Developments in the Specification, Design, Manufacture, and Quality Control of Titanium Metal-Seated Ball Valves for HPAL and POX Plant Applications

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Abstract

This paper highlights the challenges and innovative engineering that have lead to improved specification, design, manufacture, and quality control of titanium metal-seated ball valves for two of the most demanding services in the valve industry: high pressure acid leaching (HPAL) and pressure oxidation (POX) autoclave plants. These hydrometallurgical processes require highly reliable, corrosion and abrasion resistant isolation valves for performing plant maintenance activities and the emergency shutdown functions of safety instrumented systems. The paper summarizes two decades of research and development, including the initial design challenges encountered in sulphide refractory gold POX plants (1989-1995), the development of improved balls, seats, and coatings for nickel laterite HPAL plants (1995-2005), and the most recent developments undertaken by the authors (2006-present) for the new generation of POX plants that are currently under construction.
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1. **Background**

1.1 **Hydrometallurgy**

Hydrometallurgy involves the use of aqueous processes to extract and recover valuable metals from a raw or previously processed source. Mined ores, concentrates, residues, slags, calcines, slimes, and even scrap metals can serve as the starting material. At the most rudimentary level, hydrometallurgy can consist of basic physical sorting methods such as screening, flotation and separation, and atmospheric chemical reactions, such as heap leaching, whereby crushed ore is irrigated with a chemical solution to leach out precious metals into a “pregnant” solution that is subsequently recovered. Driven by increasing demand and an obvious reduction in easily extractable metals, advances in hydrometallurgical technology have led to the combination of various physical and chemical unit processes in the form of pressurized process plants that convey metal-bearing slurries through piping, valves, vessels, and other equipment. In order to decrease chemical reaction times and therefore increase throughput, these process plants now regularly operate at elevated temperatures and pressures and must additionally contend with low pH, complex chemical interactions, and both erosion and scaling by solids. This paper focuses on the challenges and developments associated with valves used in the pressurized hydrometallurgical extraction of gold and nickel.

1.1.1 **Gold**

In early gold extraction, hydrometallurgical processes involving chemical treatment were commonplace. The solubility of gold in cyanide solutions has been known since 1783 and was applied to gold ore extraction in 1887 by John Stewart MacArthur and the Forrest brothers. The first cyanidation plants followed shortly thereafter with sites in New Zealand (Crown Mine), South Africa (Robinson Deep), and the United States (Mercur) constructed from 1889-1891.\(^1\) The cyanidation process begins with a sodium cyanide leach to liberate the gold from the gangue rock and into solution. Subsequently, the gold-cyanide complex must be removed from solution via adsorption onto activated carbon (or precipitation via the Merrill-Crowe zinc process) followed by an elution process that strips the gold cyanide complex from the carbon and electrowinning to plate the gold onto cathodes. The gold is then smelted and refined to obtain a finished product. Many of the world’s remaining gold resources, however, are not readily amenable to conventional cyanidation. These ores have one or more of the following three attributes:\(^2\):

- They contain “preg-robbing” substances (notably carbon and copper-sulphide based minerals) that adsorb gold from the cyanide solution
- They contain substances that cyanide bonds to in preference to gold
- The gold is encapsulated within another substance and/or bonded to it (notably sulphur-based minerals)

The solution to these issues is to somehow remove the offending substance(s) from the ore prior to using cyanidation. Three solutions emerged to treat these types of gold ores: chlorination, roasting and pressure oxidation (POX). Chlorination was reserved for only highly carbonaceous ores or telluride ores, with low sulphides being a requirement due to their high chlorine consumption.\(^3\) It has now fallen out of favour, with roasting typically being preferred. Roasting has been successfully applied to a wide range of carbonaceous, sulphide, and telluride refractory ores for over 100 years, however it is recently becoming less economical due to more stringent emissions regulations.\(^4\) Spurred by strong gold prices, POX technology was first commercially used for pyritic ores in California (McLaughlin), arsenopyritic concentrates in Brazil (Sao Bento), and carbonaceous ores in Utah (Mercur) beginning in the 1980s. While it was the acidic POX of sulphides used in California and Brazil that would become the most
widely applied, these plants demonstrated that large-scale POX could be reliably applied to both sulphide and carbonaceous ores.

During the early 1990s, further successful applications in Nevada’s Carlin Trend (Getchell, Goldstrike), Papua New Guinea (Porgera, see Figure 1), and Canada (Campbell, Con) built upon the previous designs and stretched the boundaries of many operating parameters to optimize gold recovery. At the time, some of these were amongst the largest vessels that had been created for any form of pressurized hydrometallurgical processing. Additionally, since POX plants do not burn the ore, gaseous pollutants such as sulphur dioxide, arsenic trioxide, and mercury that were generated by roasters are significantly reduced or eliminated. In a POX process, arsenic is converted to FeAsO₄ (scorodite) which is stable and can be discharged to a tailings pond. Increasingly tight emissions standards on these pollutants have led to substantially higher off-gas treatment costs for roaster operations that will limit their use in future projects. Conversely, the vent gases that are produced from the autoclave process can be sufficiently treated through relatively low cost means. Gases are sent to cyclones and then used to pre-heat slurry or are quenched to trap condensable gases and remove solids before being scrubbed and released to the atmosphere. In an emergency situation, gases are still processed through an emergency relief cyclone before being vented from the plant.

![Figure 1: Autoclaves 1 and 2 (out of 4) at Porgera, PNG.](image)

### 1.1.2 Nickel

The history of nickel extraction can be simplified into a story of two primary ore types: sulphides and laterites. Laterite ores are those which have been formed by the laterization (tropical weathering) of ultramafic igneous rock containing iron and magnesium-based minerals. The primary mineral types are limonite, garnierite, saprolite, and nontronite. Sulphide ores are found in mafic or ultramafic igneous rock deposits formed by lava-tubes and volcanic activity (although in the case of Sudbury, it is thought to be meteoric), with the primary mineral of interest being pentlandite.

Laterite deposits found by the French in New Caledonia were the first forms of nickel to be exploited on a large scale. A smelter was built locally at Doniambo, and this source provided the primary world supply during the late 1800s and early 1900s. Major sulphide deposits were discovered in Canada (Sudbury), Russia, and South Africa during the early 20th century and this largely shifted the processing focus onto
sulphides. Processing of sulphides at these major deposits and elsewhere has primarily been accomplished by pyrometallurgical smelters and electrorefineries.

Commercial hydrometallurgical treatment of laterites was first applied by Freeport at Nicaro Nickel in Cuba in 1944. This used the Caron process (developed in Holland in 1928) which required a pyrometallurgical upstream flowsheet prior to an ammonia leaching process. Since then, the Caron process has been used in only a few plants constructed during the 1970s and 1980s. The process can tolerate higher magnesium (which consumes acid) levels than HPAL but is inefficient in that it requires both large amounts of energy for the pyrometallurgical steps and then various chemicals for the hydrometallurgical steps. Furthermore, the Caron process has lower recovery of both nickel and cobalt than either HPAL or conventional smelting.

An ammonia leach process was developed for nickel concentrates (~10-26% Ni) during the 1940s and 1950s by Sherritt, along with the University of British Columbia and Chemico, for their Fort Saskatchewan facility in Canada. By 1959, the technology had been successfully applied to nickel laterite ore using air-agitated Pachuca vessels at the Pedro Sotto Alba plant at Moa Bay, Cuba. The Moa Bay plant is now recognized as the predecessor to the modern HPAL process. Since then, the Sherritt ammonia leach process, along with sulphate oxidative leach (licensed by Sherritt to Outokumpu in 1961), and chlorine leach, have been commonly used for refining nickel matte (~70% Ni) after the concentrates have already been smelted. Due to nickel economics and the complexity of the technology, Moa Bay remained the only nickel laterite HPAL operation until three companies developed large-scale HPAL processes for their nickel laterite deposits in Western Australia in the late 1990s. Bulong, Cawse, and Murrin Murrin all struggled to ramp up to full production for a variety of reasons. These challenges were largely un-related to HPAL extraction metallurgy and more directly concerned with incorrect materials selection, general equipment design flaws, and upstream (mill) or downstream (refining/recovery) processing issues. In spite of the challenges faced by these operations, recent plant start-ups in Papua New Guinea, Australia, the Philippines, and Madagascar (projected 2011) suggest that HPAL is now the technology of choice. Figure 2 shows the three basic flowsheets for nickel laterite extraction and recovery.

![Figure 2: Laterite Processing Flowsheet Options](image)

While hydrometallurgical refining of nickel sulphide mattes is common, large-scale application to direct treatment of nickel sulphide concentrates has not been common, with smelters being the primary choice.
A notable exception is the recent development of Voisey’s Bay, which uses pressure oxidative leach autoclaves. In this process, slurry is pre-leached with chlorine and then oxygen, sulphuric acid, sodium lignosulphate (dispersant), sodium chloride, recycled leach solution and nickel anolyte are all added to the autoclave. The process is conducted at a lower temperature and pressure than either POX or HPAL.

Sulphide ores are typically discovered several hundred metres below the earth’s surface, and therefore require construction of expensive underground mines, and specialized equipment. Laterite deposits, on the other hand, are found within 20 metres of the surface and can be accessed using much cheaper open-pit mining infrastructure and conventional earth-moving equipment. Almost 60% of current world production is via smelting and subsequent refining of sulphides, but these ores represent less than 30% of known world resources. As sulphide resources are exploited and no new major deposits are found, world demand for nickel is increasingly relying on laterites. Figure 3 depicts the distribution of nickel resources and production by ore type.

