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DESIGN CRITERIA AND CONCEPTS FOR VENTED CONTAINMENT SYSTEMS*

MASTER

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Abstract

Vented containment systems are commonly considered to be effective in reducing the consequences of severe accidents in light water reactors. The principal function of venting is to prevent uncontrolled failure of the reactor containment building should its integrity be challenged by the physical conditions generated during an accident. In so doing, radioactive material can be filtered from the vented gases to reduce the environmental impact. This presentation summarizes results of research concerning potential design requirements of such systems. Findings related to air cleaning are emphasized.

Accident sequences from WASH-1400 were selected and analyzed with the MARCH/CORRAL code to provide an envelope of design conditions. The time-dependent pressures and temperatures in containment were calculated as were the concentrations of steam, non-condensible gases and airborne fission products in the containment atmosphere. The phenomenon found to be most challenging to containment integrity was a pressure spike resulting from rapid steam generation and/or hydrogen burning. The peak pressures in some sequences exceed the likely failure pressure.

Conceptual designs were developed for preserving containment integrity. These include containment pressure relief or depressurization with various venting rates. Anticipatory venting, venting to the atmosphere, venting to a separate building, and venting followed by recirculation back into containment are considered. The effects of these schemes on the important system parameters were identified. The advantages and disadvantages of alternative schemes and their implications for the design of filtration equipment are discussed.

For each venting strategy several levels of filtering effectiveness were considered. The simplest option

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developed is a once-through gravel-filled suppression pool. More sophisticated options involved sand filters, molecular sieves, charcoal adsorbers and HEPA filters. Results of accident consequence calculations using the CRAC code indicate the relatively simple options can provide substantial reductions in consequences of certain accident sequences.

Introduction

Safety research for light water reactors (LWRs) in the U.S. is increasingly focusing upon severe accidents in which core melting may occur. The primary focus of this research is on prevention rather than mitigation, however, some research has been directed toward the development and analysis of systems that mitigate severe accidents in the unlikely event that the engineered safety features (ESFs) fail.

The current interest in filtered-vented containment systems (FVCSs) in the U.S. stems from the Reactor Safety Study (RSS).[1] The RSS determined that containment failure due to overpressurization represents the largest contributor to reactor risks. Subsequent studies [2-5] have reinforced the idea that containment venting could reduce reactor risk by reducing the probability of containment overpressurization. In April 1979, the USNRC initiated a program at Sandia National Laboratories to investigate filtered-vented containment concepts for light water reactors. That program has the following features:

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.

Sandia's work on filtered-vented containment system design, development and evaluation during the first year of the program are described in Ref. (6) - (8). This paper summarizes that work and discusses the work in progress. The contents of this paper include a description of the baseline pressurized (PWR) and boiling water reactors (BWR) analyzed to date, a summary of key accident scenarios and feasible venting strategies to mitigate them and a discussion of filtered-vented containment design options. Emphasis is placed on the air cleaning aspects of such design options.

Baseline Reactors

The NRC sponsored Sandia study includes an investigation of filtered-vented containment system design concepts for the following primary containment types: (1) large-dry pressurized water reactor (PWR) containment, (2) Mark I boiling water reactor (BWR) containment, (3) ice condenser PWR containment and (4) Mark III PWR containment. Preliminary analysis for category (1) and (2) above have been performed. Some characteristics of the large-dry PWR containment and the Mark I BWR containment are presented in Table I.

Table I Characteristics of the Baseline Reactors

Reactor	PWR	BWR
Thermal Power	3025 MW	3293 MW
Containment	Steel-lined, reinforced concrete domed cylinder	Mark I drywell/wetwell, inerted to less than 5% O_2 (molar)
Containment Cooling	(1) Containment air coolers, 112 MW max. (2) Containment sprays, 20,000 ℓ/min max.	Suppression pool circulated through heat exchanger cooled by HPSW. 82 MW max. cooling
ECC Water Sources	(1) 4 accumulators pressurized to 45 bar (abs), 7.9×10^4 ℓ. (2) RWST, 1.3×10^6 ℓ.	(1) Suppression pool, 3.9×10^6 ℓ (2) CST, 5.7×10^5 ℓ.
High Pressure ECC	HPI system, injects from RWST, 4700 ℓ/min max.	HPCI system, powered by reactor steam, injects from CST or suppression pool, 19,000 ℓ/min max. Can be supplemented by RCIC.
Low Pressure ECC	LPI system, injects from RWST, recirculates from recirculation sump, 23,000 ℓ/min max.	(1) LPCI system, injects and recirculates from suppression pool, 1.5×10^5 ℓ/min max. cross tie with HPSW system allows injection of river water into reactor vessel. Some water can be diverted to containment sprays. (2) CSI system, injects from CST or suppression pool, recirculates from suppresion pool, 47,000 ℓ/min max.
Primary System Depressurization	Manual, through S/R valves. Requires ac power.	ADS. Requires dc power.

Accident Scenarios and Venting Strategies

In order to investigate design options for the filtered-vented containment system it was necessary to consider a variety of accident scenarios similar to those considered in the Reactor Safety Study (RSS). The accidents selected for study represent best estimates of those accidents from the RSS that dominate risk to the public for each reactor containment type. Also included are accidents that may not dominate risk but provide an unusual challenge to the filtered-vented containment system. Analysis of each accident scenario provided the basis for selecting design options/venting strategies capable of mitigating the effects of the accident.

PWR Accident Scenarios

A brief description of the accident scenarios selected from RSS for application to the PWR containment is given in Table II.

Table II PWR Accident Scenarios

RSS Accident Notation	PWR Accident Sequences	Estimated Contribution to Reactor Risk
TMLB'	Loss of offsite and onsite ac power for at least 3 hours.	High
	Failure of power conversion system and auxiliary feedwater system.	
S_2D	Small LOCA with failure of ECC injection and recirculation.	High
S_2G	Small LOCA with failure of containment heat removal.	Moderate
AB	Large LOCA with loss of offsite and onsite ac power.	Small

Calculations of containment pressure vs. time were made for the four listed accidents using the MARCH computer code.[9] The results of those calculations are presented in Figure 1.

The calculations indicate that a large pressure spike could occur if melt-through of the reactor vessel were to happen. The cause of the containment pressure spike varies, but combinations of the following are responsible:

1. Steam release from the primary system to the containment when the reactor vessel fails at high pressure (accidents TMLB' and S_2D).

2. Rapid steam formation caused by molten core interaction with water existing in the cavity at the time of reactor vessel failure (accident AB).

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 TMLB' and S_2D).

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 TMLB' and S_2D).

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 AB and S_2D).

