24-010

Analysis and Repair of Failed Copper SX Plant Mix Boxes: An Application of First Principles

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ABSTRACT

SX operators have conducted extensive shut-downs and repairs over the years to mitigate solution leaks from failed stainless steel false floors and walls in rectangular mixer-settler mix boxes. Hydrodynamic modeling using first principles and constitutive equations of fluid mechanics can inform an efficient structural redesign sufficient to eliminate the plate failures. Updated mix boxes have been performing without failure for over a decade. Given the extensive construction of the original Holmes and Narver mixer-settler design throughout the world that includes stainless steel lined rectangular primary and auxiliary mix boxes, SX operators may benefit from the approach, eliminating costly shutdowns, leaks to containment, and hazardous repairs.

INTRODUCTION

The mixer-settler is in integral element of SXEW technology used in many copper mining operations. It is essentially a combination liquid-liquid contacting and phase separation piece of equipment which consists of a series of mixing stages (mixers) where an Aqueous phase and Organic phase are dispersed into each other through agitation and then followed by a separation stage (settler) where the phases separate by gravity. Depending on the process function of the settler, the ions of interest or process buildup, are selectively retained or discarded via extraction, washing, or stripping. The Aqueous phase comes to the primary mixer as Pregnant Leach Solution (PLS) or Electrolyte. The PLS comes directly from leached stockpiles. Electrolyte circulates from the plant Tank Farm where it resides as feed for electrowinning processes. The Organic phase loads or unloads the ions of interest and circulates between the stripping, wash, or extraction stages, or the plant Tank Farm. The mixing stages disperse the phases into each other to provide ion exchanges or washing, depending on the process function. The mixing of the immiscible Organic and Aqueous phases forms a dispersion into each phase. The volume fraction of each phase (O:A ratio), viscosity, mix tank size, and mixer impeller speed and size, can affect the breakup and coalescence of phase droplets and whether the Aqueous phase is dispersed as droplets in a continuous Organic phase or the Organic phase is dispersed as droplets in a continuous Aqueous phase. Typically, settlers are operated as Organic-continuous at stripping and Aqueouscontinuous at extraction. The settler allows for a quiescent phase disengagement by gravity. The Aqueous and Organic phases are ultimately removed from the settler at the settler weirs. Settlers are operated to minimize entrained phases.[1]

The current study is from the Metcalf SX Plant at the Freeport McMoRan Morenci Operation located in Morenci, Arizona and was performed in 2012. The Metcalf SX Plant was originally designed by Brown and Root U.S.A. Incorporated for Phelps Dodge Mining Company around 1986 as part of the original project that brought heap leaching and SXEW technology to the Morenci copper mining operation. The Metcalf SX Plant has two separate trains fed from an elevated pregnant leach solution (PLS) plant feed pond. At the time of this particular study, each train processed approximately 7,800 gpm of PLS for a total of 15,600 gpm nominal plant capacity.

The Metcalf SX E1B mix box is the focus of the study and is part of the "B" Train and first Extractor circuit, thus E1B. This particular mix box is the first location that PLS enters the SX process from the plant feed pond. The original flow sheet values for PLS flow (commonly referred to as "Aqueous") into the E1B was 6,000 gpm along with Organic flows of 6,000 gpm. See Table 1 for representative

Table 1. Operating conditions for FMI Morenci Metcalf SX E1B Mix Box

Stream	Flowsheet Nominal	Flowsheet Maximum	Field Data 2/8/2012	Study 1	Study 2
PLS flow (gpm)	6,000	7,000	7,650	7,800	12,000
Organic flow (gpm)	6,420	7,500	3,700	3,600	6,200
Pump mixer speed	42 rpm @ 60 Hz	-	37 rpm @ 53 Hz	37 rpm @ 53 Hz	40 rpm @ 57 Hz

operating data. The E1B mix box appears to have been redesigned by Fluor Daniel Wright in 1994 and replaced. The Winters Company, as part of the Loaded Organic Wash project had revised flow sheet values as 6,000 gpm nominal and 7,000 gpm design PLS and 6,420 gpm nominal and 7500 gpm Organic flows.

