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ARGONNE FUEL CYCLE FACILITY VENTILATION SYSTEM--MODELING AND RESULTS*

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Abstract - This paper describes an integrated study of the Argonne-West Fuel Cycle Facility (FCF) interconnected ventilation systems during various operations. Analyses and test results include first a nominal condition reflecting balanced pressures and flows followed by several infrequent and off-normal scenarios. This effort is the first study of the FCF ventilation systems as an integrated network wherein the hydraulic effects of all major air systems have been analyzed and tested.

The FCF building consists of many interconnected regions in which nuclear fuel is handled, transported and reprocessed. The ventilation systems comprise a large number of ducts, fans, dampers, and filters which together must provide clean, properly conditioned air to the worker occupied spaces of the facility while preventing the spread of airborne radioactive materials to clean areas or the atmosphere. This objective is achieved by keeping the FCF building at a partial vacuum in which the contaminated areas are kept at lower pressures than the other worker occupied spaces. The ventilation systems of FCF and the EBR-II reactor are analyzed as an integrated totality, as demonstrated in Fig. 1. We then developed the network model shown in Fig. 2 for the TORAC code.[1]

The scope of this study was to assess the measured results from the acceptance/flow balancing testing and to predict the effects of power failures, hatch and door openings, single-failure faulted conditions, EBR-II isolation, and other infrequent operations. The studies show that the FCF ventilation systems are very controllable and remain stable following off-normal events. In addition, the FCF ventilation system complex is essentially immune to reverse flows and spread of contamination to clean areas during normal and off-normal operation.

1. Introduction

The Fuel Cycle Facility (FCF),located at Argonne-West, consists of five principal interconnected ventilation systems including two in which nuclear fuel is handled and processed. These two systems include the Air Cell Exhaust System (ACES) and the Safety Exhaust System (SES) for the argon cell. The remaining systems include the Building Supply Air System (BSA), the Building Exhaust System (BES), and the Stack Exhaust System (STES). In addition to the argon cell, these systems consist of a large number of rooms, doors, hatches, ducts, fans, dampers, and filters which together must provide clean, properly conditioned air to the worker occupied spaces of the facility. These systems must also prevent the internal spread of airborne radioactive materials to clean areas or to the external atmosphere. These objectives, which must be met at all times including upset conditions, are achieved in part by keeping the FCF below atmospheric pressure such that the contaminated areas are kept at lower pressures than the cleaner, worker occupied spaces. In addition, the general design objective is for air to be transported from relatively cleaner to relatively more contaminated areas, in particular for the ACES and BES systems. This causes the most contaminated spaces, in general, to have the lowest pressures in the facility.

The ventilation systems of FCF and EBR-II are analyzed as an integrated totality, as demonstrated in Figs. 1 and 2, since these two facilities have their effluents joined at the STES inlet. Some of the infrequent/abnormal cases were included to assess the mutual impact of FCF and EBR-II on each other. Note that EBR-II ventilation should itself be considered as two closely joined systems, i.e., the reactor building proper plus the Cover Gas Cleanup System (CGCS). The TORAC code [1] models the effects of the relatively high head EBR-II fans and the very low head CGCS fans as well as isolation events for EBR-II.

2. Development of the Ventilation System Model

A major purpose of the modeling effort is to calculate spatial pressures and pathway flowrates at various locations through the FCF during normal and off-normal conditions. The schematic given in Fig. 1 shows the basic flow distribution of air and argon throughout the facility which indicates that supply air is admitted to both the main floor and basement, which for the most part, is transferred to the main (first) floor in three different areas. Note that air is also supplied via infiltration through door/window leaks and small wall cracks which bypass the BSA fan.

Flow Network Model for FCF

Other than the argon cell exhausted by the SES, the most heavily contaminated air is handled by the Air Cell Exhaust System (ACES) which involves the air cell, decontamination systems, the air cell to argon cell transfer tunnel, and the suited entry repair area. The cleanest air in the facility is handled by the BES which transports air through large spaces in the basement as well as the main floor. Exhaust from the ACES and BES join via piping just before entering the STES where EBR-II/CGCS effluent also joins. Note that the SES exhaust enters the STES downstream from the stack fans near the base of the 200 ft. stack.