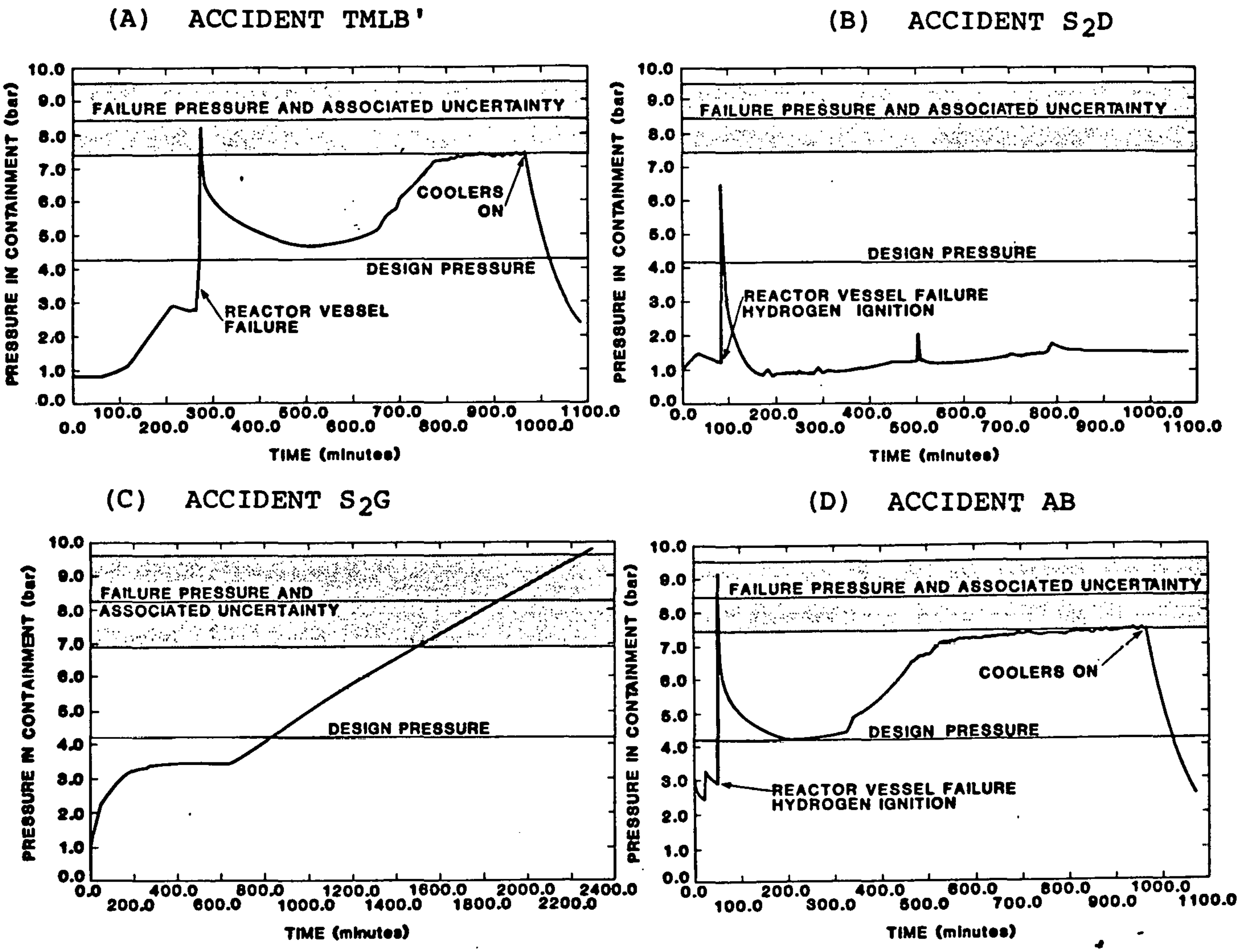

Figure 1 MARCH Code Calculations of Containment Pressure Versus Time for Four Hypothesized Accidents in the Baseline PWR Plant

The magnitude and duration of the spike are subject to assumptions regarding the nature of core material interactions with water which may prove to be conservative. Experiments will be performed soon to investigate the phenomenology of steam spikes.

PWR Vent Strategy 1. In this strategy, containment internal pressure is vented at a low flow rate (400 m^3/min) when the containment pressure exceeds 6 bar. When the internal pressure falls below 6 bar the control valve would close. In this way the containment internal pressure would be maintained at or below the containment design pressure. The advantages of this strategy are its simplicity and the minimum potential for adverse effects on engineered safety features (ESFs).

PWR Vent Strategy 2. Deliberate depressurization of the primary loop after most of the water has boiled off could be helpful during accidents initiated by transients or during small break loss of coolant accidents (LOCAs). Deliberate depressurization of the reactor primary loop would require either automatic controls or operator judgement. This vent strategy has the disadvantage that an actuation error could cause a LOCA that otherwise would not have happened.

PWR Vent Strategy 3. Anticipatory containment depressurization could prevent containment overpressurization by forecasting a core melt and venting containment in advance. During the interval between initiation of core melt and failure of the reactor vessel lower head there is time to reduce containment internal pressure to a level where subsequent pressure spikes would not exceed the containment failure pressure. Anticipatory venting could also reduce the magnitude of a hydrogen burn by removing hydrogen and oxygen from the containment.

Parameters used to initiate anticipatory venting might be sustained low reactor vessel water level, high containment radiation levels, high reactor vessel temperature and high containment internal pressure. In order to prevent the possibility of emergency core cooling (ECC) failure due to recirculation pump cavitation it might be necessary to place a booster pump into the ECC recirculation inlet to meet the net positive suction head (NPSH) requirements of the ECC recirculation pump. It would also be necessary to install vacuum breakers into the present containment boundary and to limit containment spray operation in order to counteract the possibility of a severe containment vacuum.

Anticipatory containment venting introduces greater potential for unnecessary radioactive release than other strategies because some accidents with incipient core melt might not threaten containment integrity. The anticipatory containment vent parameters (high radiation levels, high reactor pressure and temperature and low reactor water) might indicate incipient core melt, such as at Three Mile Island, and might signal the containment vent to open, whereas a full-scale core melting may not develop and no threat to the containment may occur. However it is felt that the magnitude of such unnecessary radioactivity releases via the filtered-vented containment system would be small compared with uncontrolled release via a ruptured containment.

Figure 2 shows the effect on containment pressure vs. time of implementing PWR vent strategy 2 and 3 on the TMLB' accident. It can be seen that the peak pressure is reduced below the containment failure pressure.

