REVIEW OF DATA RELEVANT TO
AIR SAMPLER IODINE LINE-LOSSES

Task 1 Report

J. A. Glissmeyer

February 1986

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Pacific Northwest Laboratory
Richland, Washington 99352

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PURPOSE

Before providing guidance on acceptance criteria for radioiodine line-loss determinations, a review of past relevant work is helpful. An earlier report (Glissmeyer 1985) reviewed line-loss experimental methods, iodine line-loss models, some of the available data and defined the concepts of deposition velocity and resuspension rates. This report expands on that limited coverage of data. The data reported here will be presented in the following order: iodine in reactor effluents; measurements of iodine deposition and resuspension onto coupons of various materials; measurements in tubes simulating sampling systems; theoretical analyses of sampling systems; and the in-place testing of sampling systems.

IODINE IN REACTOR EFFLUENTS

Extensive studies have been made of the quantities of radioiodine species in light water reactor effluents. The iodine species distribution and quantities differ widely from plant-to-plant, plant areas and plant operating mode. For the purposes of this review, the average distribution of the iodine species in gaseous effluents will be presented because the performance of airborne iodine transport through tubes is highly dependent on the form of the iodine. For three PWR's and three BWR's the average distribution of iodine species in the total plant effluent was estimated by Pelletier et al. (1978a,b). The distributions shown in Table 1 were estimated for a hypothetical year's operation including the various operating modes of the plants. It was also found that the quantity of iodine in the effluent from the plant types was comparable. For PWR's, the primary coolant system in the auxiliary building and the containment purges were the most important sources of airborne

TABLE 1. Estimated Distribution In Overall Plant Air Exhaust

Iodine Form	PWR	BWR
Particulate	2%	12%
Elemental	27%	28%
HOI	40%	20%
Organic	31%	40%

radioiodine. For BWR's the important source was the condenser area. The emission rate can fluctuate considerably depending on the power level and maintenance operations and is probably seldom at a steady state.

MEASUREMENTS ON COUPONS

KABAT

Kabat (1983) reported deposition velocities of different iodine species onto various materials with laminar flow conditions. The materials tested included:

Copper
Carbon steel
Stainless steel
Aluminum
Polyvinylchloride
Polyethylene
Teflon
Buna-N

Some metal specimens were tested as received and others were tested after cleaning. The cleaning process began with an ethanol rinse. Aluminum was cleaned with 1% NaOH and the other metals with 1% HCl. They were then rinsed with distilled water and methanol. The plastic specimens were tested as received with no cleaning. The specimens were rectangular strips of 560-1600 mm^2.

The specimens were placed in glass chambers through which the test gas flowed. The flowrate of the gas was sufficiently high that the depletion of the iodine was negligible. This permitted the use of a single iodine species sampler at the outlet of the exposure chamber for the determination of exposure concentration. The species sampler contained copper screens, HOI adsorbent and TEDA impregnated charcoal as described by Kabat (1976).

The individual iodine species were generated and mixed with air of the desired humidity level. Elemental iodine vapor was generated from a chilled solution of elemental iodine in distilled water. The HOI was generated by purging the carrier air through a 5×10^{-8} M solution of elemental iodine in distilled water. The methyl iodide was released from a cylinder. In each test, several specimens were exposed to one of the iodine forms. The amount of iodine deposited on the specimens was determined by direct counting. The concentrations of each iodine specie in the test gas were:

Elemental Iodine	10 ug/l ± 30%
HOI	0.01 - 0.05 ug/l
CH_3I	1 ug/l ± 20%

The experimental parameters were:

Temperature	20 - 24°C
Pressure	1 Atm.
Relative Humidity	5% and 97% +/- 3%
Carrier Gas	Air
Reynold's No.	16

The calculated deposition velocities for metals and plastics are given in Tables 2 and 3. respectively.

Kabat used the deposition data to estimate the performance of sampling tubes using as an example a tube 30 m long, 12.5 mm inside diameter with a 100 lpm flowrate. The fraction of each iodine form which would deposit while passing through the tube was calculated by Equation 1.

$$\text{Fraction deposited} = 1 - \text{Exp}(4V_dL/V_aD) \qquad (1)$$

where V_d = Deposition Velocity, cm/s

L = Tube Length, cm

V_a = Average Gas Velocity in Tube, cm/s

D = Tube Inside Diameter, cm

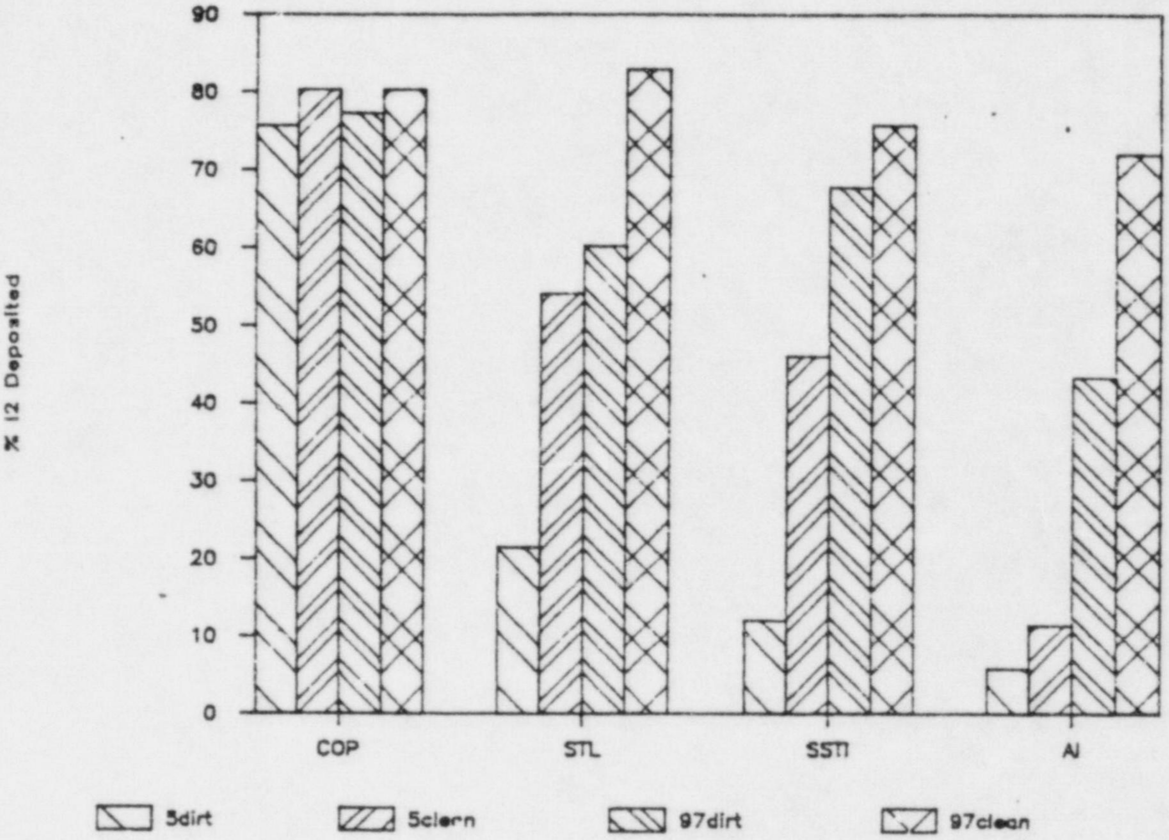
TABLE 2. Deposition Velocities For Metals, cm/s

Iodine Form	% R. H.		Copper	Carbon Steel	Stainless Steel	Aluminum
I_2	5	Uncleaned	2.0E-01	3.4E-02	1.8E-02	8.4E-03
I_2	5	Cleaned	2.3E-01	1.1E-01	8.7E-02	1.7E-02
I_2	97	Uncleaned	2.1E-01	1.3E-01	1.6E-01	8.0E-02
I_2	97	Cleaned	2.3E-01	2.5E-01	2.0E-01	1.8E-01
HOI	5	Uncleaned	1.0E-03	1.4E-03	4.0E-04	1.9E-04
HOI	5	Cleaned	1.4E-02	8.0E-04	3.3E-03	2.5E-03
HOI	97	Uncleaned	2.2E-02	2.0E-03	1.8E-03	1.2E-03
HOI	97	Cleaned	2.7E-02	3.8E-03	4.4E-03	5.6E-03
CH_3I	5	Uncleaned	2.0E-06	8.0E-06	1.0E-05	8.0E-06
CH_3I	5	Cleaned	1.0E-05	8.0E-06	7.0E-06	1.0E-05
CH_3I	97	Uncleaned	7.0E-06	4.0E-06	8.0E-06	4.0E-06
CH_3I	97	Cleaned	7.0E-06	4.0E-06	8.0E-06	1.0E-04

