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Program Plan for the Investigation of Vent-Filtered Containment Conceptual Designs for Light Water Reactors

Allan S. Benjamin

Printed October 1979

Sandia Laboratories

Prepared for
U. S. NUCLEAR REGULATORY COMMISSION

NOTICE

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Date Published: October 1979

Sandia Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
U.S. Department of Energy

Prepared for
Probabalistic Analysis Staff
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Interagency Agreement DOE 40-550-75
NRC FIN No. A1220

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ABSTRACT

The implementation of a containment venting and filtration capability has been suggeste .s a means for reducing the risk from fuel melt accidents in light wat-- reactors. The risk reduction potential of such systems depends upon the dual function of venting containment to prevent overpre. i..ization from the generation of steam and noncondensibles and filtering the effluent to limit the release of radioactive materials. This report addresses the major issues involved in such an accident mitigation system and discusses the engineering, technical, and economic questions that will have to be studied before judgments can be made regarding feasibility and effectiveness. A program plan is presented for research leading to the formulation of design requirements for vent-filter containment systems and to a comprehensive assessment of the values versus impacts of such systems.

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1. INTRODUCTION

In recent years, the development of light water reactors (LWRs) has been subject to an increased emphasis on safety as the public has become increasingly concerned about the possibility of large accidents. Responding to this concern, the United States Congress, in the Fiscal Year 1978 Budget Authorization Act, directed the Nuclear Regulatory Commission (NRC) to prepare a plan for the development of new or improved safety systems for nuclear power plants. In April 1978 the NRC submitted such a plan[1] to Congress, outlining seven key areas of research to be conducted over 3 years at a total estimated cost of $14.9 million.

Of the various research projects proposed by the NRC, a program for the development and analysis of vent-filtered containment conceptual designs was accorded particularly high priority by the NRC and the Advisory Committee on Reactor Safeguards (ACRS).[2] Vent-filter systems were identified as having a high potential for reducing the risks from large accidents, without the incurrence of unfeasibly high installation costs for either backfitting existing plants or equipping new plants. Funding of this program was subsequently approved.

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, postaccident filtration systems can reduce the risk of 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 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 this report.

The research program addressed here is designed to answer the important questions regarding vent-filtered containments and, in particular, to provide the following analyses:

1. Development of conceptual designs of vent-filter systems conceived to mitigate the effects of accidents, primarily involving core melting, that are beyond the current design basis
2. Determination of the potential reduction in radioactive releases 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

The study will include several types of containment (i.e., large dry, ice condensor, Mark I, and Mark III) and will consider both existing and new plants.

It should be mentioned that although the term "vent-filtered containment" usually connotes a process in which the filtered effluent is released to the atmosphere (a process often called "filtered atmospheric venting"), the fundamental objectives of pressure relief and mitigation of radioactive release can also be accomplished by techniques that do not involve atmospheric release. An example is the process of venting of the gases through a condensing medium to remove the steam, with subsequent circulation of the noncondensibles into an alternate containment or recirculation into the vented containment.

Since these techniques may also be reasonable from a value versus impact perspective, they will be included in the study.

The purpose of this report is first to identify all the major concerns potentially affecting the feasibility and effectiveness of vent-filter systems and then to present a program plan for studying these concerns in detail. The report is divided into the following sections. Section 2 discusses the background of the subj ct, including a summary of previous studies. Section 3 is concerned with system design and performance considerations, emphasizing those that are particularly important for vent-filter systems and that are not covered in detail in the Code of Federal Regulations, 10 CFR, Part 50. Section 4 describes various filter alternatives, including the advantages and disadvantages of each and the special problems that could be encountered. Section 5 presents the major technical questions that will have to be answered before a value assessment of containment venting-filtering can be made. Section 6 discusses the issues involved in conducting a meaningful value-impact assessment in the presence of sizeable uncertainties. Section 7 presents a program plan which both outlines the tasks and summarizes the report.

2. BACKGROUND

The use of a postaccident containment vent and filtration system for reducing nuclear reactor accident risks originated in connection with breeder reactors. The Zero-Power Plutonium Reactor (ZPPR) test facility,[3,4] constructed during 1966-68, utilizes a deep bed of graded sand and gravel as its roof to form a filtered path for plutonium aerosols in the event of a core-melt accident (see Figure 1). The sand and gravel filter is supplemented by a bank of high-efficiency particulate air (HEPA) filters which serve as a secondary filtration medium. More recently (1976), the Hanford Engineering Development Laboratory[5,6] conducted a comparative study of 24 emergency air cleaning systems for liquid metal fast breeder reactors (LMFBRs) and concluded that the best option for containment/confinement designs appeared to be a once-through filtration system comprised of a sand bed followed by HEPA and charcoal filters.

The German SNR-300 prototype LMFBR[7] incorporates an atmospheric venting feature in conjunction with a "reventing" capability (see Figure 2). After an accident involving major core damage, the gases in the reventing gap surrounding the outer containment are circulated into the containment in order to provide a negative pressure differential between the gap and the atmosphere. If the pressure in containment becomes too high, the containment can be vented to the atmosphere through a combination of sand, HEPA, and charcoal filters.

Vent-filter systems for LWRs have received considerable attention since 1975, when Norwegian and Swedish studies on underground siting considered the use of the surrounding soil and rock as a filtering medium.[8] Subsequently, a UCLA study group[9,10] presented a conceptual

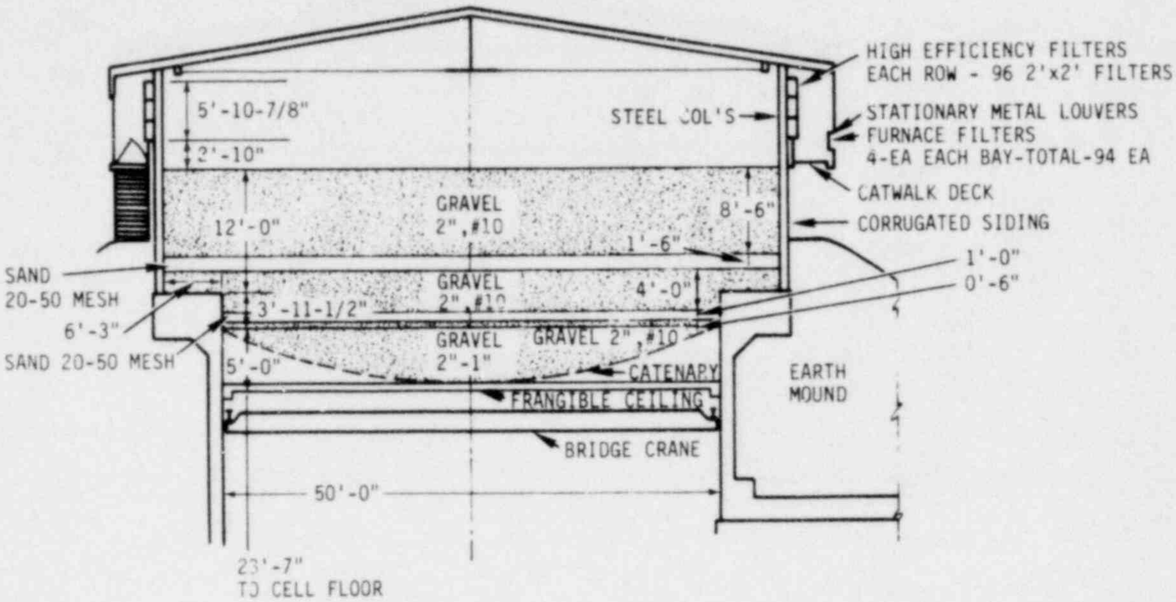

Figure 1. Roof Cross Section of the Zero Power Plutonium Reactor (from Reference 4)

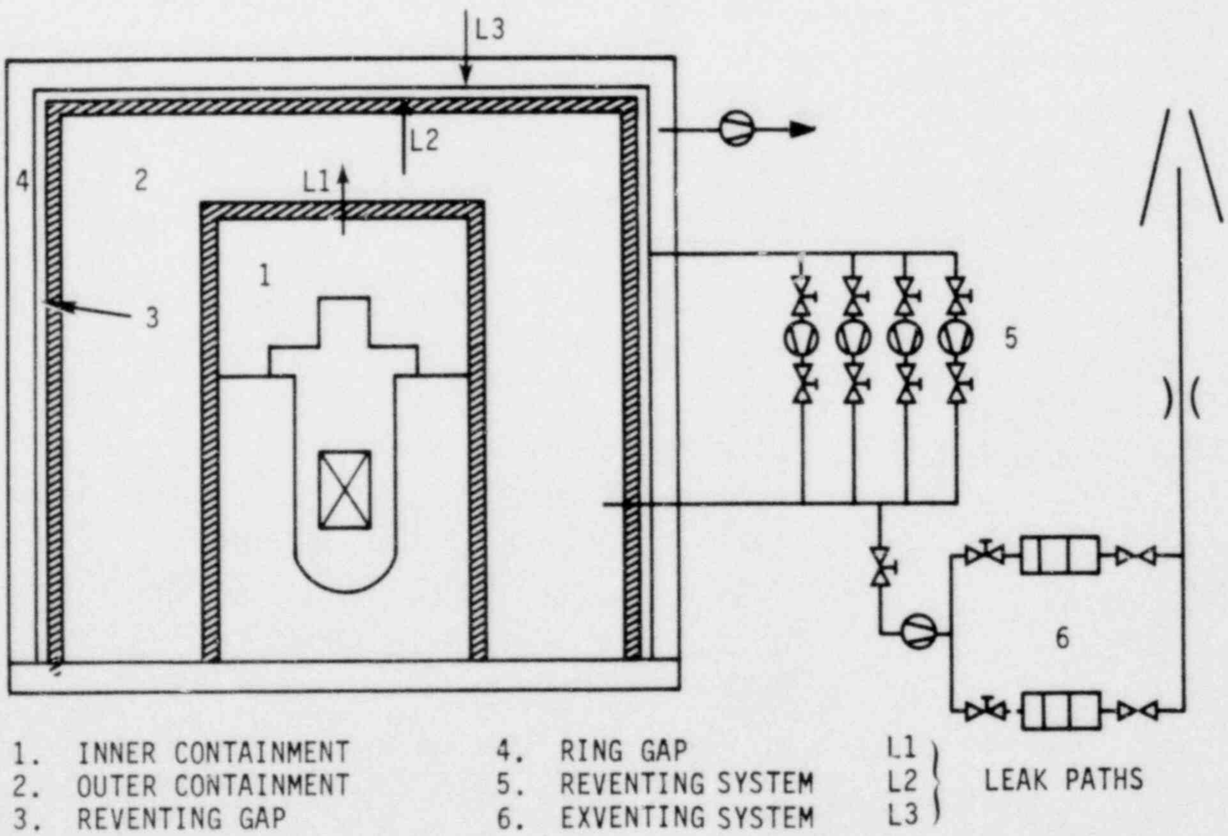

Figure 2. Off-Gas Filter System for the SNR-300 Prototype LMFBR (from Reference 7)

