Session 15

AIR CLEANING SYSTEM RESPONSE TO STRESS

WEDNESDAY: October 22, 1980
CHAIRMAN: William H. Miller
Sargent and Lundy

INVESTIGATION OF AIR CLEANING SYSTEM RESPONSE TO ACCIDENT CONDITIONS
R.W. Andrae, J.W. Bolstad, R.D. Foster, W.S. Gregory, H.L. Horak, E.S. Idar, R.A. Martin, C.I. Ricketts, P.R. Smith, P.K. Tang

A METHOD FOR ESTIMATING THE CHALLENGE TO AN AIR CLEANING SYSTEM RESULTING FROM AN ACCIDENTAL EXPLOSIVE EVENT
M.J. Steindler, W.B. Seefeldt

SEISMIC QUALIFICATION OF HEPA FILTERS BY TEST IN AN ACTUAL OPERATING CONDITION
J.R. Yow, R. Holloman, A. Algar

OPENING REMARKS OF SESSION CHAIRMAN:

Welcome to Session 15, devoted to air cleaning system response to stress. This morning we have three eminently qualified speakers who are currently performing studies on various stresses which may challenge air cleaning systems. Since, for most facilities, the air cleaning system is the primary pathway to the atmosphere, this work is of great importance. Dr. Gregory, who is a member of a working group on air cleaning and accident situations that reports to the Committee on Safety of Nuclear Installations, NEA, OECD, will discuss expanded programs underway at Los Alamos Scientific Laboratory to study tornado depressurization, explosive pressure propagation, fire spread, and induced material movement. I believe we are going to be fortunate enough to see one of his famous movies, also. Mr. Seefeldt, our second speaker, is currently engaged in nuclear fuel processing and waste management as well as safety analysis of fuel cycle facilities. He will discuss accident explosions and fuel cycle facilities and a means to estimate the challenge to an air cleaning system. Last, but not least, Dr. Yow will discuss the results of a recent seismic testing program for HEPA filters and filter frames, with some rather interesting results. He is involved in the ASME CONAGT effort, and also participates on American Society of Civil Engineering HVAC Duct Qualification Committee.

INVESTIGATION OF AIR CLEANING SYSTEM RESPONSE TO ACCIDENT CONDITIONS

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Abstract

We are investigating air cleaning system response to the stress of accident conditions. In this paper we present a program overview and highlight recent results of our investigations. The program includes both analytical and experimental investigations. Computer codes for predicting effects of tornados, explosions, fires, and material transport are described. We also describe the test facilities we use to obtain supportive experimental data to define structural integrity and confinement effectiveness of ventilation system components. Examples of experimental results for code verification, blower response to tornado transients, and filter response to tornado and explosion transients are reported.

I. Introduction

Assessment of the potential environmental consequences of a nuclear facility accident involves calculating atmospheric dispersion and radioactive dosage estimates for the surrounding population. However, this calculation is highly dependent on estimates of release or source-term characteristics determined at a facility's atmospheric boundaries. For most facilities, the air cleaning system is the primary pathway to the atmosphere and has the most pronounced effect on release estimates.

Some of the questions that could be posed concerning the response and confinement effectiveness of air cleaning systems to accident-induced stress are listed below.

- What methods best predict gas dynamic conditions and loadings in ventilation systems for various accident conditions?
- What methods best predict transport of material within ventilation systems and the challenge to the air cleaning system under accident conditions?
- What experimental data exist that define structural limits of confinement devices such as high efficiency particulate air (HEPA) filters?

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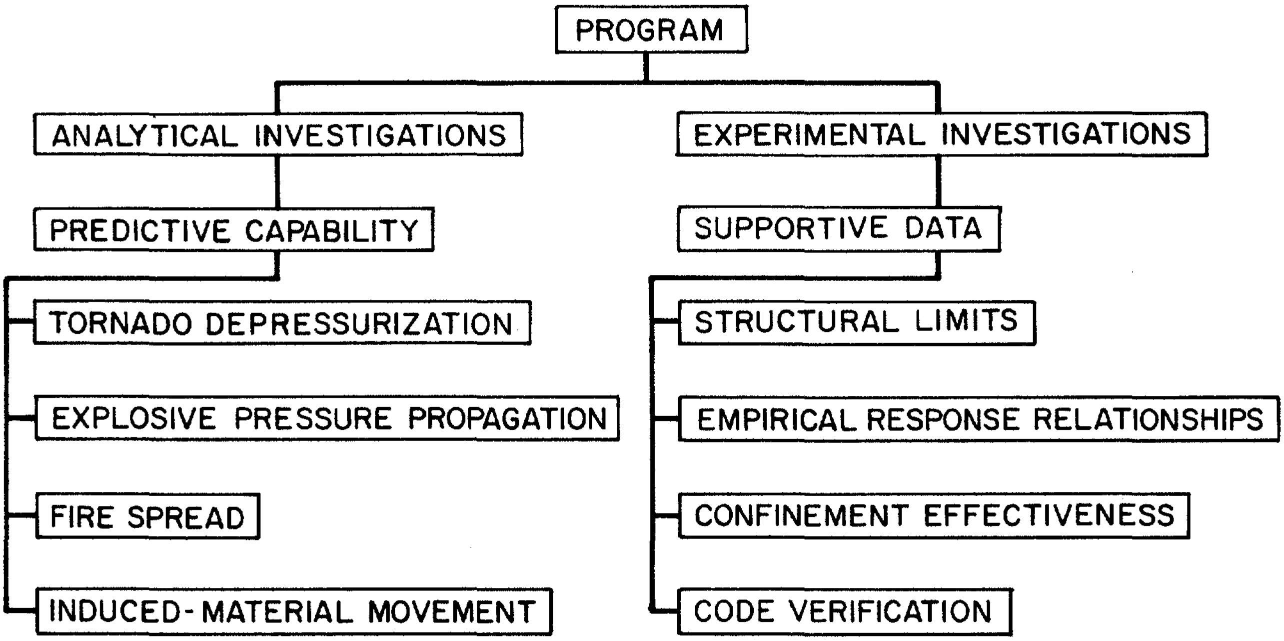

Figure 1. The Los Alamos Scientific Laboratory (LASL) accident analysis program.

- What ventilation component response data exist that can be used in mathematical modeling?
- Do various filtration devices maintain their effectiveness throughout transient accident conditions?

This list represents only a small sample of the serious questions regarding our knowledge of ventilation system behavior under the stress of accident conditions. Furthermore, we believe that the answers to the above questions are unknown or are only partially understood. For this reason, we have established a program to answer these questions.(1)

We believe that our program (outlined in Fig. 1) is a step toward answering the questions posed above. We are developing analysis tools that will allow prediction of accident-induced loads and conditions on confinement systems. At the same time, we are investigating structural integrity and transient filtration effectiveness through experimental simulation of accident conditions.

II. Program Overview

The objective of our program is to provide methods and supportive experimental data that will allow analysts and designers to evaluate the effect of accidents within nuclear facilities. The techniques and data developed in this program will yield better estimates of releases at nuclear facility atmospheric boundaries. To obtain better release information, our initial analytical emphasis has been on accident-induced gas dynamics and airborne material movement within air cleaning systems. The analysis and experimental data are particularly suited to fuel cycle and chemical processing facilities rather than reactors, but can be applied or extended to the reactor area.

Figure 1 shows both analytical and experimental investigations. We believe that developments in accident analysis will require a combined analytical and experimental approach. The two efforts are strongly interrelated and mutually supportive. For example, experimental flow resistance and blower response data are essential for computer models to predict effects of tornados or explosions. The experimental data can be converted into mathematical models that can be used in computer codes.

In the analytical area, we will describe computer codes that are being developed for predicting effects of tornado depressurization, explosions, fires, and material movement within a facility. These computer codes use multidimensional models that are tailored to be very user-oriented, that is, of particular use to safety analysts and heating, ventilating, and air conditioning (HVAC) system designers. The status of each computer code is outlined below.

We will describe the experimental facility that is used to obtain supportive data. A description of several experimental apparatus will be given, including a blowdown system, shock tube, scale model ventilation systems, and wind tunnels. Finally, we will give several examples of the experimental data that are being obtained and used to support the analytical investigations.

III. Analytical Investigations

Analytical investigations are directed toward developing computer codes that will allow the analyst or designer to predict the stress of hypothetical accidents on air cleaning systems. This work will provide some insight into the first two questions posed in Sec. I. We have developed or are developing computer codes for analyzing the effects of tornados, explosions, and fires in ventilation systems. These codes will be outlined in the sections that follow. Initial emphasis in code development has been placed on predicting accident-induced gas dynamics. However, we will also discuss our plans to add material transport capabilities to these codes.

Our approach in developing the codes is to use as much as possible from established codes. We have also separated our approach into near- and far-field analysis levels. The term far-field is used to describe the analysis of effects that are remote or relatively insensitive to the detailed characteristics of the accident. The term near-field refers to analysis techniques that include all of the details of the accident event. For several reasons, we have chosen first to develop the far-field version of these accident codes. First, the analyst may not have detailed information about the accident or the air-cleaning system. If this is the case, a detailed analysis is not warranted. Second, extension of existing codes to a far-field analysis is a natural step. Third, the far-field analysis can be developed in a much shorter period of time.

Tornados - TVENT Code

The TVENT code is a portable computer program for predicting flows and pressures in a ventilation system network subjected to a tornado. The details and use of this computer code can be found in several publications.[2--6] The code can predict both steady-state and transient flows. It has been applied successfully to many air cleaning systems by industry, the military, and other government agencies. The primary features of the code are its portability and ease of use -- typically requiring only 2 days to apply. The code and documentation are available at the National Energy Software Center located at Argonne, Illinois.

Work is currently in progress to develop a second version of this code. The second generation will implement much of the experimental data being developed for blowers, filters, dampers, protective valves, and transport of radioactive material. We expect to release this version of the code in late 1981.

Explosions - EVENT Code

We will outline the content of a computer code that is capable of predicting the flow dynamics within structures subjected to both internal and external explosions. This code, called EVENT, is capable of predicting more severe transient events than TVENT. The calculation of an explosion in an air cleaning system requires consideration of compressibility and energy. In addition, the effect of flow inertia must be included because of the rapid change in flow conditions. We also need to check for choking in some locations because of the high-speed flow. In the EVENT code, a provision for sudden area change in flow passages is added so that proper branch properties can be evaluated.

We retain most of the TVENT features in the code structure, including the numerical scheme. The EVENT code accepts some degree of idealization of a real system, namely, the system is assumed to consist of flow elements such as rooms, nodes (zero-volume room), boundaries, dampers, valves, ducts, filters and blowers. The conservation laws or certain characteristic curves describe the nature of each type of element.

In the far-field analysis, the explosive event requires some form of simulation in which the details of the event are of no major significance.(7) The simulation of an explosion by mass and energy addition is quite common in analytical and experimental analyses, as long as the rate information is known. Basically, an explosion can be defined by a rapid pressure rise, sometimes accompanied by a rapid temperature rise. These pressure and temperature increases can result from physical, chemical, or even nuclear sources such as the rupture of a highly pressurized vessel (physical), the combustion of explosive material (chemical), and a nuclear material excursion (nuclear). All of the processes mentioned above involve some form of mass and energy addition to a system. Thus mass and energy source terms are required in the mass and energy balance equations. In cases where these terms are not completely known, with some mathematical manipulation we can use pressure and/or temperature time-histories instead.

Discussion of the Governing Equations. The governing equations are the basic conservation laws for mass, energy, and momentum. We apply the mass and energy balance only to control volumes, which are rooms. The mass conservation equation states that the rate of change of density in a fixed volume is equal to the net mass flow rate entering and leaving that volume plus a source term. The large variation in density also requires consideration of an energy balance for the control volume. The first law of thermodynamics, when applied to an open system, states that the rate of change of the total internal energy for a fixed control volume is equal to the sum of net convective energy flux, energy addition through mass addition, and energy addition through other means. The convective energy consists of enthalpy and kinetic energy transported by the flow velocity. We neglect the kinetic energy in the control volume because it is small compared to the internal energy. After applying the energy equation to an ideal gas or ideal gas mixture with constant specific heat, we obtain the rate of change of pressure.

The mass and energy balance equations plus the equation of state are capable of handling unknowns such as pressure, temperature, and density. The remaining unknown is the velocity, which can be accounted for by the momentum equation or a similar consideration.

The momentum equation used in the TVENT code is quasi-steady; it is an orifice flow relationship that expresses that the pressure drop across a flow path is caused by friction loss. However, in the case of an explosion the flow properties can change quite rapidly, and the inertia of the flow must be taken into account. Let us start with the momentum equation in a differential form for a one-dimensional, constant area, compressible flow with friction. We will assume that the spatial variation of the momentum is small compared to the other terms, and we can integrate over a small distance. The validity of using this form for compressible flow is warranted if the length of the flow path is sufficiently short. This equation gives the simplest momentum balance for a duct with pressure drop, friction, and inertia effects. Also, we use the proper density in the momentum equation and include the effect of area change.

Unlike incompressible flow (where the steady-state flow rate is determined solely by the pressure drop), there is a limit in compressible flow for which the mass flow rate can no longer increase. This maximum value is established regardless of how much the downstream pressure is reduced. This condition is known as choking, and in normal operation, a ventilation system will never encounter this condition. However, in the case of an explosion choking is possible, and the flow rate is not determined by the momentum balance as we have discussed previously, but by this choking phenomenon. Additional equations are used to account for choking in the EVENT code.

We have little knowledge about the performance of filters and blowers in fast transient situations with large density variations. We now assume that their behavior is similar to that during a slow transient with small density changes. The pressure drop across a filter is proportional to the volume flow rate and for the blower a unique characteristic curve is available to relate the pressure rise and the volume flow rate. No choking is considered for either one.

The numerical scheme for the solution of the equations is given in a detailed report, and we will not repeat it here.(8)

Explosion Example. We will use a simple ventilation system to illustrate the effect of an explosion on the flow field. The

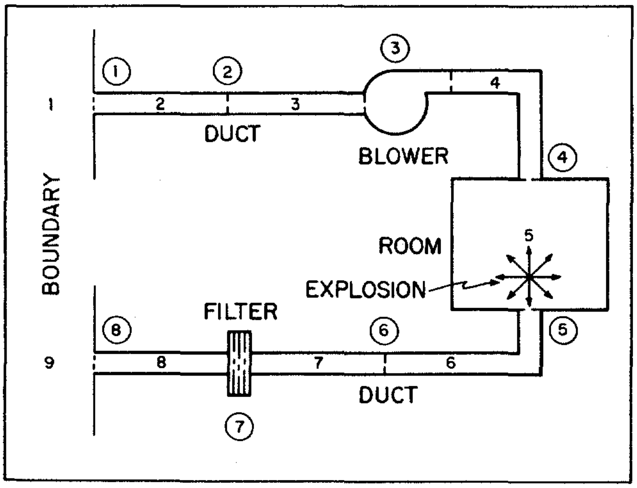

Figure 2. Schematic of ventilation system.

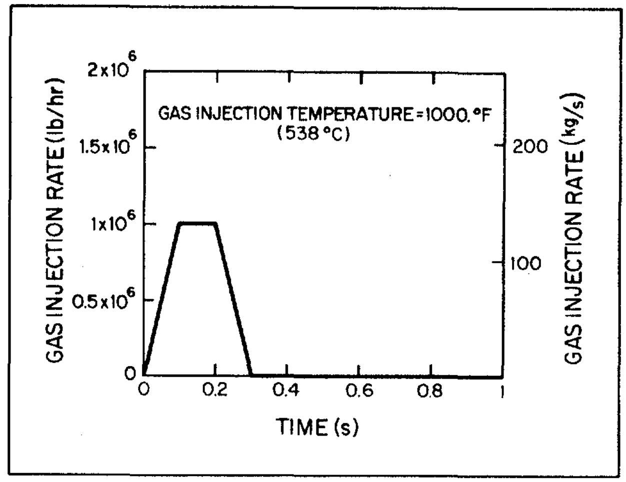

Figure 3. Explosion simulation with gas injection--Injection Rate Time History.

schematic of the ventilation system is given in Fig. 2. This system consists of ductwork, a blower, a filter, and a room. The ductwork is divided into control volumes, each of which is 30.5 m (100 ft) long and .305 m (1 ft) in diameter. The number without a circle represents a control volume, and the one with a circle indicates a branch or connecting element. An air injection to the big room (volume = 28.3 m^3 (1000 ft^3)), with the time profile given in Fig. 3, is used to simulate an explosive event. The system is operating normally at time zero with a volume-flow rate of 0.85 m^3/s (1800 cfm). A blower characteristic curve is chosen, and the pressure drop across the filter is chosen to be 498 Pa (2 in. of water) at normal flow.

