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Development and Analysis of Vent-Filtered Containment Conceptual Designs

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ABSTRACT

Conceptual filtered-vented containment systems have been postulated for a reference large, dry, pressurized water reactor containment, and the systems have been analyzed to determine design parameters, actuation/operation requirements, and overall feasibility. The primary design challenge has been found to emanate from pressure spikes caused by core debris bed interactions with water and by hydrogen deflagrations. Circumvention of the pressure spikes may require a more complicated actuation logic than has previously been considered. Otherwise, major reductions in consequences for certain severe accidents appear to be possible with relatively simple systems. A probabilistic assessment of competing risks remains to be performed.

INTRODUCTION

The use of containment venting systems has been suggested by many as a means for significantly mitigating the risks from core melt accidents. Recently, the potential benefits of filtered-vented containment systems have been cited by such diverse groups as the California Energy Commission,[1] the Advisory Committee on Reactor Safeguards,[2] the TMI Lessons Learned Task Force,[3] the Rogovin Inquiry Group on Three Mile Island,[4] and the Swedish Government Committee on Nuclear Reactor Safety.[5]

In April 1979, a program was initiated at Sandia National Laboratories under contract with the U. S. Nuclear Regulatory Commission to investigate filtered-vented containment concepts for light water reactors. The program has the following objectives:

1. Development of conceptual designs of vent-filter systems which have the potential to mitigate the effects of accidents (particularly core melt accidents) that are beyond the current design basis.
2. Determination of the potential reduction in radioactive releases for core-melt accidents and the resultant reduction in overall risks.
3. Determination of the effect of the vent-filter on non-core-melt accidents and on normal operations.
4. Specification of system performance and safety design requirements for vent-filter systems.
5. Quantitative analysis of values versus impacts.

ATTACHMENT 5

The study considers several types of containment (i.e., large dry PWR, ice condenser PWR, Mark I BWR, and Mark III BWR) and includes both existing and new plants. A program schedule is presented in Figure 1.

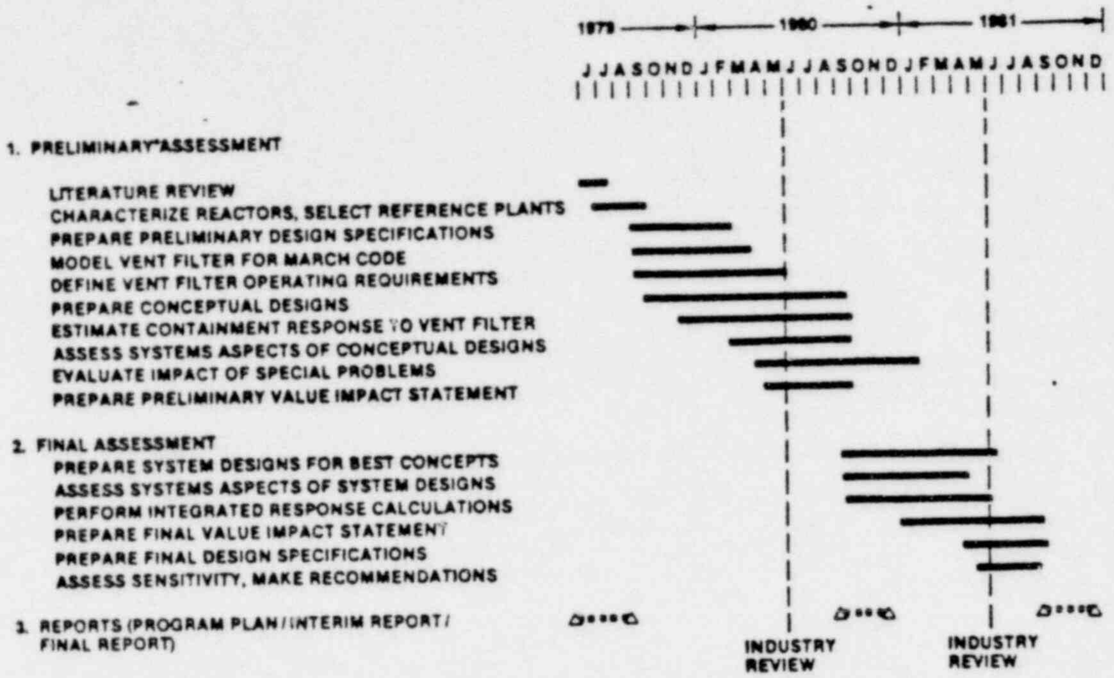


Figure 1. Program Schedule.