design of a vent-filter system for LWRs comprised of a graded sand and gravel bed with downstream HEPA and charcoal filters (see Figures 3 and 4). Their design included the use of hydrogen burners to minimize the likelihood of hydrogen explosions and air cooling fans to prevent overheating of the charcoal filters. More recently, the use of a controlled vent-filter system for core melt accidents was considered in a conceptual study of underground nuclear plants for the California Energy Commission (CEC).[11,12] The CEC design was completely passive, with the principal filtering structure being an underground pressure relief volume filled with crushed rock and gravel (see Figure 5). Conceptual designs were prepared for both aboveground and underground nuclear plants.

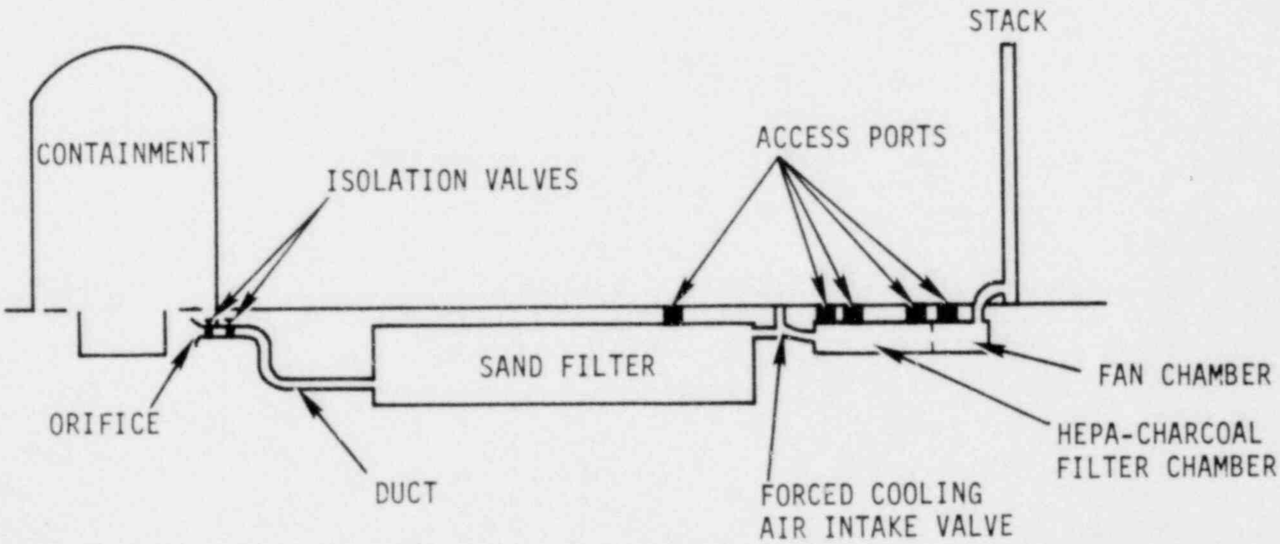

Figure 3. UCLA Conceptual Postaccident Filtration System Design (from Reference 9)

A conceptual design of a special-purpose postaccident filtration system was developed by Sandia Laboratories[13,14] during the recent accident at the Three Mile Island Unit II reactor as a contingency against a possible core meltdown (see Figure 6). The primary steam-condensing and filtering agent was water, which was contained below-grade in portable, drainable tanks and treated with sodium thiosulfate to improve its iodine retention capability. The water was kept subcooled by a single-loop direct heat exchanger that utilized

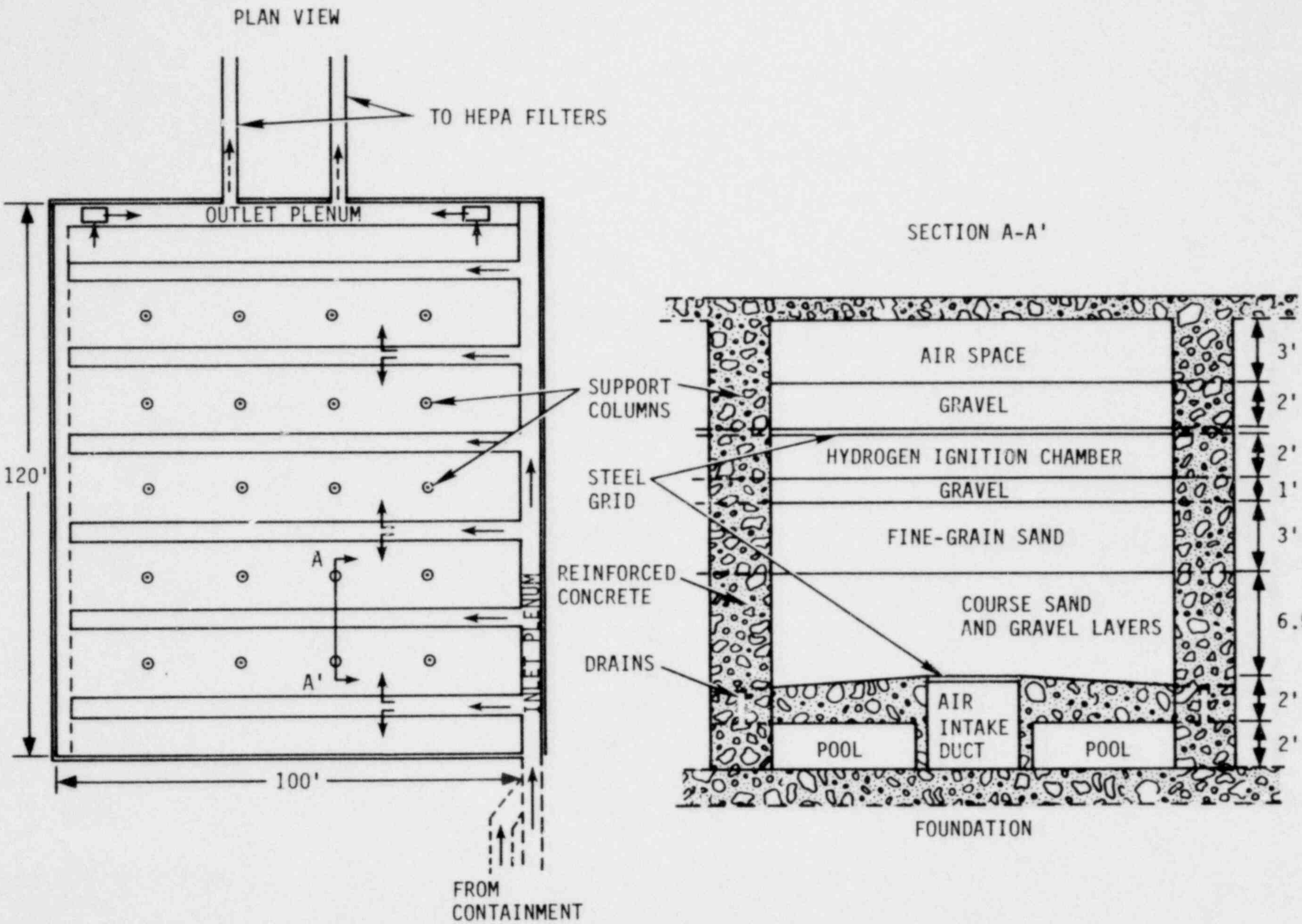

Figure 4. Sand Filter Component of UCLA Conceptual Design (from Reference 9)

