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COPPER GROUNDING SYSTEMS HAVE A NEGATIVE EFFECT ON CATHODIC PROTECTION IN PRODUCTION FACILITIES

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ABSTRACT

The common bonding of underground ferrous structures to massive copper grounding grids creates problems for corrosion engineers and their attempts to cathodically protect the ferrous structures. Conflicts between copper and ferrous underground systems are discussed and alternatives are presented. A specific case history concerning production facilities in Sindh Province, Pakistan is presented. The case history includes the initial engineering evaluation and recommended system changes as well as the results of the recommended changes on overall performance of the cathodic protection systems in multiple production facilities.

INTRODUCTION

Traditionally, most underground structures have been electrically bonded in common to reduce hazardous voltages associated with lightning and man-made fault currents or induced currents in the earth. A common grounding system provides a more economical and a lower resistance to remote-earth than does the individual earthing connections.

The U.S. National Electrical Code (NEC)[1] does not require copper grounding; instead, it requires that a permanent metallic earthing electrode and conductors must be used for earthing connections. Cathodic protection is routinely employed to overcome soil instigated corrosion cells on crude oil and natural gas production and transportation facilities. When such a system is directly connected to a bare copper earthing system, current demand may increase by several orders of magnitude. This creates a conflict between cathodic protection engineering design and electrical safety design.[2] Acceptable alternatives do exist to the use of bare copper conductors and bare copper or copper clad groundrods.[3]

DESCRIPTION OF PAKISTANI PRODUCTION FACILITIES

At the time of the study reported on in this paper, the company operated six (6) major oil and gas production facilities and a number of smaller facilities in the Badin Block, Sindh Province, Pakistan. Exploration began in 1977 with the first producer discovered at Khaskeli on June 16, 1981.[4] The production facilities separate oil and gas, knock out water, ship natural gas via pipeline and store oil and distillate production in aboveground tank farms for later transport to refinery by tanker truck. Electrical power is obtained from on-site generator sets with diesel or natural gas prime movers. Since all of the production facilities in Sindh Province are essentially similar, varying primarily in overall size and in the geometry of the layout, we will primarily discuss in detail, only two of the production facilities in this paper. These production facilities (P.F.), designated as P.F.-1 and P.F.-2, handle both crude oil and natural gas. P.F.-1 was brought on-line about 1988. P.F.-1 is a natural gas production facility that contains two aboveground oil storage tanks and a variety of process vessels. There are a total of seven incoming flow lines in the intake manifold. The P.F. contains a series of separator vessels to knock out water and to separate distillate from the natural gas. There is one outgoing gas transmission line.

The original electrical grounding grid was constructed utilizing PVC coated stranded copper conductor ranging in size from $16mm^2$ to $95mm^2$ conductor. A $16mm^2$ conductor is used for equipment grounding. Grid conductors are $70mm^2$ or $95mm^2$ and are connected to driven copper clad groundrods at 200 (61m) to 400 (122m) foot spacing around the perimeter of the plant with supplemental ground rods at major equipment. Cathodic protection is supplied to the plant by Transformer/Rectifier (T/R) Number 1, a 25 volt 75 ampere unit powering a distributed vertical anode-bed around the two production tanks. T/R Number 2 is a 25 volt 75 ampere rectifier powering a ten- anode, vertical conventional remote anode-bed which provides cathodic protection to the incoming flow lines.

At some point within the five (5) years prior to this study, a grounding system upgrade was undertaken to improve the electrical grounding at each of the P.F.s. This was considered necessary to assure adequate fault current protection should a motor winding or similar electrical element go to ground. The grounding system upgrade consisted of bare stranded copper 70 mm^2 or $95mm^2$ cable laid in parallel with the existing insulated cable grounding grid. Each bare copper grid was supplemented with additional copper groundrods and a total of four deep well ground beds were installed. The deep well ground beds consist of a copper plate approximately $1m^2$ and buried approximately four meters deep. Three separate $95mm^2$ stranded bare copper conductors were exothermically welded to the copper ground plate and were brought up to a bus bar installed in an aboveground manhole. Given the low electrical soil resistivity at this site, ranging from 80 to 200 ohm-cm, the grounding system upgrade did not seem to be necessary.