(A) PWR VENT STRATEGY 2

(B) PWR VENT STRATEGY 3

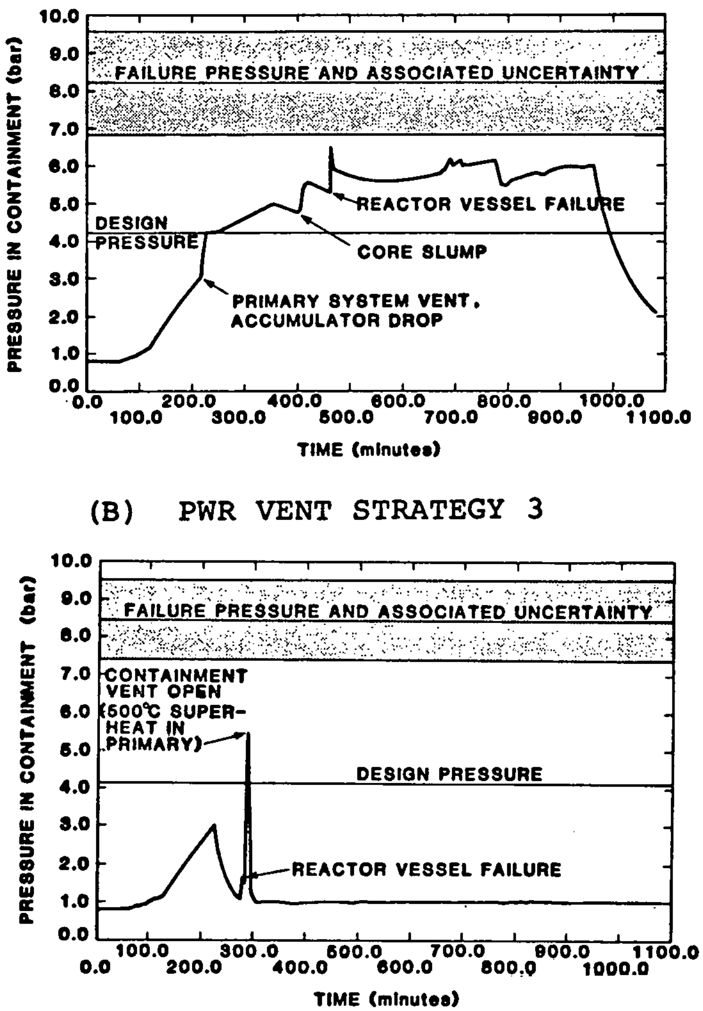

Figure 2 MARCH Code Calculations of Containment Pressure Versus Time for the Accident TMLB' in the Baseline PWR with Different Venting Strategies

BWR Accident Scenarios

Four accidents were selected from the RSS as posing moderate to high risk to the public should the primary containment fail. Those four accidents are described in Table III.

Table III BWR Accident Scenarios

RSS Accident Notation	BWR Accident Sequences	Risk
TW	Transient initiating event with failure of suppression pool cooling.	High
TC	Transient initiating event with failure of reactor protection system.	High
TQUV	Transient initiating event with failure of feedwater and ECC availability.	Moderate
AE	Large LOCA with failure of ECC injection.	Moderate

The risk dominating accident sequences in the BWR (TC and TW) lead to primary containment overpressurization while the core is partially covered with water and hence not melted. Thus a primary requirement of the BWR filtered-vented containment system would be the prevention of containment overpressurization without degradation of the ECC function.

For the accidents TQUV and AE where core meltdown precedes containment overpressure a pressure spike occurs when the reactor vessel fails. The sharp pressure rise is due to:

1. Hydrogen release from the reactor vessel to the containment. This rapid containment pressurization can be prevented by the use of the automatic depressurization system (ADS).

2. Hydrogen formation caused by zirconium-steam reaction when the reactor vessel fails and the molten core falls into water.

Figure 3 presents the pressure vs. time history of the four BWR accidents (TC, TW, TQUV and AE).

<u>BWR Vent Strategy 1</u>. This strategy (low-volume containment pressure relief) is similar to PWR vent strategy 1 and requires approximately the same flow rate (400 m^3/min). Venting from the wetwell allows the suppression pool to be used as a filter for the drywell environment.

This low flow rate option would prevent accidents TW and TQUV from overpressuring containment, but would not be adequate for AE and TC. Operation of this vent strategy during an accident with a failed suppression pool cooling system would result in a reduction of the NPSH below the design basis for the low pressure coolant recirculation (LPCR) pumps. Booster pumps could be incorporated in the LPCR system in order to increase the NPSH and prevent cavitation of the (LPCR) pumps. The LPCR pump inlet could be diverted from the suppression pool to another source (via existing cross-overs) such as the high pressure service water system (HPSW).

BWR Vent Strategy 2. During the TC accident it is possible to continue high pressure coolant injection (HPCI) and prevent a total core meltdown as long as water is available. Containment venting with a mass flow equal to the rate of steam formation (as a result of HPCI) would create a steady flow process into the primary and out to the suppression pool then into the wetwell and out the containment vent.