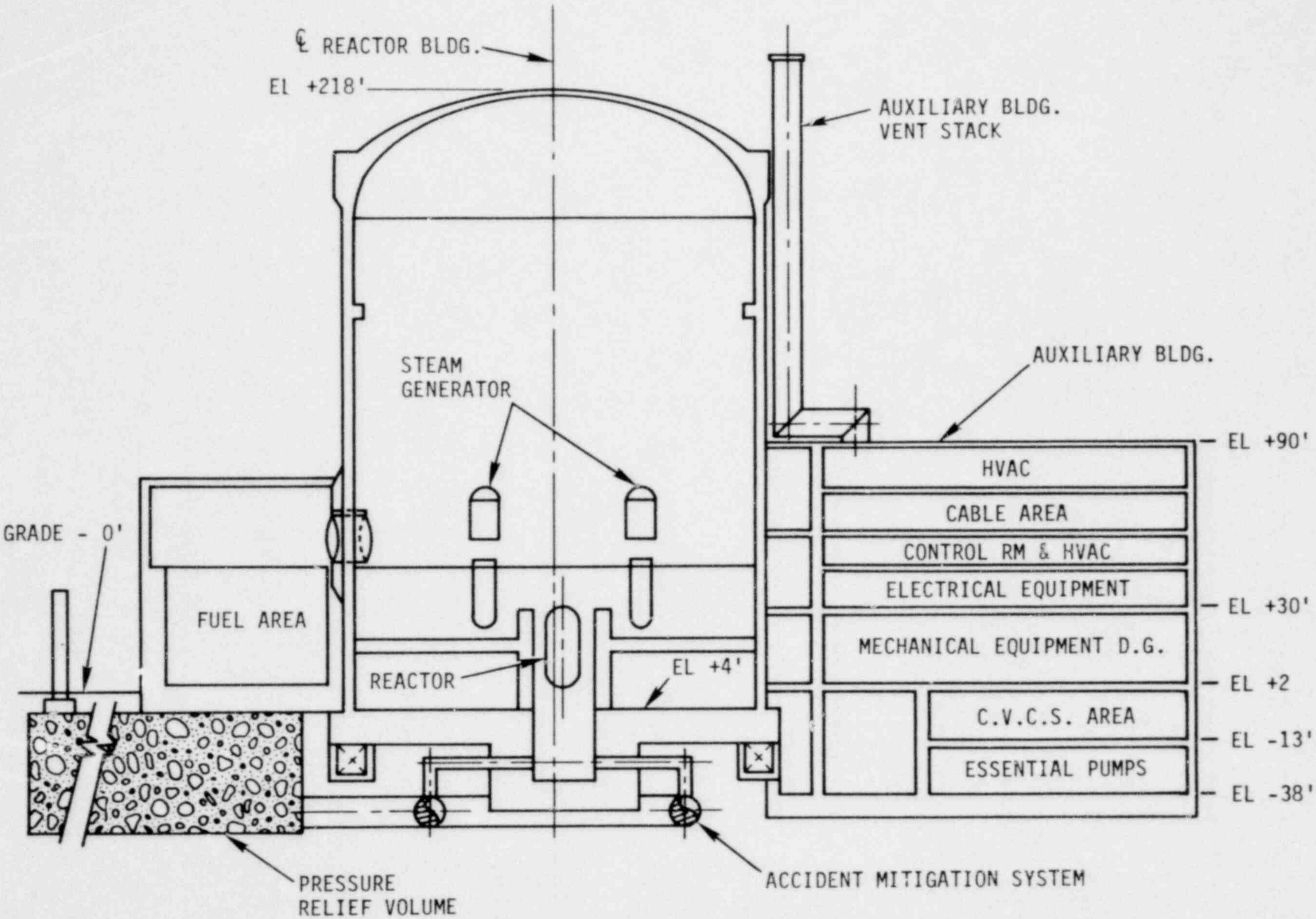

Figure 5. Conceptual Accident Mitigation System for Above Surface Reactor, from California Energy Commission Study (Reference 11)

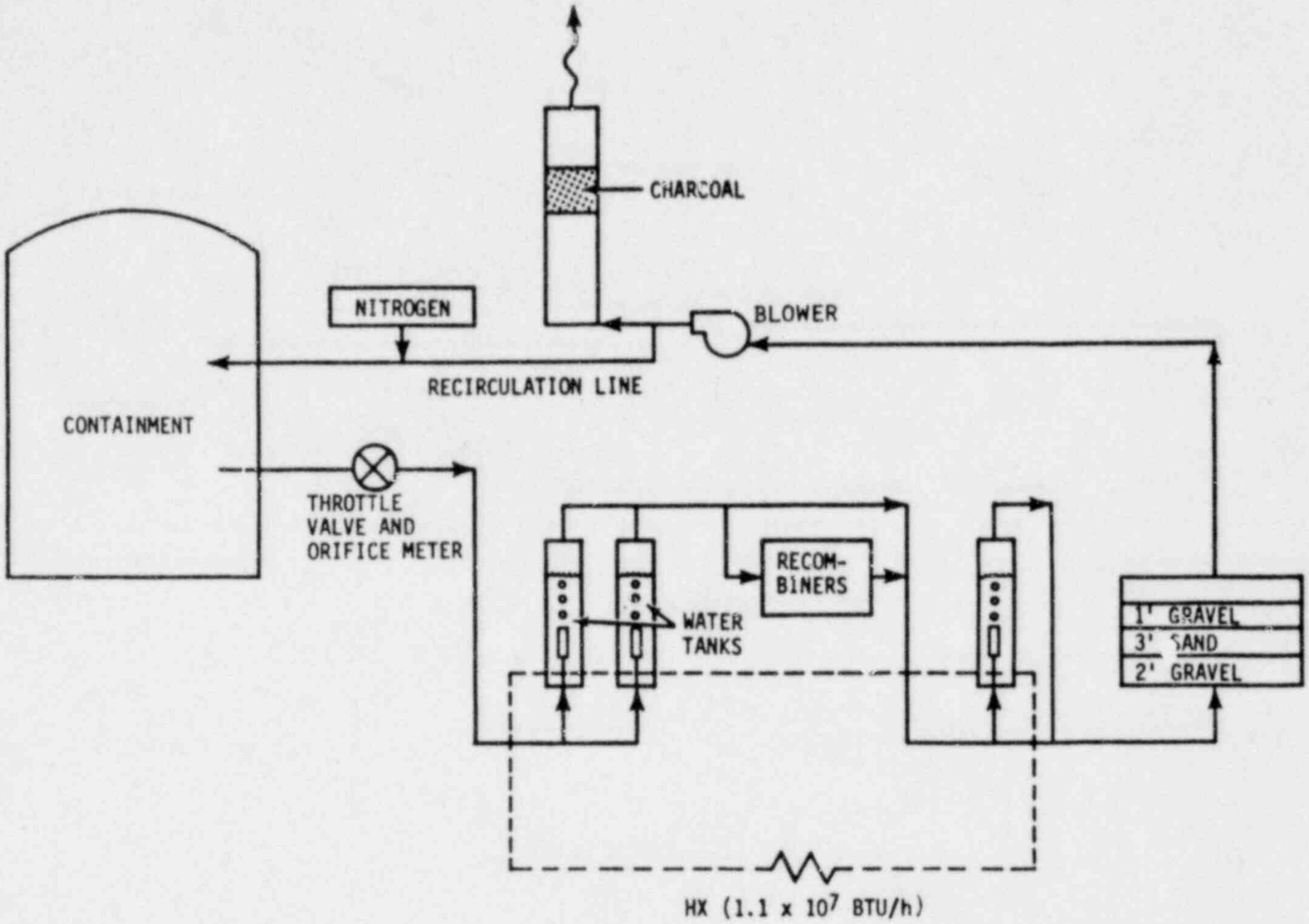

Figure 6. Schematic of Postulated Vent-Filter Design for Three Mile Island Reactor (from Reference 14)

the existing spent fuel cooling system. As options, hydrogen recombiners were provided to reduce the risk of hydrogen explosion in-line, and a gravel/sand filter was included for additional filtration and drying purposes. The exhaust from the filters could be released through the station vent, after additional scrubbing by charcoal filters, or could be recirculated back into containment. The vent-filter contingency capability was designed for rapid installation but was not implemented since the accident was successfully contained by other systems.

Value-impact assessments of vent-filter concepts for LWRs were performed by UCLA [9,10] by Battelle Columbus Laboratories,[15] and by Sandia Laboratories.[16] All three of these studies depend strongly upon the risk analyses presented in the Reactor Safety Study[17] and are therefore subject to some of the criticisms and limitations of that work.[18,19] Among these are (1) the somewhat atypical nature of the reactors considered[18] and (2) the indefensibility of certain risk estimates in the area of steam explosions.[19] Disregarding these questions for a moment, however, the UCLA, Battelle, and Sandia studies all reported that for pressurized water reactors (PWRs), filtered venting could potentially provide a factor-of-10 reduction in accident risks associated with health effects (e.g., see Table 1). These studies went on to report that for the specific reactor considered, the achievement of this risk reduction would require a substantial concommitant reduction of the failure probability of the low-pressure injection system (LPIS) check valve.*

In the case of the boiling water reactor (BWR), the UCLA study predicted that a factor-of-10 risk reduction potential was similarly available, whereas the Battelle study postulated only a factor-of-2 improvement. The difference in results for the BWR involved certain accidents initiated by a transient, and was brought about by differences in understanding over whether the vent system in a small Mark I containment could accommodate the almost instantaneous release of high-pressure steam that would follow a melt-through failure of the reactor vessel. In these accidents, the suppression pool is presumed to be at saturation temperature and therefore unable to condense steam.

In concluding this section, it should be mentioned that although most of the emphasis in the United States has been focused on atmospheric venting, the zero-release concept of venting directly into a separate vacuum containment building has been incorporated into some of the Canadian multi-unit CANDU reactors.[20]

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*Corrective action has since been taken for those reactors which were susceptible to LPIS check valve failure.

TABLE 1

Previous Estimates of Core-Melt Accident Risks for Pressurized Water Reactors, with and without Vent-Filter

Containment Failure Modes*	Early Fatalities/Yr	Latent Cancer Fatalities/Yr	Property Damage/Yr ($1000)
(a) Without Vent Filter (Reference 17)			
δ	2.6×10^{-5}	3.2×10^{-4}	8.4
γ	8.1×10^{-6}	5.9×10^{-5}	1.9
α	2.9×10^{-6}	2.8×10^{-5}	0.6
ε	0	6.5×10^{-6}	6.6
β	~0	4.2×10^{-7}	~0
TOTAL	3.7×10^{-5}	4.1×10^{-4}	17.5
(b) With Vent Filter (Reference 16)			
α	2.9×10^{-6}	2.8×10^{-5}	0.6
ε	0	1.5×10^{-5}	7.7
β	~0	4.2×10^{-7}	~0
TOTAL	2.9×10^{-6}	4.3×10^{-5}	8.3

*Explanation of Containment Failure Modes:

- δ : Containment overpressure (excludes hydrogen burning)
- γ : Containment overpressure caused by hydrogen burning
- α : Containment rupture caused by missiles from in-vessel steam explosion
- ε : Inadequate isolation of containment penetrations
- β : Basemat melt-through caused by molten core attack

Mode V (LPIS check valve failure) not included.

3. SYSTEM DESIGN AND PERFORMANCE CONSIDERATIONS

3.1 System Specifications

A major objective of this program is the specification of design criteria and performance requirements for vent-filter systems. These specifications will have to account for a wide variety of conditions under which the systems may be implemented or called upon for use. For example, the vent-filter systems should be designed to accommodate both high and low flow rates in order to cover the range of postulated accidents. In addition, separate considerations may be required for vent-filter systems that are backfit to existing reactors as opposed to those designed for future reactors.

