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# Optimization of a Digitally Controlled Rotary Steerable System for US Shale Drilling

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## Abstract

Developing a rotary steerable system (RSS) from concept through initial prototype design, in-house testing, field test validation and commercialization poses significant engineering challenges. The most successful RSS on the market today has been pioneered and scaled by major service companies for industry wide use.

Research, development and commercialization of an RSS product requires skill sets from engineering disciplines such as mechanical, electrical, software, embedded-systems software (firmware), and drilling engineering.

This paper focuses on the optimization of a digitally controlled RSS for commercial deployment in today's US shale drilling applications.

## Introduction

As we unlock US energy potential in both the oil and gas industry, and through recent geothermal exploration, drilling challenges have significantly increased. Deeper wells, extended-reach horizontal sections, and drilling in undeveloped areas has pushed the envelope in drilling technology.

Rotary steerable technology has proven to be essential in overcoming directional drilling challenges. The proportion of wells drilled on US land using RSS, as opposed to conventional technologies, continues to increase annually.

With this growing demand from energy producers and limited RSS players on the market today, there is space for a lower-cost rotary steerable system. To be successful, this system must be field tested across all major US basins to prove predictable steering and high reliability statistics.

Every product has a set of limitations that are contained within the specification. Field testing prototype and pilot tools to identify limiters, implementing engineering changes and validating through further field testing is required for successful tool development. This will ensure the product has sufficient lifecycle in the design before further upgrades are required to keep up with drilling progression.

By implementing this approach, the 9.625-in. RSS is now in its third series of upgrades to meet today's drilling requirements. A structured field-test plan was used across harsh drilling basins in US land to identify the tool's limitations. This paper discusses that approach, the solutions implemented, and the tool's progression to its current version (Series 3).

## RSS Fundamentals

Most RSS utilized in US land today are mud-operated push-the-bit fully rotational systems (Barr et al. 1995; Downton and Carrington 2003). The RSS described in this paper is a change from that convention (Jones et al. 2018).

Its basic principles are listed below. **Fig. 1** shows the main components of the 9-5/8 in. RSS (Series 3) for 12.25-in. and 13.5-in hole sections. The system has full steering control while rotating the drillstring for vertical and directional applications.

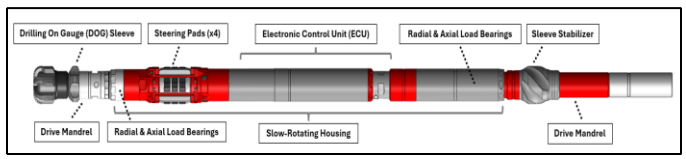



**Fig. 1 - RSS Major Components.**

To maintain lower operational costs, the RSS electronic control unit (ECU) is scalable down to 6-3/4-in. hole size.

- Push-the-Bit
- Mud operated
- Mud lubricated bearings
- Self-contained ECU (decoupled)
- Slow-rotating steering housing

## RSS Construction Advantages – Fully Rotating versus Slow Rotating Steering

The advantages of a fully rotating RSS and an RSS with a slow rotating steering housing are relative to the drilling environment and dynamic conditions (Jones and Sugiura 2023). As shale well construction continues to run at a faster pace with lower costs, drilling dynamics become an element that must be engineered around to manage component reliability and operating cost (Jones et al. 2023). In North America shale drilling, the majority of RSS have a fully rotating steering housing and either a strap-down or roll-stabilized control unit.

With fully rotating RSS, the steering pads and control units (e.g. strap-down) experience the same drilling dynamics that are present at the drill bit and trapped below the positive displacement motor (PDM). This direct mechanical coupling subjects RSS components to high-magnitude and high-frequency torsional dynamics, resulting in higher operating costs because of reduced life and premature damage.

The advantage of an RSS with a slow rotating steering housing is that the steering pads and ECU become decoupled from drill bit/BHA dynamics, such as high-frequency torsional oscillation (HFTO), stick-slip and torsional dynamics (Jones et al. 2023). This differentiator allows for an RSS with lower operating cost since the expensive components (steering housing and ECU) do not get subjected to these harmful drilling dynamics.

The RSS described in this paper is the only mud operated system with a slow rotating steering housing and control unit on the market today. This construction design is to reduce operating costs for shale drilling applications compared to fully rotating mud-operated RSS.