The risk reduction potential of vent-filter systems derives from their dual function of venting containment to prevent overpressurization from the generation of steam and noncondensibles and of filtering the effluent to limit the release of radioactive materials. In theory, post-accident filtration systems can reduce the risk from nuclear reactor accidents significantly; in practice, there are many engineering, technical, economic, and licensing questions to be answered before judgments on feasibility and effectiveness can be made. These questions include the capacity of the system to handle large pressure surges, possible interference with other engineered safety features, possible exacerbation of low-consequence accidents into high-consequence accidents, possible increase of hydrogen explosion potential, impact of uncertainties in various phenomenological and cost evaluation areas, and difficulties in reconciling vent-filter systems with the current regulatory position requiring essentially leaktight containment. These and other issues are discussed in the Sandia program plan for filtered-vented containment studies.[6]

The purpose of this paper is to provide a status report of the studies performed since the program plan was completed in October 1979, and to indicate the directions in which studies are progressing. Most of the analyses performed to date correspond to a reference large, dry, pressurized water reactor (Westinghouse design 4-loop plant) chosen because of its proximity to a population center. The results provided below correspond to this reference PWR.

TECHNICAL ISSUES

Accidents that Challenge the System

In the Reactor Safety Study,[7] and in subsequent studies based on the RSS methodology, a small number of accident sequences were found to dominate the overall risk for each reactor. For the large, dry PWR analyzed in the RSS, the dominating sequences were found to be TMLB' (i.e., loss of all AC power leading to failure of secondary heat removal), S_2C (i.e., a small LOCA with loss of containment sprays leading to loss of containment heat removal), and V (i.e., failure of the LPIS check valve leading to a LOCA outside containment).

In the present study, it has been considered important for the initial stages to consider not only those accidents which are thought to dominate the risk but also those which might provide the greatest challenge to a vent-filter system. For the reference PWR considered in the present study, the accident scenarios listed in Table I were judged to provide a reasonably complete bounding of accidents that both dominate the risk and challenge the vent-filter system.

Table I. Accident Scenarios Considered for Reference PWR Designs.

Accident Symbology	Accident Sequence	Limiting Characteristics
TMLB'	Loss of offsite and onsite AC power for 16 hours, resulting in loss of secondary heat removal, followed by the return of AC power and restart of the containment coolers.	Maximum pressure following reactor vessel failure (about 120 psia).
AB-Burn	Large LOCA plus loss of offsite and onsite AC power for 16 hours, followed by the return of AC power and restart of the containment coolers. The hydrogen ignites when the molten core drops into the cavity.	Shortest time for generation of a pressure exceeding containment design pressure (about 50 minutes).
S_2D-Burn	Small LOCA plus loss of ECCS injection capability, resulting in the loss of ECCS recirculation and containment spray recirculation capability. The hydrogen ignites when the molten core drops into the cavity.	Maximum potential pressure spike following reactor vessel failure (amount not yet established).
S_2C	Small LOCA plus loss of heat sink for containment coolers and containment sprays. This accident results in containment overpressurization before meltdown.	Maximum steam production (about 4×10^6 lbm).
TMLB"	Same as TMLB', except AC power returns after about 6 hours, leading to restart of contaiment coolers, containment sprays, and ECCS injection.	Most potential for system interactions during core-melt accident.
A-Vent	Large LOCA causing premature actuation of containment venting. All engineered safety features are assumed to operate on demand.	Potential for exacerbation of non-core-melt accident.

Pressure Spikes

A noteworthy feature of many of the accident scenarios that result in core meltdown is the occurrence of a sizable containment pressure spike at or near the time of reactor vessel failure (see, for example, Figure 2). The causes of the spike vary from case to case, but combinations of the following phenomena are generally responsible:

1. Steam release from the primary system to the containment when the reactor vessel fails at high pressure. (Accidents initiated by transients and small LOCA's, about 13 psi for reference PWR.)

2. Rapid steam formation caused by molten core interaction with water existing in the cavity at the time of reactor vessel failure. (Magnitude dependent on accident and amount of communication between sump and cavity.)