A preliminary checklist of system specifications that need to be established is given in Table 2. It is anticipated that additions will be made to this list as the program progresses.

The following subsections concentrate upon specific design and performance questions that are important for vent-filter systems and that require special analysis. Design considerations common to containment safety systems in general may be found in Appendix A of 10 CFR, Part 50.

3.2 Seismic Category

The most critical question to be answered from a structural viewpoint is whether or not the entire vent-filter system should be designed as a Seismic Category I structure. The answer is not obvious, since regulatory guidelines do not normally address mitigation procedures for accidents beyond the design basis.

TABLE 2

Preliminary Checklist of Design Criteria and Performance Requirements to be Established

I. Functional Requirements

   A. Containment pressure reduction

   B. Containment temperature reduction, if necessary

   C. Mitigation of radioactive release

II. Operational Requirements

   A. Decontamination factors for important isotopes

   B. Quality assurance criteria (especially for sand filters)

   C. Maximum filter loading capacity and re-entrainment characteristics

   D. Maximum and minimum flow rates and pressure drops

   E. Heat removal and condensate drainage requirements

   F. Capability to withstand operating environment

   G. Instrumentation requirements

III. Resistance to Hazards

   A. Resistance to earthquakes, tornadoes, and missiles

   B. Resistance to fire and hydrogen explosions within filter system

   C. Resistance to steam explosion from within containment

IV. Reliability

   A. Valve actuation reliability

   B. Reliability of mechanical components (air coolers, hydrogen recombiners, heat exchangers)

   C. Likelihood of spurious operation

   D. Likelihood and impact of human error

   E. Filter failure or bypass modes and likelihood of occurrence

   F. Emergency power requirements

   G. Redundancy

V. Control

   A. Actuation logic

   B. Flow rate control

   C. "Zero-release" options

TABLE 2 (Continued)

VI. Sabotage Protection

- A. Passive operation versus operator control
- B. Protection of piping, valves, and filters from unwanted access

VII. Inspection Considerations

- A. Ease of access
- B. Frequency of inspection
- C. Inspection objectives:
    1. Evidence of structural damage or degradation
    2. Water infiltration, weathering
    3. Contamination with foreign matter
- D. Impact on plant operating procedures

VIII. Testing Considerations

- A. Frequency of testing
- B. Testing objectives:
    1. Efficiency degradation versus time
    2. Flow resistance versus time
    3. Component availability
- C. Testing Methods

IX. Maintenance Considerations

- A. Ease of access
- B. Periodic replacement of filter materials (especially charcoal)
- C. Grooming of filters (especially sand bed)

X. Postaccident Safety and Repair-Restoration Considerations

- A. Shielding criteria
- B. Access to plant after accident
- C. Difficulty of restoring reactor to service

If the vent-filter is considered an "engineered safety feature" on the same level as those used for design basis accidents, then it would have to be designed to the same level of seismic protection. This would imply special penetration criteria for containment penetrations, vent lines consisting of double pipes with air cooling between them, and guaranteed inspectability from inside and outside the filter housing. These provisions would add very significantly to the cost of the system.[21,22]

On the other hand, it is not clear that such systems should be designed to this level of protection, given that core melt accidents are not considered to be within the design basis. As a minimum, it would certainly be necessary to design the vent line containment penetrations as Seismic Category I, in order to insure containment isolation during design basis accidents. Beyond that, the argument for or against a Category I structure depends upon a variety of considerations, including regulatory concerns, costs, and the anticipated effectiveness of the structure (i.e., its potential for reducing public risks or consequences). The last of these issues may be strongly dependent on site.

If the issue of seismic category cannot be easily resolved, it may be necessary to formulate designs that are Seismic Category I throughout and designs that are not and to perform the value-impact assessment for both cases.

3.3 Influence of Containment Type on Design

3.3.1 Introduction

The nature of the containment and its components is expected to influence the design of the vent-filter system to a degree. The primary ways in which these differences will manifest themselves in terms of venting requirements are as follows:

1. Different containment types have markedly different internal volumes and different structural failure pressures.

2. The accident sequences dominating public risk vary from one containment type to another.
3. Differences in component design or layout have an effect on determining the optimal location of the vent inlets.
4. Some containments are inerted while others are not.

A few of the implications of these differences will now be described briefly.

3.3.2 Overpressure in Small Containments

In the conceptual study performed by Battelle Columbus Laboratories [15] it was concluded that an overpressure failure of BWR Mark I containments might occur regardless of the venting capability postulated to exist. The accident sequences posing this problem were identified as TC or TW, namely the occurrence of a transient event accompanied by a failure to SCRAM (TC) or a failure to effect post-accident heat removal (TW). In either case, the reactor vessel was postulated to fail in a gross manner when the pressure inside exceeded the failure pressure of the vessel. Since the suppression pool was saturated at this time, it was assumed that the steam released to the containment did not condense. The pressure in the containment was postulated to rise immediately by about 90 psi to an absolute value of 190 psia, which exceeded the containment failure pressure by about 15 psi.

Since the TC and TW sequences contribute significantly to the overall risk for the BWR Mark I containment,[17] it will be necessary to design the vent-filter to circumvent the problem described above. One possibility will be to actuate containment venting if the pressure in the reactor vessel, rather than the containment, were to exceed the design value so that the pressure in the containment at the time of reactor vessel breakthrough would be relatively low. Another possibility is to design the vent-filter with an expansion volume in order to relieve some of the pressure increase in the containment at the time of vessel rupture.

3.3.3 Venting Locations

In BWR containments, it has been suggested[23] that one or more of the vent inlets be placed in the wetwell to take advantage of the filtering capability of the pressure suppression pool. In large, dry PWR containments, it has been suggested[24] that for cases where failure of the LPIS check valve is a large contributor to risk (i.e., the V sequence in the Reactor Safety Study), it may be possible to vent from the valve itself into the filters. The feasibility of either of these two suggestions has not been established and needs to be studied further.

3.3.4 Hydrogen Explosion in Containment

Containments that are not inerted may be made more susceptible to hydrogen explosions as a result of the operation of the vent-filter. This possibility is discussed in Section 5.3, where it is suggested that special design provisions may be desirable to reduce the likelihood of hydrogen explosions in containment.

Explosions occurring within containment, whether induced by hydrogen detonation or molten core/water interaction, can produce strong shock waves that might adversely affect the filters downstream. One method of weakening these shock waves is to design a series of expansions and contractions into the vent lines.

3.4 Design Trade-Offs

3.4.1 Method of Actuation

The reliability of the system is strongly related to the method of actuation. In the California Energy Commission study,[11,12] it was assumed that the venting process was activated passively by rupture disks that were designed to fail at specific pressures or temperatures. It was postulated that it would be possible to arrange these disks in series and in parallel in such a way as to achieve any specified level of reliability. Passivity, in this case, enhanced the reliability of activation but forfeited a level of subsequent control that may be highly desirable (see Section 5.1.2). It is also pertinent to note that the ASME boiler and pressure vessel code does not allow for a containment vessel having large rupture disks with no positive shutoff valves.

The UCLA conceptual design of a vent-filter[9,10] was based on the use of manual valves to be controlled by an operator. With this method of operation, the possibility of human error becomes important. In certain circumstances, the operator may either actuate the system at the wrong time or fail to actuate it at the right time. In addition, the UCLA design utilized only a single inlet valve, thereby increasing the chances of failure resulting from the valve being defective or plugging during use.

The means of actuation in the present study will probably involve a combination of manual and motor-driven valves, together with popoff valves or rupture disks, to achieve a reasonable trade-off between reliability and control. It may be possible to acquire some help in the valving and venting aspects of the design by referring to the existing CANDU reactors which are designed to vent into a vacuum building.[20]

3.4.2 Method of Operation

In addition to actuation considerations, the question of reliability versus control enters into many of the operating aspects of the system. Among these are (1) control of the flow rates, (2) control of hydrogen recombiners and heat exchangers, (3) condensate drainage considerations, (4) the option to recirculate--see Section 3.5, and (5) the flexibility to bypass areas of the system that are unneeded or functioning adversely (e.g., a saturated water pool or an ignited charcoal filter). Trade-offs between reliability and control will be required in each of these areas.

3.4.3 Sabotage Protection

The use of a vent-filter system in a reactor plant should have the net effect of improving sabotage protection by increasing the difficulty of achieving an accident with major health effects through an act of sabotage. A saboteur would not only have to initiate a core-melt accident but would have to incapacitate the vent-filter as well.

Generally, achievement of a high sabotage safeguard potential is consonant with the achievement of high reliability in that both are enhanced by the use of independently redundant components and an emphasis on passivity. Achievement of this potential, however, tends to conflict with the desire for controllability and ease of access. A need for controllability would suggest that the operator should have the flexibility of closing the vent valves or at least moderating the rate of venting once the system has been actuated (see Section 5.1.2). This flexibility, however, could be used to the detriment of the system if it were exercised by the wrong person. Accessibility of the filters, moreover, could increase a saboteur's opportunity for disabling the filters, causing perhaps a bypass or blowout problem to occur during an accident.

Achievement of an acceptable level of reliability, control, accessibility, and sabotage protection will require design trade-offs at the conceptual stage.

3.5 Recirculation Options

In cases where rapid depressurization of containment is necessary, a once-through filtration and exhaust system would be preferable to a system where the noncondensibles are reinjected into the containment atmosphere. If the pressure transient is not too rapid, however, the idea of recirculating the noncondensibles rather than releasing them has important advantages. First, recirculation effectively eliminates all release of radioactive material to the environment. Second, the function of the heat sink medium (e.g., water or gravel) in condensing the vented steam and condensible fission products provides a means for arresting or reducing the containment pressure, although not as effectively as in the exhaust mode. Third, a net removal of heat from containment can be effected by reinjecting the noncondensibles into containment at a lower temperature than that at which they were removed. Fourth, the filtration function can serve as a containment air cleaning system, facilitating subsequent access to the reactor.