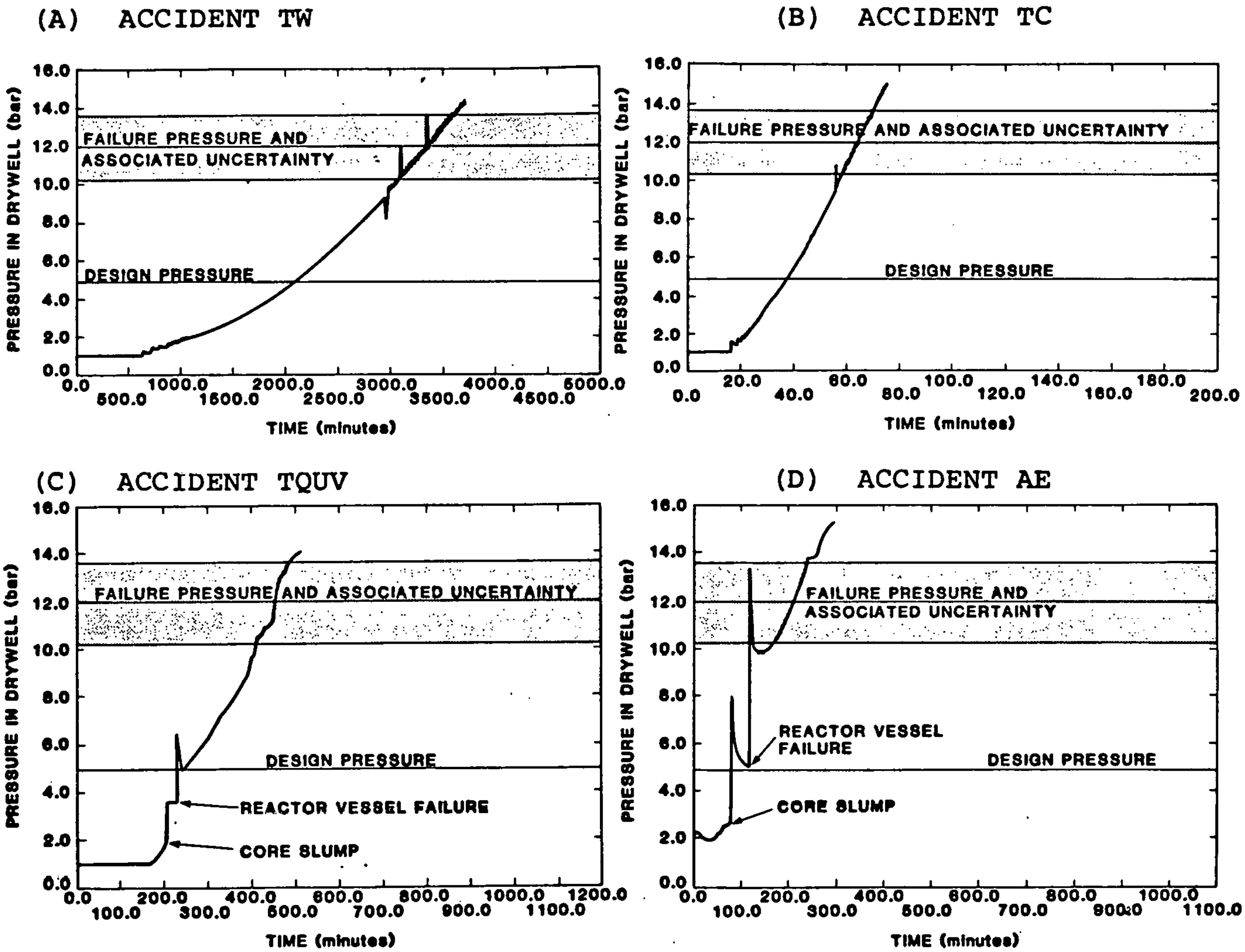

Figure 3 MARCH Code Calculations of Containment Pressure Versus Time for Four Hypothesized Accidents in the Baseline BWR Plant

This steady state situation would be achieved with a vent rate of 4000 m^3/min at a containment internal pressure of 6.8 bar.

Success for this venting strategy during the TC accident depends upon the restoration of the reactor protection system within 3 hours or the availability of an external water source (such as the high pressure service water) to supply the HPCI system indefinitely.

BWR Vent Strategy 3. This strategy (anticipatory venting) is similar to the PWR vent strategy 3. It would be effective in preventing drywell failure due to pressure spikes except when the suppression pool is saturated at the onset of wetwell venting. Suppression pool saturation would slow containment depressurization because of boiling from the pool.

Filtered-Vented Containment System Designs

PWR Design Options

Five filtered, atmospheric vented design options and a filtered, contained design option for the PWR under study were formulated. These options represent successively higher levels of fission product removal from the containment vent gas stream.

PWR vent-filter design option 1 is shown schematically in Figure 4. This is the most simple of all the options in that it consists of a gravel chamber as the only filter component. The gas stream is vented through a valve manifold in an existing penetration in the concrete containment vessel into a vent line of approximately 1.0 m diameter. The filter element

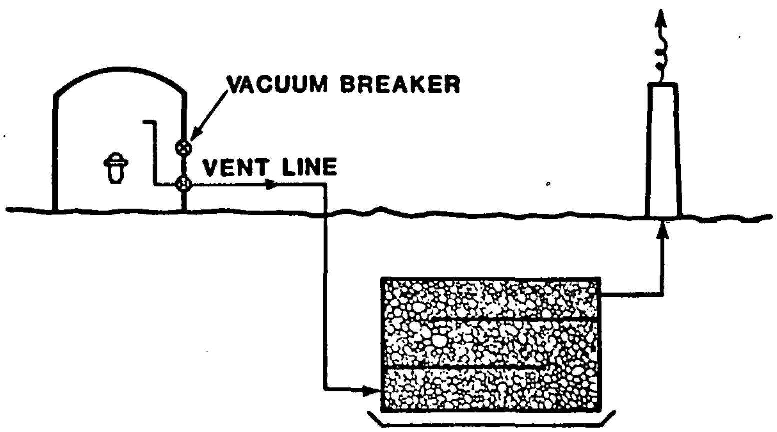

Figure 4 PWR Design Option 1

is a buried gravel bed 20 m long x 10 m deep x 40 m wide for the low flow (400 m^3/min) vent strategy. The dimensions of the bed would be larger to accommodate the vent strategy 3 (2500 m^3/min). The filtered noncondensible gas stream would then discharge to the atmosphere via a tall stack. Recent experiments with crushed gravel suggest that gravel beds of sufficient height will remove submicron particles without excessive pressure drop.[10] The pressure drop across the bed is designed to be less than 0.7 bar.

The advantages of option 1 are its simplicity, low cost, and that it requires no electric power. Disadvantages are the lack of proven performance with large scale systems and an unknown decontamination factor that is sensitive to particle size and gas velocity.

Vent-filter design option 2 is based on a system being developed at Hanford Engineering Development Laboratory.[11] This option is shown in Figure 5 and consists of a gravel bed