TABLE 3. Deposition Velocities For Plastics, cm/s

Iodine Form	% R. H.	PVC	Polyethylene	Teflon	Buna-N
I_2	5	1.0E-01	4.0E-03	3.5E-02	2.0E-01
I_2	97	2.7E-01	1.5E-02	2.0E-02	2.7E-01
HOI	5	1.2E-01	3.3E-02	2.5E-04	1.5E-01
HOI	97	1.3E-01	2.2E-02	9.5E-04	1.6E-01
CH_3I	5	3.4E-04	1.0E-04	3.4E-05	1.9E-04
CH_3I	97	6.0E-04	3.2E-05	2.5E-05	4.5E-04

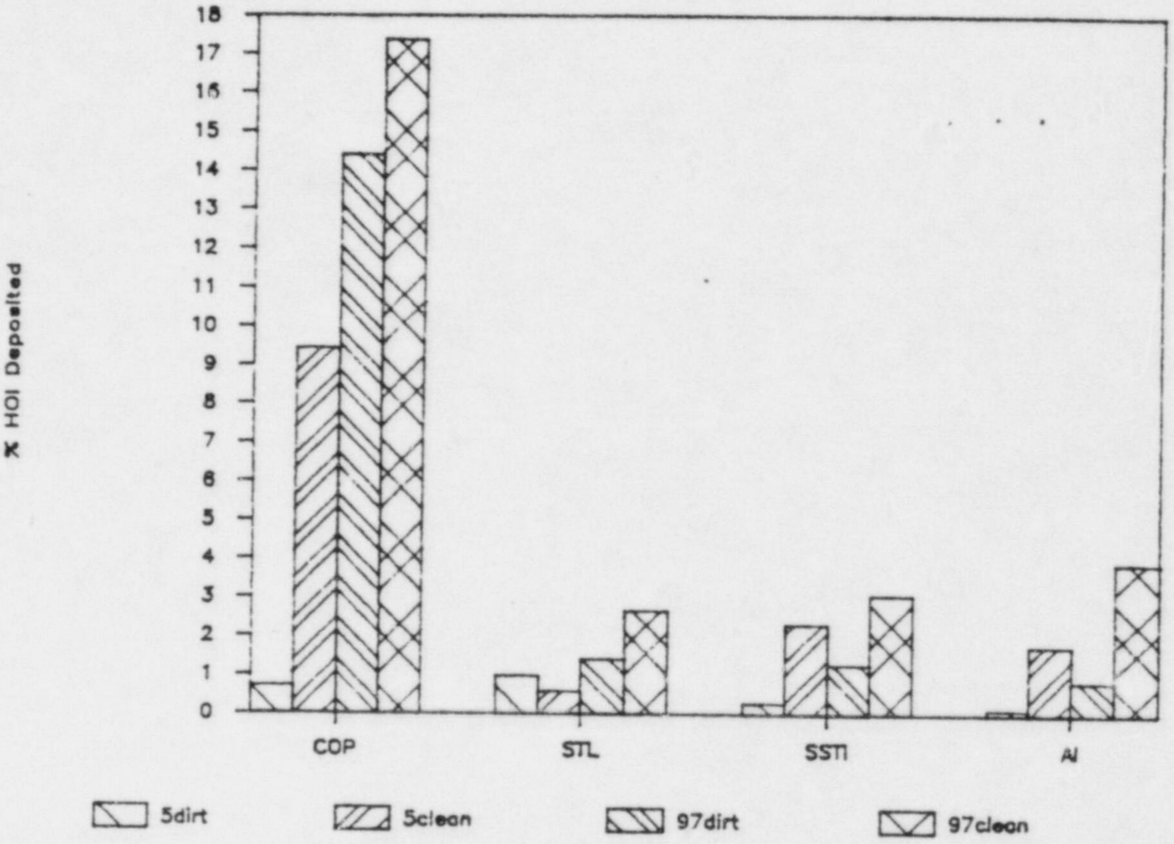
The estimated fractional deposition for metal specimens are shown in Figures 1 to 3. The cleaned metal specimens generally had greater elemental iodine deposition than those tested as received from the supplier. This was usually, but not always, the case for the other iodine species as well. This observation may not necessarily apply to tubing because the surface treatments which tubes undergo in fabrication are probably different than for sheet metal.



Legend
5 dirt - Tested as received at 5% R.H.
5 clean - Tested at 5% R.H. after cleaning.
97 dirt - Tested as received and at 97% R.H.
97 clean - Tested at 97% R.H. after cleaning.

FIGURE 1. Estimated Fraction of Elemental Iodine Deposited in a Metal 30-m Tube, 12.5 mm Inside Diameter, 100 lpm Flow

Figure 4 shows the fraction of each form of iodine that would deposit in the example sampling tube made of each of the material types tested without any cleaning. The figure shows that more elemental iodine would deposit than HOI, and more HOI than methyl iodide for all the materials except polyethylene and PVC. In those two cases, HOI was more depositing than elemental iodine; however, methyl iodine was still the least depositing. Generally, more iodine deposited at 97% R.H. than at 5% R.H. The high humidity significantly enhanced deposition over that of the low humidity tests of elemental iodine and HOI; except in the cases of HOI on polyethylene and elemental iodine on Teflon.

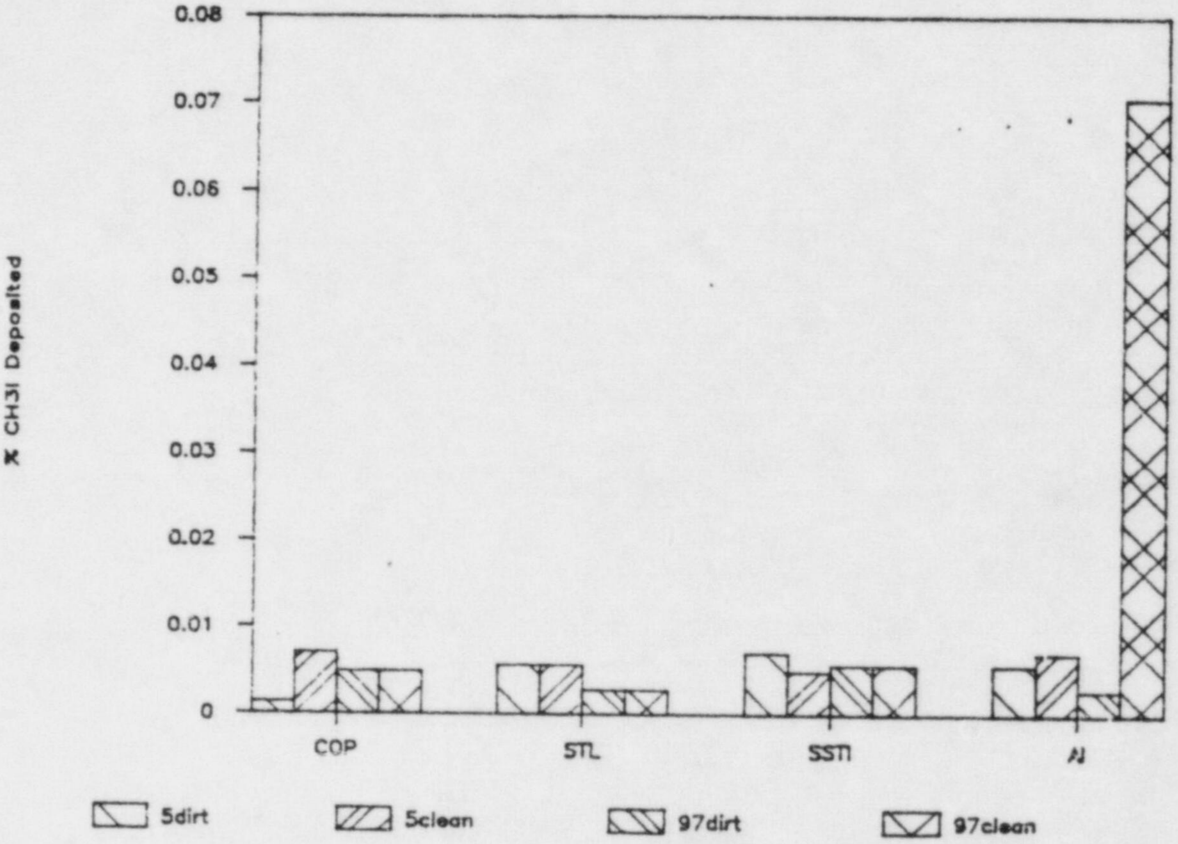


Legend

5 dirt - Tested as received at 5% R.H.
5 clean - Tested at 5% R.H. after cleaning.
97 dirt - Tested as received and at 97% R.H.
97 clean - Tested at 97% R.H. after cleaning.