The original Brown and Root structural design of the mix box itself was of 10-gauge 316L stainless steel sheet acting as a false floor and liner for a reinforced concrete box. The later design by Fluor shows a 1/4" plate design for the false floor inserted in essentially the same configuration. The pump mixer originally procured and installed by Brown and Root, Tag No. 232-W-008, consisted of a Lightnin Model 77- Q-40 Extraction Pumping Mixer with an R301 6-bladed 85.5" diameter straight radial vane impeller with 10.5" wide vanes driven at 42 rpm by a 40 hp 1200 rpm motor and right- angle speed reducer.

FAILURES AND REPAIR HISTORY

Since construction, a long history of yielding and metal fatigue related failures and subsequent solution leaks into the facility containment have occurred on the sidewalls and false floor of the primary mix boxes. Adverse hydraulic loading appeared to have initiated premature failure of much of the box structure.

Over the course of a typical year an SX train would require multiple shut-downs to drain the system, clean the boxes, and locate and repair cracks by welding. See Figures 1 and 2 for typical plate repairs. Some cracks were very difficult to locate and resulted in some being missed and not repaired, negating much of the benefits of the repair effort. Repairs were also being attempted in extremely cramped confined spaces presenting a myriad of potential hazards and requiring a variety of controls.

Freeport initiated a mix box replacement program around 2001 at the Chino SX Operation in Vanadium, New Mexico. CAID Industries, a mining technology equipment fabricator and supplier in Tucson, Arizona, was contacted to develop a reinforced drop-in replacement that could be installed within a short time-frame, which was subsequently successfully accomplished. Learnings coming from issues with the replacement boxes informed design improvements by CAID prior to attempting replacements at the Morenci operation in 2007 at the Central SX Plant where flows were higher and larger primary mixers employed.

A preliminary design from CAID was provided to Freeport in 2011 for the Metcalf SX E1B mix box. A subsequent request from Freeport was made for a third-party analysis of the efficacy of the replacement along with the development of a concise study report. The findings from that initial basic study of the original 1986 and proposed 2011 mix box designs including the mix box hydrodynamics and structural analysis follow.

