Microbiologically Influenced Corrosion in the Main Injector Magnet Low Conductivity Water System

Case History and Final Recommendations

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INTRODUCTION

In mid-November of 1997, evidence of a severe corrosion problem in the Main Injector (MI) Magnet Low Conductivity Water (LCW) System was observed. The evidence consisted of numerous pinhole leaks in the new stainless steel header system which only became apparent during start-up operations, some months after hydrostatic pressure testing. Engineering consultants called in by Fermilab immediately diagnosed the problem as Microbiologically Influenced Corrosion (MIC) and suggested treating the circulating water with biocides to stabilize the situation. Shortly after this was done, M. May and P. Hurh, Beams Division/Mechanical Support Engineering, were asked by S. Holmes, MI Project Manager, to lead efforts to repair the affected systems and bring those systems to a "stable operational state" (see Appendix A). This report describes the repair efforts, identifies some of the causes of the MIC problem, and makes some recommendations for prevention of MIC in the future.

OVERVIEW

This report is organized into seven sections. The first section describes the MI LCW Systems affected by our efforts; the middle five sections offer a case history of our efforts; while the last section includes the most probable causes of the MIC problem in the MI Magnet LCW System and recommendations for operation of this system and the design of future similar systems.

The case history presented in the middle five sections is the bulk of this report. It consists of MIC Detection and System Stabilization (eliminate culprit microbes and halt progression of damage), Damage Assessment (determine severity and extent of damage), Weld Repair (repair leaks and damaged areas), MIC Mitigation (ensure culprit microbes' habitat is destroyed), and MIC Prevention (ensure culprit microbes' habitat is not re-established). Although the case history will roughly follow chronological order, efforts in all five sections actually occurred in overlapping time periods. Appendix A contains a flow diagram of how various efforts were conducted in parallel. The diagram was used to help plan the repair efforts and has been updated recently to show the mechanical cleaning option which was not originally considered.

References for this report are included at the end of the document. However, because a fair amount of the information included in this report was accumulated over months of conversations with various experts and consultants as well as review of technical literature available on the subject, a thorough documentation of references is not possible. Instead, Appendix B contains lists of reading materials, consultants, and reviewers that were found helpful during the repair efforts.

Much of the information in the case history is supported by documents and figures included in the Appendices of this report. In many cases, the documents included are only a small portion of the actual collected documentation (such as radiographs). The full set of documentation will be kept on file by the Beams Division/Mechanical Support Department and will be made available upon request.

I. DESCRIPTION OF MI LCW SYSTEMS

I.1 MI MAGNET LCW SYSTEM

The water system primarily affected by the MIC problem is the MI Magnet LCW System. Of this system, only the stainless steel header piping is affected (secondary manifolds to magnet bus jumpers were not connected at the time of the problems). The system consists of 6 above ground pumping stations distributed around the circular magnet ring supplying cooling water to the hollow conductor bus of all Main Injector magnets in the tunnel (344 dipoles, 208 quadrupoles, and 100+ smaller magnets) and their power supplies located above ground. Appendix C describes in further detail the design of the system from a flow and cooling capacity perspective. Note that the schematics are generalized and do not include all existing valves and fittings nor do they accurately describe pipe geometry and valve locations.

All of the piping components are 304L stainless steel welded with 308L filler metal. The vast majority of piping is seam welded 6-inch nominal pipe size, schedule 10 pipe. The magnet bus is constructed from OFHC copper. The stainless steel piping system has approximately 5,412 welded connections, most of these are girth butt welds and some 5% are on smaller 2" pipe size extruded tee connections (called goosenecks by Fermi personnel). Larger pipe (up to 14-inch nominal pipe size) exists in the pumping stations to accommodate the higher flow rates.

The pumping stations are housed within service buildings, which also house magnet power supplies and other essential accelerator devices. Each service building is labeled to designate its position around the ring (MI-10, MI-20, MI-30, MI-40, MI-50, and MI-60). The stretches of tunnel between the buildings are often referred to as sectors and are differentiated by the quadrupole magnet numbers that they contain. For instance, the 100 sector is the sector that contains mostly 100 series quadrupole magnets and connects service buildings MI-10 and MI-20. Water volume averages approximately 11,000 gallons per sector (piping volume of one service building included), bringing the total approximate water volume of the system to 66,000 gallons.

Each station includes a large tube and shell heat exchanger (also 304L stainless steel) and a de-ionizing (DI) and filtering circuit. About 2.5% (40 gpm) of the system flow (1650 gpm maximum) is diverted into each of the DI circuits. All 6 pumping stations are connected through the tunnel via the return and supply headers, although a net flow of only about 110 gpm is predicted between adjacent pumping stations. One of the six pumping stations (MI-60) includes a filling station (presently limited to 20 gpm) and a 3,000-gallon reservoir tank. The design operating pressure of the system is 150 psi.

In addition to the header system which circuits the ring, there is another header system which connects the Magnet LCW System to the Central Utility Building (CUB). This header system is called the 8 GeV line header and supplies cooling water for devices in the beamline between the Booster and the Main Injector. In final operation, it is expected that low conductivity for the entire MI Magnet LCW System will be maintained using DI equipment at CUB. The 8 GeV line headers are also 304L stainless steel welded with 308L filler metal. The majority of the 8 GeV line piping is seam welded 4-inch nominal pipe size, schedule 10.

I.2 OTHER MI LCW SYSTEMS

In addition to the MI Magnet LCW System, two other MI LCW systems were investigated for MIC damage, the RF Cavity (55 Degree) LCW System and the RF 95 Degree LCW System.

These systems have their pumping stations located in the MI-60 service building and supply cooling water to RF devices and power supplies both in the MI-60 service building and 600 tunnel straight section. Both systems have the same materials of construction as the Magnet LCW System described above. However, the volumes of these systems (about 8,000 gallons each) are much less than the volume of the entire Magnet LCW System.

II MIC DETECTION AND SYSTEM STABILIZATION

II.1 FILLING HISTORY AND LEAK OBSERVATIONS

The first sector (600 sector) of the Main Injector Magnet LCW System was filled with chlorinated well water on May 29, 1997, for the purposes of hydrostatic testing of the just completed piping. Each remaining sector was then filled by "pushing" the test water from the first sector with new well water from the MI-60 pump station. In this manner the entire system was filled and pressure tested over a period of 6 months. Unfortunately, between fills, the water was allowed to remain static in the just tested piping. This resulted in piping from different sectors being exposed to standing water for different amounts of time.

During the end of November, pumps started circulating the test water in the piping. It was at this time that several pinhole-sized leaks were discovered on the weld joints of the LCW piping. Although the vast majority of leaks were observed on or right next to a weld joint, several leaks were also found as far as one inch from the nearest weld joint. Leaks were observed not only on the 6" girth welds, but also on welds connecting elbows, drains, vents, goosenecks, and other fittings. In a handful of days the number of leaks multiplied to almost 400 and consultants were called in from Packer Engineering Services and Nalco Chemical Company (see Appendix B). From visual inspections of the leaks and tests conducted on water samples both consultants suggested the cause of the leaks was Microbiologically Influenced Corrosion.

II.2 MIC DESCRIPTION

Microbiologically Influenced Corrosion (MIC) is a phenomenon whereby corrosion of a surface is induced and/or accelerated by the presence of microbiological organisms, generally bacteria, and/or their by-products. Understanding MIC requires some expertise in three bodies of knowledge: microbiology, metallurgy, and electrochemistry. Since I am only semi-knowledgeable in one of these areas (metallurgy) and only familiar with another (electrochemistry), I cannot claim to fully understand the MIC phenomenon. Indeed, it is not the purpose of this report to educate the reader to a full understanding of MIC (several MIC references that I have found useful are listed in Appendix B). However, a basic acquaintance with the MIC phenomenon is needed to understand the rationale behind our repair efforts.