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From the above basic flow diagram and requirements for nodal detail, we made a flow network representation of the above ventilation systems as shown in Fig. 2. The basic approach, which was designed to be consistent with the available analytical codes, is to have branches that join each other at nodes. By definition, each branch must contain either a fan or a hydraulic resistance and each node is either a boundary node or an internal volume node. Note that boundary nodes contain no volume and are usually simulated at atmospheric pressure where infiltration air enters or leaves the facility. The internal nodes, however, always contain volume and together include all the volume and mass within the FCF building. The basic assumptions made in the TORAC analysis, in general, can be grouped into those associated with gas dynamics, pressure loss characteristics and approximations in the detail of the hydraulic network model. Some rooms are lumped into larger regions even though these spaces may not be at truly equal pressure and may have multiple inlet/outlet flow paths. An effort was made, however, to define transfer air paths and ducted paths separately since they can have different flow characteristics. Note that transfer air paths typically include doorways and hallways but ducted paths can include fans, filters, dampers, ducts and junctions. The TORAC code can distinguish between filters having different characteristics such as HEPA filters, pre-filters, and charcoal filters. In addition, the individual ΔP vs. flow equation for filters can be adjusted to approximate the effects of being highly loaded and/or operating at very high flows.

We chose to simulate all of the branches at boundary nodes by a damper resistance and (except for nodes 44 and 54) have them represent infiltration points at atmospheric pressure. Node 44 is a simplified representation of the air inlet and fans for the FCF roof corridor. Node 54 represents the inlets and fans for the safety equipment building containing SES equipment. Note also that some flow to the roof corridor bypasses the exit cell in going to the pair of fans downstream from the cell. As described below, node 1 is the boundary node for supply air to FCF and nodes 47 and 64 represent atmospheric air inlet points to the EBR-II and CGCS, respectively.

Safety Exhaust System

The argon cell itself is not represented in the model since flow from this cell to the stack occurs only during an abnormal event involving the argon cell and/or the SES. The SES actually consists of two "trains", each of which has an argon branch (which normally does not operate) and an air branch (which always operates). In the plant, one of the trains is designated the active train and the other is thus the standby train. In the TORAC model, only the air branch of the SES is simulated and it is represented by two dampers and a fan connected in series. This branch connects the subcells and cubicles (containing air and located adjacent to the argon cell) and transports the effluent directly to a point just upstream of the stack base. The simulation of all of the branch resistance by two dampers is a good approximation because of the high hydraulic resistance in the system. Thus, the effect of the pressure drop of the two HEPA filter banks in the branch is small compared with the remaining losses. All HEPA filters in this study are assumed to have a linear pressure drop vs. flow characteristic, while a flow squared dependence is assumed for all dampers, valves, orifices, ducts and infiltration paths.

Some TORAC cases have been run that simulate both the SES air and argon branches in operation. This condition was approximated by "converting" the argon to air (by similarity laws) and increasing the total air flow through the SES dampers and fan. For a more sophisticated treatment of the SES and argon cell operation, other ANL-IL models were developed specifically to analyze the argon cell transient pressure/temperature behavior and fire dynamics, respectively.

EBR-II Reactor Building and CGCS Ventilation Systems

We included enough detail of the EBR-II ventilation systems to model the effects of FCF disturbances on EBR-II/CGCS and vice versa. The EBR-II reactor (containment) building has an air supply system which feeds two parallel cooling systems, one for the reactor shielding and the other for the instrument thimbles containing ion chambers (for measuring neutron flux). During normal operation, this air is combined and flows out of containment, passing through HEPA filters and isolation valves. Next it joins the CGCS effluent on its way to the STES fan inlet plenum. The CGCS radiation monitoring is done in the CGCS building attached to the reactor building.

3. The TORAC Code

The TORAC code employs the same node and branch flow network structure that is common to most HVAC network codes. The code is designed to predict airflows in an arbitrarily connected network that may include process cells, high bays, corridors, laboratory offices, canyons, truck locks and offgas systems. Thus, the code simulates the movement of air into, through, and out of the facility. The hydraulic network can contain components such as ducts, filters, dampers, rooms, blowers, and infiltration paths.

The code uses the lumped-parameter approach and no direct effect of spatial distribution of parameters is considered. All ventilation system components that exhibit resistance, such as dampers, filters, and blowers, are located within the branches (which join the nodes) of the network. These internal nodes all contain volume as opposed to the external boundary nodes which do not. The pressure drop characteristics of most components must vary with flow squared except for filters, infiltration paths[2] and blowers which can be different. The continuity equation must be satisfied at every node along with a pressure flow relationship for every branch. In addition, the equation of state for a perfect gas must be satisfied for each volume node.

The code also has the capability to analyze material transport with a basic model that includes convection, depletion, entrainment, and filtration of the material. Material transport effects and tornado disturbances, however, were not included in the current study. Note also that TORAC does not treat thermal effects; thus buoyancy driven flows due to temperature and elevation variations are excluded. Although the code can simulate a process in the steady-state or transient domain, most of our studies to date were solved in steady-state since only equilibrium test data were available. One very useful feature of TORAC is that it calculates resistance coefficients which can be used directly as inputs for future runs--when nodal pressures and branch flow rates are specified as input initial conditions. Note also that branches can be closed, component resistances can be changed, and fans can coast down (or start up) during a transient. Simulating branch loss changes is most easily done via damper resistance changes; thus such branches should include dampers in their paths.