Following installation of the grounding system upgrade, corrosion failures were becoming a problem at most of the production facilities. In a few instances, perimeter fencing fell down when the supporting poles corroded in two at grade level or underground due to their being bonded to the bare copper perimeter grid. Prior to the initiation of this present study, the company and contractor personnel disconnected essentially all of the bonds to the perimeter fencing and disconnected most of the bare copper perimeter ground loop from the plant grid. Perimeter fence bonding is required at electrical generating stations and at locations where external power is brought into a facility via overhead conductors.[5] This is necessary in order to protect personnel in the event of a falling conductor. Since neither of these conditions exist at the production facilities, with on-site power generation, perimeter fence grounding is not required. However, a perimeter grounding conductor/electrodes would be beneficial if one needed to lower the resistance-to-remote earth of the overall grid. That is not the case for these production facilities.

It was reported that numerous corrosion leaks had been repaired, mostly on flow lines due to active corrosion. In some instances, entire segments of a pipeline were replaced with new pipe. These corrosion losses were responsible for initiating the study reported in this paper.

FACILITY SURVEYS

Annual cathodic protection surveys by the company and in-country subcontractor personnel indicated that the majority of the buried plant piping (BPP) was not adequately cathodically protected, exhibiting pipe-to-soil potentials less negative than -0.85 volts referenced to copper-copper sulphate reference electrode. In late summer 1996, the two authors in collaboration with in-country cathodic protection subcontractors and other company personnel conducted a detailed cathodic protection/electrical grounding survey of the major production facilities and most of the minor production facilities in Sindh Province. This paper presents the results of that field investigation and the lead author's formal recommendations. These results and recommendations are representative of those obtained at the other production facilities in the Badin Block.

Resistance-to-Remote Earth Measurements

An attempt was made to measure the combined plant/electrical grounding grid resistance-to-remote earth at P.F.-1 via the IEEE fall of potential method.[6] A remote current pin (C-1) was established 8,500 feet south of the south fence of the PF. The potential pins were established by driving a galvanized iron rod approximately 5,300 feet south of the south fence of the plant. These pins were connected back to the C-1 and P-1 terminals of the low resistance AC ratio ohmmeter with individual 1.5mm^2 insulated copper conductor. Direct connection was made to the plant grounding grid via additional test leads from the C-2 and P-2 terminals of the AC ratio ohmmeter. The resistance-to-remote earth of the existing composite grounding grid and plant piping network was so low as to preclude measurement with the available instrumentation. Neither of the AC ohm meters available at the time of the survey could accurately measure a value of less than 0.005 ohms.

Therefore, an alternative DC method was used. The differences in potential (ΔE) between the "on" and the "off" <u>remote</u> pipe-to-soil potentials measured while simultaneously cycling T/R Number 1 and T/R Number 2 were used to calculate the resistance of the entire plant grounding grid to remote earth. These measurements were taken using a single, remote copper-copper sulfate reference electrode established at 8,500 (2,590m) feet remote from the plant site. When the interrupted pipe-to-soil potential survey was conducted, the close pipe-to-soil potential and the remote pipe-to-soil potential were measured and recorded at each test site with the T/Rs in both the "on" and in the "off" condition. An average of the remote pipe-to-soil ΔEs was divided by the portion of the T/R outputs that were contributing cathodic protection current to the plant piping only. This procedure disregarded the cathodic protection current that was applied to the flow lines. The calculated resistance of the grounding grid and plant piping at P.F.-1 was 0.001145 ohms.

Local contract personnel were then employed to dig up and sever connections on the bare copper grounding grid wherever this was thought to be practical. After removing as much copper from the system as was considered practical, the plant grounding grid resistance-to-remote earth was remeasured using the same DC techniques. This time, the overall grounding grid measured 0.0012 ohms-to-remote earth. This represents less than a 5 percent increase in overall plant resistance but did provide a significant decrease in the load on the cathodic protection system. For on-site electrical power generation, overall plant grounding resistance in the range of 5 to 25 ohms is considered adequate and safe. Therefore, the extensive grounding system upgrade was not necessary.

