CASE STUDIES IN IMPROVED PUMP CAGE PERFORMANCE USING AN IMPACT RESISTANT MATERIAL

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Abstract:

Rod pumps consist of several key components: at a minimum, a barrel & plunger that create linear fluid displacement, and valves that direct fluid flow in one direction. These valves contain three fundamental components: a ball (the operative element), a seat (creating a functional seal with the ball), and a cage assembly (constraining the ball when the valve is open). While traditional cage assemblies use steel throughout, the cage can be machined as a separate part and inserted in the valve body. This allows for alternative materials and geometries. The Impact Resistant Cage (IR Cage) addresses key operational challenges of temperature extremes, fluid compatibility, and most significantly cyclic impact damage through an innovative thermoplastic element design.

Introduction

Traditional steel cage assemblies in rod pump valves, despite their durability, suffer from cumulative deformation through repeated ball impacts – a phenomenon known as "beat-out". This mechanical degradation may be compounded by flow restrictions impeding fluid displacement, accelerating corrosion and erosion, or by increased ball travel which may negatively affect the ball and seat. With typical rod pumps experiencing several million valve cycles annually, these combined factors substantially reduce equipment lifespan and increase operational costs. While a valve cage is a non-sealing component, its failure can cause a complete operational breakdown requiring the pump to be pulled. The valve cage is a mostly inert component, and as such, should not be the source of a pump failure. Unfortunately valve cages are all too often the direct, or indirect source of a pump failure. The Impact Resistant cage addresses these challenges with a non-metallic liner that absorbs repeated ball impacts, significantly extending component lifespan.

Valve Failures as Part of Downhole Pump Failure

Rod pumps are generally reliable, but certain well conditions and operational practices can lead to failures in standard components. There are a multitude of pump components and configurations to deal with the various challenges. There is no one-size-fits-all pump, although there is a tradeoff with parts availability, cost, and complexity. Ideally each component of the pump would be selected based on a comprehensive analysis of the specific well conditions. In practice however, pump components are often selected based on factors not related to longevity or applicability to well conditions. This can result in failed components. What works in one well rarely works in all wells. This paper discusses a specific solution that does apply to a wide range of wells and resolves a significant source of failure, namely failures related to valve cages (either direct or indirect failures).

Valve failure typically involves either ball and seat issues or cage damage. Corrosion or erosion may also affect the valve body itself. In some situations, a cage failure can cause damage to other pump components, such as chipping of stellite lining from the standing valve cage, which may score the plunger/barrel. Additionally, cage deformation due to “beat out” might restrict flow by encroaching on fluid passages. Excessive ball travel can also harm the ball and/or seat due to the kinetic energy of the fluid column forcing the ball onto the seat. The Impact Resistant Cage (IR Cage) is designed to address these problems through a material that is resilient and resistant to corrosion, and through an improved geometry.

Traditional Valve Assemblies

Rod pumps consist of a traveling valve (TV), located on the plunger, and a standing valve (SV) located at the bottom of the barrel. Double valves are sometimes used to improve reliability and longevity. In general, pump valves utilize a ball and a matched seat to create a positive seal. The ball & seat are enclosed in a housing that holds the seat firm and allows the ball to move freely within a small region.

The cage is a critical component that serves two fundamental functions:

1) To constrain the movement of the ball in the open position, preventing it from escaping the valve assembly.
2) To provide a path for the fluid to flow around the ball and up through the valve assembly when the valve is open.

Unlike the operative ball and seat, which form a metal-to-metal seal, the cage is a non-sealing component. The cage only performs its function when the valve is open. When the valve is closed, the ball rests on the seat and is held firmly in place by fluid pressure, with no interaction with the cage. Without a properly functioning cage to hold the ball in the open position while allowing fluid flow, the pump would not effectively operate.

In some cases, such as the traditional API style, the cage is an integral part of the valve body. Many modern designs such as the IR Cage, use a separately machined cage which is inserted into the valve body. This allows advanced materials and geometries that would be difficult, expensive, or impossible to manufacture as a single component. In short, the cage can be constructed from a wide range of materials and manufacturing processes.

Traditional Valve Cage – Standard Design

Traditional cages employ a one-piece body design, typically constructed from alloy steel materials. As designated by API, the ball and seat are loaded from the bottom. A seat plug, or a double valve cage, is subsequently affixed via a threaded connection to secure the seat against the internal shoulder of the cage body. The internal geometry of the cage and the valve seat together create an axially-constrained space in which the ball can move while fluid flows around the ball, or through the bypass. The internal geometry of the cage typically features diametrically-patterned ball guides (usually 3 or 4), which further constrain the ball movement radially (or side-to-side). The top of the ball guides includes inward-forming tabs where the unseated ball comes to a stop. Additionally, the cage incorporates receded regions between the ball guides, known as "bypasses," which allow fluid to flow around the ball and upward.