The TORAC source code was obtained from the Software Center and was installed at ANL-IL in 1991. We later converted the IBM mainframe version of the code to the SUN System (of the ANL Reactor Analysis Division) in 1992.

4. Method of Analysis

The flow network model, shown in Figs. 2-5, has inscribed values of nominal pressures and flows at the nodes and branches, respectively. Although these values were derived from acceptance test/flow balancing data, measurements were not directly available for all 64 nodes and 85 branches--but instead for only 16 internal nodes and 25 branches. Thus, the nominal values for the remainder of the network were obtained using fundamental principles such as mass balances in order to make hydraulic loss estimates from the basic set of measured pressures and flows. Because TORAC does not perform an engineering analysis from physical data such as duct dimensions, valve coefficients or filter properties, the above set of node and pressure data becomes the basic input to establish the initial conditions for transient analyses. Note that the flow (CFM) is given for each branch, and the pressure (in. w.g.) is given (in italics, with decimal point) for each node.

Head vs. flow data were required for the nine fans in the network (5 in FCF and 4 in EBR-II/CGCS). Since data for normal fan operation were available for only the BES and SES fans, the remaining head curves had to be estimated from similarity laws knowing only the design operating points for these fans. All fans operate at constant speed, except for startup/coastdown conditions, and most of them have attached inlet vanes (IV) for automatic flow control. Although the effect of variable IV can be modeled by TORAC, in this study we held them at constant settings (usually 100% open or full closed). For off-normal fan operation, we needed unpowered fan characteristics for forward and reverse flows, for both stationary and free-spinning fan blades. This information is difficult to obtain and we had direct measurements for these conditions for only the BES fans. The unpowered data for the remaining fans were then estimated from the BES data using similarity laws and taking into account each fan's operating characteristic.

All pressures shown are relative to the local atmospheric pressure at the INEL site (338 in. w.g.), and all nodes are taken to be effectively at the same elevation because isothermal conditions are assumed. Thus all pressures are shown as differentials relative to atmosphere.

5. Results of TORAC Analyses

General

The TORAC hydraulic network model is the only tool utilized at ANL thus far for analyzing complex interconnected ventilation systems. Besides our validation studies with measured FCF data, earlier TORAC simulations have been validated elsewhere for other facilities.[1] The data obtained from flow balancing and infrequent operations testing indicated that the main floor pressures and infiltrations were higher than expected, while most of the pressures in the basement and ACES spaces were lower than expected. Although not all cases studied can be included in this paper, our complete study did include the following aspects:

- o Parametric variations about the normal operating state
- o Infrequent/abnormal operation
- o Local and overall electric power failures
- o Single failures of active components
- o Unlikely stack exhaust system failures
- o EBR-II isolation

Normal Operation--With and Without the Supply Fan

After the TORAC model was "calibrated" to the nominal operating pressures and flows, another (near normal) condition was simulated in which the BSA fan was turned off and no other system changes were made. The TORAC results for the BSA fan turned off are given in Fig. 3 which shows, by comparison with Fig. 2, the supply fan to have a very small effect on the total FCF flow and its distribution, but a large effect on the building infiltration flowrates. It is important to note that no infiltration rates were directly measured--they are deduced from internal flow balances made from test data. As shown in both Figs. 2 and 3, the main floor pressure differentials for the BSA fan on or off remain very small. They range from -.005/-.008 in. w.g. below atmosphere (BSA fan on) to -.024/-.025 in. w.g. (fan off), as noted in the main floor nodes 5, 27 and 38 shown in Figs. 2 and 3. Noting the increases in the infiltration rates (see flows in branches 53, 54 and 55), we observe that the infiltration path resistances must also be small.

With the BSA fan turned off, the total infiltration increases by about 97% which is reflected in the main floor pressure changes and in the decreased BSA flow (through the free-spinning supply fan)--a predicted decrease of about 95%. The assessment of this operating condition showed that the FCF design requirements of pressure and flow distribution were still met and, in addition, provided valuable data for additional TORAC code validation.

