figure 5 summarizes a typical ACT-Frac stimulation process. The lowest ACT-Frac perforating gun is positioned adjacent to the first zone (using the CCL for depth control) and the perforating gun is fired. The BHA is lowered below the perforations and the slips and packer are set. The stimulation treatment is then pumped at high flow rates through the casing-tubing annulus. When the stimulation treatment is completed, pumping is terminated, the BHA is released, and moved uphole to the next interval. When the second gun is positioned adjacent to the second zone the perforating gun is fired, the BHA is lowered below the perforations, and the process is repeated. The number of intervals treated is limited by the number of guns deployed on the BHA. If more than one deployment of the ACT-Frac BHA is required, the tool is redressed on the surface (new guns/consumables) and then redeployed to continue stimulating, starting above the last zone treated. After all desired intervals have been treated, the stimulation equipment is de-mobilized and the well is placed on production. No mobilization of plug drill-out equipment is required.

![ACT-Frac Stimulation Process](image)

The ACT-Frac process provides "leak-tight" positive isolation between the interval being stimulated and the intervals previously stimulated; this allows a single pumping event to place a tailored interval-specific treatment while ensuring that previously placed stimulations are not damaged or altered by subsequent stimulation treatments. There are no bridge plugs deployed using the approach and the technique is amenable to application in deviated and horizontal wellbores. In addition, since the ACT-Frac process is essentially a rapid succession of conventional high-quality single zone stimulations, the approach provides the option of stimulation fluid flowback after each treatment is placed (either with the packer inflated below the perforations or with the packer deflated, e.g., during the interim/transit time period between zones). This can be used to force-close fractures and/or to minimize treatment fluid contact-time with the reservoir rock.

**ACT-Frac Tool Operation** - The ACT-Frac stimulation method relies upon the performance of various "operations". In addition to firing the perforating guns and activating the slips these "operations" include: 1) circulating fluid from the CT to the annulus while the BHA is moved uphole or downhole (without inflating the packer); 2) inflation and deflation of the packer; 3) opening and closing of pressure/flow equalization pathways through the packer at appropriate times during the packer inflation and deflation process to prevent the BHA from being pushed uphole via uphole cross-flow, or damaging the packer element from downhole cross-flow; 4) maintenance of the packer pressure (e.g., pressure decrease associated with treatment fluid induced cooling, or pump operation induced pressure cycling); 5) packer over-pressure protection; and 6) initiation of wash flow at the end of a stimulation treatment with the
packer still inflated, or at the discretion of the operator, the initiation of wash after a stimulation treatment with the packer deflated.

A novel solution was devised to effectively and reliably perform the "operations" listed above, in the correct sequence, and at the proper time. The solution is called a Remote Intervention Logic Valve (RILV) and it was designed to make ACT-Frac applications simple and robust by automating and relocating the required operations downhole.

The RILV acts as a pressure actuated downhole "brain". The RILV is configured to reliably and repeatedly perform a logical set of tasks by systematically plumbing numerous single function cartridge valves together and applying a pressure. A cartridge valve is loosely defined as a self-contained valve (typically cylindrical) that can be freely inserted/removed from a chamber. Connecting various chambers together creates a pressure actuated hydraulic circuit and allows the BHA to perform a user defined number of different operations in the right sequence and at the proper time. Reliability of the RILV system is ensured because cartridge valves can be selected from industries that offer the most reliable valves with proven histories of repeatable trouble-free operation (e.g., aerospace valves designed and used for thousands of high pressure, high temperature activations). While the RILV operates solely on fluid pressure (no electric interactions), it is conceptually analogous to a computer circuit. A computer circuit is designed to repeatedly and reliably perform a logical set of tasks by systemically wiring numerous simple single function components (e.g., resistors, capacitors, diodes, etc.) together and applying a voltage. The RILV is essentially a fluid/pressure driven circuit with cartridge valves acting as the simple highly reliable components networked together to perform the pre-programmed set of operations.

An RILV was designed to perform the "operations" discussed. The RILV functions via an increase in coiled tubing pressure prior to performing a stimulation treatment and then a decrease in coiled tubing pressure after the stimulation treatment is complete. The following example illustrates the activation of the BHA for a single ACT-Frac stimulation (Figure 6 shows the surface pressures for the coiled tubing, packer, and annulus during the example treatment).