As the explosion occurs, the pressure pulse travels upstream and downstream from room 5, and flow reversal takes place in branches 1, 2, 3, and 4, with increased rates in branches 5, 6, 7, and 8 (see Figs. 4--9). After the termination of air injection, the system will take time to return to normal condition. We must emphasize that both the system and the explosive event are hypothetical, and from a structural point of view, the system integrity is assumed unaffected by the severe transient.

We have presented a computer code (EVENT) that can analyze severe transient flow dynamics in a ventilation system. The explosive event can be simulated by adding mass and energy or by other parallels. We have illustrated the use of the EVENT code with an example. This is the first version of our explosion code, and it will be followed by versions that include near-field analysis capability.

Fires - Fire Code

We are developing a computer code that will predict the propagation of fire-induced transients within a ventilation system. In developing the code, our approach incorporates into this code as many models as possible from existing codes. The EVENT code will serve as a basis for the fire code. Additional models will be incorporated

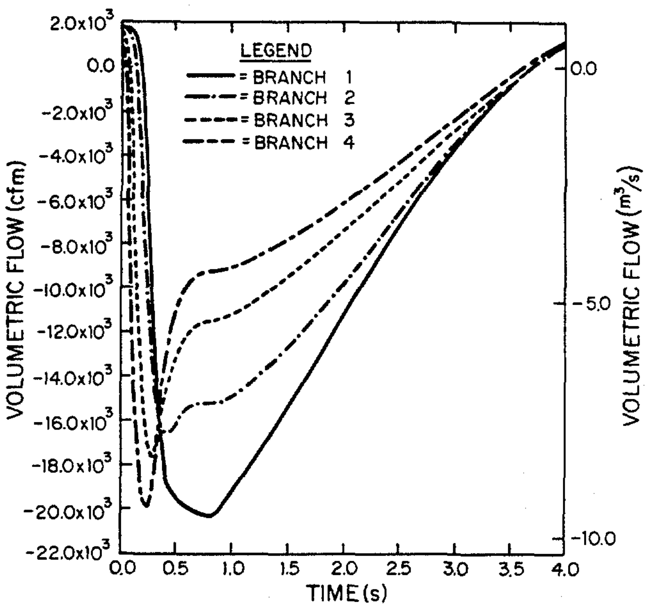

Figure 4. Transient flow rates in ducts 1, 2, 3, and 4.

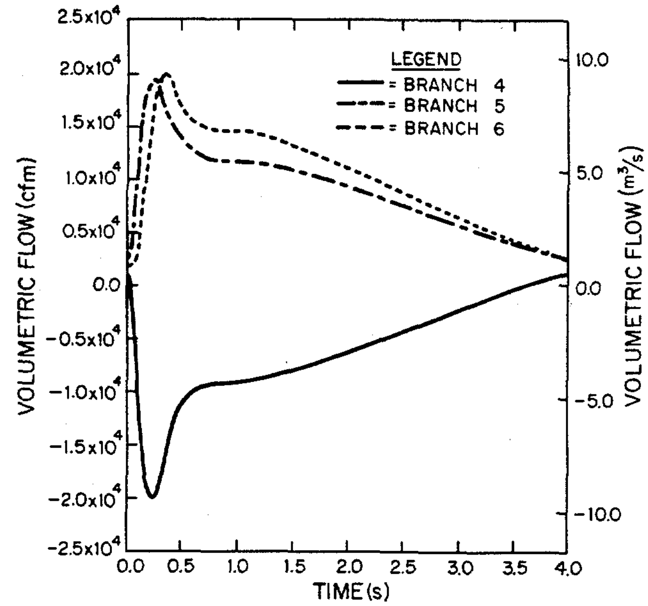

Figure 5. Transient flow rates in ducts 4, 5, and 6.

into this base as necessary to extend its capabilities of predicting effects unique to fires.(9)

The transient portion of the code will be divided into near- and far-field categories. The near-field analysis will concentrate on detailed effects that occur near the fire itself (typically in the room or duct containing the fire). The primary function of the far-field analysis will be predicting the transport of energy, momentum,

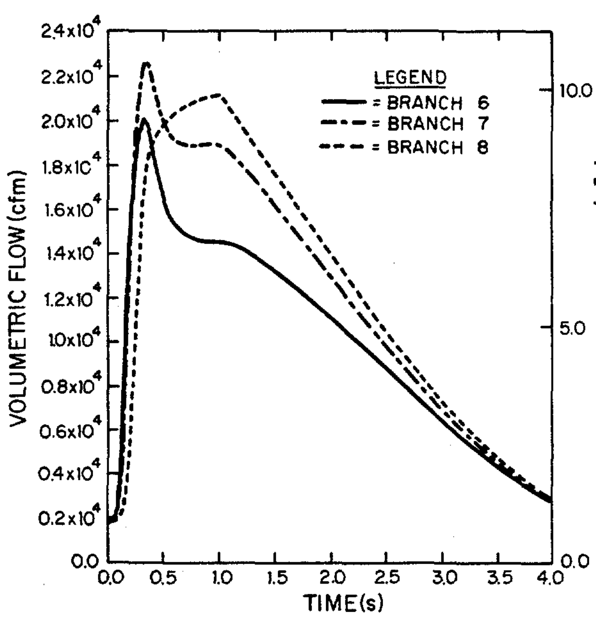

Figure 6. Transient flow rates in ducts 6, 7, and 8.

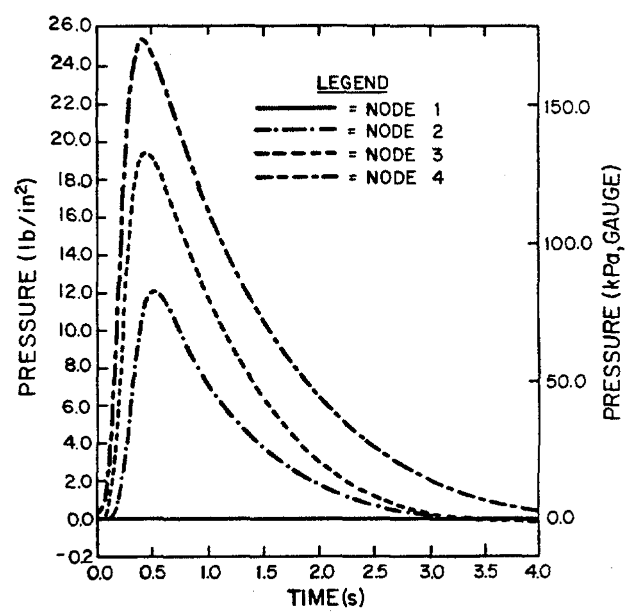

Figure 7. Transient nodal pressure at nodes 1, 2, 3, and 4.

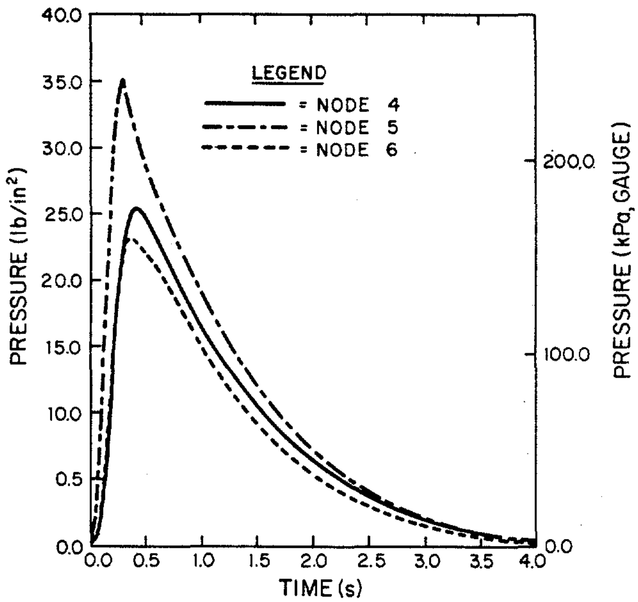

Figure 8. Transient nodal pressure at nodes 4, 5, and 6.

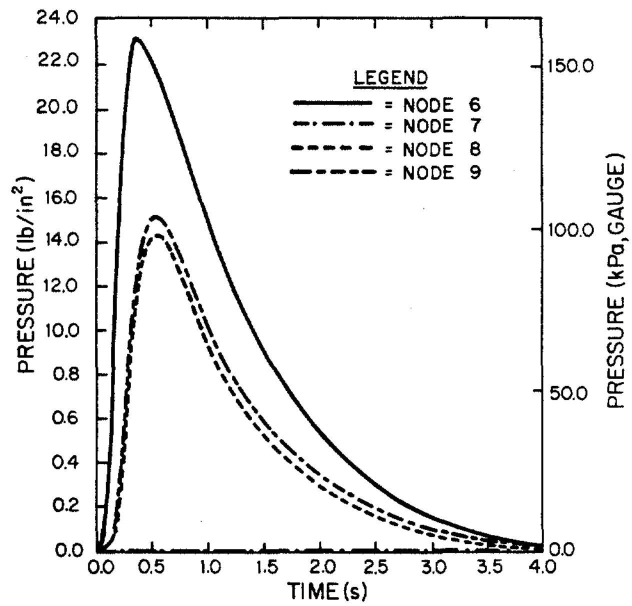

Figure 9. Transient nodal pressure at nodes 6, 7, 8, and 9.

and mass throughout the ventilation system. This analysis will use the results of the near-field analysis and the boundary conditions of the problem as input.

The near-field analysis will be similar to that contained in the EVENT code. In addition, a model must be added to predict the complex interactions between the fire- and flow-fields (that is, the fire behavior is influenced by the air flow and vice versa). Additionally, a model must be included to account for the heat transfer processes between the gas environment and its surrounding structure. The material transport model is also needed and is discussed later.

The momentum transport model for the far-field analysis is similar to that contained in EVENT. The energy transport model is also similar, but additional models will be included to account for duct- and compartment-wall heat transfer. The duct heat-transfer module includes natural convection and radiation from the outside of the duct to the surroundings and forced convection and combustion gas radiation from the combustion products to the inside of the duct wall. The compartment heat transfer model will include heat transfer between the gas and the compartment walls through mixed convection and radiation as well as the energy capacitance and heat-up of the walls themselves. The far-field analysis material transport model will be based on the model described in the next section.

The far-field analysis is also influenced by the behavior of various active and passive components contained within the ventilating system as well as the physics of the transport processes. The EVENT far-field model already contains models that describe the coupling between the transport processes and blowers, ducts, filters, dampers, and compartments. We may have to add models for additional components in the far-field fire model because of the presence of engineered safeguard equipment whose activation drastically alters the calculated consequences of the event. Fire dampers, air scrubbers, smoke removal systems, smoke removal flaps, explosion flaps, water sprays, and electric heating coils are some of these components under consideration. The decision on the necessity of inclusion of any of these models in the code will be based on the specific facilities and scenarios that will be simulated with the code.

Example of Fire Code Results. Much experimental data that quantify fire effects can be found in the literature. Of particular interest are data reported by Gaskill, et al., because data are given for a full-size fire test compartment and exhaust ventilation system equipped with ducts, HEPA filter, and blower.[10]

Although the final Fire Code has not yet been assembled, these data have provided us with an opportunity to test our gas dynamics, heat transfer, blower, and filter models, as well as the corresponding numerical procedure for solution of the interdependent processes. We simulated a full-scale fire transient (Lawrence Livermore National Laboratory (LLNL) test PB-7) to assess the adequacy of the code models formulated to date. This test is a check on not only the heat transfer models, but also the gas dynamics, blower, and filter models.

This test was conducted to determine the effect of smoke on filter plugging using a clean burning fuel under well ventilated conditions. The fuel was a douglas fir wood crib with a fuel loading of 8.2 kg/m^2 (220 kg total). The fire burned for about 960 s, and then it was extinguished by sprinklers. See Ref. 10 for more test details.

Because the actual time-dependent energy source for the experiment is not known, the test was simulated with the code using an assumed energy addition function. A comparison of the code-calculated results with the measured experimental data is shown on Figs. 10--12. Figure 10 shows excellent agreement between the calculated and measured duct flow rates. The agreement provides verification of the homologous blower models applied over a range of a factor of 10 in the gas temperature. Figure 11 shows good agreement between the fire compartment outlet gas temperature and the measured experimental temperature up to the time that the sprays were turned on (spray systems are not modeled in the present version of the code). Figure 12 shows the comparison between the calculated and experimental gas temperatures at the filter (~10 m (33 ft) downstream from the compartment). The calculated temperatures slightly overpredict the experimental temperatures at later times, but, in general, the agreement is quite good. This agreement serves as a partial verification of the duct heat transfer module.

Material Transport

In a nuclear facility, the ultimate concern in an accident is the release of radioactive material to the environment. A severe gas-dynamic transient can cause protective devices, such as filters, to fail, and excessive material release can result. It is desirable to devise an analytical tool that can work with particulate movement in a ventilation system. We are developing a very simple particulate

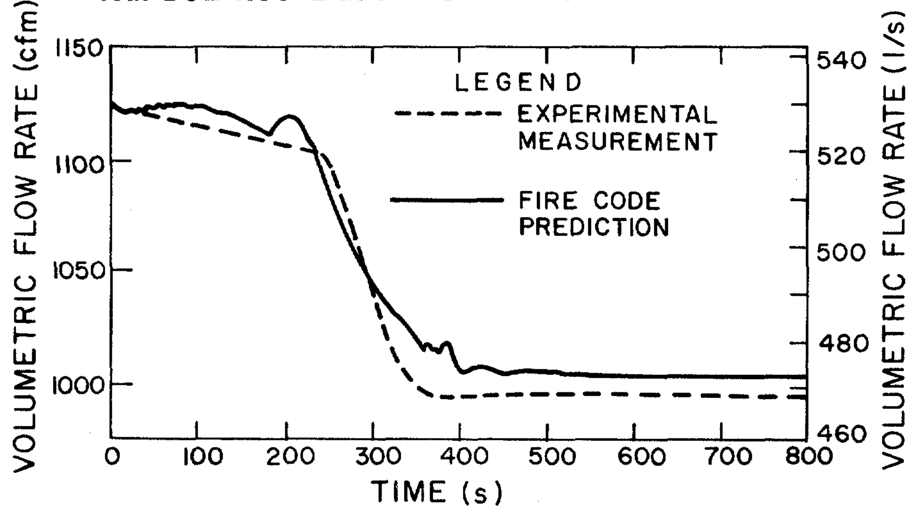

Figure 10. Comparison of fire code prediction with experimental measurement data for the duct flow rate for LLNL full-scale fire test PB-7.

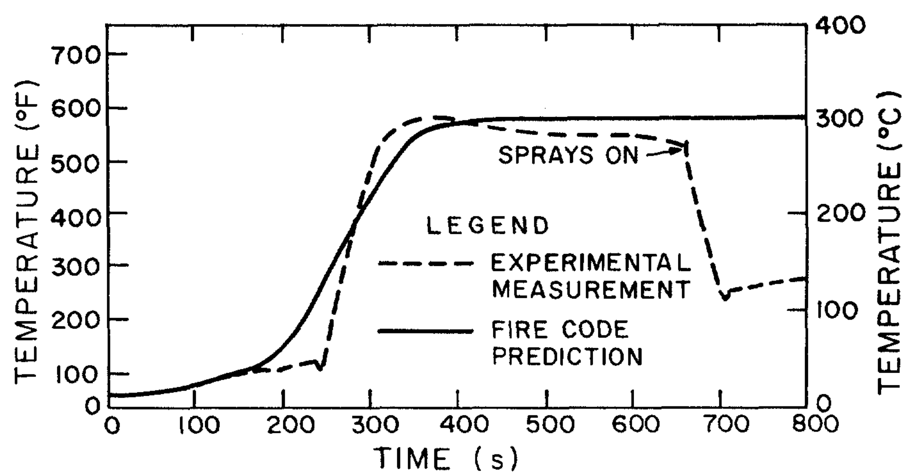

Figure 11. Comparison of fire code prediction with experimental measurement data for the test cell outlet temperature for LLNL full-scale fire test PB-7.