3. Rapid steam formation caused by flashing of some of the residual water in the primary loops when the reactor vessel fails, and by dumping of the remainder of this residual water onto the molten core in the cavity. (Accidents initiated by transients and small LOCA's, about 16 psi for reference PWR.)

4. Rapid steam formation caused by discharge of accumulator water at the time of reactor vessel failure and interaction of this water with the molten core in the cavity. (Accidents initiated by transients and small LOCA's, about 34 psi for reference PWR.)

5. Deflagration of the hydrogen produced by Zircaloy-steam reaction, triggered by the interaction of the molten core with the concrete in the cavity. (Accidents resulting in a flammable mixture, about 60 psi for reference PWR.)

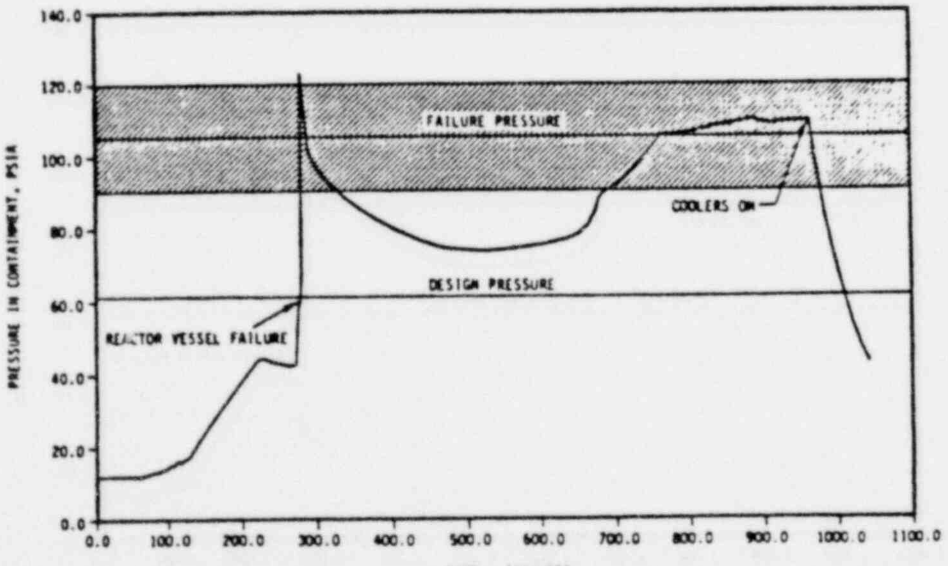


Figure 2. MARCH Code Calculation of Containment Pressure Versus Time for the TMLB' Accident in the Reference PWR.

The pressure spike in Figure 2 was the cumulative result of Items 1, 3, and 4, above.

The interactions of the core materials with water in the reactor cavity pose a particular concern. The rate of the interaction depends upon a number of difficult phenomenological questions, such as the size of the vessel rupture, the rate of dropping of the molten core into the reactor cavity, the degree of core fragmentation in the cavity and the resulting debris geometry, the possibility of steam explosions, and the question of whether the debris dries out and remelts or remains coolable. Since the data are inconclusive in all of these areas, it was considered best at present to make the apparently conservative assumptions that the vessel rupture area is very large, that the dropping of the core is immediate, that complete fragmentation occurs without dispersal out of the cavity, and that the debris does not dry out prior to the boiloff of the water. With these assumptions, the duration of the pressure rise caused by core-water interactions is about 15 seconds, the time required for the accumulators to discharge in the absence of a back pressure.

System Interactions

There are several plausible scenarios in which adverse system interactions could be caused by the venting of containment. During accidents such as S_2G (Table I), a rapid venting of containment can cause the recirculation pumps to cavitate as a result of sump flashing, leading to core uncovering and meltdown. During TMLB", the restoration of sprays and coolers after venting can create a severe vacuum which could cause containment failure in compression. During A-Vent, the premature venting of containment might degrade the reflood operation by removing the back pressure. Avoidance of these adverse interactions requires either design solutions, such as the incorporation of vacuum breakers, or preventive administrative procedures, such as a temporary realignment of the recirculation pumps to an outside source or a revision of set points for coolers and sprays. Evaluation of these interactions and their possible solutions is not yet complete.