The CCL readout and CT depth are used to move the lowest gun adjacent to the desired interval, surface personnel fire the gun, the BHA is lowered below the perforations, and the slips are toggled to the set position (washing is performed as desired during these operations without inflating the packer). After the slips are set, the CT pressure is raised to ~7,500 psi and held. Raising the CT pressure to ~7,500 psi initiates the automatic performance of downhole operations as follows. Pressure is applied to the coiled tubing, initiating flow through the wash tool (wash flow cleans the region of wellbore where the packer will be set). At a predetermined rate/pressure (~2 bbl/min / ~1,500 psi) the wash tool closes. Flow begins to enter the packer when the CT pressure passes ~2,500 psi (the packer inflation flow rate is throttled to ensure uniform inflation). The equalization valve closes when the CT pressure passes ~5,000 psi (shutting the downhole flow path through the packer while the uphole path remains open). When the CT pressure reaches ~7,500 psi the packer is inflated to ~5,000 psi, leaving a differential pressure of ~2,500 psi between the CT and the packer.

With the packer inflated, the stimulation treatment is pumped down the annulus (the pressure in the CT prevents CT collapse under the external pressure loading from the stimulation). CT pressure changes within the ~7,500 psi to ~5,000 psi range do not impact the packer pressure. If this differential pressure goes above ~2,500 psi, due to a reduction in pressure in the packer, a valve opens to further inflate the packer and re-establish the differential of ~2,500 psi.

Once the treatment is completed, release of the ACT-Frac tool is initiated by reducing the pressure in the coiled tubing with operations automatically performed as follows. When the coil pressure decreases to ~5,000 psi, valves open to begin deflation of the packer, and the equalization valve opens enabling downhole flow. At this point, the coiled tubing and packer pressure track together (as shown in Figure 6). Once the pressure lowers below ~1,500 psi, the wash tool re-opens with the packer still inflated, allowing for circulation up the annulus (if desired) to clean the wellbore of treatment fluid or debris prior to freeing the assembly. The coiled tubing pressure is then reduced to zero, completely deflating the packer, and the assembly is pulled up-hole to release the slips and move to the next zone. Wash flow is available as desired without inflating the packer.

![Figure 6. Example Pressures During an ACT-Frac Stimulation](image_url)

Although numerous "operations" are taking place during an application, the operator is only required to raise the CT pressure to ~7,500 psi, hold the CT pressure during the stimulation (between ~5,000 and ~7,500 psi), and release the CT pressure after the stimulation is completed. This approach ensures that the ACT-Frac process is simple to apply and provides a robust system suitable for reliable and routine application.

The prototype ACT-Frac tool included the ability to execute all of the "operations" previously described, however, through field trial it has been determined that some of the degrees of functionality can be removed from the system without compromising reliability (for the specific resource in which...
The RILV and all of the supporting

An integrated testing facility was used to support the resolution of the key technical issues. A summary of the testing that supports the resolution of the key technical challenges was addressed through the application of learnings gathered from engineering analysis, laboratory testing, and full-scale integrated testing. A summary of the testing that supports the resolution of the key technical issues is summarized below.

Resolution of several of the challenges listed above were addressed through the development of the RILV, specifically:
1) the reliability of the RILV system is ensured through the use of cartridge valves with a proven history of repeatable trouble-free operation (e.g., leveraging valves from the aerospace industry, oilfield industry, etc.); 2) the RILV automates and relocates the control operations that would need to be performed by personnel on the surface, thus minimizing the risk of human error and maximizing time efficiency; 3) it provides on-site flexibility via adjustments to the cartridge valve settings or valve circuit (e.g., blank-out part of the circuit, change a valve type); and 4) after field trial learnings are captured, the system is easily adjusted to incorporate the learnings, and then deployed as a highly reliable commercial system.

The remainder of the key technical challenges were addressed through the application of learnings gathered from engineering analysis, laboratory testing, and full-scale integrated testing. A summary of the testing that supports the resolution of the key technical issues is summarized below.

Component Testing - The RILV and all of the supporting cartridge valves were experimentally tested to ensure that the system could reliably execute countless cycles at conditions comparable to the expected downhole environment. These tests included individual qualification testing of each cartridge valve as well as testing on the integrated RILV system.

In an effort to appropriately design the ACT-Frac BHA to reliably move uphole in the presence of settled or packed proppant/sand/particulates above the BHA, rigorous full-scale laboratory testing was performed to conservatively determine an appropriate radial gap to ensure that settled and packed (vibrated) sand could fluidize (without wash fluid) and pass by the BHA.

Full-scale testing within an acrylic wellbore model was used to evaluate the performance of various wash tool jet configurations in the presence of settled proppant/sand.