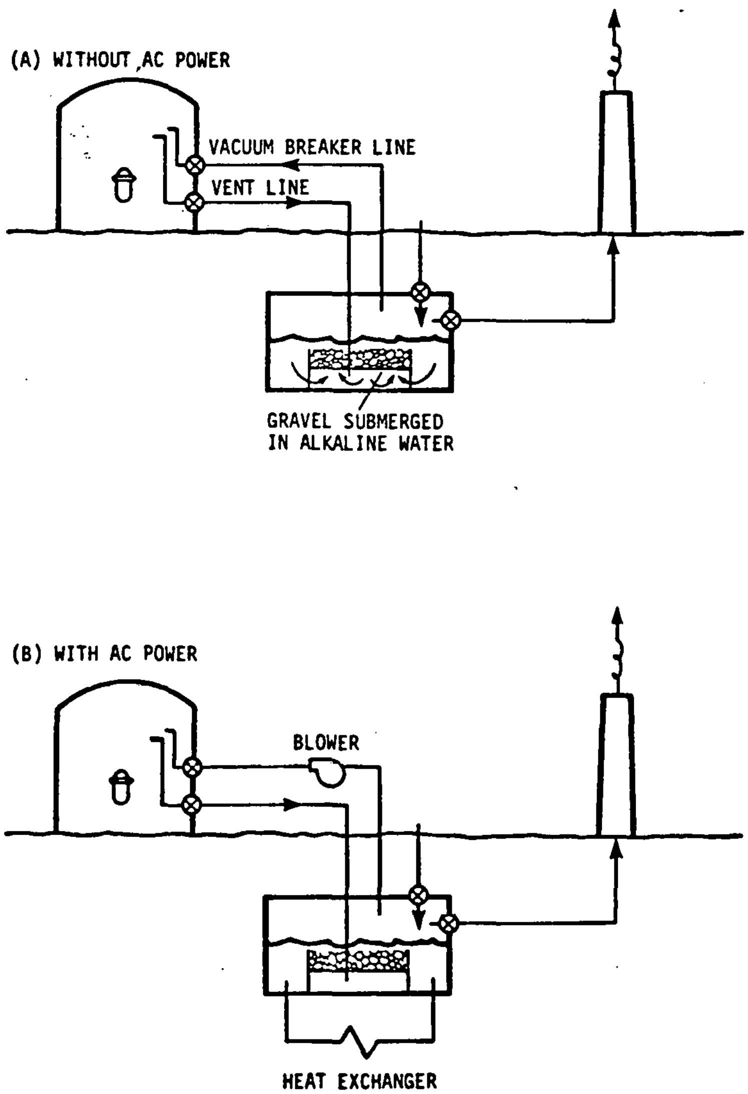

Figure 5 PWR Design Option 2

submerged in an alkaline water pool. This option has the capability to condense steam, which option 1 does not. Estimated fission product removal efficiencies are: 98% particles, 98% I_2, 50% CH_3I, 0% Xe and 0% Kr. In this option a provision for re- circulation of the filtered containment exhaust and long term heat removal from the suppression pool has been made.

Design option 3 is shown schematically in Figure 6 in both the passive and recirculation mode. This option consists of a

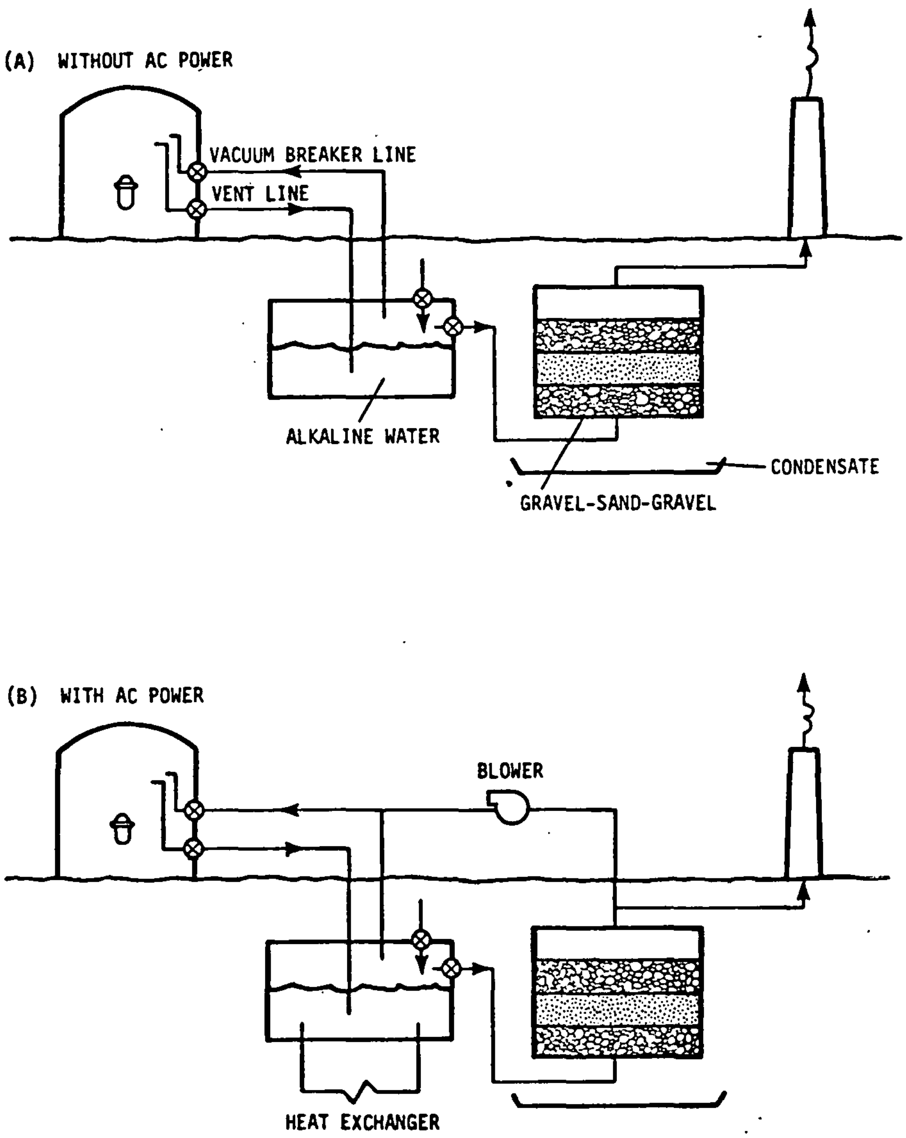

Figure 6 PWR Design Option 3

BWR type suppression pool shown in Figure 7 and a sand-gravel filter shown in Figure 8. Suppression pools are a tested and proven method of cooling and condensing gas streams. Suppression pools require less volume than crushed rock for the same heat load and provide a solution to the long term heat removal via heat exchangers in the wetwell. In this option the toroidal shell has a volume of 8500 m^3 of which 50% is chemically treated water. The 4250 m^3 of water will condense all the steam generated during the TMLB', AB and S_2D accidents. The 4250 m^3 air space allows for the condensate storage. The entire torus and all piping is located below grade in a concrete lined pit. In order to maintain a 1.25 m submergence over the downcomer outlets a spillway is located to allow for condensate carryover into the air space. The pressure drop across the suppression pool is designed to be 0.13 bar. This pressure drop should present no problems because the driving pressure (containment internal pressure) will be on the order of 5.0 bar. The piping from containment to the suppression pool would have to be capable of transmitting a peak flow rate