![World Nickel Resources](image1.png)

![World Nickel Production](image2.png)

**Figure 3: World Nickel Resources and Production by Ore Type**

As with sulphides, laterites have been extensively processed using smelters to produce ferronickel. A couple of large current projects such as Koniambo (New Caledonia) and Onca Puma (Brazil) indicate the current economic viability of this option. Only laterite ore that is primarily composed of high grade (greater than 2% Ni) saprolite ore is currently economically feasible for smelters. Additional factors include whether the site has access to low cost power and existing or low-cost infrastructure. Due to the pollution (SO₂), low recovery of associated cobalt, and lack of potential for cost-reduction associated with laterite smelters, hydrometallurgical high pressure acid leach (HPAL) plants are the most favourable option for developing the majority of the world’s remaining nickel laterite.

### 1.1.3 HPAL and POX Processes

Figure 4 chronologically displays the major POX and HPAL plants that have been constructed in the modern era.
The most recent of these plants is Pueblo Viejo, for which Hatch is currently constructing and will be commissioning the autoclave and oxygen plant facilities, having spent the past several years performing feasibility studies and basic and detailed engineering. The plant has four autoclave trains, and uses whole-ore acidic pressure oxidation to process 24,000 tonnes of ore per day. The oxygen plant has the ability to produce 4,000 tonnes per day of oxygen. The project features the largest brick-lined autoclaves ever constructed and, when fully operational, will have the highest throughput of any gold POX operation to date. Pueblo Viejo also features titanium metal-seated ball valves in sizes ranging from 0.5” to 10”.

1.1.3.1 Simplified Plant Design

In the typical POX or HPAL processes, which are shown in Figure 5 and Figure 6 below, slurry is fed into a horizontal autoclave vessel that has several stages/compartments separated by baffle walls. Large quantities of reagent, usually 99.5% oxygen for POX and 98% sulphuric acid for HPAL, are fed into each compartment to instigate the oxidation or leaching reactions. These reagents are often produced in large dedicated plants located on site and piped directly to the autoclave. Mechanical agitators disperse the reagent throughout each compartment to ensure that the slurry becomes well oxidized/leached. The slurry flows over the baffle walls of each compartment and is eventually discharged to the flash vessel where pressure is letdown. Steam injection is used to pre-heat the autoclave vessel to the correct temperature and is necessary to maintain the desired temperature if the reaction is not sufficiently exothermic. Although only shown in the HPAL diagram, it is not uncommon for POX plants to also have slurry pre-heat vessels. Gas (primarily steam) from the flash vessel is vented to a cyclone (not shown) and can then be re-used to pre-heat the slurry in a counter-current, direct contact fashion.
1.1.3.2 Process Conditions and Materials

In attempting to characterize process conditions for autoclave discharge slurry, it must be understood that referring to a plant as POX or HPAL is a large generalization. In reality, both hydrometallurgical processes are used to treat endlessly different varieties of ores or other feed sources and therefore each plant has its own custom attributes and parameters depending on the exact metallurgy that is involved. The two harshest services for valves in POX and HPAL plants are considered to be the autoclave discharge valves and autoclave vent valves. These valves are depicted in Figure 5 as numbers 7 and 5 and in Figure 6 as numbers 10 and 8, respectively.

In the preliminary stages of the plant, common stainless steels such as Types 304 and 316 can be used so long as any re-used gases (for pre-heating stages) do not contain significant amounts of acidic carry-over.
from the flash vessel. This can be minimized by the use of cyclones to remove acidic media. In the preliminary stages, the ore is simply being pumped from feed tanks through centrifugal pumps, slurry basket strainers, potentially heater vessels or heat exchangers, and piston-diaphragm autoclave feed pumps, and it is usually at relatively low temperature (typically between atmospheric and 80°C) and neutral pH since it has not undergone oxidation or leaching. Downstream of the feed pumps, piping is changed to a more corrosion resistant and higher strength material such as 904L stainless steel or 2205 duplex stainless steel and then subsequently changed to a titanium alloy (such as grade 2 or 12) close to the autoclave. Although the media does not usually become acidic until it is inside the autoclave (POX plants can pre-treat with acid if they have low sulphur and/or high carbon ore), there is potential that a pump failure could cause reverse flow of partially or fully oxidized or leached slurry back into the feed lines.

1.1.3.2.1 Autoclave Discharge Slurry Application (Oxidized or Leached)

Table 1-1 provides a summary of the key process parameters for oxidized/leached slurry in a wide range of gold POX and nickel HPAL plants. The conditions are valid for the autoclave vessels, discharge lines, and, in upset conditions, may be realized in the various other lines connected to the autoclave.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gold POX</th>
<th>Nickel Laterite HPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Minerals</td>
<td>Iron Sulphides, Arsenic</td>
<td>Goethite, Ferralite, Nontronite, Saprolite, Serpentine, Garnierite, Asbolane, Smectite, Kaolinite, Chromite, Silicates</td>
</tr>
<tr>
<td></td>
<td>Sulphides, Copper Sulphides</td>
<td></td>
</tr>
<tr>
<td>Desirable Metals</td>
<td>Gold, Silver, Copper</td>
<td>Nickel, Cobalt</td>
</tr>
<tr>
<td>Liquids</td>
<td>H₂SO₄, H₂O</td>
<td>H₂SO₄, H₂O, HCl</td>
</tr>
<tr>
<td>% Solids (by weight)</td>
<td>40-50</td>
<td>30-35</td>
</tr>
<tr>
<td>Particle Size (P80, microns)</td>
<td>&lt; 75</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>180-235</td>
<td>250-275</td>
</tr>
<tr>
<td>Operating Pressure (kPag)</td>
<td>1800-3500</td>
<td>3000-6600</td>
</tr>
<tr>
<td>Free Acid (g/L) @ 25 °C</td>
<td>10-80</td>
<td>30-60</td>
</tr>
<tr>
<td>Chlorides (ppm)</td>
<td>10-20</td>
<td>20-80000</td>
</tr>
</tbody>
</table>

In instances where an “operating” parameter is given, these represent actual conditions during the “day to day” normal production run of the plant. For the purposes of designing the plant’s equipment, higher valued “design” parameters are specified in order to provide a margin of safety. This designed buffer zone ensures that the equipment will work correctly to perform corrective safety functions in the case of an accidental over-pressurization and allows for some degree of variation in the complex metallurgical feed of the plant, which can increase the heat generated by exothermic reactions inside an autoclave.

Titanium metal-seated ball valves (like the ones shown in Figure 8) are used for isolation on the autoclave discharge lines. The primary reason for the choice of titanium for metal-seated ball valves in this application is that it provides the necessary corrosion resistance to the high temperature, high pressure, acidic slurry of generated by the autoclave process. In a POX plant, the addition of oxygen to the slurry creates an oxidizing and highly acidic environment due to the irreversibly oxidized sulphur that forms H₂SO₄ in solution. In an HPAL plant, slightly reducing conditions may exist in the autoclave due to the combination of the reducing effect of intermediate levels of H₂SO₄ in solution (from direct addition of concentrated acid to the autoclave) and the oxidizing effect of iron ions that are liberated from iron oxides in the ore. Titanium alloys are highly reactive and form a very stable oxide layer that offers protection against the hot oxidizing and acidic conditions. In the reducing conditions, titanium grades such as 7, 11, and 17 must be used in the autoclave where the acid is concentrated, but the valves and piping see
environments that often allow grades without noble metals, such as 2, 5, and 12. Figure 7 shows the performance of various materials in oxidizing, reducing, and chloride-containing environments.

![Figure 7: Relative Corrosion Resistance Ranges of Various Alloys in Oxidizing and Reducing Environments with Varying Chloride Concentration.]

1.1.3.2.2 Autoclave Vent Gas Application

In order to maintain a relatively constant operating pressure and temperature, an autoclave must continuously vent both unused reagent and chemical by-products that build in the vapour space of the autoclave. Table 1-2 shows the characteristics of the vent service for POX and HPAL.
Traditionally, autoclave vent valves have experienced the most rapid corrosion. This is due to the constant venting of autoclave gases which are a variable multiphase composition of steam, oxygen, other non-condensable gases, acidic liquids, and slurry particulate. The condensation of hot H\textsubscript{2}SO\textsubscript{4} on the valve components as the gaseous vent mixture passes through the valve can lead to rapid corrosion of both substrate and coating if suitable materials are not chosen. Recent information from Ravensthorpe suggests that vent valves are lasting longer than discharge valves in that particular application.

1.2 The Role of Titanium Metal-Seated Ball Valves in Pressure Hydrometallurgy

Throughout the development of the POX and HPAL technologies, the high temperature, high pressure, acidic, scaling, and erosive slurry generated by autoclaves has posed a significant challenge to the design, materials selection, and maintenance of all related process equipment. Pressures commonly require ASME Class 600-900 ratings, and temperatures are usually 230-275 °C. Valves for isolating process pipe lines are absolutely critical to plant operation. Valve-related problems can lead to an inability to positively isolate hazardous process slurry, pure oxygen, or pure acid lines, and operators are placed in an unsafe work environment and also forced to perform unplanned shutdowns (depressurization of the autoclave). Depressurization alone can take over 24 hours, with subsequent delays resulting if valves must be sent out for repair. Frequent occurrence of these delays is incredibly costly, especially when precious metals extraction is concerned.