One generally accepted description of the MIC mechanism to failure is as follows. A thick biofilm (layer of live bacteria) develops on a susceptible metal surface. The microorganisms (may be several different types at one site) develop colonies and form nodules or tubercles (biomass containing microbiological and corrosion by-products and deposits). These formations can trap ions and occlude the metal surfaces directly beneath them from oxygen dissolved in the water. Thus the nodules and tubercles can create localized physical and chemical gradients at the metal surface, which initiate electrochemical corrosion cells (such as a differential aeration cell[1]). The electrochemical process dissolves metal beneath the biomass and a localized pit is formed.[2]

In the above description, the process starts with susceptible metal surfaces, bacteria laden water, and the right environmental and nutritional conditions to encourage culprit bacteria growth. All three conditions must be present for MIC to develop. Susceptible metal surfaces include most engineering alloys. Problematic bacteria seem to be attracted to less corrosion resistant areas of a metal surface.[3] This can be explained in two ways: First, the features that make a metal surface less corrosion resistant are usually also features of an environment that encourages microbiological growth. Features such as crevices (incomplete penetration in welds) provide a physical foothold for sessile bacteria colonies to form (localized areas of stagnant water and trapped organic matter).[4] Secondly, rather than microorganisms initiating the corrosion process, less corrosion resistant metal surfaces may actually be corroding already. These corrosion sites may attract the bacteria in the water because they become sources of dissolved metal ions and other nutritional requirements. In essence, the corrosion site may set up the proper environment that certain problem bacteria actually seek out.[5,6]

Regardless of how the microbes pick a site to start forming colonies and consortia, the corrosion mechanism occurring at the metal surface (pitting) is very damaging to the host metal. The corrosion process is very similar to a type of corrosion called crevice corrosion by corrosion engineers. In crevice corrosion, corrosion is often initiated by the creation of an oxygen or ion concentration cell. Stagnant water in a crevice cannot supply oxygen to maintain a passive oxide layer in the crevice. As oxygen is consumed in the crevice by the corrosion reaction, the water in the crevice becomes depleted of oxygen while oxygen is still available in the water at the mouth of the crevice. This creates a differential aeration cell accelerating the corrosion further.

Corrosion rates for MIC can be even greater than that for crevice corrosion usually because of the smothering coverage of the growing biomass. In addition, byproducts of some bacteria growth can be very acidic, accelerating the localized pitting even further. Some case histories report through-wall pitting of stainless steel pipes in just a handful of months.[7] One of these reported an effective corrosion rate of 0.055 inch per month for a 308 stainless steel weld.[8]

II.3 PRELIMINARY CONFIRMATION OF MIC

While water samples from both the MI Magnet LCW System and the RF 95 Degree LCW System were being tested by Nalco for the presence of viable bacteria, one of the header pipes in 500 sector was drained to gain a closer look at the interior of a leaking weld. Two girth welds in the 6-inch piping were cut out and removed for inspection. Visually, the interior surfaces of the pipe samples were obviously corroded. Orange and brown corrosion deposits could be seen on and around the weld area. Especially evident were nodules and/or biomasses built up on the edges of tack welds usually directly on the site corresponding to an observed leak. The poor quality of the welds was also evident from internal visual inspection. Lack of penetration, extreme heat tint (lack of backing gas), and pipe misalignment added to the poor appearance of the weld. Photographs of these samples are included in Appendix D. One pipe sample was given to Nalco and the other was given to Packer for further mechanical, chemical, and metallurgical analysis. The header pipe in 500 sector was refilled with domestic water from MI-60 (treated well water).

Another consulting firm, Bioindustrial Technologies, Inc. (BTI; see Appendix B), was then contacted for further examination and analysis of the corrosion problem. BTI is a bioindustrial engineering consulting and service firm headed by Dr. Daniel H. Pope, a microbiologist well known for his work on the MIC problem in industry. He was recommended to Fermilab by Dr. James Frank, manager of Argonne National Lab's Waste Management and Bioengineering Section. After viewing the corrosion problem first hand in the MI Magnet LCW System, Dr. Pope took some water samples from the system for further bacteria testing.

Testing for bacteria in water samples requires actually culturing the bacteria in a culture media specific for that type of bacteria. Concentrations of specific bacteria types can be determined by mixing different dilutions of the sample water with the culturing media. It should be noted that water samples can only tell us the levels of bacteria in the moving water. Bacteria colonies that are adhered to the walls of the pipe are obviously missed when testing only the water. Tests for the bacteria clinging to the pipe walls can be made using swab testing methods as described in Section VI. Most bacteria types can be cultured in a few days (3 to 5 days). However one type of bacteria usually associated with MIC, sulfate-reducing bacteria, can take up to 28 days to culture. Thus, testing for bacteria is not instant and care must be taken to ensure water samples are labeled accurately so that results are correctly attributed to the right samples.

Nalco's water sample test results and BTI's water sample test results both showed concerning levels of bacteria in the water samples. Appendix E contains their reports. Both Nalco and BTI discovered high levels of aerobic bacteria (greater than 10,000 colony forming units per ml (cfu/ml)). In addition Nalco found trace levels of sulfate reducing bacteria while BTI found traces of iron related bacteria and large amounts of low nutrient bacteria. It is interesting to note that the highest bacteria levels were found just downstream of the MI-60 charcoal filter bed. This is expected since chlorine has been removed from the water at this point and the filter bed acts as a host for bacteria colony growth. In short, although no "smoking gun" was found (extremely high levels of sulfate reducing or iron related bacteria), the high levels of aerobic and low nutrient bacteria indicated large colony growth in the system.

II.4 STABILIZING THE SYSTEM

Since the preliminary diagnosis pointed to MIC (primarily based on visual inspection and water sample testing), Nalco recommended immediately treating the suspect systems with two types of liquid biocides in alteration, Nalco product numbers 7338 and 9210. The 7338 product is an aqueous solution of glutaraldehyde which kills bacteria cells by poisoning their metabolisms. The 9210 product is an aqueous solution of alkyl benzyl ammonium chlorides (or quaternary ammonium compounds) and ethanol. Quaternary ammonium compounds kill bacteria by destroying the effectiveness of cell membranes.[9] Because it coats the surfaces of the bacteria cells, a high level of suspended solids in the water can reduce its effectiveness drastically.

The glutaraldehyde solution was added to the system first at an estimated concentration of 220-ppm product (100-ppm glutaraldehyde) and allowed to circulate for several days. After 72 hours of circulation, Nalco suggested another dose at half the concentration of the first dose to keep the concentration lethal to the bacteria while suspended solids were reduced. 72 hours after this was done, the quaternary ammonium product was added at an estimated concentration of 400-ppm product. At this point water samples were sent to both Nalco and BTI for microbiological evaluation. Both sets of test results showed drastic reductions in the bacteria concentration levels. Of course, even though bacteria in the water was reduced, swab tests were not performed on suspect welds so live bacteria underneath the nodules may not have been effectively eliminated. Test results after biocide circulation are included in Appendix F.

At this point, the piping system and MIC problem was assumed to be under control. The rate of new leaks observed diminished to 1 or 2 per week and thoughts began to turn to leak repair. However, Nalco was insistent that the biocide treatment continue in order to keep bacteria levels under control. Realizing that it could take quite some time before the repair options were evaluated and that adding more chemicals to the system could be detrimental to safe waste disposal, it was decided to not continue the biocide treatments and instead try to drain and dry the entire piping system. Dr. Pope of BTI was consulted and he confirmed that if the system were dried thoroughly, further damage of the pipes by MIC would be minimal.

One by one, each sector of the MI Magnet LCW System was drained. Since the water contained significant amounts of the biocides, the water was pumped out of the header system and into stainless steel tanker trailers. Periodic tests for the biocides were conducted and Fermilab's ES&H Section (R. Walton, B. Fritz) calculated safe disposal rates in conjunction with the Batavia City Water Department. The water was then drained from the tanker trailers into the sanitary sewer system at those pre-determined rates (generally around 3,000 gallons per day). Because the draining was done in the dead of winter, the task of draining 66,000 gallons of water in this manner (using tanker trailers) was like playing musical chairs. In order to keep valving from freezing on the tankers, they had to be parked in various heated bays scattered around the site during the overnight hours.

Special blowers were purchased to blow air through the header pipes in an effort to dry out the pipes completely. This seemed to work quite well and by 1-28-98 the entire MI Magnet LCW System (including the 8 GeV line headers) was drained and dried. The RF 95 Degree LCW System continued to circulate biocide until 3-17-98 when it was drained in a similar manner.

