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Assessing the Impact of Equipment Aging on System Performance Using Simulation Modeling Methods

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ABSTRACT

The radiological Inductively Coupled Plasma Mass Spectrometer (ICP-MS) is used to analyze the radioactive samples collected from different radioactive material processing operations at Savannah River Site (SRS). The expeditious processing of these samples is important for safe and reliable operations at SRS. As the radiological (RAD) ICP-MS machine ages, the experience shows that replacement parts and repairs are difficult to obtain on time for reliable operations after 5 years of service. A discrete event model using commercial software EXTEND was prepared to assess the impact on sample turn around times as the ICP-MS gets older. The model was prepared using the sample statistics from the previous 4 years. Machine utilization rates were calculated for the new machine, 5 year old machine, 10 year old machine, and a 12 year old machine. Computer simulations were run for these periods and the sample delay times calculated. The model was validated against the sample statistics collected from the previous 4 quarters. 90% confidence intervals were calculated for the 10th, 25th, 50th, and 90th quantiles of the samples. The simulation results show that if 50% of the samples are needed on time for efficient site operations, a 10 year old machine could take nearly 50 days longer to process these samples than a 5-year old machine.

1.0 INTRODUCTION

Savannah River Site (SRS) is a 50+ years old facility and produces nuclear materials for the nation's defense. The facility is an industrial complex in itself where all types of engineering and business operations are performed. Some of the important operations include R&D for the design and operation of nuclear reactors, separation of fissile materials, design of complex remotely operated equipment, large HVAC systems, vast nuclear waste handling complex, and many more. As the systems age, their performance degrades and the management is faced to make critical decisions whether to retire the equipment or keep fixing it. As a member of the simulation and modeling group at the SRS, we were asked if we could build a sound case based on simulation modeling methods to replace an aging (> 5 years old) radiological Inductively Coupled Plasma Mass Spectrometer (ICP-MS). The ICP-MS analyzes radioactive material samples, including waste, for characterization to facilitate proper handling and disposal. Mass spectrometer operations include remote sample handling equipment, chemical analysis equipment, data recording system, QA inspection, and disposal of the samples. This simulation effort quantifies the impact on sample turn around time as the ICP-MS gets older.

2.0 SAMPLE ANALYSIS OPERATIONS

The samples come from four different radioactive material handling operations, namely WPT, Actinide, RPP, and ITS. The samples are received at the sample receiving station and entered into the Laboratory Information Management System (LIMS). The samples are then prepared for analysis, analyzed in the RAD ICP-MS, analysis results are QA'd and documented, and the samples are then properly disposed. Elaborate records are kept for all the samples, but no time data exist on routine handling and book keeping operations. Some time estimates are available for the actual ICP-MS operation part of the work.

2.1 Performance Measure

The important performance measure is the sample turn around time. 50% of the samples should be processed within a month to support plant operations.

3.0 DATA COLLECTION

The data were collected for incoming samples, breakdown frequency of the ICP-MS, repair time, analysis time, sample turn around times, and the number of processed samples.

3.1 Incoming Samples

There is no well defined pattern for the incoming samples. The samples come one at a time and also in batches. Manny times the samples just sit on the incoming shelf before they are logged in. Since the emphasis in this study was to assess the impact of machine degradation on sample turn around time, the arrival process was simplified as exponential with the interarrival times calculated from the yearly average. The incoming data were available for 5 quarters starting from fall 2001 to the winter of 2002. The yearly average of incoming samples for this period was

1821 samples. The distribution of incoming samples from various operations is as follows:

WPT: 1417; Actinide: 171; RPP: 138; ITS: 95 Total = 1821. The mean time between arrivals for each type of sample is calculated on a 2000 hours per year basis. Therefore, the mean interarrival times are: WPT: 1.41 hrs; Actinide: 11.7 hrs; RPP: 14.5 hrs; and ITS: 21 hrs.

3.2 Machine Breakdown Frequency

The following data on time between failures (TBF) in days were collected for the years 2001 and 2002 starting January 2001.