The existing cathodic protection system in both P.F.s were preferentially protecting the fire water loop and not providing enough cathodic protection current flow to the varied plant piping which contains the valuable production fluids and gases. During the electrical grounding system dig-outs, deliberate cross bonds were made between fire water piping and plant piping and between insulated plant grounding grid conductors and buried plant piping. This was done to assure adequate electrical continuity between the various systems; that is, grounding grid conductors, buried production piping and varied fire water mains. This is important to overcome cathodic interference problems between various segments of the underground systems. Cathodic interference was noted at more than one location within the plant site. Notably, this was usually occurring on the grounding grid which had not previously been deliberately connected to the BPP but was interconnected only via aboveground connections.

Results of the Investigations

Approximately 800 (244m) lineal feet of additional large diameter bare copper grounding conductor and three groundwells were physically disconnected at P.F.-1. The second set of "on-off" close pipe-to-soil potential data at P.F.-1 did not show an increase in potentials after removal of additional bare copper.[7] This was due to T/R Number 2 (which is dedicated to protection of plant piping) going into halfwave rectification due to a blown diode in the rectifier bridge. Valid data were obtained for the change in the overall grid resistance-to-remote earth, but improvement in pipe-to-soil potentials could not be demonstrated since we had no time to repair the rectifier bridge prior to conducting the final survey. Results of the second survey at P.F.-1 did show elimination of the cathodic interference that was initially noted during the first survey. Cathodic interference had been previously noted on both BPP and on the grounding grid.

Therefore, data presented here in Table 1 is on another production facility, designated as P.F-2, where valid initial and final survey data points were obtained. P.F.-2 plant construction was started about 1990. It is primarily a gas facility. Approximately 890 (271m) lineal feet of additional large diameter bare copper grounding conductor were physically disconnected from this plant grid. While prior efforts by the company had disconnected some segments of the perimeter copper grounding grid from plant fencing, cross connections still existed. As a result of the additional excavation work carried out during these studies, neither the perimeter fencing nor the perimeter bare copper grounding loop remained connected to the plant grid. Several of the data points are marked F.W., designating the fire water system. The reported data points have been selected from across the plant site and are representative readings. All readings shown in Table 1 through Table 7 are close pipe-to-soil potentials measured to a saturated copper-copper sulphate reference electrode. Table 1 lists steady on and immediate off values to demonstrate the voltage shift from the interrupted power source. All other tables show steady on pipe-to-soil potentials under the stated conditions.

Upon review of these data, one will note that the pipe-to-soil potentials on all of the F.W. readings have all decreased in magnitude, while the BPP test points all showed an increase in magnitude in pipe-to-soil potentials. The overall result is more uniform pipe-to-soil potentials throughout the facility. In addition, the "off" pipe-to-soil potentials are more uniform, indicative of improved electrical continuity between the various underground structures. Initially, the T/Rs dedicated to protection of plant piping were provided with the lowest resistance connections to the F.W. loop. There appeared to be more resistance in the negative connections to the BPP. There were no direct connections from the T/Rs to the plant grounding grid. However, there were numerous cross connections between the grounding grid and the BPP.

The reason for the decrease in pipe-to-soil potential magnitudes on the F.W. lines is because of deliberate cross bonding between the F.W. system, the buried plant piping and the electrical grounding grid. Since we can not take the grounding grid out of the equation, a better choice is to bond the grid in common with the balance of the piping system to eliminate stray current cathodic interference problems and to produce more uniform pipe-to-soil potentials. The net result of the improved cross bonding and the elimination of some of the bare copper grounding is more uniform pipe-to-soil potentials on the buried plant piping and elimination of cathodic interference between various elements of the underground system.

At P.F.-2, there are three functioning T/R units. T/R Numbers 1 and 2 power a total of thirty (30) vertically installed distributed anodes around the perimeter of nine production tanks. T/R Number 3 powers a conventional remote vertical anode-bed and is dedicated to cathodic protection of the incoming flow lines and trunk lines from remote production facilities. All three of these T/R's are rated at 25 volts 75 amperes DC. Calculated resistance-to-remote earth of P.F.-2 was 0.001294 ohms prior to removing the additional copper grounding and was 0.00139 ohms after removing the additional copper grounding. This represents a 7.7% increase in overall plant resistance. However, the final overall plant resistance is still more than three orders of magnitude lower in resistance-to-remote earth than is required to operate a safe system. A review of the company's early cathodic protection data would probably show that the installed T/R capacity was adequate to cathodically protect each of the production facilities prior to installation of the "grounding system upgrade".

Similar surveys were carried out at the remaining facilities by local C.P. consultants as per procedures provided by the lead author. One of these outfits was trained for this work by involving them in the surveys in PF-1 and PF-2. Various amounts of copper conductor was eliminated from the grounding grid at these other production facilities also.

Several current requirement tests were conducted at one or more locations throughout the larger plant sites to assist in determining the additional T/R and anode-bed capacity requirements for each facility. In some instances, a complete anode-bed was simulated utilizing temporary driven rods or existing isolated underground facilities, such as roadway culverts, as an anode-bed element. In other instances, a single driven groundrod was energized at incremental amperage values to determine electrical gradient fields around each impressed current anode.

RECOMMENDATIONS

Based upon the extensive investigations carried on throughout the Badin block production facilities, specific cathodic protection system upgrade recommendations were made for each facility. These upgrades ranged from a few zinc anode and test lead installations in one remote production facility to the installation of as many as two additional and much larger T/R units at some of the larger facilities.

We recommended the installation of two additional T/R units in P.F.-1. Proposed T/R Number 3 was installed on the west side of the plant as two split segments of a conventional distributed horizontal anode-bed in close proximity to the process piping. T/R Number 4 was installed on the east side of the plant as one long continuous conventional semi-remote anode-bed.

Recommendations were made for two additional T/R installations at P.F.-2. T/R Number 4 is a 10 volt 100 ampere unit powering a split horizontal anode-bed containing 11 anodes. It is installed on the west side of the plant. This anode-bed is not truly a remote anode-bed but almost could be considered a distributed installation. T/R Number 5 is a 10 volt 150 ampere oil cooled T/R on the east side of the plant. This unit powers a 16-anode horizontal anode-bed which is fully remote from the plant piping.

Similar recommendations were made for other facilities also. Table 2 presents a summary of the recommended cathodic protection upgrades at various facilities.

In addition, we made recommendations for additional cross bonds and for removal of some of the resistor junction boxes (RJB) that were used to cross connect some of the plant piping. Some of the RJBs are appropriate to control pipe-to-soil potentials on flow lines and other isolated piping. However, within the plant site itself, these RJBs introduce unacceptably high resistances in the bonding circuits. This leads to uneven pipe-to-soil potentials and always presents the possibility of cathodic interference on some of the underground structures.

RESULTS OF THE CATHODIC PROTECTION UPGRADES

The field installation work for the recommended C.P. system upgrades started at the end of 1997 and finished by the end of 1998 in three facilities, viz. PF-1, PF-2, and PF-4. No upgrade in ICCP capacity was deemed necessary for the rest of the major facilities. Just removing excessive bare copper grounding at these facilities was sufficient to restore effective levels of cathodic protection. Table 3 presents some of the data from PF-1 collected after commissioning the ICCP system upgrade. The data shows significant improvement in the level of potential of the buried piping at test point locations which are difficult to protect due to their closeness with buried bare copper conductors.

Table 4 presents some of the CP potential data for P.F.-2 after commissioning the recommended ICCP upgrades. Table Numbers 5 through 7 present similar data for P.F.-4. These data also show significant improvement in the CP potential of most of the test points on buried plant piping.

Note that there still are a small percentage of low pipe-to-soil potentials at some of the facilities after final data. All of the final data are gathered within a week of commissioning the upgrade at each facility. It is felt that continuing polarization over the next four to eight weeks will result in protected potentials at most or all of the low potential sites. It not, supplemental cathodic protection in the form of point anodes will be employed.

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TABLE 1
EFFECT OF BARE COPPER REMOVAL ON CP POTENTIAL OF BURIED PIPING in P.F.-2

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO $Cu-CuSO_4$				
DESCRIPTION	BEFORE COPPER REMOVAL		AFTER COPPER REMOVAL	
	CLOSE "ON"	CLOSE "OFF"	CLOSE "ON"	CLOSE "OFF"
F.W. - Water Cannon M-7	-1245	-735	-1005	-660
F.W. - Pump Discharge	-980	-745	-820	-645
2" Fresh Water Line	-755	-635	-785	-645
10" T.R. Inlet Line	-720	-540	-750	-570
Water Injection Pump Suction Line	-760	-580	-780	-580
4" Brine Line – West End	-685	-539	-690	-550
3" Line to Tank S-212	-955	-565	-970	-560
BPP – 47	-545	-475	-560	-485
F.W. - Fire Cannon M-11	-1160	-770	-920	-630
F.W. - P.I.V. H-7	-1200	-770	-980	-670
BPP - 38 - Plant Side	-665	-560	-690	-575
F.W. - Fire Hydrant H-6	-1225	-775	-995	-660
8" Drain Line at Skim Pond	-640	-535	-640	-550

TABLE 2
SUMMARY OF RECOMMENDATIONS
FOR MAJOR PRODUCTION FACILITIES

Facility Identification	Facility Name	Existing CP System		Additional Equipment Recommendations		Upgrade Completion
		T/Rs	G. Beds	T/Rs	G. Beds	
PF-1	Turk Gas Facility	TWO	TWO	TWO	THREE	July'98
PF-2	Golarchi Gas Facility	ONE	TWO	TWO	TWO	May'98
PF-3	Bukhari Gas Facility	TWO	TWO	NIL	NIL	–
PF-4	Mazari Oil/Gas Facility	THREE	THREE	THREE*	THREE	Nov'98
PF-5	Laghari Oil Facility	TWO	TWO	NIL	NIL	–
PF-6	Khaskehli Oil Facility	THREE	FOUR	NIL	NIL	–

* One of the three T/R units recommended is replacement of one of the existing T/R with higher output unit.

TABLE 3
CATHODIC PROTECTION DATA AFTER COMMISSIONING
ICCP UPGRADE FOR P.F.-1

	Date	T/R 1	T/R 2	T/R 3	T/R 4
Initial Data	12-13 May'98	ON	ON	OFF	OFF
Start-up Data	14-15 May'98	ON	ON	ON	ON
Final Data	16-17 May'98	ON	ON	ON*	ON*

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO $Cu-CuSO_4$				
Test Point	**Location Description**	**Initial Data**	**Start-up Data**	**Final Data**
BPP NO.	**BURIED PLANT PIPING (BPP)**			
BPP 6	4" SOUTH EAST OF MCC	-535	-831	-779
BPP 6A	4" SOUTH EAST OF MCC	-530	-802	-754
BPP 2	4" TO DEGASER	-539	-824	-802
BPP 2A	4" DRAIN	-536	-844	-762
BPP 1	4" DRAIN FROM TANKS	-558	-850	-792
BPP 7	2" V-512	-542	-823	-742
BPP 8	2" STUB UP	-529	-766	-702
BPP A	4" TO BURN PIT	-632	-1053	-945
BPP B	4" TO BURN PIT	-678	-1205	-1057
BPP C	2" FROM V-1210	-545	-690	-782
BPP 4	4" NEAR V-1200	-504	-829	-748
BPP 5	1" AT KHOREWAH RECEIVER	-499	-785	-708
BPP 9	8" SSGC METERING SKID	-1126	-1401	-1408
BPP 10	½" AT INCINERATOR	-670	-1058	-1136
BPP 16	8" SSGC MANIFOLD		-1602	-1419
BPP 11		-850	-1064	-1251
BPP 12		-535	-786	-774
BPP 13		-533	-786	-774
BPP 14		-521	-789	-772
BPP 15		-521	-789	-772
G-NO.	**GROUNDING CABLES**			
G-1	FLP 511	-607	-819	-930
G-2	NEAR MCC	-507	-675	-779
G-11		-910	-1642	-1408
G-12		-917	-1178	-1070
G-13		-998	-1565	-1118
G-14		-738	-1691	-1434
G-15		-700	-983	-900
G-3	E-50	-496	-726	-669
G-4	V-505	-506	-782	-714
G-5	D-501	-530	-839	-795
G-6	S-501A	-473	-829	-752
G-7	TR-1	-166	-1120	-470