If a recirculation capability were to be implemented, it would be used as an option rather than a replacement for the once-through filter and release mode. It would obviously involve added complexity and the need for at least one additional active component (i.e., a blower to pump the noncondensibles back into containment), and it might provide an additional mechanism for human error. Particularly, the operator would have to be careful not to use the recirculation mode if the containment pressure were rising too rapidly or if too much hydrogen were being recirculated back into containment. Whether its advantages outweigh its disadvantages must be determined.

As a variation on recirculating back into the vented containment, the option of venting through filters into an adjacent containment can also be considered. The second containment might be an actual reactor containment housing another nuclear reactor, or it might be a special structure designed as part of the vent-filter system. In either case, venting into the second containment would accomplish a more rapid pressure reduction than recirculating into the vented containment and would eliminate the need for a blower. The disadvantages are (1) that it might be unacceptable to contaminate a second reactor unit and (2) that the cost of a special leaktight containment structure might be high compared to the cost of the vent-filter itself.

3.6 Filter Locations

Assuming that the filtering media are located outside containment, a choice exists as to how the filters should be placed. Underground burial offers the advantages of providing protection against certain external hazards (e.g., missiles, hurricanes, and tornadoes) and of utilizing the natural shielding capacity of the earth to protect personnel from radiation exposure. If it should develop, however, that underground burial of the filters places a substantial imposition on the accessibility and maintainability of the system or increases the cost due, for example, to excavation or containment penetration expenses, then an alternative might be to place most of the system below grade (but not underground) or to place the filters above ground in a separate building, and to use existing containment penetrations that are above grade.

3.7 Nuclear Air Cleaning Guidelines

Guidelines for the construction of nuclear air cleaning systems appear in various references.[25-27] Some of the recommendations are listed below:

1. Filter housing should be of heavy, welded construction. Sealants should be avoided because they deteriorate with time, do not always adhere properly, and do not withstand radiation well.
2. Unnecessary penetrations (e.g., for electrical conduits) should be avoided. Drains should be well seated and individually trapped. Valves should have position indicators and be checked periodically.
3. Turning vanes, flow straighteners, and other devices may be necessary to avoid an uneven air distribution. ANSI-N510 specifies that flow volume and uniformity must be demonstrated as a prequisite to in-place testing.
4. Unnecessary system flow losses should be minimized by avoiding sharp bends in ducting and poor inlet/outlet design for fans and housing.
5. Instrumentation should be located in places not subjected to intense heat, cold, or condensation which might cause them to degrade. Adjacent lines should be sloped to drain moisture away from the instruments.

4. FILTER ALTERNATIVES

4.1 Gravel/Sand Filters

Sand filters have been used in the ventilation and process exhaust systems of radiochemical processing facilities since 1948. In addition, the use of sand filters for bomb shelter ventilation systems was to some extent adopted in Germany and other European countries at about the same time. The major attractions of sand filters include their large aerosol holding capacity, low maintenance requirements, inertness to chemical attack, high heat capacity, fire resistance, and the ability to withstand shock loadings and large changes in airstream pressure without becoming inoperative. The disadvantages, relative to other filtering media, include high capital cost, large area, high pressure drop, availability uncertainties, and disposal considerations.[28]

The type of sand, the bed dimensions, and the grading details are important design considerations if the sand filter is to function well. The lower gravel layers must be able to condense most of the steam and condensible vapors exhausted from the containment. The intermediate sand layers must be capable of capturing and retaining most of the aerosol particles. The upper gravel layers must be sufficient to prevent levitation of the sand. The system as a whole must be resistant to dynamic shock loading conditions as might be experienced as a result of a hydrogen or steam explosion in containment. These prerequisites must be balanced with the need for avoiding an excessive pressure drop across the filter under the maximum flow conditions expected.

The early use of sand filters for bomb shelter ventilation established the capacity of sand to protect such shelters from the blast effects of nuclear explosions and the heated air resulting from fires. The ability of sand filters to attenuate shock waves of up to 100 psi overpressure and to absorb large amounts of heat was demonstrated in experiments conducted by the US Naval Civil Engineering Laboratory in 1963.[29]

The effectiveness of sand filters for capturing fission products depends upon two properties: efficiency and loading capacity. There is a fair amount of data relative to the efficiency of sand filters, particularly for particulate capture, but a much smaller amount of data is available regarding loading capacities.

The filtering efficiency of sand for particulates has been found to vary widely according to the grain size distribution and surface texture of the sand. Tests at the Savannah River Plant (SRP) with polydisperse DOP aerosol having a mean-mass particle size of 0.8 micron showed that a filtering efficiency of 99.98% (i.e., decontamination factor of 5,000) should be possible if the sand is properly selected and the layer is sufficiently thick (~1 metre).[30] Experiments conducted in support of the ZPPR sand filter[31] corroborate that an efficiency of 99.98% is reasonable as well for uranium and plutonium aerosols having mean particle sizes significantly less than 1 micron. These tests, which were conducted over a wide range of superficial velocities, tend to resolve uncertainties that have been expressed about the ability of sand filters to entrap submicron particles.[9] Note that a filtering efficiency of only 99% for particulates and elemental iodine (i.e., a decontamination factor of 100) has often been postulated as adequate to reduce the risk of overpressurizing accidents below that of other types of accidents.[9,15]

The particulate loading capacity of sand has been shown to be quite high as a result of long-term experience in fuel processing plants.[30] There is, however, a need for data to establish more completely the magnitude of the loading limits.

The efficiency of sand filters relative to vapor species will vary according to the volatility of the species and, to some extent, their solubility in water. Species of low vapor pressure (including most of the metallic compounds) will tend to condense along with the steam on the gravel. Species with high solubility in water (such as cesium and rubidium compounds) will tend to be captured by the condensed water as well. It may be possible with current knowledge to estimate the fraction of vapor species that can be captured by condensation or dissolution; however, these estimates will certainly be very approximate. For that matter, predictions of the effectiveness of gravel in condensing the steam are limited by uncertainties regarding the heat transfer characteristics of a gravel bed and, more critically, the drainage characteristics of the condensate. There is a definite need for experiments to study these problems.[23,24]

Vapor species with moderate or high volatility, such as the halogens and noble gases, will be attenuated less effectively in the gravel/sand filter than the more condensible species. The filter may be reasonably successful in capturing elemental iodine, which is only moderately volatile and which adsorbs to some degree upon sand; experiments and analyses should be performed to determine whether gravel and sand by themselves are sufficient for this specie. Organic iodine and the noble gases, however, will tend to pass through the filter without significant attenuation. Whether or not these species pose a significant enough risk to warrant special design provisions for limiting their release remains to be determined.

It has been suggested that additives such as ferrous oxide have the potential for removing additional amounts of iodine due to their iodine-adsorption capabilities.[24] The impregnation of the sand with additives, however, may introduce new problems that require special consideration. In particular, it is quite possible that additives may increase the hydrodynamic resistance of the filter, and if the additives are hygroscopic, they may absorb enough moisture over a period of time to markedly affect both the resistance and the efficiency.

A number of potential problem areas regarding the design and construction of sand filters were highlighted by experience at Savannah River. These problems are not necessarily restricted to filter systems that are in continuous service but could occur as well with systems that are in place but inactive over a period of time.

During operation of one of the processing buildings, it was found that a substantial increase in pressure drop developed across the sand filter between 1954 and 1972, necessitating the removal of 1 foot of fine sand from this unit. The increased resistance was attributed to one or more of the following possibilities:

1. Concrete dust loading from construction nearby,
2. Concrete and sand fines from erosion of the concrete walls,
3. Nonsilica materials present in the sand,
4. Accumulation of moisture together with calcium and magnesium salts.

Clearly the filter system must be designed to reduce the likelihood of contamination with foreign matter, and any proposed additives must be tested to verify that they do not aggravate one problem while alleviating another.

A second difficulty encountered with the SRP sand filters was a progressive weakening of the underbed supports and air distribution systems caused by acid attack and erosion. By 1971, both units had suffered a localized loss of filter medium caused by failure of the support and leakage of sand. The bottom support systems on both were modified to temporarily prevent any further penetration of the bed, and the units were subsequently replaced by new units in 1975-76. Although acid attack, per se, may be more of a problem for processing plants than for one-time reactor applications, the experience at SRP demonstrates the need for underbed construction procedures that will preclude the possibility of any significant sand leakage in the event of a support failure (e.g., from a seismic event).

At SRP, episodes were encountered in which external ground water and rain reached the bed or in which periods of high humidity produced increased water loadings. During these occurrences, higher pressure drops were observed but filtration efficiency was not adversely affected. Although these experiences indicate that nominal amounts of water loading will not produce deleterious results affecting filter operation, it is not clear that the same will be true when much greater amounts of water are encountered as a result of steam condensation during postaccident filtration. Experiments to investigate the effect of water loading on sand bed performance would be desirable.[24]

With a wet sand bed, there is also a possibility for water to aspirate up through the bed and carry radioactive material through to the outlet side. Although this was not observed at SRP, where air velocities were under 4.0 cm/s, it may occur more readily in a postaccident situation if the vent-filter system is designed for higher carrier gas velocities. Experiments, again, would be the desirable way of answering this question.

In summary, gravel/sand filters appear to offer a high potential as a primary filtering medium for Class 9 accidents, but there are a number of properties which need experimental investigation. These include (1) fission product loading capacities, (2) the heat sink and condensate drainage properties of gravel, (3) decontamination factors for iodine, (4) the effect of additives such as FeO, and (5) the effect of large amounts of water loading.

Finally, the emergence of a dry mixture of air and hydrogen from the sand bed increases the possibility of explosion. The impact of a hydrogen explosion on the system and the incorporation of design features to reduce the probability of occurrence should be considered (see Section 5.3).

