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Preliminary Evaluation of Effluent Radioactivity Monitoring Systems for BWR Plants

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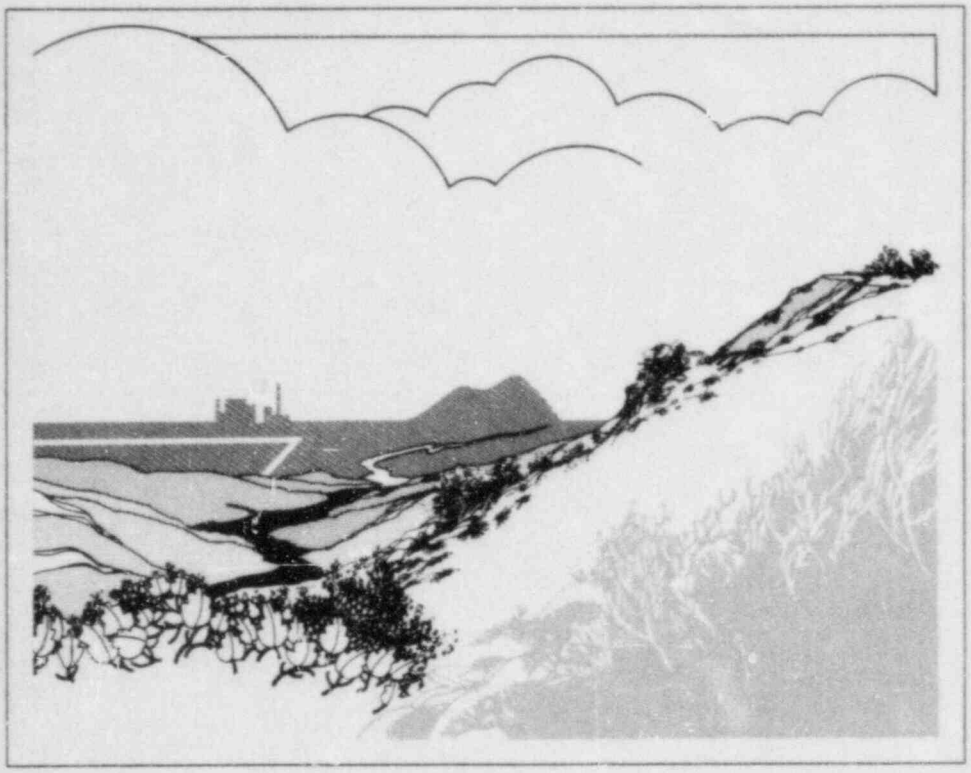

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PRELIMINARY EVALUATION OF EFFLUENT RADIOACTIVITY MONITORING SYSTEMS FOR BWR PLANTS

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ABSTRACT

The need for upgrading the effluent monitoring systems at commercial nuclear power plants was recognized following the TMI-2 accident in 1979 (NUREG-0737, *Clarification of TMI Action Plan Requirements*). Improvements have been made to these systems since then, but not all problems dealing with the measurement of radioactive releases during severe accident scenarios have been addressed. This report discusses some of the generic issues associated with the transport and subsequent sampling of noble gases, particulates, and iodine species that utilities must consider to ensure accurate reporting during severe accident conditions. In light of these generic concerns, a specific postaccident upgrade is discussed, major measurement uncertainties are identified, and recommendations are made. The focus of these recommendations is the transport behavior of iodine; sample-line losses may result in an order of magnitude error for near-real-time measurements. Finally, a recommendation for a laboratory sample-line test program is made. The laboratory effort would better define the uncertainty of the commercial measurements and also provide data for the improvement of line-loss algorithms.

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SUMMARY

The research branch of the Nuclear Regulatory Commission (NRC) has chartered the Idaho National Engineering Laboratory (INEL) to evaluate the effectiveness of nuclear power plant effluent radioactivity monitoring systems, and subsequently determine areas of high measurement uncertainty during severe accident conditions. The effort is an activity of the "Performance Evaluation of Electrical Equipment During Severe Accident States" Program, funded under FIN No. A6832.

The emergency action plan for a severe accident in a commercial nuclear power plant requires that plant monitors quantitatively measure and alarm (in near-real-time) the combination of nuclides present in the main exhaust stack. Unfortunately, transport of samples of radioactive materials (including particulates, various iodine species, and noble gases released from the main exhaust stack to the environment) may distort both the measurement of composition and real-time concentrations. Distortion of composition is primarily the result of iodine transport behavior leading to line losses; distortion of real-time concentration is primarily the result of iodine deposition/resuspension phenomena. Theoretically, the uncertainty of line losses can be minimized by applying a correction factor based on diameter and length of the transport tubing, sample flow rate, and empirical data. Unfortunately, there are no correction factors for the response time issue, and particularly for the varying stack release concentration conditions. These problems are a major concern, because uncertainty of concentration measurements of iodine species (including elemental iodine, as well as iodine-containing particulates) impact critical offsite body dose calculations during and after a severe accident. As an example, laboratory analyses in near-real-time of collected samples can have more than a factor of 10 difference between indicated and actual concentrations. Based on the work presented in this report, it is recommended that two sizes of sample lines be tested in the laboratory to define the uncertainties of the transmission line-loss correction factors and transmission line response times. Data obtained from these laboratory tests would then be used to determine the effectiveness of existing system models and to make recommendations for their potential improvement.

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FIGURES

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ACRONYMS AND ABBREVIATIONS

BWR Boiling Water Reactor
INEL Idaho National Engineering Laboratory
NRC Nuclear Regulatory Commission
SBGTS Standby Gas Treatment System

PRELIMINARY EVALUATION OF EFFLUENT RADIOACTIVITY MONITORING SYSTEMS FOR BWR PLANTS

1. INTRODUCTION

The research branch of the Nuclear Regulatory Commission (NRC) has chartered the Idaho National Engineering Laboratory (INEL) to evaluate nuclear power plant effluent radioactivity monitoring systems. This work is an activity of the "Performance Evaluation of Electrical Equipment during Severe Accident States" Program, funded under FIN No. A6832.

This report discusses the effectiveness of nuclear power plant effluent monitoring systems[1] and uses the existing Browns Ferry plant installation as the basis for conclusions and recommendations dealing with this particular measuring system. Although the report is "plant specific," many of the concerns brought to light by this study are generic and apply to a greater or lesser degree to all Boiling Water Reactor (BWR) nuclear power plants.

Regulatory Guide 1.97, *Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident* (R.G. 1.97)[2] and NUREG-0737, *Clarification of TMI Action Plan Requirements*, Part II.F.1-6,[3] provide the basis for design considerations, requirements, and recommendations for measurement ranges and capabilities.

Section 2 of this report provides sufficient background material to understand the recent history of effluent monitors, including TMI-2, and the resulting requirements. Section 3 describes effluent monitoring systems that are installed at BWR nuclear power plants and includes a brief description of the effluent monitors at the Browns Ferry facility. Section 4 presents the concerns associated with the performance of effluent radioactivity monitors during severe accident conditions, and Section 5 recommends additional studies including testing of sample lines to determine the accuracy of predicting losses and response times of a line. Section 6 summarizes the conclusions of this preliminary evaluation.

2. BACKGROUND

This section provides background information on the pre- and post-TMI design criteria, performance of the radioactive effluent monitors during the TMI accident, and current requirements for emergency response actions.

2.1 Sampling and Detection Considerations

Effluent radioactivity monitors installed before the TMI accident were designed to detect and measure only releases associated with normal reactor operations and anticipated operational occurrences.[4] Such monitors were required to measure concentrations of radioactivity approaching the minimum amount detectable, with the then state-of-the-art sample collection and detection methods. In general, the monitors complied with the criteria of Regulatory Guide 1.21[5] with respect to releases from normal operations and anticipated operational occurrences, but did not have sufficient dynamic range to function during the release conditions associated with some severe accidents.

The effluent radioactivity monitors at TMI were no exception; they failed to perform properly during the initial phases of the accident. Specifically:

- The plant vent gas effluent radioactivity monitor gave erroneous indication of high radioiodine content in releases from the stack vent.[6] The erroneous indication was caused by concentrations of short-lived noble gases being retained in the charcoal iodine adsorption filter cartridge, and being indicated as radioiodine by the monitor readout system.

- The plant vent effluent radioactivity monitor which was designed to detect and measure the presence of particulate radioactive material in the plant had similar problems.

- The plant air effluent monitor for noble gas sampling in the auxiliary building vent went offscale at 10^{-2} μCi/cc. Estimates of actual release concentrations were calculated to be on the order of 10^{-1} μCi/cc to 1 μCi/cc.

- Samples taken in the field could not be analyzed after the onsite laboratory was disabled because of contamination from high airborne activity. The source of the contamination was a primary coolant sample being analyzed at the time.

The measurement problems of the TMI effluent radioactivity monitoring system were considered generic and applicable to other plants. As a result, NUREG-0737,[3] II.F.1, Attachments 1, 2 and 3 and Regulatory Guide 1.97[2] were published to provide guidance for the specification of systems that would help ensure that accident-monitoring instruments have sufficient operating range to yield onscale readings under accident conditions.