## Field Testing

Most RSS development programs incorporate the use of research and development (R&D) test rigs/wells for downhole system validation. Although this approach can provide basic operational insights, the ability to replicate the complex drilling environments experienced in commercial applications is limited.

R&D drilling test facilities come with a considerable cost. This increases the cost of bringing the product to the market and is reflected in its final pricing. The RSS described in this paper has only been tested on commercially drilled oil and gas wells by forming operator partnership agreements.

Specific basins were targeted in the field-test stages to subject the tool to harsh drilling. For example, the Texas Delaware basin presents some of the most challenging shock and vibration conditions on US land. Here the tool was subjected to severe HFTO and whirl. In addition, drilling fluid quality was often inconsistent due to open pit systems. The abrasive nature of rock in the Green River Basin revealed a rate of wear not seen anywhere in the Permian Basin. Fast penetration rates in East Texas drilling combined with sticky clays and hole problems exposed the tool to high concentrations of lost circulation material (LCM). These are just a few examples. **Fig. 2** provides a full list of areas where the RSS has been tested to date.

**Texas / New Mexico**
- Permian (Delaware)
- Permian (Midland)
- TX-LA-MS Salt (Haynesville)
- Western Gulf (Eagle Ford)
- Palo Duro

**Oklahoma**
- Anadarko
- Ardmore

**Pennsylvania**
- Appalachian

**Wyoming**
- Greater Green River

**Fig. 2 – RSS Operator Partnership Test Locations.**

## Drilling Dynamics Recorder Placement and Data Utilization

From the beginning of the field test campaign, the focus has been on the need for downhole measurements to drive improvements. All RSS have been outfitted with drilling dynamics recorders in the bit box and slow rotating housing. **Fig. 3** shows the sensor placement (Jones et al. 2023). Drilling dynamics sensor form factors and specifications are detailed in **Fig. 4** (Sugiura and Jones 2019).

Data has confirmed that there is a huge contrast between shock levels measured at the bit box and the slow-rotating housing (Sugiura and Jones 2020). Since the steering housing and ECU are decoupled from the drive mandrel, HFTO only travels through the mandrel and does not damage sensitive electronics in the ECU.

Correlating HFTO with RSS mandrel life has been essential in optimizing material selection and correcting mandrel design features. In severe HFTO environments, a torsional isolation tool below the motor has been utilized.

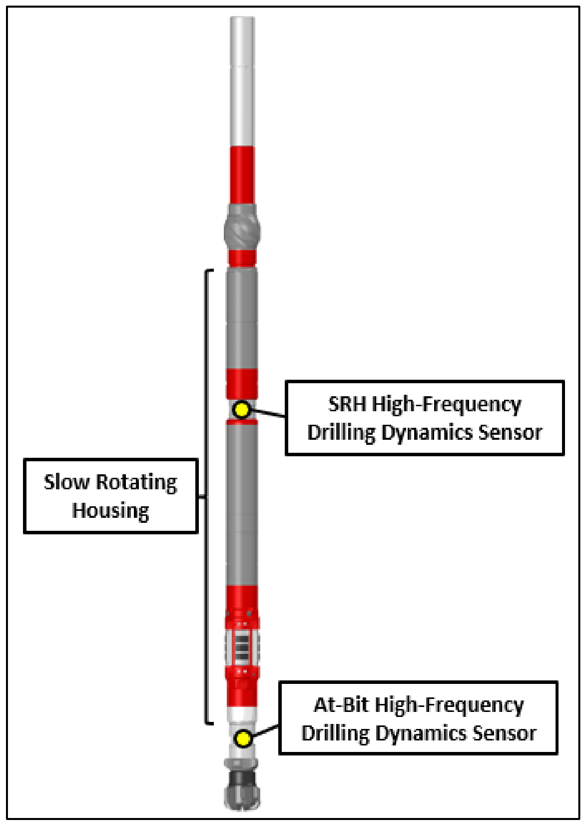
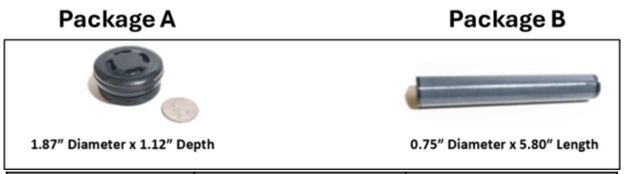