FIGURE 2. Estimated Fraction Of HOI Depositing in a 30-m Metal Tube, 12.5 mm Inside Diameter, 100 lpm Flow

Accounting for deposition only, the performance of the various materials tested without the cleaning process and at 97% R.H. is estimated in Figures 5 and 6. The line loss for each form of iodine in the example sampling tube was calculated as before, except the losses were weighted by the fraction of each gaseous iodine form estimated to be present in the total effluent of BWR's and PWR's (from Tables 1 and 2). Thus the sum of the losses (shown by the stacked bars) for each form represents the total estimated gaseous iodine losses in the sampler when sampling from the total effluent from that type of plant. The figures suggest that the ranking of preferred gaseous iodine sampling line



Legend

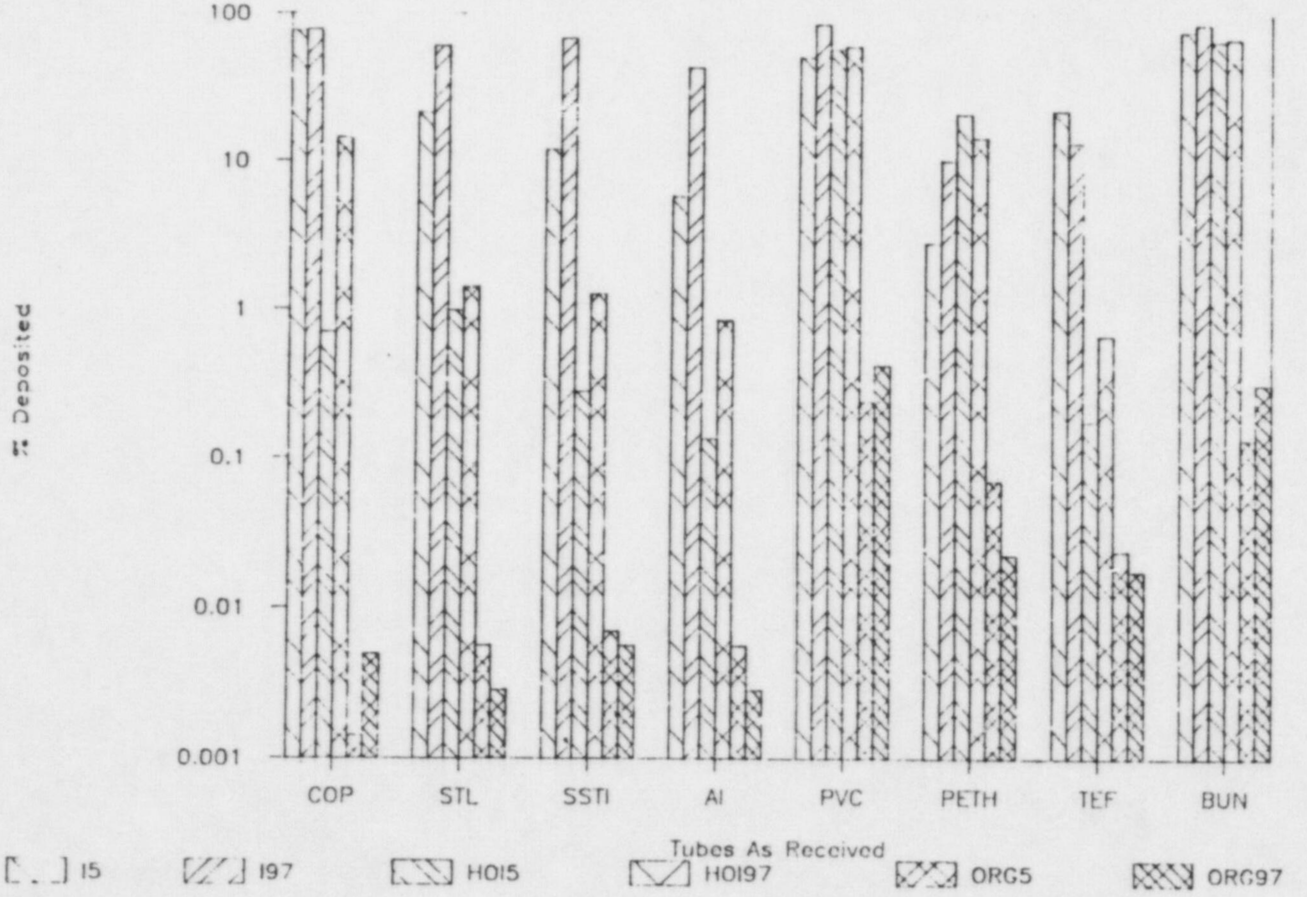
5 dirt - Tested as received at 5% R.H.
5 clean - Tested at 5% R.H. after cleaning.
97 dirt - Tested as received and at 97% R.H.
97 clean - Tested at 97% R.H. after cleaning.

FIGURE 3. Estimated Fraction Of Methyl Iodide Depositing in a 30-m Metal Tube, 12.5 mm Inside Diameter, 100 lpm Flow

materials may be (best to worst): Teflon, polyethylene, aluminum, carbon steel, stainless steel, copper, PVC and Buna-N.

HEMPHILL

Hemphill and Pelletier (1978), of Scientific Advances Incorporated Co. (SAIC), reported deposition velocities and resuspension rates for elemental iodine from coupons of various materials including aluminum (type 5052 which contains 2.5% magnesium and 0.25% chromium), galvanized steel, concrete and two



Legend

I5 = Elemental Iodine @ 5% R.H.

I97 = Elemental Iodine @ 97% R.H.

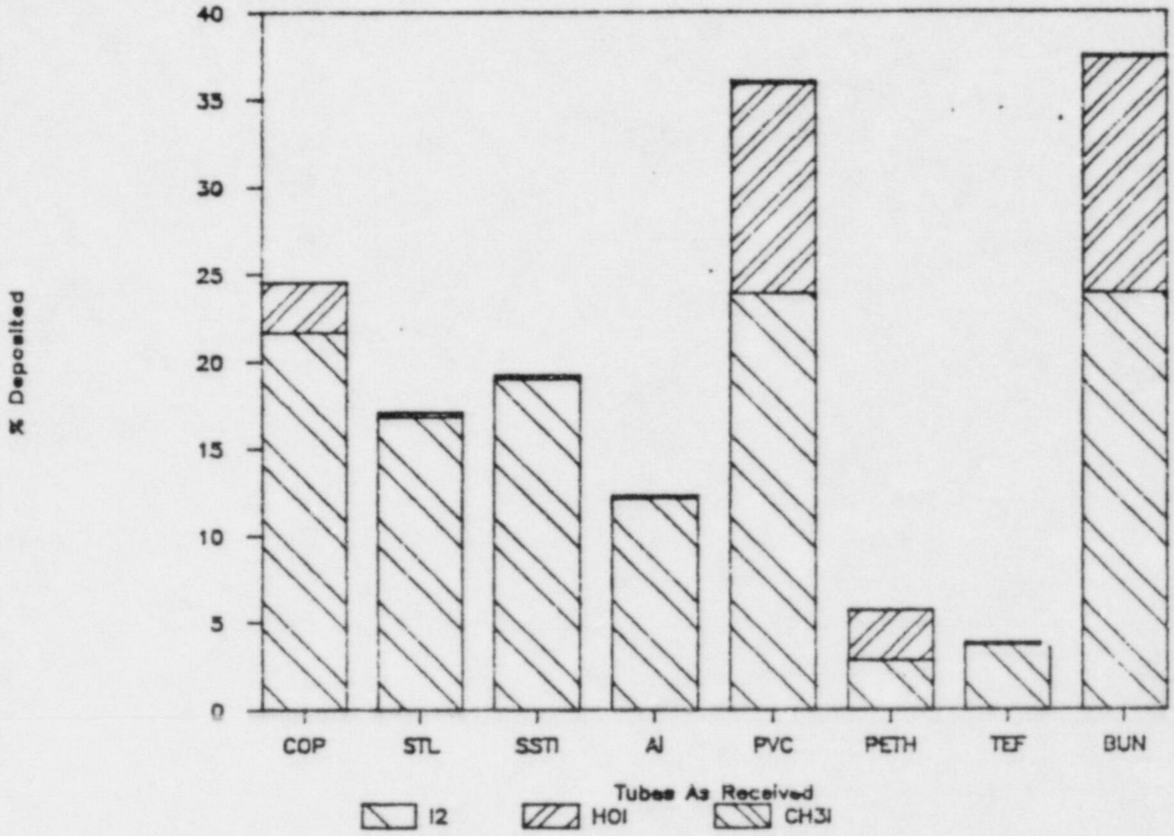
HOI5 = HOI @ 5% R.H.

HOI97 = HOI @ 97% R.H.

ORG5 = CH3I @ 5% R.H.

ORG97 = CH3I @ 97% R.H.