Operation with Failure of One BES Fan

FCF operation with one BES fan failed is infrequent but still regarded as allowable in terms of maintaining acceptable pressures and flows throughout the building. In this event, the isolation damper of the failed fan branch is closed, and the BSA fan is interlocked to trip out upon a low BES fan flow. Note that the IV control for the operating BES fan would attempt to maintain total BES flow and thus open its IV to maximum. In addition, the STES IV control would attempt to do likewise to maintain the stack flow; however, the TORAC study did not include these control effects. The results given in Fig. 4 show that the FCF pressures and flows of primary concern are not strongly affected by the failure of one BES fan. The total BES flow would decrease by no more than 35% and the STES flow by no more than 14%, while the total ACES flow is predicted to increase by about 7% due to compensating changes in system pressures.

TORAC does predict flow reversals in two main floor branches, namely 25 and 27. The consequences of these reversals are not serious, however, since they involve supply air flowing in ducted paths between clean areas. Note that the pressures mainly affected by this event, as expected, are basically associated with the BES, such as nodes 6-9, 12, 13, and 39.

Operation with Failure of One ACES Fan

FCF operation with one ACES fan failed is also infrequent and regarded as allowable because acceptable pressures and flows are maintained throughout the building. In this event, the isolation damper of the failed fan branch is again closed, and the BSA fan is interlocked to trip out upon a low ACES fan flow. Note that the IV control for the operating ACES fan would attempt to maintain total ACES flow and thus open its IV to maximum. The STES IV would again attempt to go full open to maintain stack flow. Since the TORAC study did not include these control effects, all changes in pressures and flows will again tend to be overpredicted. The results given in Fig. 5 show that the pressures of primary concern are not significantly affected by the failure of one ACES fan. The total ACES flow would decrease by no more than 36% and the STES flow by no more than 8%, while the total BES flow is predicted to increase by about 8% due to system pressure changes.

TORAC again predicts benign flow reversals in the main floor branches 25 and 27. Note that the pressures mainly affected by this event, as expected, are associated with the ACES such as nodes 21, 23, 28-33, and 52.

6. Conclusions

Upon completion of this study, we conclude that the effects of hydraulic disturbances to the interconnected ventilation systems do not severely challenge the FCF. The results reported herein show that the ventilation systems are very controllable and remain stable following off-normal events. In addition, the FCF ventilation system complex is essentially immune to reverse flows, negative infiltration, and spread of contamination to clean areas during normal and off-normal operation. Compared to normal conditions with all fans operating, the acceptance/infrequent operational testing and TORAC analyses showed that the ventilation systems have a high tolerance for a major fan being out of service. The examples studied include a failure of the building supply fan considered separately; and failure of one of the air cell exhaust fans, and one of the building exhaust fans--each interlocked to trip out the supply fan. These results indicate that the facility can continue to operate under these abnormal conditions and still provide acceptable pressures and flows throughout the building.

The comparison of the TORAC code predictions with measured results of many aspects of upset scenarios indicated good agreement. The code was judged to be a satisfactory tool for analyzing various FCF operating conditions with the simulated hydraulic network that includes both FCF and EBR-II/CGCS.

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2. D. E. Hintenlang and K. K. Al-Ahmady, "Influence of Ventilation Strategies on Indoor Radon Concentrations Based on a Semi-empirical Model for Florida-Style Houses," Health Physics, Vol. 66, No. 4, April 1994 (Eq. 1).