**Fig. 3 – Drilling Dynamics Sensor Placement in RSS.**




| Description | Package A | Package B |
|---|---|---|
| Placement | RSS Bit Box | Slow-Rotating Housing |
| Logging Trigger | RPM or RPM Delay | RPM or RPM Delay |
| 3-Axis Shock | -200G to +200G (+/- 100mG) | -200G to +200G (+/- 100mG) |
| Shock Sampling Rate | 800Hz-1600Hz | 800Hz-1600Hz |
| Shock Record | Continuous | Continuous |
| Gyro RPM | +/- 1000 RPM | +/- 1000 RPM |
| Gyro Sampling Rate | 100 Hz | 100 Hz (1000 Hz for Centerline) |
| Gyro Record | Continuous | Continuous |
| Temperature | 150°C (302°F) 175°C (350°F) Option | 150°C (302°F) 175°C (350°F) Option |
| Pressure Rating | 15,000 psi | 15,000 psi |
| Record Life | 150 hours at 800 Hz 100 hours at 1600 Hz | 150 hours at 800 Hz 100 hours at 1600 Hz |

**Fig. 4 – Drilling Dynamics Sensor Structure and Specifications.**

## Pressure Recorder Placement and Data Utilization

Embedded pressure recorders were developed and implemented to understand the hydraulic response of the RSS. Various pressure sensor form-factors were utilized dependent on the placement within the tool. **Fig. 5** details the current pressure sensor specifications. Previously, this pressure recorder was used in a steerable mud motor to detect the pressure fluctuations caused by mud pulse telemetry sequences (Sugiura and Jones 2021).

| Description | Specifications |
|---|---|
| Logging Trigger | Pressure @ 400 PSI ON / 200 PSI OFF |
| Pressure | 0 to 15,000 PSI |
| Accuracy | +/- 100 PSI |
| Resolution | +/- 20 PSI |
| Pressure Sample Rate | 200 Hz |
| Pressure Record | Continuous |
| Temperature | 150°C (302°F) |
| Pressure Rating | 15,000 psi |
| Record Life | 120 Hours |

**Fig. 5 – Pressure Sensor Specifications.**

Downhole recorded pressure data provided a comprehensive understanding of fluid hydraulics within the tool. Detailed pressure analysis after every run allowed for clear identification of areas creating flow inefficiencies. Pressure recorded at each steering pad aided in the creating and validation of a hydraulics calculator. This calculator considers actual fluid reaching the steering pads and drill bit after bypass through mud lubricated bearings on drilling motor and RSS. Typically, off-the-shelf software does not account for these losses.

By gathering downhole pressure data from field tests, correlations could be made to bearing wear rates. Now initial bearing clearances and predicted degradation rates are incorporated into the pre-planning models. This procedure ensures that a sufficient pressure drop (pad force) will be maintained from the beginning to the total section depth.

From a failure-analysis perspective, pad pressure data is valuable in diagnosing steering issues. It allows for verification of correct or incorrect pad actuation. Also, correlating pad pressures with high viscosity and LCM sweeps showed the effect that various types and concentrations had on tool functionality.

**Fig. 6** is an example of the pressure logs for each of the steering pads. This data is continuously sampled at 200-Hz downhole and averaged over 1 second to be merged with Electronic Drilling Recorder (EDR) data. The steering pads on the tool serve two primary functions: (1) providing push force on the bit to create an offset from wellbore center (steer force) and (2) controlling the roll rate of the steering housing (grip force). As the housing slowly rotates within the wellbore, pad activation will alternate between two pads steering with two gripping, and one steering with three gripping. This is dictated by pad position relative to target tool face direction.

In Fig. 6, the shift from pad steer force to grip force is labeled. Target toolface and housing rotation rate are not shown.