4.2 Fiberglass Filters

As an alternative to sand filters, deep-bed fiberglass filters are being used successfully for the filtration of ventilation and process air in a number of radiochemical and fuel processing operations. These filters are less costly than sand filters, have more controllable physical features and a more assured availability than filter-grade sands, require less volume for the same air flow, and have lower operating costs and potentially lower disposal costs. On the negative side, fiberglass filters have neither the particle collection efficiency of sand filters nor the heat sink and vapor condensation capacity, they offer a lower resistance to fire and corrosion, and they lack the self-repair properties and the capability of sand filters to withstand shocks and high-pressure transients. In addition, they are reported to have a bypass leakage problem, which hampers their efficiency.[9]

The use of fiberglass filters may be investigated as a lower cost alternative to gravel/sand filters.

4.3 Water Pools

Water pools have several advantages over sand filters and fiberglass filters and also several disadvantages. One primary advantage is a proven effectiveness to condense steam. Unlike sand and fiberglass filters, which have not been tested in large-scale steam flows and which, consequently, are subject to uncertainties in such environments, water pools have been tested extensively and successfully as scrubbers in high-flow steam environments and have been included for vapor suppression in BWRs. Furthermore, water is readily available, is inexpensive, and has fewer of the special preparation and maintenance problems of sand and fiberglass filters.

Water pools are reasonably effective at removing fission products by particulate capture, by vapor condensation, and by dissolution from the vapor phase. Experimental results summarized elsewhere[32] indicate that the efficiency of water for capturing small particles can be expected to be on the order of 98%, which is respectable even though the corresponding decontamination factor (50) may be two orders of magnitude less than that for sand. Data for iodine capture by water pools are quite variable but indicate that fairly high efficiencies (>99%) can be obtained by using additives such as sodium hydroxide or sodium thiosulfate. Methyl iodide and noble gases tend to pass through water pools relatively unaffected, but the same would be expected for sand and fiberglass filters.

A significant advantage of water pools is their adaptability to a heat exchange system. In the simplest form, the pool water can be circulated through a direct-loop heat exchanger in a manner similar to current spent fuel pool cooling systems. If the heat exchanger is large enough to absorb most of the latent heat of the steam exhausted from containment as well as the decay heat of the captured fission products, then the size of the pool can be reduced accordingly. A gravel/sand filter, on the other hand, must rely on its heat-sink capacity to remove the latent and decay heat. The use of a heat exchanger, of course, would add an active component to the system, and the probability of failure of that component would have to be considered in evaluating the risks/benefits of the concept.

Since the fission product capture efficiency of water is generally not as high as for other filter media, it is reasonable to think of utilizing a water pool for heat sink, condensation, and prefiltering purposes while utilizing a different agent for backup filtration. Since a water sump would be necessary anyway for collecting the condensate from a deep-bed sand or fiberglass filter as well as collecting any water carried out from the containment, it might be natural to direct the containment exhaust into the sump water before entering the deep bed.[33] The feasibility of using the sump for heat sink and prefiltration purpose requires further study.

4.4 HEPA, Charcoal, Zeolite, and Cryogenic Filters

The postaccident filtration system conceptual design developed at UCLA (Figure 3) utilized both HEPA and charcoal filters downstream of a gravel/sand filter to enhance the removal of very small particles and iodine compounds from the carrier gas. The charcoal filters were considered to be impregnated with I_2, KI, or triethylenediamine (TEDA) to promote the retention efficiency for organic iodine.

The penalties associated with using HEPA or charcoal filters are considerable and may well outweigh the benefits. First, the dry hydrogen-air mixture emerging from the sand or fiberglass filter might have to be recombined to rule out any possibility of explosion, which could destroy the HEPA and charcoal filters. The resulting gas mixture would then have to be cooled substantially since its temperature after the hydrogen burning would be far too high for the downstream filters. As in the UCLA design, the cooling function might be provided by having an additional layer of gravel or other heat sink material (e.g., water pool) above the zone of recombination.

Charcoal filters, in particular, have a low resistance to fire, and if a fire were to develop in a charcoal filter, most of the trapped radionuclides would be released and re-entrained. If the charcoal filters were expected to capture significant amounts of iodine, therefore, they would have to be air-cooled. The use of hydrogen recombiners and air cooling fans may reduce the reliability of the system. In addition, the adsorption capability of charcoal filters decays with time, and even in a standby mode it is usually necessary to replace the filters at 3-year intervals.[28]

As an alternative to charcoal filters, inorganic silver zeolite can be used effectively to retain iodine. Zeolite filters have high absorption efficiencies for both elemental and organic iodine, are effective at relatively high temperatures and high humidities, and do not ignite. Their disadvantage is their high cost.

Cryogenic filters have been suggested as a way to remove noble gases from the containment environment.[9] These filters, however, are very expensive, and it is not clear that the reduction in overall risks attainable by elimination of the noble gases would justify that cost. Nonetheless, the feasibility of using cryogenic filters or other means for retaining noble gases will be studied.

4.5 Tentative Filter Combinations

Among the filter types discussed above, a number of reasonable filter systems can be proposed. Some of these are listed below:

One Filter Component

1. Water
2. Gravel/sand
3. Fiberglass

Two or More Filter Components

4. Water ⟶ gravel/sand or fiberglass
5. Gravel/sand or fiberglass ⟶ zeolite or HEPA/charcoal
6. Water ⟶ gravel/sand or fiberglass ⟶ zeolite or HEPA/charcoal

The choice of filter combinations for the conceptual study may differ from one reactor type to another. In the case of BWR reactor containments, for example, it may be possible to vent from the wetwell, utilizing the suppression pool as a prefilter and obviating the need to consider a separate water pool for filtration outside the containment (see Section 3.3.3).

5. TECHNICAL QUESTIONS

5.1 Interaction with Other Safety Systems

5.1.1 Operation as Designed During Core-Melt Accidents

As presently conceived, the vent-filter would not operate until a set design pressure or temperature condition had been exceeded. As discussed in Section 3.3.2, the actuation criteria might be based on conditions in the reactor vessel as well as in the containment. Regardless, operation of the vent-filter would be limited to cases that exceeded the design basis.

Upon actuation of the vent-filter, it would be desirable, if possible, to reduce leakage of fission products from the containment by rapidly reducing the containment pressure to essentially ambient conditions. This in fact was the philosophy governing both the UCLA and California Energy Commission postaccident filtration system designs. Unfortunately, a reduction of the containment pressure to ambient levels would likely cause some flashing of the containment sump water, which might result in cavitation in those pumps that draw suction from this sump.[34,35] In the case of PWRs, this could lead to failure of the low-pressure recirculation system (LPRS), the containment sprays, and the containment heat removal system.

Since it is important that these systems operate for as long as possible, alternative approaches may have to be considered. One possibility might be to vent only enough steam from the containment (e.g., by the use of pressure relief valves) to lower the pressure to a reasonable value that does not jeopardize the other containment systems. Another approach might be to provide a larger supply of water for emergency core cooling system (ECCS) and containment spray injection, so that intake from the sump would not be required until after the vent-filter had been operating for some time. A third approach might be to replace the pumps in question with new pumps that can operate successfully with two-phase flow. A fourth possibility might be to redirect the pump intake to an external source, which might possibly include the water sump for the filter system.

In addition to the question of pump cavitation, there are possible interfaces between the vent-filter system and other engineered safeguards, such as the containment isolation system and the emergency air cooling system. The effect of the vent-filter on these systems must also be studied.

5.1.2 Fallibility of Actuation Logic

It has been suggested that operation of the vent-filter as designed might in some cases escalate an accident of minimal consequence into an accident of large consequence.[36] One example is the case of a loss-of-coolant accident (LOCA) where the containment sprays are delayed, causing the containment pressure to temporarily exceed the design pressure without exceeding the failure pressure. Subsequent actuation of the sprays would normally reduce the containment pressure and temperature below the design levels and allow a successful termination of the LOCA.

If the vent-filter were designed to actuate when the containment pressure exceeded the design value, however, the venting operation would reduce both the noncondensible inventory in the containment atmosphere and the liquid water inventory in the sump. (The reduction of sump water inventory is caused by the tendency of the sump to replace the steam that is vented from containment by the process of vaporization.) When the sprays become activated, two adverse possibilities could occur. First, the sprays might condense so much ste in containment that a severe vacuum might result. This could create a structural problem for containments that are not designed for vacuum operation, especially those that are already prestressed in compression. Secondly, the sump might run dry prematurely, eliminating the source of water for the ECCS and containment sprays and escalating the accident into a core melt.

The possibility of exacerbating a tolerable situation into an intolerable one must be studied very carefully. In the particular case mentioned, it is first necessary to determine whether the venting process would in fact create a vacuum, deplete the containment sump, or cause the pumps to cavitate as discussed in the preceding section. Problems of this sort, if they do exist, would seem to argue for a controllable venting system. It might be desirable, for example, to initially vent only enough steam to keep the containment pressure from exceeding the design level. If the pressure reduced of its own accord, e.g., by delayed initiation of the containment sprays, the vents could be closed. If the high pressure persisted, the venting rate could then be progressively increased to reduce the containment pressure and prevent excessive leakage.

5.1.3 Spurious Operation During Non-Core-Melt Accidents

If a vent-filter utilizing atmospheric release were incorrectly set in operation during a non-core-melt accident, there would obviously be some release of radioactive fission products through the filters into the environment. The magnitude and associated risk of this occurrence is expected to be small if the filters operate as designed. If, however, the filters were somehow bypassed, the magnitude of release might be significant. The risks of spurious operation with and without filter bypass will be considered during the study.

Aside from direct releases, there is also some concern that a vent-filter operating spuriously during the early portions of a LOCA might adversely affect the reflood operation. The source of the concern is identical to that expressed in Section 5.1.1, namely the loss of backpressure in the containment. This loss of pressure is postulated to cause an increased spillout of reflood waters through the LOCA hole in addition to an increased amount of spatter and boiling in the reactor vessel and the reactor coolant system (RCS), resulting in a degradation of the reflood efficiency. Calculations used in formulating the Interim Acceptance Criteria 10 CFR 50.46 for the ECCS indicate that a minimum containment pressure of around 25 psia may be required to insure effective operation of the system.