FIGURE 4. Estimated Percentage of Iodine Deposited In Example Tube as a Function of Material And Humidity



Legend

I_2 = Elemental Iodine

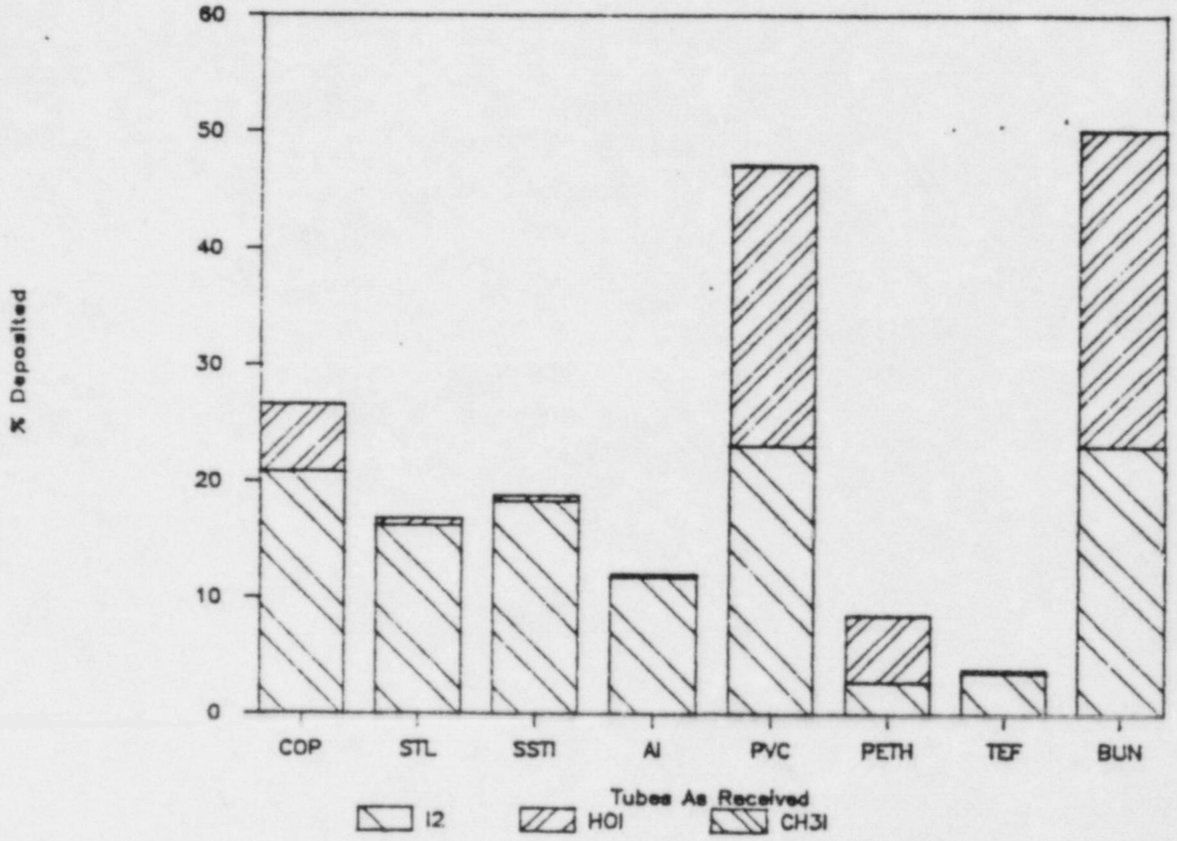
HOI = HOI

CH_3I = CH_3I

FIGURE 5. Estimated Gaseous Iodine Line-loss for Sampling Total BWR Effluent at 97% R.H.

paint formulations. The test chamber was aluminum with an applied teflon coating. Deposition and resuspension measurements were also made on the test chamber so those effects could be accounted for.

The test procedure was similar to that used in later tests of air sampler tubes as described in our previous task report (Glissmeyer, 1985). Elemental stable iodine tagged with ^{131}I was generated by a method similar to that described in Glissmeyer (1985). Iodine concentrations were measured with an



Legend
I_2 = Elemental Iodine
HOI = HOI
CH_3I = CH_3I

FIGURE 6. Estimated Gaseous Iodine Line-loss for Sampling Total PWR Effluent at 97% R.H.

early version of the species sampler consisting of two particle filters in series (Flanders F-700 paper), an elemental iodine adsorber (10% by weight cadmium iodide on Chromosorb-p), an HOI adsorber (4-iodophenol on activated alumina), and an organic iodide adsorber (TEDA impregnated charcoal).

In the samplers, a significant amount of the iodine was collected on both of the particle filters. The authors reasoned that particles should be collected mostly on the first filter and not penetrate to the second; therefore, it was suspected that much of the iodine on the filters was really adsorbed vapors. This suspicion was investigated with two sets of the test data. It was assumed that the amount collected on the second filter was adsorbed vapor and that the first filter would have adsorbed the same amount. The difference between the measured radioiodine and the amount assumed to be adsorbed on the first filter was taken to be the true particle-borne amount. As shown in Table 4, the thusly estimated amounts of particles were only a few percent of the sum of the iodine assumed to be adsorbed on the filters plus the iodine measured on the adsorber stage of the sampler; therefore, thenceforth, the iodine measured on the filters was combined with that of the elemental iodine adsorber to give the total elemental iodine fraction.

Iodine concentrations were measured before and after the test chamber during the iodine injection part of the experiment which lasted 2 hr. After iodine injection was completed, iodine sampling at the outlet of the chamber was continued for up to 30 to 330 hr to measure the resuspension rate. After the injection of iodine, a portion of the specimen was removed to measure the surface activity by direct counting. The surface activity count was also verified by mass balance on the iodine generator, samplers, etc.

TABLE 4. Effect of Subtracting Adsorbed Iodine from Particulate Stage

	Measured % Activity		True % Activity	
Test 13 Samples	Filters	CdI_2 Bed	Particles	I_2
1	33.7	66.3	12.9	87.1
2	52.1	47.9	14.3	85.7
3	23.0	77.0	4.9	95.1
4	31.9	68.1	9.6	90.4
5	24.7	75.3	0.5	99.5
Mean	33.1	67.0	8.4	91.6
Test 17 Samples				
1	25.2	74.8	2.9	97.1
2	12.0	88.0	3.4	96.6
3	14.8	85.2	2.6	97.4
4	5.3	94.7	2.1	97.9
Mean	14.3	85.7	2.8	97.2

Tests were conducted at humidities in the 20 to 90% R.H. range and temperatures in the 64 to 85 °F range. Airflows in the test chamber were both laminar and turbulent. Turbulence was created by a small teflon fan inside the exposure chamber. The authors pointed out that the deposition velocity under laminar conditions is diffusion limited and would be applicable only for similar laminar conditions; therefore, the turbulent data would be of most use in sampling systems.

Table 5 lists Hemphill and Pelletier's (1978) deposition data for the aluminum specimens and the Dupont perfluoro-alkoxy teflon coating on the exposure chamber. Note that for aluminum the deposition rates were higher for the high humidity tests than for the low humidity. For teflon coating, there was no correlation with humidity; however, all the teflon tests were under laminar flow which would be diffusion controlled. The authors did observe that the resuspension rate seemed to decline with time for aluminum which may have been due to some irreversible deposition or an artifact of the experimental and data reduction method. It was also observed that the species distribution measured at the chamber inlet was more than 90 to 98% elemental iodine. The distribution shifted during the resuspension experiment to the less reactive HOI and organic iodine so that the elemental fraction was 62 to 95%.

MEASUREMENTS ON TUBES

EPRI TESTS

While obtaining data for EPRI on the sources of radioiodine in BWRs, Pelletier et al. (1978a) made iodine transmission tests on several simulated sampling tubes. Three each of 0.635 cm (1/4 in.) inside diameter stainless steel and aluminum tubes were installed at a reactor site. Radioiodine from the plant ventilation system was injected into each tube. Iodine species samplers were used to measure the inlet and outlet activity of I-131, I-133, and I-135. The tubes varied in length from 183 to 732 cm (6 to 24 ft) and the flow velocities were 300 - 540 cm/s (5.7 - 10.26 lpm). The resulting mean

TABLE 5. Deposition Velocities and Resuspension Rates for Aluminum and Teflon Coating

	Deposition	Resuspension		
	Velocity cm/s	Rate sec^{-1}	% Relative Humidity	Flow Profile
Teflon #3	0.014		42 - 44	Laminar
Coating #4	0.005		30 - 37	Laminar
#5	0.015		46 - 50	Laminar
#6	0.010		42 - 43	Laminar
#7	0.026	7.5 (-6)	36 - 39	Laminar
#12	0.014	7.5 ± 0.1 (-6)	54 - 61	Laminar
#14	0.0076	8.5 ± 1.8 (-6)	>90	Laminar
#16	0.0064		<26	Laminar
Aluminum #8	0.038		<26	Laminar
#9	0.051	1.1 ± 0.6 (-5)	46 - 52	Laminar
#13	0.063	3.5 ± 0.5 (-6)	>90	Laminar
#17	0.51	3.3 (-5)	>88	Laminar
#18	0.43	1.5 ± 0.7 (-5)	>92	Turbulent
#28	0.075	<1.8 (-6)	<26	Turbulent

residence times were between 0.4 and 2.4 s. Before testing began, ventilation air flow was maintained through the tubes for a month so that the measured transmission would be for equilibrium conditions. Inlet and outlet sampling was then done for a 40.9 hr period.