Years 2001 to 2002: 1,20,5,17,12,15,22,67,33,83,27,21, 22,128,36,11,2,5,16,19,17,17,12,7

A histogram of this data is shown in Figure 1.

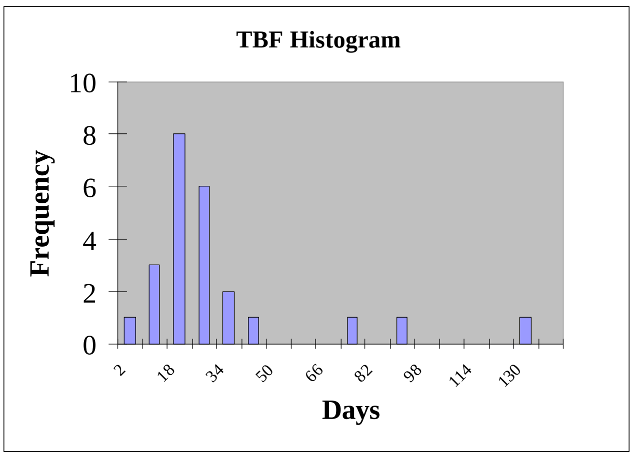

Figure 1 – Time Between Failures

Gamma distribution fits very well (p = 0.17) to this data with a shape parameter α • 1.5. The scale parameter β was calculated using the equation, $Mean = ab$. On the average, there were 12 to 13 breakdowns per year for this period. The value of the mean (TBF) will go down as the equipment ages. The value of α was kept constant and the scale parameter β was adjusted to match the number of expected breakdowns for 5 year, 10 year and 12 year old machines.

3.3 Repair Time

It is estimated that the repair time is about 2 days for every ICP-MS breakdown. However, the total system downtime includes failure detection time, repair time, administrative time, scheduled downtime for preventive maintenance, and the logistics time connected with the repair cycle. This maintainability of the system is dependent on personnel availability which is affected by personnel overhead hours like training, vacations, etc., and therefore, the TTR model includes the effect of these overhead hours. These considerations increase the variability of the TTR. Section 3.4 gives more details for the TTR calculations. Gamma distribution is a good distribution for TTR [1] and was used with shape parameter = 2 in the simulation. The scale parameter was calculated using the equation, $Mean = ab$.

3.4 Machine Degradation Rate

The Table 1 was compiled after discussions with the technicians and the managers responsible for the ICP-MS operations.

Table 1 – Utilization Calculation

Age (YR)	Hours/Yr (Hrs) (1)	Overhead (Hrs) (2)	Breakdowns per Yr
New	2000	400	4
7-May	2000	400	13
10	2000	400	18
12	2000	400	24

Table 1 cont'd:

Repair Time (HRS) (3)	Available Hours (1-2-3)	Utilization (%)
64	1536	77
208	1392	70
288	1312	65
384	1216	61

Notes for Table 1:

1. Hours/Yr are calculates assuming (2080-10 holidays) = 200 hours
2. Overhead hours are calculated assuming 5-weeks vacations (including 1-week of personal time) plus training and other official activities. A 20% time for overhead is used.
3. Repair time is calculated using an average of 2 days per breakdown and 8 hours per day.
4. The available hours consider the loss due to overhead. ICP-MS operations involve many tasks that are labor intensive. Actual machine time is relatively small.
5. Utilization of the machine is calculated as Available Hrs/2000.

If the degradation rate is calculated on the basis of lost hours when the machine is new (464 hrs) and the lost hours when the machine is 10 years old (688), the rate comes out to be 4.2% per year. This is calculated by the equation, $464 * (1 + D\_Rate)^{10} = 688$. This gives D_Rate = 4.2%.

3.5 Outgoing Samples

The processed sample data were available for 3 years starting from year 2000 to year 2002. On the average, 1550 samples were processed per year during this period. The remaining samples remain backlogged and are processed on priority basis in overtime. The records show that, on the average, about 10% samples are in the system for as long as 4 to 6 months before they are processed. The time basis for analysis in this report is 2000 hours per year of regular work. The sample turn-around times for the 4 quarters starting 3QFY01 to 2QFY02 were collected. The times in days are given for 25%, 50%, 60%, 90%, and 100% samples processed. These times along with the averages are given in Table 2.