The risk of interference with the emergency core cooling system in the event of spurious operation of the vent-filter will be studied further and taken into account during the value-impact assessment.

5.2 Long-Term Containment Integrity

Calculations performed in connection with the California Energy Commission study[11] indicated that although the venting process should succeed in reducing the pressure of the containment to manageable values, it might not be so successful in keeping the temperatures down on a long-term basis. Within 2 to 4 days after accident initiation, the temperature of the containment was predicted to exceed 400°F, a temperature which threatens the integrity of the containment seals. Temperatures around 700°F were predicted to occur after about 1 to 2 weeks.

If the containment seals should fail in the time frame of 2 to 4 days, there will undoubtedly be releases of radioactive materials to the environment. The amounts of release may, however, be quite small in view of the time available for radioactive decay and gravitational settling of the aerosols, as well has the low-pressure driving force afforded by the previous exhausting of steam through the vent-filter. The risks associated with this mode of failure, nevertheless, will have to be evaluated, and if there is a problem, the possibility of replacing the existing seals with high-temperature resistant seals will have to be considered.

In addition to a possible failure of the containment seals, the long-term integrity of concrete above the boiling temperature of water (212°F) is a source of uncertainty which will have to be taken into consideration.[21]

5.3 Hydrogen Explosion Potential

It is conceivable that venting may increase the likelihood of hydrogen ignition within the containment by increasing the concentration of hydrogen relative to air. This may happen in a containment that is not inerted if the vent exhausts much of the air in the containment prior to the interaction of core melt with concrete.[34] A possible solution would be to utilize hydrogen recombiners in the reactor cavity to burn the hydrogen as it is emitted from the concrete.

A problem of hydrogen deflagration within containment might also occur if there were any backflow from the filters to the containment.[33] This possibility may be circumvented by utilizing one-way valves.

Hydrogen explosions in the vent line may also pose a particular hazard to the system. After condensation of the steam carrier, the remaining noncondensible gases may be rich in hydrogen and therefore potentially explosive. Hydrogen recombiners located downstream of the condensing medium may provide a way of circumventing hydrogen explosions in the line (see Figures 4 and 6, for example), but it is not clear that this would be the best solution. Other methods of dealing with large amounts of hydrogen will also be considered, including the use of transition elements to form hydrides, molecular diffusion through a diffusive barrier, chemical fixation, and regenerative liquefaction.

The main difficulty at this point with utilizing an antideflagration agent, such as bromotrifluoromethane, is that the effectiveness of these additives has not been established in radiation environments. Some testing of antideflagration substances in simulated accident environments would be useful.

5.4 Filtering Effect on Plume Transport

Depending upon the design of the vent-filter system, the exhaust from the filters may emerge and be discharged from the station vent at a considerably lower temperature than that which would escape from a conventional containment by leakage or outright failure. The filtered plume might therefore be considerably less buoyant than an unfiltered one. An attempt will be made to account for this buoyancy effect in assessing the consequence of filtered venting versus conventional containment.

5.5 Containment Failure Uncertainties

Although the use of a vent-filter system appears to offer a potential for a significant reduction in risk, it has been suggested[36] that this potential is based on possibly conservative estimates[17] of the risk from overpressurizing accidents as compared to other types of accidents. According to this suggestion, the failure mechanism for reinforced concrete may not be nearly as catastrophic as has been assumed in the estimates. The failure pressures, it is argued, may be considerably higher than the values assumed, approaching possibly three to four times the design pressure. The mode of failure, it is further stated, may not be one of rupture or breakthrough but rather a more benign propagation of small cracks that remain open while the pressure is very high and reseal when the pressure drops. These cracks would operate as tortuous paths which would attenuate a large fraction of the aerosols.

If the containment failure mechanism is as benign as is suggested by these comments, the vent-filter might actually create a higher risk than the current containment approach, though this risk in fact might be very small. The need for filtered venting, though not necessarily the effectiveness, would thence be annulled.

To elucidate this question, a search of available data will be made to determine how well the containment failure pressure and the mode of failure are known. If it is determined that the state of knowledge is inadequate or that a benign failure of the type described above is plausible based on existing knowledge, then attempts will be made to factor this information into the value assessment.

It should be noted, however, that failure of the concrete may not be the primary mechanism by which containment is likely to fail, and that penetration failures may actually precede concrete failure.

6. VALUE-IMPACT CONSIDERATIONS

6.1 Values

6.1.1 Risk Reduction

The keystone for determining the worth of filtered atmospheric venting is the degree to which it can reduce the public risk. The major obstacle to evaluating this risk reduction potential resides in the large uncertainties that exist in several areas. Some of these are listed below.

6.1.1.1 Steam Explosion Uncertainties

As has been pointed out by the chairman of the Risk Assessment Review Group,[19] the understanding of steam explosions is still so tenuous that their probability of occurrence and severity of force cannot be predicted with confidence. Clearly, efforts to reduce the risk of containment overpressurization by filtered venting will be fruitless if the overall risk is dominated by the threat of containment rupture from missiles generated by steam explosions. On the other hand, the advantages of reducing the risk of overpressurization might be large if steam explosions represent a small contributor to risk.

Since the physics of steam explosions are so uncertain at the present time, it may be necessary to parameterize this risk; that is, to consider the steam explosion risk as an unknown parameter and to determine the overall risk reduction achievable from vent-filter systems as a function of the unknown parameter. The advantage of this approach is that it specifies the level of risk that could be tolerated from steam explosions and provides an answer to the question of whether vent-filter systems are effective, contingent upon future clarification of the steam explosion issue.

6.1.1.2 Containment Failure Uncertainties

Possibly conservative estimates of the failure pressure of the containment and the assumption that the mode of failure involves gross rupture rather than crack development with self-repair capabilities may cause the evaluation of the risk of overpressurizing accidents to be conservative (see Section 5.5). Moreover, uncertainties in the structural integrity of concrete at temperatures above the boiling point of water could cause the evaluation of the vent-filter concept to be optimistic, unless this uncertainty is properly taken into account (see Section 5.2). Taken together, these two issues regarding containment failure may contribute a sizeable uncertainty to the evaluation of risk reduction achievable with vent-filter systems.

A literature review will be undertaken to establish the magnitude of uncertainties that currently exist with regard to failure pressures, failure modes, and temperature dependencies. Any statement of risk reduction achievable from filtered venting must also realistically define the overall uncertainty in these estimates.

6.1.1.3 Consequence Evaluation Uncertainties

Consequences caused by nuclear reactor accidents are usually stated in terms of health effects (early fatalities, latent cancer fatalities, genetic defects, etc.) and the cost of property damage. There is considerable controversy regarding the accuracy of these estimates given a particular release of radioactivity from the reactor site. The practice of using health indices (number of early fatalities per reactor-year, etc.) to define risk should be continued, since the risk is most easily understood in terms of effects rather than causes (i.e., the amount of radioactive release per reactor-year). However, these estimates should be presented in a relative rather than absolute sense, emphasizing the relative reduction in the indices achievable with vent-filter systems rather than the absolute values of the indices. In addition, the risk estimates based on health effects and property damage should be accompanied, step by step, by corresponding estimates stated in terms of radioactive releases.

6.1.1.4 Source-Term and Phenomenological Uncertainties

Significant uncertainties exist in the evaluation of fission product releases from fuel, fission product deposition within the primary coolant system and the containment, containment thermal-hydraulics (pressure, temperature, gas composition, and fission product inventory), and the response of filter systems to accident environments. The contribution of these uncertainties to the overall risk uncertainty will be taken into account.

6.1.2 Other Values

In addition to reducing the public risk, the use of vent-filter systems may have other advantages worth considering. Some of these are listed below:

1. Safeguard Advantages -- The vent-filter may improve sabotage protection for the reactor plant by increasing the difficulty of achieving an accident with major consequences through an act of sabotage (see Section 3.4.3).
2. Siting Options -- If the vent-filter significantly improves the safety of reactor plants, it may be possible to site future reactors closer to load centers.
3. Design Pressure -- With an effective vent-filter, it may be possible to significantly lower the containment design pressure for future reactors.
4. Double Use -- It may be possible to use the vent-filter as both an emergency air cleaning system for Class 8 accidents and a filtration system for Class 9 accidents, thereby reducing its cost impact.[37]

6.2 Impacts

6.2.1 Costs

Previous estimates of the costs of a vent-filter system[9,12] have been criticized for omitting important considerations. For example, the California Energy Commission study, which included a separate cost evaluation for a vent-filter system in an above-surface plant, did not consider first-of-a-kind costs such as protracted licensing and developmental costs. Their estimate of $10 million per reactor, in 1977 dollars without escalation or interest, was based on the additional cost of including a vent-filter during the construction of a new plant and did not therefore address the cost of backfitting an existing plant. The estimate included $4 million for the system, $3 million for supporting structures, $2 million for extra excavation, and $1 million for other requirements.

A breakdown of individual costs that should be considered in determining the total cost of the system is given below:

1. Capital Costs, New Plants -- The cost of the system, the supporting structures and equipment, and required additional excavation and backfill.
2. Capital Costs, Existing Plants -- Those above plus the cost of penetrating an existing containment, and if necessary, altering existing systems.
3. Cost of Shutdown, Existing Plants -- The monetary cost associated with having to shut a plant down long enough to backfit a vent-filter.
4. Testing and Maintenance Costs -- The cost of inspection, routine testing and maintenance, and replacement of filters as necessary.
5. First-of-a-Kind Costs -- Costs associated with first-of-a-kind licensing problems and scheduling delays; developmental costs such as the testing of the proposed filters under dynamic loading conditions and the testing of possible interactive effects with other systems.
6. Restoration/Repair Costs -- The costs of restoring the reactor to service after an accident involving use of the vent-filter, including the cost of decommissioning the contaminated filters and installing new ones.

As discussed in Section 3.2, the costs will be affected in a major way by whether or not the entire system has to be designed as a

Seismic Category I structure, as opposed to merely designing the containment penetrations as Seismic Category I.