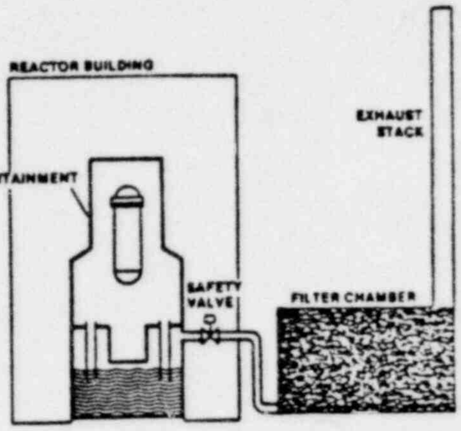
DESIGN POSSIBILITIES

Containment Vent Strategies for New Reactors

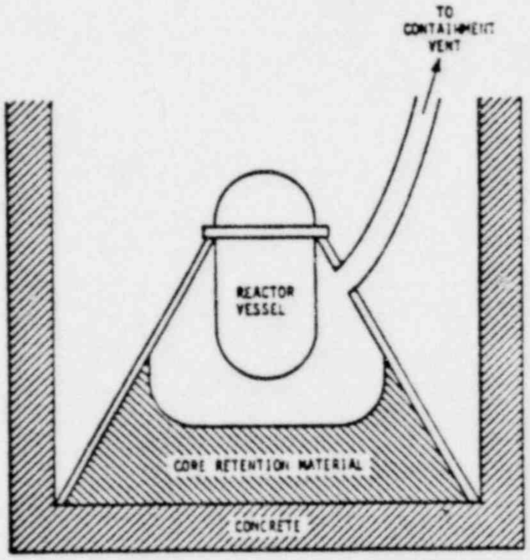
The primary challenge to a vent-filter system is its ability to mitigate the pressure spikes in containment. To accomplish this goal, it is much easier to formulate design concepts for new reactors (i.e., reactors that have not yet been built) than for reactors that already exist.

Three design possibilities for new reactors are shown in Figure 3. In one concept (Figure 3a), a large vapor suppression pool is placed within the containment to suppress a portion of the pressure spike as well as to remove the steam, cool the noncondensibles, and trap most of the particles and iodine. This design is similar to one suggested by the Swedish[5] for their boiling water reactors, except that the suppression pool is enlarged in order to accommodate steam generation during core melt accidents. Another design possibility being investigated is the use of a vented guard structure around the reactor vessel with core retention materials (Figure 3b). This concept diffuses and mitigates the containment pressure spike at the time of reactor

(a) Suppression Pool in Containment



(b) Reactor Vessel Guard Structure



(c) Vacuum Vent Building

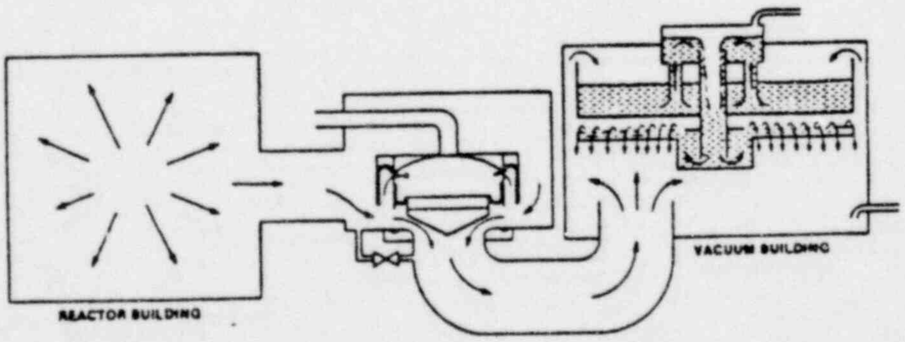


Figure 3. Schematics of Vent-Filter Design Concepts for New Reactors.

vessel failure by slowing the rate of primary system depressurization and accumulator discharge and by venting the primary system hydrogen before it mixes with the containment atmosphere. In another concept similar to that used in some Canadian reactors[8] for design basis accidents (Figure 3c), a large vent (on the order of 20 feet in diameter) may be used to connect the reactor containment to an evacuated vent building.