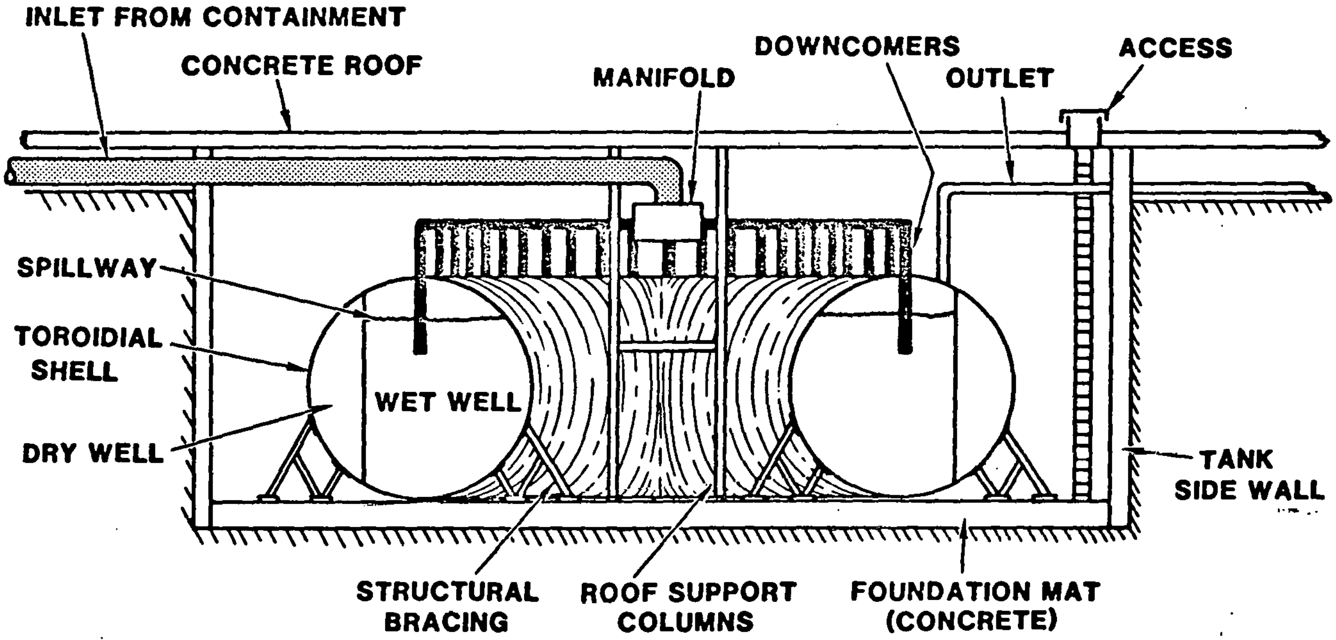

Figure 7 Suppression Pool Section

of 7000 m^3/min and a nominal flow of 1400 m^3/min. The existing purge penetrations would satisfy these requirements.

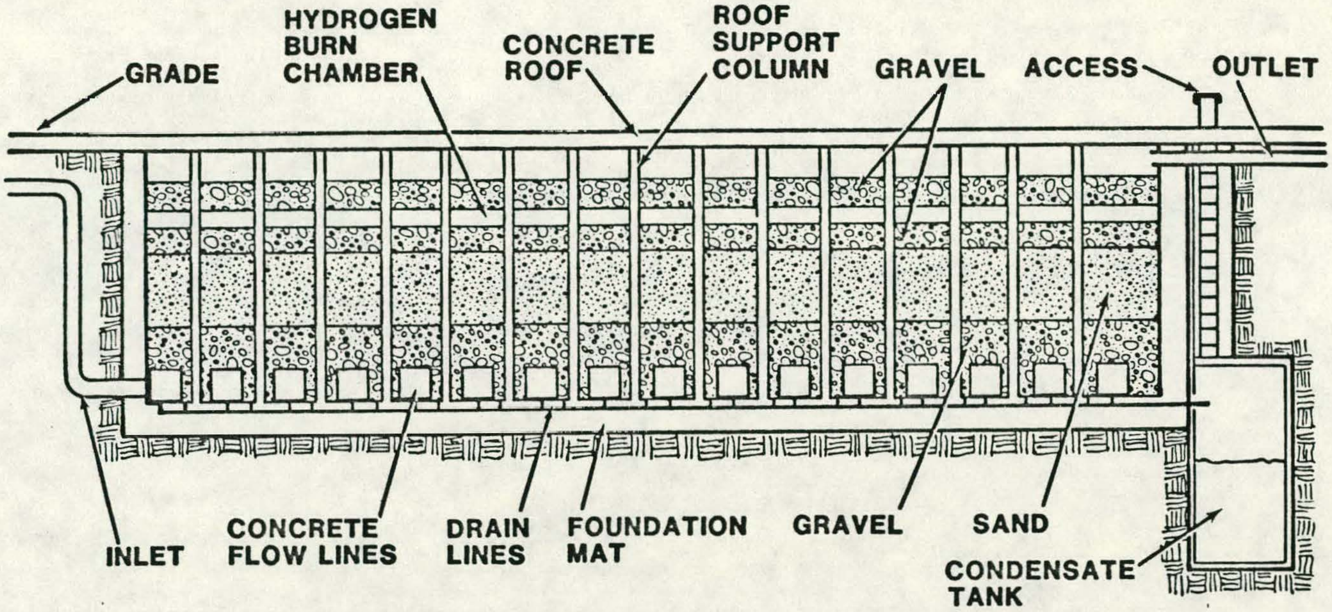

Figure 8 Sand-Gravel Filter Section

The sand-gravel filter shown in Figure 8 consists of a large buried concrete vault filled with alternate layers of gravel and sand. The approximate dimensions of the vault are 36 m long by 36 m wide by 15 m deep. A drain network and integral condensate storage tank are provided to store the contaminated condensate. The structure was designed to handle a flow of 1400 m^3/min at a pressure drop of 0.04 bar maximum. A space is provided in the chamber to accommodate a hydrogen ignition source. The so-called hydrogen burn chamber/space is overlaid by a gravel layer; this layer serves as a flame arrestor and heat sink for the combustion gases. Total fission product removal efficiencies for Option 3 are estimated to be: 99.98% particles, 98% I_2, 50% CH_3I, 0% Xe and 0% kr.