II.5 FINAL CONFIRMATION OF MIC

While draining and drying was occurring, Nalco and Packer presented the final results of the metallurgical examinations of the two sample welds. Both reports concluded that the damage to the pipe samples was caused and/or accelerated by MIC. Sectioning done by Packer revealed pit morphology typically found in MIC and typical MIC deposits (sulfur, carbon) left in the pitting. Also of considerable note are the indications that poor weld quality significantly contributed to the problem. The welds displayed higher ferrite content than expected (although not sensitized) especially at the tack welds (evident at the top, bottom, and each side of all the welds) which indicates high heat input. Many studies of MIC on austenitic stainless steels have shown that the preferential affinity of MIC causing bacteria for weld areas is somehow related to the segregation of materials that results from the solidification process during welding (ferrite formation). Higher heat input usually means greater segregation of materials and may contribute to the susceptibility of the weld to MIC.[10] Also, the excessive amount of heat tint on the interior surfaces of the welds indicates that a backing gas (purge) was not utilized properly. This amount of heat tint could result in a poorly passivated (protected) metal surface susceptible to corrosion.[11] Finally, most pitting sites seemed to stem from other flaws in the weld such as lack of fusion and incomplete penetration. Clearly the longitudinal seam weld performed during original pipe manufacture was not affected, thus indicating that the field welds were more susceptible to corrosion. Both reports are included in Appendix G.

The results of the biological evaluations of water samples and metallurgical examinations of the weld samples confirmed that the corrosion problem observed was a case of MIC of austenitic stainless steel. It was also obvious that the poor condition of the welds contributed to the severity and extent of damage suffered. Our efforts now began to concentrate on recovery of the damaged system.

III DAMAGE ASSESSMENT

III.1 WELD LABELLING

As each sector was drained and dried, it was necessary to assess the MIC damage to the welds and how pervasive the damage was throughout the system. It was quickly recognized that a weld labeling system had to be devised in order to not only catalogue the damage but also effect repairs in an organized and efficient fashion. R. Ducar of the MI Department created the labeling system based on the location of the welds with respect to quadrupole magnet locations. With the help of C. Gattuso, also of MI Department, and others, R. Ducar used permanent marker to physically label every accessible weld in the MI Magnet LCW System. A weld inventory was created which was then expanded into a crude database used to track each weld's condition and status during the weld repair process. A sample of this inventory for one header in a single sector is included in Appendix H.

III.2 RADIOGRAPHIC EXAMINATION

As sectors were drained, 10% of the accessible welds in those areas were radiographed to assess the damage to the welds. An inspection service, Elite Inspection (see Appendix Q), was utilized to perform this work on an as needed basis. B. Hanna, of Tevatron Department, with help from the Radiation Safety Group of the Beams Division ES&H Department, planned the logistics of the radiography in the tunnel. Only welds in the MI tunnel enclosure were radiographed because the enclosure provided a radiation shielding environment that was relatively easy to control. Radiography was performed on evening shifts to reduce conflicts with workers that occupied the tunnel enclosure during the day shifts.

The results of the radiography are summarized in Appendix I. Also included in Appendix I are some representative positive prints from the actual exposed film. The results indicated that 61% of the total number of welds radiographed (228) showed flaws that could be associated with MIC (deep pitting or tunneling). In addition, when the results were sorted by sector and by flaw type, three general observations were made:

(a) The number of MIC flaws observed was relatively low in 200 sector header piping and zero in 300 sector header piping. This was expected since 300 sector piping was the last sector to be filled and only held stagnant water for two to three days before leaks were found in the other sectors. In 200 sector only one of the headers (the return header) held stagnant water for an appreciable time (about 4 weeks). The other header (the supply header) was filled at the same time as the 300 sector. Indeed the radiographs revealed that MIC flaws were only observed on welds in the 200 sector return header piping and were not observed on any welds in the 200 sector supply header piping.

(b) A significant number of welds exhibited MIC flaws located not only in the welds themselves but also in the base metal adjacent to the welds and/or both in the welds and the base metal. Flaws located *both* in the base metal and in the welds were tunnel-like pitting flaws that started on the weld and then corroded longitudinally through the pipe wall into adjacent base metal. Flaws located in the base metal *only* were pitting flaws that did not come in contact with the weld areas. Some of these were up to one inch from the weld centerlines. These off-weld flaws, although few in number had to be considered when evaluating weld repair options (see Section IV).

(c) A vast majority of the radiographed welds showed flaws that could not be associated with MIC. It is important to note that these non-MIC flaws were observed on almost all the welds that also showed MIC type flaws. The non-MIC flaws consisted of incomplete fusion, incomplete penetration, root concavity, root convexity, and undercut as defined by ASME/ANSI B31.3 Code (Normal Fluid Service). Porosity flaws were also observed in most of the welds, but since these flaws are hard to distinguish from MIC flaws, all porosity flaws were assumed to not be associated with poor welding practice (however, not all porosity flaws were considered to be MIC flaws). Section III.5 discusses the implications of these flaws on the MIC problem and the overall system's code and specification conformance.

III.3 INTERNAL VISUAL INSPECTION

Although conventional light fiber bore-scopes provided some views of the interior surfaces of the affected piping, it was decided to develop remotely operated video camera devices to visually inspect suspect weld areas. These devices, designed and fabricated by D. Plant of the BD MI Department and T. Johnson of BD Operations, consisted of CCD type video cameras mounted on movable carts with lighting provided by white LED's. Several versions were created, but the most useful was a unit that utilized a radio controlled gimbal mount to aim the camera (+/- 45 degrees) in both yaw and pitch. This device was inserted into the piping via cutouts that were made during the draining and drying process. The camera was pulled through the piping to the various weld locations using a nylon line that was previously blown through the piping. In this manner, operators were able to videotape all accessible welds in the entire system.

The internal visual inspection of tunnel piping revealed that almost every weld in the piping that had held stagnant water for a significant period of time (4 weeks or greater) exhibited signs of advanced corrosion. Most welds had orange colored streaks flaring out from tack welds that had not been consumed by the final weld pass. A majority of welds had a build up of corrosion byproduct in several places on each weld. Nodule formation (see Section II.2) was obvious on a majority of the welds inspected. Some of the nodules were crumbled and/or knocked off by the passage of the camera device. The worst damage was usually at the bottom of the pipe (on or near tack welds), although some damage was recorded even at the very top of the pipe interior on some joints.

Inspection of service building piping (above ground) was limited to bore-scope inspection due to the complexity of the piping geometry (too many consecutive turns prohibited passage of video camera devices). Similar damage was seen in these inspections, although because of the pipe's thicker walls (larger pipe diameters in the service buildings), through wall pitting was not as frequent.

As videotapes of the damaged welds were completed, the tapes were reviewed and data about each weld was entered into the weld database. From comparing the video images with radiography results, it was concluded that severely damaged welds and off weld flaws could be identified from viewing the videotapes. This type of information was entered into the database so that each weld received the proper amount and type of weld repair (see Section IV). Appendix J contains some still frames from the damaged piping videotapes. Unfortunately because of video interlacing, the resolution of the still frames is quite poor. The actual videotapes will be kept on file for future review if desired.

III.4 DAMAGE ASSESSMENT CONCLUSIONS

From the evidence gathered during damage assessment efforts, it was obvious that the majority of the welds in the MI Magnet LCW System were affected. In addition, internal visual inspection allowed us to tailor weld repairs to each individual weld. In other words, if a weld did not appear to be damaged, the weld repair for that weld could be skipped. If a weld exhibited a large amount of damage in a certain area, that information could be relayed to the weld repairer so that extra care could be taken in that area. If a weld exhibited off weld damage, a repair option could be chosen that would have a high probability of success with off weld leaks (see Section IV). Of course, in reality, a conservative approach was taken so that any weld that exhibited damage (including non-MIC flaws) received some type of suitable weld repair.

The 8 GeV portion of the MI Magnet LCW System was also radiographed. The results showed only minor pitting damage (pitting was not deep). This, coupled with the fact that no leaks had been identified on that portion of the system, led us to decide that weld repairs were not required on the 8 GeV header piping.

The two RF LCW systems at MI-60 were also investigated as described above. They exhibited very minor signs of corrosion (some discoloration) and very little pitting. Weld repairs were considered not necessary on either RF LCW system.

III.5 WELD CODE CONFORMANCE ISSUES

The large number of non-MIC flaws caused some concern about the entire piping system's conformance to contract and code specifications. Investigations into these issues revealed that the original design specifications for the welding of the header system were insufficient to ensure consistent, good quality welds. Although the specifications called for adherence to ASME/ANSI B31.3 Code and full penetration welds, the specifications failed to call out the fluid service category for the piping system. Examination and inspection requirements vary depending upon the fluid service category. A fluid service category could have been inferred from the original specifications based upon other data included in the specifications. Since the hydrostatic pressure tests were specified to be performed at 225 psi (suggesting a design operating pressure of 150 psi) and the system was to carry water (suggesting non-hazardous fluid), the inferred fluid service category would be Category D Fluid Service. This category of fluid service only requires visual examination of the welds. Since it is the owner's (Fermilab's) responsibility as per ASME/ANSI B31.3 Code to ensure proper examinations are performed and since the original specifications did not require internal visual inspection, the welds were considered to be acceptable based upon only external visual inspection. None of the weld flaws identified by radiographic examination could have been revealed by only external visual inspection.

Aside from the reference to ANSI/ASME B31.3, the original specifications called for full penetration welds and proper use of a backing gas. However, use of a Weld Procedure Specification was not specified, and mandatory inspection requirements were not specifically outlined. Thus, although it is clear that full penetration and well purged welds were not produced, the specified inspection requirements and examination methods were not sufficient to ensure good quality welds. Section IV.3 discusses the means by which good quality welds and weld repairs were ensured during repairs to the MI Magnet LCW System.

From a MIC standpoint, I believe the poor quality of the welds (including the tack welds) contributed to the susceptibility of the piping to MIC attack. As mentioned previously, poor welds exhibiting incomplete penetration, excessive heat tint, and increased ferrite formation can encourage bacteria growth and accelerate corrosion rates. However, they are not the only reason why MIC developed. Section VII discusses some of the probable causes, including poor weld quality.

IV WELD REPAIR

IV.1 REPAIR OPTION CRITERIA

Even before the MIC situation was stabilized, research and development began to explore weld repair options. As different options were developed and tested, a set of criteria by which to judge the options was created. The criteria used, along with the ranking of the various repair options, is included as a table in Appendix K. A description of the criteria follows:

(a) *Weld Type Application* - The type of weld that a particular weld repair option could be performed upon successfully. Each weld repair option was not applicable to every type of weld in the affected piping. Weld types included straight girth welds (butt welds which joined straight pipe ends), elbow girth welds (butt welds which joined elbow fittings to straight pipe ends or another elbow fitting), weldlets (small pipes welded in a tee configuration with the main header to provide pipe thread connections for drain and vent valves), and goosenecks (extruded tee connections, typically 2 inch pipe size).

(b) *On-weld Quality* - The qualitative measure of how well the weld repair option repaired leaks or potential leaks on the existing weld. This was usually based on comparing radiography before and after effecting the weld repair option.

(c) *Off-weld Quality* - The qualitative measure of how well the weld repair option repaired leaks or potential leaks in the base metal adjacent to the existing weld. This was usually based on comparing radiography before and after effecting the weld repair option.

(d) *Longevity* - The qualitative measure of our confidence that a particular weld repair option would last as long as a new, unaffected weld. This was usually based upon past experience, pressure testing, internal visual inspection and metallurgical testing of the repaired weld.

(e) *Ease of Installation* - The qualitative measure of the ease of effecting a particular weld repair option. This was based upon the time required to perform the weld repair and upon the skill level required of the weld repairer.

(f) *Individual Inspection* - This indicated the requirement for some type of inspection (radiography, internal visual, etc.) to be performed on each individual weld to be repaired in order to locate the damaged areas for the repair to be successful.

(g) *Serviceability* - The qualitative measure of the ease with which the weld repair option could be removed and/or replaced if it was not successful.

(h) *Cost* - The qualitative measure of the predicted cost of effecting a particular weld repair option and cost of materials.

(i) *Labor* - The estimate in man-hrs for effecting a particular weld repair option.

IV.2 WELD REPAIR OPTIONS

Many repair methods were investigated, from installing pipe liners to removing entire pipe sections. The most promising weld repair options are described in the following list along with some of the test results that helped us develop the comparison table in Appendix K:

(a) *Spool Weld Replacement* - This was the most drastic of the weld repair options considered, short of rebuilding the entire header system. It consisted of cutting out a short section of pipe that contained a damaged weld (a spool piece), and then replacing it with a new section of pipe, making two new welds (with improved quality from the original weld). Since it was obvious that this repair option would replace all the damaged areas, it received high marks in On-Weld and Off-Weld Quality. It was tested to ensure that new good welds could be made (see Sections IV.3 & IV.4) and performed many times to estimate the time required to perform the repair.

(b) *Whole Weld Replacement* - This weld repair option was very similar to Spool Weld Replacement in that it involved removing the old weld. However, in this option only the original weld metal was removed by using an automatic pipe cutting machine (about a 1/4-inch wide cut). The cut ends of the pipes were then prepped and pulled together and a new weld was made. Although this saved the time required to make the second weld in Spool Weld Replacement, it still involved re-aligning the pipes (pipes tended to spring apart when cut) and did not address leaks in the adjacent base metal. This repair option was tested by radiography and was performed to estimate the time required to perform the repair.

(c) *80% Wall Weld Replacement* - This weld repair option was similar to Whole Weld Replacement in that it involved removing the old weld metal using an automatic pipe cutting machine. However, in this option only 80% of the wall thickness was removed so that the pipe ends did not require re-alignment and chips from cutting did not enter the piping. A welding pass was then used to re-fuse the old weld metal left in the joint and add filler metal to create essentially a new weld. This method did not address leaks in the adjacent base metal. Prepared test samples of this repair method underwent tests for sensitization (ASTM A 262) and acceptable ferrite content (2.5-5.0%) performed by Packer Engineering Services as well as before and after radiography.

(d) *Local Grind (80%)* - This weld repair option required identifying damaged (pitted) areas prior to repair. The damaged areas were ground out to 80% of the wall thickness (to avoid chip entry into the piping) and then re-fused and filled with new weld filler metal. This was very successful, but required radiography of every weld to identify each pitted area.

(e) *Overlay Weld* - This weld repair option involved grinding off the crown of the original weld (weld metal which protrudes from the outer diameter surface of the header pipe) and overlaying an additional weld pass. Manual welding actually utilized two welding passes: the first to re-fuse existing weld metal and get full penetration, and the second to add filler metal and rebuild the crown. Automatic welding (orbital machine) was able to accomplish both re-fusing and overlaying at the same time in one pass. This method did not address leaks in the adjacent base metal. Prepared test samples of this repair method underwent tests for sensitization (ASTM A 262) and acceptable ferrite content (2.5-5.0%) performed by Packer Engineering Services as well as before and after radiography. In addition a prepared sample was pressure tested by Packer Engineering Services, undergoing 20,000 cycles from atmospheric pressure to 225 psi without leaking. Internal inspection revealed that the original corrosion deposits and microbiological byproducts present on the weld surface had been consumed by the fusion weld in the weld area, leaving a smooth, dull gray surface.

(f) *Epoxy/Fiberglass Wrap* - This repair option was an attempt to seal the leaks and potential leaks rather than remove/fill them. It involved wrapping layers of fiberglass cloth and epoxy resin around the affected area of piping and then curing at room temperature. Unfortunately, pressure tests showed that this repair method was not reliable. In addition, future repair efforts were hampered by epoxy residue left on the pipe surface.

(g) *Repair Clamp* - Two similar repair clamp designs were tested from different manufacturers. Both clamps had the same basic design, a stainless steel sheet lined with rubber (Buna-S) that had a cellular, waffled texture. The sheets were held on to the pipe by steel clamps and bolts that utilized a tapered design to increase pressure between the rubber and the pipe outer surface. It was found that the addition of spring washers under the bolt heads improved performance during thermal cycling. Both clamp styles were tested by pressure testing them (20,000 cycles, 15 to 225 psi). There were no detectable leaks (with spring washers installed).

Results of the various weld repair option tests indicated which weld repair options were most desirable for our situation. We decided that we would use the Overlay Weld method on the majority of welds to be repaired due to its relatively low cost, excellent on-weld quality, very good longevity and good serviceability. This method also exposes the entire weld area to high heat which effectively destroys any bacteria colonies which may still exist. In addition to the Overlay Weld option, the Local Grind (80%) method was chosen for observed leaks especially those in off-weld locations. Finally, a number of repair clamps were ordered to cover the predicted number of off-weld damaged joints that might be missed by the Overlay Weld method. It was assumed that if leaks developed off-weld or on welds that were not touched by repair efforts, the repair clamps could be used to seal the leaks until the operating schedule allowed time to drain that section of piping and perform a Local Grind (80%) repair.

IV.3 WELD REPAIR TECHNICAL SPECIFICATIONS & QUALITY ASSURANCE

In order to ensure the quality of the weld repairs and the quality of any new welds added to the piping system, several procedural requirements were enacted during the repair process that were not put in place or were not adequately enforced during the original fabrication of the system. Most of these were outlined in Welding Technical Specifications written for each type of weld repair and new weld that was to be performed. Typical Welding Technical Specifications for an Overlay Weld repair and a new weld on schedule 10 piping are included in Appendix L. In brief, technical requirements that were emphasized in the specifications included weld preparations, pipe alignment, tack welds, backing/shielding gas (purge) requirements, and post-weld cleaning.

In addition to technical requirements for performing the weld repairs, the specifications also outlined the examination methods. These included external visual examination of every weld, the provision for internal visual examination of every weld, radiography of up to 5% of all weld repairs, pneumatic bubble test of all welds, and hydrostatic pressure test of all welds. Inspection requirements (size of flaws allowed, number of flaws allowed, type of flaws allowed, etc.) were covered through the specifications by requiring ANSI/ASME B31.3 compliance for Category D Fluid Service. However, because radiography is not required by

ANSI/ASME B31.3 for Category D Fluid Service, radiography was performed under Fermilab direction and at Fermilab's cost. Also, because of the nature of the weld repairs, responsibility for re-work of weld repairs that failed any examination was assigned depending upon the type of flaw identified (see Section IV.5).

The Welding Technical Specifications also required the welding contractors to provide a Welding Bureau approved Welder Qualification Record (WQR) for each welder that was to weld on the system along with a Welding Procedure Specification (WPS) for any new welds, and its associated Procedure Qualification Record (PQR). These documents show that the contractor can follow an approved procedure for creating a code (ANSI/ASME B31.3) weld. In addition, the specifications required that each welder perform one of each type of weld repair and new weld procedure in the field under the eye of a Fermilab welding inspector (R. Hiller or I. Stauersboll) to ensure that every welder was capable of performing satisfactory weld repairs and new welds.

Documentation of the welder field tests was generated by creating a qualification sheet for each welder with places for the Fermilab welding inspector to sign for each weld repair method and new weld procedure satisfactorily performed. In this way, even if a welder could not perform one type of weld repair, they could still be qualified to execute another, less stringent, type of weld repair.

Documentation of each weld repair examination and each new weld examination was generated by utilizing the weld inventory database (see Appendix H). Each weld entry had fields for each examination. As the welds passed inspection, dates were entered into the corresponding fields by Fermilab Weld Technicians (see Section IV.5).

IV.4 WELD REPAIR METHOD REVIEW

Although the chosen weld repair options had undergone thorough testing for weld quality, we desired to have the repair methods reviewed by a welding engineer to identify any pitfalls or omissions in our repair procedures. Thielsch Engineering, Inc. from Rhode Island was chosen for its past experience in welding technologies and because it had dealt with a very similar incident successfully.[12]

After review of our Welding Technical Specifications for the weld repair options we chose, and after touring the facility, M. Dowling, Vice President of Utility Engineering Services of Thielsch Engineering, concluded that the repairs will "meet or exceed original design requirements". In addition, he predicted that the repairs would result in a weld suitable for continued service for a period of at least 10 years with the system's operating parameters. A copy of his letter is included in Appendix M.

IV.5 EFFECTING WELD REPAIRS

After the weld repair methods were chosen, arrangements were made with the original welding contractors to perform the repairs. Since Fermilab's actions (leaving well water to remain stagnant in the piping for long periods of time) contributed to the MIC susceptible environment, the contractors did not feel responsible for the state of the corroded welds. On the other hand, since welds were found to have flaws which also contributed to the MIC susceptible environment (see Sections II.2 & II.5), Fermilab felt that the contractor had some complicity in the corroded state of the welds. Through Fermilab Business Services, a compromise was reached whereby the contractors would perform the repairs at cost under Fermilab's direction and in-process inspection.

The scope of the weld repairs included full Overlay Weld repairs on all welds in the header system (excluding the 8 GeV line header) which were either hard to access during operations (all tunnel piping) or in the vicinity of sensitive equipment (such as power supplies). The only exceptions were those welds identified by either radiography or internal visual examination to be free of MIC damage. The general result of this scope definition was that almost all welds in the tunnel were destined for repair, while only about half of the welds in the above ground service buildings were chosen for repair. More welds were passed in the service buildings because possible future leaks in service buildings could be addressed without serious detriment to MI operations (access is allowed to service buildings during MI beam operations, but not to the tunnel enclosures.

On March 2, 1998, welders and pipe fitters from both contractors arrived on site to begin weld repairs. Besides the normal training for working on the MI site, the workers also attended meetings to learn the weld repair techniques and review the Welding Technical Specifications. Field testing of welders was also begun immediately and the first weld repairs were made on March 3, 1998.

Initially, both contractors had 2 welders and 2 pipe fitters working an 8-hour day shift (8 workers total). After two weeks, the number of workers was doubled by adding an evening shift (16 workers total). There were several periods of time during the weld repairs during which less than 16 workers were available due to lack of qualified welders and worker illness/personal leave. Lost time was made up by working on Saturdays during the last 2 months of weld repairs. The last repairs were made on July 16, 1998.

Early in the weld repair process, purge dams were used to isolate each weld repair from the rest of the piping. This enabled a good local purge without the wait to purge an entire length (usually over 400 feet) of continuous piping. However, it soon became clear that, with proper management, purging the entire length of piping was more efficient. Use of the purge dams was hindered by the difficulty of pulling the dams, in coordination with the welders' progress, to the proper locations. By using pipe fitters to set up purges on entire lengths of piping in advance of the welders (usually a day in advance), the welders did not have to set up each purge individually with the cumbersome dams.

During the weld repair process, both manual and automatic welders were able to identify large MIC flaws as they made their fusion passes. They were even able to follow the flaws off of the weld itself and re-fuse damaged areas off of the weld. Due to this technique, a large number of off-weld flaws were repaired successfully.

As weld repairs progressed, inspection of the work was performed and results recorded in the weld database. Four technicians (see Appendix Q for acknowledgements), trained by Fermilab's Weld Shop, performed visual examinations of each weld and weld repair within one day after they were made. In addition, suspect welds were visually examined internally using the remote video devices. As sectors of piping were completed, 5% radiography and 100% pneumatic bubble tests were performed to ensure quality. R. Slazyk, BDMS Water Group, oversaw the weld repair work (Fermilab Task Manager), and directed the weld technicians.

After weld repairs were complete, the piping was filled sector by sector with filtered and UV treated water (see Section VI) and then hydrostatic pressure tested (225-psi). Pressure testing found several leaks (14-20 out of approximately 4000 weld repairs) due to off-weld damage that was not caught during the weld repair. These leaks were repaired by the Local Grind (80%) method and re-tested successfully. A sample of the weld inventory with results of the after repair inspections described above is included in Appendix H.

IV.6 REPAIR CLAMP USAGE

Although all the off-weld leaks were repaired, the fact that not all were identified until after hydrostatic pressure testing led us to believe that a substantial number of off-weld flaws could have been left untouched by the weld repair process. If these flaws were left unattended, it was feared that they could begin to corrode again (even without the influence of microbiological organisms). To combat this possibility, 340 repair clamps of various sizes were purchased. The quantity and sizes of the clamps ordered were determined by estimating the number of off-weld flaws based on the internal visual inspection videotapes. From our testing of the clamps, we were confident that if a leak developed we would be able to apply a repair clamp that would hold tight for a very long time (years) or at least until a scheduled shutdown allowed for draining of the system and permanent repair.

In actuality, due in part to the ability of the welders to identify and fill in off-weld MIC flaws during the weld repair process, we have not yet had to use a single repair clamp (over two months of operation). This indicates that the number of clamps needed may have been overestimated. However, given the fact that not all welds were inspected and/or repaired (especially in service buildings), and because not all welds could be cleaned (see Section V), we expect to keep the repair clamps in on-site storage for at least one year of operation.

V MIC MITIGATION (PIPE CLEANING)

V.1 PIPE CLEANING OPTIONS

While weld repair options were being considered, final mitigation of the MIC infestation was also being investigated. Although the addition of biocides and draining/drying of the pipes presumably halted the MIC process, complete mitigation required the removal of the entire MIC habitat. Deposits in the pipe, in the form of nodules and tubercles, were tenaciously adhered to the pipe walls and could not be removed from water circulation alone. These deposits were of concern because, besides harboring bacteria, the deposits could have been sites for future infestations (ideal habitats for bacteria to thrive in). Thus, removal of as much heat tint and MIC deposit as possible was considered necessary to leave a clean, passivated stainless steel surface that would resist future corrosion.

Initially the various consultants (Nalco, BTI, and Packer) suggested using chemical methods to actually etch away the deposits and heat tint. Several welds cut out of the infected system were sent to two companies, which offered chemical services of this nature (Bio Clean Services and Hydrochem; see Appendix Q). The samples were used to determine the composition of etching solution, duration and temperature of treatment required. Results indicated that 20% nitric and 4% hydroflouric acid combination was required to remove the deposits and heat tint completely.

Possible treatment using such a harsh etchant in such large volumes created environmental, safety and health concerns along with schedule and cost concerns. Drs. P. Mazur and G. Pewitt, Technical Division, worked with both chemical-cleaning companies to address these concerns. Results of their work indicated that a massive orchestration of people and equipment within a vacated MI site for over two weeks would be needed to clean the pipes. Besides the negative impact this would have on the MI construction schedule, the cost estimates were also very high (approximately $300,000). Due to these concerning developments with chemical cleaning, Drs. P. Mazur and G. Pewitt looked at other possibilities for cleaning the pipes, namely mechanical cleaning.

Mazur and Pewitt began conversing with companies that provided remote robots for the purpose of repairing underground piping. After a few initial talks and meetings it became clear that these companies utilized robots that offered more features than our application required. Use of these multi-articulated and self-propelled machines for our purposes would not have been cost effective. It was decided to develop custom mechanical cleaning devices that were simple, inexpensive, and effective. M. May, Beams Division/Mechanical Support, developed several devices for this purpose.

The devices all utilized spinning sets of abrasive pads (silicon carbide) driven by an air motor. Each device was designed for a slightly different application. One device simply consisted of a spinning abrasive disk and an air motor mounted on spring-loaded wheels. This device was designed to be pulled through the pipes (via a nylon line previously blown through the pipes) and buff the entire pipe inner surface including welds. Another device using a long flexible shaft was designed to clean pipes that had many bends and elbows. A more sophisticated device design utilized a video camera similar to the internal inspection video camera devices to allow the operator to precisely locate the cleaning pads on top of the dirty welds.

Tests using these devices showed that the abrasive wheel technique eliminated all discoloration, both from heat tint and MIC deposits, on the pipe inner surface. Cleaned welds exhibited smooth surfaces free from all debris except for a few deep pits that still showed some dark (black) discoloration. Pictures of typical welds before and after cleaning are included in Appendix N.

Major advantages of using mechanical cleaning rather than chemical cleaning were identified. These included more flexibility in scheduling (Fermilab technicians could perform the work at the same time that contractor work in the MI tunnel proceeded), lower environmental, safety and health concerns, and much lower cost (less than $100,000) than chemical cleaning.

A major disadvantage of mechanical cleaning was identified as various cleaning techniques were evaluated. This disadvantage was the inability to effectively clean welds that were located in the convoluted service building piping. The drastic changes in pipe diameters and multiple tee and elbow fittings made it difficult to clean these welds mechanically, while chemical cleaning would reach these welds through normal circulation.

In order to assess the impact of this disadvantage of mechanical cleaning, and to confirm the effectiveness of our mechanical cleaning method, two independent reviewers were asked to review the mechanical cleaning method and make relevant recommendations. Dr. Daniel Pope of BTI, microbiologist, and Prof. Robert Rose of MIT (see Appendix B), metallurgist, reviewed the weld repair methods, the mechanical cleaning methods, and associated documentation (videotapes, photographs, metallurgical reports, and microbiological evaluations). Their reports are included in Appendix O. In brief, they concluded that the mechanical cleaning techniques described were adequate to remove the present MIC infestation and protect against future MIC attack. They also believed that unreachable welds in the service building piping may continue to corrode if already damaged, but that their damaged state would not affect (spread to) other repaired and cleaned welds elsewhere in the piping system.

The results of the cleaning method review and comparison of the advantages and disadvantages of the two cleaning methods convinced us to choose the mechanical cleaning method.

V.2 EFFECTING PIPE CLEANING

Shortly after confirmation of the mechanical cleaning method (April 28, 1998), pipe cleaning in the MI tunnel was begun. In general, all pipe cleaning was performed in a particular piping section after weld repairs were conducted on that section. Weld repairs and new welds were performed with good argon purge practices so that the resulting welded interior surface was as free from contaminants as possible (see Section IV.3 and Appendix L).

After cleaning devices were used in a section of piping, another device was pulled through the pipe section to remove loose debris. This device used multiple nozzles to direct compressed air at the pipe inner surface. Loose debris and abrasive grit from the cleaning process was blown through the pipe in this manner, leaving clean pipe behind.

Cleaning progress was rapid and had no problems keeping up with weld repairs. A three-man crew was able to clean an entire sector's worth of piping in approximately 4 days.

VI MIC PREVENTION

Mitigation of the MIC problem in the MI Magnet LCW System, as described in the previous section, was performed in a manner that helped create an environment not susceptible to MIC attack. However, maintaining that environment is necessary to prevent MIC attack in the future. The prevention plan options that we investigated all assumed that entry of microbiological organisms into the system could not be entirely halted. The introduction of these organisms was very likely given the normal operations of the piping system (frequent addition of make-up water, numerous accesses during start-up, and planned piping additions to the system). Therefore, all the prevention plan options (in addition to simply maintaining flow conditions, see Section VI.2) were based upon the premise that microbiological growth and MIC could be monitored and preventive actions could be taken before serious damage was done.

It should be noted that there are many general corrosion prevention methods that are not described here (such as cathodic protection, corrosion inhibitors, and pipe liners). These methods may also help prevent MIC, but are not discussed here because they are not specific to MIC (see Section VII.2).

VI.1 MONITORING MIC

Our investigations indicated two approaches to monitoring MIC in a piping system. One is to monitor the actual bacteria concentrations that exist in the system. The other is to monitor the actual MIC corrosion damage. Monitoring the microbiological growth has the advantage of indicating probable MIC conditions before any damage actually occurs. However it also has the disadvantage that results can be misleading (high levels of bacteria in the piping system water does not necessarily mean MIC is occurring). Monitoring MIC corrosion damage yields very positive evidence of MIC, however it may not offer enough advanced warning to be used on its own. Note that monitoring MIC activity only is being addressed here. Monitoring corrosion in general is possible using various standardized methods and may indirectly indicate the occurrence of MIC (see Section VII).

Bacteria concentrations can be monitored using several different commercial testing kits. In general the kits use sample material from the system in question (water or slurry) and their provided culture media in an attempt to culture (or grow) the culprit bacteria. Various dilutions of the same sample may be used to determine the approximate concentration (usually in units of colony forming units per milliliter, cfu/ml) present in the original sample. It usually takes several days for the bacteria to culture adequately enough to make a positive or negative reading. Sulfate-reducing bacteria (SRB) may take up to a month to culture, although some test kits offer a more instant result by testing for SRB byproduct. Results from bacteria testing can be misleading. If a water sample is used, the test will only identify those bacteria that are water-borne and not those that may be sessile (or clinging to the pipe walls) in some localized section of piping. Thus a water test may underestimate the effect of bacteria in the tested system. On the other hand, a test using a slurry sample made from swabbing an area of actual pipe wall will indicate much more accurately what consortia of bacteria are thriving on the pipe wall. In either case, swab or water test, the presence of bacteria does not necessarily mean that MIC is occurring. In many cases the existence of a thin biofilm of bacteria is to be expected and will not likely develop into MIC.

MIC damage can be monitored by destructive and non-destructive methods. Obviously non-destructive methods are desirable because they will not impact operations. Of these methods, visual and radiographic examinations are most commonly used. Visual confirmation of MIC is difficult and must be coupled with other test methods to confirm that the corrosion is microbiologically influenced. However, corrosion in general is very easy to spot internally (via bore-scope or other internal viewing device) from the corrosion deposits and stains that accompany a local corrosion cell. The additional presence of a thick biofilm or slime on the corroded area can help indicate a microbial influence. Radiography will show corrosion damage by revealing voids or pockets of less dense material within the pipe wall or weld joint. Although there is a typical pit morphology associated with MIC (deep pits and tunneling), the presence of MIC cannot be confirmed by radiography alone. In addition radiography may require draining of the working fluid (especially on large diameter pipes) in order to produce helpful information. So, in either instance, radiography or visual examination alone will not confirm the presence of MIC. However, either method will confirm corrosion damage and that alone is enough to warrant further investigations.

VI.2 SANITIZATION/REDUCTION OF MICROBIOLOGICAL GROWTH

Once microbiological growth has been confirmed to be a problem (or during initial start-up operations), methods of sanitization must be utilized to reduce the concentrations of culprit bacteria to a tolerable level (generally as low as reasonably achievable). In our investigations of sanitization methods, we identified several possible methods that could be of use in our system. Two of these, biocides and heat treatment, were methods that could be utilized on an as-needed basis. Three other methods, continuous water circulation, ultraviolet radiation treatment, and continuous polishing (de-ionization and filtering), could be utilized on an on-going operational basis. A combination of these methods was thought to be the best solution for our recently repaired system.

(a) *Water Circulation* - Circulating water through the entire system is probably the easiest and most basic method to try to control microbiological growth. The principle of this method is keeping water velocities high enough to prevent a thick biofilm from forming on pipe surfaces, but not so high that corrosion by erosion is a threat. Water velocities of 6 ft/sec or higher are recommended to minimize biofilm growth. Velocities of 3 ft/sec have been shown to actually encourage biofilm growth, presumably by increasing the diffusion of nutrients to the biofilm organisms.[13] Water velocities above 25 ft/sec in stainless steel piping have been shown to cause erosion corrosion problems.[14] So, simply keeping water flowing throughout the system piping (avoiding dead-legs) can help prevent thick biofilm growth, a precursor to MIC.

(b) *Biocides* - Biocides, such as the glutaraldehyde and quaternary ammonium compounds first added to our system, reduce microbiological growth by killing bacteria in the system. Biocides can be circulated throughout the system to reach all of the affected piping. However, if biofilm (nodule) build-up is quite thick, the biocides may not be able to penetrate and come in contact with bacteria directly adjacent to the pipe surface. Biocides have a residual effect; the biocides are effective for some length of time after introduction to the system. Of course the effect of biocides on the system's operational processes must be evaluated including disposal of biocide-laden water.

(c) *Ultra-violet (UV)* - UV radiation can be used to reduce bacteria concentrations in the water system by passing the water through one or more commercially available UV disinfection units. The radiation damages the replicating process of the bacteria (causes DNA mutation) and renders bacteria sterile. Cloudy water or improperly high flow rates through the disinfection chambers can drastically reduce the effectiveness of these devices. Unlike biocides, UV treatment does not have a residual effect. Treatment occurs at the unit itself and cannot treat bacteria lodged or adhered elsewhere in the system. Thus UV seems to be most useful when it is utilized to treat all of the water flow into an already sterilized system.

(d) *Heat treatment* - Thermal treatment can be used to effectively kill bacteria in a piping system. The temperature and time combination to be effective for a particular system varies (depending on what bacteria strains need to be eliminated). However, sterilization has been shown to occur at 60°C for 10 minutes under controlled conditions.[15] Heat treatment has the advantage that, like biocides, it can reach throughout the system wherever the temperature can be raised to sterilization temperatures (including bacteria sheltered under nodules). Unlike biocides, though, there is no residual effect and after treatment any non-sterile piping may re-infect the just treated system. Although heat treatment avoids detrimental additives, the system must be able to endure elevated temperature without suffering damage.

When considering the heat treatment option, we conducted several tests to determine what temperature would be effective for sterilizing our system. For operational concerns, the lowest temperature that was still effective was considered desirable. Two sections of piping containing similar, corroded welds were removed from the LCW system. The sections were capped off and filled with well water. After one week, swab tests were conducted to show that bacteria colonies were well established on the weld surfaces. Then, keeping one section as a control, one of the pipe sections was heated in a convection oven to various temperatures and for various lengths of time. Between test runs, the experimental section was tested for bacteria and re-infected if necessary. The control specimen was tested periodically to confirm bacteria remained viable without heat treatment. Results are shown in Appendix P. In brief, we concluded that, although sanitizing effects were seen as low as 120°F, a minimum of 130°F for 3 hours was necessary for our application.

Of course we did not expect such complete sterilization when attempting to heat treat our entire piping systems. Therefore we performed two tests on sub-sections of our systems to gauge the effectiveness of heat treatment in practicality. In the first test, the RF 95°F LCW System (previously found to be unaffected by MIC) was filled with well water through the UV disinfection devices. The water was circulated in the system for a few days at about 80°F. Tests confirmed bacteria concentration level in the water was about 100 cfu/ml. Then the heat exchanger on the system was bypassed and pumps were run at full flow capacity. This heated the water in the pipes (and the pipes themselves) to about 132°F for a period of 4.5 hours. Testing of water samples immediately after heat treatment showed a reduction of bacteria concentration to less than 1 cfu/ml. However, two weeks later, tests showed that bacteria levels were greater than 100 cfu/ml again. This can be explained by the fact that during the two weeks of operation several piping sub-systems and make-up water were added to the treated system.

The second test was similar to the first except it was performed on the first sector to be completed after weld repairs, the 600 sector. The sector's piping was filled with UV treated water and circulated at high flow with the heat exchanger bypassed. This resulted in heating the water to greater than 130°F for a period of 5 hours. Comparing bacteria concentration measurements before and after heat treatment revealed a two order of magnitude reduction. However, concentrations were still at the 100 cfu/ml level. After the heat treatment was concluded, the system was put into trial operation. Several de-ionizing resin filters and standard yarn-type filters (20 micron equivalent screen size) were used to polish the water (lower conductivity). Testing two weeks after heat treatment revealed that bacteria concentrations had fallen to less than 1 cfu/ml. Subsequent tests confirmed this and led us to the next prevention method, polishing the water.

(e) *Continuous Water Polishing (de-ionization and filtering)* - From our tests on the 600 sector trial operation and microbiological evaluations of other operating LCW systems, we concluded that continuous polishing of the water (to above 6-7 mega-ohm-cm) helped reduce bacteria concentration levels. We postulated that a combination of very clean water (absence of bacteria nutrition) and filtering (de-ionizing resins act as a sub-micron filter) could help rid a system of problematic bacteria at a moderate rate. Of course, since in most LCW systems only 2-3% of the total system flow is polished, if a piping system starts out with a large amount of corrosion and/or high levels of bacteria, then polishing alone probably will not be enough to overcome the bacteria reproduction rate. In addition, since the filters and resins trap bacteria and the nutrition that bacteria need to survive, they must be changed frequently to avoid simply providing the bacteria with a wonderful breeding ground.

VI.3 EFFECTING THE MIC PREVENTION PLAN

Using the knowledge gained from investigating the various prevention methods, a short-term start-up plan was devised and executed. In addition, groundwork for a long-term prevention plan was developed. The start-up plan involved filling each sector with UV treated water and circulating that water immediately through several standard filter housings (to remove starch paper purge dams, metal chips, and other loose debris). Then attempt to heat treat as much of the piping as we could utilizing the technique developed while testing earlier (high flow, no heat exchanger). This would hopefully reduce the initial bacteria in the system piping, especially bacteria left in nodules on welds that were not repaired and could not be cleaned properly. Finally, after heat treatment we decided to begin polishing the water immediately to attempt to reduce the bacteria levels as quickly as possible. Measures for long-term prevention were put in place by utilizing Fermi designed corrosion coupons to monitor bacteria levels and possible corrosion damage. Indications of MIC in the coupons would then trigger biocide treatment, heat treatment, or some other control method.

(a) *Start-up Plan* - As each sector's weld repairs were completed, it was readied for filling, flushing and heat treatment. This entailed installing bypass hoses around the magnet manifolds (manifold connections were not complete), installing flushing filters, and aligning valves. Filling with UV exposed water and then flushing with that water were accomplished without major incident. Flushing filters were changed frequently to ensure as much debris was removed from the piping as possible. Heat treatment was only moderately successful. Because of the size of the pumps and the lengths of the piping runs, only every other sector could be heat treated at one time. Although temperatures of greater than 130°F were reached for time periods of over 4 hours, the piece-meal treatment probably resulted in bacteria laden water from untreated piping moving into neighboring, just treated piping. In addition, the later connection of the magnet manifolds provided another route for bacteria entry. Bacteria tests before and after the heat treatment again indicated a reduction from over 1,000 cfu/ml to 10-100 cfu/ml. Immediate polishing after the heat treatment was begun in earnest on September 3, 1998. However, tests showed an increase in bacteria concentration (back to greater than 1,000 cfu/ml) probably explained by the addition of the magnet manifolds.

(b) *Long-term Plan* - The details of the long-term prevention plan have not been finalized and put into effect yet due to the start-up nature of operations thus far. However the basis of the plan consists of both continual preventive measures and periodic monitoring and treatment (if necessary). The continual preventive measures are simply sustaining both cooling water circulation (avoiding dead-legs and long periods of insufficient water circulation) and cooling water resistivity (polishing). Both of these measures are already part of the normal operating conditions. However, awareness of the risks associated with halting water flow or insufficient polishing shall be substantially raised by the prevention plan by including them in a set of operating guidelines written by knowledgeable Fermilab staff. The present plan is to have the guidelines available to equipment operators as well as required reading for responsible engineering staff.

The periodic monitoring plan utilizes Fermilab designed corrosion coupons to gauge the level of harmful bacteria on the piping inner surfaces and amount of corrosion damage that may be occurring in the system. The corrosion coupons are simply constructed of two short pieces of pipe butt-welded together. The pipe material is representative of the piping in the system (304L SS, schedule 10, 308L filler metal) and the weld is representative of a poor weld in the original piping system (lack of penetration, large tack welds, excessive heat tint, absence of backing gas, etc). In this manner, we are encouraging corrosion problems and bacteria growth in the coupon as an early warning sign before the other, more corrosion resistant welds in the system are affected. The coupons are flanged at either end to allow easy removal from the piping system for testing.

Six coupons have been installed in six different places in the header system. All six coupons have been radiographed to document their original state. If future monitoring indicates a possible corrosion problem, they may be radiographed again and compared to the original radiographs. In addition, the coupons are sized to allow easy internal visual inspections of the weld areas. The coupons are connected across the return and supply headers and have their valves configured to limit water velocity to less than 3 ft/sec. During the initial start-up period, several bacteria swab tests were made on one of the coupons (installed at 617 in the 600 sector). These tests have shown that bacteria concentrations have been slowly reduced from greater than 1,000 cfu/ml down to less than 10 cfu/ml over a period of two months. Although polishing has continued during this time, work on the system (connection of magnets) has exposed the piping to more sources of contamination. We hope to keep polishing the water to maintain these low levels indefinitely.

The frequency of long-term monitoring has not yet been determined because normal running conditions have not yet been reached. A MIC prevention plan in the form of an engineering specification will be written that describes the frequency of monitoring required. At this time it is expected that the plan will specify a fairly frequent monitoring schedule (twice a month) just after any significant down-time or change to the system, while a less frequent monitoring schedule (quarterly) will be specified after normal operating conditions (less than 10 cfu/ml) are established. If a MIC problem is identified, the specification will recommend possible treatments, but will also emphasize the need for professional assessment of each individual suspect case.

Both the operating guidelines and the MIC prevention plan are expected to be written over the next two to three months. It should be noted that the MIC prevention plan might be incorporated within a more general corrosion prevention plan (see Section VII.2).

VII PROBABLE CAUSES AND RECOMMENDATIONS

As may be obvious from the previous sections, pinning down a MIC occurrence to a single cause is a very difficult, if not impossible, task. Many factors come into play, including material selection, workmanship, environmental and nutritional conditions, exposure to harmful microorganisms and others. However, some of the observations we made during damage assessment suggest a few of the major contributing factors to our specific dilemma. In addition, our experiences over the past year allow us to make a few specific recommendations for the future operation of the MIC affected MI Magnet LCW System along with some general recommendations for the design of future similar systems.

VII.1 PROBABLE CAUSES

Two direct causes of the MIC problem have been identified. One is simply the fact that low quality water (well water) was allowed to stand in sections of the piping system for extended periods of time (months). The other is the poor corrosion resistance of the piping welded areas that existed due to improper welding practices during initial installation. Both of these causes can be linked to one underlying root cause. This fundamental cause is the lack of awareness and education of the piping designers and system operators of the problems associated with MIC and corrosion in general during the design, fabrication, and start-up phases of the original system.

Allowing the hydrostatic test water to remain stagnant in the piping for long periods of time is a direct cause of our case because of several reasons. The water was of poor quality and could have introduced the harmful strains of bacteria into the piping (although the bacteria could have already been present in the pipes) as well as supplied some of the nutritional requirements. The presence of the water also completed the electrochemical circuit required for localized corrosion (especially via ion and aeration differential cells). Finally, and most importantly, the stagnant quality of the water allowed thick biofilms and nodules to grow on the pipes and welded areas since insufficient water velocity was present to shear away the biofilms as they formed.

The vast majority of the welds investigated showed signs of lowered corrosion resistance. These signs were excessive heat tint (improper purge/backing gas procedure), incomplete penetration and fusion (improper alignment and preparation of pipe ends), and excessive heat input among others. All of these defects encouraged localized corrosion and, we believe, played a large role in the susceptibility of the welds to MIC attack. Indeed, a handful of original welds not exhibiting these defects weathered the MIC attack with only minor signs of corrosion (slight orange-brown discoloration and absence of pitting/nodule formation).

Both direct causes stem from one root cause, the lack of awareness and education about MIC dangers. The original piping designers, fabricators, and operators were unaware of the problems that MIC can cause in piping systems. In addition, the topic of corrosion in general was not properly addressed either. Simply specifying corrosion resistant materials (such as stainless steel) and final water quality (de-ionized and filtered water) will not ensure corrosion prevention or abatement. Start-up, lay-up, and maintenance operations must also be addressed. During the design, fabrication, and start-up operations, corrosion issues must be addressed just to get the system to normal operating conditions. From that point, maintenance and lay-up issues must be addressed to protect the system while running.

It is clear that if the original designers and operators of the new system would have been aware of the corrosion dangers, the two direct causes described above could have been avoided. By taking more care in specifying and inspecting the welding work, better quality and more corrosion resistant welds could have been produced. Likewise, start-up operations (in particular hydrostatic pressure testing) could have been performed in a manner avoiding low quality, standing water in the piping system.

VII.2 RECOMMENDATIONS

As Section VI indicates, future operations of the MIC affected MI Magnet LCW System should take into account MIC preventive measures. Keeping the system circulating with good quality water (maintain low conductivity) is vital along with using UV radiation disinfection units during fill operations. These measures can be encouraged through the use of a set of operating guidelines. In addition, a MIC prevention plan should be enacted which uses the Fermilab designed corrosion coupons to monitor MIC activity on a set schedule. Suspicion of recurring MIC problems should result in using suitable treatment methods (heat treatment and biocides are recommended), however experts should be consulted before embarking on any mitigation path.

The MIC prevention plan should be considered as only a part of the larger preventive maintenance plan for the entire system. The Fermilab system engineers and operators should develop this plan with advice from corrosion engineering experts. During our investigations, several reviewers indicated that it would be helpful to install equipment that monitors water quality and various ion species continuously. This on-line monitoring equipment would reveal any substantial changes to the system and could be used to help diagnose future corrosion problems. It is not clear whether this equipment is necessary to monitor Low Conductivity Water systems, where the water is de-ionized and very clean during normal operations. Historically, the Beams Division Mechanical Support Water Group has not seen the need for this in the past. However, with this particular repaired system, we recommend that this type of corrosion monitoring be investigated further.

Our experiences over the past year should serve as a wake-up call for the designers of future, similar water systems at Fermilab. Although every situation is different, corrosion, especially Microbiologically Influenced Corrosion, should be addressed early in the design process. Besides obvious issues such as material selection and water quality, the water system designer should consider compatibility with heat treatment and biocides during the design process. Welding technical specifications should describe acceptable welding practice in detail plus fully explain mandatory inspection requirements. Start-up and lay-up guidelines and/or procedures should be written and enforced with corrosion problems in mind.

Finally, educating the engineers, fabricators, and operators of new water systems on the subject of MIC and corrosion in general is crucial to avoiding problems of this type in the future. Designers and operators of future systems should be encouraged to explore industry and academic literature on corrosion (including MIC), attend industry seminars and courses, and utilize expert advice from consultants when approaching the design of new systems. We identified lack of awareness and education as the fundamental cause of our MIC problems in the MI Magnet LCW System. Prevention of these types of system specific problems cannot be ensured by simply following a set of mandates without first understanding the nature of the problems. Education is the first step to this understanding. As we have seen, without education, simple, yet not obvious, steps to ensure a successful system may be easily missed. With proper and timely education, these same simple steps to success are difficult to miss.

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