The model used in Pelletier's study was an earlier form of SAIC's model in that the resuspension rate is for total iodine. Deposition velocities and resuspension rates were calculated assuming equilibrium in the surface activity and equal deposition velocity and resuspension rates for the different iodine isotopes. The decontamination factor equation for each isotope includes the deposition velocity and resuspension rate as parameters. Ratioing the decontamination factors for the isotopes through the tubes eliminated deposition velocity and allowed solution for the resuspension rate. Once the resuspension rate was calculated, the deposition velocity was found from the decontamination factor equation for one isotope. The authors did not give detailed data, but reported the mean and median deposition velocities and resuspension rates from the tests as shown in Table 6.

TABLE 6. Deposition Velocity And Resuspension Rate for Equilibrated Tube Experiment

	Mean Value (std.dev.)		Median Values	
Tubing	Resuspension Rate x E-6/s	Deposition Velocity x E-3 cm/s	Resuspension Rate x E-6/s	Deposition Velocity x E-3 cm/s
Stainless Steel	11.2 (4.0)	78 (12)	7.9	76
Aluminum	6.6 (3.4)	30 (9)	3.5	25

During the tests, it was observed that some of the iodine collected on the particle filters could be removed by purging and collected on the downstream CdI_2 bed. This was assumed to be gaseous iodine adsorbed and then desorbed from the filter paper. For this reason, the iodine collected on the particle filter was combined with that collected on the CdI_2 adsorber and counted as I_2.

PRIVATE CUSTOMER TESTS

SAIC has performed laboratory tests on iodine line-losses. Several tests were reported by Unrein et al. (1985) for stainless steel tubing to simulate common effluent air samplers. SAIC has also conducted laboratory tests of iodine line-loss for at least four reactors specifically simulating certain air sampling systems. Staff from three of the reactor sites have made the test data available to us.

Table 7 is a summary of the simulated sampling line characteristics, test conditions and results. The results shown in the table include: the injected radioiodine concentration; the transmission factor measured during the injection experiment; the reported elemental iodine deposition velocity; the total I_2 product species resuspension rate; and, the predicted equilibrium transmission factor. The tests summarized in Table 7 are listed in order of the transmission factor measured during the injection portion of the experiment.

TABLE 7. Summary of Air Samplers Simulated in Tests

								Test Conditions		Injection Experiment				Resuspension Experiment		Predicted Elemental Iodine Product	
Site	Line No.	ID cm	Length ft.	Flow-rate lpm	Surface:Vol Ratio 1/cm	Residence Time s	Approx. Re No.	Deg C	%RH	Duration min.	Inlet uCi/ml E-7	Observed C/Co	Depostn Vel. cm/s	Duration Hr.	Rate E-6/s	Transmission Factor	Approx. Time to Reach
Unrein	4	0.64	140.0	1.7	6.25	48	376	30	25-70	30		0.0013	0.027	742	1		
HN	2	0.64	140.0	1.7	6.25	48	376	30		30	19.7	0.00133	0.023	521	0.075	0.14	
Unrein	4	0.64	140.0	1.7	6.25	48	376	30	25-70	128		0.0045	0.021	904	1		
HN	2	0.64	140.0	1.7	6.25	48	376	30		128	4.24	0.0045	0.019	904	0.38	0.19	2 wk
Unrein	3	1.91	140.9	56.6	2.09	13	4192	30	25-70	30		0.23	0.054	742	7		
HN	1	1.91	140.9	56.6	2.09	13	4192	30		30	19.7	0.235	0.054	521	0.95	0.58	
SUS	C	1.57	198.0	113.3	2.55	5	10209			[illegible]	2.77	0.397	0.06	232	0.28	0.46	>160 hr
Unrein	5	2.21	256.0	56.6	1.61	32	3623	25-30	25-70	258		0.58	0.0095	282	7		
HN	1	1.91	140.9	56.6	2.09	13	4192	30		128	4.24	0.62	0.018	904	2.2	0.86	2 wk
Unrein	3	1.91	140.9	56.6	2.09	13	4192	30	25-70	128		0.62	0.018	904	10		
SUS	B	3.48	195.0	396.5	1.15	9	16119			[illegible]	0.605	0.657	0.038	234	0.91	0.82	>160 hr
SUS	A	3.48	68.0	363.4	1.15	4	14773			[illegible]	6.15	0.693	0.076	237	0.071	0.71	24 hr
Unrein	6	2.12	245.0	79.3	1.69	20	5292	25-30	25-70	258		0.72	0.0089	282	10		
Unrein	1	2.22	100.0	85.0	1.80	5	5417	25-30	25-70	72		0.75	0.02	455	5		
Unrein	2	2.22	50.0	85.0	1.80	4	5417	25-30	25-70	72		0.78	0.032	455	5		

The Appendix Tables show the detailed test data that is available. The test procedure was described in detail in our earlier task report (Glissmeyer 1985).

Table 7 illustrates that the blind comparison of results from.different researchers is risky. As shown in the first six lines of the table, three of the tests reported by Unrein were the same as tests made for utilities. This repetition is included in the table to point out that the resuspension rates in the report furnished to the utility were significantly lower than reported by Unrein. This was because an earlier form of the evolving SAIC iodine line-loss model was used to derive the values in Unrein's report. The resuspension rates reported by Unrein cannot be used in the SAIC model we described (Glissmeyer 1985) nor usefully compared with values obtained by other methods. The resuspension rate reported for site MY was derived for the more recent form of SAIC's model assuming twenty tube segments connected in series. Unless one knows that the same experimental and mathematical methods were used to obtain the values in the table, comparisons are open to criticism.

The methods used to calculate deposition velocity differ to a lesser degree. The tabulated values agree fairly well with values calculated per the preffered method given by Glissmeyer (1985) and should be fairly comparable.

Some preliminary analysis using scatterplots of sampler characteristics (tube diameter, length, flowrate, Reynold's number, residence time and surface:volume ratio) versus the listed deposition velocities and resuspension rates revealed no significant correlation. This is disappointing; however, it may be due to differences in the methods used to calculate the resuspension rate and deposition velocity from test to test. A lack of correlation would add to the uncertainty in choosing, from existing data, the model paramters for input to a purely theoretical prediction of sampler performance. This would lend credence to the argument that each system should be tested. The apparent lack of repeat tests to demonstrate the precision of the results casts some doubt on whether the results can be reliably applied to the real systems in question.

SAIC has performed tests that at least partly cover the range of air sampler operating characteristics commonly observed at reactor sites during normal operation. The range of characteristics include:

Tube Inside Diameters -- 1/4 to 1-3/8 in.
Flowrates -- 0.06 to 14 cfm
Tube Lengths -- 50 to 256 ft.
Temperature -- 25 to 30°C
Relative Humidity -- 25 to 75 %R.H.

This range of characteristics may adequately cover effluent samplers under normal conditions, but there is some question whether accident conditions or containment sampler conditions are satisfactorily covered.

A comparison of the tabulated values of transmission factors measured during the injection experiment and the predicted equilibrium values points out the difference that accounting for resuspension can make. The predicted equilibrium values suggest that the eventual performance of a sampling line can be better than what might be determined from a short test; however, to our knowledge, there has been no direct experimental verification of the predicted transmission factors based on these lab tests.

The first four lines in Table 7 show what may be typical of post-accident samplers (PAS). The performance during the injection experiment was exceedingly poor. The predicted equilibrium transmission performance is much better but still not as good as would be desirable and the time to reach the improved performance is long, perhaps too long compared to the duration of a significant release event of short duration. This result has prompted some utilities to modify the post accident air sampler to extract the high level samples as a subsample from the routine sampling system operated in the normal manner; thus, taking advantage of the better performance of the normal sampler to transport the sample to the subsampling point.

SAIC's reports to its customers present predicted transmission factors for depositing iodine species during transient events. The purpose is to assist the customer in interpreting sample data during and following such events. Examples are given for performance following a step increase and decrease in concentration. Because the injection part of the experiment simulates a step increase of short duration, it seems reasonable to assume that the predicted performance immediately following a step increase should be comparable to the performance observed during the experiment. As shown in Table 8, this was

TABLE 8. Predicted and Measured Transmission Factor Following a Step Increase in Deposting Iodine Species

System	Measured in Injection Experiment	Predicted
HN1b	0.62	0.67
HN2b	0.0045	0.15
MY	0.68	0.68
SUSA	0.693	0.69
SUS B	0.697	0.69
SUS C	0.397	0.40

generally true except for the HN1b and HN2b tests. The model predicts that if the increased concentration persists, the performance improves until the equilibrium value is reached in the time given in Table 7.

Example transient performance is also given for a step decrease if the sampling system had been operating at equilibrium and only sampling depositing species of iodine. Table 9 shows the predicted measured airborne concentration of previously deposited iodine that would be measured by 24-hr samples terminated on the day shown following a decrease to zero iodine in the stack. The quantity shown is that relative to the concentration previous to the event. The iodine collected is previously deposited iodine that has become resuspended. If depositing iodine was only a portion of the total iodine before the event, the total measured iodine after the event would be proportionately lower. Unfortunately for comparison and verfification purposes, the situation modelled here does not correspond to the conditions under which the resuspension data is taken. It would be of interest to see if the model could reproduce both the deposition and resuspension data.

TABLE 9. Measured 24-hr Concentration Relative To Starting Concentration for a Step Decrease to Zero Iodine in Stack

	System					
Day	SUS A	SUS B	SUS C	MY	HN1b	HN2b
1	0.023	0.15	0.17	0.20	0.18	0.22
2	0.021	0.13	0.15	0.16	0.15	0.20
3	0.018	0.11	0.14	0.12	0.12	0.18
4	0.016	0.10	0.13	0.097		
5	0.015	0.08	0.11	0.076	0.08	0.15
6	0.013	0.07	0.10	0.060		
7				0.047	0.06	0.13
8	0.011	0.05	0.08			
10					0.03	0.10
15					0.01	0.06

THEORETICAL ANALYSES

SAIC has used modelling techniques to analyze the performance of several iodine air sampler systems for reactor sites. Two sites have made these reports available to us. The characteristics of the analyzed systems are listed in Table 10. The model used has been described in our earlier task report (Glissmeyer 1985); however, SAIC will sometimes modify the model as appropriate to fit various conditions.

To apply the model to predicting sampler line-loss, SAIC must select a deposition velocity and resuspension rate to use. Only one of the reports showed the values chosen. In this case, only the total radioiodine resuspension rate was given. Presumably, SAIC chooses these values from experimental data taken for a tube size and flowrate that best fits the situation or selects convenient values, trusting that a system with really poor performance will be correctly identified. To our knowledge, no sensitivity analysis has been performed to show the effects of the assumptions on the results.

The SBGT B and the Main C lines of Table 10 are both PAS systems. We presume that the deposition and resuspension values were selected from earlier tests with similar systems. The Main C line is for a PAS system modified to

TABLE 10. Sampling Systems Analyzed Theoretically

									Assumed	Assumed	Predicted Individual Species Equilibrium Transmission Factor		
Site	Line	ID cm	Line Length ft	Flowrate lpm	Surface:Vol Ratio 1/cm	Residence Time s	Approx. Re No.	Operating Temp. Deg C	Depostn Vel. cm/s	Resuspension Rate E-6/s	I2	HOI	CH3I
LABL	SBGT B	0.95	155	1.70	4.20	120	252	32	?	?	0.025	0.85	0.99
SAL	1	2.54	250	40.00	1.57	53	2226	21	0.01	1	0.54	0.93	0.99
SAL	2	2.54	250	99.12	1.57	23	5521	21	0.01	1	0.77	0.97	1
LABL	MAIN A	3.18	220	70.20	1.26	47	3155	32	?	?	0.85	1	1
LABL	MAIN A	1.91	85	65.14	2.10	7	4837	32	combined end-to-end with above				
LABL	SBGT A	1.91	161	42.48	2.10	20	3135	32	?	?	0.86	1	1
LABL	MAIN C	0.95	3.5	1.70	4.20	3	252	32	?	?	0.9	1	1

use a subsample from the normal sampling system line, Main A. The elemental iodine transmission through Main A and Main C combined result in about 77% transmission. Compared with the similar line, SBGT B, the modified system should perform much better. (It is unfortunate that most reactor PAS systems are of the same type as SBGT B.)

The SAL 2 line in Table 10 is a hypothetical illustration of how the performance of the SAL 1 line in the table could be improved by increasing the flowrate from 40 to 99 lpm.

IN-SITU TESTS

STROM AND HESBOL

The previous task report (Glissmeyer 1985) described in detail the work of Strom and Hesbol (1977) where elemental radioiodine was injected into the ventilation streams of pre-operational reactor effluents for a period of about 1/2 hr. The quantity of stable iodine injected in the stacks varied from 10 to 100 mg and contained 3 to 5 mCi (24 to 40 ng) I-131. Iodine was sampled both in the stack and at the normal air sampler. The details of the method will not be reiterated here; however, the findings relative to performance for sampling elemental iodine are shown in Table 11.

TABLE 11. Average Gaseous Iodine Concentrations in Four Stacks and Samplers, pCi/m^3 (Strom and Hesbol 1977)

	Stack Identifier			
	OII	RI	RII	B2
In-Stack Sampler	1270	10150	1220	14830
Regular Sampler	1430	8400	2490	13000

While a description of each sampling system is not given in their paper, Strom and Hesbol described a typical sampling system as having two circuits. The primary circuit isokinetically extracts the sample from several points in a cross section of the stack, transports the sample to the collection point, and returns excess sample to the stack. The sample collector draws a subsample from the primary circuit. The dimensions of the primary circuit tube are: 10 m (32.8 ft) long, 10 cm (3.94 in.) inside diameter, and 60 lps (3600 lpm or 127 cfm) flowrate. The results in Table 11 show agreement within a factor of two which was judged as being acceptable.

Strom and Hesbol(a) have indicated that this test has been performed at all Swedish nuclear power stations before they were operational. Additional data has been requested.

ONTARIO HYDRO

Alan Guest, Ontario Hydro, has conducted similar tests of 10 air samplers at the Bruce A Station, and the results will be made public at this year's Air Cleaning Conference. The experiments involved the injection of stable elemental iodine, sodium fluoroscein submicron aerosol and stable methyl iodide into the inlets of the ventilation fans. The iodine was analyzed by neutron activation. Stack concentrations were simultaneously measured with a modified

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(a) Private conversations with Hesbol revealed a technique developed to eliminate chemisorption of iodine on surfaces. The stainless steel tubing is polished inside and heat treated with steam to obtain a very thin layer of Fe_2O_3 on the inside walls. The same is done with glass sampling tubes to obtain a thin layer of SiO_2. This technique has only been applied to experimental sampling systems associated with tests at the Malviken reactor. It is unknown how long such a treatment of the tubing would be effective.

EPA Method 5 train located at a "Y" in the sampling line at the stack penetration and with the normal sampling system. Iodine injections lasted for 3 to 8 hr. In the case of one stack with a 20 m long, 1 in., OD tube and a 72 lpm flowrate, the sampler results and a mass balance on the generator agreed reasonably well.

DISCUSSION

The data reviewed here is of great import to the problems of sampling airborne iodine. The work done is pioneering and demonstrates that there is promise for obtaining quantititative iodine concentration data if systems are properly engineered. The modelling work done at SAIC presents a reasonable and intuitive approach to accounting for some of the observed phenomena. The available data is, however, insufficient to make a rigorously scientific judgement on the applicability of any of the line-loss determination methods. There are many questions which remain unanswered and a need for experience that could be gained by verification research. Some of these questions are identified in the following listing of the pros and cons of the available methods and suggest possibly fruitful areas for further research; which unfortunately, in the short run, does not help the NRC with its current regulatory dilemma.

The literature reviewed here suggests several possible methods that could be used for estimating elemental iodine line-losses in air samplers. Most of the methods were reviewed by Glissmeyer (1985). The three main approaches, and some pros and cons of each, are:

1) Measurement of deposition velocity and resuspension rate in the lab for tubing simulating the actual system followed by model extrapolation to equilibrium and transient conditions.

   Pros

   a. The results should be applicable to the system tested.

Cons

b. The predicted equilibrium and transient responses have not been verified.

c. The model used to predict performance is unpublished and unavailable for detailed peer review.

d. To date, most customers are unsure enough about the results that they have gone through the motions for NRC's benefit and are unwilling to apply the results.

e. There is insufficient evidence of precision in the data

f. There has been no verification that the results can be confidently transferred to the real system.

g. The tubing used in the testing may not (maybe cannot) have the same surface contamination or operating history as the simulated tubing.

2) Model equilibrium and transient performance based on measurements of deposition velocity and resuspension rates for similar systems.

Pros

a. Potentially the least expensive, fastest method for the utilities.

Cons

b. A more extensive data base would have to be developed, but may be less expensive for the industry as a whole than tests for each site by methods 1 or 3.

c. There is a lack of correlation in the basic data between the important deposition/resuspension parameters and the sampler characteristics making the selection of the basic inputs uncertain.

d. A sensitivity analysis of the effects of the selection of the input deposition/resuspension parameters on the predicted performance is needed.

e. Cons b,c,d,e and f from above also apply.

3) In-situ tests by injection of iodine or use of levels already present in the ventilation.

Pros

a. The result would be specific for the tested system

b. A repeatable result would be hard to dispute

c. May avoid expensive generic lab testing that would be needed before adopting the other two methods

d. The test is conducted with the actual tubing with its own operating history and surface contaminants (oils, carbon dust, etc.) which may produce results significantly different from tests with other tubes.

Cons

d. Tests are more difficult than lab tests unless there is already a capability to collect samples at the stack elevation of the probes.

e. Would be expensive for the industry taken as a whole.

f. Tests may be disruptive of site operations.

g. The injection of radioiodine may be prohibited; however, stable iodine may be useable.

h. May require some facility modifications at the stack and sampling skids.

i. A short test does not address transient response, but TF may be conservative during a step increase and equilibrium conditions, and about right during the critical initial phase of a step decrease.