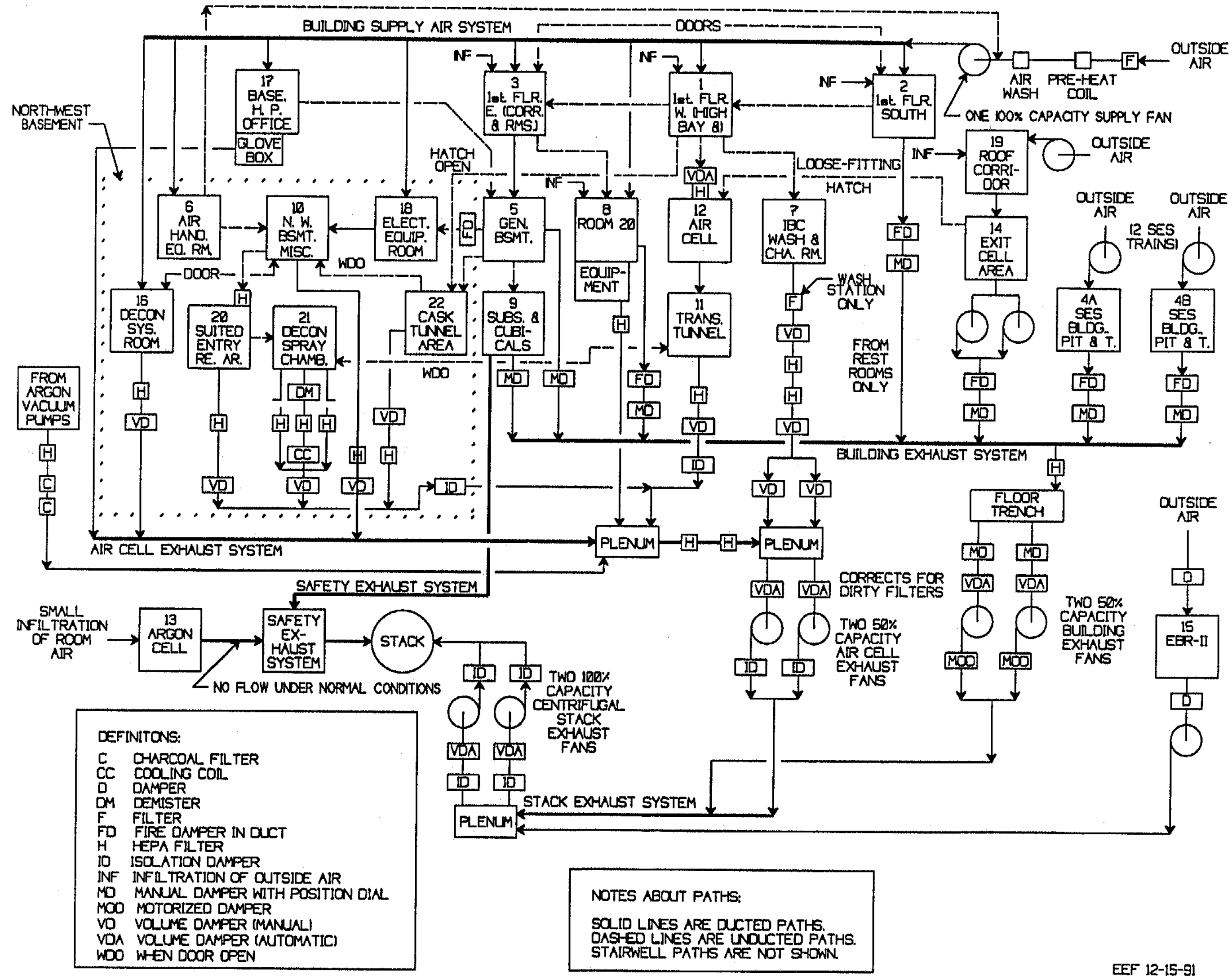

Figure 1. FCF Air/Argon Flow Distribution Diagram

TORAC ANALYSIS MODEL
FOR FCF VENTILATION SYSTEMS
(VERSION 7/94)

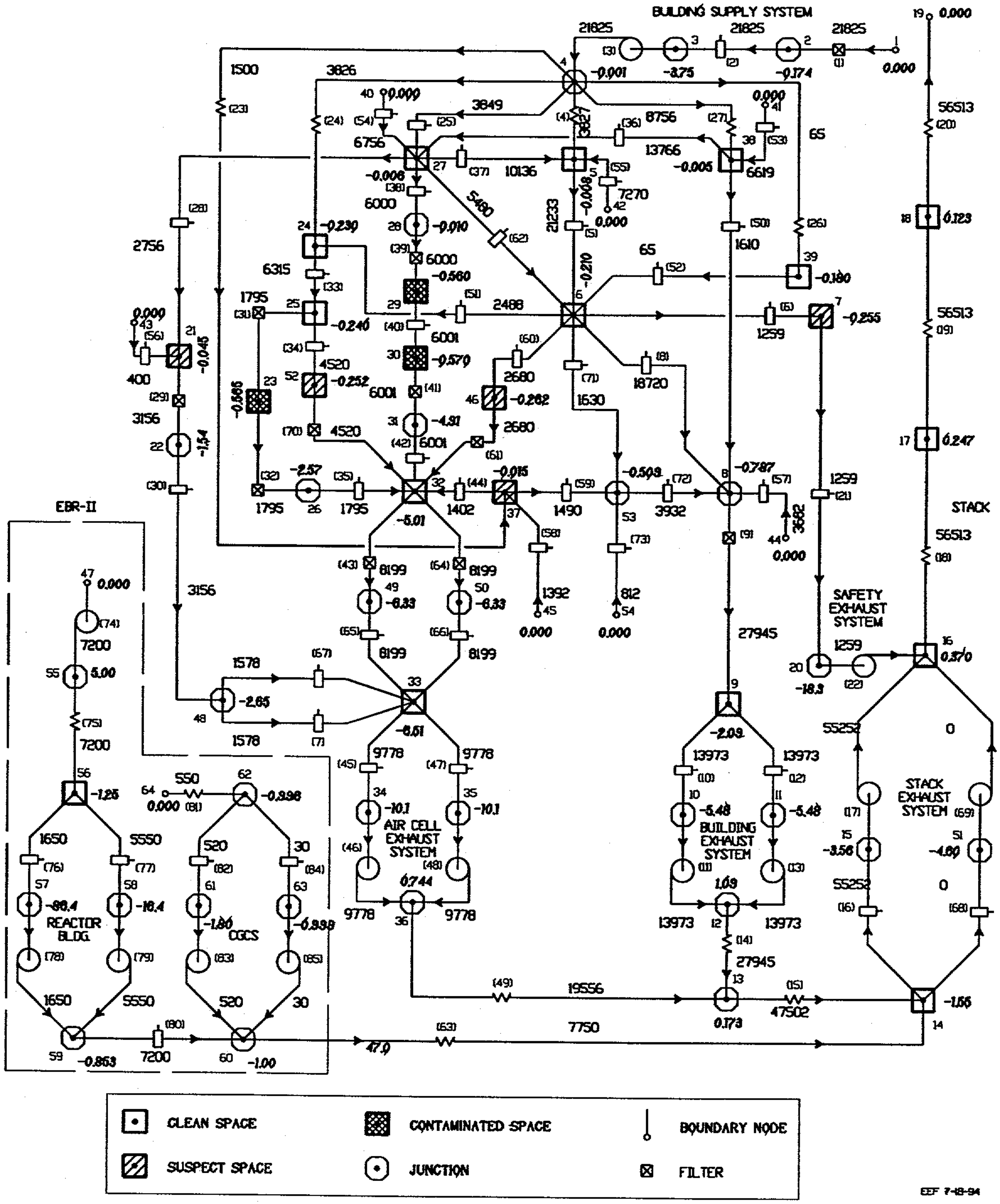

Figure 2. Normal Operation

TORAC ANALYSIS MODEL
FOR FCF VENTILATION SYSTEMS
(VERSION 7/94)