Design option 4 consists of the toroidal suppression pool and sand-gravel filter of option 3 plus a zeolite-charcoal filter downstream from the sand-gravel filter. This option is shown schematically in Figure 9. The zeolite-charcoal filter consists of a wafer shaped tank about .5 m thick and 12 m in diameter. The wafer is fabricated of 304 stainless steel and is gas/water tight. The wafer is filled with a top layer 10 cm thick of triethylenediamine (TEDA) impregnated charcoal. These two layers are followed by a layer of HEPA filters to trap charcoal and other particulate. The layers of filter media

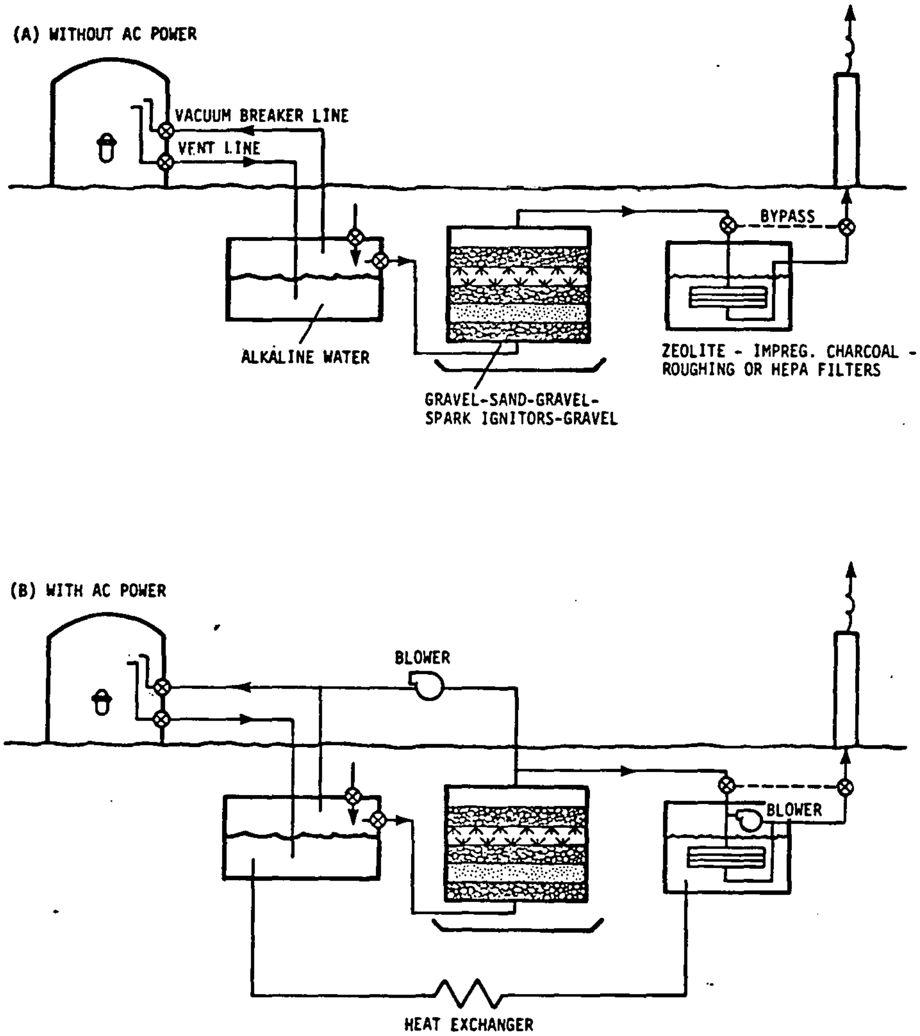

Figure 9 Design Option 4

could be separated by packed fiber. This filter component is designed to be submerged in a 250 m^3 water tank. The water tank would provide passive cooling of the fission product decay heat (during TMLB' accident) from the wafer. The estimated total fission product removal efficiencies for Option 4 are: 99.98% particles, 99.95% I_2, 99.90% CH_3I, 0% Xe and 0% Kr.

Design option 5 is essentially the same as option 4 except xenon holdup is provided for. This requires a thick layer of charcoal trays (1.7 m thick) between the TEDA charcoal and the HEPA filter trays. This option is shown schematically in Figure 10. The estimated total fission product removal efficiencies for Option 5 are: 99.98% particles, 99.98% I_2, 99.98% CH_3I, 98% Xe and 10% Kr.

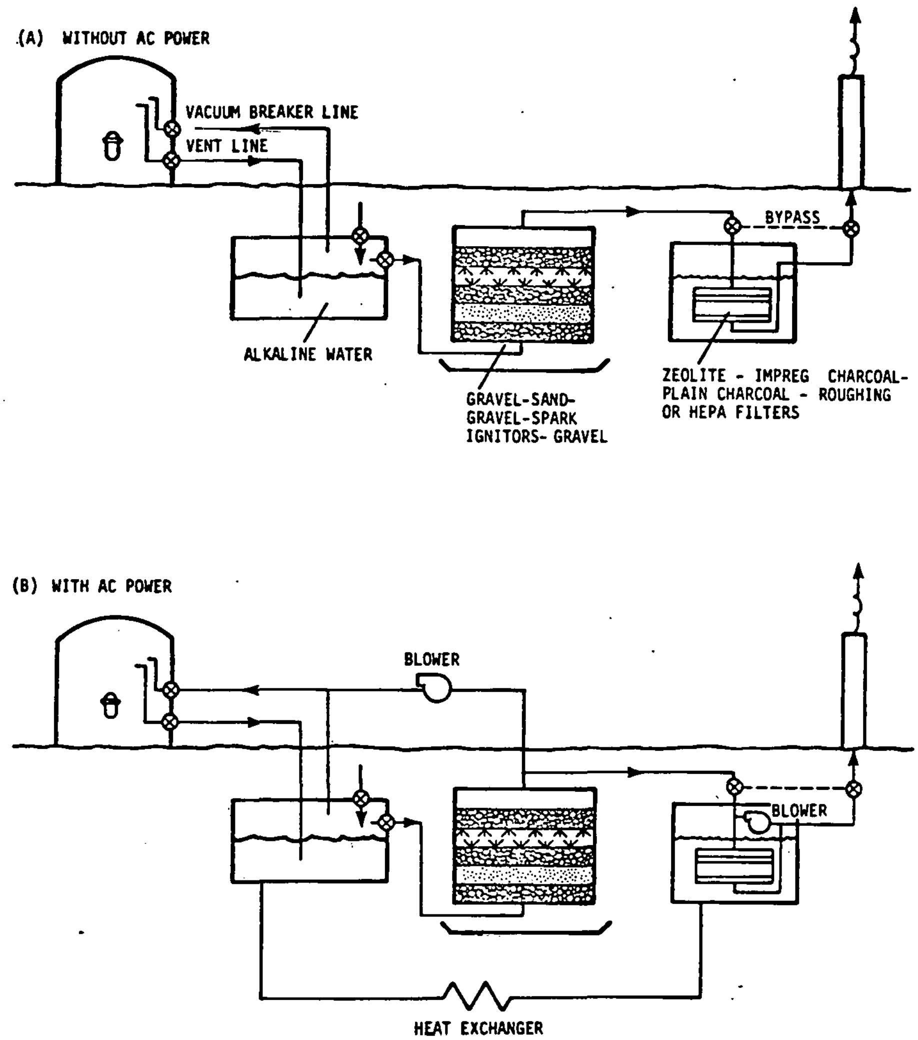

Figure 10 Design Option 5

Design option 6 is a completely contained (no vent to the atmosphere) system. This option is presented in Figure 11. The main features of the system include a toroidal suppression pool and a hydrogen burning area plus a large (30,000 m^3) second containment building. At this volume, the design pressure of the second containment would have to be about 2.8 bar. The hydrogen carried over from the first containment building would have to be burned in the vent line in order to prevent overpressurization in the second containment due to hydrogen burning there. This option has the potential of holding up all fission products from the damaged reactor. The main disadvantage of this option is the high cost of the second containment building and the difficulty of finding space for this size structure at existing reactor sites.