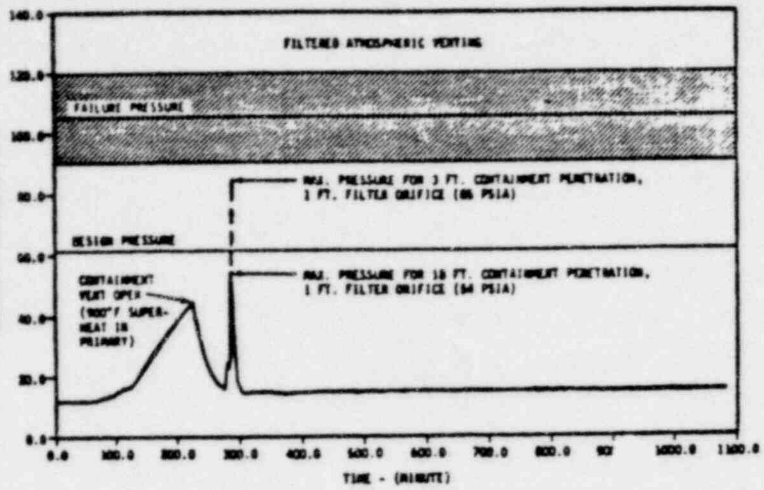
Containment Vent Strategies for Existing Reactors

The possibilities for retrofitting existing containments are limited by the fact that there is generally not room within containment for a large suppression pool or in the reactor cavity for a guard structure. Also, the creation of a large penetration in the containment boundary is prohibited for structural reasons. If it develops, therefore, that a rapid pressure spike does represent a serious threat to containment integrity (i.e., that it cannot be ruled out on phenomenological grounds), then one might consider several alternative strategies. One strategy might be to anticipate the reactor vessel failure and to initiate filtered atmospheric venting in advance. This strategy would reduce the containment pressure to a point where a sizable pressure spike could be accommodated without threatening the containment. A variation of this strategy for accidents initiated by transients or small LOCAs might include venting the primary system into the containment (or into the containment vent line) through existing primary system vent paths. Such an action allows the accumulators to discharge before the core melts down, which increases the chances for recovery and, if the reactor vessel still fails, reduces the magnitude of the steam spike. A different variation might include flooding the containment while the accident is progressing by gravity-induced flow from a large, elevated water tank. A million gallons of water in the bottom of the containment would offer a very large, passive heat sink that could function as an internal suppression pool. Still another vent strategy might be to use the existing equipment hatch to provide a large enough opening to vent a portion of the steam spike to a large external suppression pool or vacuum building. This strategy may be more costly to implement but is less likely to depend upon operator judgment.

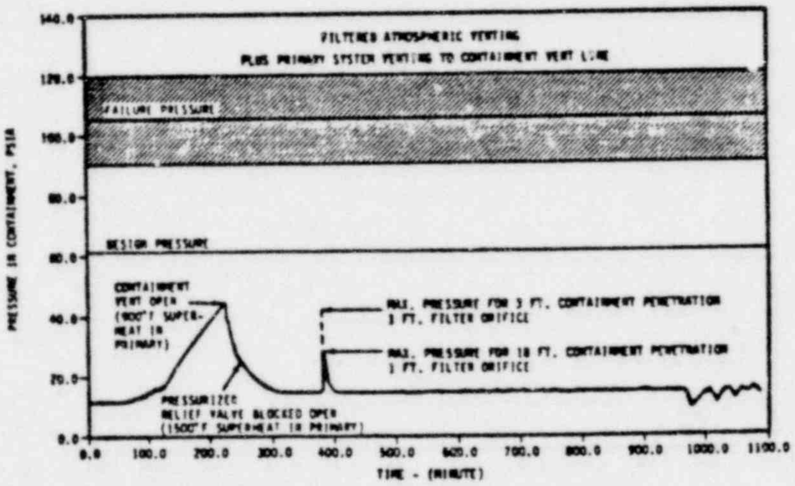
All of these strategies have implied risks, such as possible system interactions or human errors, that require a careful examination. When all the risks are evaluated, a simple vent strategy such as containment pressure relief at a setpoint above the design pressure, though perhaps less effective for the most severe accidents, may be more attractive overall.

The results of MARCH code[9] calculations of containment pressure and temperature response are shown for certain vent strategies in Figures 4 and 5. Figure 4 shows containment pressure histories for the TMLB' accident in the reference PWR for the following cases: (a) venting through filters to the atmosphere based on anticipation of reactor vessel failure, (b) venting through filters as in Case (a), but also with anticipatory primary system venting to the containment vent line via the pressurizer relief valve, and (c) venting from containment to a second building. Figure 5 shows the temperature of the containment atmosphere as a function of time for the various cases considered in Figure 2 (without venting) and Figure 4 (with venting). It may be observed that the utilization of containment venting lowers both the maximum containment pressure and the containment temperature.