NRC Regulatory Guide 1.97, *Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident*,[2] increased the upper limit of the detection sensitivity for particulates, halogens, and noble gases in airborne releases to 100 μCi/cc for particulates and halogens, and 100,000 μCi/cc for noble gases (see Table 1). These higher range severe accident requirements have made past effluent monitoring equipment inappropriate because of detector saturation. In addition, radiation damage may occur at the required measurement and working conditions. Therefore, a new generation of effluent radioactivity monitors is now being installed in many plants. Retrofitting of these instruments to existing plant sample lines, and sample points, leaves some doubt about measurement accuracy during a severe accident; this will be discussed in Section 4.

NUREG-0737, *Clarification of TMI Action Plan Requirement*, specifically states in II.F.1, Attachment 2, "Sampling and Analysis of Plant Effluents," that "iodine gaseous effluent monitors for the accident condition are not considered to be practical at this time. Capability for effluent monitoring of radioiodines for the accident condition shall be provided with sampling conducted by adsorption on charcoal or other media, followed by onsite laboratory analysis." It also states that "sampling of particulates and iodines should provide for sample nozzle entry velocities which are approximately isokinetic with expected in-duct or in-stack air velocities" per ANSI N13.1-1969.[7]

Table 1. NUREG-0737 upgrade monitor range guidelines

Sample Source	Noble Gas Range	Particulates and Iodine Range
Plant stack release	.000001 to 100,000 μCi/cc	.001 to 100 μCi/cc
Reactor building Turbine building Refueling zone	.000001 to 10,000 μCi/cc	.001 to 100 μCi/cc
Turbine building upper atmosphere	.000001 to 1,000 μCi/cc	.001 to 100 μCi/cc
Rad waste building release	.000001 to 100 μCi/cc	.001 to 100 μCi/cc

Some plant owners[8] have questioned the need for isokinetic sampling since it is probable that errors in the deposition of iodine in the sample line will far exceed nonisokinetic sampling errors for the particulate releases expected. This question arises from a conflict in sample flow rate design criteria for minimizing deposition of iodine versus that for particulates. Generally, isokinetic sample flows need to be laminar in order to minimize particle deposition, while turbulent flow conditions provide minimum iodine deposition.

The unresolved issue of how much iodine actually deposits inside the sample line continues to plague plant analysts when they try to determine the actual iodine concentration in the exhaust duct from samples taken at the end of long transport lines. Some questions are answered by measurements of transmission factors, deposition velocities, and resuspension rate constants using replicas of specific utility sample line configurations in laboratory mockups.[9] However, these tests are generally conducted with elemental iodine; the accuracy with which the resulting empirical sample line loss correlations can be used depends on the amount and kind of iodine species actually present at the sample location for a given accident scenario.

2.2 Plant Emergency Response Considerations

NUREG-0654, *Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Plants,*[1] has, among its many requirements, effluent radioactivity monitor measurement and operator guidelines that are relevant to evaluation of the performance of effluent radioactivity monitors. Four classes of emergency action levels were established (NUREG-0610 *Draft Emergency Action Level Guidelines for Nuclear Power Plants,* September 1979), each with initiating conditions, among which are effluent monitoring guidelines. The classes are as follows:

- Notification of unusual event
- Alert
- Site area emergency
- General emergency.

The declaration of a general emergency class accident is due to substantial, actual, or imminent, core degradation or melting, with the potential for loss of containment. The discussion below points out the system operator interface and measurement response requirements that are relevant to the evaluation of effluent radioactivity monitors during a severe accident.

The effluent radioactivity monitoring system provides the operator with information for classifying the emergency, calculating initial conditions of the emergency, and evaluating postaccident information. The decision to initiate the "general emergency" evacuation plan depends on the effluent

radioactivity monitoring systems giving alarms at preset levels, in conjunction with other "general emergency" initiating criteria. Stack alarms are usually triggered by noble gas detectors; because noble gas detectors provide real time information. Initial emergency action requires real time information about releases to the environment in order to notify state and local government organizations in less than 15 minutes (the time is site specific) of the first indication of an emergency. The immediate action for this class is sheltering rather than evacuating people until an assessment can be made that (a) an evacuation is indicated and (b) an evacuation can be completed before significant release and transport of radioactive material to the affected areas.

Provision must be made to send a follow-up message from the facility to offsite authorities within 30 minutes of reporting the emergency. The message should contain the following information about the potential human exposure dose calculated from the radioactivity measurements:

- Type of actual or projected release (airborne, waterborne, or surface spill), and the estimated duration/impact times
- Estimate of the quantity of radioactive material released or being released, and the points and height of release
- Chemical and physical form of released material, including estimates of the relative quantities and concentration of noble gases, iodines, and particulates
- Meteorological conditions
- Actual or projected dose rates at the site boundary, and the projected integrated dose at site boundary
- Projected dose rate and integrated dose at the projected peak at 2, 5, and 10 miles from the site boundary.

In addition to initial emergency declaration information, the effluent radioactivity monitoring system must provide ongoing and postaccident quantitative data for monitoring actual or potential offsite consequences.[4] Effluent monitor measurements are used in conjunction with containment radiation monitor measurements and in-plant iodine instrumentation measurements to determine source term releases. Also, effluent monitor measurements are used in conjunction with meteorological information and field monitoring equipment to determine offsite exposures and contamination.

Thus, effluent radioactivity monitors must provide the following:

- Part of the information used to determine when a "general emergency" should be declared
- Initial data to decide on appropriate offsite emergency action
- Postaccident data for calculating potential offsite human exposure consequences.

3. DESCRIPTION OF EFFLUENT RADIOACTIVITY MONITORING SYSTEMS

This section provides an in-depth description of the subsystems that compose most effluent radioactivity monitoring systems installed at BWR nuclear power plants, and also a brief description of the Browns Ferry Plant monitoring systems.

3.1 Description of a Generic Effluent Radioactivity Monitor

Figures 1 and 2 show simplified piping and instrumentation diagrams of effluent radioactivity monitoring systems like those used for monitoring plant ventilation exhaust and main stack exhaust radioactivity in real time. The four major subsystems which typically comprise effluent radioactivity monitoring systems are described below.

3.1.1 Sampling Pickup Duct Section. The pickup point for sampling the duct effluent is configured in a special duct section designed for the particular sample location, and typically contains the following:

- Flow straighteners
- Isokinetic sampling manifold
- Absolute pressure transmitter
- Temperature transmitter
- Total pressure (high) manifold
- Static pressure (low) manifold
- Protective purging air filter/regulator
- Pneumatic differential pressure transmitter.

Figure 3 is a diagram of a typical pickup duct section. A brief description of the duct section hardware follows.

Flow Straighteners—A flow straightener is mounted ahead of the flow sample tubes and pitot tubes. The flow straightener is a 4-in.-thick honeycomb structure with a 1/16-in. hex to a 1/2-in. modified hex cross section.

Sample Pickup Probes—Sample pickup probes in the exhaust ducts are designed to operate under isokinetic conditions per ANSI-N13.1, "Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities."[7] This means that the sample flow velocity must be controlled so that particulates in the duct are sampled without disturbing their velocity or direction of travel at the entrance into the sample probe. Some isokinetic designs use multiple probes and connect all the probes into a larger diameter manifold. This design assumes turbulent flow conditions in the exhaust duct (the same flow velocity across the duct). In reality, there is some degree of particle stratification. In addition, there are variations in the velocity profile caused by less-than-ideal duct geometry, and the relatively low flow rates expected during severe accidents.

Duct Pressure and Temperature—Absolute pressure and temperature sensors located in the duct, with the isokinetic sampling probes, are used to provide temperature and pressure data to the microprocessor for the purpose of calculating density corrections between the sample probe and the detector gas volumes. These sensors have associated transmitters mounted on the sample duct section.

Pitot Tube Hardware and Differential Pressure Transmitters—A rake of pitot tubes in the same sample configuration as the sample pickup probes measures the duct air flow velocity. This velocity measurement is used to control the sample velocity so that isokinetic conditions exist at the sample probe inlet. The pitot tubes' impact pressure (high) is connected into a total pressure manifold. The static pressure (low) at each impact pressure point connects into a low-pressure manifold. The delta pressure between these high and low pressures is measured with a three-stage pneumatic amplifier. The rugged amplifier, and associated pressure transmitter, are located in a housing mounted near the duct. This housing also contains a clean, dry-air purge system to keep the pitot tube inlet ports free of condensation and particulates that could cause measurement errors.