The API-style cage is "closed" meaning the region directly above the ball is solid, with passages drilled for fluid flow. The IR Cage is an open design which improves flow above the ball. An open design can be seen in Figure 1 below.

Figure 1 – A full open, metal cage is shown above. The IR cage utilizes a similar geometry to improve flow, compared to a standard API style cage.

<u>Issues Stemming from Downhole Cage's Design</u>

The valve's opening and closing actions impose great physical stress on the cage body. One well-known effect is commonly referred to as ball "beat-out". During pumping cycles, the ball "seats" and "unseats" in violent fashion as the differential pressure across it abruptly changes. The impact of an accelerated ball against the valve seat & cage's body leads to small deformation on their surfaces that accumulate. These small deformations and cracks, accumulated over millions of pumping cycles, can result in surface stress crack and subsequent failure. The cycle time factor is significant; consider a 5 stroke-per-minute well produces 7,200 cycles per day, or roughly 2.6 million cycles per year. This is 7,200 initial cage impacts plus an additional 7,200 seating impacts. The ball sees both of those. Generally, the ball seats once per cycle, but certain dynamics can result in multiple seatings (ball-on-seat) per cycle.

Mechanical impacts on the cage can be considerably more complex. Within the cage, the ball is free to move, and so fluid flow may cause the ball to “rattle” against the cage. How significant this “rattle” is, depends on ball density, fluid flow, and fluid properties. A ball “rattling” in the cage (or bouncing around in the open, or partially open, position due to fluid flow dynamics) creates many small impacts. Even though these impacts are tiny in comparison, they are cumulative when applied to non-resilient material. In other words, millions of tiny taps can permanently deform steel. Deformation of the cage through these impacts can restrict flow, cause chipping/fragmentation resulting in damage to other components, or increase ball travel.

Ball travel is another factor in valve performance and longevity. From a flow perspective, it is desirable to maximize ball travel. This is in direct opposition to the fact that further the ball travels, the more kinetic energy it gains. This kinetic energy is then transferred alternately to the seat and cage, which can result in failure (of the ball, seat, and/or cage. See Case Studies). In order to minimize stress on the ball, the travel should be kept at a minimum, while not compromising flow.

Current industry-standard adoption of Hardlined Cages

Common industry practice to combat beat-out mainly involves metallurgy. Valve cages that utilize Stellite linings on the ball guides came to be the preferred option in most rod pump builds. Stellite is a Cobalt-based alloy with great resistance to corrosion, physical wear, and impact. “Hardlined” or “Stellite-lined” cages typically feature layers of Stellite welded onto the based alloy material (on the ball guides area), which are then re-machined to achieve the desired ball guides’ clearance.

Problems with Existing Hardlined Cages

Stellite-lined cages have shown mixed field performance. The hardness of Stellite makes it brittle and prone to fracture from repeated impacts, causing shards of extremely hard material to break off and lodge between the plunger and barrel, leading to failures. Additionally, bare-metal bypasses are vulnerable to fluid erosion/corrosion, requiring cage replacements. Design variations by manufacturers also affect ball clearance and travel, with key parameters like layer thickness, weld quality, and machining impacting cage performance. Poor quality in these areas can cause weld adhesion issues, rough finishes, and jagged transitions on Stellite layers.

Figure 2 – The cages show above are severely beat-out. The chipping of the lining and undermining of the softer base material can be clearly seen around the edges of the lining face.

Figure 3 – Corrosion is another factor in metal cages, particuarly hardlined cages. In the photo on the left, the base material corroded to the point where the lining completely separated from the body. These pieces of hardened material likely caused damage elsewhere in the pumping system. The photo on the right shows severe corrosion, but the hardened tabs are still present. The area around the ball has also corroded allowing the ball excessive lateral movement, which can indirectly result in ball and seat damage.

Figure 4 – Ball and seat issues are not always attributed to cages. The ball impacts both the seat and the cage and so it sees twice as many impacts (if not more due to ball rattling around in the cage and chattering, or reseating multiple times through the stroke). The significant stress a ball sees can result in catastrophic failure, as seen above. The IR Cage lessens the impact and can extend the service life of a ball.