Table 2

Quarter	Turn Around Time - Days				
	25%	50%	60%	90%	100%
3QFY01	11.3	21.3	23.4	56.4	124.6
4QFY01	7.3	13.4	14.3	48.6	122.3
1QFY02	18.36	27.64	33.31	56.32	129.53
2QFY02	16.32	30.33	37.39	82.66	180
Average	**13**	**23**	**27**	**61**	**139**

3.6 Service Time

Service time includes the actual machine analysis time plus other manual tasks needed for the processing of samples. It was difficult to figure out how to account for the average time spent for manual tasks such as the bookkeeping, QA, and other sample handling steps. After discussions with the technicians and the managers, it was agreed that an average of 1500 hrs (75% utilization) are available for the ICP-MS operations. The experience also showed that about 10% samples were recycled due to analysis missteps or interruptions during analysis. So for an output of 1550 samples per year (Section 3.5), about 1722 samples were processed. Therefore, we get an average service time of 0.87 hours for each sample. A small time variation was applied to the service time by using a TRIANG(0.7,1.0,0.87) distribution. Law and Kelton [1] also suggest that a triangular distribution can be used if a better choice cannot be found.

4. DISCRETE EVENT SIMULATION MODEL

The steps or tasks identified in Section 2 are modeled into a discrete event simulation model using the commercial software EXTEND [2]. This software is capable of simulating sample queues, machine breakdown times, machine repair time, service time, sample recycle rate, etc. with appropriate distributions and then calculate the total turn around time. The model includes an item (sample) generator, total turn around timer, service station (mass spectrometer), TBF and TTR generators, a recycle loop, and statistics recorder. The statistics recorder keeps track of breakdown frequencies, utilization factor, turn around time for each sample item, item counts, and waiting times in queues. Figure 1 shows the model consisting of these blocks and the top level hierarchical blocks. Figure 2 shows the details of the mass spectrometer block that contains the TBF and TTR generators. Simulations were performed for four different machines: new, 5-year old, 10-year old, and 12-year old machines.

The mass spectrometer operations are continuous operations. So the simulations are non-terminating in nature. Each simulation run was made for 20,000 hours (10 years) to ensure good estimate of sample turn around time for steady state operations. Furthermore, 50 replications were made for each case to get good independent sample size. TBF and TTR times were adjusted for each machine in accordance with the times in Section 3.4 to achieve correct utilization factor. NO attempt was made to apply any variance reduction techniques.

4.1 Model Validation

The ICP-MS operations in the validation run represent a 5 year old machine, the life of the machine at the time of this analysis. Table 3 gives a comparison of the sample turn around times calculated from simulations and the actual data collected from ICP-MS operations.

Table 3 - Turn Around Times in Days

% Samples	Actual	New	5 Yr	10 YR	12 Yr
25%	13	1	4	26	46
50%	23	5	14	57	92
60%	27	7	19	68	110
90%	61	34	55	136	221
Utilization		**77%**	**71%**	**65%**	**62%**

The above results are plotted in Figure 2. The blue and yellow lines show the comparison between the validation results for the 5 year old machine and the actual data collected from operations. The plot shows that the model predicts somewhat shorter turn around time than the actual operations. The utilization factor is 71%. The simulation results could be improved by reducing the utilization factor to 70% by increasing the failure rate and the repair time. So it appears that the model is capable of reproducing the historical results well. Also the trend of the simulation results is consistent with the observed data. Therefore, this model was accepted for prediction the response of a 10 year and a 12 year old machine.