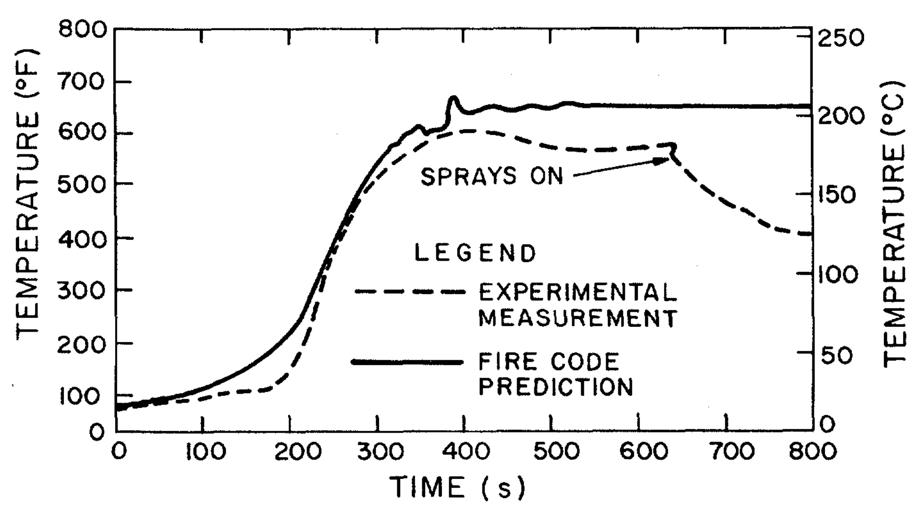

Figure 12. Comparison of fire code prediction with experimental measurement for the duct temperature upstream of the HEPA filter for LLNL full-scale fire test PB-7.

transport model that can be readily incorporated into the gas dynamics codes such as EVENT, TVENT, or the Fire Code.

Homogeneous Equilibrium Model. For now we will ignore the more complicated phenomena, such as particle generation, deposition, reentrainment, or particle growth, and focus our attention only on the convective effects of particulate once it is airborne. We assume that the gas and the particulate phase form a homogeneous mixture. Even for a dusty cloud, the volume occupied by the particulates is small compared with the air volume. Thus we assume that this is the case in our first model and refer to it as a dilute condition. A consequence of this assumption is that the particulate cloud motion is dominated by the aerodynamic drag, which is proportional to the velocity difference between the gas phase and the particulate phase. We will not give the mathematical proof here.[11]

We expect the particulate in a ventilation system to be approximately 1 m in size or smaller. The aerodynamic response time is quite small for these particle sizes compared with the typical residence time; that is, the particulate velocity is almost identical to the gas velocity at any location and time. This is called dynamic equilibrium and this approximation leads to the fact that only the particulate continuity equation is needed to analyze the particulate flow aspect if the gas velocity is known.

We have not investigated how the presence of a particulate cloud affects the momentum balance in the gas phase. When we use the assumptions made, the momentum equation for the mixture has the same form as the one for the single gas phase equation except that the mixture density should be used. To simplify the matter further, we define the ratio of particulate mass to the amount of gas in a volume as a mass fraction. If this value is small, then the gas phase momentum equation is not affected by the presence of the particulate cloud, a dilute condition. We can also show that the gas phase energy equation can be decoupled from the particulate phase as well. This leads us to a set of gas phase equations that do not involve the particulate phase, and they can be solved separately. After the gas dynamic segment is solved, we use simple continuity equations to calculate the particulate phase properties such as velocity (same as the gas), mass concentration, or particulate mass flow rate. This work is in the initial development stages, and no examples will be given at this time.

IV. Facility Description

The LASL test facility is located on the New Mexico State University (NMSU) campus with operation and testing provided by the Mechanical Engineering Department. Many of the test components are located outside the test building and are shown in Fig. 13. From left to right in the foreground of Fig. 13, the components are the model ventilation system, the large blowdown tanks, and the shock tube. The test building is in the background.

The apparatus at this test facility are used to test the capability of filtration devices under abnormal conditions. Using these apparatus, we are able to generate varying degrees of flow transients to simulate both natural and man-caused accidents. The facility has

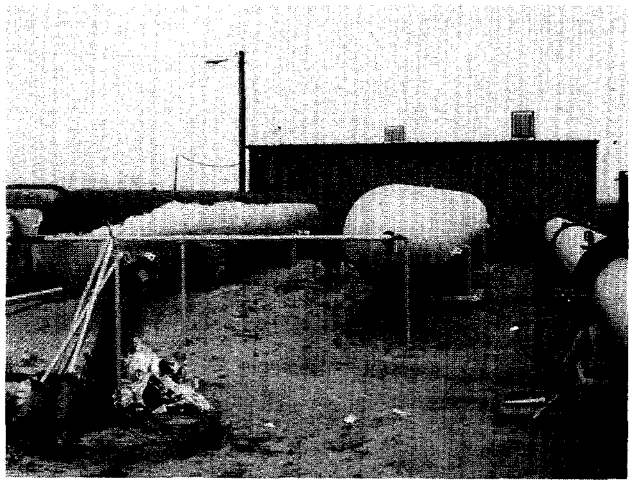

Figure 13. Experimental apparatus at the LASL test facility.

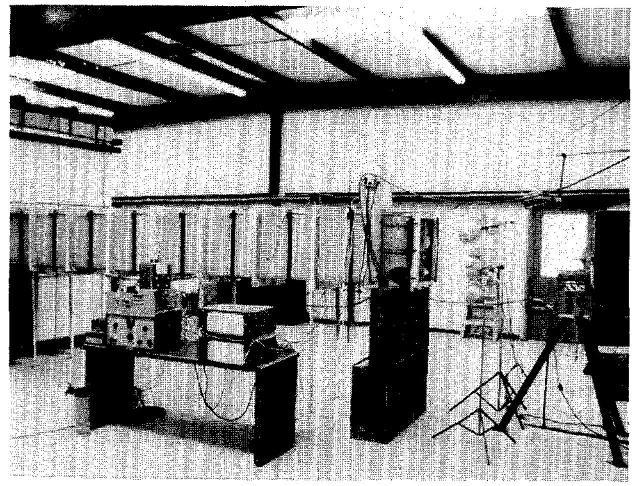

Figure 14. Blowdown chamber and HEPA filter testing apparatus at LASL test facility.

also been used by Karlshruhe Nuclear Research Center, Federal Republic of Germany, to test their filtration devices. A large wind tunnel that will also be used to obtain experimental data on reentrainment and deposition is under construction at NMSU. Some of the experimental apparatus are described in greater detail below.

Blowdown Apparatus

The purpose of the blowdown apparatus is to impose relatively slow (0.5 s to 6 s) pressure pulses across ventilation system components. The system is capable of generating pressure levels of 27.6 kPa (4 psi) and volumetric flows of 11.8 m^3/s (25 000 cfm). The system consists of two large pressurized tanks, sonic nozzles, a prefilter chamber, and a wind tunnel. The prefilter chamber, wind tunnel, test filter, and high-speed camera are shown in Fig. 14.

The air flows from the pressurized tanks through twelve 31.75-mm (1.25-in.) solenoid valves. The mass flow rate is regulated by sonically choking the flow at each valve, and the pressure pulse rise is regulated by controlling the number of valves opened at any time.

The air passes from the valves into a 3.0- by 3.0- by 3.0-m (10- by 10- by 10-ft) expansion chamber and impinges on an impaction plate. The air is then prefiltered by a bank of 25 HEPA filters.

From the prefiltering chamber, the air passes through a 0.6- by 0.6-m (2- by 2-ft) duct and impinges on a test component at the end of the duct. HEPA filters and blowers have been evaluated thus far. We will present recent structural testing results for HEPA filters and blowers in later sections.

Shock Tube

The purpose of the shock tube facility is simulating low-grade explosions and thereby creating shock waves that can be imposed on ventilation system components. The shock tube is shown in Fig. 15 and is 914 mm (36 in.) in diameter with a 11.2-m (36.9-ft) driver section and a 35.4-m (116.1-ft) driven section. Figure 15 also shows other test devices that are used to evaluate filtration devices for explosive transients. From left to right in the foreground of Fig. 15, the devices are the large shock tube, a small shock tube, and an aerosol efficiency test device. A double-diaphragm technique is used to control driver firing pressure of the shock tubes. This method allows us to reduce diaphragm costs by eliminating the need for machine-scored diaphragms. The conceptual design and small scale experiments have been reported.[12,13]

We intend to control the total impulse that is imposed on the test specimen. That is, we will control both peak pressure and duration (dwell time) of the high pressure behind the shock wave. A wide range of dwell times can result from internal explosions. Diverse systems within facilities and their geometrical configurations are responsible for part of the variability in dwell times, but other conditions may be even more influential. These conditions result from the character of the material causing the explosions. Fuel cycle operations typically involve gases, vapors, and dust or fine granular material. These materials often have explosive potential and vary widely in their deflagration or detonation characteristics. We have concluded that it is impossible to pick a single representative dwell time for a detonation wave. Thus we have devised a method to allow variable dwell times within the shock tube.

The physical phenomena occurring in the shock tube suggest the method used. Gas at different pressures is separated by a diaphragm. When the diaphragm is ruptured, a compression wave travels down the low-pressure region of the shock tube while an expansion wave travels in the opposite direction into the high-pressure region of the shock tube. When the expansion wave arrives at the end of the high-pressure section, it is reflected and races back down the shock tube, tending to overtake the shock wave. By varying the length of the driver section of the shock tube, we can obtain any dwell time desired. The dwell time will be the difference between the arrival times of the compression and expansion waves at the test specimen.

We plan to evaluate the effect of total impulse on ventilation system components during the remainder of 1980 and 1981. Initial tests will be described below.

Scale-Model Ventilation Systems

The primary purpose of the two scale model ventilation systems is providing system pressure and flow data for comparison with the TVENT tornado computer code predictions. The scale-model ventilation system test facility described here will also be used for future material transport and fire code verification studies.

In addition to code verification studies, a second objective of the scale model program is to confirm similitude relations that were developed using the Buckingham Pi theorem. These relations, together with previously obtained HEPA filter data, were used to design the scale models. They are also used to design experiments and to interpret results from the two model systems. To investigate the scaling laws used, we will compare experimental results from two model ventilation systems. The test results from the larger model will be

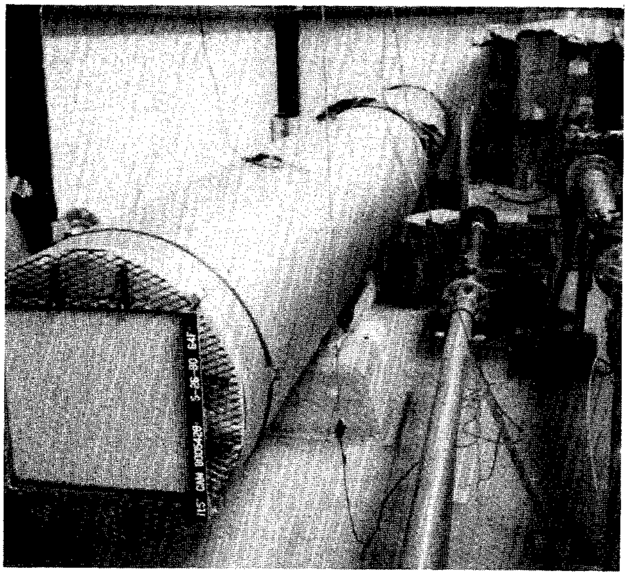

Figure 15. Large-diameter shock tube at LASL test facility.

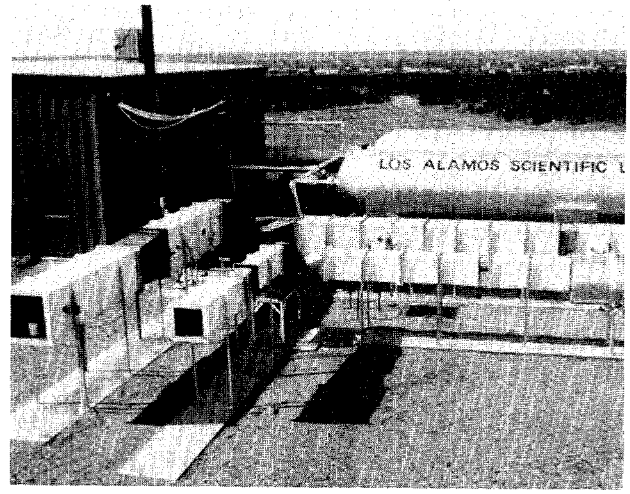

Figure 16. Scale-model ventilation systems at LASL test facility.

called prototype results for comparison with the smaller model results. Verification of the similitude relations will confirm our ability to scale up to even larger sizes.

The two scale models differ by a geometric scale factor of 2.0. A brief description of the larger model shown in Fig. 16 should suffice. It consists of one each of four of the most common ventilation system components: a room, a filter, a blower, and a damper. The blowdown apparatus described above is used to control and shape the tornado pulse. The overall system is over 24 m (80 ft) long and has 0.6- by 0.6-m (2- by 2-ft) ductwork. The room has a volume of 17.4 m^3 (613 ft^3). The filter is a standard 0.3-m (12-in.)-thick HEPA filter. The centrifugal blower has a 0.6-m (24-in.)-diam wheel running at 2000 rpm and the damper has opposed blades. All of the components were purchased from commercial suppliers. The entire system has been fully instrumented according to AMCA Standard 210 for ambient conditions, fan parameters, pressures, flow rates, and temperatures.

Wind Tunnels for Material Transport Studies

An accident in a fuel cycle facility glovebox or process cell might aerosolize a relatively high concentration of solid or liquid material. Conceivably, such an accident could breach the absolute filter containment and allow hazardous material to enter the facility ventilation system in significant quantities. (Such material is normally present in the ventilation system but in lesser concentrations such that many months may pass before the HEPA filters are bagged-out and the precious metal oxide is recovered.) At present, no known computer code will handle the complex problem of modeling ventilation system pathways, predicting the energy propagation away from an event, predicting the flow of accident-generated gases and aerosol-laden air, and keeping track of material accumulation on the HEPA filters. In developing such codes, we will have to make many assumptions. However, much of the needed basic information that is not presently available can be obtained from aerosol transport experiments. Our immediate explosion (also fire and tornado) computer code needs are for basic material transport models. Consequently, near-term experiments will be directed in this area.

We will use two wind tunnels. One tunnel has a 0.5- by 0.7-m (20- by 28-in.) cross-section and a top speed of 18 m/s (60 ft/s). A second tunnel is under construction and will feature higher speeds, interchangeable sections, improved visibility, and a larger cross-section. The new tunnel will have a 1.2- by 1.2-m (48- by 48-in.) cross-section and a top speed of 46 m/s (150 ft/s).

Facility Modifications for Fire Experiments

A nuclear fuel cycle facility fire might progress from the pyrolysis of solid material to complex chemical reactions between the resulting gases and air releasing large amounts of thermal energy. Assuming incomplete combustion, particulate material and numerous gaseous compounds will form. Uneven heating will induce updraft, eddies, and abnormal flow rates, locally at first and eventually perhaps throughout the entire ventilation system. Aerosolized material may be transported through the system and eventually captured on HEPA filters. Sufficient loading and caking of the filter banks could lead to filter failure or pressurization of the system and a release of hazardous material. Our immediate fire computer code needs are for filter plugging and compartment fire models. Thus near-term experiments will be directed in these areas.

The first filter fire response experiments will determine the resistance of HEPA filters as a function of aerosol loading and flow rate. Initially, filters will be loaded with cool, dry smoke from a smoke generator. This smoke will simulate a smoldering fire. These tests can be performed using an existing filter loading facility modified to accept the smoke generator. This initial test series allows us to establish a data base for filter plugging without the added complexity of heat addition. Later, this testing will be continued using the existing larger scale model fire chamber that has a volume of 17.4 m^3 (613 ft^3) and 50.8-mm (2-in.)-thick steel walls connected to 0.6- by 0.6-m (2- by 2-ft) ducts. We will generate two fires with widely different combustion products. This test series will allow us to obtain filter-plugging data for more realistic smoke particulates. The data in the second test series (with heat addition) will be correlated to baseline data obtained earlier for filter plugging without heat addition. First, a very dirty fire will be produced by burning fuel oil or kerosene at a low air/fuel ratio. Next, a relatively clean fire will be produced by burning natural gas at near stoichiometric conditions. With these fires, we will be able to bracket the gaseous and particulate combustion products that are likely to occur.