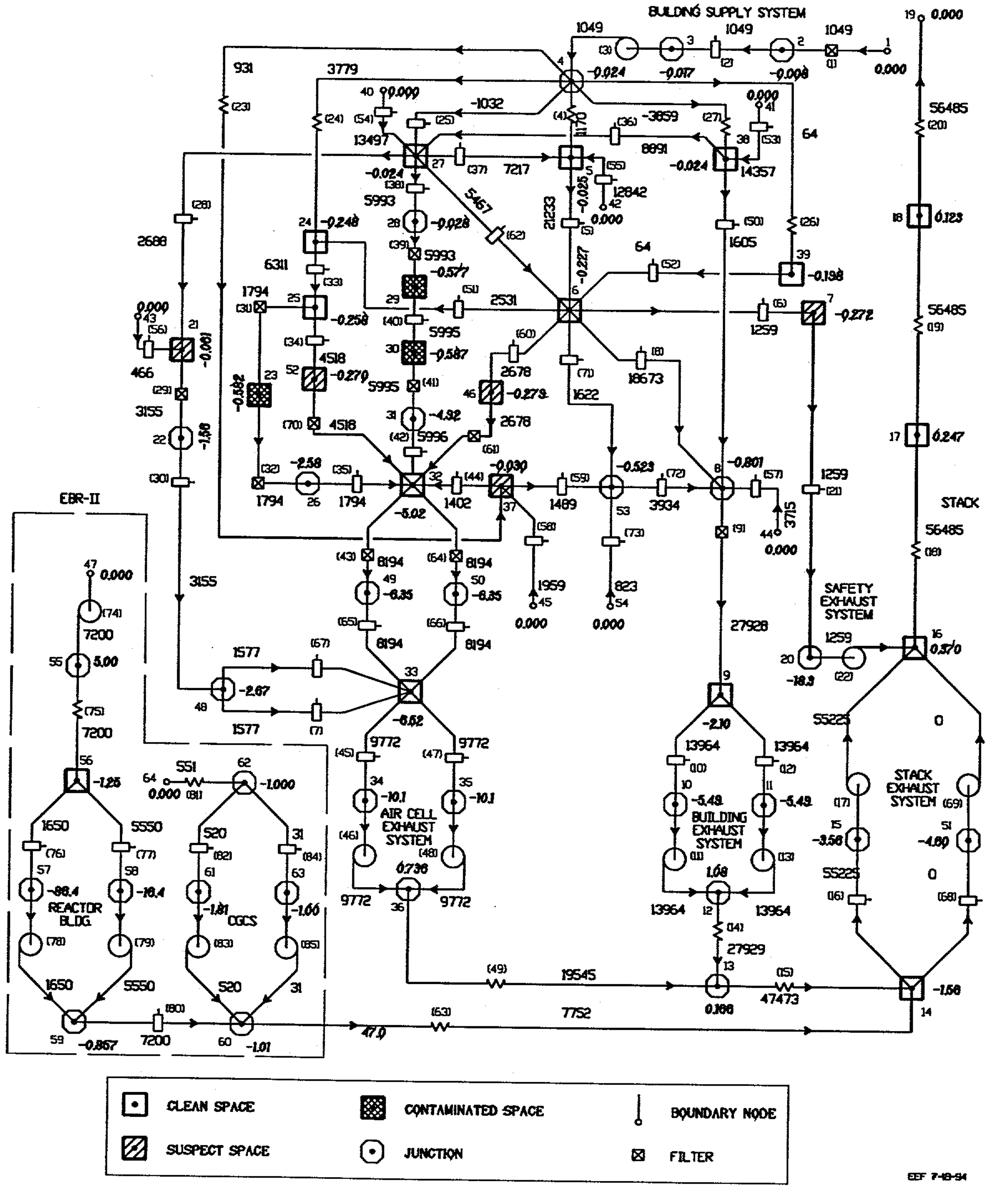

Figure 3. Normal Operation Except Supply Fan Off

TORAC ANALYSIS MODEL
FOR FCF VENTILATION SYSTEMS
(VERSION 7/94)