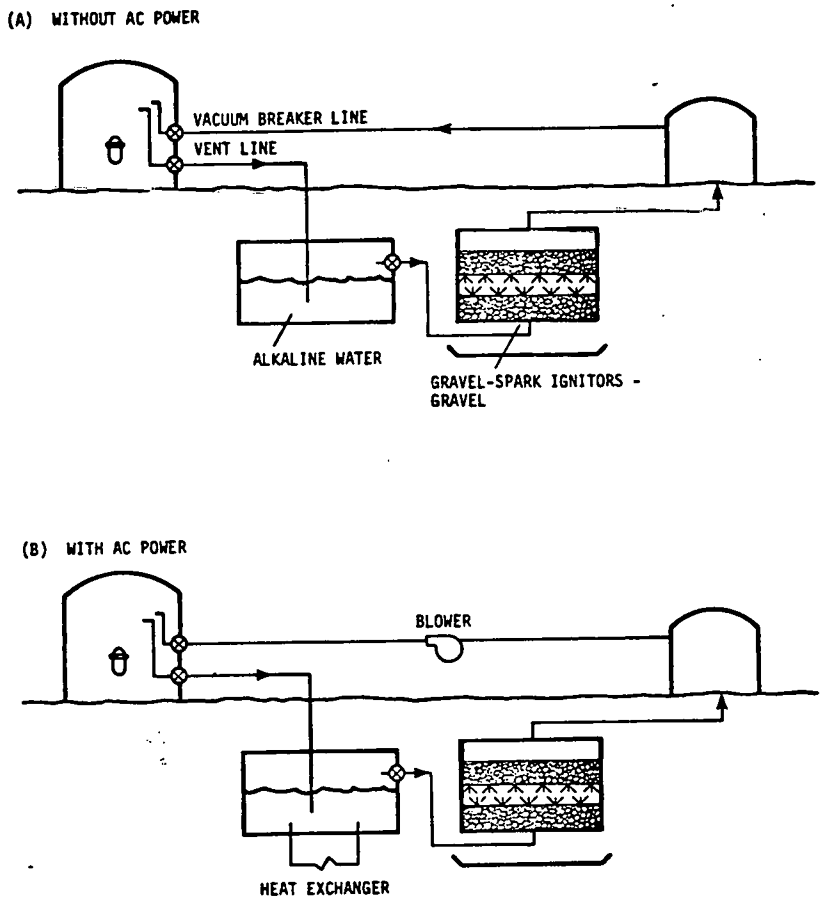

Figure 11 Design Option 6

BWR Design Options

The design options for the baseline BWR are similar to the PWR options except there is no need of a suppression pool since the BWR Mark I has a suppression pool in the primary containment. The option 1 gravel bed would be somewhat larger because it is designed to the heat loads of accident TC.

Consequence Evaluation of the Design Options

An evaluation of the public health consequences using the CORRAL and CRAC computer codes for the TMLB' accident was made. The calculations were made by using the RSS fission product transport and consequence models and the fission product removal efficiencies of the individual design options. Furthermore it was assumed that the containment vessel would be completely failed if there were no FVCS and the filtered-vented containment design options would operate at their predicted efficiencies and prevent containment failure. Weather and population profiles specific to a densely populated Northeast site were used. The results of those calculations are shown in Figure 12.

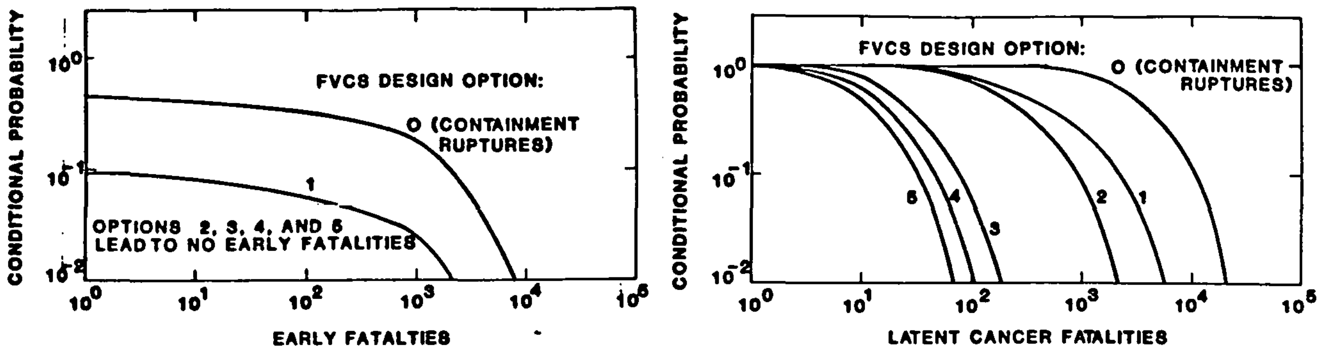

Figure 12 Probability of Early Fatalities and Latent Cancers for TMLB'

Conclusions

Relatively simple filtered-vented containment systems have the potential for significant reductions in reactor consequences. For the particular accident analyzed in the baseline PWR, a single-component system such as a submerged gravel scrubber could provide enough fission product retention to eliminate early fatalities and reduce latent cancer fatalities tenfold, compared to the consequences resulting from an overpressurization rupture of containment. We have estimated that such a system would cost about 16 million U.S. dollars per reactor, but believe that less costly systems with comparable benefits could also be developed. Additional components to contain the noble gases do not appear to be cost effective.

The as-yet unanswered questions are whether or not a complicated venting strategy is necessary in order to circumvent pressure spikes, and whether or not the competing risks would render such a strategy undesirable. We are currently planning experiments to answer the first question and performing a comprehensive probabilistic risk analysis to answer the second. Until these questions are answered, the overall benefits of containment venting remain uncertain.

Acknowledgements

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