6.2.2 Other Impacts

In addition to monetary costs, other impacts include the possibility of interference with normal plant operations and the possibility of increased risks for certain non-core-melt accidents that may be exacerbated by a vent-filter (see Sections 5.1.2 and 5.1.3).

6.3 Value-Impact Methodology

Since the Nuclear Regulatory Commission is presently planning studies to develop a methodology for value-impact assessments of improved safety systems, only a few general comments on the subject will be made at this time.

The objective of any value-impact analysis is to provide a definitive statement about the technical and economic feasibility and the overall effectiveness of the proposed system. Generally, the justification of such a statement is based on a comparison of the system in question with existing or proposed alternatives. In the case of vent-filter systems, the existing engineered safeguards or the proposed "dedicated shutdown system" could be used as a basis for comparison. Although the engineered safeguards are designed for design basis rather than core melt accidents and the dedicated shutdown system is associated with licensing requirements in the areas of fire protection, sabotage safeguards, and emergency core cooling, a quantitative comparison between these systems and vent-filter systems can still be made on the basis of such generic issues as risk reduction and cost.

It should be recognized, moreover, that although the objective is a definitive statement, a possible conclusion might be that the net worth of vent-filter systems cannot be specified within reasonable confidence limits. If this is the case, then the study will at least define the types of data that are needed to resolve the issues.

7. PROGRAM PLAN

Presented below is a program plan for the investigation of vent-filtered containment designs. The program plan is intended to serve not only as a statement of tasks but also as a summarization of the report. Following the plan is a schematic of the program flow (Figure 7), which is divided according to the following task categories: phenomenological tasks, systems tasks, design tasks, and overview tasks. Figure 7 includes cross references to task numbers that appear in the program plan.

Figure 8 presents a schedule of tasks, utilizing the task category format of Figure 7. As shown in Figure 8, industry reviews are scheduled after the first and second year of the program. An interim report is to be published after the first year and a final report after the second year.

TASK I. Review current vent-filter containment concepts and extract applicable information.

A. Review the existing literature on vent-filter concepts and designs (see References 3-14, 20, 28, 30).

B. Review the performance characteristics of various relevant filter materials (see References 3, 5, 9, 28-32).

C. Review any additional relevant literature (see References 1, 2, 15-18, 25-27).

TASK II. Develop a set of general design concepts applicable to a spectrum of LWR accidents and to various containment designs (i.e., large dry containments, ice condensors, Mark I, Mark III).

A. Perform a survey of operating and proposed reactors to characterize pertinent containment structures, safety systems, site characteristics, etc. -- The pertinent information will be obtained mainly from Final Safety Analysis Reports (FSARs).

B. Select reference plants characteristic of each important containment type. -- The reference plants will probably be selected from among those for which detailed accident analyses have been or are being performed. These include the following plants: Surry, Oconee, or Calvert Cliffs (large dry PWR), Sequoyah (ice condensor PWR), Peach Bottom (Mark I BWR), and Grand Gulf (Mark III BWR). Important differences between these plants and others surveyed in Task II.A will be noted.

C. Establish source terms for design purposes. -- These source terms will be adapted from the existing accident analyses mentioned in Task II.B. The process will include the following subtasks: (1) identification of changes in the prioritization of the risk-dominating accident sequences caused by the presence of the vent-filter, (2) estimation of the corresponding fission-product source terms, and (3) determination of the pertinent containment properties (temperature, pressure, atmosphere composition) which govern the operating requirements of the vent-filter. Conditions corresponding to the less severe accidents involving partial core damage (e.g., the Three Mile Island accident) will also be considered.

D. Define vent-filter functional requirements, operating requirements, and design specifications. -- A preliminary list of requirements and specifications to be established has been presented in Table 2. All of these items will be addressed at this point, but the level of detail will be limited to that required to prepare general design concepts, as described in the following subtask. A more detailed development of system requirements and specifications follows in Task VII.A.

E. Formulate general vent-filter concepts that appear to most reasonably satisfy the design specifications, and specify the primary components, general layout, filter and construction materials, and overall dimensions. -- The number of variations considered will be sufficient to include a diversity of vent-filter concepts applied to the four reference containments listed under Task II.B. Variations in flow rate capability will be included as a parameter in distinguishing one concept from another. Design modifications required for backfitting of existing plants as opposed to construction of new plants will be developed, and the design impact of seismic constraints (i.e., Category I versus non-Category I) will be considered (see Section 3.2). Specific design questions discussed in Sections 3.3 and 3.6, such as locations of vent inlets, penetration requirements, and burial of filtering media, will be addressed. General operational characteristics such as actuation criteria, method of actuation (passive, motor, manual), and level of controllability will be established.

F. Identify compliance with or deviation from current licensing procedures. -- Included in this task will be an assessment of the regulatory impact of controlled atmospheric venting as opposed to leak-tight containment.

TASK III. Perform preliminary engineering analyses of each concept to identify the most promising concepts for further study.

A. Estimate the containment temperature/pressure transient and the effluent release through the filters for the accidents selected in Task II.C, assuming that the vent-filter operates as designed. -- Also obtain estimates of the corresponding consequences (health effects, property damage).

B. Estimate the containment response, effluent release, and consequences in the event of vent-filter malfunction, and estimate the probability of malfunction. -- Possible modes of malfunction include (1) premature actuation or actuation during non-core-melt accidents, (2) delayed actuation or failure to actuate, (3) filter bypass, and (4) mechanical failure of associated heat exchangers, air coolers, or blowers.

C. Explore possible system interaction problems, and define design modifications that would be necessary to circumvent them. -- Possible problems include cavitation of pumps drawing from the containment sump (see Section 5.1.1), adverse effects caused by delayed containment spray actuation (see Section 5.1.2), and degradation of reflood effectiveness if the vent-filter operates prematurely (see Section 5.1.3).

D. Explore other possible technical problems and determine how they might be circumvented. -- Possible problems include loss of containment integrity due to long-term elevated temperatures (see Section 5.2) and enhanced potential for hydrogen explosion (see Section 5.3). In particular, an assessment will be made of various techniques for managing large amounts of hydrogen, such as recombiners, the use of transition elements, molecular diffusion, chemical fixation, and regenerative liquefaction.

E. Perform a preliminary value-impact assessment to determine which, if any, of the vent-filter concepts are worthy of further study. -- Estimate the overall accident risks for the various vent-filter concepts and containment types, and estimate the confidence limits accounting for uncertainties in such areas as steam explosion risks, containment failure criterion, consequence evaluation, source-term evaluation, and thermal-hydraulics evaluation (see Section 6.1.1). Estimate costs, including backfitting costs and first-of-a-kind costs (see Section 6.2.1), and evaluate the associated uncertainties.

F. Prepare a list of areas where further research (e.g., bench-scale experiments) would be useful.

TASK IV. Develop conceptual system designs and perform reliability assessments.

A. For the best concepts, formulate conceptual systems designs, incorporating specific layouts, dimensions, equipment characteristics, etc. -- Separate designs will be developed for each of the four reference plants (Task II.B), including both backfit of existing plants and new construction. The level of detail will be limited to that necessary for carrying out the objectives of formulating design criteria for vent-filter systems and performing a rigorous value-impact assessment.

B. Perform reliability assessments, including estimates of demand unavailability, operational unreliability, spurious operation during normal reactor operation or during non-core-melt accidents, restoration/repair considerations, and human interaction. -- Assess the trade-offs between reliability, accessibility, controllability, and sabotage protection (see Section 3.4).

C. Evaluate the licensing impact.

TASK V. Develop improved vent-filter hydraulic and effluent models, perform integrated containment response calculations, and estimate consequences.

A. Develop analytical models for predicting the thermalhydraulics and radionuclide transport/capture characteristics of the vent-filter systems, and couple these with existing models of containment thermalhydraulics (i.e., MARCH/CORRAL codes).

B. Determine accident sequences to be analyzed for each reference containment and estimate the corresponding fission-product source terms. -- In determining important accident sequences, the possibilities of vent-filter system failures, adverse system interactions, long-term containment integrity loss, and enhanced hydrogen explosion potential will be taken into account (see Tasks III.B through III.D). Accidents involving both high and low vent flow rate requirements will be considered.

C. Using the improved analytical models developed in Task V.A, calculate the containment temperature/pressure transients and the effluent releases for each accident sequence and reference containment.

D. Estimate the corresponding consequences (health effects, property damage), accounting for the plume temperature effect on buoyancy (see Section 5.4).

TASK VI. Perform value-impact assessments for the most promising vent-filter designs.

A. Perform detailed value assessments, including quantification of risk reduction and consideration of safeguard advantages, as well as possible expansion of siting options. -- Also, evaluate special values that are pertinent to future reactors, such as possible reductions of the containment design pressure or double use of the vent-filter as an emergency air-cleaning system.

B. Perform more detailed cost and impact assessments, including quantification of construction, testing, maintenance, developmental, and first-of-a-kind licensing costs as well as consideration of the impact on normal operations. -- Also, identify and quantify the increased costs pertinent to backfitting existing reactors, such as down-time costs, backfitting costs, and the cost of upgrading existing pumps, if necessary.

C. Reestablish the confidence limits of the value-impact assessments (see Task III.E).

D. Provide perspective for the value-impact assessments by comparing the overall values and impacts of vent-filter systems to those that have been obtained with other containment systems or those that may be obtainable with proposed new systems, such as a dedicated shutdown system (see Section 6.3).

TASK VII. Make recommendations regarding performance requirements and design criteria, and identify areas for further research.

A. Based on the results of the previous tasks, provide detailed specifications for performance requirements and design criteria needed to achieve significant risk reduction. -- See Table 2 for an itemization of specifications to be established.

B. Perform limited sensitivity analyses to assess the impact of specific parameters and assumptions on the overall assessment of value versus impact.

C. Identify areas for further research. -- Such research might include further systems analyses to answer questions of value versus impact for other containment accident mitigation systems, including those that might be used in conjunction with vent-filter systems. