RAMI Modeling of F-Area Ground Water Facility @ SRS

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ABSTRACT

Reliability, availability, maintainability, and inspectability (RAMI) analysis tool has been used to help control life-cycle cost of several systems and facilities at Savannah River Site (SRS). Recently a RAMI assessment was performed to determine how well the installed F-area Water Treatment Unit (WTU) will meet the established goal for plant availability committed to the State Regulatory Agency, South Carolina Department of Health and Environmental Control (SCDHEC).

The mission of F-area ground water remediation facility at SRS is to reduce concentration of RCRA metals, radio-nuclides and other contaminants in ground water influents to a level where it can safely be returned to the aquifer. The process chosen for treatment of the ground water was determined by review of chemical data, published reports, bench testing as well as discharge requirements that meet commitments made to SCDHEC. Contaminated water is drawn from an underground aquifer located at the F-area seepage basin, pre-filtered through sand filters and then passed through the Reverse Osmosis (RO) system where the ground water is separated into permeate and concentrate. The permeate will have 99% of all suspended solids removed and suitable for discharge to the injection well system. The concentrate is further processed to reduce volume and then disposed of in standard containers.

Per agreement with SCDHEC the unit must operate with an availability of at least 85% including scheduled shutdowns. The unit experienced troubles in meeting this goal from the very beginning. A preliminary RAMI analysis performed after unit commissioning identified problem components and sub-systems and need for redundancy in design of certain systems. Some of these were resolved through procurement of better performing components and elimination of a poor-performing process sub-system that was found to be non-essential. Additionally some new equipment were added to provide for greater operational flexibility. Some regulatory concessions were also negotiated where short duration (<4 hr) maintenance/repair related shut-downs could be ignored for availability computation. A detailed RAMI analysis of the modified unit was then initiated to consider and evaluate all identified operational modes and maintenance policy as well as regulatory relief.

The availability of the unit is estimated using a mathematical model that incorporates the basic RAMI inputs, mean time between failures (mtbf), mean time to repair (mttr) for each system components. The unit was subdivided into total of seven systems where failure in any one will directly impact unit's availability. The model estimates availability at component level and then rolls up to system level. Finally the systems are rolled up to obtain the overall unit availability.

Results from the analysis indicate that some of the systems in their present configuration and under current maintenance policy (only on day shifts and no week-ends) are most likely to cause the WTU to fall significantly short of the 85% target goal. Sensitivity studies with various operation modes, maintenance policies as well as component redundancy were performed. Dominant contributors to unavailability were identified and recommendations were made to ensure that the availability goal of 85% would be achieved with some margin for unexpected contingencies.

INTRODUCTION

Reliability, availability, maintainability and inspectability (RAMI) analysis is an effective tool that can be used to control life cycle lost of DOE systems and facilities. It is however, most effective when incorporated during the early stages of system design process. Early recognition of potential system problem areas allows corrective actions to be taken at a time when there is minimum impact on cost, schedule and other systems. Once a system has been fielded, improvements in facility design to improve performance are more likely to incur expenses that could have been avoided if a RAMI analysis had been provided in the design stage.
A RAMI analysis of the overall system can be used to:

- establish the requirements for reliability, availability, maintainability and inspectability at the subsystem and component levels
- influence the level of design redundancy

The availability of each unit is estimated using a mathematical model that incorporates the basic RAMI inputs, Mean Time between Failures (MTBF) and Mean Time to Restoration (MTTR), for each system component modeled. If the overall unit availability goal is met, then the values used for the MTBF and MTTR for the system components should become required specifications in purchasing, installing, operating, maintaining, or inspecting these components. Typically, initial MTBF and MTTR values for component availability are taken from historical data. However, these values are often adjusted to better represent any atypical conditions that may be anticipated, or intentionally implemented. If the overall unit availability goal cannot be met, then the design of the systems must be reviewed for possible improvements obtained by combinations of the following: component redundancy or programs for maintainability and inspectability that effectively increase component MTBFs or decrease MTTRs. Often a graded approach can be taken where more stringent requirements on MTBF and MTTR are imposed on only a limited number of critical components to achieve the required availability.

The uncertainty regarding the degree of applicability of the historical generic data to a site-specific, newly installed facility is normally addressed by having Operations and Maintenance (O&M) personnel with experience in running the facility, or similar facilities, review the MTBFs and MTTRs and their underlying assumptions. Based on the O&M group's input, the sensitivity of system availability to different maintenance and repair policies is determined using the pre-developed RAMI system models.

The process chosen for treatment of the SRS F Area Seepage Basin Groundwater was determined by a review of the chemistry data, published reports, bench testing performed by ADTECHS (vendor of the "turn key" facilities), and discharge requirements that meet commitments made to South Carolina DHEC. The process selected utilizes reverse osmosis design combined with pre-filtration and secondary waste stream treatment using precipitation, flocculation, and clarification to achieve acceptable TCLP results for the filter cake. The resultant liquid stream is polished and combined with the reverse osmosis permeate into the effluent stream. "Polishing" is provided by ion exchangers which remove the low level

cesium and uranium. After the sludge precipitates out of the concentrate in the Clarifier, it is pumped to a variable plate filter press where it is de-watered and dried and then dumped into a B-12 container for disposal. The container is completely enclosed to contain any dust.
The sequence of the process water flow through the unit (Figure 1) is given by:

- Pumps that transfer water from the Extraction Water Tank
- Reverse Osmosis (RO) trains
- Chemical treatment precipitation
- Clarification
- Sludge de-watering and drying
- Effluent polishers
- Effluent Discharge Tank

For the purpose of this assessment, the Waste Treatment Unit is grouped into four primary systems and three support systems which are then analyzed. These seven systems account for all the major components that must be discussed:

- Reverse Osmosis (RO) Feed and Filter System, which consists of Extraction Water Transfer Pumps that draw ground water from the Extraction Water Tank that is filled by the well pumps. Two out of three pumps must operate in F-Area to obtain the required flow of 165 gpm (maximum 240 gpm); four sand filters which operate in parallel but which are briefly taken off-line individually during backwashing. Only three out of four sand filters are required. Backwash system involves 32 valves that require realignments at various times during operations; two of the reverse osmosis filter trains out of three are required. Of the total flow, approximately 75%, called the permeate, passes further processing and then on to the Effluent Discharge Tank and 25%, called the concentrate, passes to the Concentrate Tank.
- Clarifier System, which consists of the chemical addition systems, and polymer addition system.
- Sludge Filtration and Dryer System, which consists of the sludge transfer pumps and filter press and dryer.
- Effluent Polishing and Discharge System, which consists of a pump, duplex pre-filter, CG8 column (cation adsorption), Dowex column (anion adsorption), and bag filter.

Finally, the Instrument and Service Air System, the Computer Control System and the Facility piping, tank/vessel failure modes are also included in the model.

MAJOR ASSUMPTIONS

Listed below are the major assumptions and limitations pertaining to this study.

- The scope defines the WTU to include all components located between, but not including, the Extraction Water Tank and the Injection Water Tank.
- Scheduled maintenance activities (including Preventive Maintenance (PM) on critical components like Sludge Transfer pumps etc.) and end-of-life replacement of components (eg., Ion-exchange resin columns, RO filter train modules, Sand filters etc.) may reduce unit

availability by about 5% (~ 2.5 weeks per yr). This amount should be subtracted from the computed Unit availability figure shown in the Excel spreadsheets.

- Natural Phenomena Hazards like high winds, lighting etc. may cause facility shutdown not exceeding 100 hours per yr (~ 1%). This amount may be subtracted from the computed Unit availability figure shown in the Excel spreadsheets.
- Routine cleaning operations of redundant process components like back-wash of Sand filters, RO filters, Ion-exchangers etc. are of relatively short duration and can be performed without impacting normal facility operation.
- Adequate manpower to perform all identified/known operation and repair/maintenance tasks (including system backwash, timely component replacement etc.) would be available during all normal operation and maintenance shifts respectively.
- The effect of the present practice of no repair work being performed or continued on night and week-end shifts on component mean repair time (MTTR) will be estimated assuming uniform frequency distribution over all shifts and are as follows:

  For generic repair time H < 8 hr, MTTR = H+10 hrs
  For 48 hr > H > 8 hr, MTTR = 2*H + 8 hrs
  For H > 48 hr, MTTR = 2* H
- Delays and losses due to Human errors attributable to or related to over stress or excessive workload (eg. replacing Duplex Pre-filters every hour) will be minimized and, therefore, can be omitted from the present analysis.
- Also an inherent assumption with input data is around-the-clock availability of operation force of proper skill-mix and immediate access to replacement "spare parts" components on-site.