3.1.2 Collection and Detection of Particulates, Iodine, and Noble Gases. Sample inputs from ventilation exhaust ducts go to the effluent

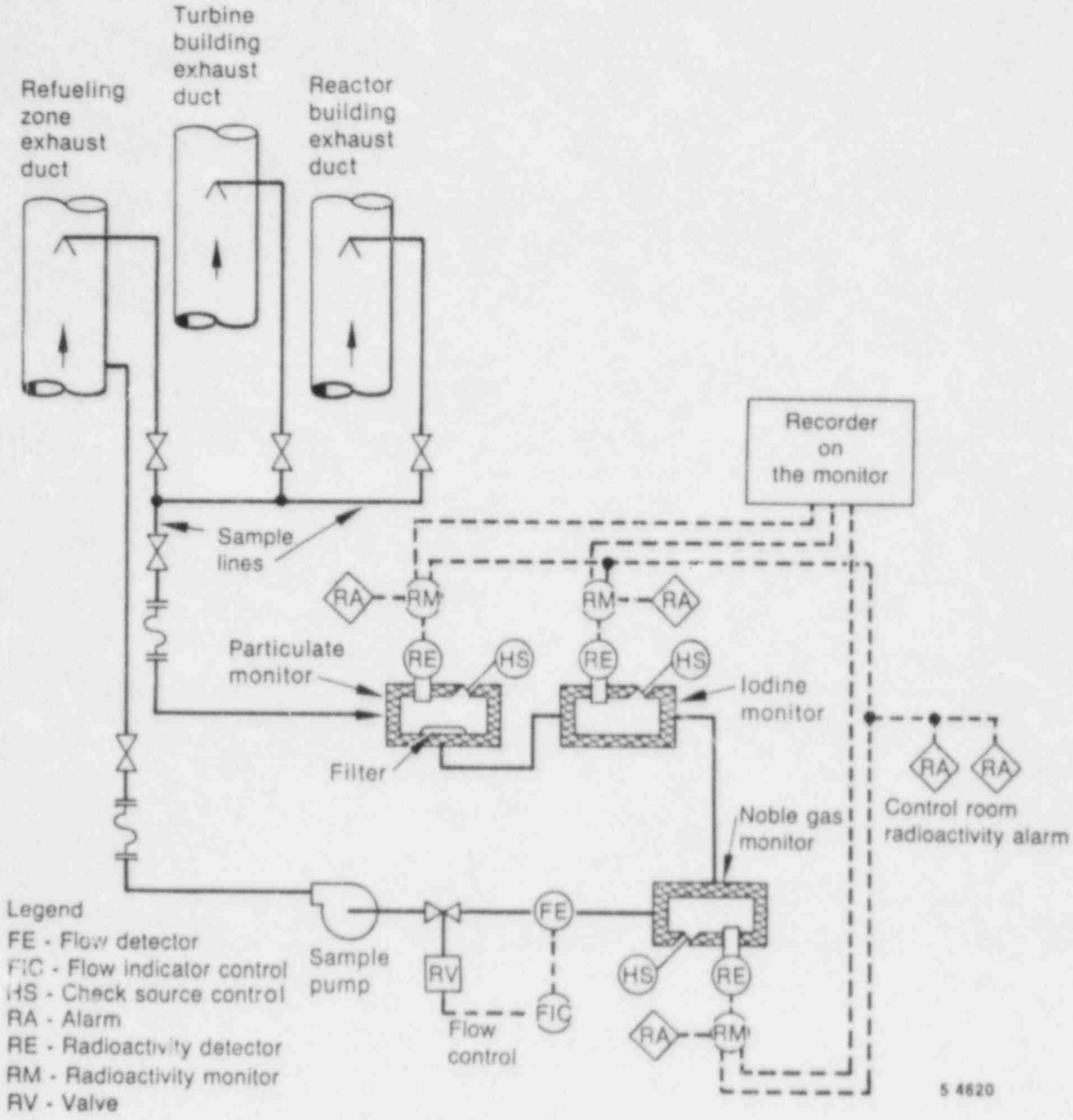

Figure 1. Reactor and turbine building ventilation exhaust radiation monitoring.

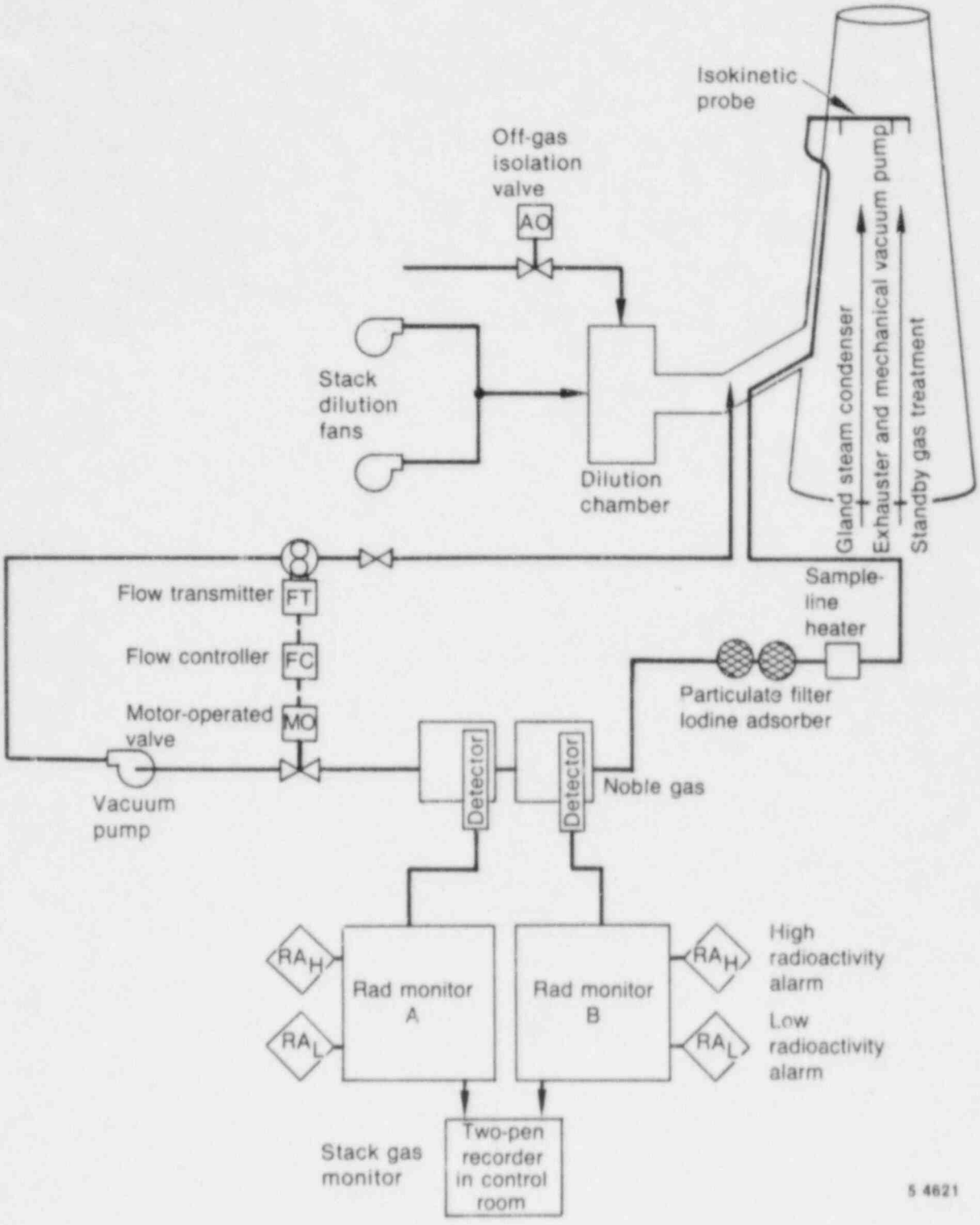

Figure 2. Stack gas radiation monitoring system.