Development of IR Cage

This industry has a tendency toward bigger and stronger solutions. “A bigger pipe wrench” is almost always the solution. This is the case with hard-lined cages. The soft metal was too easily deformed and so the logical solution was to reinforce that through harder, stronger material. In some wells, that is an appropriate solution, but it does not apply across the range of operating conditions. The approach of the IR cage was the opposite. Instead of a harder, tougher material, the issue was assessed and determined that a more resilient material was a preferable solution. A material that absorbs the kinetic energy of the ball, without permanent deformation is optimal. Recall from above that the cage serves to keep the ball constrained and allow for fluid flow. This is a different set of requirements relative to many other components in the system. Thermoplastic is the material selected for the cage liner (the cage body remains steel).

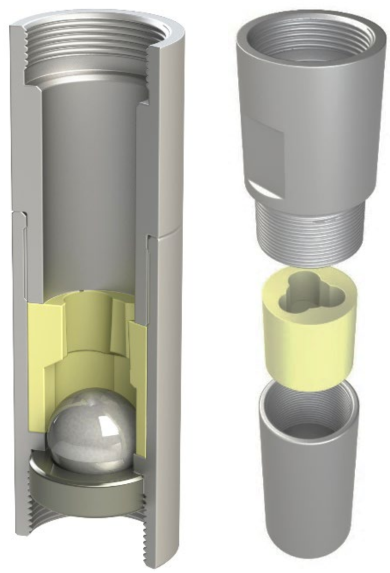

Figure 5 – The IR cage assembly is shown. The IR Cage refers to the entire assembly, but the main component is the thermoplastic liner shown in yellow. This liner is inserted in the valve body and assembled as illustrated. Of note, the fluid path around the ball is surrounded by thermoplastic. This serves to reduce corrosion/erosion within the valve body by isolating the high velocity fluid (bypassing the ball) from the steel valve body.

Existing Thermoplastic Applications in Oil & Gas

The most notable use of thermoplastics in a rod pump well is rod guides and lined tubing. Rod guides are distinctive in that they encounter significant side-load against the tubing and wear as they move through the tubing. Rod guides are deployed in a wide range of wells and temperatures with a great deal of success. Their primary issue, assuming the appropriate chemical composition is selected, is wear. The pump valve cage does not experience any mechanical or fiction wear. The force experienced by the cage is the momentary impact from the ball, but apart from that, the ball does not exert a significant continuous force on the cage, nor does it rub or scrape the cage. Fluid erosion & corrosion are factors that affect steel, but pose much less concern in thermoplastic.

Another notable application of thermoplastics in rod pumped wells is lined tubing. Thermoplastic lined tubing addresses a similar fundamental problem to that of rod guides, namely rod-on-tubing wear. Lined tubing is also deployed to address chemical and corrosion issues by isolating the fluid from the metal tubing wall. The use of thermoplastics can also address certain fluid erosion conditions. This is notable as it demonstrates a high degree of chemical compatibility with produced fluid.

Selecting the appropriate thermoplastic can be extremely successful in lined tubing application, particularly in corrosive environments. The nature of a pump valve creates a restriction in the flow of fluid. The according pressure drop through the valve can compound the corrosive/erosive environment within the cage itself due to the complex fluid flow path through the cage. Applying the thermoplastic at this pressure drop in the pump valve protects the metallic components from this additional corrosion/erosion. Thermoplastics are very resilient when exposed to this velocity induced erosion compared to bare metal.

Impact Resistant Cages

As shown above in Figure 5, the Impact-Resistant (IR) Cage employs a three-piece design, featuring a “shell” and “connector” that fasten together to enclose a thermoplastic “insert”. The shell and connector retain all standard API valve’s interfaces (upper and lower threaded connections), while the insert’s internal geometry forms the ball’s constraint features (ball guides & fluid bypasses/exits).

When assembled, the IR Cage assembly creates a fully enclosed bore that shields the metal valve body from the high-velocity fluid moving through the bypasses. Many insert-style cages employ “windows” to achieve maximum bypass. This exposes the bare metal valve body to corrosion and erosion. The IR cage insert does not have windows, but rather a thin wall between the ball guides. The fully, circumferentially enclosed liner can be seen in Figure 5.

While the insert’s design resembles that of tested ball-guides and bypasses geometry found in metal cages, it attempts to minimize ball travel without restricting fluid flow, effectively diminishing the impact the ball has on the seat and insert’s body. The insert’s design also significantly improves the ball’s radial clearance by reducing lateral movement of the ball without compromising flow, further mitigating the effect of “beat-out” from ball rattling.

Additionally, an inherent benefit of a machined insert is the ability to produce consistent geometry across the IR Cage manufacturing process, making them less susceptible to quality-control issues found in hardlined cages. Further, the smooth machined surface of the IR Cage’s insert can resist both the erosive effect of solid-fluid mixture, and the adhesion of foreign substances (minerals/scale and wax). While these properties cannot reduce failures elsewhere in the pumping system, related to corrosion/erosion and plugging, they do effectively remove the valve cages as weak points in a rod pump design.

Challenges in Thermoplastic Downhole Valve Design – Temperature

The inclusion of thermoplastic in valve cages is not without challenges. Unlike metals, thermoplastic material’s performance can be sensitive to a variety of factors ranging from material processes, part designs, and operating parameters. The most obvious limitation is temperature. matching a suitable thermoplastic material to an appropriate operating temperature range and fluid properties becomes the single most critical step in the design. A material suitable at lower temperatures may not perform at higher temperatures, and vice versa. This process is further complicated by potential fluctuation of downhole temperatures in oil wells, especially when well treatments such as steam-flooding are used.

To address the temperature concerns, several materials were evaluated to determine the optimal performance. This involved a robust trial process, beginning with flowline check-valves (see below). The flowline check-valve shares the same IR Cage design and is subject to the same fluids and temperatures, making it an ideal test bed for various materials. The check-valve is accessible at surface and is easily inspected. This allowed a wide variety of high temperature materials to be rapidly tested. From these flowline tests, the best performing material was selected before deploying a downhole pump valve version. The IR Cage is available in 2 versions to target specific temperature ranges; a standard temperature insert, up to 210ºF and a high temperature version, up to 450ºF.

Thermoplastic materials' properties are also highly sensitive to the control of their manufacturing processes, further stressing the importance of vendor & specification in the selection of the raw material itself. The design and fabrication of thermoplastic valve cage also necessitates careful consideration of elements like thermal expansion, water absorption, and seal surfaces, which are not relevant for single-body metal cages. However, in face of such limitations, the IR Cage's documented success provides validation for the use of thermoplastic materials as a legitimate and, in many cases, more suitable alternative to the long-standing Stellite-lined valve cages.

<u>Additional application of IR Cage – Flowline Check-valve</u>

While particularly suited to downhole pump applications, the IR Cage has also been adapted to serve as a flowline check-valve. Typical flowline check-valves are "flapper" style and present their own challenges and failure modes. While that discussion is beyond the scope of this paper, it is notable that the downhole pump valve undergoes far more abuse than a surface valve. As they effectively serve the same mechanical function, the ball and seat style check-valve has proven very reliable in surface facilities, relative to the standard check-valves. The additional corrosion benefits make the IR Cage suitable in a wide range of flowline conditions. Approximately 1000 flowline check-valves have been deployed.

<u>Field Results</u>

The IR Cage has seen active deployment, in some form (downhole pump or surface check-valve), for several years and thousands of installs. Over 5000 IR Cage inserts have been deployed in new installs. In most cases, the cage is suitable for reuse, even after years of service. The total number of deployments, when considering re-ran valves, is substantially higher. As shown in Case Studies below, each consist of wells that were pulled (for unrelated issues) where the IR Cage was re-ran. These cases studies were specifically selected as evidence that the IR Cage is a vast improvement over the previous cage configuration. So much so that the cages in each case were inspected and re-deployed as-is, multiple times in some instances.

Impact and wear are rarely factors in replacing the IR Cage. Chemical compatibility and temperature are the driving factors in the success of the IR Cage. When selecting the IR Cage, bottom-hole temperature and chemical composition should be considered, in much the same way as when selecting a material for rod guides. The cage, not experiencing any friction or abrasive wear, is far more forgiving in chemical compatibility compared to a rod guide.

Case Studies

The following case studies are structured to show the original configuration, pictures of the failed components, followed by the updated configuration and runtimes. All 3 case studies are still producing with the original IR Cages. These particular case studies were selected because the IR Cages were re-run and are currently still running. This provides strong evidence the IR Cage solved the previous cage-related failures.

Case Study #1

Stroke Length: 192”	Stroke Speed: 6.3 SPM – *Nominal Cycles: 3.31 million/year*

Original Valve Configuration:

Cage: Stellite-Lined	Ball: Tungsten Carbide	Seat: Tungsten Carbide

Previous Well Run-Time & Failure:

128 days Pulled for Valve failures. Destroyed Seat. Severely beat-out cage.

Discussion: The standard API cage show on the left indicates the ball spent most of the open phase rattling (or floating) within the cage, not pinned in the full open position. Excessive wear on the lateral ball guides and seat indicate the ball was not adequately constrained. The IR Cage provides uniform ball guides through the travel of the ball to better position the ball for closing cycles and to reduce rattling.

Replacement Valve Configuration:

Cage: IR (Standard Insert)	Ball: Tungsten Carbide	Seat: Tungsten Carbide

Well Run-Time:

- 281 days Pulled for Hole in Tubing.
    - Cages were in good condition & redeployed.
- 388 days Pulled for Hole in Tubing.
    - Cages were in good condition & redeployed.
- **<u>Still running</u>**
    - 1,025 days as of last reported contact

Discussion: Runtime represents a substantial improvement over the previous failure of a combined cage beat-out and seat failure. The improvement is due to reduced ball travel in the lateral direction, resulting in less of an impact between the ball and seat. Lateral movement is a problem when the flow through the valve is insufficient to fully lift the ball to the open position. The weight of the ball opposes the flow meaning the ball can “hover” or rattle in a partially open position. The IR Cage addresses this by constraining lateral ball movement. The improved flow area around the ball (between the ball guides) also lessened the force in which the ball was pushed down onto the seat.

Case Study #2

Stroke Length: 168”	Stroke Speed: 7.1 SPM – *Nominal Cycles: 3.73 million/year*

Original Valve Configuration:

Cage: Stellite-Lined	Ball: 440C S.S.	Seat: Tungsten Carbide

Previous Well Run-Time & Failure:

42 days Pulled for valve failures. Split Ball. Damaged Seat

Discussion: A split ball and damage seat might not appear to be related to the cage, but recall the ball impacts both and so it sees twice as many impacts, if not more.

Replacement Valve Configuration:

Cage: IR (Standard Insert)	Ball: Tungsten Carbide	Seat: Tungsten Carbide

Well Run-Time:

- 674 days Pulled for Hole in Tubing.
  - All valves were in good condition & redeployed.
- 1,699 days Pulled for Hole in Tubing.
  - All valves were in good condition & redeployed.
- **Still Running**
  - 318 days as of last reported contact.

Discussion: In addition to the IR Cage, the ball material was also changed. This may have contributed to resolving the previous failure (cracked ball). It is important to note that the valve was re-run showing a remarkable improvement with just changing 2 components (ball and cage).

Case Study #3

Stroke Length: 120”	Stroke Speed: 9.7 SPM – *Nominal Cycles: 5.1 million/year*

Original Valve Configuration:

Cage: Stellite-Lined	Ball: 440C S.S.	Seat: Tungsten Carbide

Previous Well Run-Time & Failure:

232 days Pulled for poor pump efficiency (worn barrel/plunger).
184 days Beat-out cages.

a) Scored barrel
Failure #1

b) Beat-out Cages
Failure #2

Discussion: The previous 2 failures were attributable to cage issues. Specifically chipped Stellite. In the picture of the first failure, this material entered the pump barrel and scored the barrel and plunger. The second failure is likely a repeat of the first. This well is a high producer and the operator elected to replace the pump immediately without waiting for the teardown report.

Replacement Valve Configuration:

Cage: IR (Standard Insert)	Ball: Tungsten Carbide	Seat: Tungsten Carbide

Well Run-Time:

- 293 days Pulled for wellbore issues.
  - All valves were in good condition.
- **Still Running**
  - 206 days as of last reported contact.

Discussion: As mentioned above, this well is a high producer, and the operator decided to proactively replace the pump during this workover. There was nothing wrong with the pump, but was swapped for a new pump along with new IR Cages. The good pump components were inspected and re-run in another well.

Figure 6 – Typical IR Cage inspection. The cage material has some minor surface discoloration, but this does not affect its performance. The material is inspected, specifically around the tabs and ball guides and determined to be fully functional. Balls and seats are assessed through the usual vacuum test process. In all of the above Case Studies, the cage and ball/seat were assessed to be in good condition and re-deployed as-is.

Conclusions

The cage assembly is a non-sealing component, it is only functional when the valve is open. As a result, the forces and factors related to its success are very different from the ball & seat, and virtually any other downhole component. While the ball & seat have a high compressive load due to bearing the entire weight (or pressure) of the fluid column, the cage does not have a significant sustained load applied. It does, however, see significant and repeated impact force due to the acceleration (or de-acceleration) of the ball mass when the valve opens. Thermoplastics are very resilient in this regard as they absorb that impact and return to the original shape. Unlike steel, these minor deformations do not accumulate with repeated impacts. The new high temperature material has proven very successful and greatly expands the opportunity to resolve impact, corrosion, and flow challenges in downhole rod pump valves. In conclusion, the IR Cage has exceeded expectations when addressing specific and persistent valve failures. In addition to the cage beat-out and corrosion benefits, the reduced ball travel also contributes to improved ball seating and extended life.

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