V. Examples of Supportive Experimental Data

We wish to illustrate several examples of supportive data that were obtained in the experimental area. These examples include code verification using scale model ventilation systems, quasi-steady blower response data, and HEPA filter structural limit data for tornado and explosion loads. These investigations provide data and

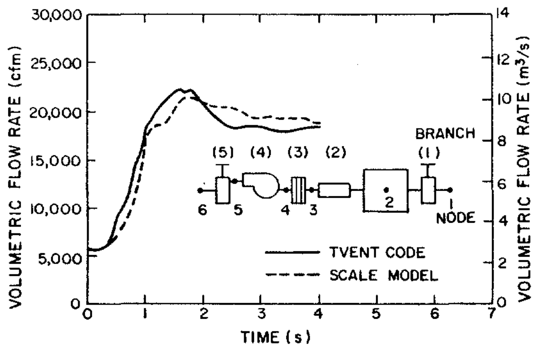

Figure 17. Comparison of TVENT predictions with scale-model experimental results.

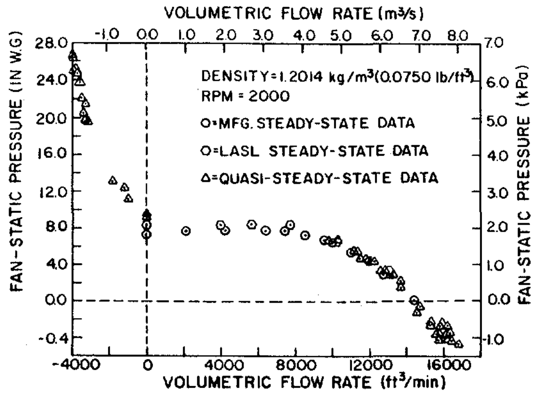

Figure 18. Steady-state and quasi-steady-state performance for the NYB 24 in. centrifugal blower.

partial understanding to the last three questions posed in the Introduction.

TVENT Code Verification

Tornado simulations are being performed at both the scale-model ventilation system exhausts and inlets to verify the TVENT computer code. As an example, experimental results simulating a Region I 20.7 kPa (3 psig) peak pressure at a rate of 13.8 kPa (2 psig/s) tornado applied at the exhaust (Node 6) of the larger model are shown in Fig. 17. The experimental flow data are shown compared to TVENT code predictions for the same pulse. Notice that TVENT has successfully predicted the overshoot in flow rate into the room (through Branch 1). Other results not shown here confirm that TVENT successfully modeled the pressure drop across the HEPA filter (between Nodes 3 and 4). The installed HEPA filter failed structurally during these tests.

Blower Response to Tornado Loading

Experimental evaluation of blower response to simulated tornado pressure transients is accomplished with the aid of the blowdown apparatus in Fig. 14. Using this facility, we tested a New York Blower (NYB) Model 249 centrifugal blower for quadrant 1, 2, and 4 performance characteristics. Quadrant 1, representing normal or nonaccident conditions, implies positive values of both fan-static pressure and flow rate. However, under tornado loadings, a blower may be forced to operate in quadrant 2 (backflow) or quadrant 4 (outrunning flow) flow regime.

We obtained quadrant 1 data for the NYB Model 249 blower by taking the appropriate static and velocity pressure measurements under steady-state conditions. Quadrant 2 and 4 data were obtained under quasi-steady-state conditions by initially running the blower at steady-state conditions and then pulsing the blower (through its inlet or exhaust) by successively opening more solenoid valves in the blowdown system to produce higher pressure levels. Static and velocity pressures, temperatures, fan speed, and fan power were measured. The results of this experiment are presented in Fig. 18. In this figure, steady-state data (hexagonal symbols) and quasi-steady-state data (triangular symbols) are compared with the manufacturer's performance data (circular symbols). Note that our test data were corrected, using the appropriate fan laws, to a standard density of 1.2 kg/m^3 (0.0750 lb/ft^3) and an rpm of 2000 to compare our results with the manufacturer's data. As indicated in Fig. 18, our test results in quadrant 1 compare very well with the manufacturer's data. Also, note the linear behavior of the fan-static pressure with the volume flow rate in quadrant 4. This result confirms TVENT's assumption for blower performance in this quadrant. Quadrant 2 data indicate a nonlinear variation of fan-static pressure with the reverse volume flow rate. We also observed that blower speed (rpm) did not remain constant during these tests. During quadrant 4 quasi-steady-state testing, the blower was observed to overspeed by as much as 15% of its steady-state value, whereas for quadrant 2 testing, blower speed never varied more than 1%. No attempts have been made to simulate a continuous tornado pressure transient. However, we have made plans for such dynamic testing. These tests will yield data concerning dynamic response times and heuristic effects.

HEPA Filter Structural Response to Simulated Tornado Loadings

Standard HEPA Filter Tests. We are using the word standard to refer to filters of American or British design. We are using nonstandard to mean filters of European design or filters with higher design flow rates. These tests were performed with two separate objectives--determination of the structural limits of HEPA filters and determination of parameter effects upon that structural limit.

Structural Limits. HEPA filters fail under tornado conditions when the downstream fold of the filtration medium breaks, allowing unfiltered air to pass through the filter. The size of this break will grow with increased airflow after the initial break. The mean static pressure drop across the filters at their initial break point is listed in Table I.

The break pressure values are listed by manufacturer in Table I. The strongest filters are built by manufacturer B, whose filters broke at a mean pressure of 20.1 kPa (2.91 psi). Manufacturer C built the weakest filters, which broke at a mean pressure of 9.1 kPa (1.32 psi). The filters of manufacturer C also had the least data scatter, with an uncertainty of 1.5 kPa (0.22 psi). A larger area of medium is broken out of the weaker filters than out of the stronger filters at peak pressure levels of 20.7 kPa (3 psi). Considering all

Table I. Standard HEPA filter break pressures for simulated tornado loadings.

Manufacturer	Break Pressure + One Standard Deviation kPa	psi
A	17.3 ± 3.9	2.50 ± 0.56
B	20.1 ± 3.2	2.91 ± 0.46
C	9.1 ± 1.5	1.32 ± 0.22
D	18.4 ± 2.2	2.66 ± 0.32
Average	16.4 ± 4.9	2.37 ± 0.71

the filters as one data set, we obtain the average values listed at the bottom of Table I--16.4 ± 4.9 kPa (2.37 ± 0.71 psi).

Parametric Study. Our off-the-shelf HEPA filters varied in many more aspects than we desired for our parametric studies, and correlations were difficult to identify. The parameters that correlate strongly to the HEPA filter static break pressure are the manufacturer, the medium paper tensile strength, the medium paper impact strength, and possibly the medium paper batch. Parameters that did not correlate strongly were tornado pressurization rate and duration, pack tightness, flow direction, separator type, and particulate loading.

Nonstandard HEPA Filter Tests. We subjected four types of nonstandard HEPA filters to simulated tornado loadings to determine their structural limits. The initial break pressure for each manufacturer is listed in Table II.

The break pressure for these nonstandard filters is below the break pressure for all standard HEPA filters except those built by manufacturer C. The HEPA filters built by manufacturer G were almost as strong as the standard HEPA filters. Also, the type of failure in these filters is far more catastrophic than for standard type HEPA filter failure; that is, most or all of the medium is blown out of the frame.

HEPA Filter Structural Response to Simulated Explosive Loadings

The shock tube described in Section IV was used to examine structural response of standard and nonstandard HEPA filters to simulated explosion waves. First, we will discuss the results of tests on standard HEPA filters and then discuss nonstandard filter results. We will only highlight the test results, and detailed reporting of the testing will be made elsewhere.[14]

Standard Filters. The test results for the standard HEPA filters are shown in Table III. We exposed each type of filter to shock loadings only once, using a shock wave duration of 47 ms. Table III shows that the failure range for these types of filters ranged from 18.1 to 7.2 kPa (2.63 to 1.05 psi). These failure pressures were calculated by taking the average between the maximum shock pressure that did not break the filter and the minimum shock pressure that did break the filter.

Table II. Nonstandard HEPA filter break pressure for simulated tornado loadings.

Filter Manufacturer		Filter Break Pressure kPa	psi
E		11.0	1.6
F		9.0	1.3
G		15.9	2.3
H		9.0	1.3
	Average	11.2	1.6

TABLE III. Structural limits of standard HEPA filters subjected to simulated explosion waves.

Filter Manufacturer	Shock Duration ms		Shock Overpressure to Break Filter kPa	psi
A	47		17.6	2.55
B	47		18.1	2.63
C	47		7.2	1.05
D	47		9.5	1.38
		Average	13.1	1.90

The failure shock pressures found in these tests are all lower than those reported in the literature for similar testing. Anderson and Anderson(15) found that these types of filters failed at shock pressures of about 22.0 kPa (3.19 psi). The duration behind the shock front was approximately 50 ms. The authors did not reveal the manufacturers of the filters used in their tests. The results of our study show that the breaking point of the filters from shock overpressure is very dependent upon the manufacturer.

Nonstandard Filters. In Table IV, the results are listed for simulated explosion tests on four manufacturers' nonstandard HEPA filters. These filters are the European V-type or American separatorless type filters. The highest break pressure was found for filter type G at 9.7 kPa (1.4 psi), and the lowest pressure was found for filter type E at 5.5 kPa (0.8 psi). The average for these types of filters is 6.9 kPa (1.0 psi). Tests of standard filters indicated an average of 13.1 kPa (1.90 psi). Thus the nonstandard filters are 1 psi weaker than standard filters for the same type of simulated explosive wave.

VI. Summary

We discussed unanswered questions dealing with the safety of air-cleaning systems under the stress of accident conditions. We described LASL's accident analysis program, which is directed toward providing answers to or some understanding of these safety questions. Our approach in developing computer codes and supportive experimental data is both analytical and experimental. We described a unique test facility that can be used to simulate accident conditions in ventilation systems. Several examples were given that show the type of supportive experimental data that can be obtained from the test facility

TABLE IV. Structural limits of nonstandard HEPA filters subjected to simulated explosion waves.

Filter Manufacturer	Shock Duration ms		Shock Break Pressure kPa	psi
E	47		5.5	0.8
F	47		5.5	0.8
G	47		9.7	1.4
H	47		6.9	1.0
		Average	6.9	1.9

Acknowledgements

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DISCUSSION

FREEMAN: I infer that for your EVENT that the HEPA filters you are talking about are on exhaust only. Or am I to infer that they are on the supply side as well? If not, why not?

GREGORY: With regard to the computer analyses, filters can be located anywhere you like.

FREEMAN: Do you recommend they be on the supply side, the inlet to the building? That is a great big opening to the environment.

GREGORY: Yes, I do. I would say that whenever you start talking about conditions such as fire or explosion, you are certainly going to get reverse flows, so you must try to maintain confinement on the supply side.

MURROW: Your pictures of the last few explosions did not indicate that there were faceguards on the filters like the ones that W. Anderson used a number of years ago. He found that they helped a good deal. Have you tried any filters with faceguards?

GREGORY: Yes and no. For the tornado conditions, we have tried them with faceguards, both upstream and downstream. We find for that condition that faceguards are of no help whatsoever. With regard to the explosive effort, we have not yet used faceguards on those tests. I might add that we recognize Mr. Anderson's work. These first sets of tests are to compare our results with his work. His tests were, roughly, around 50 milliseconds, whereas ours were about 47 milliseconds. We shortened the duration to simulate filters that are closer to the explosives.

MURROW: There has not been a lot of work done on smaller filter sizes such as the 250 cfm sizes, the 12 x 12 x 11-1/2 in. filters. Do you believe that smaller sizes might be an advantage in systems subject to explosions, overpressures, etc.?

GREGORY: We have tried to be very careful in our experimentation when employing the large filters, because of the fact that the expense is quite high when you are engaged in destroying these filters. Therefore, we preceded all the full scale tests with smaller scale tests. In this case, we experimented with 8 x 8 in. filters. The indications are that the smaller filters are much stronger.

SHAVER: Typically, in a tornado, the time related to the pressure development would be an important factor. In other words, what values did you consider in the generation of pressure? Did you consider negative pressure evaluations, also?

GREGORY: As far as the analytical cases available, one actually does use depressurization. But let us talk about experimental considerations. We are trying to make a case here that one is concerned about the pressure differential. It seems to us that it does not make too much difference whether that is negative or positive. It is very convenient for us to bottle up a tornado in these tanks and create a pressure differential across the test component. I think that there may be a certain amount of skepticism with regard to your question. We have plans,on the scale model systems, not only to inject an overpressure. We also have a large vacuum system where we will duplicate these tests with a suction type of test. But I expect no difference.

CLIFTON: I understand the codes, TVENT and EVENT, do not include provisions for restrictive devices in these systems such as backdraft dampers. Are there any plans to incorporate such features?

GREGORY: That is right. In other words, a kind of active element, rather than a passive element. We are developing a new version of TVENT that will have that capability. We see that a lot of it is based upon experimental data that one has got to incorporate. We are getting the experimental data now and it will be TVENT, Modification 1, that will be available by the end of 1981.

MILLER: Is it also possible to run the tornado analysis on other codes such as CONTEMPT-4, and if so, what are the advantages of the TVENT over the CONTEMPT-4?

GREGORY: From my understanding, you are referring to a loss of coolant containment type of code. CONTEMPT-4 has a lot of heat transfer in it. So, if we are comparing TVENT to CONTEMPT-4, the comparisons would not be very good. However, if you used EVENT, which does take into account thermal energy balances, the comparison, I suspect, would be fairly good; although we do not have any two-phase flow dynamics in it.

BALFOUR: Do you assume these movies we just saw are an accurate picture of what would happen in an actual system fouled up with a fan?

GREGORY: I am not sure that I completely understand your question.

BALFOUR: Well, evidently this is open on both ends. The explosion on one end, and the other end open to the atmosphere. Do you think what happens in your experiments is comparable to an actual system, where you have one end bottled up with a fan and the pressure differential taking place on one side?

GREGORY: There is no way that we could have put the blowers, the dampers, and the other things that are actually present in the system in the pictures. I should have mentioned that. They are really there. I think the representation is fairly accurate.

A METHOD FOR ESTIMATING THE CHALLENGE TO AN AIR CLEANING SYSTEM RESULTING FROM AN ACCIDENTAL EXPLOSIVE EVENT

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Abstract

A method is presented for determining the challenge to an air cleaning system resulting from an accidental explosion in a process cell of a fuel cycle facility. In many safety analyses, this quantity is estimated by multiplying the volume of the process cell by the maximum concentration of airborne material that is reasonably stable to agglomeration and sedimentation. Particle sizes are inferred from the assumption of concentration stability. The suggested method is based on extrapolation of data obtained for the explosive dispersal of chemical agents. Application of the extrapolated information to fuel cycle facilities results in an estimate of total material airborne as well as particle size distribution. An important variable is the weight ratio of inert material to that of explosive (mass ratio). As the mass ratio is expected to be high in fuel cycle facilities, the method predicts that airborne material will have size distributions that have relatively large mean values following which substantial settling will occur. An illustrative calculation that takes mass ratio and settling into account suggests that total filter challenge may be greater than previously estimated, but that the fraction of that challenge that is smaller than 10 micro-meters may be very low. For use in safety analyses, the method requires experimental validation of the extrapolation of reference data to the conditions existing in a fuel cycle facility.

I. Introduction

The objective of this paper is the presentation of a method of estimating the challenge to an air cleaning system in the event of an accidental explosion in a fuel cycle facility. No new experimental data nor the results of new experiments are presented. The method involves the use of data obtained for one purpose, and via extrapolation, the application of that data to another purpose.

The dissemination of process materials in a process cell has not been a major subject of experimental investigation, and, as a result, there is little information that is directly applicable. However, there does exist in the ordinance literature a body of experimental information on the explosive dispersal of chemical agents in both solid and liquid form. This reference data forms the basis of the new method, although the conditions under which the data was obtained differ markedly from the conditions existing in a fuel cycle facility. The validity of the assumptions and the extrapolations needed for application to a fuel cycle facility have not been demonstrated.

Explosions that have occurred in fuel cycle facilities have been attributed to the presence of residual organic materials associated with conventional solvent extraction processing of nuclear fuels. These organic materials, because of operational anomolies, were nitrated and formed explosive compounds. Current plant design philosophies provide for the removal of residual organic materials by a succession of additional processing steps. Hence, in order for an accident to occur requires the failure of these ameliorating steps plus those combinations of operating conditions that lead to the formation of explosive compounds.