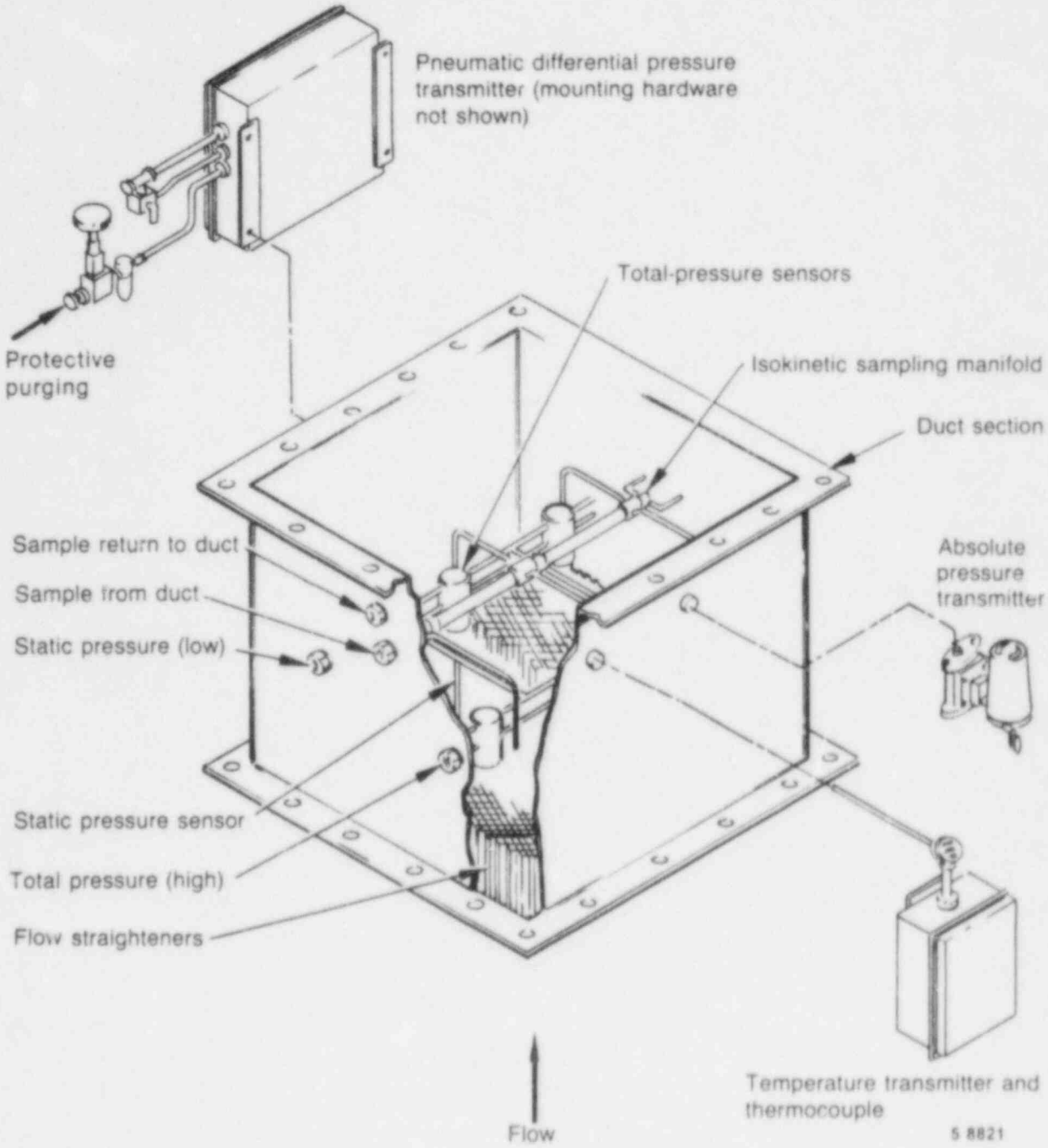

Figure 3. Sample pickup duct section.

radioactivity monitoring system through sample transport lines. The transport lines should be designed to have short lengths and large diameters[a] with optimum sample flow rates to prevent sample plateout losses. After passing through the transport line, the sample first flows through a particulate filter; here, the radioactivity of the captured particles is monitored by a beta radiation detector, utilizing a plastic scintillator and photomultiplier tube.

After the sample leaves the particulate filter, it enters the iodine monitor. The gaseous sample is forced to flow through a fixed silver zeolite or charcoal filter that is designed to trap most of the radioiodine present. The filter is monitored with a gamma scintillation detector utilizing a thallium-activated, sodium-iodide crystal and a photomultiplier tube. The amount of iodine collected in the filter should be directly proportional to the rate of sample flow, the iodine concentration, and the time the filter has been subjected to the flow. However, high concentrations of radioactive noble gases during a severe accident may mask the iodine signal, and the iodine measurement capability would be lost. Under these conditions, the iodine filter must be taken to the laboratory for measurement of iodine concentration with an isotropic system. Before measurement at the laboratory, the sample should be flushed with a stable, inert noble gas to remove residual radioactive noble gases.

After the sample flows through the iodine filter, the noble gases present are monitored with a beta scintillation detector, which views the gases as they flow through a sample chamber. The sample is then exhausted back into the main duct or stack.

3.1.3 Check Sources. Each of the three monitoring units described above is equipped with a check source for testing the units. The check source is a radioactive sample that, on command, positions itself immediately in front of the detector. This provides a standard reference condition against which the detector and the associated electronics can be checked. However, to limit health hazards, the strength of the check source generally extends only to the midrange scale.

3.1.4 Electronic Control. Microprocessor-based electronics mounted in the monitor automatically perform the following functions:

- Isokinetic flow control at the sample probe
- Compensation for changes in concentration of radioactive material during transport
- Selection and initiation of commands or requests (or both) for action or display (or both).

The microprocessor controls the flow at the tip of the sample probe to obtain optimum isokinetic sampling conditions. It uses signals from the pitot tube delta pressure sensors, along with duct absolute pressure and temperature, to adjust the sample line flow rate. It also compensates for sample concentration changes during transport in the sample line to the detector. Measurement of temperature, pressure, and flow at the inlet and outlet provide the information needed to compensate for changes in sample density.

In addition, the microprocessor automatically controls detector and valving power-up and power-down sequences as required.

3.2 Description of the Browns Ferry Power Plant Effluent Radioactivity Monitoring Systems

This section briefly describes the Browns Ferry power plant effluent radioactivity monitoring systems.[11] The three nuclear power plants share three effluent gas process radiation monitoring systems:

- Main stack
- Plant ventilation exhaust
- Reactor building ventilation.

These systems record the rate of release of gaseous and airborne radioactive material in order to determine the total amounts released to the environment. The main stack system not only records radioactivity of noble gases in real-time, but provides samples taken periodically for laboratory analysis of iodine and particulate concentration. The plant ventilation exhaust monitoring system records (in real-time) a measurement of all three radioactive materials for quick action in case of an

a. Lengths of less than 50 ft and 1 in. (or greater) diameter.

accident. The reactor building ventilation monitoring system provides gross counts of all radioactive materials for alarm and action purposes.

The following subsections give a brief functional description of the systems taken from the Browns Ferry Final Safety Analysis Report[11] and from discussions with Browns Ferry personnel, These systems are composed of subsystems previously described in Section 3.1.

3.2.1 Main Stack Radiation Monitoring System. The main stack radiation monitoring system provides an indication to operations personnel of when the radioactive materials released to the environment have reached or exceed specified limits. The system consists of two individual channels so that maintenance can be performed on one channel without losing the alarm capability of the system. Each channel consists of a gamma-sensitive detector, a check source, a log count rate monitor (including a power supply and meter), and a strip chart pen recorder (see Figure 2). The monitors and the two-pen recorder are located in the control room.

Each monitor has two upscale trips and one downscale trip, each of which initiates an alarm in the control room, but does not control action. The upscale alarms are triggered at different high-radiation levels; the downscale alarm indicates instrument trouble. The main stack gas stream is sampled with an isokinetic probe located high in the vent stream. A sample of the effluent is then transported to the monitoring equipment through a 2133 cm long, 1.27 cm diameter sample line with a flow rate of 2360 cc/sec. Two shielded chambers connected in series house scintillation detectors which measure the radioactivity of the gas sample passing through the chambers.

Iodine and particulates are captured in an adsorption filter connected in series with the gas sample monitoring stream. The filters are changed weekly during normal plant operation, and analyzed in the laboratory.

3.2.2 Plant Ventilation Exhaust Radiation Monitoring Systems. The plant ventilation exhaust radiation monitoring system monitors composite samples of ventilation exhaust from the (a) turbine building, (b) reactor zone, and (c) refueling zone during normal operating conditions. The system uses three separate detectors to measure and record particulate, iodine, and noble gas radioactivity (see Figure 1). The release rate is recorded by three separate pens on a strip chart recorder located with the monitor. The alarm for high activity, or monitor malfunction, sounds in the main control room. Sample lines, electrical power, and signal leads are connected so that a spare unit can be quickly installed if required. The particulate, iodine, and total gas detectors each include a built-in check source.

During a severe accident, the plant ventilation exhaust isolation valves should close. With no flow in the exhaust duct the effluent monitor indications become meaningless; periodic flow measurements at selected points in the system are made to verify that there is no flow in the exhaust ducts.

3.2.3 Reactor Building Ventilation Exhaust Effluent Radiation Monitoring Systems. The reactor building ventilation system uses Geiger-Müller type detectors (mounted in the exhaust ducts of the reactor building and refueling floor) to transmit measured gross radiation level signals to indicators and trip units in the control room. The system consists of two individual channels that share a two-pen strip chart recorder (Figure 4); it functions as a process safety system in monitoring the reactor building atmosphere for abnormal radioactivity (resulting from nuclear system leakage) during normal operations.

High radioactivity from a refueling accident or severe accident results in automatic isolation of the primary and secondary containment through closure of isolation valves. The Standby Gas Treatment System (SBGTS) is initiated at the same time to maintain a controlled release to the environment through the main stack. Radioactive materials are then measured by the main stack monitoring system. Until normal heating and ventilation flow conditions return, the reactor building process control effluent measurement system output has no meaning.

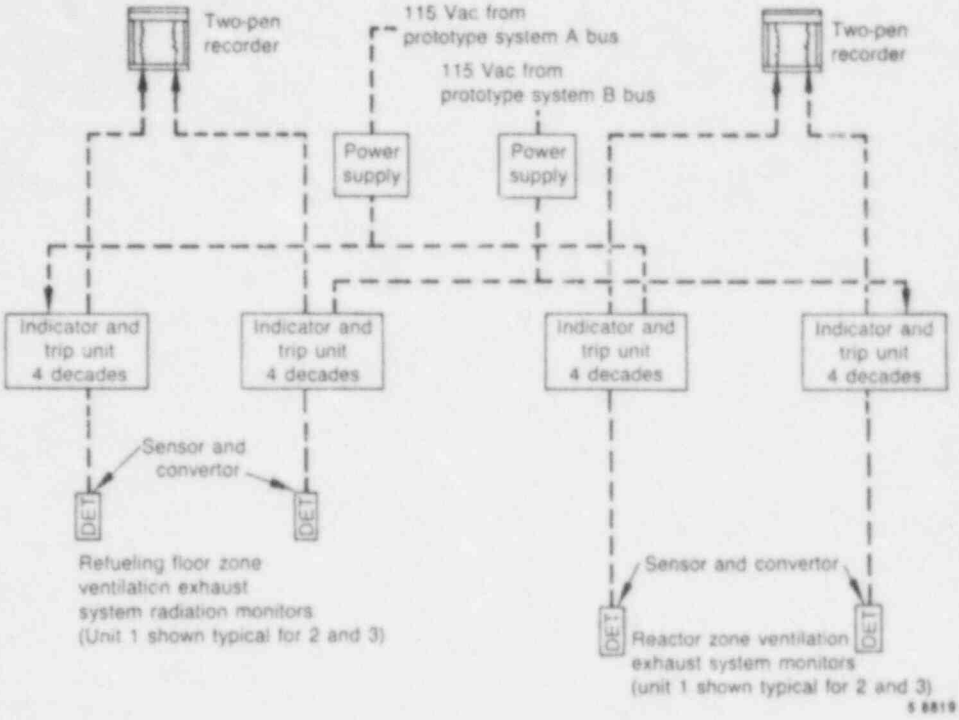

Figure 4. Reactor building ventilation exhaust radiation monitors.

4. EVALUATION OF EFFLUENT RADIOACTIVITY MONITORING SYSTEMS

This section presents a discussion of the generic concerns related to effluent radioactivity monitoring systems, and the results of an initial evaluation of the Browns Ferry main stack monitoring system.

4.1 Generic Sampling Concerns

Ideally, an effluent radioactivity monitoring system must withdraw a representative sample at a known flow rate from the exhaust duct and transport it through sample lines unchanged (or compensate for the change) to the remotely located particulate, iodine, and noble gas collectors and/or detectors. This requirement is relatively simple for the noble gases, but difficult for particulates and iodine. The inertial properties of the particles, and the deposition characteristics of the iodine, cause adherence to the surfaces inside the sampling system which, in turn, causes sample losses and contamination of the sample system. Sample loss and system contamination degenerate the system's performance and give rise to the generic concerns expressed in Sections 4.1.1 through 4.1.4 under the following headings:

- Position of the withdrawal tube
- Withdrawing a representative sample with a tube
- Sample transport including vapor condensation
- Sample collection and detection

4.1.1 Position of the Withdrawal Tube. The design of a system which will obtain a representative sample of particulates in a large duct is a very difficult task, requiring knowledge of maximum particle size, mean size, standard deviation of the dispersion of sizes, and density of the particles. In the absence of specific particulate data for a severe accident, the pessimistic prediction of large particles being present must be used, since large particles are more likely to be stratified.

In addition, the design of the exhaust duct sample withdrawal point should consider the following:

- The velocity profile of the flow
- The need for five or more duct diameters of straight section before the sample point (to establish stable flow conditions)
- The need to be as near to the exhaust point as practicable to ensure a true exhaust sample.

Most of the time, these ideal conditions are sacrificed for safety or for convenience of installation.

Uneven distributions (stratification) of radioactive materials and gases in large exhaust ducts and stacks can cause sampling errors if not enough sample probes are used to obtain a representative sample. Error can also be caused by stratification of particle concentrations if withdrawal points are too near centrifugal exhaust fans, in the vicinity of bends, or too near transitions.

Most ventilation systems are designed for turbulent flow during normal operating conditions; however, sample points need to be five duct diameters or more downstream from flow injection points to ensure good mixing, even for turbulent flow conditions. Under severe accident conditions, flow reduction or diversion of the exhaust systems can cause laminar flow conditions. In this case, multiple withdrawal points must be used to ensure an average representative sample from the velocity profile in the duct. Sample systems designed for normal operation flow conditions may have only one sample probe in a duct, i.e., the designers may have assumed turbulent flow conditions.

In summary, utilities that have designed effluent radioactivity monitor sample pickup hardware for normal turbulent flow conditions and then attempt to use the same sample pickup design to satisfy system upgrades to meet the guidance of NUREG-0737,[3] might not obtain a representative sample under severe accident conditions. During an accident, lower than normal flows could require more sample points than exist across the duct, to obtain a representative sample. The calculated radioactivity concentration could have an order of magnitude error if the sample withdrawal design does not consider complicated low flow velocity profiles. Using

models to calculate average sample concentration from limited sample probes in the exhaust duct works well for flat turbulent velocity profiles but is difficult otherwise. Verification of representative sample withdrawal accuracy can best be obtained by testing at both normal and accident flow conditions after system installation.

4.1.2 Withdrawing a Representative Sample With a Tube. Ideally, the probe and sampling rate should not distort the flow and particle streamlines. When sampling only gases, the withdrawal probe can be of any configuration and need not face directly into the gas stream. However, sampling an exhaust duct containing particulates requires the probe to have an inlet flow area, and flow rate, such that the inlet velocity and direction nearly matches the average flow of the duct. This condition is known as isokinetic sampling.

Several other critical system performance characteristics depend on sample flow rate besides isokinetic sampling. For example:

- Sensitivity of the counting system
- Collector characteristics
- Sampling duration
- Maximum sample concentration
- The settling rate of the particulates in the sample line
- Iodine deposition and resuspension rates in the sample line.

Deciding on the appropriate sample flow rate for any given stack flow is an iterative process, with the final sample flow rate somewhat different than ideal isokinetic conditions. This is in order to optimize other flow dependant characteristics.

Errors introduced by deviations from true isokinetic sampling are a function of the particle size and density.[7] Table 2 lists the errors caused by various sampling rates. If the sampling probe inlet velocity is only 50% of the duct velocity, and all the large particles in the projected area of the probe inlet enter into the probe, the concentration of large particles will be twice as high as it should be. Similarly, should the sampling probe inlet velocity be twice the duct velocity, and particle inertia be such that only those large particles approaching the projected area of the probe are collected, then the observed concentration of large particles will be one-half the actual concentration. Specifically, when the probe velocity is different from duct velocity by a factor of two, the sampling error can vary from 6 to 14% for 4 micron average diameter particles, and 14 to 40% for 12 micron average diameter particles.

In summary, true isokinetic sample withdrawal conditions do not exist in many designs. The degree of variation from isokinetic conditions is a function of the specific flow profiles at the location of sampling, the design of the withdrawal probe configuration, and sample flow rates. The sampling errors caused by a sample flow velocity differing from the duct flow velocity by a factor of two can approach 50% if particles larger than 12 microns are being sampled. Quantitative definition of errors during a severe accident is difficult without a knowledge of particle size distribution, mean particle size, deviation from mean size, and particle density for the accident sequence being considered. Even if the errors could be quantified, the isokinetic flow control might not be able to follow the full range of accident flow conditions, resulting in errors for smaller or larger flow rates. The errors introduced by anisokinetic flow are relatively small (0 to 14%) for particulates less than 4 microns in diameter.

4.1.3 Sample Transport Considerations. Gases and particles must be transported in the sample lines to the collector and detector within a range of acceptable loss. Losses as a result of deposition, chemical reactions and condensation in the line can be significant (a factor of 10 or greater) and are discussed below.

Vapor Condensation Errors—If gases condense in the sample line during transport, the radioactivity measurement will be in error. Condensation of nonradioactive gases such as water vapor can act as a catalyst for collecting radioactive gases and solids. For example, EPRI studies[12,13] show the iodine deposition velocity increases by a factor of six on aluminum surfaces with a change from low to high humidity. The same data show resuspension rate increases of approximately a factor of 3 from low to high humidity. Water vapor, which would likely be present in a severe accident, can easily condense out in a sample line, adsorbing the iodine in transport and react with it to produce hypoiodous

Table 2. Ratio of observed to actual concentration of particles when sampled at various fractions and multiples of isokinetic flow

$\frac{U}{U_d} = \frac{\text{Probe Inlet Velocity}}{\text{Duct Velocity}}$	$\frac{C}{C_o} = \frac{\text{Observed Concentration in Sample}}{\text{Actual Concentration}}$					
	$d_\rho = 4\ \mu m$	$d_\rho = 12\ \mu m$	$d_\rho = 17\ \mu m$	$d_\rho = 31\ \mu m$	$d_\rho = 37\ \mu m$	Limit for Very Large Particles
0.5	1.06	1.14	1.20	1.23	1.46	2.0
0.6	1.03	1.09	1.13	1.23	1.41	1.67
0.7	1.02	1.05	1.08	1.14	1.32	1.44
0.8	1.01	1.02	1.04	1.06	1.16	1.25
0.9	1.00	1.01	1.01	1.03	1.07	1.11
1.0	1.00	1.00	1.00	1.00	1.00	1.00
1.1	0.99	0.98	0.98	0.95	0.93	0.90
1.2	0.98	0.96	0.95	0.92	0.87	0.83
1.3	0.97	0.94	0.94	0.95	0.84	0.77
1.4	0.97	0.92	0.93	0.83	0.81	0.72
1.5	0.96	0.89	0.93	—[a]	0.76	0.67
1.6	0.95	0.83	—[a]	—[a]	0.74	0.63
1.7	0.94	0.78	—[a]	—[a]	0.71	0.59
1.8	0.92	0.72	—[a]	—[a]	0.68	0.55
1.9	0.90	0.65	—[a]	—[a]	0.66	0.53
2.0	0.86	—[a]	—[a]	—[a]	0.64	0.50

a. Data does not cover this range.

acid and organic iodide. However, water vapor will not condense and will, therefore, have minimum affect on the sample transmission factor—if the sample lines are heat traced to a high enough temperature.

Some species of iodine have a high enough condensation temperature to condense inside the sample line at ambient temperature conditions, resulting in a greatly reduced transmission factor. Fission gases with very low condensing temperatures, such as argon and krypton, do not have sample line condensation or other transport problems.

Particle Deposition—An estimate of particle losses can be made by considering several fluid-particle-surface interactions that result in deposition of particles moving through a sample line. Particle deposition mechanisms are Brownian diffusion, gravitational settling, and inertial effects; these are briefly described below.

Very small particles are subject to Brownian diffusion, with changes in the flow rate making the biggest difference in deposition. They move from point to point in a flowing gas, eventually reaching a wall, where they plate out. In sample lines with small laminar flows, only a small fraction of particles ever reach the detector.[7]

All particles carried by flow in a horizontal tube will tend to settle to the bottom of the tube because of the influence of gravity. The degree to which particles settle out in a horizontal tube is a function of size and density of the particles, sample flow velocity, tube diameter and length, and sample media viscosity and density.

Airborne particles in motion tend to travel in straight lines unless acted upon by aerodynamic forces of sufficient magnitude to change the particle direction. Because of inertia, particles larger than about 1 micron in diameter tend not to follow the change in flow direction of the sample gas. Anything in the sample line that causes additional turbulence or change of flow direction can cause additional deposition, for example, couplings, reducers, expansions, dents, constrictions, rotameters, tees, elbows, etc. From the standpoint of inertia, large, laminar flow rates in the sample line are optimum. Very little experimental data are

Table 3. Length of horizontal tube for 100% and 50% deposition due to gravity

Particle Diameter d_p - μm	Inside Tube Diameter (cm)(2r)	Flow cm^3/s	Particle Density of $\rho = 2$		Particle Density of $\rho = 5$		Particle Density of $\rho = 10$	
			L_{100} · cm	L_{50} · cm	L_{100} · cm	L_{50} · cm	L_{100} · cm	L_{50} · cm
2	1	39	2620	930	1050	370	525	135
	2	157	5240	1860	2100	740	1050	372
	4	628	10500	3720	4190	1480	2100	744
	6	1413	15700	5550	6290	2230	3150	1120
5	1	39	437	310	136	87	87	31
	2	157	880	620	272	96	175	62
	4	628	1760	1240	544	192	350	124
	6	1413	2620	1860	816	288	525	186
10	1	39	110	39	44	16	22	8
	2	157	220	78	88	31	44	16
	4	628	400	156	176	62	88	31
	6	1413	680	234	265	93	132	47

Average flow rate—50 cm/s.

available to define deposition losses quantitatively. ANSI N13.1 indicates that as much as a 30% loss can be expected in one 90 degree elbow,[7] depending on particle size, density and flow rate.

Particle interactions are not perfectly known, but estimates of the fractions of entering particles that will ultimately be transported to a downstream point can be made if the dimensions of the system, particle properties, and flow rates are known. Experimental data for specific conditions also give the designer an idea of what to expect.[10] Table 3 shows the lengths of horizontal sampling line in which 50 and 100 percent of the particles of stated size will deposit for various tube diameters and sampling flow rates. For example, when 2 micron diameter particles having a density of 5 g/cc are transported in a 2 cm diameter tube with a flow rate of 157 cc/sec, 50% of the particles will deposit in 1480 cm of horizontal length.

Iodine Deposition—Iodine can react with materials or condensates in the sample line and cause significant measurement errors. Studies of deposition and resuspension rates of iodine have resulted in some data that can be used for reference.[9,12] All the variables that control the deposition of iodine (which is chemically active) have eluded characterization. As a result, quantitative conclusions from studies and test data are configuration, environment, hardware and iodine species specific. Therefore, the loss correction factors used are large and uncertain for the different iodine species being sampled during an accident.

Transmission percentages of radioactive iodine through a sampling line depend primarily on five factors:

- Inside diameter and the ratio of the sample line surface area to volume
- Length of the sample line
- Sample line geometry (number and type of bends and elbows)
- Sample flow rate
- Iodine chemical species.

Measurements on mockups of nuclear power plant sample lines[9,10] show that deposition and subsequent resuspension of elemental radioiodine

are important transport processes to consider in a sample line. Sample lines of 1/4 inch diameter, with a length greater than 50 feet, have very high losses. Sample lines 100 feet long, with a 1 inch diameter, have significantly lower losses; the losses might be acceptable in 1 inch pipes up to twice this length. However, standards to give guidance for designing sample transport lines (to minimize iodine deposition) do not exist, and data on the transport of other iodine chemical species do not exist.

For long sample lines, calculation of actual exhaust duct radioactive iodine concentration requires a sample line transmission correction factor to be applied to the indicated value. This factor corrects for the change in concentration during transmission to the detector and/or collector. This correction factor can be the source of large errors in calculated radioactivity doses if obtained from data for other sample lines, or transmission of other similar materials. Even though the transmission factor could be in error, the worst case would be not using any transmission correction factor when the sample line has large losses. Testing (to determine transmission factors for iodine) is an acceptable way of justifying a given sample line configuration and correction factor.

Some investigators have speculated that elemental iodine is the most reactive and, therefore, the gaseous species of greatest interest. P. J. Unrein, et al., have stated that:

> "Transmission of radioiodine through a sampling line depends upon the characteristics of the line and on the radioiodine species present. Early measurements in operating power plants showed that deposition and subsequent resuspension of radioiodine were important processes and that changes in chemical form probably occurred while the material resided on the surface. Previous measurements of deposition of iodine species onto test coupon surfaces in the laboratory and onto vegetation have shown that elemental iodine (I_2) is the most reactive of the gaseous species. The deposition velocity of hypoiodous acid (HOI) is $< 5\%$ of that for I_2. Deposition velocities of organic iodides, such as methyl iodide (CH_3I), are even smaller, $\sim 0.1\%$ of the deposition velocity of I_2. Thus the gaseous species of greatest interest is I_2."[9]

This is one of the reasons tests on mockups of nuclear power plant sample lines have utilized elemental iodine. However, it should not be assumed from this that I_2 is the only species or form of iodine of concern during a severe accident. Some investigators have suggested that most of the iodine may be in the form of cesium iodide (particulate) or hydrogen iodine (usually a gas).[14,15]

Experimenters[9] have conducted tests in the laboratory on transport line mockups to obtain transmission factors for elemental iodine. The characteristics of the specific transport lines tested with elemental iodine are shown in Table 4. Table 5 shows the radioactive elemental iodine injection periods, measured transmission fractions, and the average estimated deposition velocities for the specified lines. Tables 6 and 7 show the measured resuspension rates using filtered clean air flowing through the same sample lines. These data support the conclusions that, though not well understood, the mechanisms of gaseous iodine transport in sample lines are the following:

- Deposition of reactive species on surfaces
- Species transformation on the surfaces
- Resuspension of deposited radioiodine.

Including resuspension, as well as deposition, in current models greatly improves calculated transmission factors for normal, steady state operational conditions. However, it is even more important for time varying releases that would likely be present during a severe accident. This is true because the deposition and resuspension mechanisms delay the delivery of the iodine to the detectors, thereby masking the concentration changes taking place in the duct. Iodine transport delays for long, small-diameter sample lines can result in a much smaller-than-actual measurement of iodine release during the initial hours of an accident; and (possibly) a much greater-than-actual iodine concentration measurement later on in the accident, when the released iodine concentration decreases but resuspension in the sample line continues.

Summary of Sample Transport Concerns—The primary concerns (with respect to transporting a sample through a sample line) are vapor condensation errors, particle deposition and iodine deposition. Vapor condensation errors affect both particle

Table 4. Characteristics of sample lines tested[a]

Characteristic	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
Inside diameter (cm)	2.22	2.22	1.91	0.64	2.21	2.12
Length (cm)	3048.0	1524.0	4293.0	4267.0	7803.0	7498.0
Flow rate, Q (cm^3/s)	1416.0	1416.0	944.0	28.3	944.0	1321.0
Ratio A/V (cm^{-1})	1.80	1.80	2.10	6.30	1.81	1.89

a. All lines tested were of Type 316 or 304 stainless steel; table courtesy of Science Applications, Inc., Reference 9.

Table 5. Injection periods, measured transmission fractions, and average deposition velocities for I_2 in sampling lines[a]

	Experimental Results for Elemental Iodine (I^2)		
Line	I^2 Injection Period (hr)	Measured Transmission Fraction	Average Deposition Velocity (cm/s)
1	1.2	0.75	0.020
2	1.2	0.78	0.032
3	0.5	0.23	0.054
3	2.1	0.62	0.018
4	0.5	0.0013	0.027
4	2.1	0.0045	0.021
5	4.3	0.58	0.0095
6	4.3	0.72	0.0088

a. Table courtesy of Science Applications, Inc., Reference 9.

Table 6. Measured resuspension rates[a]

Line	Number of Measurements	Total Duration (hr)	Average Resuspension Rate[b] ($r \times s^{-1}$)
1	4	455	6×10^{-6}
2	4	455	5×10^{-6}
3	9	742	7×10^{-6}
3	15	904	1×10^{-5}
4	9	742	1×10^{-6}
4	15	904	1×10^{-6}
5	9	282	7×10^{-6}
6	9	282	1×10^{-5}

a. Table courtesy of Science Applications, Inc., Reference 9.

b. Resuspension rate decreased with time; multiple component parameter would be more representative.

Table 7. Measured distributions of resuspended radioiodine species (%)[a]

Line	Particulates[b]	I_2	HOI	Organic Iodides
1[c]	15.1	81.5	1.0	2.4
2[c]	10.4	85.8	1.3	2.6
3	9.2	79.3	7.0	4.5
3	2.5	85.5	8.0	4.0
4	~12[d]	~53	~23	~12
4	0.4[e]	38	36	25
5	6.8	83.9	5.6	3.7
6	4.9	85.9	5.5	3.8

a. Table courtesy of Science Applications, Inc., Reference 9.

b. Radioiodine associated with particulates.

c. Laboratory air drawn through the line was not filtered.

d. Species concentrations variable; one or more components were below detectable levels during some sampling periods.

e. Radioiodine species measurements made during first resuspension period; total ^{131}I activity measured during the other 14 periods.

deposition and iodine deposition. However, this error can be reduced to a very low level if the sample line is heat traced to a temperature higher than the condensation temperatures of the vapors. Noble gases normally do not present transport problems and their errors are essentially zero. The two areas of greatest concern are deposition of particles and deposition of iodine, with deposition of iodine being the least understood.

The mechanisms for particle deposition are primarily Brownian diffusion, gravitational settling, and inertial effects. Brownian diffusion is a factor for very small particles and small laminar flows. Gravitational settling and inertial effects are a concern for larger, more dense particles; gravitational settling occurs in laminar flows and inertial effects are more significant in turbulent flows. Small particle (less than 1 micron diameter) deposition can be less than 10% in a larger diameter tube (2.54 cm), 3048 cm long with turbulent flows. However, nearly 100% of a group of large particles (10 micron diameter or greater) being transported in the same tube with the same flow, could be lost due to deposition.

The radioiodine present in exhaust ducts is usually a mixture of several iodine chemical species. Elemental iodine is very chemically active and can have significant plate out as it flows through a sample line. The length and diameter of the sample lines, the flow rate of the sample, and the amount of each chemical species affect the amount of iodine deposition. Measured elemental iodine transmission fractions in laboratory mockups of sample lines (Tables 4 and 5) range from 0.0013 for long, small diameter lines (4267 cm long, 0.64 cm diameter) to 0.78 for shorter, larger diameter lines (1524 cm long, 2.22 cm diameter). The models used to predict the transmission fraction of a sample line for iodine, which consider both deposition and resuspension, are an improvement over the models which only consider deposition.[9] However, these improvements might not be as applicable to the initial transient phase of a severe accident as they are to steady state operations.

4.1.4 Sample Collection and Detection. Most, but not all, effluent radioactivity monitoring systems have a three-stage detection configuration that first collects the particulates with a filter, then collects the iodines with an adsorber, and finally, detects the noble gases in real time, as described in Section 3.1.2. Errors introduced by the detection equipment are usually small, when compared to the errors related to withdrawing the sample and then transporting it to the detectors through a sample line. INEL personnel experienced with detection equipment located at nuclear power plants, indicate that during normal plant operation this equipment is usually accurate to within a factor of two (including sample collection, equipment calibration and counting accuracy).

The integrated concentrations on the particulate filter and the iodine filter are measured with scintillation detectors matched to the expected disintegration energies as follows:

- The gross gamma activity of the particulates collected on the filter are counted with a calibration relative to cesium-137

- The gaseous radioiodine is collected either on a charcoal or silver-zeolite cartridge and the gross gamma activity is detected by a single-channel sodium iodide gamma spectrometer. Since the gross activity on the cartridges is assumed to be iodine-131, the spectrometer is centered on the 0.364 MeV peak of I-131.

- The noble gases gross activity is counted with a calibration relative to Xe-133.

Integration time depends on how often the filter/adsorber is changed out. The lower the radioactive nuclide concentration, the longer the integration time in order to build up a concentration level significantly above the background level of the detector. As will be discussed below, filter/adsorber change-out time must consider the detector low- and high-range capability, or no measurement will be obtained.

Particulate Filter Measurement—The particulate filter is usually a fixed filter, During a severe accident, the presence of high concentrations of noble gas can cause error in the particulate radioactivity measurement. When the scintillator saturates, all information will be lost until it comes out of saturation.

Iodine Adsorber Use—Large concentrations of short-lived noble gases are produced during a severe accident. Quantities of these gases, preferentially adsorbed and retained in the air space between adsorber particles will increase or mask the desired I-131 measurement.[4] For fast severe accident iodine changes, no credence should be given to these real-time measurements.

4.2 Initial Evaluation of Browns Ferry Effluent Radioactivity Monitoring System

The previous discussion of effluent radioactivity monitoring systems has shown that, during a severe accident, only the main stack effluent radioactivity monitoring system measures controlled release to the environment—if all the heating and ventilation isolation systems function properly. The reactor building system and the plant exhaust system effluent measurements are important in identifying an accident. However, they do not provide meaningful data during an accident, since the exhaust vents they monitor are closed off as part of the primary and secondary containment heating and ventilation isolation procedure. Therefore, this section will discuss only the Browns Ferry main stack monitor system.

While all the concerns described in Section 4.1 apply to Browns Ferry, it is the losses in the sample line that seem to be of most concern. The main stack sample line is 2133 cm (70 ft) in length, 1.27 cm in diameter, with a flow rate of approximately 2360 cc/sec. ANSI N13.1-1969 guidance for vertical lines with the above characteristics (Table 8) indicates that if particles are less than 2 microns in diameter, less than 10% deposition can be expected. For particles greater than 6 microns in diameter, and greater than 4 g/cc in density, more than 90% loss might be expected. This assumes no losses in the elbows and nearly all of the 2133 cm of length to be vertical up the side of the stack. During a severe accident, release of radioactive materials is through the SBGTS and out the main stack. The first stage of the SBGTS filters removes 99.95% of the particles smaller than 0.3 micron in diameter, if the filters do not degrade. In the second stage, more than 99.95% of the elemental iodine and 95% of the organic iodine will be adsorbed in charcoal filters (assuming filters perform to manufacturers' specifications). Therefore, as long as the SBGTS filters perform to specification, the errors caused by particulate deposition should be small. However these errors could be large if the filters fail.

Considering data found in the literature[9,16] (see Tables 4 and 5, and Figure 5), the iodine transport efficiency could be estimated for the line characteristics stated above. Sample line transmission response times[a] for elemental iodine transport in some lines have been found, from empirical data, to be as great as 30 days.[16] The magnitude of errors caused by transmission delays depends, primarily, on the sample line characteristics and sample flow rate. For the example in Figure 5 (a 0.62-cm diameter line, 3100 cm long, with a 54-cc/sec sample flow rate), the transmission fraction in the first hour of an accident could be as small as 0.10. The

a. The time required for the sample line outlet to reach steady state condition with a change at the inlet.

Table 8. Fraction of entering particles which deposit in a vertical sampling line

Particle Diameter (μm)	Tube Diameter (cm)	Tube Reynolds Number (Re)	Flow Rate (cc/sec)	p = 1[a] Tube Length (cm)			p = 4[b] Tube Length (cm)			p = 6[b] Tube Length (cm)			p = 8[b] Tube Length (cm)		
				200	500	2000	200	500	2000	200	500	2000	200	500	2000
1	0.5	4000	241	Less than 0.01			Less than 0.01			0.01	0.01	0.05	0.01	0.02	0.09
	1.0	6000	723							0.00	0.00	0.02	0.00	0.01	0.04
	2.0	8000	1928							0.00	0.00	0.01	0.00	0.00	0.01
	4.0	10000	4820							0.00	0.00	0.00	0.00	0.00	0.00
2	0.5	4000	241	Less than 0.01			0.04	0.09	0.31	0.08	0.19	0.87	0.14	0.31	0.77
	1.0	6000	723				0.01	0.04	0.14	0.04	0.08	0.29	0.05	0.14	0.45
	2.0	8000	1928				0.00	0.01	0.04	0.01	0.02	0.06	0.02	0.04	0.15
	4.0	10000	4820				0.00	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.03
6	0.5	4000	241	0.11	0.26	—	0.93	0.99	1.00	1.00	1.00	1.00	**1.00**	**1.00**	**1.00**
	1.0	6000	723	0.01	0.01	—	0.68	0.93	1.00	0.89	1.00	1.00	**0.97**	**1.00**	**1.00**
	2.0	8000	1928	0.01	0.00	—	0.25	0.51	0.94	0.45	0.77	0.99	**0.62**	0.91	0.99
	4.0	10000	4820	0.01	0.00	—	0.06	0.14	0.46	0.12	0.27	0.77	0.19	0.41	0.88
10	0.5	4000	241	1.00	1.00	—	1.00	1.00	1.00	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
	1.0	6000	723	0.50	0.82	—	1.00	1.00	1.00	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
	2.0	8000	1928	0.02	0.04	—	0.81	0.98	1.00	0.95	1.00	1.00	**0.99**	**1.00**	**1.00**
	4.0	10000	4820	0.00	0.00	—	0.30	0.59	0.98	0.48	0.80	0.98	0.14	0.99	1.00

a. Experimentally derived data for monodisperse uranine-methylene blue particles. (Data of Sehmel, Postma, Schwendiman: to be published).

b. Experimentally derived data from several particle sizes and densities.