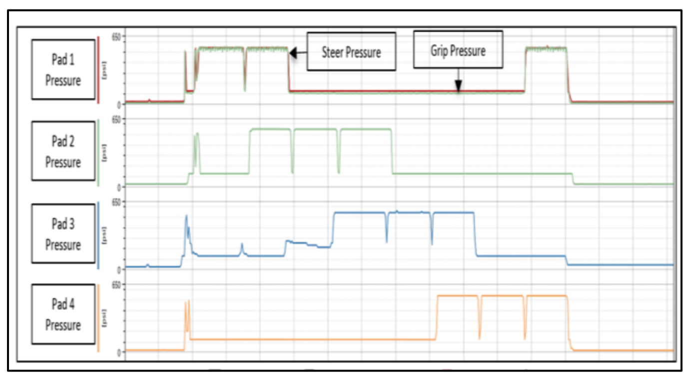



**Fig. 6 – Downhole pad pressure recorder logs showing change from steer pressure to grip pressure.**

Pad forces can be calculated from the measured downhole pressure. Knowing the continuous pressure at each pad (force exerted), along with housing position relative to the high side of the wellbore, enables an accurate real-time tool face calculation. This is particularly useful when correlated with measurement-while-drilling (MWD) survey data to assess directional performance and more accurately understand the RSS maximum build rate capabilities.

In the event of a directional control issue, this data becomes key in pinpointing if an incorrect toolface is the root cause. **Fig.**

**7** shows the derived tool face using pressure measurements compared to the tools programmed toolface. This example shows data from drilling seven stands with the tool in closed-loop control, alternating between inclination hold, and inclination hold with a manual turn. In hold inclination mode, the toolface is targeted as 0° (highside) because inclination is slightly below target. With the manual turn element added, the toolface is autonomously adjusting to maintain inclination while yielding the desired turn percentage dictated by the operator.

The bottom track shows the block height (black trace). The second track from the bottom is the tool mode (grey trace), which is controlled through surface RPM downlinks sent from the operator. The middle track overlays the actual toolface (red trace) and programmed toolface (green trace). The programmed toolface, defined by the RSS control system, directs the digital mud valve movement. The actual toolface is the resultant vector derived from steering pad-pressure measurements and position.

The final two tracks are the interpolated survey inclination (orange trace) and azimuth (blue trace). This example shows a functional RSS. Automatic toolface adjustments are being updated regularly as seen by the fluctuations in the red trace. The digital mud valves response is to adjust its orientation to increase fluid flow to the correct steering pads. The programmed and actual toolface traces exhibit very close alignment which validates correct valve response and steering pad functionality. This is reflective in the steady inclination and azimuth through this interval.

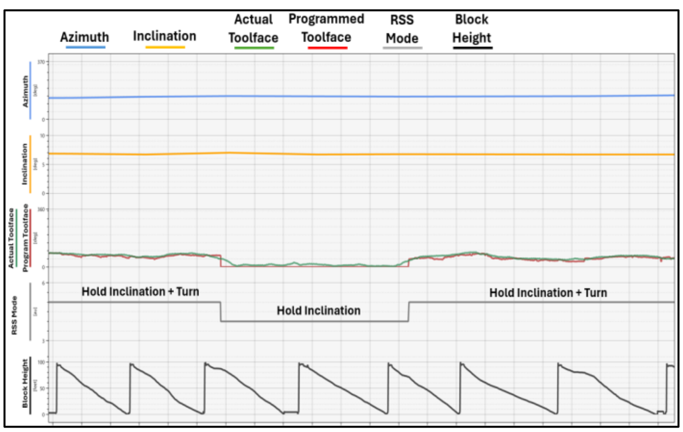



**Fig. 7 – Actual toolface derived from pad pressure measurements overlayed with target toolface.**

**Fig. 8** shows the additional option for pressure sensor placement on the RSS. A mid-body sensor has been run to continuously measure wellbore annulus pressure. Equivalent Circulating Density (ECD) and Equivalent Static Density (ESD) can be computed from sensor readings. This is an effective way to attain near-bit pressure data for use in validating ECD models without the additional cost of pressure-while-drilling (PWD) equipment.

From an RSS design perspective, the annular pressure sensor provided an understanding of fluid flow around the RSS steering housing and stabilizer. Field tests were conducted with the mid-body pressure sensor in the RSS and a secondary pressure sensor in the mud motor top sub. These tests were carried out to assess the effectiveness of fluid bypass around the upper sleeve stabilizer on the RSS. It was concluded that pressure drop across this component was minimal and that ECD measured at both locations aligned with expectations.

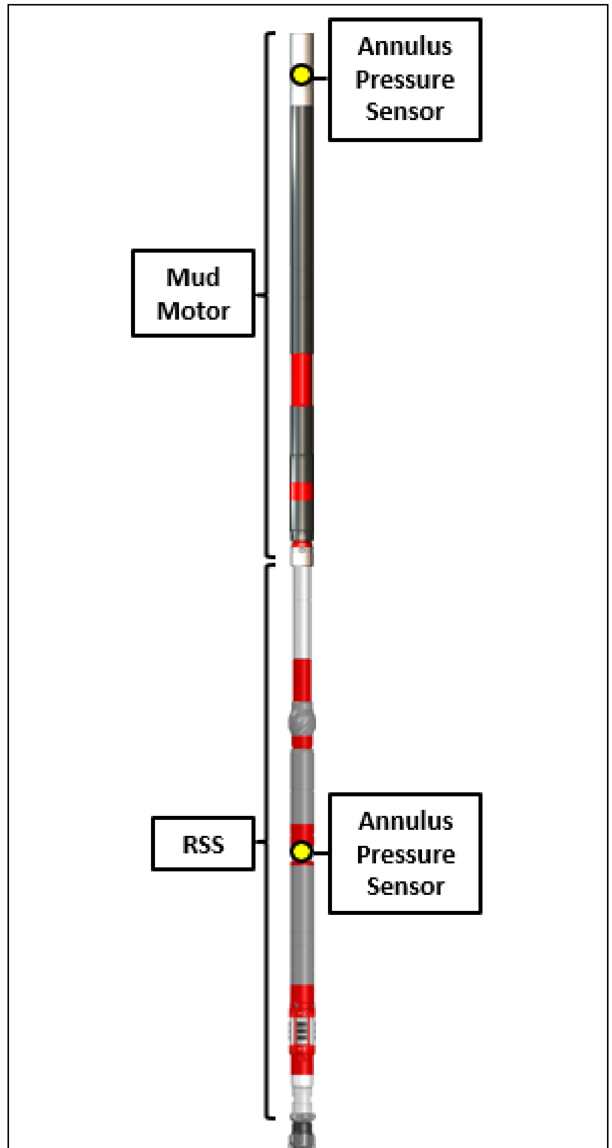



**Fig. 8 – RSS and mud motor annulus pressure sensor placement.**

## Previous Version Limitations

Over the duration of field tests, it was discovered that the RSS had LCM and high-viscosity fluid limitations (like other RSS and MWD systems). The RSS operated effectively in most environments but proved to have some limitations with high LCM concentrations common to US land shale drilling.

To effectively operate in all basins and all sections of the well, it was decided that these limitations needed to be corrected.

**Fig. 9** is an example of how pressure sensors can detect when a high-concentration LCM sweep passes through the RSS.

Item 1 – 24 BBL high LCM sweep leaving the slug tank (gold trace). This sweep consisted of Gel, Cal-Carb, and Lignin Cellulose Fiber (LCF) Blend.

Item 2 - Pressure spikes seen at all steering pads when the sweep passes the tool (shown in black dotted box).

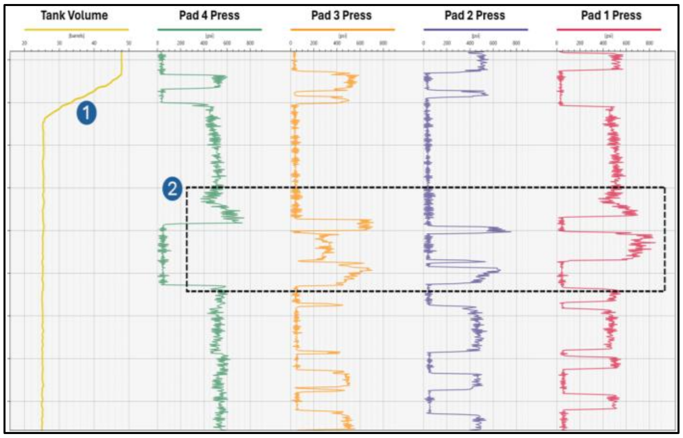



**Fig. 9 – Brief increase in pad pressure observed at the steering pads as the LCM sweep passes through the RSS tool.**

### *Flow Loop Testing*

To better understand the impacts that LCM was having on the tool, an in-house flow test program was started. The goal was to replicate what was being seen downhole when high concentrations of LCM were pumped. The test program initially involved testing on the current tool design that was in the field test (Series 2). Findings indicated that an upgrade to the steering housing (Series 3) was required; this is explained later in the paper. The same testing was then carried out on the new housing to validate the improvements prior to any downhole field trials. **Fig. 10** shows the RSS in the flow tester. The cage is secured around the steering housing and contains load cells that measure the force applied by each steering pad. Pressure transducers are connected into the flow channels feeding the steering pads. These force and pressure measurements can be viewed in real time.

**Fig. 10 – RSS in flow tester with force and pressure test cage around the steering housing. Measuring real-time pad force and pad pressure during in-house LCM threshold testing.**

**Fig. 11** Provides an overview of the RSS Series 2 major components and details the fluid flow path through the steering housing. The blue arrows show the fluid path.

**Manifold** – Contains four steer inlet ports and four grip ports. These ports are the fluid entry points connected to fluid channels going to each individual steering pad. The steer and grip ports are in the same location but differ in size.

**Ring Valve** – Spring loaded to create a mechanical seal against the manifold. The valve is connected and driven by the ECU. It rotates to align open slots (blue circle) with ports on the manifold, opening fluid flow to pad pistons. The housing orientation dictates whether the steering pad receives full steering flow or grip flow.

**Pad Pistons** - Each steering pad is driven by two pistons. The pistons convert pressure to a pad force that can be applied to the wellbore.

**Exhaust Ports** – One piston under each steering pad contains an exhaust nozzle. When the valve position shifts, and the pad no longer needs to apply force, fluid is not trapped and can discharge through the exhaust port to wellbore annulus.

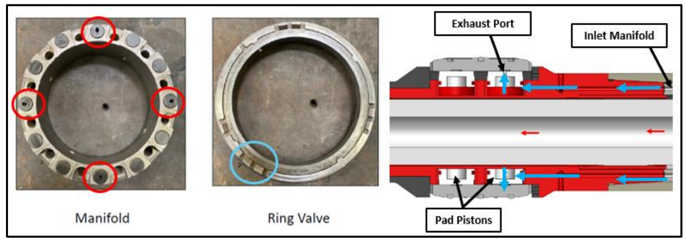



**Fig. 11 – Series 2 RSS steering valve, inlet manifold, fluid exhaust ports and fluid path.**

Multiple tests were conducted by adjusting flow area variables. For clarity in this paper, a simplified overview of the test procedures is explained below.

9.0 ppg mud with a funnel viscosity (FV) ranging from 40-110 sec/qt was circulated through the tool to establish baseline pressure and pad force values.

LCM mixtures containing Cedar Fiber, LCF Blend, and Medium Nut Plug were added to the fluid system. The testing required many steps, for example Step #1, 5 ppb LCM, at a FV of 40 sec/qt. Concentration started low and gradually increased, alongside staged adjustments to viscosity.

Through the process pressure and pad force were monitored in real time to detect any anomalies. When an anomaly was observed, it was identified as the upper threshold. At this point, the tool was disassembled and closely examined to identify areas of LCM accumulation or blockages.

Based on the findings, modifications were made to components, and the tests were repeated to establish new upper operating limits. The objective was to get the system to a point where it could withstand LCM concentrations that would be expected in shale drilling environments.

### *Flow Loop Test Conclusion*

Findings from these tests were the driver behind the RSS steering housing upgrades (Series 3).

The hydraulic limiters experienced with the Series 2 design revolved around the quality of the drilling fluid and LCM handling capabilities. These limiters were clearly recognized utilizing downhole pad pressure sensors and in-house fluid viscosity/LCM testing.

## Series 2 versus Series 3

The Series 3 design has overcome the hydraulic limiters by increasing the size of the fluid ports through the manifold, steering housing, and exhaust ports. The key hydraulic related changes and their associated benefits are listed below.

**Increased steering housing flow channel TFA (+78%).**

- Greater flow capacity to steering pads.
- Improved pressure stability with high-viscosity fluids (reduced pressure losses).
- Enhanced mobility of solids and LCM materials.

**Increased fluid exhaust TFA (+230%)**

- Ability to bypass larger quantities of LCM.

**Fluid exhausting through tool body vs through pistons.**

- Streamlined fluid exit path minimizes risk of debris build up.
- Ability to increase exhaust port diameter to accommodate high-concentration LCM environments.

**Increased manifold inlet port TFA (+150%).**

- Less susceptible to blockages.
- Allows increased fluid flow into the steering housing resulting in higher fluid velocity (but not excessive to minimize wash erosion).
- Enhances solids carrying capacity.

Additionally, the steering pads were moved to the same plane. This design provided space for an additional piston behind the pads. Further advantages of the upgrades are listed below.

- More balanced side force exerted on the bit.
- Direct flow path to steering pad pistons and fluid exhaust ports eliminating areas for potential debris accumulation.
- Improved flow efficiency by reducing pressure losses.

A balance between control pad flow rate and wash characteristics/rate is important to keep RSS operating costs low. To maintain the internal flow rate at an acceptable level to limit wash, combined with optimal pad force for predictable steering are the main upgrades to the RSS design.

The steering pad force has been increased by 50% utilizing increased total pad piston area (additional piston). This design upgrade provides a larger flow operating window for higher steer force and controlled housing-roll at high ROP.

**Fig. 12** shows Series 2 vs Series 3 steering housings with steering pads, clearly showing the difference of having the pads on the same plane.

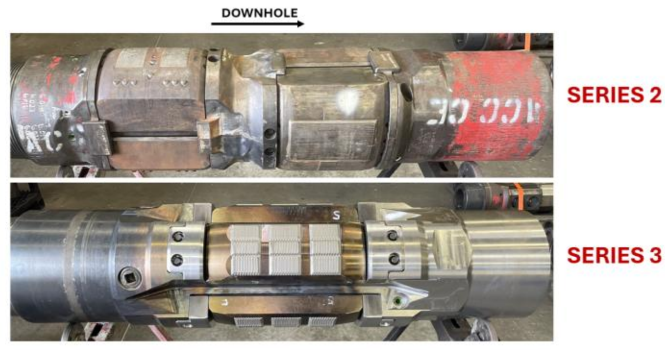



**Fig. 12 – Series 2 steering housing vs upgraded Series 3 steering housing.**

## Conclusions

The new Series 3 RSS constuction has been engineered by utilizing many years of field test data that was gathered in harsh North America drilling basins. This data has been critical in the design upgrades by understanding today's operating environment, particulary drilling dynamics, drilling fluid quality and LCM. The upgrades deliver an operating window that will carry the product well into the future.

Delivering a lower-cost RSS to the North America shale market is a balance between three fundamental requirements, namely reliability, steerability and operating cost. Bringing these requirements together takes time during the field test stage. The journey from prototype to pilot to commercial product is an important journey in the development of an RSS. This is especially true when refining a product to compete against the major oilfield service companies.

Ultimately, a lower-cost solution for drilling fast and safe shale wells in North America land takes time. The overall cost associated with the development phase dictates the operating rate when the product reaches commercial state.

## Acknowledgments

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## Nomenclature

*BBL* = *Barrel*
*BHA* = *Bottomhole Assembly*
*DLS* = *Dogleg Severity*
*ECD* = *Equivalent Circulating Density*
*ESD* = *Equivalent Static Density*
*ECU* = *Electronic Control Unit*
*EDR* = *Electronic Drilling Recorder*
*FV* = *Funnel Viscosity*
*HFTO* = *High-Frequency Torsional Oscillation*
*LCM* = *Lost Circulation Material*
*MWD* = *Measurement While Drilling*
*OD* = *Outside Diameter*
*PDM* = *Positive Displacement Motor*

*PPG = Pound Per Gallon*
*ROP = Rate of Penetration*
*R&D = Research and Development*
*RPM = Revolutions per Minute*
*RSS = Rotary Steerable System*
*TFA = Total Flow Area*
*WOB = Weight on Bit*

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