In most safety analyses made to date, the challenge to the air cleaning system has been estimated by multiplying the volume of the process cell by the maximum concentration of airborne material that is reasonably stable to agglomeration and sedimentation. The analysis of the LMFBR Program Environmental Statement is typical of those used in most analyses.(1) The most serious accidents were identified as those occurring in a high-level liquid waste concentrator or a plutonium product concentrator. Assuming a process cell volume of 1000 m^3 and a "stable" aerosol concentration of 10 mg/m^3, it was estimated that the filter challenge was 10 g of material. Estimates of particle size distributions were not made.

The same reference used a comparable technique for an explosion in a fabrication plant. In this case, the cell volume was estimated at $\sim$7000 m^3, and the resulting aerosol concentration was estimated as 100 mg/m^3. This lead to an estimate of 700 g of solid material that challenged the air cleaning system. Particle size distributions were not given. Selby, et al., using the same technique, considered the total airborne material as respirable.(2)

II. Reference Studies of the Explosive Dissemination of Materials(3,4,5,6,7,8)

Experimental Method

The technique most widely used for the studies of explosive dispersal of both solids and liquids is the detonation of an appropriate device in a closed chamber of sufficient volume to preclude the build-up of substantial pressure. Maximum dispersal of material occurred when the device was suspended centrally in the chamber. The chamber was equipped with one or more fans that gently circulated the air in a manner such that the airborne material was homogenized throughout the entire chamber volume. This arrangement is generally referred to as stirred settling. Suspended particles having a wide distribution of sizes settled in conformity with the principles of Stokes Law, thus leading to the gradual reduction of suspended particles with time. By any one of several techniques, the mass concentration of the airborne materials was determined as a function of time; this data constituted the raw data from which all other computations were made.

The configuration of the device usually used was either spherical or cylindrical with a height to diameter ratio of near one. The explosive was usually placed at the center of the device with material to be dispersed placed in the annular space surrounding. Though other configurations were employed, the basic configuration described was found to yield most efficient dispersal.

The raw data, the mass concentration decay curves, were analyzed to determine the initial quantities of airborne material having diameters less than 10 μm (in some cases 6 μm). Most results were presented in this form in the references.

The single most significant parameter of the studies was the weight ratio of inert solid or liquid material to explosive (mass ratio). The results presented in the next section indicate that high yields of inhalable airborne materials require low mass ratios on the order of one to two; most of the reference data was obtained in the range of one to fifteen. Application of the data to a fuel cycle facility requires extrapolation to much higher mass ratios. Other parameters were explored and are reported in the next section.

Results

The results of the reference experiments are presented in Figure 1 as the mass median diameters of a lognormal distribution *vs.* the most significant parameter, the mass ratio. This method of presentation has been used because it is compatible with the extrapolations that will be used for the fuel cycle facility in the next section. To obtain this information from the reported data of the original authors, two principal assumptions were made that are reasonably compatible with the reported data: (1) the initial as-generated particle sizes are lognormally distributed, and (2) the geometric standard deviation of the distributions is 2.0.

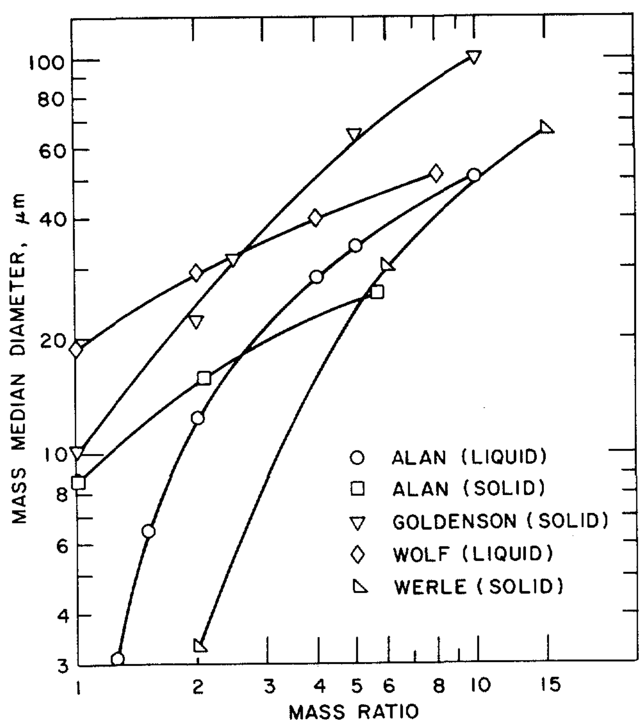

Figure 1. Results of Explosive Dissemination Tests, Median Particle Diameter *vs.* Mass Ratio.

The lognormal distribution has frequently been used as a standard distribution for describing particle sizes. It differs from the normal distribution in that the logarithm of the diameter is used as the argument of the frequency distribution rather than the diameter itself. It is characterized by two parameters, the median, and the geometric standard deviation. To test a given distribution, the cumulative frequency is plotted against diameter on lognormal probability graph paper. If a straight line results, the particle sizes are considered to be lognormally distributed.

The spread of the data in Figure 1 is evident, but there are a number of pertinent features of the data that may aid in the extrapolation. As mass ratio increases, the mass median diameter of the distribution increases substantially, thus resulting in a lower production of small diameter material. Within the spread of the data, no significant differences are evident between solid and liquid materials. The slopes of the curves are near one and decrease as mass ratios are increased.

Not indicated in Figure 1, is that several authors have observed bi-modal particle size distributions in the higher range of mass ratios (ten and above). This could explain the decreasing slopes of the curves as mass ratio is increased. If it is assumed that the total surface area formed from an explosive event (normalized to one unit of explosive) is independent of mass ratio, a straight line with unit slope would be obtained for uni-modal distributions. A slope of less than one is consistent with the observed bi-modal distributions, with the fraction of the small sized portion of the distribution decreasing as mass ratio is increased.

Other parameters studied included type of liquid and solid, state of solid (cast, degree of compaction), thickness of casing surrounding the device, type of explosive, shape of device, implosion configuration of device (inert material surrounded by explosive), and scale. The authors reported that the type of liquid or solid had no pronounced effect on dispersion. The most efficient dispersion (small mass median particle diameters) was obtained with cast or highly compacted solids, with thin casing, with spherical or near spherical geometries, and with the explosive in the center surrounded by inert fill. Increasing test scale reduced the dispersion effectiveness modestly. The results shown in Figure 1 reflect only the results of those tests in which the selection of parameters yielded maximum dispersion.

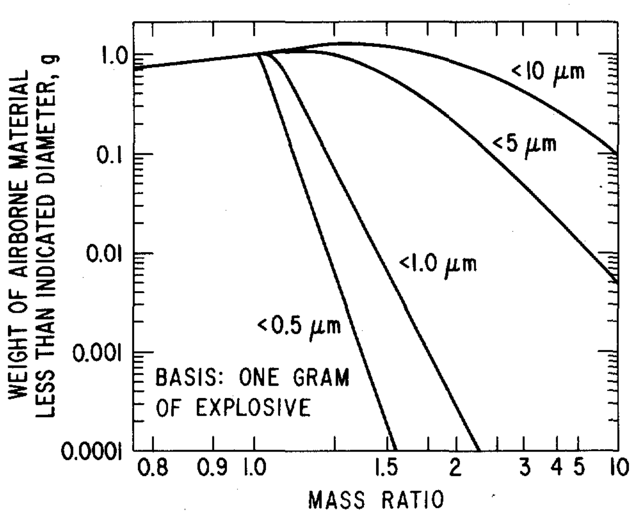

Figure 2. Initial Weight of Airborne Material vs. Mass Ratio (Calculated from Allan's Data).

Figure 2 shows Allan's data in an alternate form.(4) The data has been transformed to show the absolute quantities of airborne material having less than the indicated diameters as a function of mass ratio. Inherent in the transformation is the assumption of lognormal distributions with a geometric standard deviation of two. It is evident that the absolute quantities decrease rapidly, with the effect becoming increasingly pronounced as particle diameters become smaller. It is this curve that gave rise to the expectation that extrapolation beyond mass ratios of ten would result in further substantial reductions of the absolute quantities of small diameter particles.

III. Application of Reference Data To Fuel Cycle Facility

Introduction

As a first step, the method of analysis proposed in this paper is the extrapolation of the reference data obtained for low mass ratios to the larger mass ratios considered to be realistic in terms of conditions existing in a fuel cycle facility. The curve shown in Figure 1, relating the degree of dispersion as measured by mass median particle diameter, will be extended to cover the higher range. It is emphasized that the actual extrapolation should not be used for safety analyses until it has been experimentally verified. The second step is the determination from Figure 1 of the absolute quantities of material initially airborne as a function of particle diameter and mass ratio. In the third step, the amount of airborne material reaching the air cleaning system is determined based on assumed quantities of explosive, process cell dimensions, ventilation flow rate, and the configurations and volumes of the connecting ducting. Numerical results are included to illustrate the method, but these are not to be construed as realistic estimates.

Expected Mass Ratios in a Fuel Cycle Facility

A mass ratio range of 100 to 400 is thought to be reasonably realistic for the conditions existing in a fuel cycle facility. If it is assumed that the equivalent of ten pounds of TNT (4.54 Kgs) is a realistic estimate of the explosive source, 454 kilograms of high level waste in an evaporator would yield a mass ratio of 100. This weight of waste solution would appear to be somewhat low relative to conditions existing in a real plant, and a value four times higher, 1816 Kgs (yielding a mass ratio of 400), would not seem unreasonable. Actual values may be even higher.

Extrapolation of Reference Data to High Mass Ratios

Figure 3 shows the extrapolated curve of mass median diameter *vs*. mass ratio. The curve is not completely arbitrary as it represents a reasonable judgment based on fragmentary but undocumented tests. The curve is an extension of Figure 1 with a slope that is compatible with the experimental curves and which takes into account the bi-modal distributions observed above mass ratios of ten. It is this curve for which experimental validation is most needed for serious application of the method.

The second step is the presentation of data in Figure 3 to the alternate form (Figure 4) in which the absolute quantities of material initially airborne are shown as a function of particle size and mass ratio. Again, the dual assumption of lognormal distribution and geometric standard deviation has been used. It is evident that a marked reduction in the quantities of small sized particles occurs with increasing mass ratio. As an example, the absolute weight of material with particle diameters of 10 μm or less is seen to decrease from about 10^{-2} g/g of explosive at a mass ratio of ten to less than 10-5 g/g of explosive at a mass ratio of 400. Reductions for smaller particle sizes are greater.

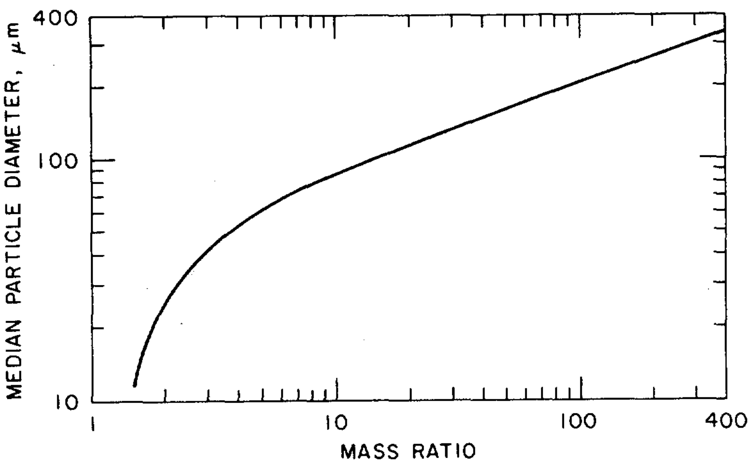

Figure 3 Extrapolation of Explosive Dispersal Data to High Mass Ratios.

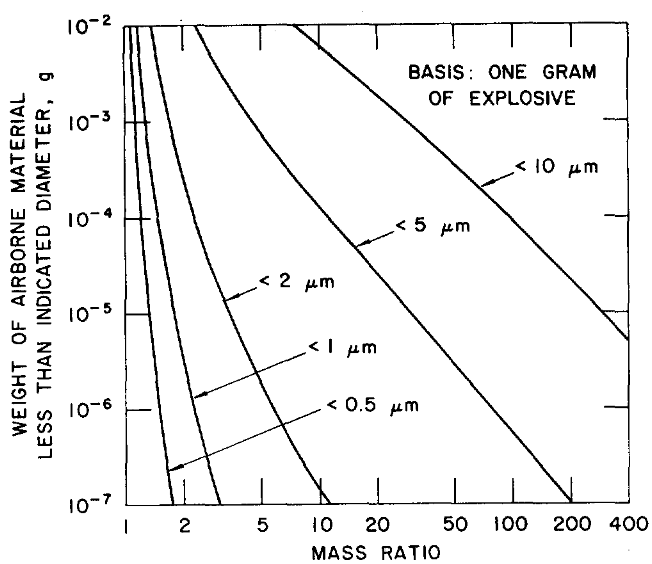

Figure 4 Initial Weight of Airborne Material vs. Mass Ratio.

Application of Extrapolated Data to Fuel Cycle Facility Conditions

Figures 3 and 4 describe the airborne material as initially generated at the time of the explosive event. The characteristics of the airborne material after the event, and hence the ultimate challenge to the air cleaning system, is dependent on the dimensions and configurations of the process cell, the connecting ducting, and ventilation flow rate. For the illustrative calculation, the height and area of a process cell have been assumed to be 100 feet and 8000 square feet respectively. A ventilation flow rate was selected such that a complete change in cell volume air occurred every twenty minutes. Connecting ducting was assumed to have a volume 0.5 percent of that of the cell, and a vertical height of ten feet.

Several other assumptions were necessary to provide a basis of computation. At the time of the explosive event, the airborne material is assumed to be instantly distributed over the cell volume, following which settling according to Stokes Law immediately begins. An unrealistic assumption--but one that results in high estimates of airborne concentrations--is that airborne material in the cell air space is continuously homogenized under stirred settling conditions. Overall concentrations of the airborne material are gradually reduced by (1) settling, and (2) removal by ventilation air. In the ducting to the air cleaning system, unhindered settling is assumed to occur.

Figures 5 through 7 show the results of the illustrative computations. Figure 5 shows the decrease of the total quantities of airborne materials present in the cell vs. time and mass ratio under stirred settling conditions (no ventilation). At high mass ratios, the initial quantities of material airborne at the time of the explosive event are higher than with low mass ratios, but because particle sizes are larger, the reduction with time is substantially greater. For example, at time zero, the total quantities airborne are 6.4 and 24.3 g/g explosive for mass ratios of 10 and 400 respectively. After 80 minutes of settling, these values reduce to 0.05 and 0.0004 respectively.

Figures 6 and 7 show the calculated filter challenge as a function of particle size and mass ratio. The emphasis is on small particle sizes in Figure 6, and on large ones in Figure 7. Though the total amounts initially airborne increase with mass ratio, the total quantities reaching the air cleaning system decrease. Considering only particle sizes of 10 µm or less, the filter challenge decreases from 4.6 x 10^{-3} g/g explosive at a mass ratio of 10 (0.57 percent of the total challenge), to 4.0 x 10^{-6} g/g explosive at a mass ratio of 400 (0.003 percent of the total challenge). Referring to Figure 7, it is evident that large size particles (e.g., >100 µm) make up 4.5 percent of the total filter challenge at a mass ratio of 10, but increases to 36 percent at a mass ratio of 400.

All of the above data has been normalized to one gram of explosive. In Table I, the normalized results have been scaled up to an explosive event of ten pounds of TNT equivalent for a mass ratio

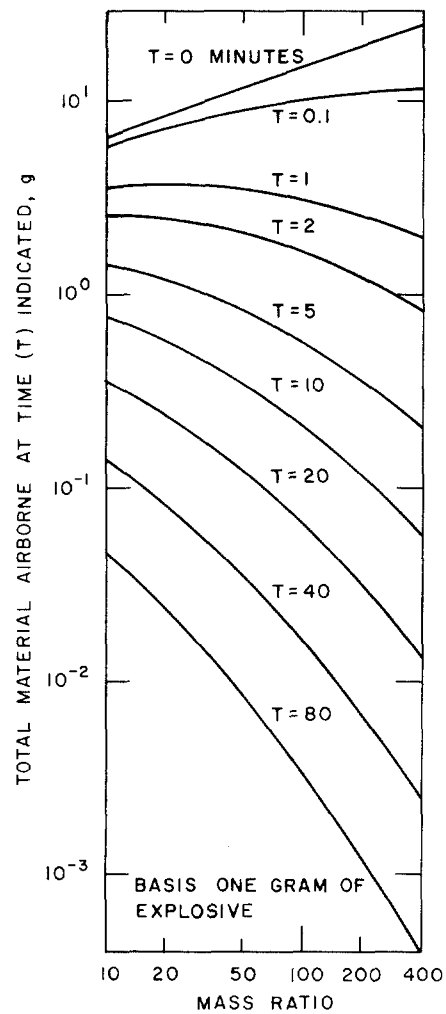

Figure 5 Total Material Airborne as Function of Time and Mass Ratio.

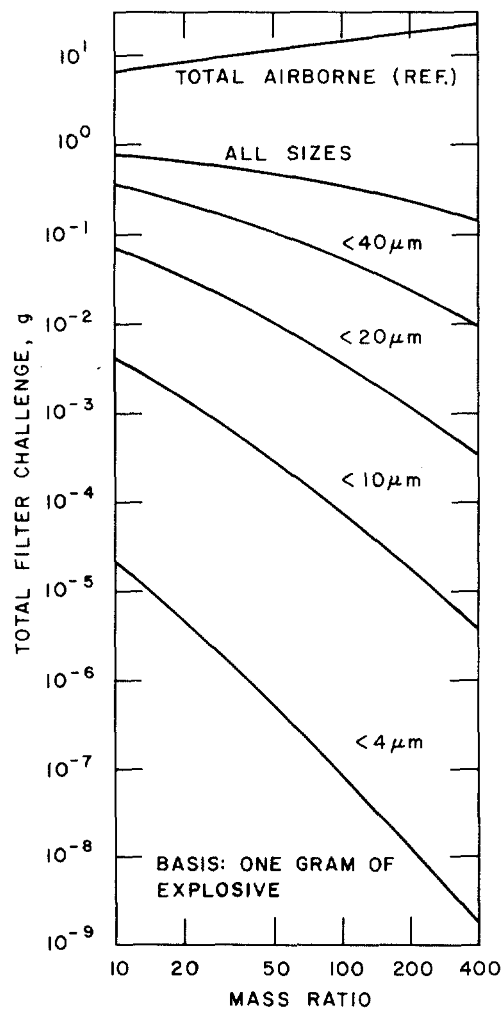

Figure 6 Total Filter Challenge as Function of Particle Size and Mass Ratio.

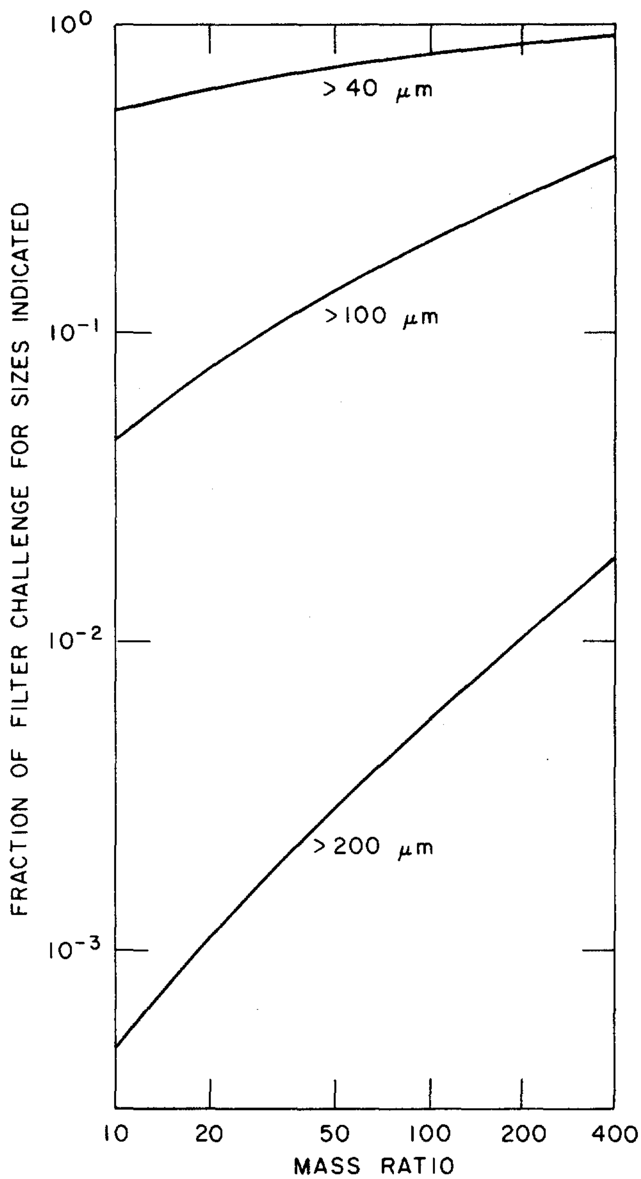

Figure 7 Composition of Filter Challenge vs. Mass Ratio.

of 100, and values compared with those obtained in previous safety analyses. In general, the proposed method shows that total quantities airborne and total filter challenge are greater than those obtained in prior safety analyses; however, quantities associated with particle size of less than 10 μm are very much less.

Comparison of Conditions for Reference Data and Fuel Cycle Facility

It can be argued that application and extrapolation of the reference data cannot be made sensibly because the conditions in a process cell are very different. For example, what if the explosion in a process vessel does not originate in the center of the vessel, but in a corner, or at the surface. The response is that any deviation from conditions under which the reference data was obtained are likely to result in poorer dispersion, i.e., the particle size distributions will be larger, and less small sized material will be produced. Great efforts were made in the reference tests to maximize the production of small particles, and the conditions for achieving that maximum production have been well characterized. Thus the proposed method, with the qualification that the needed extrapolations are verified experimentally, constitutes an envelope of small particle production that is not likely to be exceeded; it thus constitutes an upper limit.

IV. Conclusions

A method of realistically estimating the challenge to an air cleaning system of a fuel cycle facility as a result of an accidental explosion has been described. The method is based on experimental data obtained in studies of the explosive dispersal of chemical agents. The methodology used in the studies is straighforward, reliable, and well established. Extrapolation of the data is required for application to fuel cycle facilities. The validity of the extrapolation needs to be experimentally verified before serious application to safety analyses is attempted.

Table I. Comparison of Data Obtained by Proposed Method with Previous Safety Analyses (1,2)*

Assumptions: Mass Ratio = 100
10 lb. TNT equivalent

	Proposed Method	Previous Analyses For:** Processing	Fabrication
Material Initially Airborne, g			
Total	66800	--	--
<10 μm	0.42	--	--
"Inhalable"	--	10	700
Initial Airborne Concentrations, mg/m^3			
Total	2900	10	100
<10 μm	0.02	--	--
"Inhalable"	--	10	100
Filter Challenge, g			
Total	1580	10	700
<10 μm	0.40	--	--
"Inhalable"	--	10	700

* Proposed method is based on extrapolation that has not been experimentally validated.

**Values shown have been considered as inhalable in reference 2.

Illustrative calculations using the method indicate that at the high mass ratios expected for a fuel cycle facility (>100), the quantities of inhalable airborne materials (<10 μm) expected to be produced are very small ($<10^{-4}$ g/g of explosive at a mass ratio of 100). The filter challenge of these small particles is similarly small. However, total filter challenge, including large particles of sizes >100 μm, will be much larger (<0.35 g/g of explosive).

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3. C. R. Allan and R. V. Jolliffe as referenced in M. J. Steindler, et al., Chemical Engineering Division Fuel Cycle Programs, October-December, 1977, ANL-78-37, pp. 27-33.

4. C. R. Allan as referenced in M. J. Steindler, et al., Chemical Engineering Division Fuel Cycle Programs, January-March, 1978, ANL-78-68, pp. 58-60.

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DISCUSSION

MARTIN: I would like to know if you have any plans to obtain experimental data to verify your calculations.

SEEFELDT: We are not in a position to get experimental information. This work was obtained six months to a year ago. We have completed the work and I have simply put it out for consideration.

MARTIN: We have a program to calculate the source terms of radioactive material at the boundaries of fuel cycle facilities. I would just like to make the comment that we are in desperate need of these types of calculations. We have a great interest in this area. I would like to know if, in your calculations, you considered turbulent inertial deposition in addition to gravitational settling as a mechanism for depleting the material.

SEEFELDT: No, this model was quite a simple one. We used the stirred settling model and none other.

MARTIN: I would like to suggest, in light of some information that is going to be presented by Norm Alvares from Livermore, that, potentially, a great amount of material can plate out under fire conditions due to deposition. We has given out a number, on the order of 60% of the total material, that can become depleted.

SEISMIC QUALIFICATION OF HEPA FILTERS BY TEST IN AN ACTUAL OPERATING CONDITION

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I. Abstract

Flanders Filters, Inc., has completed an analysis and test program which has resulted in a seismically prequalified high efficiency particulate air (HEPA) filter housing with the HEPA filters installed and operating during the qualification testing. The nuclear seismic qualification program was performed by Corporate Consulting and Development Company, Ltd. During the seismic qualification testing a dioctylphthalate (DOP) test was performed for the duration of the shake table test and the system performed successfully. The details of the seismic qualification test procedure, housing and filter design, and the structural performance results are presented. Comparisons are made between theoretically predicted results and test results. The preliminary test program pointed out some potential vibration problems with separator type filters due to media puncture during shaking.

HEPA filters have typically been given less emphasis from a seismic qualification standpoint than the primary structure and equipment (such as fans, cooling coils, heaters, etc.) in filter trains and/or air handling units. This nuclear seismic qualification program has shown that this design for filters and housing will withstand the seismic occurrence and perform its required safety related function during and after the seismic occurrence. Conclusions resulting from this test program are presented and some recommendations and precautions are given.

II. Introduction

This paper reports the results of a recently completed seismic qualification program for a HEPA filter system. The primary program goal was the seismic qualification of a standard filter housing, with minimal design changes, to the highest feasible seismic levels. The filters were to be operated continuously during the test (before, during, and after the shaking). The acceptance criteria was the requirement to maintain a filtering efficiency greater than 99.97% based on the standard dioctylphthalate (DOP) test, continuously monitored during the test. A secondary goal was to seismically qualify the HEPA filters for use in housings other than the housing used for the test program. This will allow the use of other housing configurations of the same design, or the application of these filters into housings fabricated by other manufacturers.

The standard side-servicing bag-out housing design is a modular construction which utilizes a single filter module, consisting of a single filter and its associate filter housing. Figure 1 shows a housing of this type. This is referred to as a one high by one wide arrangement, or a 1 x 1 system. In general, the designation for a housing configuration is m x n, where m is the number of filters high and n is the number of filters wide. Figure 2 shows a 3 x 3 filter housing.

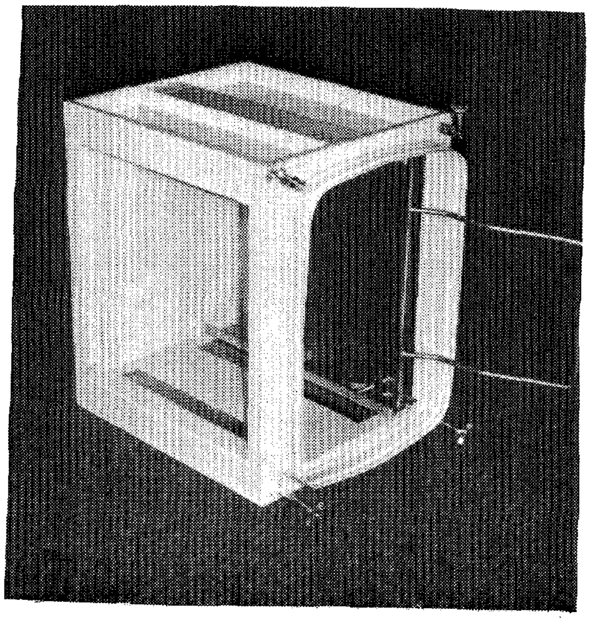

FIGURE 1
PHOTOGRAPH OF A 1 X 1 HOUSING

The housings and filters were qualified by testing to envelope all requirements of the Uniform Building Code along with a large portion of present and anticipated seismic requirements for nuclear generating stations and process plants. Test and analyses were designed to meet the requirements of IEEE 344-1975, "IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations" and the more common design specification requirements now being utilized by nuclear power plant design firms.

The qualification program included all E-4 and NBC-4 type filter housings from single filter unit (1 x 1) to the largest standard size unit, four filters high by three filters wide (4 x 3). The qualified filters include both separator and separatorless types in stainless steel or 3/4-inch fire retardent plywood frames.

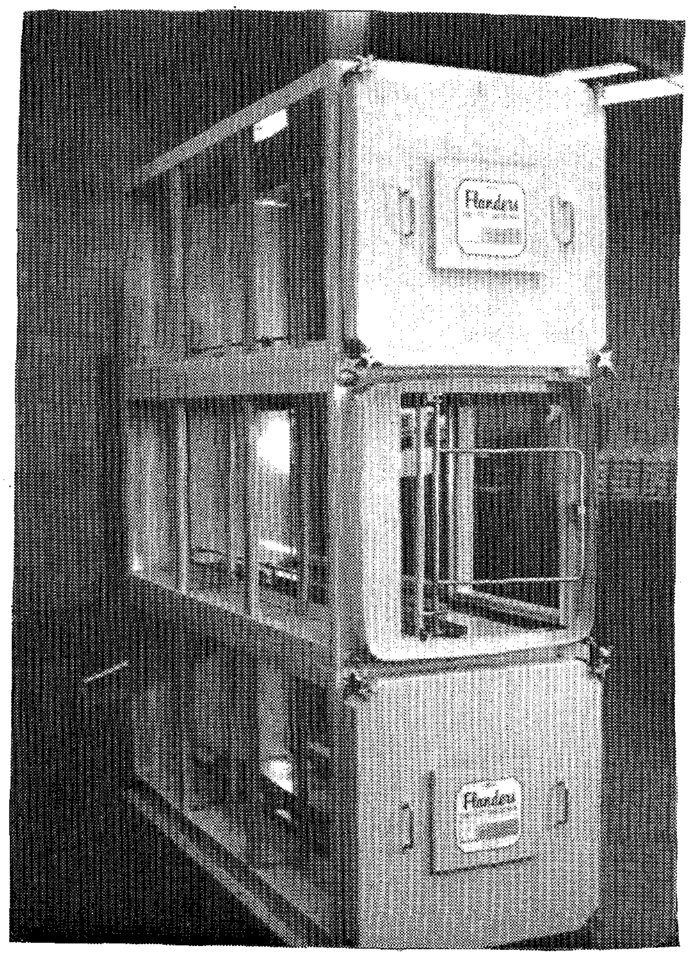

FIGURE 2
PHOTOGRAPH OF A 3 X 3 HOUSING

In summary, the objectives of the qualification test program were:

a. Seismically qualify type E-4 Side Service Bag-out Filter Housings and NBC-4 Side Servicing Filter Housings in the following configurations:

    (1) 1 x 1, 1 x 2, 1 x 3

    (2) 2 x 1, 2 x 2, 2 x 3

    (3) 3 x 1, 3 x 2, 3 x 3

    (4) 4 x 1, 4 x 2, 4 x 3

b. Seismically qualify HEPA type filters in both separator and separatorless styles using either stainless steel or 3/4-inch fire retardant plywood frames.

c. Qualify the filters for use in housings of other designs.

d. Qualify the housings and filters to a major portion of the Nuclear Power Plant Seismic Specifications that have been published or expected for equipment to be used in the continental United States and Alaska.

e. Qualify the housings and filters for use in applications subject to the requirements of the 1979 Uniform Building Code.

f. Qualify the equipment in accordance with the guidelines of IEEE 344-1975.

III. Performance Requirements

The safety related function of these filter housings is to provide continuous filtering of the airstream before, during, and after the design basis event. The acceptance criteria was thus determined to be a continuous filtering efficiency greater that 99.97%. Structural deflections and deformations were to be permitted provided they did not interfere with the filtration capability of the system. Gross deformations of the structure caused by sustained stresses significantly above the material yield stress would not, however, be permissible.

IV: Methodology of the Qualification Program

The qualification program presented the opportunity to optimize the system design based on several considerations:

a. Minimize the number of design changes required,

b. Minimize the complexity of the design changes,

c. Maximize design standardization, between the seismic and non-seismic housing,

d. Maximize the seismic levels which the system will withstand,

e. Maximize the number of projects to which the results will be applicable, and

f. Minimize the total cost of the qualification program.

Some of these considerations are contradictory, and several design trade-offs were required during the course of the qualification program.

The qualification analysis and test program was designed to address these requirements. The engineering involved in this program proceeded as follows:

a. Research the seismic requirements of existing nuclear facilities and seismic zones. Determine the "worst case" seismic conditions to which the housings and filters would be tested. The final seismic test levels were determined based on a review of the applicable "worst Case" seismic design levels and a design analysis of the equipment which determined the maximum levels that the equipment could successfully withstand. This study also included an analysis of several possible design modifications ranging in complexity from very sophisticated and involved design changes to minimal changes. The end result was some moderately complex design changes which offered the optimum tradeoff between increased fabrication costs and maximum allowable seismic levels.

b. Conduct preliminary analyses and tests to determine the "worst case" unit to be tested and recommend any necessary structural changes prior to final qualification testing.

c. Establish the seismic test plan.

d. Mathematically extrapolate data from the seismic tests to qualify non-tested configurations.

Preliminary computer analyses indicated that the 4 x 3 filter housing represented the "worst case" seismic design. By testing this housing and using identical construction methods for all other units, the remaining housings are qualified by similarity. From the analyses also came recommendations for increased metal thickness in some members, cross-bracing in individual filter portals, and a new mounting base. Initial testing of the filters indicated that separatorless filters would be adequate while separator types might be marginal. These points are covered in more detail in a later section of this paper.

V. Details of the Seismic Qualification Program

The qualification program consisted of four major phases:

1. Preliminary finite element analysis of the housing,
2. Biaxial testing of a 1 x 1 housing to determine preliminary filter performance and structural dynamics behavior,
3. Design modifications for the 4 x 3 test housing, and
4. Final shake table testing.

Preliminary Analysis/Design Reviews

Major analysis was performed on a finite element model of a 4 x 3 filter housing. Figure 3 shows the mathematical model used for this analysis. For the purpose of this discussion, the following definitions are made:

1. Lateral direction is the horizontal direction parallel to airflow,
2. Longitudinal direction is the horizontal direction perpendicular to airflow, and
3. Vertical direction is the direction normal to the plane of the mounting base.

The modal analysis of the mathematical model was accomplished by use of the Lanczos (FEER) process. The results of the modal analysis included mode shape, frequency, generalized weight, modal participation and modal weight (generalized weight x modal participation factor squared) for each mode requested. These results were used to evaluate the overall significance of the mode.

A detailed analysis was also performed on a 4 x 1 housing in order to determine the most critical configuration to be used for testing. It is not obvious in this case whether the 4 x 1 or the 4 x 3 housing is the most critical from a seismic standpoint. This analysis indicated that the added mass of the 4 x 3 housing had a dominating effect over the additional structure required, thus the 4 x 3 housing was chosen for the actual qualification test.

Preliminary Biaxial Testing

Preliminary biaxial tests were run on a 1 x 1 housing while being continuously subjected to DOP testing. The shake table was a phase coherent, biaxial machine capable of frequencies from 1 to 40 Hertz and maximum table input accelerations of approximately 10g's. For this test, the input accelerations were approximately 1 to 1-1/2 g's. Figure 4 shows this test setup.

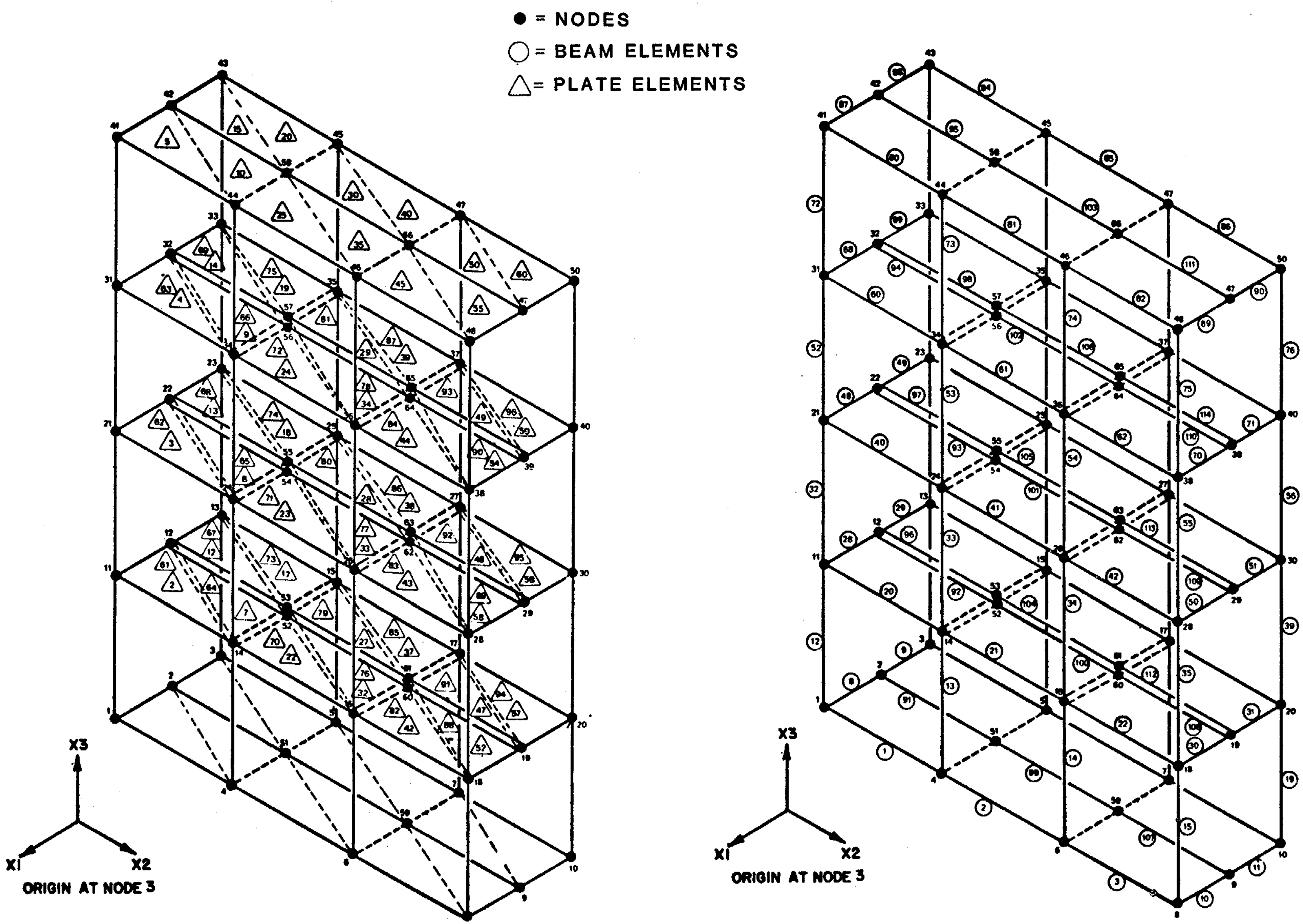

Figure 3. Finite element model of 4 x 3 filter housing.

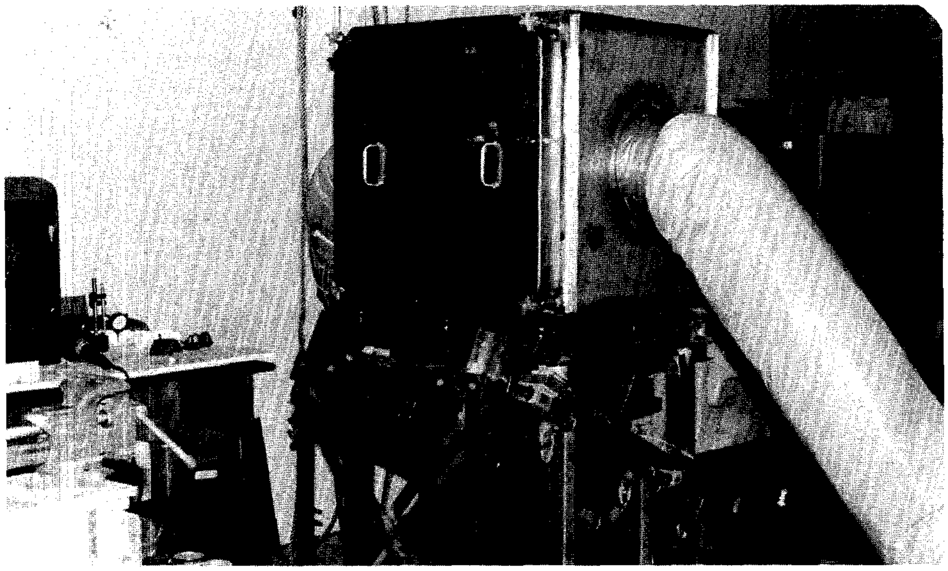

FIGURE 4
SHAKE TABLE TEST OF 1 X 1 HOUSING

Results from this portion of the test program indicated that:

1. Separatorless HEPA filters could be expected to withstand some rather high seismic acceleration levels,

2. Separator type HEPA filters are less desirable from a seismic qualification standpoint. During these tests, it was shown that the separators vibrated during these tests and actually punctured the filter media in several locations, significantly degrading the filtering efficiency. These tests did, however, subject the filter to many more cycles of vibration than would be expected in a normal seismic occurrence. It should be noted that these same filters did qualify when subjected to the final qualification tests which subjected the housing to a more realistic number of cycles. The lesson to be learned from this test is that separator type filters are more vulnerable to damage in a vibration environment than the separatorless type.

3. The fluid seal will perform its sealing function during a severe vibrational event. No "pumping" of the sealant was evident and no degradation of the seal was evident, either visually or by test measurements.

4. A 1 x 1 housing is very nearly seismically rigid (i.e. fundamental natural frequency $\geqslant$ 33 Hertz), but that the 4 x 3 housing could be expected to exhibit resonances significantly less than 33 Hertz.

Design Modifications

The detailed analysis as described earlier indicated that the structure of the conventionally designed housing would not be adequate to withstand the desired seismic loads. The major design modifications were:

a. One-half inch (12.7mm) diameter rods were welded in a cross brace in each filter portal to increase stiffness in the longitudinal direction.

b. Lateral stiffness was increased by increasing the material thickness and cross-sectional properties of the housing corner posts.

c. An inverted T-type mounting base of 3/8 inch (9.5mm) steel plate was added to uniformly distribute anchor loads into the sheet metal modules, and to provide a positive means of anchorage for the housing.

Final Shake Table Testing

Shake Table testing of the modified design for the 4 x 3 housing was performed at Wyle Laboratories in Huntsville, Alabama. Figure 5 shows a schematic of the seismic shake table set-up for one orientation. Figure 6 is a photograph showing the actual test setup in the second orientation.

The complete test program consisted of two test series; the first series accomplished qualification of the housing and the separatorless filters while the second series qualified the separator type filters. Filter efficiency was monitored by DOP tests conducted in accordance with ANSI-N510-Section 10. The filter housing was attached to a fabricated basemount test fixture using twelve 3/4-inch bolts. The housing and fixture were installed on the Seismic Simulator Table with the fixture's base flush with the top of the table. This mounting simulated the actual in-service mounting. The housing was initially oriented with its longitudinal horizontal axis colinear with the longitudinal axis of the test table. For the second orientation of tests, the housing was rotated 90 degrees in the horizontal plane.

A low level (approximately 0.2g) single axis sine sweep from 1 to 40 Hertz was performed in the vertical and two horizontal axes to establish major resonances. The frequency sweep rate was one octave per minute. The housing was then subjected to 30-second, simultaneous horizontal and vertical inputs of phase-incoherent random waveform motion. Frequency band widths for the input motion were spaced one-third octave apart over the frequency range of 1 to 40 Hertz. Each one-third octave frequency was independently adjusted in amplitude until the Test Response Spectra (TRS) enveloped the Required Response Spectra (RRS) of Figure 7. The resulting table motion was analyzed by a spectrum analyzer at 1%, 2%, 3% and 5% damping and plotted at one-third octave frequency intervals over the frequency range of 1 to 35 Hertz. Figure 7 shows the Test Response Spectra plotted at 1% damping for these tests for the Operating Basis Earthquake (OBE) and Design Basis Earthquake (DBE) for horizontal and vertical motions.