NOTE: Numbers in bold represent short extrapolations from experimental data (L. G. Schwendiman, G. A. Sehmel, and A. K. Postma, "Radioactive Particle Retention in Aerosol Transport Systems," *Proceedings of the International Conference on Radioactive Pollution of Gaseous Media, Saclay, France, November 1963*, Vol. II, p. 373.

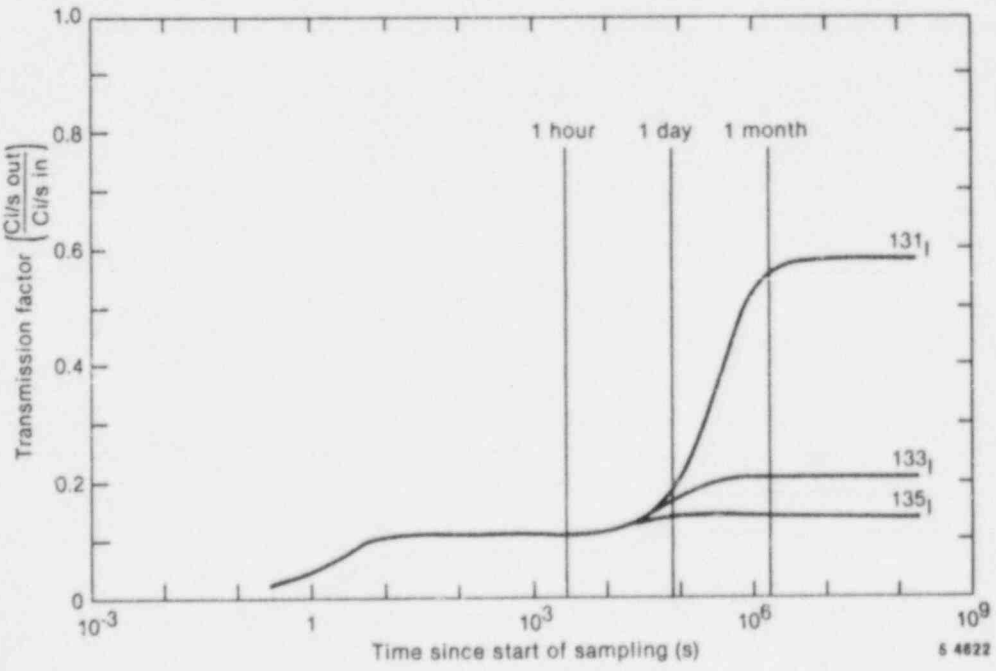

Figure 5. Elemental iodine transmission through a stainless steel sampling line (31 m length, 0.62 cm diameter, 54 cc/sec flow rate; table courtesy of J. Z. James, Reference 16).

Browns Ferry line is 1.27 cm in diameter, 2133 cm long, with a flow rate of 2360 cc/sec. Extrapolating the experimental data to the Browns Ferry sample line, one might estimate that the transmission fraction for elemental iodine in the main stack sample line could be 0.5, or less, during the first 30 minutes of a severe accident. Quantitative definition of the sample line transmission response characteristics is limited to the available data for iodine transport. Since the Browns Ferry sample line is much different from those in Tables 4 and 5, there is a large uncertainty in the estimated transmission fraction.

5. RECOMMENDATIONS FOR DETAILED SYSTEM EVALUATION STUDIES

Recommendations for detailed studies of effluent radioactivity monitoring systems are based on the largest severe accident measurement uncertainty findings in this report. Since environmental release during a severe accident is monitored by the main stack exhaust system, and the samples can have unpredictable losses of a factor of 10 (or greater) in transport, recommendations center on sample line losses. This section recommends methods to obtain data that will help quantify these losses and identify how to minimize them.

Evaluation of effluent radioactivity monitoring systems, as described in Section 4, has shown that the loss of both particulates and iodine in the sample line (from the exhaust duct sample probe to the sample collection cartridges) is a major source of error. The extent of the losses, especially the iodine losses, is not known and the uncertainty of the correction factor for these losses is not established. In addition, the sample line transmission response time during the initial phases of a severe accident is unknown. Therefore, it is recommended that quantitative iodine and particulate transport losses, and transmission response times[a] be measured in sample-line mock-up laboratory tests which include typical elbows, bends, and other flow disturbances.

It is also recommended that iodine, and particulate transport models, be evaluated to determine the accuracy of predicting losses and the transmission response times of a line. This can be done by comparing line mock-up loss data to model calculations. It is doubtful that existing models include all the variables that are significant to determining the transmission factor.

These data will help provide a basis for evaluating sample line designs and will facilitate the development of methods to check the losses and transmission response times of sample lines. It is expected that appropriate empirical transport parameters can be defined for typical sample lines, and specific sample line loss and transmission response time calculations can be made with the help of a generic transport model.

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a. Transmission response time—The time for the sample line outlet to come to equilibrium conditions with a change at the inlet.

6. CONCLUSIONS

This report contains an evaluation of commercial nuclear power plant effluent radioactivity monitoring measurement uncertainties during a severe accident. The accuracy of projected offsite radioactivity dose calculations during a severe accident depends on the accuracy of the radioactive gas, particulate, and iodine release measurements. Upgrades since the TMI accident have increased the range of the monitors and, in general, have solved the problem of radioactive noble gas release concentrations, saturating the detectors during a severe accident. Improved handling and shielding procedures have also solved the problem of measuring low level radioactive iodine in the presence of high background radioactivity.

However, the problem of radioactive particulate and iodine sample line transport loss in long stack sample lines remains. Recommendations for acceptable sample line designs are needed. It appears that some utilities may have minimized the problem by increasing the size of the sample line and the sample flow rate. Even though some sample line mockup data have been taken to identify elemental iodine transmission fractions, justification of these designs remains a concern.

Iodine and particulate transport models for sample lines are needed. It is recommended that some laboratory tests be performed on typical sample lines to define the extent of the elemental iodine and particulate transmission response errors for different sizes and geometries of sample lines. Tests are also recommended to define the ability of existing models to predict those errors.

Some of the more significant design considerations affecting the accuracy of an effluent radioactivity measurement, during a severe accident, are outlined below.

Isokinetic sampling of the exhaust duct is a source of error in obtaining good particulate samples. These sampling errors are small, compared to elemental iodine transport errors in long tubes. Sampling with a factor of two variation in sample probe flow velocity, from isokinetic duct exhaust velocity, has less than 15% loss for a sample with smaller than 4-micron average particle diameter; there is a 15 to 40% loss for a sample with less than 12-micron average particle diameter.

Particulate transport errors in long stack sample lines can be significant for particulates with diameters larger than 2 microns. Particulate concentration loss factors, for known mean particulate size and size distribution, can be calculated quite accurately for simple geometries. Many tests have been conducted to verify the models used to make the loss calculations. The most concern comes from predicting what the particulate size will be during a severe accident, and in determining how to account for complex geometries (elbows, etc.).

Measurement of radioactive elemental iodine releases to the environment (during a severe accident) can have errors as large as a factor of ten from the actual concentration released. For a system with post-TMI upgrades, an error this large is possible because of the following reasons:

- Elemental iodine deposits very rapidly on surfaces. During transport in the long stack sample lines, most of the elemental iodine being transported can be adsorbed.

- Elemental iodine does resuspend after being deposited, allowing the iodine to eventually escape from the end of the line. However, the amount of iodine subject to radioactive decay while being held up, is hard to predict. This is because the length of hold time depends on accurate analytical knowledge of deposition and resuspension rates, which does not exist.

- Elemental iodine transmission delays in the sample line can introduce large errors when measuring in near-real-time large changes in iodine concentration during a severe accident. Periodic sample collection and analysis in the laboratory can be done with delays as short as 30 minutes, whereas it is not uncommon for the sample-line elemental iodine transport delays to be days.

7. REFERENCES

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13. ABSTRACT (200 words or less)

The need for upgrading the effluent monitoring systems at commerical nuclear power plants was recognized following the TMI-2 accident in 1979 (NUREG-0737, Clarification of TMI Action Plan Requirements). Improvements have been made to these systems since then, but not all problems dealing with the measurement of radioactive releases during severe accident scenarios have been addressed. This report discusses some of the generic issues associated with the transport and subsequent sampling of noble gases, particulates, and iodine species that utilities must consider to ensure accurate reporting during severe accident conditions. In light of these generic concerns, a specific postaccident upgrade is discussed, major measurement uncertainties are identified, and recommendations are made. The focus of these recommendations is the transport behavior of iodine; sample-line losses may result in an order of magnitude error for near-real-time measurements. Finally, a recommendation for a laboratory sample-line test program is made. The laboratory effort would better define the uncertainty of the commercial measurements and also provide data for the improvement of line-loss algorithms.

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