(a) Filtered Atmospheric Venting



(b) Filtered Atmospheric Venting and Primary System Venting



(c) Venting to a Second Building

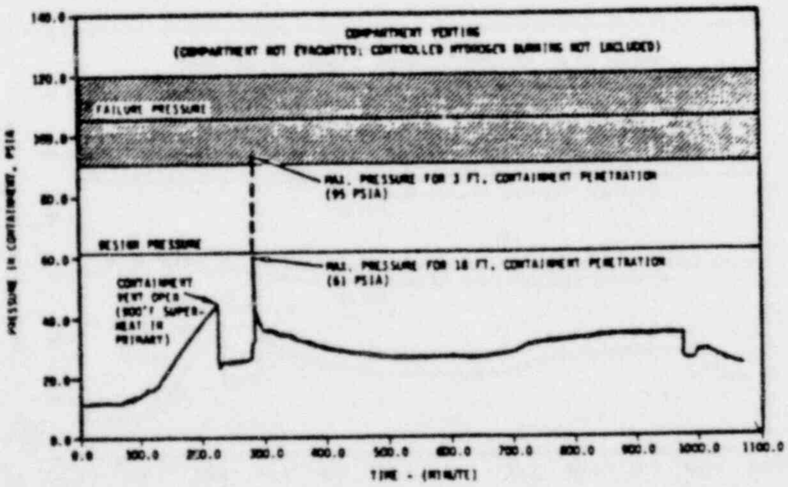


Figure 4. MARCH Code Calculations of Containment Pressure Versus Time for Various Venting Options During the TMLB' Accident in the Reference PWR.

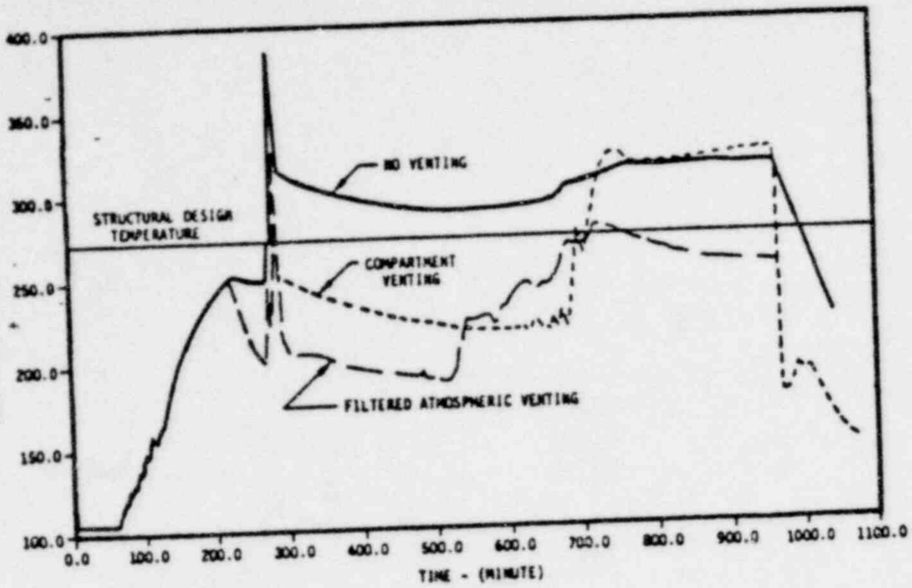


Figure 5. ARCH Code Calculations of Containment Atmospheric Temperature Versus Time for Various Venting Options During the TMLB' Accident in the Reference PWR.

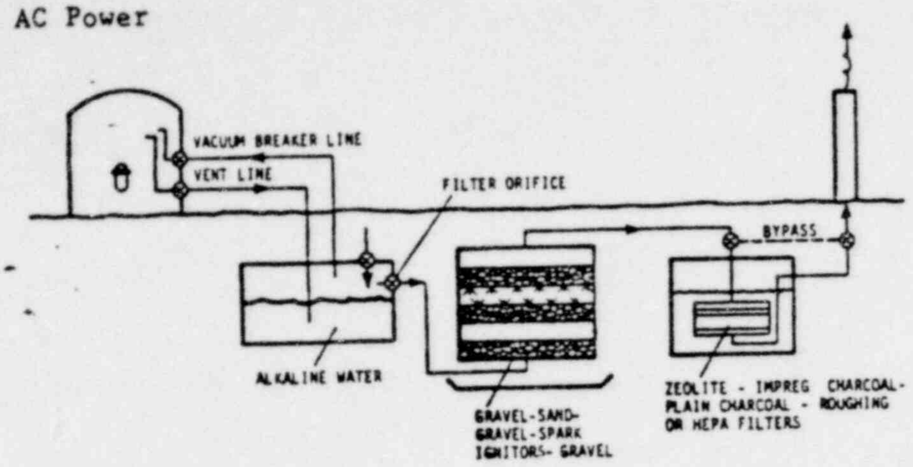
Cooler/Condenser and Filter Components

Various options are being considered for the external portion of the vent-filter system, with different degrees of complexity and different costs, corresponding to various levels of fission product entrapment. One of the options is shown schematically in Figure 6. The system is designed to operate successfully without AC power during a loss-of-power accident for a period of well over 16 hours, the time at which power is assumed to be restored. Thereafter, the operation of the system changes from a vent to a recirculation mode so as to eliminate further releases to the atmosphere. In the recirculation mode, the designs incorporate a heat exchanger to remove heat from the water and blowers to drive the circulating flow and to cool the charcoal filters.

The primary condensing/cooling component preceding the filter trains in the option shown is a vapor suppression water pool. The submerged portion of the pool (about 150,000 ft^3) provides enough heat sink to passively condense all the steam that is generated during the accidents TMLB', AB-Burn, and S_2D-Burn. The air space (also about 150,000 ft^3) allows for the additional amount of water produced by vapor suppression during accidents such as TMLB" and S_2G.

If the filters in the vent-filter system were designed to accommodate the flow rates required for anticipatory containment venting, the gravel-sand filter would have frontal dimensions of about 120 ft x 100 ft and a height of about 20 ft, including spark ignition sources for burning hydrogen. The adsorber system would have a frontal diameter of about 36 ft and a depth of about 6.5 ft, including a 4-inch zeolite guard bed to retain inorganic iodine, a 2-inch impregnated charcoal bed to capture organic iodine, a 5.5-ft (100 ton) plain charcoal bed to retain the xenon, and 2 inches of roughing or HEPA filters to prevent charcoal particles from escaping up the stack. The entire assembly, in a waterproof container, could be immersed in a 20,000 ft^3 water tank to remove heat via natural convection until power is restored.

(a) Without AC Power



(b) With AC Power

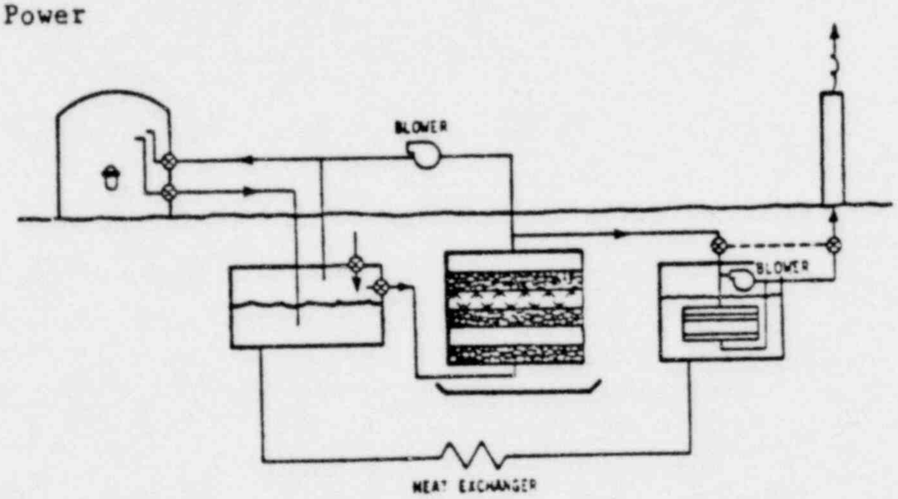


Figure 6. Filtered Atmospheric Venting Option. Estimated Collection Efficiencies: 99.98% Particles, 99.98% Inorganic Iodine, 99.95% Organic Iodine, 98% Xenon, 10% Krypton.