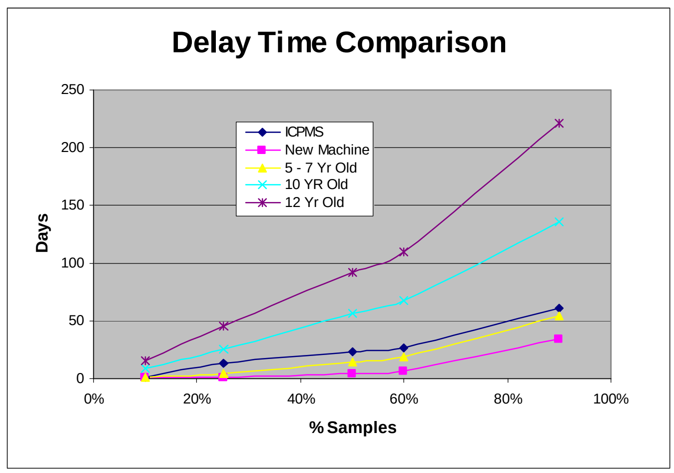

Figure 2

4.2 Simulation Results for Older Machines

Based on the above model, simulations were run for a new machine, a 10 year old, and a 12 year old machine. The plot in Figure 3 shows the sample turn around times for individual samples in days for the new machine, 5 year old machine, and a 10 year old machine. The plot gives a probability mass function. No data are shown for the 12 year old machine as the time delays were absurdly long. It is clear that a reduction in utilization factor from 70% (5 year machine) to 65% for a 10 year machine can have a severe impact on the turn around times. A very large number of samples have much longer delays for the 10 year machine than a 5-year old machine.

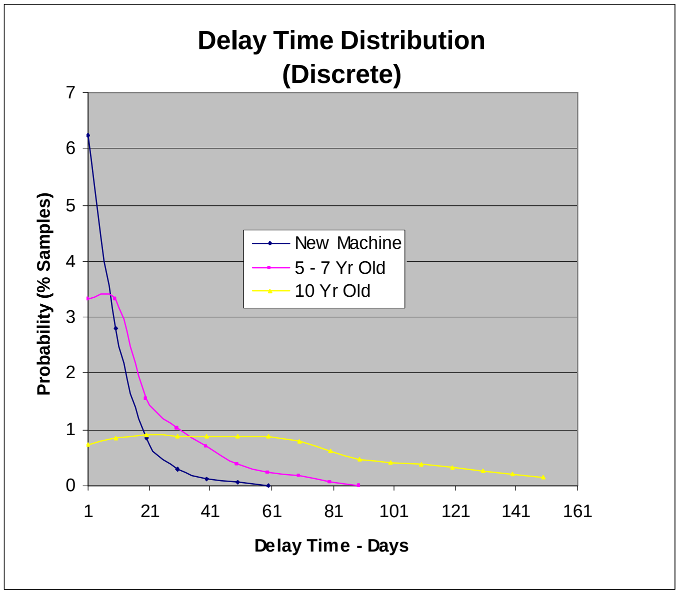

Figure 3

The above results are plotted in Figure 4 for the cumulative percentage of samples. The ordinate shows the cumulative percentage of samples processed. Again it is clear that there is profound increase in delays from a 5 year old machine to a 10 year old machine.

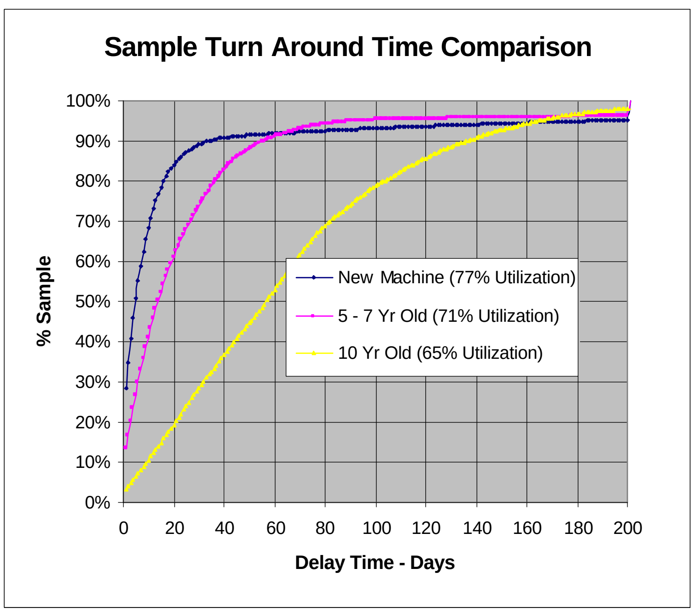

Figure 4

The important observations from the above results are summarized in Table 4.

Table 4

Samples Processed	New Machine	5 Yr Old	10 YR Old
25%	1	4	26
50%	5	14	57
90%	34	55	136

90% confidence intervals were calculated for the 10th, 25th, 50th, and 90th sample quantiles. These are given in Table 5.

Table 5

	Turn Around Time - Days (90% Confidence)			
Samples ->	**10%**	**25%**	**50%**	**90%**
New	1	1	5	50
5 - 7 Yr	1	4	17	83
10 YR	4	20	67	197
12 YR	9	42	128	329

5.0 CONCLUSIONS

The simulation results show that even a small degradation rate of 4.2% in the machine performance could have a severe impact on day to day operations. It is concluded that the samples turn around times could increase from 17 days for a 5 year old machine to nearly 67 days for a 10 year old machine. Therefore, it is recommended that advance planning should be started to replace the ICP-MS after about 5-years of operation.

6.0 ACKNOWLEDGMENT

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7.0 REFERENCES

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2. EXTEND, Version 5.0, Imagine That, Inc., San Jose, Ca.

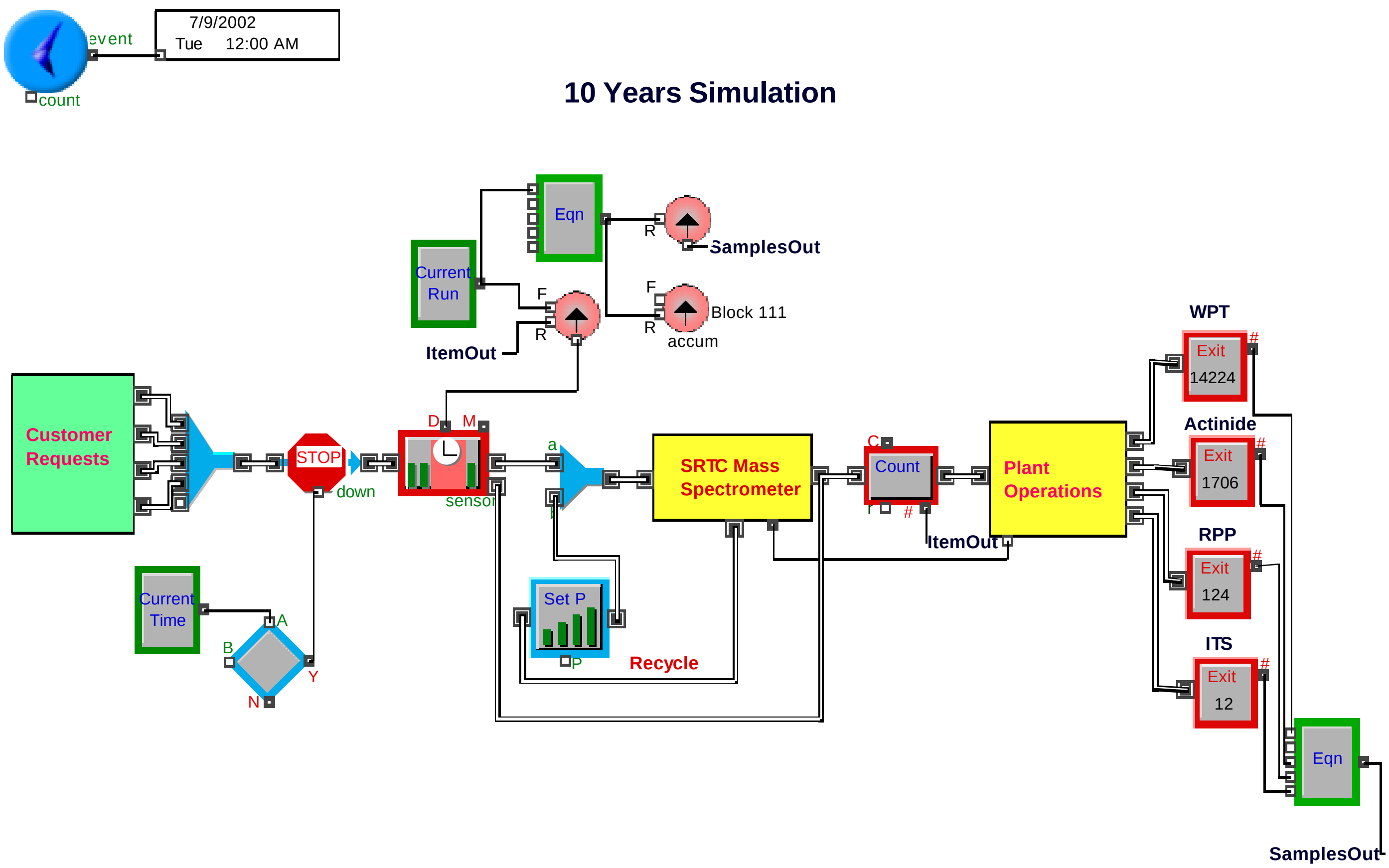

Figure 5 – Complete Model

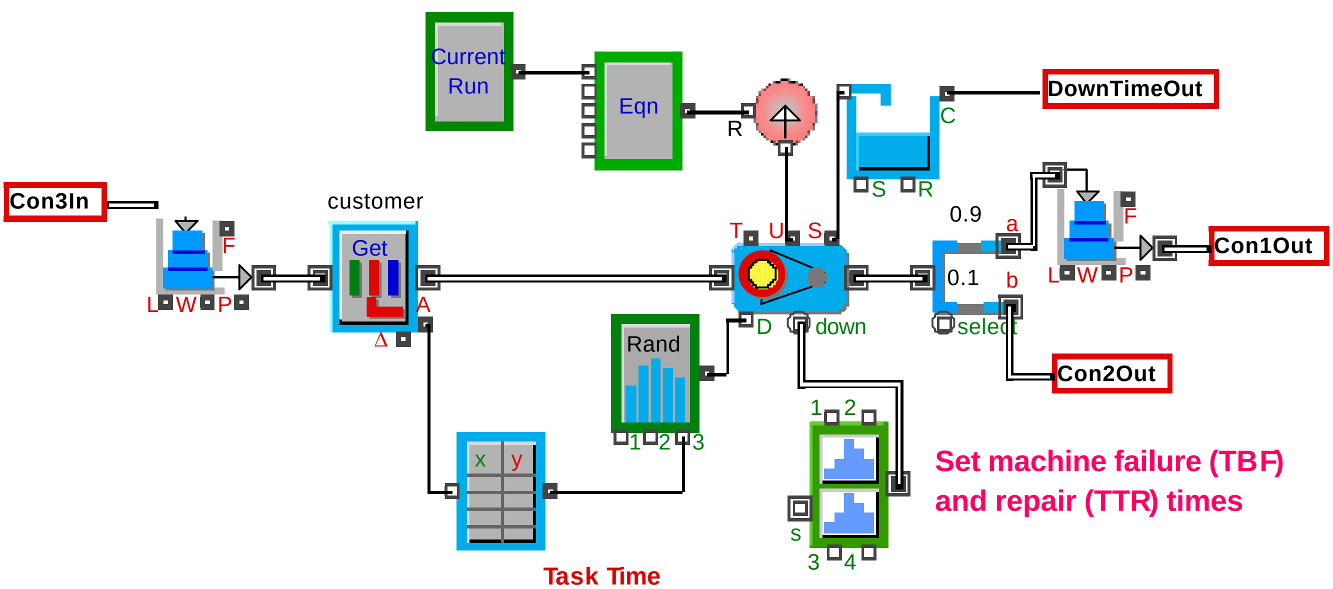

Figure 6 – Detailed Layout of SRTC Mass Spectrometer Block