* ON, but set at reduced output. All potentials are steady on

TABLE 4
CATHODIC PROTECTION DATA AFTER COMMISSIONING
ICCP UPGRADE FOR P.F.-2

	Date	T/R 1	T/R 2	T/R 3	T/R 4
Initial Data	12-13 May'98	ON	ON	OFF	OFF
Start-up Data	14-15 May'98	ON	ON	ON	ON
Final Data	16-17 May'98	ON	ON	ON*	ON*

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO $Cu-CuSO_4$				
Test Point	**Location Description**	**Initial Data**	**Start-up Data**	**Final Data**
G-8	KHOREWAH RECEIVER	-478	-772	-681
G-9	EAST OF V-512	-577	-957	-852
G-10	NEAR FH (5)	-607	-955	-868
T-NO.	**STORAGE TANKS**			
T-501	NORTH	-1132	-1451	-1165
	EAST	-958	-1318	-1065
	SOUTH	-1156	-1459	-1156
	WEST	-1148	-1455	-1179
T-502	NORTH	-1225	-1495	-1159
	EAST	-1158	-1464	-1104
	SOUTH	-1157	-1441	-1110
	WEST	-1151	-1425	-1120
FWL-NO.	**FIRE WATER LOOP**			
1	AREA-2	-856	-1892	-1463
2	AREA-2	-667	-965	-1065
2A	AREA-2	-867	-1155	-922
3	AREA-2	-1122	-1770	-1459
4	AREA-2	-910	-1325	-1244
4A	AREA-2	-984	-1559	-1380
5	AREA-2	-873	-1476	-1210
6	AREA-1	-804	-1409	-1256
6A	AREA-1	-846	-1530	-1344
7	AREA-3	-775	-990	-1095
7A	AREA-3	-813	-1064	-1248
7B	AREA-3	-810	-1066	-1224
8A	AREA-3	-852	-1105	-1353
8	AREA-3	-849	-1108	-1346
9	AREA-3	-844	-1068	-1288
9A	AREA-3	-1058	-1282	-1496
10A	AREA-3	-856	-1096	-1303
10	AREA-3	-850	-1090	-1314
3A	AREA-3	-1286	-2089	-1802

* ON, but set at reduced output. All potentials are steady on

TABLE 5

CATHODIC PROTECTION DATA AFTER COMMISSIONING THE ICCP UPGRADE FOR P.F.-4

	Date	T/R 1	T/R 2	T/R 3	T/R 4	T/R 5
STEP-1	13-14 Nov'98	OFF	OFF	OFF	ON	ON
STEP-2	16-17 Nov'98	ON	ON	ON	ON	ON
STEP-3	19-20 Nov'98	ON*	ON*	ON*	ON*	ON*

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO Cu-$CuSO_4$					
Test Point	**Location Description**	**Initial Data**	**STEP-1**	**STEP-2**	
BPP NO.	**BURIED PLANT PIPING (BPP)**				
BPP 82	½ " GAS TO INCINERATOR	-451	-803	-933	
BPP 82A	½ " GAS TO INCINERATOR	-443	-773	-898	
BPP 81A	2" WATER	-450	-762	-895	
BPP 81	3" WATER	-452	-771	-909	
BPP 78	8" DIA TO SKIM POND	-450	-822	-939	
BPP 79	1-1/2" TO BURN PIT	-452	-787	-894	
BPP 80	2" CRUDE OIL	-452	-788	-896	
BPP 79A	1-1/2" GAS AT BURN PIT	-468	-799	-917	
BPP 80A	2" CRUDE OIL	-468	-779	-919	
BPP 38	8" SALES GAS LINE (LINE/PLANT)	-442	-771	-929	
BPP 36	DRAIN TO SKIM POND 2" FROM V-612	-453	-753	-894	
BPP 35	DRAIN TO SKIM POND 2" FROM V-605	-536	-720	-867	
BPP 37	2" DIA	-446	-737	-857	
BPP 44	4" STUB UP	-453	-715	-857	
BPP 42	1" TO BPP-41	-443	-718	-857	
BPP 41	1" TO T-601	-486	-677	-788	
BPP 40	2" TO T-601	-467	-693	-813	
BPP 43	4" STUB UP	-433	-713	-853	
BPP 39	4" STUB UP	-449	-758	-904	
BPP 12C	½" DIA DIESEL LINE FROM DIESEL TNK	-450	-881	-1081	
BPP 12B	1" DIESEL RETURN	-454	-829	-1016	
BPP 12	2" DIESEL SUPPLY ER-6	-457	-833	-1027	
BPP 12A	1" FROM DIESEL ENGINE	-444	-840	-1030	
BPP 11	2" DIA	-382	-677	-651	
BPP 9	2" FROM AIR COMPRESSOR	-427	-696	-839	
BPP 10	1-1/2" F.G. FROM SCRUBBER GAS ENG.	-434	-702	-861	

* ON, but set at reduced output. All potentials are steady on

TABLE 6

CATHODIC PROTECTION DATA AFTER COMMISSIONING THE ICCP UPGRADE FOR P.F.-4

	Date	T/R 1	T/R 2	T/R 3	T/R 4	T/R 5
STEP-1	13-14 Nov'98	OFF	OFF	OFF	ON	ON
STEP-2	16-17 Nov'98	ON	ON	ON	ON	ON
STEP-3	19-20 Nov'98	ON*	ON*	ON*	ON*	ON*

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO $Cu-CuSO_4$					
Test Point	Location Description	Initial Data	STEP-1	STEP-2	STEP-3
BPP NO.	**BURIED PLANT PIPING (BPP)**				
BPP 83	3" WATER FROM F.W. POND	-476	-779	-1211	
BPP 84	6" WATER FROM F.W. POND	-470	-826	-1225	
BPP 85	6" WATER/PLANT TO F.W. POND	-475	-861	-1257	
BPP 86	3" WATER FROM BPP-83 TO MZ-2	-487	-781	-1250	
BPP 87	6" FROM BPP-84	-545	-751	-1145	
BPP 38A	SSGC AT PLANT (SSGC SIDE)	-872	-790	-1000	
BPP 18B	3" DIA STUB UP (Not connected to CP)	-505	-507	-551	
BPP 45	6" DIA FROM T-S211	-448	-588	-965	
BPP 46	8" DIA FROM T-S211	-450	-589	-969	
BPP 45A	CONTINUATION OF BPP-45	-449	-618	-945	
BPP 46A	CONTINUATION OF BPP-46	-442	-612	-942	
BPP 88	3" WATER TO EV. POND	-453	-590	-926	
BPP 88A	3" WATER (CONTINUATION OF BPP-88)	-483	-636	-961	
BPP 89	8" DIA FROM T-S211 (BPP-89A)	-445	-637	-992	
BPP 32	6" DIA	-441	-632	-993	
BPP 31	4" DIA	-447	-633	-992	
BPP 30	2" WATER	-445	-621	-985	
BPP 29	2" AIR FROM AIR COMPRESSOR	-447	-627	-983	
BPP 28	2" GAS	-447	-629	-986	
BPP 27	8" OIL	-446	-630	-987	
BPP 26	8" OIL	-446	-630	-990	
BPP 19	8" DIA	-431	-619	-1033	
BPP 20	8" DIA	-431	-621	-1027	
BPP 21	2" DIA	-433	-611	-1008	
BPP 22	2" DIA	-431	-615	-1008	
BPP 23	2" DIA	-434	-614	-1008	
BPP 24	4" DIA	-434	-617	-1011	
BPP 25	6" DIA	-433	-619	-1018	
BPP 89A	8" DIA "IF" (ABOVE GRADE)	-433	-615	-1001	
BPP 18A	3" DIA	-439	-613	-910	
BPP 18	4" DIA	-431	-589	-853	
BPP 17	4" DIA	-421	-598	-867	
BPP 16	4" DIA	-418	-607	-893	

* ON, but set at reduced output.   All potentials are steady on

TABLE 7

CATHODIC PROTECTION DATA AFTER COMMISSIONING THE ICCP UPGRADE FOR P.F.-4

	Date	T/R 1	T/R 2	T/R 3	T/R 4	T/R 5
STEP-1	13-14 Nov'98	OFF	OFF	OFF	ON	ON
STEP-2	16-17 Nov'98	ON	ON	ON	ON	ON
STEP-3	19-20 Nov'98	ON*	ON*	ON*	ON*	ON*

SELECTED PIPE-TO-SOIL POTENTIALS MILLIVOLTS TO $Cu\text{-}CuSO_4$					
Test Point	**Location Description**	**Initial Data**	**STEP-1**	**STEP-2**	**STEP-3**
BPP NO.	**BURIED PLANT PIPING (BPP)**				
BPP 15	4" DIA	-418	-602	-897	
BPP 14	6" DIA	-418	-602	-900	
BPP 13	8" DIA	-417	-601	-902	
BPP 90	2" GAS	-421	-865	-996	-979
BPP 91	2" AIR FROM AIR COMPRESSOR	-422	-874	-984	-978
BPP 53	6" OIL	-421	-847	-952	-957
BPP 92	4" GAS	-423	-875	-979	-969
BPP 93	4" AIR	-422	-857	-957	-961
BPP 52	8" GAS	-420	-840	-945	-949
BPP 94	2" AIR FROM AIR COMPRESSOR	-421	-833	-942	-946
BPP 51	6" OIL	-418	-808	-999	-902
BPP 50	8" OIL	-413	-790	-876	
BPP 54	6" STUB UP	-415	-769	-859	
BPP 55	4" STUB UP	-415	-767	-851	
BPP 56	1" OIL DRAIN FROM LIARI PIG REC.	-414	-753	-840	-641
BPP 57	2" FROM LIARI PIG REC.	-424	-776	-876	
BPP 58	2" FROM MATLI PIG REC.	-420	-774	-873	-876
BPP 59	1" DRAIN FROM MATLI PIG REC.	-413	-752	-840	-841
BPP 61	6" OIL FROM DHABI PIG REC. TO BPP-51	-417	-751	-843	-850
BPP 62	1" DRAIN FROM DHABI PIG REC.	-401	-693	-757	-758
BPP 63	2" FROM DHABI PIG REC.	-402	-697	-760	-761
BPP 64	2" FROM S. MAZARI PIG REC.	-400	-697	-763	-763
BPP 65	1" DRAIN FROM S. MAZARI PIG REC.	-399	-680	-748	-748
BPP 67	4" OIL FROM ER-11 (Disconnected)	-413	-718	-819	-819
BPP 70	4" DRAIN TO PIT	-418	-711	-792	-793
BPP 68	1" STUB UP (REMOVED FROM ER-11)	-418	-718	-802	-806
BPP 69	2" STUB UP (REMOVED FROM ER-11)	-433	-747	-839	-844
BPP 71	8" OIL TO V-800 FROM SDV-5000 A&B	-412	-707	-794	-796
BPP 72	1" DIA	-400	-683	-757	-756
BPP 73	6" TO V-700 (REMOVED) OIL	-405	-683	-759	-762
BPP 77	8" FROM INLET MANIFOLD	-408	-686	-771	-773

* ON, but set at reduced output. All potentials are steady on