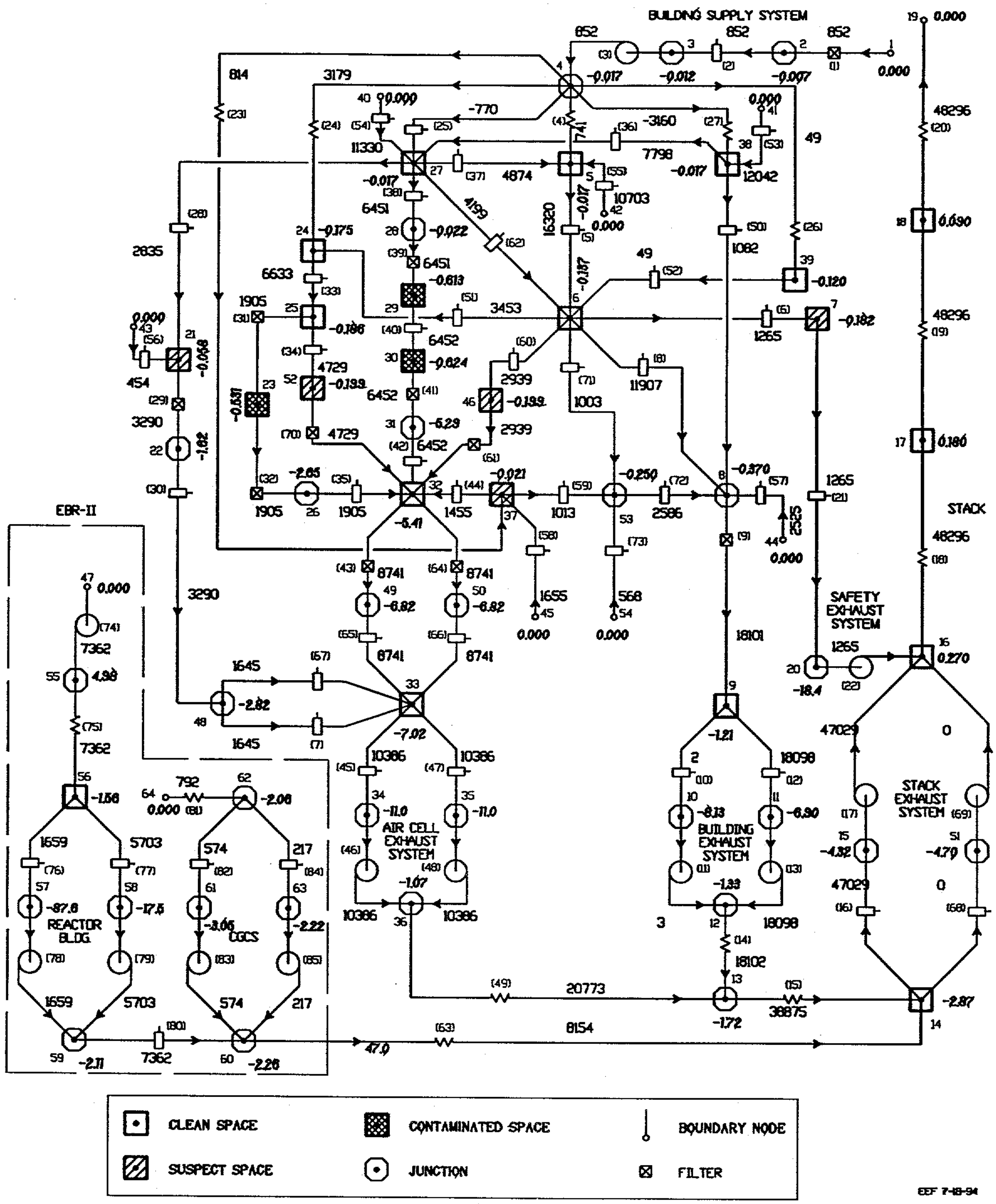

Figure 4. One BES Fan Off and Supply Fan Off

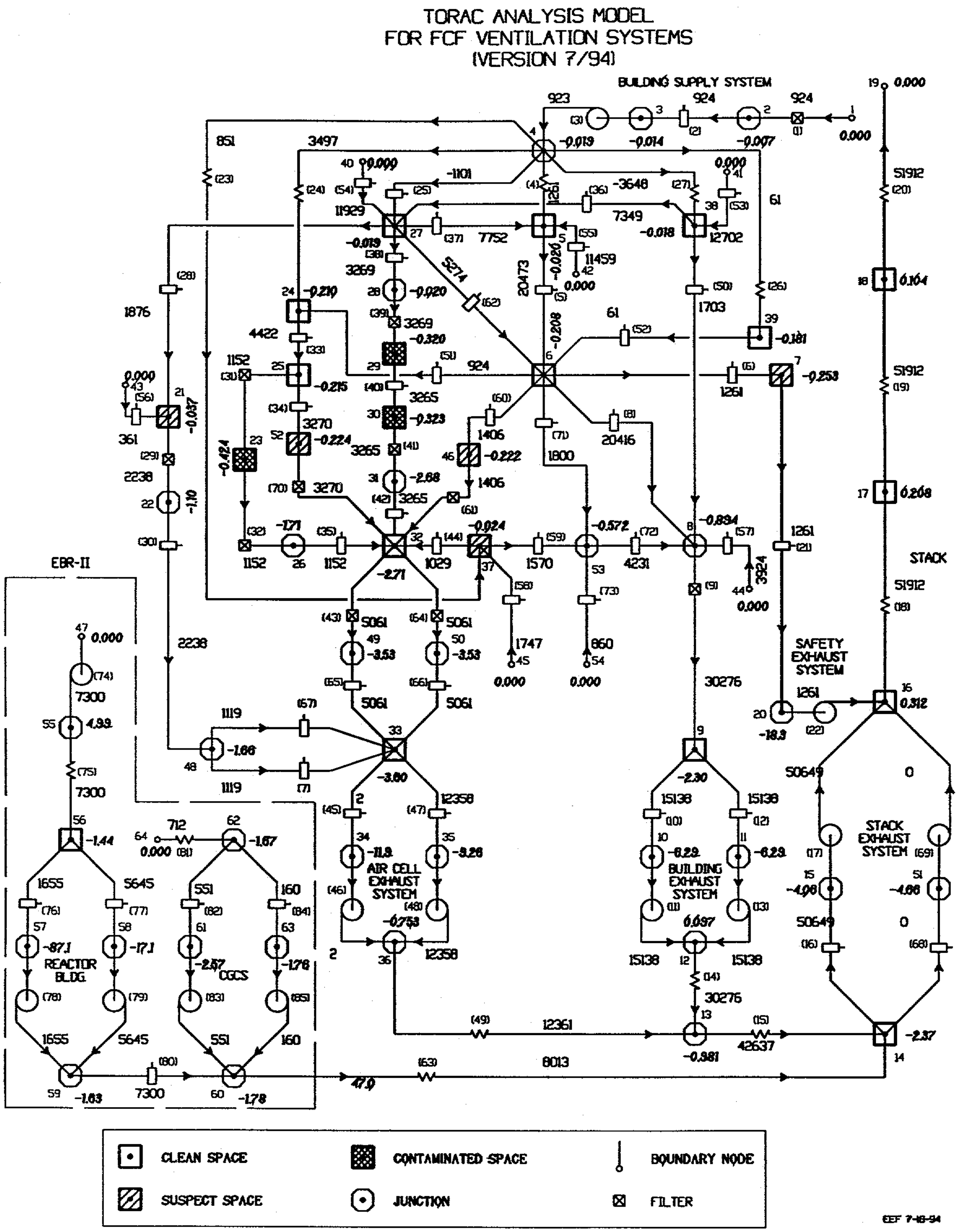

Figure 5. One ACES Fan OFF and Supply Fan OFF