The packer was qualified at temperature for 20+ inflation cycles without failure (internal and differential pressure cycles), and the packer mandrel was tested to verify sufficient resistance to buckling. The testing captured leak-rate data past an inflated packer, if leakage occurred, as well as the deflated diameter profile after numerous sets. Full-scale packer element bladder extrusion testing was performed at temperature to quantify the external pressure limits of a deflated packer element.

Commercial slips were modified (motivated by experimental testing results) and qualified to: 1) set reliably in the presence of various proppant slurries; 2) hold ~100,000 lbs of downhole force, the expected loading on the packer when pumping at high pressures in 5-1/2 inch casing; 3) release at a tension load appreciably lower than the release load of the shear sub; and 4) consistently satisfy these loading requirements over multiple cycles.

Integrated Testing - An integrated testing facility was constructed to qualify the full-scale assembled tool in conditions similar to the downhole environment and model the associated surface operations. The facility setup included numerous pumps (including a triplex pump), fluid delivery through a string of coiled tubing, CT fluid control using automated drilling chokes, hot oil jackets surrounding a 5-1/2 inch casing string for temperature control, capability to deliver sand into the system (settled onto BHA), capability to flow uphole or downhole past the BHA with the packer inflated or deflated (modeling cross-flow), ability to move the BHA uphole or downhole and pull at loads comparable to the capacity of CT injectors used in the field, and extensive instrumentation dedicated to capturing data from all aspects of the system. The integrated testing facility was used to implement an aggressive battery of qualification tests and refine the equipment and operations prior to deploying the technology in the field.

Field Experience

JITP has been used and refined over the past six years in tight gas basins in the Western U. S. To date, over 600 proppant fracture treatments have been successfully pumped in over 25 vertical and S-turn wells having 4-1/2-inch or 5-1/2-inch production casing. Zones have been stimulated at depths of 14,400 ft MD, formation temperatures up to 320ºF, and maximum surface treating pressures up to 9,500 psi. Up to 14 treatments have been pumped in a single day, and as many as 48 zones have been stimulated in a 4-day period. The JITP process has also been successfully used for acid fracturing.

ACT-Frac is at an earlier stage in the development/commercialization curve than JITP. The technical viability of ACT-Frac has been demonstrated, with 20 proppant fracture treatments pumped in 4 vertical and S-turn wells having 5-1/2-inch production casing. Zones have been stimulated at depths of 11,400 ft MD, formation temperatures up to 280º F, and surface treating pressures up to 7,500 psi. Up to six zones have been treated during a single deployment of the tool (7 guns deployed). A number of learnings were identified during these initial field demonstrations and adjustments to the
equipment and operations are now incorporated into the technology.

Current Status
The JITP process has recently been optimized by allowing for the setting of bridge/frac plugs on the same gun assembly used for perforating the zones during the stimulation treatments. This provides a significant time savings in the operations by eliminating the need for a separate wireline deployment to set the plug. This optimized JITP gun assembly has been successfully used in the recent field work and is expected to be the preferred configuration for all future operations.

A version of the ACT-Frac BHA has recently been developed that includes real-time downhole measurement capabilities. This tool provides measurement of: 1) the pressure above the packer; 2) the pressure below the packer; 3) the pressure inside of the packer; 4) the downhole pressure in the coiled tubing; and 5) the temperature. These diagnostic capabilities are expected to provide valuable insight into the local environment before, during, and after an ACT-Frac treatment, as well as vital information for prediction of fracture placement. More specifically, the acquisition of real-time flowing bottom-hole pressure can be input into a real-time fracture modeling software package thus permitting real-time visualization of fracture growth/placement while a treatment is being pumped. This capability enables value-added real-time treatment adjustments while a frac is being placed. This new ACT-Frac BHA has been successfully qualified in a test well. In addition, ACT-Frac is currently being adapted for use in other multi-zone stimulation applications, including corrosive environments (e.g., acid stimulation, H$_2$S).

ExxonMobil has licensed ACT-Frac and JITP to service providers and is in the process of transferring ACT-Frac and JITP technology to its licensees for the purpose of expediting commercialization.

Conclusions
JITP and ACT-Frac have enabled the development of tight gas resources that previously could not be developed economically. These technologies are expected to become the methods-of-choice for numerous applications worldwide due to their ability to: 1) rapidly place numerous stimulation treatments that are tailored to the specific needs of each zone; 2) pump each treatment efficiently and effectively; and 3) provide positive isolation between zones. With their continued enhancement and demonstration in various environments, JITP and ACT-Frac will be valuable assets for ExxonMobil and its operating partners.

References