Simpler variations of the system in Figure 6 can be obtained by removing various components. Consequence evaluations for four variants of Figure 6 illustrate that for the TMLB' accident in the reference PWR, a large reduction in latent cancer fatalities and property interdiction and an elimination of early fatalities can be accomplished just by venting the containment through an alkaline suppression pool (See Figure 7). The consequence calculations were based on the Reactor Safety Study models applied to the reference PWR using site-specific weather and population data and a 5-mile evacuation radius (instead of a 25 mile evacuation radius). It was assumed that the vent-filter systems operate as designed and that the effluent from the filters is released (at ambient temperature) at an elevation of 180 ft. It should be emphasized that these calculations correspond to one accident only, and do not reflect the effect of vent-filter systems on overall reactor risks.

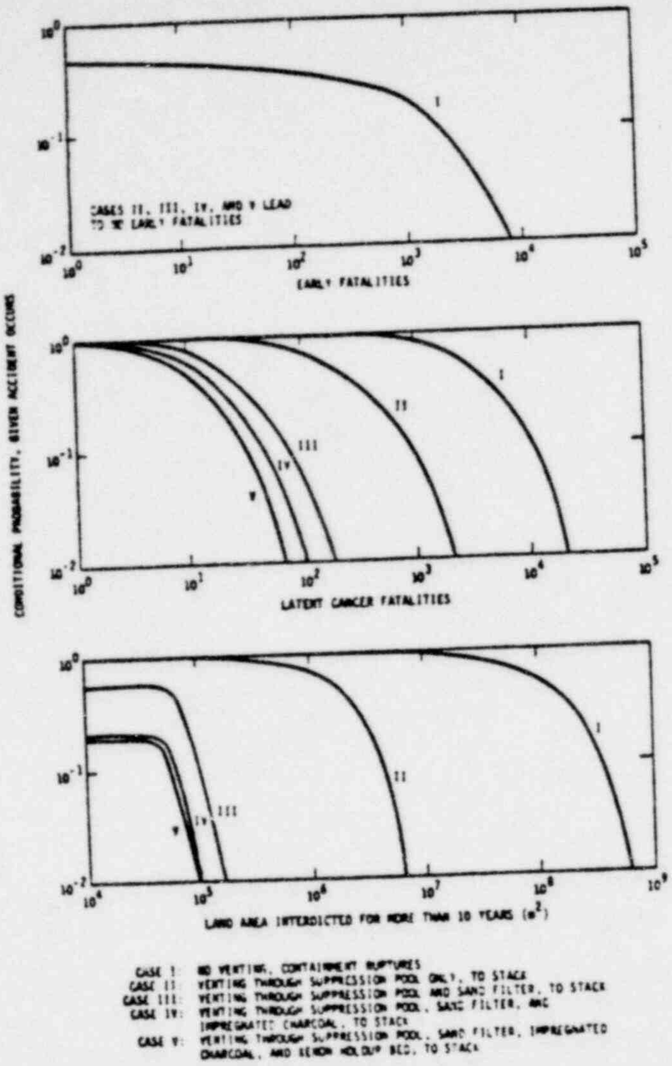


Figure 7. Probability of Early Fatalities, Latent Cancer Fatalities, and Land Interdiction for Various Filtered Venting Options, Given Occurrence of the Accident TMLB'.

CONCLUSIONS

The primary challenge to a filtered-vented containment system is the pressure spike that could occur in containment if the molten core penetrates the reactor vessel and drops into the cavity. The main contributors to the spike in a large, dry PWR are rapid vaporization of water in the cavity and the possibility of hydrogen deflagration caused by core-concrete interaction. Large phenomenological uncertainties are associated with these processes, and exploratory research is needed to better define the rate and magnitude of the pressure transient.

It presently appears that for certain severe accidents in large, dry PWRs, retrofitted vent-filter systems can be successfully utilized to circumvent containment overpressurization. For these accidents, major reductions in consequences appear to be possible with relatively simple systems. Because of space limitations and containment structural considerations, however, the actuation and operation of a retrofit system is likely to require a greater degree of automatic control and/or operator participation than has previously been assumed. Before the overall risk reduction potential of vent-filter systems can be established definitively, a more detailed evaluation of a variety of accidents including considerations of actuation reliabilities, potential adverse system interactions, and possible failure modes including operator error is required. These analyses, which are now in progress, will provide the required inputs for a comprehensive assessment of competing risks.

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