SYSTEM AVAILABILITY MODEL

The F-Area Water Treatment Unit was subdivided into a total of seven (7) systems. Failure of any one system will directly impact Unit availability. The models were developed to estimate availability at component level and then rolled up to system level. Finally, the systems were rolled up to obtain the overall unit availability.

Availability Equations utilized in the model:

- Single Components: Availability = MTBF/MTBF+MTTR
- 2-Redundant 100% capacity Components :

  Both running, Two must fail, Availability = 1-2x[MTTR/MTBF]^ 2
  One running, 1 standby (fails to start or stops prematurely),
  Availability = 1-(MTTR/MTBF)x[FS+ MTTR/MTBF],
  where FS is Failure to Start probability per demand.
- 3-Redundant (~50% capacity each) all running, 2 must fail,

  Availability = 1-6x[MTTR/MTBF]^ 2
- 4-Redundant (~35% capacity each)

- All 4 running, 2 must fail, Availability = 1-12x[MTTR/MTBF]^ 2
- 3 running, 1 down for restoration (backwash etc.), 1 of remaining 3 must fail, Availability = 1-3x[MTTR/MTBF], where MTTR is time associated with component backwash.

Details of individual system models are discussed below.

Note: Failure rates (λ_t) are /hr, MTBF and MTTR are hr.

RO Feed & Filter System

The major components modeled are :

4 Sand Filters & Back-wash system (with 4x8=32 valves requiring re-alignments), failure rate (λ_t) for individual sand filter is assumed at 1E-5/hr., Thus the mean time between failures MTBF=1/λ_t =1/1xE-5=1E+5 for sand filters.

For backwash valves, there is daily demand on a 8-valve train. The failure rate per demand, λ_d is 3E-4/d. Converting per demand failure to per hr. rate for 24 hr. day, equivalent λ_t = 3E-4/24 hr. For all 8 valves together, effective λ_t =3E-4x8/24=1E-4/hr. Hence effective MTBF = 1/1E-4 = 1E+4.

3-Redundant RO Filter trains, with each train containing 46 modules. Module failure rate λ_t =1E-5/hr. Hence effective failure rate for a single RO filter train is 46x1E-5/hr. Thus the MTBF for single RO filter train = 1/1x46x1E-5 = 2175 hr.

3-Redundant RO Feed Pumps: λ_t for pump is 5E-5/hr. Fail-to-Start (FS or λ_d) is .005 per demand, assuming a weekly start demand on the pumps the effective λt for one pump is [5E-5+.005/24x7] per hr. and the effective MTBF = 1/[5E-5+.005/24x7] = 1.25E+4.

[Used MTBF =725 hr together with MTTR =12 hr per site experience]

CIP sub-system (1 pump+1 valve+1 agitator): Pump λ_t =2E-4, Valve λ_t =1E-4, Agitator λt= 2E-4, λ_d =.02/d, (Note: higher value due harsh cleaning chemical) , assuming daily demand schedule, effective λ_t =[2x(2E-4+.02/24) +1E-4]. Thus effective MTBF= 1/[2x(2E-4+.02/24)+1E-4] = 4.70E+2.

Feed Tank Control Valve (1) : λ_t = 1E-5, λ_d = .005/d, Daily demand. MTBF= 1/[1E-5+.005/24]= 4.58E+3.

Clarifier System

2 Redundant Pumps, 1 standby; λ_t = 5E-5, FS= .005/d

NaOH sub-system: 1 Pump (λ_t =2E-4), 1 valve λ_t =1E-4, 1 Agitator λt= 2E-4, λ_d =.02/d, Daily demand, MTBF= 1/[2x(2E-4+.02/24)+1E-4] = 4.70E+2.

Fe-Cl sub-system: same as NaOH sub-system

Polymar sub-system: 2 Pumps running(λ_t =2*2E-4), 2 valves (λ_t =2*1E-4) [Used MTBF =725 hr per site experience]

Control valve. : λ_t =1 E-4 (higher value for conc.), λ_d = .005/d, Daily demand

RO Cln. Waste: λ_t =2 E-4, λ_d = .005/d, weekly demand

Clarifier w/2 agit+1 pump : λ_t =1E-5+3x2E-4, λ_d =.02/d, weekly

Sludge Dry & Filtration System
Sludge Transfer Pumps:

1 pump to Tank, λ_t =5 E-4, λ_d = .005/d, Daily

2 pumps to Filter/Press, each, λ_t =5 E-4, λ_d = .005/d, Daily, FS=.005/d, [note -high value for sludge]

2 Filtrate Pumps, 1 standby, λ_t =5 E-5, FS=.003/d

2 [Sludge] Filter / Press and Dryer & Conveyor assemblies : effective λ_t (each assembly)= [1E-4+.001/12] + 2x[1E-4+.001/12], 2 demands/day with λ_d=.001/d,

Effluent Polishing & Discharge System
2 redundant Clearwell Pumps : each λ_t =5 E-5, FS=.003/d
2 redundant Effluent Pumps: each λ_t =5 E-5, FS=.003/d
Ion-exchangers. (3): λ_t = 1E-4 each
System back-wash(4), effective λ_t = 4x1E-5
Chem. Metering pump w/mixer : λ_t = 2x1E-4, λ_d = .02/d, weekly demand

Instrument & Service Air System
2 non-redundant Compressor lines: λ_t = 1.14E-4 each, per site experience
1 set of non-redundant Filters & dryer

Facility Piping/Vessel Leak etc.
Assume 500 vessels (λ_t =1E-7 each) plus 10000 ft piping (λ_t =3E-9/ft)

Control System
PLC MTBF adjusted downwards from generic value per site experience
DWS/EWS adjusted downwards. Also one acts as back-up, hence redundancy rule applies.

SUMMARY OF RESULTS & RECOMMENDATIONS

Run - A Existing Facility Configuration

All MTTR's include delay effects of no maintenance work done on night and week–end shifts

The overall unit availability is at **61.7%** (not including the 5% allowance for scheduled maintenance which will reduce it further).
The dominant contributors to unit's un-availability are:
Sludge Filtration and Dryer system: ~ 47%
Note: The *two non-redundant Sludge Transfer Pumps* to Filter Press/ Dryer are the most critical components in this system. *Addition of one standby transfer pump* would reduce the system's contribution to unit's un-availability to 32% and improve unit availability to *68.7%* (gain of 7%).
Clarifier System: ~22% (NaOH /Fe-Cl- most dominant)
RO Feed-Filter Sys.: ~ 20% (Pmp./Flt.Train.-most dominant)
The high values of component repair times due to night and week-end delays contributed heavily to the low availability of the unit, as compared to the earlier unit availability figure of ~76% indicated in the previous issue of the report.

Run – B Run –A, together with the 'funded improvements'
One standby Fe-Cl Pump and no Roughing Filters
The supporting systems (back-wash, cleaner waste etc.) are assumed to be only used and/or repaired during day shifts.
The overall unit availability is at **66.5%** (not including the 5% allowance for scheduled maintenance).
The dominant contributors to unit's un-availability are:
Sludge Filtration and Dryer system: ~ 56%
Note: The *two non-redundant Sludge Transfer Pumps* to Filter Press/ Dryer are the most critical components in this system. *Addition of one standby transfer pump* would reduce the system's contribution to unit's un-availability to 40% and improve unit availability to *74%* (gain of 7.5%).
Clarifier System: ~19% (NaOH addition- most dominant)
RO Feed-Filter Sys.: ~ 15%(Pmp./Flt.Train.-most dominant)

Run – B+ Run –B with the following changes:
One Ion-exchanger bypass may be allowed
Repair time (MTTR) ≤ 4 hr may be ignored for support systems under the de-minimus rule
Only the large Sludge Pump/Press/Dryer is needed at all time. The Re-route system (18-hr bypass) may be used to compensate for the smaller pump/press/dryer un-availability.
The overall unit availability is at **73.3%** (not including the 5% allowance for scheduled maintenance)
The dominant contributors to unit's un-availability are:
Sludge Filtration and Dryer system: ~ 48%

Note: The *non-redundant Sludge Transfer Pumps* to Tank and Filter Press/ Dryer are the most critical components in this system. *Addition of one standby transfer pump to either the Tank or the Filter Press* would reduce the system's contribution to unit's un-availability to 35% and improve unit availability to *77.8%* (gain of 4.5%).

Clarifier System: ~25% (NaOH addition- most dominant)

RO Feed-Filter Sys.: ~16% (Pmp./Flt.Train.-most dominant)

Note: *Addition of a standby air compressor* would yield an *additional* unit availability *gain of 1.5%*.

Run – B++ Run –B+ with the following change:

Assumed that repair work will be performed/ continued through night and week-end shifts

The overall unit availability is at **86.7%** (not including the 5% allowance for scheduled maintenance)

Note: Continuing *repair works through night and week-end shifts* increases facility availability by ~ 14% and can bring the unit's availability close to its target goal of 85%.

The dominant contributors to unit's un-availability are:

Sludge Filtration and Dryer system: ~ 51%

Note: The *non-redundant Sludge Transfer Pumps* to Tank and Filter Press/ Dryer are the most critical components in this system. *Addition of one standby transfer pump to either the Tank or the Filter Press* would reduce the system's contribution to unit's un-availability to 37% and improve unit availability to *89.5%* (gain of 2.8%).

Clarifier System: ~17% (NaOH addition- most dominant)

Instr. & Serv. Air Sys: ~16%(Compressors-most dominant)

Note: *Addition of a standby air compressor* would yield an *additional* unit availability *gain of 1.8%*.

RO Feed-Filter Sys.: ~14% (Pmp./Flt.Train.-most dominant)

Comments:

1. The uncertainties in the values used for the MTBF and MTTR for the Waste Treatment Units are larger than the generic values that apply to typical industrial experience.
2. Availability will be sensitive to procedures where personnel may tend to "stack" actions in a consecutive order, like maintenance or change-outs. These non-parallel activities will cause a loss of availability in maintaining the required flow. Procedures must ensure as many required actions be done in parallel as possible so that delays in full-flow operation is eliminated, or significantly minimized.
3. The availability remains very sensitive to non-redundant 100% components (no online backup) that must operate at their full flow capacity, such as the Sludge Transfer Pump.

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24-Jun-99 **F AREA WTU AVAILABILITY STUDY (Run-B++.)**

RO FEED/FILTER SYSTEM

Component	MTBF	MTTR	Availability	mttr/mtbf	1/mtbf	Avg. MTTR	Avg. MTBF	Sys.'s Contrib. To Unit's Un-availability Method-1	Method-2	*Average*
			=1-12*(E6)^2-3*C6/B6							
Sand Filters-(4)	1.00E+05	12	0.999640	0.00012	0.00001					
RO FPump-(3)	7.25E+02	12	0.98371777	0.01655172	0.00137931					
RO Filter-(3x46modules)	2175	24	0.98908595	0.01103448	0.00045977		=G9*(D9/(1-D9))			
Sgl. FPmp-RO F Trn.			0.97298143	0.02758621	0.00183908	15	540.173678			
Fpump-ROF Trns.(3)	540.173678	15	0.981736	0.05517241	0.00367816					
RO FTk Cntl.Vlv(1)	4.58E+03	4	0.9991274	0.00087336	0.00021834			=(1-D12)/(1-E74)		=AVERAGE(I12:J12)
	System Availability Results:		**0.98052608**	0.11133819	0.00758466	14.6793863	739.117782	0.14587998	0.12891657	***0.13739828***
			=PRODUCT(D6,D10:D11)			=E12/F12	=G12*(D12/(1-D12))		=(1-(1-E74/D12)/(1-E74))	

CLARIFIER SYSTEM

Component	MTBF	MTTR	Availability	mttr/mtbf	1/mtbf
			=1-E17*(0.005+E17)		
Clarifier FPump(2)	2.00E+04	48	0.99998224	0.0024	0.00005
Control Vlv. (1)	3.24E+03	4	0.99876695	0.00123457	0.00030864
NaOH Pmp.+Agit.+V	4.70E+02	4	0.99156118	0.00851064	0.00212766
Polymar(2Pmp+2V)	7.25E+02	4	0.99451303	0.00551724	0.00137931
Fe-Cl	4.70E+02	4	0.9998850	0.0085106	0.0021276

Pmp.+Agit+V				2	4	6					
Clfr w/2 Agit.+Sd Pp	1.43E+03		12	0.99164927	0.00842105	0.00070175					
	System Availability Results:			**0.97655027**	0.03459414	0.00669503	5.16714039	215.182492	0.17566297	0.15586831	***0.16576564***

SLUDGE DE-WTR.,DRY & FILTRATION SYSTEM

=B28/(B28+C28)

Sldg.Xfr.Pp.to Tk(1)	1.43E+03	48	0.967524	0.03356643	0.0006993					
Sldg.Xfr.Pp.to Prs(2)	1.43E+03	48	0.967524	0.03356643	0.0006993					
Fltrt.Rtn.Pumps(2)	2.00E+04	48	0.99998704	0.0024	0.00005					
Sldg.Fl-Pr/Dr-Cnv.	1.67E+03	12	0.99284863	0.00720288	0.00060024					
	System Availability Results:		**0.92939561**	0.07673575	0.00204884	37.4532381	493.012934	0.5289005	0.49311198	***0.51100624***

EFFLUENT POLISHING & DISCHARGE SYSTEM

=1-E37*(0.003+E37)

Clfr. Cl-wl Pmps(2)	2.00E+04	48	0.99998704	0.0024	0.00005
Ion Exchgrs(3)	3.30E+03	8	0.999965	0.00242424	0.00030303
Effluent Filter(1)	1.00E+05	6	0.99994	0.00006	0.00001
Effl. Wtr. Pmps(2)	2.00E+04	48	0.99998704	0.0024	0.00005
Control Vlv.(1)	4.58E+03	4	0.9991274	0.00087336	0.00021834
Chem.Metr.Pp.+Mix	3.85E+03	4	0.99896212	0.00103896	0.00025974

System Availability Results:			**0.99796948**	0.00919657	0.00089111	10.3203351	5072.28818	0.01521071	0.01320701	*0.01420886*

INSTRUMENT & SERVICE AIR SUPPLY SYSTEM

Srv.Ar w/2 Cmpr.Ln	4380	96	0.97855228	0.02191781	0.00022831					
Pre+Aft.Filtr+Dry.(3)	3.33E+04	4	0.99987989	0.00012012	3.003E-05					
Control Vlv.(1)	4.58E+03	2	0.99956351	0.00043668	0.00021834					
System Availability Results:			**0.97800767**	0.02247461	0.00047668	47.1480986	2096.69486	0.16474548	0.14596322	***0.15535435***

FACILITY PIPING/VESSEL LEAK/RUPT. & OV.-FLOW

Leak/Rup.Ppg.+Tks	1.00E+04	12	0.99880144	0.0012	0.0001					
System Availability Results:			**0.99880144**	0.0012	0.0001	12	10000	0.00897848	0.00778925	*0.00838386*

CONTROL SYSTEM

PLC	1.00E+04	12	0.99880144	0.0012	0.0001					
DWS/EWS	1.00E+05	12	0.99999997	0.00012	0.00001					
System Availability Results:			**0.99880141**	0.00132	0.00011	12	9999.75972	0.00897869	0.00778944	*0.00838407*

Un-availab.	*Summation:*	*1.0005013*

COMPLETE UNIT AVAILABILITY : **0.86650724**

=D66*D58*D51*D43*D32*D23*D13

Comments:

1. Supporting Sys. Repairs (MTTR) of <= 4 hrs. ignored (de-minimus rule)
2. Ion-exchg. Bypass (one at a time) allowed
3. Assumed only the large Sldg. Pmp./Press/Drier needed at all time, Re-route sys. to be used to compensate for the smaller one
4. *Assumed repair work continued through night and week-end shifts*
5. Typical equations are shown in smaller font above/below results in the same column