There are other lines of inquiry useful for evaluating the differences between the line-loss methods which should be addressed, including those enumerated below.

- A comparison of a SAIC model predicted transmission factor for the systems tested by Guest and Strom and Hesbol against the results from their field tests.
- Investigate the typical range of variability in effluent radioiodine concentrations and the rate of concentration fluctuations. It may be that the usefull assumption of equilibrium between deposition and resuspension may not be realistic if the sampling tubes are continually challenged by transients.
- Address the effects of accident conditions by including them in the range of tested parameters. This may be especially important regarding containment sampling.
- Kabat's work definitely showed a ranking in the deposition performance of materials. The effects of resuspension should be considered in the ranking of materials. It may be that an iodine sampling system should be made of different materials than one designed for particles.

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APPENDIX A

SAIC PRIVATE CUSTOMER TEST DATA FOR INJECTION EXPERIMENTS

TABLE A.1. Inlet and Outlet Concentrations and Iodine Species Distributions

System		I-131 uCi/cc x E-7	Two Sigma %	Species Distribution, %			
				Particulate	I_2	HOI	Organic
HN1a	Inlet	19.7	1.8	1.5	98.4	0.05	0.01
	Outlet	4.62	1.6	1.4	97.7	0.9	0.1
HN1b	Inlet	4.24	0.7	0.24	99.2	0.45	0.07
	Outlet	2.63	1.1	0.57	98.8	0.41	0.2
HN2a	Inlet	19.7	1.8	1.5	98.4	0.05	0.01
	Outlet	0.0262	11	7.9	46.8	33.3	12.1
HN2b	Inlet	4.24	0.7	0.24	99.2	0.45	0.07
	Outlet	0.0191	1.8	3.1	36.2	36.7	24.0
MY	Inlet	2.18	1.7	2.2	96.9	0.8	0.1
	Outlet	1.48	1.2	2.1	95.7	2.1	0.1
SUSA	Inlet	6.15	0.6	NA	NA	NA	NA
	Outlet	4.26	1.7	NA	NA	NA	NA
SUSB	Inlet	0.805	1.5	NA	NA	NA	NA
	Outlet	0.553	1.7	NA	NA	NA	NA
SUSC	Inlet	2.77	1.3	NA	NA	NA	NA
	Outlet	1.1	0.9	NA	NA	NA	NA

NA = Not Available

APPENDIX B

SAIC PRIVATE CUSTOMER TEST DATA FOR RESUSPENSION EXPERIMENTS

TABLE B.1. Resuspension Data from Test HN1a

Period	Duration (minutes)	Average Concentration(a) (μCi/cm^3) of ^{131}I	Species Distribution (percent)			
			^{131}I Associated with Partic.	I$_2$	HOI	Organic Iodides
1	345	2.05×10^{-9} (1.4%)	33.6	58.6	6.9	1.0
2	840	2.90×10^{-10} (2.8%)	11.7	75.6	8.7	4.0
3	1,251	3.62×10^{-9} (1.9%)	1.2	92.8	4.4	1.5
4	5,694	1.44×10^{-10} (1.0%)	6.3	74.3	14.2	5.2
5	5,830	8.71×10^{-11} (1.6%)	4.3	79.5	12.2	4.0
6	10,080	5.20×10^{-11} (1.4%)	11.3	82.2	3.6	3.0
7	7,200	3.86×10^{-11} (1.8%)	4.1	72.5	7.8	15.6
Σ =	31,240					
		Abnormal Conditions				
8(b)	7,020	1.62×10^{-11} (1.3%)	8.6	87.2	1.7	2.5
9(c)	6,240	1.58×10^{-11} (2.5%)	2.0	91.4	3.3	3.3

(a) Two-sigma counting uncertainties are given in parentheses.
(b) Sampling flow rate increased from 944 to 1,888 cm^3/s during this period.
(c) Sampling line temperature raised from 30 to 50°C during this period; normal flow rate used.

TABLE B.2. Resuspension Data from Test HN1b

			Species Distribution (percent)			
Period	Duration (minutes)	Average Concentration(a) (μCi/cm^3) of ^{131}I	^{131}I Associated with Partic.	I_2	HOI	Organic Iodides
1	890	7.07×10^{-9} (0.6%)	2.3	95.1	1.4	1.3
2	1,440	2.93×10^{-9} (1.3%)	0.7	95.2	2.9	1.2
3	1,440	7.90×10^{-10} (2.6%)	1.7	90.7	5.3	2.3
4	1,470	7.11×10^{-10} (0.9%)	1.6	88.6	7.7	2.1
5	1,884	4.68×10^{-10} (1.1%)	1.1	87.6	8.8	2.5
6	2,436	1.85×10^{-10} (1.4%)	1.8	85.1	10.6	2.5
7	3,060	7.21×10^{-11} (2.0%)	3.8	81.2	9.7	5.4
8	3,120	6.23×10^{-11} (1.3%)	8.6	84.1	5.2	2.2
9	4,030	5.98×10^{-11} (1.5%)	0.9	90.9	6.4	1.8
10	4,715	3.26×10^{-11} (1.6%)	5.2	68.6	7.7	18.5
11	5,280	2.00×10^{-11} (1.6%)	1.0	79.1	16.6	3.3
12	5,715	1.24×10^{-11} (1.8%)	0.7	83.7	9.9	5.7
13	5,760	8.89×10^{-12} (2.6%)	0.8	87.6	8.8	2.9
14	5,820	1.17×10^{-12} (4.7%)	5.4	79.0	11.6	4.0
15	7,200	1.90×10^{-13} (4.2%)		(b)		
Σ =	54,260					

(a) Two-sigma counting uncertainties are given in parentheses.

(b) Radioiodine species distribution not measured.

TABLE B.3. Resuspension Data from Test HN2a

Period	Duration (minutes)	Average Concentration(b) (μCi/cm^3) of ^{131}I	Species Distribution (percent)(a)			
			^{131}I Associated with Partic.	I_2	HOI	Organic Iodides
1	345	1.92×10^{-10} (18%)	19.4	55.3	22.8	<2.5
2	840	4.38×10^{-11} (9%)	<2.7	54.2	31.7	<11.4
3	1,251	3.19×10^{-11} (13%)	<6.6	71.4	18.8	3.2
4	5,694	1.01×10^{-11} (21%)	<5.6	43.5	18.6	32.3
5	5,530	1.92×10^{-12} (44%)	38.3	30.5	<11.6	<19.6
6	10,080	$<5.2 \times 10^{-14}$		(c)		
7	7,200	5.84×10^{-12} (4%)		(c)		
Σ =	31,240					
		Abnormal Conditions				
8(d)	7,020	8.90×10^{-13} (2.9%)		(c)		
9(e)	6,240	9.23×10^{-13} (21%)		(c)		
Σ =	44,500					

(a) The distributions shown assume that the undetected species were present at levels just below the detection limit. Assuming that the undetected species were completely absent would give the other extreme values for the distributions.

(b) Two-sigma counting uncertainties are given in parentheses.

(c) Radioiodine species distribution not measured.

(d) Sampling flow rate increased from 28.3 to 198 cm^3/s for this period.

(e) Sampling line temperature raised from 30 to 50°C during this period; normal flow rate used.

TABLE B.4. Resuspension Data from Test HN2b

Period	Duration (minutes)	Average Concentration(b) (μCi/cm^3) of ^{131}I	Species Distribution (percent)(a)			
			^{131}I Associated with Partic.	I_2	HOI	Organic Iodides
1	890	4.33×10^{-10} (3.0%)	<0.34	38.4	35.9	25.4
2	1,440	4.39×10^{-10} (1.8%)		(b)		
3	1,440	3.37×10^{-10} (1.6%)		(b)		
4	1,470	6.69×10^{-10} (1.9%)		(b)		
5	1,884	1.36×10^{-10} (5.0%)		(b)		
6	2,436	5.45×10^{-11} (2.9%)		(b)		
7	3,060	7.36×10^{-12} (2.7%)		(b)		
8	3,120	2.78×10^{-12} (4.5%)		(b)		
9	4,030	6.49×10^{-11} (1.3%)		(b)		
10	4,715	3.66×10^{-11} (1.4%)		(b)		
11	5,280	5.21×10^{-11} (1.0%)		(b)		
12	5,715	1.75×10^{-11} (3.6%)		(b)		
13	5,760	1.74×10^{-11} (4.1%)		(b)		
14	5,820	2.05×10^{-12} (21%)		(b)		
15	7,200	2.10×10^{-13} (71%)		(b)		
Σ =	54,260					

(a) Two-sigma counting uncertainties are given in parentheses.
(b) Radioiodine species distribution not measured.