1.2.1 Valve Types – Why Metal-Seated Ball Valves?

Historically, there have been several popular types of valves used in lower pressure and/or lower temperature slurry services. PFA/PTFE-sleeved or lined plug valves, elastomer-sleeved knife gate valves and elastomer-lined diaphragm/pinch valves are commonly used. Plug valves are available with pressure ratings up to ASME Class 600 and temperature (continuous) ratings up to 260 °C. The performance and durability of PFA/PTFE at continuous elevated temperatures is questioned though, and engineers do not often specify them for autoclave applications above 200 °C. Further concerns include high torque requirements, general sleeve maintenance, erosive body wear (if the traditional irregular port design is used), and the high cost for forged valves since most of the valve is constructed from one piece.

Knife gate and diaphragm/pinch valves are typically not available with pressure ratings above ASME Class 300, and this fundamentally limits their use for isolation around autoclaves. The elastomers/rubbers that line the diaphragm valve and are used for seating the knife gate and are temperature limited to around 150 °C and also experience wear that requires continual replacement over the valve’s life. For wear purposes, knife gate speed is limited at around 1” per second, so quick shutoff is not possible. Designs where the gate fully pushes through the sleeves are required because otherwise the gate crushes slurry into the seat cavity causing wear and loss of isolation, however pushing through the sleeves causes a discharge.
of process media that must somehow be drained away or dealt with, posing a safety issue. Fully-metal versions are available, but these are also pressure-limited to Class 300, do not typically use push-though designs, and have not been commonly/successfully used in autoclave operations.

With the significant limitations and questions associated with other valve types, ball valves have emerged as the predominant choice for autoclave isolation. Ball valves have virtually no pressure limitation and have been designed and used to pressures far in excess of that required by POX or HPAL. As with soft-sleeved plug valves, both floating and trunnion soft-seated ball valves are considered to be temperature-limited and can fail due to seat wear since the seats are often directly exposed to the process solids. Metal-seated ball valves can be designed to temperatures that greatly exceed typical autoclave requirements. These are also available in both trunnion and floating designs. Although floating ball valves have fewer parts and are often a cheaper design, as valve sizes increase, most manufacturers switch from floating to trunnion in order to reduce the torque required to move the ball and to ensure that the heavy ball is well supported and maintains alignment while being rotated. The first large-scale horizontal autoclaves used trunnion valves since process lines were up to 10”-12” in size. It was observed that the trunnion valves used would fail due to solids causing the trunnion mechanism to bind and seize the valve. The trunnion valves were quickly replaced with floating ball valves and although these have also had their share of issues, they have outperformed all other valve types and the industry has not looked back since. Metal-seated floating ball valves that are specifically designed for autoclaves and other harsh acidic slurry services are commonly referred to as “severe service ball valves”.

1.2.2 Implications of Valve Technology on Plant Costs and Safety

While the industry may have found the best type of valve for autoclave isolation from a technical standpoint, it is by no means an inexpensive proposition. Recent POX and HPAL plants have seen metal-seated ball valves represent 1-4% of total autoclave facility initial capital costs. This percentage may seem relatively small, but it routinely translates to actual cost of about 20-50 million USD of valves for a modern plant. From recent data for the Pueblo Viejo POX project in the Dominican Republic, titanium metal-seated ball valves are responsible for about 40% of the total titanium-derived equipment costs. Figure 9 depicts titanium use within Pueblo Viejo distributed by cost. It should be noted, however, that Pueblo Viejo uses brick and lead-lined carbon steel autoclaves, whereas some of the other POX and HPAL facilities choose fully titanium autoclaves and this would obviously reduce the percentage by cost attributed to ball valves.

Figure 9: Distribution of Titanium-Related Costs in a POX Plant

The initial capital cost is only a fraction of the impact that the valves have on plant economics. Neglecting labour costs, metal-seated ball valves are responsible for about 20-30% of POX maintenance costs and 30-40% of HPAL maintenance costs. The valves use thermal spray coatings to extend the life of the ball and seat sealing surfaces, but these, along with other components, experience wear over
time and must be routinely refurbished or replaced. This maintenance also represents lost production time. In POX plants of the 1980s, valve failures contributed up to 10% of total plant downtime.\textsuperscript{29} This downtime meant limited plant capacity, and low operational availability.

Autoclave plant initial feasibility, design (throughput limitation, stress analysis), operation/availability, maintenance, and profitability are all directed affected by titanium metal-seated ball valves. In the worst case scenarios, a valve-related problem can cause a catastrophic event resulting in loss of human life and major capital equipment damage. Table 1-3 summarizes some of the major safety hazards and their outcomes. The flammability of titanium in oxygen-rich environments is a major issue that is further addressed in section 2.2.1.1.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocked autoclave feed valve</td>
<td>Slurry pump explosion, damage to feed lines</td>
</tr>
<tr>
<td>Blocked autoclave discharge</td>
<td>Autoclave over-pressurization, safety relief event</td>
</tr>
<tr>
<td>Autoclave vent valve failure</td>
<td>Autoclave over-pressurization, safety relief event</td>
</tr>
<tr>
<td>Autoclave low slurry level</td>
<td>$O_2$ migration into discharge and vents, potential $O_2$ fire</td>
</tr>
</tbody>
</table>

2. Technical Specification

The specification of valve requirements has advanced largely as a reactionary response to the multitude of problems that have been witnessed in various autoclave plants. In addition to the practical safety implications of using poorly functioning valves, the extraordinary financial cost that has been associated with shutting down plants and repairing, re-designing, and/or replacing large quantities of valves has provided an impetus for end-users and engineering firms to challenge the limits of what manufacturers can and will produce. What may have once been specified on a single page now demands a large binder worth of specifications and data sheets filled with process information, performance expectations, maintenance philosophies, materials of construction, quality requirements, and test procedures. The rise in the use of engineering design firms in place of end-user design groups has also led to increased requirements for submission and approval of vendor documents. This section examines the aspects of a current metal-seated ball valve specification and the rationale behind them.

In late 2001 and early 2002, as part their work for Inco on the Goro Nickel HPAL autoclave project, Hatch ATG was commissioned to write a report on the current status of severe service ball valve technology and to recommend the type of ball valve that should be used for critical applications at their New Caledonia based HPAL plant. As part of this report, Hatch ATG and Inco, along with experienced autoclave plant designer and operator, Jack Irvine from ABI Consultants, conducted a series of meetings with the six major players in the metal-seated ball valve market to discuss their valves and the potential of each manufacturer as future partner in the continued development of valves for autoclave processes. Additionally, Hatch and ABI visited several operational autoclave facilities and related valve servicing sites (Goldstrike, Lone Tree, Twin Creeks, Bulong, Murrin Murrin, Cawse, Ravensthorpe, Score Pacific,
Geographe) in order to speak with operators, mechanics, engineers, maintenance and repair staff about the service history of their valves. Much of what was learned in this extensive process has formed the basis for expanding Hatch ATG’s specification requirements to their present state.

### 2.1 Control Documents

Due to the limited number of experienced manufacturers, complicated specification requirements, and high cost, metal-seated ball valves are specified and procured as a standalone work package by Hatch ATG. Some documents contained within the specification are common across all work packages for an entire project. These include specifications for site conditions, operating manuals, and general vendor quality requirements. Other specifications are project standards for such things as specific material properties, oxygen cleaning methods, and ferroxyl testing for iron contamination, which apply to metal-seated ball valves, amongst other types of process equipment. The main unique components of the work package are the customized summary of work, bidder and vendor data requirements, severe service ball valve equipment specification, engineered coating application specification, valve datasheets, and actuator datasheets.

#### 2.1.1 Summary of Work

The summary of work provides a scope of what is included in the package and lists general criteria, descriptions, and quantities of the valves to be provided by the vendor. Typically it will specify that the work includes:

- Valves
- Pneumatic (typically < NPS 6”) or electro-hydraulic actuators (typically >= NPS 6”)
- Actuator automation accessories (solenoids, limit switches, tubing).
- Actuator mounting hardware
- Dedicated hydraulic power units
- Ferroxyl testing and oxygen cleaning (where applicable)
- Assembly/testing/inspection of all components, including actuator mounting
- Project-specific tagging
- Shop/field testing
- Preparation of installation/operation/maintenance manuals.

The valves are listed in several tables, separated by installed manual, installed actuated, capital spares manual and capital spares actuated. The tables itemize the valve types and provide the quantity, size, valve and actuator tags, service description, and a general description. The general description is used to provide a summary of the valve and actuation required including information concerning materials of construction for major components, whether pneumatic or hydraulic actuation is required, and the failure mode of the valve/actuator. Additionally, the summary of work refers the vendor to the various specifications and datasheets included in the work package.
2.1.2 General Service Information and Refurbishment Schedules

Depending on the end user’s requirements and budget, capital spares purchased with the package may include any combination of the valve/actuator or valve/actuator/HPU assembly. This section is provided to inform the vendor of anticipated valve maintenance requirements. Typically the valves are considered from the perspective of medium maintenance, high maintenance, and an emergency repair scenario. For “medium” maintenance valves such as those on oxygen, steam, high-pressure water, and slurry feed isolation, one set of spare valves is often purchased. “High” maintenance valves are those on the autoclave discharge and vent lines. These typically see the worst corrosion and wear and therefore 2 sets of spare valves are purchased. For all valves, one set of trim kits (ball, seats, spring, fasteners, gaskets, etc.) is requested and generally stored at the manufacturer. For an emergency spare situation, the vendor must identify what the shortest turnaround time for various valve types would be.

2.1.3 Valve Equipment Specification

The equipment specification for the metal-seated ball valves is a document that outlines the codes/standards, design requirements, materials selection, and quality control procedures that are to be applied.

2.1.3.1 Design and Materials

The first portion of this section of the specification focuses on the requirements for cycling and isolation capabilities. Reference is made to valve datasheets where specific process information is given for each valve application. Recent specifications, such as the “Severe Service Ball Valves” package for the Pueblo Viejo project, call for the valve to provide “positive isolation” for at least 49 out of every 50 cycles (1 cycle is open stroke then close stroke or close stroke then open stroke) between servicing, and indicate to the vendor that mature plant operation will see this occur over a period of 120 days. Some historical data on valve cycling and life is shown below in Table 2-1. As can be seen, plants have achieved significant increases in valve life over the past decade. The specification defines positive isolation as per the MSS SP-61 definition, so as to provide the vendor with clarity on the potentially ambiguous term.

Table 2-1: Discharge and Vent Valve (Various Brands) Cycling and Life at Autoclave Plants

<table>
<thead>
<tr>
<th>Site</th>
<th>Discharge Valve</th>
<th>Vent Valve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cycle Frequency (per month)</td>
<td>Life (months)</td>
</tr>
<tr>
<td>Lone Tree, 2001</td>
<td>0.25-1</td>
<td>12</td>
</tr>
<tr>
<td>Twin Creeks, 2001</td>
<td>Rare</td>
<td>0.5-10</td>
</tr>
<tr>
<td>Goldstrike, 2001</td>
<td>0.5</td>
<td>&gt;12</td>
</tr>
<tr>
<td>Bulong, 2001</td>
<td>2-8</td>
<td>1-3</td>
</tr>
<tr>
<td>Cawse, 2001</td>
<td>12</td>
<td>&gt;24</td>
</tr>
<tr>
<td>Murrin Murrin, 2001</td>
<td>&lt;1</td>
<td>Rare</td>
</tr>
<tr>
<td>Macraes, 2001</td>
<td>0.67</td>
<td>-</td>
</tr>
<tr>
<td>Ravensthorpe, 2007</td>
<td>16</td>
<td>23-24</td>
</tr>
<tr>
<td>Goldstrike, 2010</td>
<td>-</td>
<td>18-24</td>
</tr>
<tr>
<td>Twin Creeks, 2010</td>
<td>-</td>
<td>12-14</td>
</tr>
</tbody>
</table>
The major structural components of the valve: ball, seats, stem, and body, must each be constructed from one solid forged or bar stock piece. Given the high actuation torques, hazardous media, thermal/physical stresses, erosion, and scaling, the engineer does not allow castings to be used. Historically, casting quality of titanium alloys has been somewhat suspect, and even with “low” defects, their mechanical properties are poorer and more inconsistent than forgings or bar stock.

The valve must be of a floating ball design, but various seat configurations, if proven in service, are permissible. The valve must seal bi-directionally, meaning that the ball must be adequately loaded by springs or the service pressure to maintain positive contact with either seat depending on which direction the flow comes from. Although used as a quick fix by some Western Australian HPAL operations, welded seats are prohibited by the specification. The two major reasons behind this are that the seats must be easily removed for repair and welding requires them to be cut out, and welding the seat to the body increases the chance that loss of tolerance in the ball/seat stack-up will occur. Typically, manufacturers that use one fixed seat screw it to the body. The stem slot (where the stem torques the ball) must be designed based to have minimal deformation upon loading by the corresponding part of the stem (stem tang).

As with the majority of ball valves now on the market, the stem must have a shoulder that prevents blowout through the top of the valve. Any hysteresis between the actuator and ball can cause the valve not to fully close or open, leading to wear and leakage, so it is desirable to have as direct coupling of the stem to the actuator as is possible. The stem tang must be designed to minimize point loading and elastic deformation. All parts of the stem must be capable of withstanding the maximum actuator torque, which is typically 2-3 times the “clean break” torque of the valve, and listed on actuator datasheets. The top of the stem is to use shear keys that will fail before the stem, but above the required torque, in order to prevent major plastic deformation of the stem itself.
2.1.3.2 Quality, Traceability, Inspection & Testing

General requirements related to these topics are discussed in this section. The vendor must submit and perform work in accordance with an approved Inspection and Test Plan (ITP). Additionally, as part of the formal document submission, the vendor must provide all inspection records, laboratory certificates and any other documentation deemed by Hatch to be required. From a materials standpoint, specific reference is made to the requirement for 100% positive material identification and submission of material test reports for each heat number used on the major valve components. The vendor must also adhere to the Hatch standard material specifications provided. In order to prevent iron contamination of titanium or any contamination of oxygen cleaned parts, the vendor must use some method of part segregation, involving cleaning machines prior to use, bagging/packing parts to avoid contamination, and using clean rooms for assembly.

Inspections are normally carried out several times over the course of manufacturing to inspect various processes and progress. Hatch requires notification 2 weeks in advance of ITP hold/witness points, and confirmation 48 hours in advance. As part of materials quality assurance, Hatch declares that they reserve the right to take scrap materials from manufacturing for independent materials testing, and any deviation in material identity or properties can result in scrapping parts at no cost to Hatch.

2.1.4 Engineered Coating Application Specification

This specification details the specific requirements for the design, surface preparation, contamination control, quality (sampling), and documentation of the coating that is applied to the ball and seats of valves.

2.1.4.1 Design

In order to achieve satisfactory performance in autoclave valve applications, it is recognized that coatings must have a certain set of design characteristics. Fundamentally, any coating in a metal-seated valve must be capable of forming a leak-tight seal when it placed on the ball and seats of the valve. Additionally, it is clear that it must adequately resist any wear and normal/shear loading that occurs during the operation of valve, as excessive wear or general coating failure will directly lead to leakage and total valve failure to isolate. In this particular application, hot slurry is present so the coating is subjected to thermal cycling (valve opening/closing), corrosion, erosion, and scale build-up.

Although a lot of how well a coating meets these criteria can be gathered from the experiential history of valves in-service and observing which coatings fail and why, Hatch requires that several measurable characteristics of the coating be determined through the testing of samples and either characterized (i.e. measured once or infrequently) or continuously measured for each “lot” of coating against a predetermined pass/fail value. This ensures that the coatings are produced to a consistent level of quality over long production runs. An inspection lot is defined as one 1) production run of one (1) size and material of valve, using one spray powder lot on one piece of spray equipment in one work shift. More than one production run, if required, will constitute separate lots.

2.1.4.1.1 Adhesion/Bond Strength

The normal (perpendicular to surface) bond strength test provides a measurement of the adhesion of the coating to the metal substrate. This test is relevant for valve coatings because poor bond strength can lead to premature failure of the coating by several modes. ASTM C633 is the usual standard specified. This involves gluing a coated coupon to another piece of metal, fixing them in a holder apparatus, and then pulling the apparatus in a tensile tester until either the adhesive or the coating fails. ASTM D4541, which uses a portable device, has also been used to test bond strength.

2.1.4.1.2 Shear Strength
Traditionally, there has been no test for shear strength performed on thermal spray coatings. If the coating is used in a shear application, like ball valves, it has been assumed, either intentionally or unintentionally, that the normal bond strength is correlated to the shear strength. In reality, these attributes could yield very different values depending on the coating material, the substrate, the use of base coatings, and the thickness of the coating deposition. At Hatch’s instigation, some manufacturers are doing work to identify methods by which the shear strength can be accurately measured for thermal spray coatings.

2.1.4.1.3 Porosity
Porosity is an important attribute because it is related to the bond and shear strength of the coating. Greater porosity results in more cracks propagating through the coating upon loading and failure at lower applied loads. It also allows for the process media to seep into the coating, which could potentially decrease the coating life. Hatch requires porosity to be evaluated based on ASTM E2109. This standard allows for visual comparison and software image analysis. It is widely recognized that the trained eye can reasonably indicate a ballpark percentage (1%, 5% etc.) using visual inspection, but with strict porosity requirements, the more scientific software image analysis approach is favoured. Specialized software can be programmed to recognize particular colour shades and pore sizes within the coating so that it does not select coating splats or un-melted portions, and only detects actually voids in the coating.

2.1.4.1.4 Bond Line Contamination
Particulate at the coating bond line can be problematic for coating quality. If a foreign object exists that is somewhat large in size, it can, in theory, be a potential site for the initiation of coating failure. Whether initially loose or mechanically impacted into the substrate, there is no guarantee that the contaminated spot would have the required bond strength. Therefore when the coating is loaded in shear, it could begin to dislodge the particle and cause localized cracking and even spalling/flaking of the coating. Ceramic coatings have some degree of porosity (1-3% for coatings used by Hatch). As mentioned above, this suggests that it is possible for pathways to form in the coating that allow process media to reach the substrate and therefore contact any particulate there. If the particulates are of low corrosion resistance, they could dissolve into the solution and leave gaps at the bond line, allowing for the crushing and cracking of the coating at that spot under load and/or flaking of the coating since it is no longer sufficiently adhered to the substrate. Either of the mechanisms can be involved regardless of whether there is a one part or two part coating applied. In some recent work by one manufacturer using a two part coating, it seems apparent that, in some cases, bond line contamination may not significantly affect the sample bond strength, but there is no data from previously in-service valves or samples in order to compare what the effect of valve usage and process media is on the contamination and bond strength.

There is no standard on bond line contamination so a couple of methods are used. Traditionally, a digital image of bond line at a magnification of 200-500X is fitted with straight line segments across the bond line and then a ratio is computed to give a percentage of total length that is contaminated. A more accurate, but more time consuming method is to fit splines to the bond line instead of straight lines.

2.1.4.1.5 Abrasion Resistance and Microhardness
An ideal abrasion test would require testing a coating in several sample slurries in such a way that the valve opening and closing action is replicated and the trapping of particles between the seat and ball occurs. To our knowledge, such a specific method does not exist. Currently, ASTM G195 and F1978 are specified. These standards relate to the use of a Taber abrasion device that applies an abrasive disc to the coating. After a fixed period of time, the sample is then weighed to determine the amount of coating loss. This process allows for the coating to be benchmarked against other coatings when the same wheel material is used. Microhardness is tested using ASTM E384. This involves a series of Vickers indentation tests to a coating sample.
2.1.4.2 Sampling

In order to ensure the consistency and quality of thermal spray coatings, the authors have applied statistical, lot-oriented, pass/fail sampling procedures. ANSI/ASQ Z1.9 provides a set of guidelines for “Sampling procedures and tables for inspection by variables”. For the Pueblo Viejo project, Hatch has implemented an Acceptance Quality Limit (AQL) of 4.00 and General Inspection Level II. These values correlate to range of k values and number of samples that vary depending on lot size. “Section B: Variability Unknown – Standard Deviation Method, Part 1: Single Specification Limit”, and “Form I” are referred to for the procedure of determining the acceptability of a coating lot. Either an Upper (U) or lower specification (L) limit is established for each of the measurable parameters (e.g. L=10000 psi for bond strength). The exact value of each of these parameters will vary from manufacturer to manufacturer depending on what they are capable of and what has been agreed upon. The mean (x) and the standard deviation (s) of the sample values are also calculated. For a lot to pass, the following criterion must be satisfied:

\[
(U - x) / s \geq k \quad \text{OR} \quad (x - L) / s \geq k
\]

If the lot is not passed, the parts are rejected and must be re-coated. Failure of several consecutive lots can result in tightened inspection, which is more difficult to pass due to a higher k value being instituted for each particular lot size. This pass/fail sampling is applied to bond strength, porosity, bond line contamination, and hardness.

2.1.5 Valve Datasheets

The valve datasheets provide typically specified details such as the design and operating pressure/temperature, materials of construction, flange rating, valve design, codes/standards, and testing requirements. To assist with the vendor’s understanding of the particular conditions and use of the valves, the process chemistry, scaling potential, relative abrasion potential, thermal shock, and differential pressures experienced in each of the several service applications are also indicated. Datasheets are made for each of the valve tags (“V-____”), which are assigned to each valve type rather than to each individual valve. Valves of identical specification requirements are all covered by the same valve tag. Individual distinction between identical manual valves is often not required nor desirable at the specification stage and can complicate matters upon installation or when maintenance staff wishes to swap valves. For instrumentation purposes, actuated valves have additional actuator tags that are unique to each individual actuator.

2.1.6 Actuator Datasheets

The actuator datasheets are based on the ISA 20C1001 template for the operating parameters of valve or regulator devices. Actuators are given separate tags (“XV-____”) on the P&IDs for instrumentation purposes, and usually 1-3 actuators of an identical spec are listed on each datasheet, although occasionally more are combined with chart referencing all of the tags. Key information included on the datasheet includes:

- Safety factors relating the actuator torque to the valve clean break, run, and end torques
- Safety factor relating the actuator torque to the valve maximum allowable stem torque
- Pneumatic/Hydraulic/Electro-hydraulic actuation
- Terminal block allocations
- Requirements for Partial Stroke Test Devices
- Requirements for SIL rating
- Solenoid valve and limit switch specification/description
2.1.7 **Standard Material Specification for Titanium and Titanium Alloys**

This standard specification refers the manufacturer to the various ASTM standards required for each type of titanium product and indicates that MTRs with heat numbers are required. If plate is used, a supplementary bend test to ASTM E190 is required.

2.1.8 **Standard Specification for Ferroxyl Testing**

Originally used by Hatch ATG to apply to plate and welding on custom fabricated vessels and mechanical components made from non-ferrous alloys, the standard specification for ferroxyl testing is now being applied to valves constructed from any non-ferrous alloys that are used in severe services. Iron contaminated areas on a non-ferrous metal surface can become pitting corrosion initiation sites, thus reducing the life of the material. The fundamental goal of the specification is not only to provide a suitable method for determining if iron contamination of titanium has occurred, but to also encourage the manufacturer to adopt practices that prevent or limit the occurrence of contamination. The manufacturer is informed that titanium should not come into contact with iron or steel fabrication tools and that a segregated area or clean room may be required if titanium welding is performed.

Prior to assembly, wetted titanium valve components are subjected to ferroxyl testing using the solution prescribed by ASTM A967, Practice E. The solution is comprised of potassium ferricyanide, nitric acid, and distilled water. The ingredients are mixed together and must be stored in an opaque bottle and used within 24 hours. Prior to application of the solution, test surfaces are cleaned with austenitic 300 series stainless steel or fibre brushes and with acetone. The test solution is applied with either an atomizing spray bottle or a clean white cloth and then the surface is observed for 30 seconds. If blue spots appear, this is indication of iron contamination. Regardless of the result, the surface is then rinsed clean with warm water within 15-30 seconds after the witness period in order to prevent permanent metal staining. If water alone does not suffice, a solution of 10% acetic acid and 8% oxalic acid can be used to scrub the surface prior to further water rinsing.

Removal of iron contamination is accomplished by wire brushing and re-passivation. If this fails, burring can be used to remove material and a weld repair performed to fill cavities produced. The entire ferroxyl test procedure is repeated until the part passes. Hatch ATG requires that vendors provide test reports indicating components tested, test results, and names/signatures of inspector(s).

2.1.9 **Standard Specification for Oxygen Cleaning**

In order to prevent oxygen fires, it is well established through ASTM, NASA, and other literature that titanium should not be used in any process lines that carry high purity oxygen. For most oxygen users, titanium does not even enter the engineer’s thought process because, depending on velocity, stainless steels and variety of nickel-copper alloys are chemically compatible and do not promote ignition. These ignition-resistant materials are used within the piping that provides oxygen supply to the autoclave. Autoclave vent lines, however, present a difficult challenge because normally vented gases from the autoclave are corrosive and therefore often must be made from titanium alloys to prevent excessive material loss. The titanium valves used in the vent line are therefore subjected to oxygen cleaning.

Oxygen cleaning aims to remove any contaminants that could be the source of a fire, whether by causing impingement or acting as fuel source. These contaminants include hydrocarbons, paints, rust, loosely adhered oxide films, mill scale, dirt, filings, weld splatter, and water. CGA 02-DIR provides a directory of agents that may be used for cleaning. Cleaning may be accomplished by immersion, flushing, or spray. Typically small components can be immersed, whereas large components will be sprayed. Inspection of the cleaning is as per CGA G-4.1 and ASTM G93, Section 11. Direct visual inspection, ultraviolet light,
and wipe tests are done to verify that no contamination exists. The valve components are re-assembled in a clean room, and the valve is bagged and taped (up to the mounting flange in the case of an actuated valve). The bag is then labeled as per Section 12 of both CGA G-4.1 and ASTM G93. Commonly labeling warns the end user not to open the bag until the valve is being installed. For plants in non-English speaking countries, the warning is written in the local language as well.

2.2 Materials Selection – Titanium Grades

Throughout the history of autoclave isolation valves, many grades of titanium have been used. Each mine site has inherently unique ore, and while benchmarking and coupon testing has been done in some instances, materials selection has been somewhat of a trial and error process for valves. Originally, little knowledge of titanium or of the service often led the valves to be constructed from all one grade that was not necessarily optimal for the application or valve design. As each valve component requires different material properties due to its particular function and process exposure, it is increasingly common to find multiple grades used within the same valve. ASTM Grades 2, 3, 5, 7, 12, 28, and 36 are amongst those that have been used in various POX and HPAL metal-seated ball valves. Pueblo Viejo uses the following titanium grades in metal-seated ball valves:

- Balls: 12, 36
- Seats: 12, 36
- Bodies/Ends: 12, 36
- Springs: 5
- Stems: 5

2.2.1 Drawbacks of Titanium Use

2.2.1.1 Oxygen Fires with Titanium

In the presence of oxygen at elevated temperature and/or pressure, titanium spontaneously ignites due to the acceleration of its reaction with oxygen to form titanium dioxide. For corrosion purposes, titanium has been used in autoclave vent lines that do not normally see oxygen at titanium ignition conditions, but may encounter this environment in an upset situation. Table 2-2 provides examples of some oxygen fires at POX plants.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Scenario/Cause</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Getchell, Nevada</td>
<td>Failure of autoclave LE to establish LALL</td>
<td>Vent gas infiltration into slurry discharge line resulting in an O₂ fire in the discharge valve</td>
</tr>
<tr>
<td></td>
<td>No redundancy in O₂ isolation valves</td>
<td>Isolation valve failure and valve fire</td>
</tr>
<tr>
<td>Twin Creeks, Nevada</td>
<td>Leakage of O₂ isolation valve and failure of the autoclave pressure control system to monitor O₂ pressure</td>
<td>O₂ Enriched autoclave atmosphere resulting in autoclave vent valve ignition and oxygen fire</td>
</tr>
</tbody>
</table>
2.2.1.2 Mitigation of Oxygen Ignition Potential with Titanium Grade 36

Titanium grade 36, which contains 55% titanium and 45% niobium, is favoured for its corrosion resistance to sulphuric acid in oxidizing conditions and its resistance to ignition in high pressure, high purity oxygen applications. The first autoclave application of titanium grade 36 was at Getchell in 1991. Getchell operated at 210 °C and 3200 kPa, with an oxygen partial pressure of 700 kPa. Getchell had a fire in their titanium vent piping causing them to switch to Ferralium 255, which subsequently corroded in a short period of time. The titanium grade 36 pipe was installed and proved to be the best available solution. This logic has subsequently been applied to valve materials of construction.

2.2.1.3 Raw Material Economics and Availability

Compared to other traditional process plant materials, titanium is very expensive. The primary production process for titanium, the Kroll Process, is laborious, and produces toxic waste. The process also sacrifices magnesium, another expensive metal. There is currently research being done into new titanium production methods that may eventually replace the Kroll Process with a cheaper alternative.

As with any exotic material, some of the lesser used alloys are substantially more expensive and difficult to find. This has been an implicit consideration throughout pressure hydrometallurgy development as the industry’s demand remains small relative to the dominant titanium users in aerospace and retail goods, and therefore cannot dictate the alloys that are commonly available.

2.2.1.4 Welding and Weld-Overlay

Due to titanium’s high reactivity, specialized procedures are required in order to prevent contamination by oxygen, nitrogen, or hydrogen during a weld. Generally, this is not an issue for initial valve construction as most metal-seated ball valves do not require welding. Once the erosive/abrasive service has damaged the valve components, however, it is often desirable to apply a weld-overlay to build up the lost material rather than to discard the entire component. The specialized procedure and qualified welder place obvious restrictions on the deployment of weld-overlay in remote locations or even the average valve manufacturers.

3. Design

Since being originally installed in the POX plants of the 1980s, autoclave metal-seated ball valve design has evolved from being a “borrowed” medium-temperature, high-pressure valve produced in exotic alloys to truly being a custom-designed valve that addresses the many severe aspects of autoclave service. A labeled cross-section of a modern titanium metal-seated ball valve is depicted in Figure 11. Amongst other flaws, the traditional designs often did not adequately account for solids accumulation, erosion and reparation, thermal cycling, corrosion allowance, and increased torque due to scaling. These flaws were compounded by a lack of understanding and proper design modification for the variety of materials (titanium alloys, high-PREN stainless, duplex, super duplex, nickel alloys) that were often requested. This section addresses the improvements that have been made with respect to the major components of metal-seated ball valves.
3.1 Body

The first metal-seated ball valves used in autoclaves featured cast bodies. The first titanium castings used were ASTM B367 grades C2 and C3. Throughout the valve industry, castings have traditionally been favoured for the mass production of “commodity” valve bodies due to their low overall cost, reasonable quality, and ability to produce complex shapes and contours. The cast titanium alloy bodies performed reasonably well and some valves with these bodies are still in operation at Goldstrike and Twin Creeks to this day. With that said, many of the original valve bodies have also been replaced for a variety of reasons. Figure 12 shows both cast and forged titanium bodies.

Figure 12: (From L to R) 12” Titanium Gr. C3 (Cast) Valve Body and a Forged Gr. 12 Replacement Body – Both Currently in use at Twin Creeks, Nevada

During the first several years of operation of Western Australian HPAL plants, valves at the Bulong and Cawse sites were observed to have surface cracks in the cast valve body. These were shallow cracks and did not pose a failure issue but were disconcerting to the operators and maintenance staff. The valve body manufacturers determined that the surface finish specification was the source of the problem and
subsequently changed the specification preventing further incident. In spite of this solution, occurrences such as these have given castings a bad name within the industry and helped to drive the switch from castings to forged or bar stock valves.37

Casting titanium is a much more complicated process than casting most other materials and a thorough review of the castings providers would need to be done to guarantee the quality of supply. Titanium’s high reactivity means that it requires an argon casting atmosphere to prevent atmospheric contamination during the casting process. Ventilation must be provided to allow the escape of gases and a thermal gradient between the molten titanium and crucible wall must be maintained. Due to titanium’s inherent properties, it also difficult to maintain proper flow over distinct changes in geometry. Structurally, castings contain a dendritic (long crystal) structure as well as porosity, inclusions, and other discontinuities. Forgings are wrought, with fine homogeneous grains that typically do not contain significant porosity or other defects. Another major drawback of castings is that specific moulds must be made for each component in order to achieve optimal performance. Data from HIP casting has shown that simply machining components out of castings produces lower mechanical properties than casting the exact shape.

From a design standpoint, the original bodies met ASME B16.34 for wall thicknesses, but experience has driven manufacturers to exceed the required minimums of these codes so as to allow sufficient thickness for the corrosive and erosive attack of the media. While the material is typically specified such that they would be considered corrosion resistant (less than 0.1 mm/yr of material lost) given the known process data, autoclave plants have often proven to be variable and difficult to predict in these regards. Modern autoclave valves are almost universally made with bodies (and all other major components) that are machined from machined from large billets or sections of bar stock. The use of these raw material forms necessitates designs that inherently contain a significant amount of additional wall thickness. This wall thickness makes future repairs much easier and allows extra material for erosion and corrosion allowance.

3.2 Stem

A valve is basically a machine with each component experiencing different loads and requiring different properties. The stem and spring experience higher stress levels than the body and seats. The stem stress is intermittent whereas spring stress is always present. The size of the stem is directly related to the strength of the material.

Grades 2, 3, and 12 have been used in stems, but grade 5 has been the predominant choice. Amongst others, Lone Tree, Twin Creeks, Lihir, Bulong, Macraes, Sepon, Con, Pueblo Viejo, and Ambatovy have all used grade 5 stems. It was reported that the grade 5 used on 6” Macraes vent valves was being chemically attacked and was subsequently replaced with Grade 12.38 In most cases, grade 5 is well suited to use in this component because of its high yield strength (120ksi min), availability (thanks to aerospace) and good general corrosion resistance. Valve stems constructed of grade 12 are approximately 34\% larger in diameter then those constructed of grade 5. With the large diameter, comes a significant increase in operating torque due to packing stem diameter. This operating torque increases actuator size and weight, and complicity piping design and maintenance access.

3.2.1 Example: Stem Failure at Twin Creeks

A 12” Class 300 Mogas discharge valve installed at Twin Creeks experienced a brittle fracture of a Titanium 6-2-4-6 (6% Al, 2% Sn, 4% Zr, 6% Mo) material. This is a non-ASTM titanium grade that is made to AMS 4981 or MIL-T-9047. This fracture initiated in the stem and progressed through the entire stem section breaking the stem into two pieces. The fracture was outside of the packing box and no leakage occurred. Follow-up investigation indicated the titanium 6-2-4-6 had apparently good physical
properties of 180.8 ksi ultimate tensile strength, 162.9 ksi yield strength and 15.0% elongation. Despite these properties, brittle fracture apparently occurred well below the yield strength of the stem.

The material was next considered from a fracture mechanics perspective. Specifically, the ability of this material to resist crack propagation with defined defect sizes was examined. Three sample forgings were reviewed with yield strengths of 155, 172, and 167 ksi and elongation ranging from 16% to 35%. The $K_{IC}$ fracture toughness for these three forgings was between 20 and 27 ksi-in$^{0.5}$. A fourth forging was located with a yield strength of 164 ksi and only a 7% elongation but with a fracture toughness of 47 ksi-in$^{0.5}$. This suggests that the fracture toughness of this titanium alloy could not be assumed to be good or bad based solely on the strength or elongation. The variance in fracture toughness suggests a range of possible defect sizes and quantities within the forgings sampled. This example shows that, when using high strength titanium at high stress levels, it is important to not only control the conventional mechanical properties of strength and elongation, but to also recognize maximum defect sizes in components and require minimum fracture toughness values.

### 3.3 Ball

Within a metal-seated ball valve, the ball and seats are precision mate-lapped components that must achieve a perfect fit in order to prevent leakage. The ball is spherical with a cylindrical section cut through the center for the valve bore and a rectangular section cut out perpendicular to the bore for the stem to connect to the ball. One important aspect of the ball, and indeed of the body also, is that in a slurry application it is desirable to have a “full bore” or “full port”. This means that the bore of the valve must not have any significant restrictions or tapers as is commonly done in commodity valves to reduce material costs. Hatch specifies the valve bore to match the ID of the pipe that the valve is connected to, which often requires the manufacturer to make a custom bore. The full port ensures that there are minimal pressure losses through the valve and reduces the erosive impact of the slurry on the ball, seats, and body. The design of the stem slot has also been examined. A stem slot with small contact area and/or small width means that the stem tang will be susceptible to shear or deformation. Generally the stem tang and stem slot are significantly over-designed to allow for much higher stresses than expected.

The ball is often damaged when the loss of coating or incorrect alignment allows “wire draw” to occur. This is essentially high velocity flow that proceeds through a small opening at the ball-seat interface and erodes a path across the ball and seat. In order to prevent small misalignments from causing issues, manufacturers usually oversize the ball so that even if it is off by several degrees, there will not be any leakage or wire draw. Additionally, the impact of solids hitting the outside of the valve or the scraping of built up scale upon closing by the seats can cause damage to the outside of the ball. An example of ball damage is shown below in Figure 13.
3.3.1 **FlexStream™ Ball**

Recognizing that depressurization is a time consuming and poorly controlled phenomenon in many different chemical process industries, Mogas has produced a line of FlexStream™ ball valves that can be used to accelerate the depressurization process by more precisely controlling the pressure drop across a ball valve than could previously be accomplished. Plates that use alternating hole sizes partially fill the ball bore to create tortuous flow paths that reduce the velocity of the flow when the valve is initially opened. This allows the valve to maintain a very low $C_V$ for any desired portion of the stroke and either gradually or instantly transitions to a high $C_V$ once the differential pressure is reduced.\(^\text{39}\) This limits the erosion of the valve internals caused by particulate in the flow and allows depressurization to occur faster. Theoretically, this will reduce the time for autoclave depressurization to the quench vessel from over 24 hours to approximately 13 hours. The valve design also benefits from the fact that it fits into a standard Mogas ball valve and can therefore be retro-fitted or removed at minimum cost.

The valve is being trialed on one train of the Pueblo Viejo plant and has the trim components and downstream end connection of the valve constructed from titanium grade 36, with grade 12 being used on body and upstream end connection. These valve materials of construction are common among the all 8” vent valves, so valves can be interchanged readily. For attaching the throttle plates for the FlexStream™ seat, a new electron beam process was qualified and applied. This process required no consumables and was conducted in a vacuum atmosphere. Figure 14 shows the customized plates and seat.
3.4 Seats and Spring

There are two prominent seating designs that have been successful in autoclave applications. In one valve design, tolerated seats that are not affixed to the valve body are used. Each seat has a Grafoil gasket behind it that provides sealing between the seat and body and acts as a spring in holding the seats against the ball. At Bulong, a forerunner to the current valve design had seat gaskets that were exposed to the process and experience washout. This was resolved by stepping the seat so that the gasket was no longer exposed. A concern with this design is that it does not provide sufficient loading of the ball to prevent leakage around the ball and seats in higher pressure environments. In spite of this criticism, the valves have continued to perform well in the Nevada (gold) and Arizona (copper/molybdenum) autoclave operations.

Other manufacturers use a spring-loaded upstream seat and a fixed downstream seat. The fixed seat is connected to the valve body using a series of screws. This was first used at Cawse, when it was discovered that leakage behind the downstream seat was causing damage and valve failure. A concern with the spring-loaded seat is that scale build-up can interfere with the spring causing it to jam into the ball, increasing actuation torque and eventually seizing the valve. Some designs have incorporated special seats or other sealing mechanisms that enclose the spring between the seat and the valve body, in theory reducing the possibility of slurry affecting the spring’s operation. This seat design has found successful application in several POX and HPAL plants.

3.5 Thermal Spray Coating

At the advent of gold POX technology, the application of thermal spray coatings to metal-seated ball valves was still in its infancy. Some ball valve manufacturers had dealings with coating companies, but often these were simple vendor to sub-vendor exchanges rather than anything approaching a fully integrated partnership. Exchange of information concerning application details and field performance was haphazard at best and often the valve manufacturer and end-user had little to no knowledge of what coating would work in a particular application or even what attributes would make one coating superior to another in service.
Initially, POX plants tried carbide cermets that had been used in high-wear applications in other industries. These coatings used hard ceramic particles in a metal matrix that was composed of tungsten, carbon, nickel, cobalt and/or chromium alloys. The carbide coatings failed very quickly due to corrosion of the metal matrix. The first coatings used with some degree of success were “chrome oxide” or “chromia blend” ceramic coatings, which had lower bond strength, but similar hardness, and superior corrosion resistance. Tantalum base coats were used to increase bond strength to the substrate. These coatings were applied using atmospheric plasma spray (APS) and were used on titanium and CD4MCu/Ferralium 255 valves in Nevada autoclaves. While the coatings were labelled “chrome oxide”, they generally contained a wide range of chromia phases and had small percentages of silica and titania added to them.

Based on the use of the chrome oxide coatings in Nevada, the Australian HPAL plants built in the late 1990s were specified with the same coatings. Typically, the coatings were still APS, although vacuum plasma spray (VPS) was also tried with varying success. The chromia coatings did not work well in the more severe conditions of the HPAL plants and manufacturers began using APS TiO2 coatings instead. These were shown to perform better than the chromia coatings in HPAL but still had relatively poor mechanical properties.

The chromia coatings in Nevada eventually gave way to a superior 99% Cr2O3 with Ta base coat and this improved coating/valve life. The coating has also been successfully applied to other components that experience severe wear such as autoclave agitator blades and autoclave oxygen spargers. This 99% Cr2O3 with Ta base has not yet been tried in the HPAL plants.

The latest significant advances have been in the development and application of nano-structured TiO2 coatings by Mogas, F.W. Gartner, and Perpetual Technologies. This coating was developed in response to the continuous failure or poor performance of other chromia and titania coatings in the HPAL environment. Analysis has shown that when these coating are applied via HVOF, the lower porosity and un-melted nano-structured portion of these coatings help to increase their hardness, and resistance to crack propagation and wear, which are all thought to be the underlying causes of its higher bond strength. Figure 15 and Figure 16 display some of the properties of the nano-TiO2 coating.

![Figure 15: Microhardness of APS TiO2 and nano-TiO2](image-url)
Although the coatings have improved substantially, they still represent a primary cause of valve failure. Failure manifests itself in two main fashions. Firstly, the ceramic coatings can separate from the ball or seat substrate by corrosion of the substrate metal, corrosion of the coating and/or low bond strength between the coating and substrate. Coating will be visibly spalled from the surface in patches. Secondly, the coatings can fail due to poor abrasion and wear resistance. In this scenario, depending on the coating, brittle fractures along splats and cracking, cutting, and/or ploughing marks are visible on the coating when viewed microscopically.

The substrate metal is known to affect the performance of coatings. Different substrates yield significant differences in coating bond strength even at ambient temperature due to the fact that coating simply does not adhere to all materials in an identical fashion. Additionally, corrosion of the top layer of the substrate can lead to coating failure. The increased usage of titanium as a ball and seat base material, however, has greatly reduced the likelihood of coating separation due to substrate corrosion. It is thought that the difference in coefficient of thermal expansion between the substrate and coating also contributes to a loss in mechanical properties after thermal cycling.

### 3.6 Actuation

Typically, actuation is supplied by a sub-vendor that the valve manufacturer corresponds with to ensure that design requirements are met. Pneumatic actuators have been historically used, but larger sized valves are now specified with hydraulic or a self-contained electro-hydraulic system in order to reduce the weight of the actuator. Since hydraulic actuators use a fluid with greater density, the required actuator is smaller to achieve the same force. The drawback is that a hydraulic power unit (HPU), involving a pump, valves, electronics, accumulators, and other components is required, and this can be more expensive than the pneumatic option. If the HPU is of significant weight, it can be placed off of the valve, so as keep the weight savings gained by using the hydraulic actuator.

To support the various types of actuators, actuator mounting brackets must be designed by the valve manufacturer so as to provide a rigid platform that will allow the actuator to sit directly on top valve stem. It is important that these brackets take into account the tremendous torque produced by larger actuators as this can cause significant stresses and potentially lead to bracket damage, stem misalignment, and damage to other components inside the valve.
In order to avoid any adjustment once installed, some manufacturers use interference pins in addition the mounting studs used to connect the actuator to the valve body. Some manufacturers use vertically (parallel to the stem) installed studs/pins, whereas others use horizontal (perpendicular) stud/pins. In order to prevent twisting of the bracket, the units with vertically installed studs/pins have brackets that directly mate with a raised edge on the valve body such that the bottom surface cannot physically rotate when affixed to the valve.

There have been some issues relating to the thermal expansion that the bracket undergoes relative to the valve body. Usually it is desirable to construct the bracket from a cheaper material such as carbon or stainless steel, rather than the exotic alloy of the body. In high temperature services, the differing coefficient of thermal expansion between the body and the bracket can cause thermal stresses and cracking of the bracket. One innovation that has been used recently is to design a cut section through the center of each side of the bracket. This patented design allows the bracket to be relieved of some of the stresses associated thermal expansion/contraction.
4. **Manufacturing and Quality Control**

4.1 **Positive Material Identification (PMI) and Material Test Reports (MTR)**

Once raw material has been supplied to the valve manufacturer, the valve specification requires the manufacturer’s quality control department or a manufacturer-appointed sub-vendor to verify the materials of construction using some form of positive material identification. This task is readily accomplished with a handheld analyzer that uses either X-ray fluorescence (XRF) or Optical Emission Spectroscopy (OES) to determine the percentage of each major element contained in the test component. From this information, the analyzer displays the closest material name from its database to the user for validation. Additionally, the data can be uploaded from the device to produce a report for the engineering consultant’s verification and records. MTRs are also required to be submitted, and the engineer verifies that the heat numbers on the PMI match those on the MTRs.

4.2 **Material In-Process**

During the manufacturing process, all major components are individually serialized and logged on job travellers. This includes: the body, end connection, stem, gland, gland flange, spring(s), ball, and seats. Tracking these components through the process provides a high level of certainty that components of differing materials or specifications are not accidentally swapped between valves and that materials requiring special treatment in the shop, such as titanium alloys or alloys used for oxygen service, are handled carefully and not machined inappropriately or contaminated. As discussed previously, iron contamination of titanium can lead to accelerated corrosive attack when the valve is placed in service and incorrectly using a titanium component in a 99% pure oxygen service alloy 20 valve would almost certainly lead to a catastrophic oxygen fire. Having a high level of traceability, with respect to the heat number, also allows for more accurate determination of the impact of any material flaws that arise on the entire quantity of valves produced.

4.3 **Thermal Spray Coatings**

Quality control is of paramount important in autoclave valve thermal spray coatings because it is most commonly the first area to fail. The development of automated coating systems using thermal spray guns attached to multi-axis robots has been a major factor in improving the consistency and overall quality of coatings. As recent as the mid-1990s, leading manufacturers of autoclave ball valves unanimously had their ball and seat coatings applied manually by sub-vendors. The combination of a somewhat “hands-off” attitude towards coater’s practices by the valve manufacturers and the manual coating method led to coatings that were of inconsistent quality. As discussed in the specification portion of this paper, Hatch now requires a variety of tests to be conducted throughout the production process to ensure quality is maintained throughout.

4.3.1 **Grit Blasting**

For APS and HVOF ceramic coatings, just prior to thermal spray, an operator pneumatically blasts parts with grit in an enclosed cabinet or chamber and then blasts the parts with air in an attempt to remove any loose or embedded grit remaining on the surface. There are two major purposes for this operation:

- Remove debris and contaminants from the surface of the ball and seats
- Sufficiently roughen the surface of the part to provide greater surface area and microscopic surface upset that will mechanically enhance the bonding of the coating to the substrate
The pressurized grit physically removes a thin layer from substrate and therefore any chemicals or foreign particulate on this thin layer. Additionally the grit creates microscopic “peaks and valleys” that help to anchor the coating to the substrate. The degree to which this surface undulation occurs is known as the upset ratio. Typically it is calculated by measuring the width of a magnified bond line image and comparing it to the actual length of the bond line. From this ratio, the coater can compare test cases and identify which grit produces better upset, although this must be balanced with other resulting metrics such as the bond strength and bond line contamination.

Recently, grit blast media has been varied in an attempt to optimize these desired results. As expected, it has been found that varying the mesh size of the grit can increase or decrease the roughening effect on substrate surface, but that an ideal size is reached where past this size there are diminishing returns in terms of the effect on the coating bond strength. Grit material has also been varied in order to provide greater upset or simply to eliminate the concept of contamination altogether.

### 4.3.2 Sampling

In practice, accurate coating sampling presents some unique challenges to the vendor. The first challenge is to determine how the samples will be coated to provide the most representative version of what is actually on the ball and seats. The key to having a representative sample is having the coating gun moving in relation to the sample in an identical manner to how it moves relative to the part, and to accomplish these tasks as part of the same coating run so that gun parameters are identical. The ball and seats have their own complex geometries while the samples are typically small cylindrical pieces (in the case of ASTM C633) or may be strips of plate in the case of other bond strength or metallurgical tests. Obviously, there is no resource or standard that provides information on how to correlate these geometries, it must be investigated and developed by the coater.

Achieving a representative coating on the seats is relatively simple, as seats are typically coated while sitting flat on turntables. The samples are generally placed on either the same turntable or a separate one rotating at the same speed. The coating robot approaches and coats the samples in very similar manner to that used on the seat. With the ball, it requires more ingenuity to obtain a representative sample. The ball is coated by rotating it on a horizontal axis positioner and using the robot arm to move the coating gun horizontally in a curved path across the ball. When the ball is large enough, a sample is usually placed in the stem slot area (normally not coated) so that as the coating gun moves across the rotating ball, its program deviates slightly to coat the flat coupon and the gun continues across the remainder of the ball. At smaller sizes, samples often do not fit in the stem slot, so the surface velocity used on the ball must be as closely matched with the method used to coat the coupon as possible.

Once samples are made, additional preparatory steps are usually required. For bond strength testing, samples must have adhesive applied and then are bonded to a text fixture for a tensile test device. For metallurgical analyses, the samples must be polished and cut correctly so that coating is not smeared or otherwise distorted when viewed under a microscope. The preparation, visual inspection, and data acquisition for the samples of many lots make the quality control stage of production highly time consuming.

### 5. The Future

The future of titanium metal-seated ball valves in pressure hydrometallurgy is promising. Although it has been an arduous process, the valve technology is now well developed and has been applied across many plant configurations and ore metallurgies. In spite of the variety of challenges posed, POX and HPAL technology have gained global acceptance as viable methods for processing large quantities of ore in an economic and environmentally preferable way. The long term fundamentals for gold and nickel remain
the same. These are non-renewable resources in a world with increasing population growth and resource demand. Continued exhaustion of easily extracted sources of gold and nickel is only possible in the short term. Metallurgists and plant designers will require plants to have higher throughput, higher temperature, and higher pressure operating conditions, continually challenging the limits of metal-seated ball valve technology. The historical performance and our academic knowledge of titanium alloys dictate that they will continue to be a material of choice in the autoclave valves of the future.

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Kim.

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Overview

• What are HPAL and POx?
• What are Metal-Seated Ball Valves?
• Valve History
• Valve Specification
• Why Titanium?
• The Future...
What are HPAL and POx?

• Hydrometallurgical Processes
  – High Pressure Acid Leaching (HPAL) and Pressure Oxidation (POx)
  – Extract metals from ores via aqueous chemical/physical processes

• High Pressure (400-1000 psi) & Temperature (400-600 °F)
  – Chemical reactions in large horizontal “autoclave” vessels
  – Depressurize slurry into “flash” vessels, gas into “quench” vessels

• Acidic, Erosive, Scaling Media
  – Acid is either a by-product generated via oxidation (POx) or added to leach the metal into solution (HPAL)
  – Solids erode equipment
  – Precipitation of certain minerals (gypsum, clays, silicates) and solidification of slurry causes thick, “rock-like” scaling
Gold POx & Nickel Laterite HPAL Ball Valves

Con, NT, Canada
Campbell Red Lake, ON, Canada
Goldstrike, NV
Lone Tree, NV
Twin Creeks, NV
Pueblo Viejo, Dominican Republic
Murrin Murrin, WA
Ravensthorpe, WA
Bulong, WA
Hillgrove, NSW
Cawse, WA
Ramu River, PNG
Porgera, PNG
Macraes, NZ
Goro, New Caledonia
Lihir, PNG
Porgera, PNG
Amursk, Russia
Chelopech, Bulgaria
Sepon, Laos
Coral Bay, Philippines
Ambatovy, Madagascar
Kittila, Finland
Amursk, Russia
Gold POx
Nickel Laterite HPAL
In-Service HPAL Valves

RAVENSTHORPE, AUS

CAWSE, AUS

CAWSE, AUS

BULONG, AUS
The Importance of HPAL

World Nickel Resources

- 28% HPAL Laterites
- 44% Pyro Laterites
- 28% Sulphides

World Nickel Production

- 58% All Laterites
- 42% Sulphides

• HPAL Laterites are primary source of future Ni & Co
• High throughput technology, proven economic viability

Dalvi, Bacon & Osborne, 2004
POx Autoclave Valves
GOLD POx

SEPON, LAOS

PORGERA, PNG

MACRAES, NZ
In-Service POx Valves

LIHIR, PNG

MACRAES, NZ

GOLDSTRIKE, NV

LONE TREE, NV
The Importance of Gold POx

- Increasing viability of processing refractory ores requiring oxidation
- POx is high-throughput, high-recovery, low arsenic & sulphur emissions

Marsden, 2006
Importance of Metal-Seated Ball Valves to HPAL and POx

- 1-4% of Total Capital Costs (20-50 million USD per project)
- Caused 10% of Plant Downtime in Early POx
- 20-30% of POx Maintenance Costs
- 30-40% of HPAL Maintenance Costs
- Failure/leakage is a safety issue – hazardous media
What are Metal-Seated Ball Valves?

1. Stem
   Ti Gr. 5, 12, 28, 36
2. Ball/Seats
   Ti Gr. 5, 12, 36
3. Body/End
   Ti Gr. 12, 2, 36
4. Spring
   Ti Gr. 5, 12
5. Coating
   Nano-TiO2 and Cr2O3
Valve History – 1st Generation

The first round of valves were “Borrowed” Designs

• Basically Commodity floating ball valves

• Castings

• Minimal wall thickness

• Preliminarily engineered for soft seats not hard ceramics

• Not designed considering solids and abrasion

• Small stems and actuator mounting capability
Ball Corrosion and Erosion
Stem

- High Actuator Torque – up to 260,000 in-lbs for 10” valve

- Traditionally Ti Gr. 2, 3, 12

- Now Gr. 5 chosen for high yield strength

- Gr. 12 stem 34% larger than Gr. 5

Ti-6-2-4-6 stem - the result of low fracture toughness
Valve History – 2nd Generation

The second effort became Custom “Engineered” valve designs from forgings

- Continued issues with solids packing in
- Scaling caused not only potential leaks but increased torque
- Erosion
- Coatings – brittle, not resistant to corrosion, poor bond
Valve History – 3rd Generation

The next series of valves were “application specific” in design with new advancements to address total cost of ownership

- Designed to resist solids accumulation and scaling
  - Geometry
  - Plant Operations, partial stroking
  - Purging of bodies
- Advances in coating technology
  - Bond strength
  - Ductility
  - Corrosion Resistance
  - Erosion Resistance
- Improvements in Plant Design and Operations
  - Hydraulic Actuators
  - Sequencing
- Better Engineering Understanding of Performance Requirements and Yield Expectations
Valve Specification

Highly Defined Requirements:

- Valve design attributes
- Valve performance, # of cycles
- Materials selection
  - Ti Gr. 2, 3, 5, 7, 12, 28, 36
- Complete traceability of components
- Thermal Spray Coating characteristics
  - Bond strength, Porosity, Hardness, etc.
- Actuator torque safety factors due to scale build-up
Why Titanium?

- Oxidizing and Slightly Reducing Acidic Environments
- High strength required for components
- Lighter weight lowers piping stresses
Valve Specification

Ball – Coating / Lapping Process for 10” Ti Gr. 12
Valve Specification

10” Ti Gr. 12 Valve and Hydraulic Actuator

Hydraulic Power Unit
Valve Specification

- New welding challenge
- Ti Gr. 36 FlexStream™ Trim for Depressurization to Quench
The Future…

• Growing number of HPAL and POx plants
• Higher temperatures/pressures to optimize reactions
• Incorporation of new titanium alloys for enhanced corrosion resistance and O2 ignition prevention
Questions, contact:

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