Figure 1. Typical fatigue cracking repair

Figure 2. Fatigue crack repair

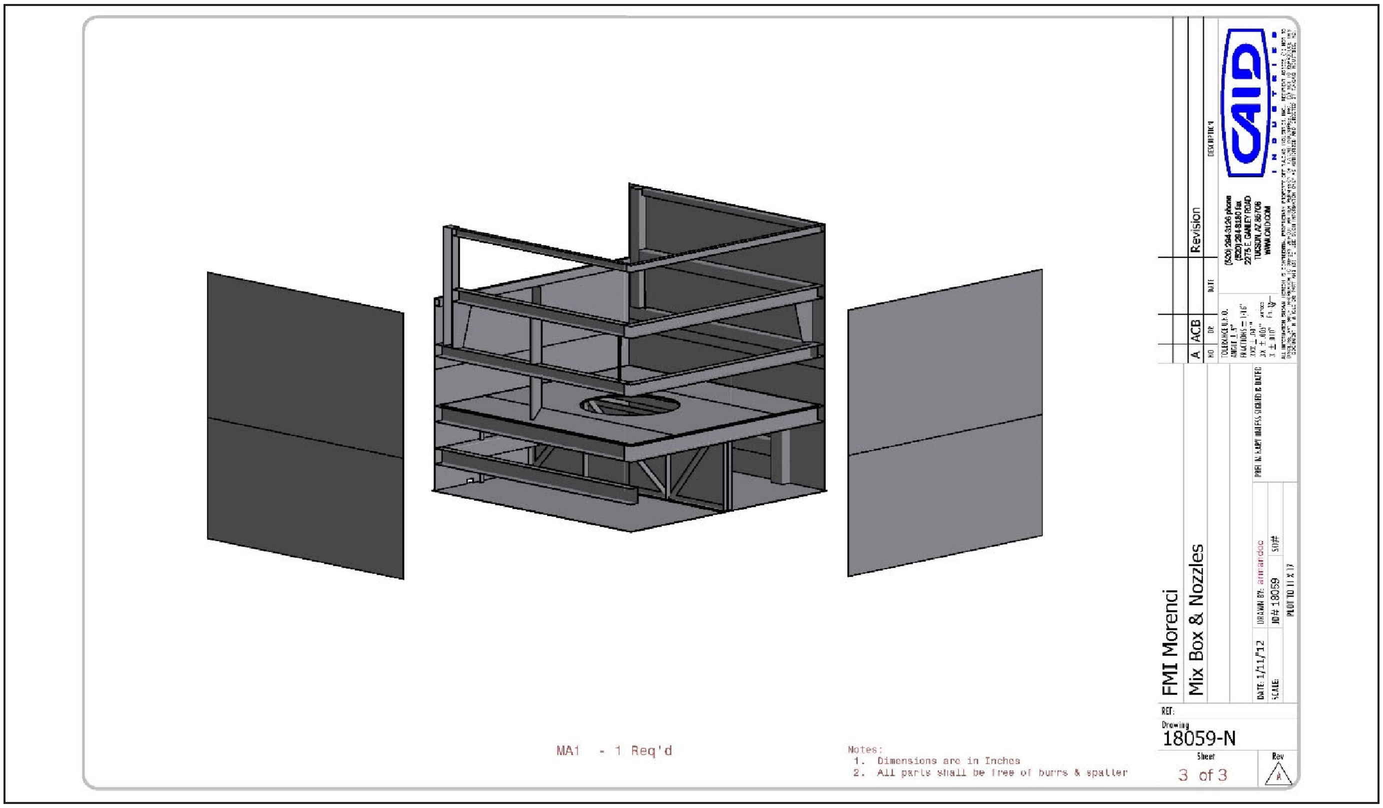

Figure 3. CAID proposed mix box replacement design

MODES OF FAILURE

Failure modes were deduced from observations of photographs and interviews with mechanics involved in the repairs. The cracks in the false floor originated at the plate edges and stich-welded connections radiating into the unreinforced areas of the sheet which are highly characteristic of stress reversals and metal fatigue. Yielding failures of the intermediate wall between aqueous and organic sides below the false floor were also reported as broken members and metal deformations.

BASIS OF ANALYSIS

The analysis of the existing E1B mix box and the CAID preliminary design was generated from information collected at the site, including field observations, operator interviews, real-time operational data, and field measurements, original engineering drawings, and preliminary drawings from CAID.

Considering first principles, balance of mass and energy, balance of momentum and moment of momentum, etc. led to the identification of the sources of the forces that develop the ultimate static and dynamic loading on the plate structure of the mix box which include the flow dynamics of entering, internal, and exiting fluid flows, and mixer dynamics.

Applications of Navier-Stokes as well as constitutive equations of fluid and solid mechanics and general plate theory were utilized to evaluate the hydrodynamics and states of stress in the platework and reinforcing. Some simplifying assumptions were made to enable the modeling of the flows with fundamental equations of momentum, fluid statics, and other constitutive equations.

ANALYSIS

E1B Feed Piping System Analysis

The lower flow conditions of PLS and Organic into the E1B mix box, namely 7,650 gpm Aqueous and 3,700 gpm Organic werae analyzed to determine the flow regime, and whether unsteady or surging flow conditions exist. Each of these were evaluated to understand the dynamic flow conditions into the lower chamber of the E1B mix box. It was found that neither system would operate in an unsteady flow condition that could result in transmitted surge effects from pipeline surging. In other words, pressure loads should be fairly static over time at the pipe discharges into the mix boxes.

Mix Box Flow Analysis and Pump-Mixer Dynamics

The Flow conditions in both the lower and upper chambers of the mix box calculate as turbulent. The hydrodynamic loading conditions on the mix box structure were observed to be highly variable and complex. See Figure 4.