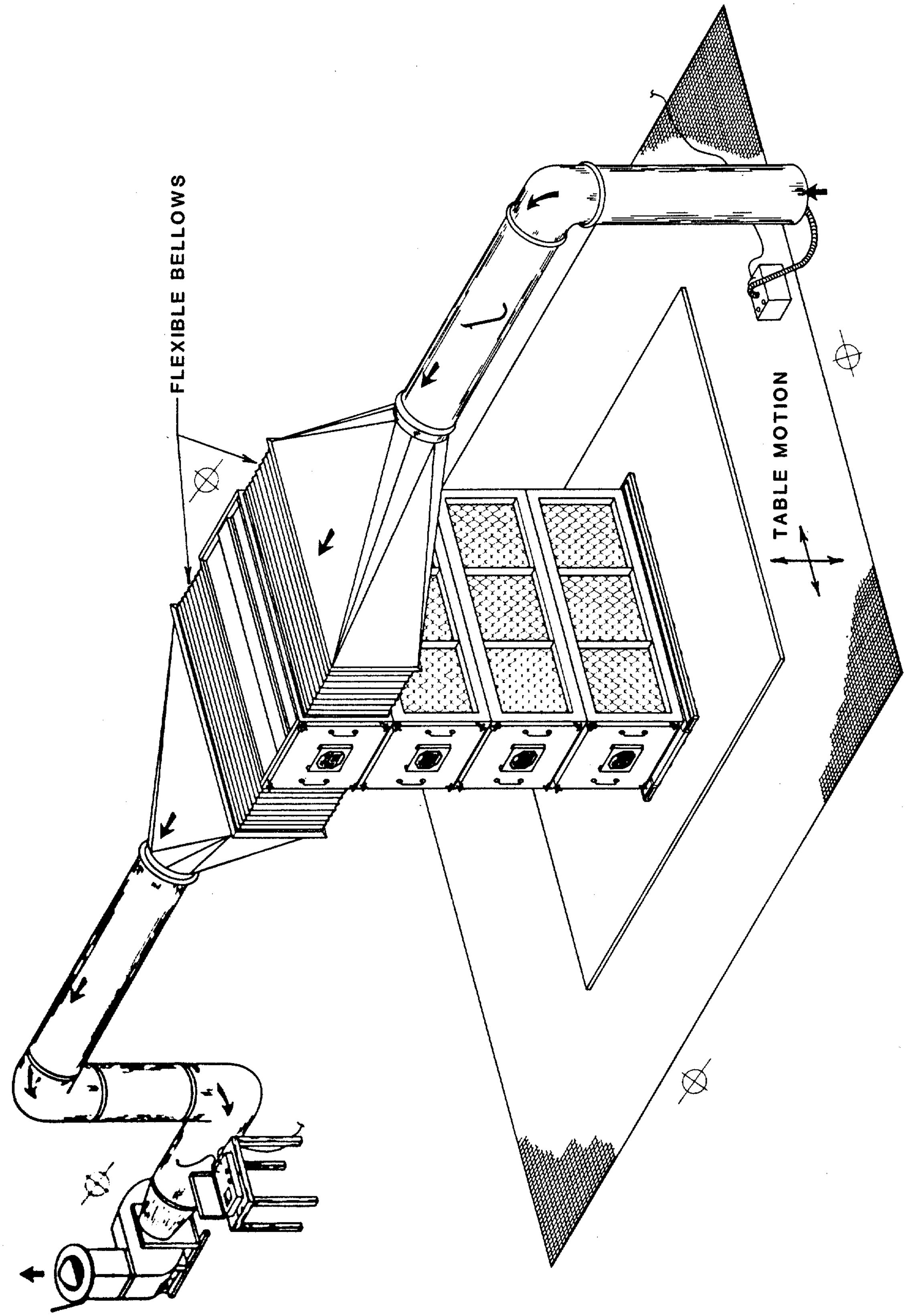

FIGURE 5 SCHEMATIC OF SHAKE TABLE CONFIGURATION

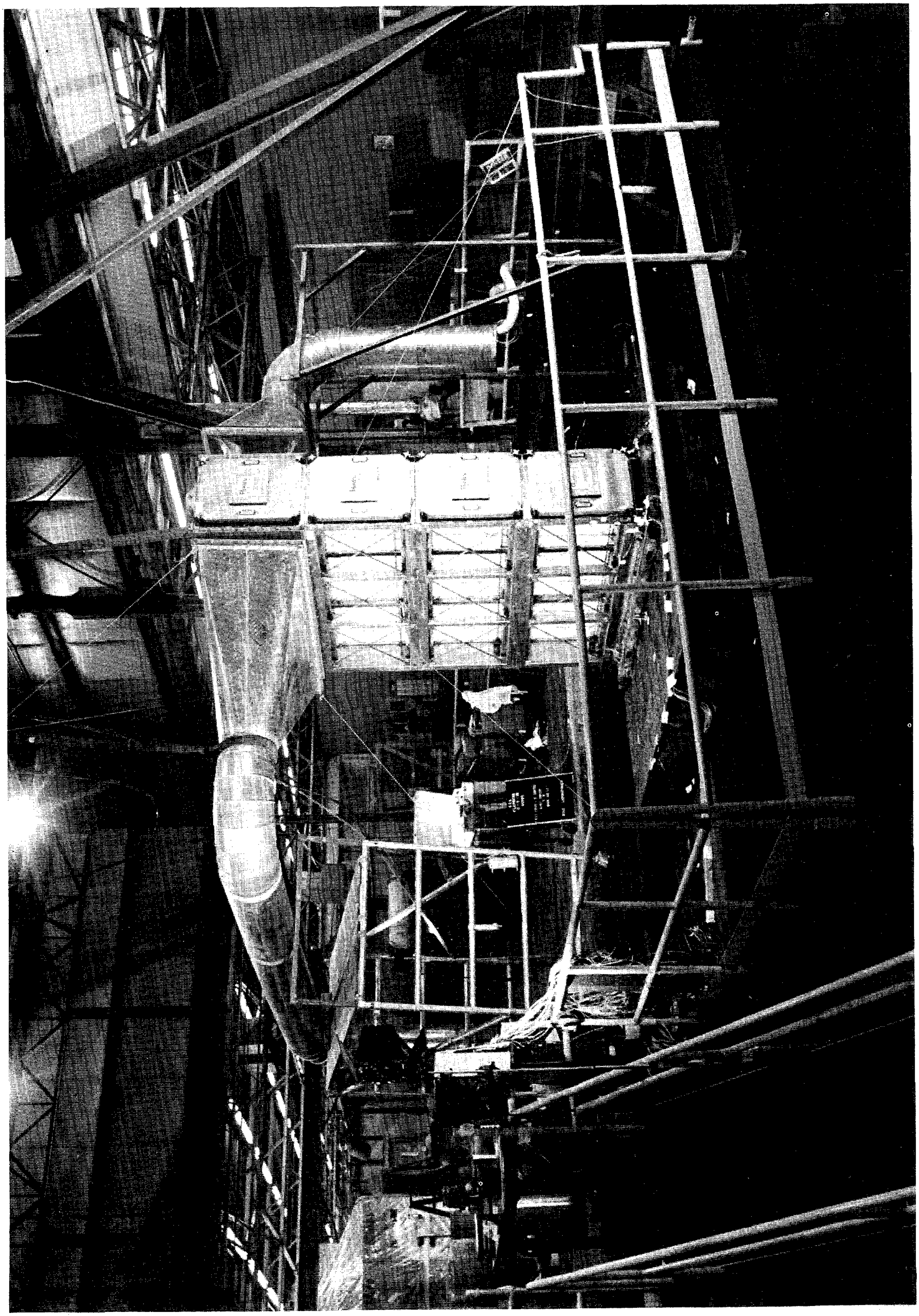

FIGURE 6 PHOTOGRAPH OF TEST SET-UP

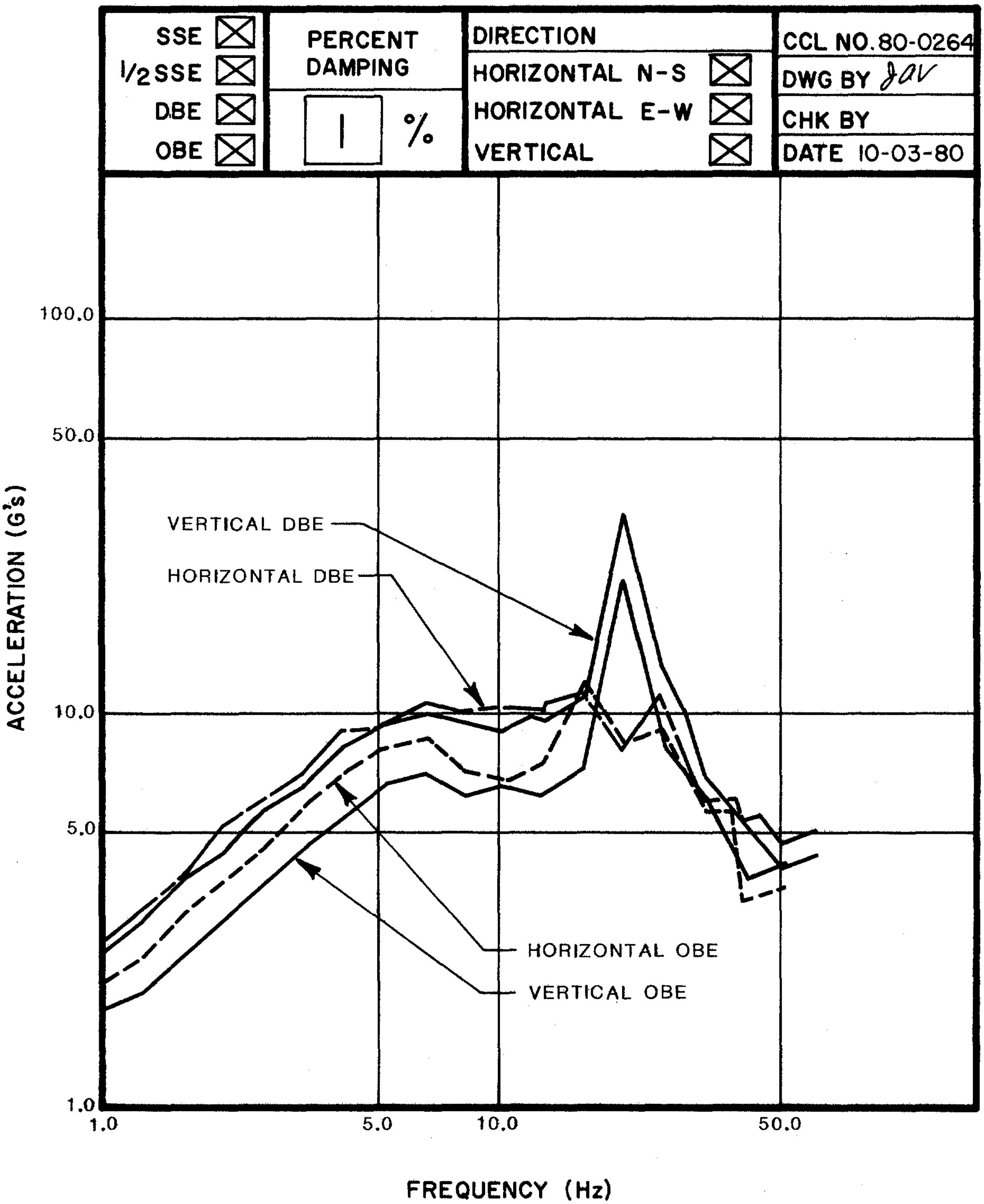

Figure 7 Seismic Test Response Levels.

A minimum of five Operating Basis Earthquake (OBE) tests were performed prior to application of a Safe Shutdown Earthquake (SSE) test in each orientation for each of the two test series. Filters were installed in all sections of the housings throughout the testing. During Test Series 1 separatorless filters were installed in the top section and monitored for efficiency by DOP tests. For Test Series 2, separator type filters were installed in the top section of the housing and monitored for efficiency.

Nine unaxial piezo-electric accelerometers were installed at various locations on the housing. Transmissibility plots from the resonance search tests and TRS plots from the OBE and SSE tests were generated. Twenty monitoring channels were used for recording strain gages during the tests. The gages included rectangular rosette and uniaxial gages along with two strain measuring anchor bolts.

Operability tests were conducted on the top bank of filters during each seismic simulation. The upper bank was chosen for tests due to the increased response acceleration at that point. A system of 16-inch diameter ducting was connected to the top section of the housing by two transition sections and flexible connections. A particulate (DOP) generator was placed ten duct diameters away on the upstream side of the duct opening. On the downstream side a fan was attached at the end of the duct to provide a negative pressure on the system. The DOP test was conducted in accordance with ANSI-N510 -Section 10. The downstream sample was monitored throughout the test to record any variation in efficiency.

VI: Significant Test Results

Several significant findings resulted from these tests.

Filtration Efficiency Tests

Both the separatorless and separator type HEPA filters were subjected to continuously monitored DOP tests during all testing. The airflow through each filter was 1000 cfm (3000 cfm total) with an approximate 1" water gage pressure drop. The specific filters used in the test were:

1. T-7025-NU, size GGF. Superflow (separatorless) nuclear grade filter with 14 gage 409 stainless steel frame. Filter media-to-frame seal is fire retardent solid urethane. Filter-to-housing seal is by channel and silicone grease (fluid seal). Filter size GGF (24" x 24" 11-1/2").

2. T-7C45-NL, size GGF. Separator type nuclear grade filter with 3/4-inch fire retardent plywood frame. Filter media-to-frame seal by fire retardent polyurethane foam. Filter-to-housing seal by groove and silicone grease (fluid seal). Filter size GGF (24" x 24" x 11-1/2").

The results of these tests are given in Table I. Both the separatorless and the separator type filters qualified based on these tests, even though the earlier tests had indicated that the separator type filters have the potential for puncturing of the media due to shaking of the separators during the test. It was also found that there was no intermittent operation of the filters during the seismic simulation.

TABLE I. FILTER EFFICIENCY TEST DATA

FILTER NUMBER	BEFORE/AFTER SEISMIC	TEST NUMBER	AIR FLOW PER FILTER (CFM)	SYSTEM PENETRATION	FILTER EFFICIENCY (%)
T-7025-NU-GGF	BEFORE	1	1000	.010	99.990
T-7025-NU-GGF	AFTER	2	1000	.010	99.990
T-7C45-NL-GGF	BEFORE	1	1000	.015	99.985
T-7C45-NL-GGF	AFTER	2	1000	.015	99.985

Structural Dynamics

Several analyses were made using the finite element model of the filter housing. In the first analysis the doors on the side of the housing were included as shear panels in the model. It was evident from results of the test that these doors did not significantly strengthen the structure. Therefore, in the second analysis the stiffness of these doors was removed from the mathematical model and the door weight lumped at the four door corner nodes. Two dynamic analyses were made; the first with base acceleration input in the vertical and longitudinal directions, and the second with base acceleration input in the vertical and lateral directions.

Table II summarizes the results of the modal parameter calculations and measurements. The experimental results revealed modes with frequencies at 9, 15, 22 and 35 Hertz. Corresponding modes were determined analytically at frequencies of 9, 26, 27 and 41 Hertz. Mode shape correlation is made through comparison of maximum transmissiblity and modal weight in the three directions. Modal damping calculated from the test results ranged from approximately 2.7% critical to 3.5% critical for the significant modes. There was very good agreement for the mode with a frequency of 9 Hertz. This mode is the most significant structural mode. Agreement is evident between calculated and measured values of higher modes, although the accuracy is not as good as might be desired.

TABLE II. COMPARISON OF RESULTS OF MODAL TEST AND ANALYSIS

MODE NUMBER	TEST FREQUENCY HERTZ	CALCULATED FREQUENCY (HERTZ)
1	9	9
2	15	26
3	22	27
4	35	41

Stresses

Table III compares the results of the stress with test results. The analysis based on linear behavior predicted stresses in the corner post which were greater than the yield value of the material. The test results showed stresses in the post near the material yield, as expected from the analysis. Differences can be attributed to the nonlinear behavior of the material near the yield point, and the fact that 1% damping was assumed for the dynamic analysis, while the actual damping was measured at approximately 3%. It is significant that all of the stresses predicted by the analysis are conservative.

Table III Comparison of Stress Results

LOCATION	LOAD	TEST RESULT (psi)	ANALYSIS RESULT (Psi)	% ERROR
Corner post, bottom	Lateral & vertical	38,000	72,150	+89.87
Corner post, 1/4 way up	Lateral & vertical	31,679	66,759	+110.74
Corner post, bottom	Long & vertical	7,782	20,129	+158.66
Corner post, 1/4 way up	Long & vertical	11,157	21,591	+93.52
Cross brace	Lateral & vertical	8,960	9,464	+5.62

Anchor Bolt Loads

The results of the anchor analysis are compared in Table IV. The most conservative analysis technique appears to be the finite element dynamic analysis for base acceleration in the lateral and vertical directions. However, the technique is nonconservative for base acceleration in the longitudinal plus vertical directions. This discrepancy can be explained by the observation that the dynamic analysis did not fully account for vertical acceleration effects, which were of the same magnitude as the overturning moment effects in the longitudinal direction. Hence, the dynamic analysis shows nonconservative tensile loads in the bolt from base acceleration in the longitudinal plus vertical direction. The static analysis techniques yielded excellent correlation with the test results. However, it should be noted that the simplified techniques are highly dependent on assumptions about the dynamic behavior of the specimen. In these cases, the acceleration loads used in the analysis were determined after the dynamic characteristics of the structure, (frequency and significance of modes) were known. A detailed study of these results is beyond the scope of this paper. Reference 10 gives additional detail relative to the stress and load results and Reference 11 proposes a new method of combining modal responses which will more accurately account for high frequency ("rigid") modes in the analysis.

Table IV. Comparison of Anchor Bolt Loads

SOURCE	LOAD	RESULTS (lbf)	% ERROR
Dynamic analysis using finite element model	Lat & Vert	16,417	+18.96
	Long & Vert	4,198	-49.56
Static analysis using rigid anchor plate technique	Lat & Vert	13,257	-3.93
	Long & Vert	8,375	+0.38
Static analysis using pseudo-flexible behavior technique	Lat & Vert	13,914	+0.83
	Long & Vert	9,013	+8.26
Test Results	Lat & Vert	13,800	---
	Long & Vert	8,325	---

VI. Conclusions and Precautions

Conclusions resulting from this engineering design and test program can be summarized as follows:

1. The E-4 and NBC-4 housings and filters, as modified based on a structural dynamics analysis, will perform their safety related function for seismic levels up to those given in Figure 7.

2. Separator type HEPA filters do have the potential for puncturing the media when used in a high vibration environment.

3. Analysis, when properly performed, is more conservative than test, if the dynamic analysis adequately describes the response of the equipment to base acceleration in all directions. Equipment which cannot be qualified by analysis, due to prediction of stresses which exceed yield, can be qualified by test. Even though predicted yielding does occur during the test, the equipment will be qualified and delivered to a nuclear generating station for installation and use.

4. Analysis of complex systems, using complex finite element models for structural dynamics, should utilize some means to experimentally verify the dynamic behavior predictions.

This qualification program proved the seismic withstand capability of a HEPA filter housing that is used throughout the Nuclear Industry with filters installed and operating during the seismic test. It should be noted that this qualification program did not account for any external loads applied to this housing, such as loads generated by connected duct or other housings. Implicit in this approach is the assumption that this housing will not impart significant loads into its attached structure and also that the attached structure is adequately designed to stand alone during the seismic occurrence and thus will not impart significant loads into the filter housing. This approach is consistent with the current industry approach for this type of HVAC systems. This technique is valid for seismically rigid systems, i.e. systems whose dynamic behavior does not amplify, or magnify, the floor input motions. For systems which are "seismically flexible", this assumption is somewhat less acceptable since there can be significant interaction between components in non-rigid systems. In cases where this is true, it is generally assumed that when two non-rigid systems, which individually are designed to withstand the seismic occurrence, are attached together (by welding, bolting, or other means), the resulting structure has a higher overall "section modulus" and is thus able to withstand higher loads as a composite structure than either of the individual structures will withstand alone. It is the opinion of the authors that more study is desirable in this area for HVAC systems.

APPENDIX I -REFERENCES

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DISCUSSION

ANON.: I noticed your work was done in conjunction with Flanders. We purchased a large number of the earliest E-2 housings. Based on your work, will you be willing to work with us to determine whether there are any changes necessary to those E-2 housings? We are in the process of installing them now.

YOW: Yes, we will. We have also looked at the earliest E-2 housings and found that they are good for certain seismic levels. It depends on the particular housing configuration, of course.