TABLE B.5. SAIC Estimated Resuspension Rate Constants for Tests HN1a and HN2a

	Average Resuspension Rate Constants (s^{-1})[(a)]					
	HN1a			HN2a		
Measurement Period	I_2+ Particles	HOI	Organic	I_2+ Particles	HOI	Organic
1	1.7×10^{-6}	5.3×10^{-8}	7.7×10^{-9}	2.6×10^{-7}	1.3×10^{-8}	6.6×10^{-9}
2	2.5×10^{-7}	9.9×10^{-9}	4.6×10^{-9}	6.2×10^{-8}	3.0×10^{-9}	1.6×10^{-9}
3	3.8×10^{-6}	7.1×10^{-8}	2.4×10^{-8}	4.8×10^{-8}	2.3×10^{-9}	1.2×10^{-9}
4	1.7×10^{-7}	1.2×10^{-8}	4.4×10^{-9}	1.9×10^{-8}	9.0×10^{-10}	4.7×10^{-10}
5	1.5×10^{-7}	9.0×10^{-9}	2.9×10^{-9}	5.0×10^{-9}	2.4×10^{-10}	1.3×10^{-10}
6	1.7×10^{-7}	2.6×10^{-9}	2.2×10^{-9}	2.9×10^{-8}	1.4×10^{-9}	7.2×10^{-10}
7	1.8×10^{-7}	7.3×10^{-9}	1.5×10^{-8}			
Mean[(b)]	9.2×10^{-7}	2.4×10^{-8}	8.7×10^{-9}	7.0×10^{-8}	3.4×10^{-9}	1.8×10^{-9}
			High Flow Rate[(c)]			
8	2.1×10^{-7}	2.1×10^{-9}	3.2×10^{-9}	1.7×10^{-8}	3.2×10^{-9}	1.7×10^{-9}
			High Temperature[(d)]			
9	2.2×10^{-7}	3.2×10^{-9}	3.2×10^{-9}	1.5×10^{-8}	7.1×10^{-10}	3.7×10^{-10}

(a) Average species distribution fractions used for all periods.

(b) Unweighted average values for measurement periods above.

(c) Sampling flow rate increased from 944 to 1888 cm^3/s for Line 1 and from 28.3 to 198 cm^3/s for Line 2 during Period 8.

(d) Sampling line temperature raised from 30 to 50°C during Period 9.

TABLE B.6. SAIC Estimated Resuspension Rate Constants for Tests HN1b and HN2b

Measurement Period	Average Resuspension Rate Constants (s^{-1})[a]					
	HN1b			HN2b		
	I_2+ Particles	HOI	Organic	I_2+ Particles	HOI	Organic
1	1.0×10^{-5}	9.9×10^{-8}	9.2×10^{-8}	6.5×10^{-7}	3.2×10^{-8}	1.7×10^{-8}
2	6.5×10^{-6}	1.3×10^{-7}	5.5×10^{-8}	7.2×10^{-7}	3.5×10^{-8}	1.8×10^{-8}
3	2.4×10^{-6}	9.5×10^{-8}	4.1×10^{-8}	6.1×10^{-7}	2.9×10^{-8}	1.5×10^{-8}
4	2.7×10^{-6}	1.6×10^{-7}	4.3×10^{-8}	1.3×10^{-6}	6.5×10^{-8}	3.4×10^{-8}
5	2.4×10^{-6}	1.6×10^{-7}	4.6×10^{-8}	3.1×10^{-7}	1.5×10^{-8}	7.7×10^{-9}
6	1.3×10^{-6}	1.0×10^{-7}	2.5×10^{-8}	1.4×10^{-7}	6.8×10^{-9}	3.6×10^{-9}
7	6.3×10^{-7}	4.9×10^{-8}	2.7×10^{-8}	2.2×10^{-8}	1.1×10^{-9}	5.7×10^{-10}
8	7.9×10^{-7}	3.0×10^{-8}	1.3×10^{-8}	1.0×10^{-8}	4.9×10^{-10}	2.6×10^{-10}
9	1.1×10^{-6}	5.2×10^{-8}	1.5×10^{-8}	3.0×10^{-7}	1.4×10^{-8}	7.5×10^{-9}
10	7.5×10^{-7}	5.3×10^{-8}	1.3×10^{-7}	2.2×10^{-7}	1.1×10^{-8}	5.6×10^{-9}
11	8.3×10^{-7}	1.2×10^{-7}	2.3×10^{-8}	4.3×10^{-7}	2.1×10^{-8}	1.1×10^{-8}
12	9.6×10^{-7}	7.6×10^{-8}	4.4×10^{-8}	2.1×10^{-7}	1.0×10^{-8}	5.2×10^{-9}
13	1.4×10^{-6}	9.3×10^{-8}	3.1×10^{-8}	2.9×10^{-7}	1.4×10^{-8}	7.5×10^{-9}
14	3.1×10^{-7}	2.9×10^{-8}	1.0×10^{-8}	5.0×10^{-8}	2.4×10^{-9}	1.3×10^{-9}
15	8.3×10^{-8}	5.1×10^{-9}	2.5×10^{-9}	7.5×10^{-9}	3.7×10^{-10}	1.9×10^{-10}
Mean[c]	2.1×10^{-6}	8.4×10^{-8}	4.0×10^{-8}	3.5×10^{-7}	1.7×10^{-8}	9.0×10^{-9}

(a) Average species distributions for Periods 1--14 used for Period 15.
(b) Average species distributions from Test A used for all periods.
(c) Unweighted average values for measurement periods above.

TABLE B.7. Resuspension Data for Test SUSA

Period Number	Duration (minutes)	Average I^{131} Conc. (uCi/cc)[(a)]
1	1185	2.82E-10 (5.4%)
2	1540	1.82E-10 (4.1%)
3	1420	1.46E-10 (3.1%)
4	1355	6.92E-11 (5.7%)
5	1455	6.51E-11 (4.6%)
6	1500	3.63E-11 (1.6%)
7	1440	3.92E-11 (0.6%)
8	1440	6.40E-11 (2.6%)
9	1440	2.07E-11 (4.6%)
10	1440	1.80E-11 (4.0%)
Σ =	14215	

(a) Two-sigma fractional counting uncertainties are given in parentheses.

TABLE B.8. Resuspension Data for Test SUSB

Period Number	Duration (minutes)	Average I^{131} Conc. (uCi/cc)(a)
1	1200	7.04E-10 (1.7%)
2	1395	4.31E-10 (0.6%)
3	1470	9.86E-11 (1.7%)
4	1455	5.92E-11 (4.5%)
5	1400	3.15E-11 (6.1%)
6	1530	3.13E-11 (2.3%)
7	1440	3.11E-11 (2.1%)
8	1290	9.56E-12 (5.3%)
9	1380	1.90E-11 (1.4%)
10	1500	8.11E-12 (2.4%)
Σ =	14060	

(a) Two-sigma fractional counting uncertainties are given in parentheses.

TABLE B.9. Resuspension for Test SUSC

Period Number	Duration (minutes)	Average I^{131} Conc. (uCi/cc)(a)
1	1275	2.24E-09 (2.3%)
2	1440	8.40E-11 (1.0%)
3	1230	5.61E-11 (3.2%)
4	1470	4.39E-11 (5.0%)
5	1980	2.12E-11 (4.0%)
6	1080	1.37E-11 (4.0%)
7	1440	8.07E-12 (1.9%)
8	1440	6.57E-12 (1.9%)
9	1440	5.97E-12 (3.3%)
10	1110	9.30E-12 (3.3%)
Σ =	13905	

(a) Two-sigma fractional counting uncertainties are given in parentheses.

TABLE B.10. Resuspension Data for Test MY

Period	Duration (minutes)	Average Concentration[a] (uCi/cm^3) ^{131}I	Average Resuspension Rate Constant (s^{-1})
1	1005	2.14×10^{-9} (1.9%)	2.7×10^{-6}
2	1440	3.39×10^{-9} (1.4%)	5.9×10^{-6}
3	1440	9.05×10^{-10} (1.8%)	2.2×10^{-6}
4	1620	4.95×10^{-10} (1.1%)	1.5×10^{-6}
5	1925	1.55×10^{-10} (2.4%)	5.6×10^{-7}
6	735	1.15×10^{-10} (3.6%)	4.6×10^{-7}
7	2880	7.77×10^{-11} (2.8%)	3.6×10^{-7}
8	2880	7.88×10^{-11} (1.7%)	4.6×10^{-7}
9	4290	3.56×10^{-11} (1.9%)	2.7×10^{-7}
10	1695	2.08×10^{-11} (2.8%)	1.9×10^{-7}
11	5595	1.01×10^{-11} (1.6%)	1.2×10^{-7}
12	5700	9.03×10^{-12} (3.4%)	1.5×10^{-7}
13	5820	4.80×10^{-12} (1.9%)	1.3×10^{-7}
14	4500	1.50×10^{-12} (2.5%)	5.2×10^{-8}
Σ =	41,525		$\bar{x}$ = 10.75 E-7

(a) Two-sigma fractional counting uncertainties are given in parentheses.