Solution static pressures in a mixed condition for the upper chamber and in unmixed conditions in the lower chambers were calculated at a maximum of 5.13 psig on the Aqueous side and 4.69 psig on the Organic side. Pressures on the exterior walls and the bottom of the false floor in the lower chamber are increased as solutions are forced up through the semi-circles in the false floor, which have been modeled as a modified orifice. In the calculation, the traditional constitutive equation coefficient components of the frictional and contraction orifice coefficients have been modified to account for the sharp-edged semi-circle together with the flat wall which bisects the circle through the center. For the CAID design, and an orifice diameter of 48," pressures calculated at 0.0621 psig and 0.147 psig on the Aqueous side at 7,800 gpm and 12,000 gpm respectively and 0.0108 psig and 0.0319 psig on the Organic side at 3,600 gpm and 6,200 gpm respectively. For the original design of a 30" diameter orifice the initial calculation resulted in an Aqueous side pressure of 0.409 psig.

Power draw information was taken in the field on 8 February 2012 for the E1B pump-mixer. The mixer currently has a Lightnin R301 impeller, 85-1/2" diameter with six straight radial vanes. At approximately 40 amps, the power consumption of the unit is around 38 hp. At a noted Lightnin design lift of 3 ft. pumping efficiency is around 22%, corroborated by the high specific speed of the impeller at 1744. The ideal head development of the radial vane impeller configuration calculates to 7.63 ft at 42 rpm and ideal inlet conditions.

Additional information was available on the FMI-Chino Operations E1B mixer where the mix box geometry is similar to the Morenci E1B, but the mixer is a Lightnin R320D, 64" diameter with six curved radial vanes. Data had been taken at 56 rpm and 31 amps, giving approximately 30 hp. Impeller specific speed calculated to be 2512. The ideal head development is 7.58 ft. at that speed. Morenci also has the R320D impellers on site as uninstalled spares.

Fluid forces from impeller rotation were derived from evaluating the velocity polygons between inlet and outlet of the impeller.[2] Pressure differentials and changes in momentum from directional changes of the fluid were imparted to the plate as distributed loads. The unbalanced force of the solution stream coming from the R301 impeller and impacting on the lower part of the upper chamber wall and locally near the corner of the false floor is quite small and calculates around 0.0611 psi at approximately 11,350 gpm solution flows. The vane pass frequency for consideration of fatigue loading at 42 rpm computed to 252 impulses per minute or over 360,000 impulses per day. Therefore, it would take 2.76 days to reach one million cycles. As the vanes pass from the Aqueous side of the false floor orifice to the Organic side the pass frequency is 42 impulses per minute or over 60,000 impulses per day and

16.5 days to reach one million cycles. Due to the significant velocity change that would happen near instantaneously as the impeller passes from the Aqueous side of the false floor orifice to the Organic side, a high positive-pressure impulse is likely to occur on the false floor plate in the vicinity beneath the impeller. An opposite effect or

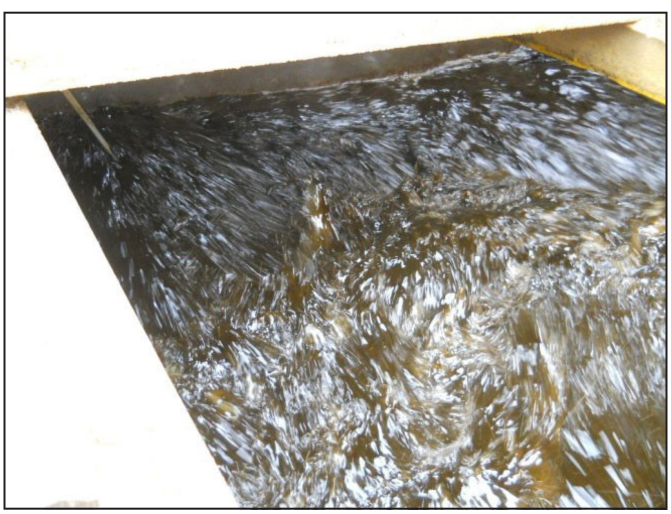

Figure 4. Typical turbulent solution surface in the E1B mix box with R301 impeller

Figure 5. Typical semi-quiescent solution surface in the E2B mix box with R320A impeller

negative-pressure impulse (in direction) is likely to occur as the impeller passes from the Organic side to the Aqueous side. This impulse is calculated to be around 0.141 psi and would occur locally at these transitions around 4 times per second or at the impeller vane pass frequency.

The R301 impeller provides a 1.56 psi pressure pulse to the top of the floor plate as the flow migrates through the radial vanes into the open flow of the mix box at the stated flow and rotational speed.

The backward curved radial vanes of the R320D impeller provide a much smoother flow transition and resulting pressure characteristics are much more favorable for the mix box structure. See Figure 5. Chamber wall momentum- derived pressures calculate at 0.102 psig. Aqueous to Organic impeller pass impulses calculate at 0.0465 psi and flow migration pressures through the curved radial vanes results in a 0.152 psi pulse to the false floor plates.

Determination of Fatigue Limit

A literature search[3] for ASTM A240 316L SS plate gave an ultimate tensile strength S_{ut} of 70,000 psi for the base material of the mix box. A suggested endurance limit in the literature was given as 35% of S_{ut} or an S'_e of 24,500 psi. A purely analytical approach was also used to corroborate this number as a design basis from a power curve fit of data from a strength/cycle diagram or S-N diagram and the stated S_{ut} of 70,000 psi.[4] Results yielded 35.28 kpsi at one million cycles,

29.1 kpsi at ten million cycles and 23.99 kpsi at one hundred million cycles. It should be noted that these calculated values are from an idealized completely reversed axial fatigue test of a round bar in simple tension. Because of this, precise results are not obtained, but rather should be used as a guide. The S'_e of 24,500 psi appears to be corroborated with the analytical approach and would at least be conservative. This value was used in the analysis.

The fatigue strength is determined by applying a surface factor, size factor, temperature factor and miscellaneous effects factor (i.e., notch/defect sensitivities factor) to the endurance limit[4] which yields a maximum allowable stress of 5,683 psi. With an additional applied factor of safety of 1.5, the target maximum stress under fatigue loading conditions is suggested to be 3,800 psi.

For non-cyclically loaded areas, the allowable stress determination was taken from the ASTM A240 316L stainless steel value of S_y = 25,000 psi. Taking 0.66 S_y, yields 16,500 psi. This is the value utilized for maximum allowable stress for pure static loads.

Plate Analysis

The static and dynamic loads were applied to the conceptual platework as distributed loads. Plate spans and reinforcement sections were modeled as both simply supported and fixed-fixed structures depending on position and orientation. Plate thicknesses and reinforcement section geometries were repositioned or thickened to ensure plate stresses were below the determined fatigue limit of 3,800 psi or 16,500 psi given the loading condition.

RESULTS AND DISCUSSION

Based on the analysis, the preliminary design presented by CAID required some slight, key modifications for the Metcalf E1B replacement.

The analysis identified that the reinforcing on the existing and proposed design appeared insufficient while utilizing the R301 impeller design. The suggested floor reinforcement redesign consisted of a composite arrangement of the upper 3/8” plate with an 8-3/8” deep Tee with 8” x 3/8” flange and 1/4” web, continuously welded throughout in two locations spanning the entire false floor. In addition, a 6”x3/8” flat bar welded on edge to the underside of the floor as stiffeners on approx. 33” centers (3 total) in the opposite direction as the Tees will be required to stiffen the floor plate sufficiently against the cyclic hydraulic load. If the R320D impeller is used, the proposed CAID design qualifies without modification. It is recommended that the reinforcing be added in order to keep the flexibility of utilizing the R301 or R320D impellers in the process.

It is also suggested that the orifice be kept at a minimum of 48” diameter for the plate design considered. A larger opening, if possible, would improve the pressure design of the system. A larger opening would likely result in a slight loss in efficiency of the pump mixer, but it is felt that it would be “small.”[5] A cone inlet is recommended to stiffen the free edge of the orifice and to improve the head losses through the orifice over the current flat-plate orifice design proposed. Stiffening of the Divider Wall is recommended. Based on the analysis, a suggested Divider Wall reinforcement is suggested as two 4”x3/8” flat bars oriented vertically on either side of the orifice cone as shown in the sketch, continuously welded on the Organic side. The proposed continuously welded angle sections running along the perimeter and angled across the face of the Divider Wall should remain. The Divider Wall should be welded continuously to the False Floor and box walls.

Stiffening of the lower chamber exterior walls was not required over the proposed CAID design. It was recommended though to lower the lowest horizontal stiffener by two inches to obtain a maximum plate stress of 16,500 psi in the lower portions of the upper chamber mix box wall. The other dimensions and suggested reinforcement could remain the same.

CONCLUSIONS

The updated design has reportedly been maintenance-free over the past decade. Additional mix boxes have since been replaced in other plants across the property with similar results. Shut-downs, worker exposure to the hazards of the previous repair approaches, and solution losses to containment have been in large measure eliminated due to the strengthened mix box design.

DECLARATIONS

Mention of any company name or product does not constitute endorsement by Freeport McMoRan or CAID Industries or those companies herein named. The findings and conclusions in this paper are those of the author and do not necessarily represent the official position of any named company.

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Analyzing the Effectiveness of Fire Suppression Systems to Extinguish a Fire on Mobile Mine Equipment Used in the Mining Industry

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ABSTRACT

To reduce the number of injuries resulting from fires on mobile, diesel-powered mine equipment, it is crucial to promptly suppress a fire once it is detected. The focus of this research was to determine the effectiveness of fire suppression agents. Large-scale tests were conducted using five different fire suppression systems based on: dry chemical, wet chemical, dual agent (dry and wet chemical), carbon dioxide, and water mist. Suppression nozzles were placed around the diesel engine where diesel fuel, engine motor oil, and hydraulic circulating oil spray fires were ignited. The results of this study can help mining companies and manufacturers by providing scientifically based data on the capabilities of the different fire suppression systems.

INTRODUCTION

Mineworkers often face a threat from mine equipment fires that can occur both at surface mines and in underground mine environments that can cause injuries or fatalities. The effectiveness of the fire suppression system installed on mine equipment can be limited by design quality, installation practices, and the type of fire suppressant employed. There are not any scientifically based measures available to help mine operators effectively prevent and suppress equipment fires. Most of the reportable mine fires are equipment fires caused by ignitions of combustible fluids such as hydraulic fluid released from a hose rupture onto hot engine surfaces. To reduce the number of equipment fires, it is necessary to develop effective measures to limit or prevent hot surface ignitions on mine equipment. To reduce the number of fire-related injuries and fatalities, it is important to improve the suppression techniques for the equipment fires to protect the equipment operators. Although some mine equipment include a fire suppression system, the efficacy of the system is compromised by poor design, ineffective installation, and fire damage to the system if not activated in time [1].

Various fire suppressing agents can be used for a fire suppression system such as dry chemical, wet chemical, carbon dioxide, water mist, and foam. Each fire suppressing agent has a different degree of effectiveness, depending on the type of fuel involved in the fire and fire conditions such as location, amount of fuel available, and ventilation surrounding the fire. The major fire-extinguishing mechanisms include cooling, separation or removal of fuel, dilution of oxygen, and breaking combustion chain reaction. Every fire suppressing agent acts on one or more mechanisms. Dry chemical fire suppressing agents generally consist of a chemical powder mixture that is electrically non-conductive. Dry chemical extinguishing systems are primarily suited for surface fires but are not effective on deep-seated fires. Wet chemical fire suppressing agents consist of a mixture of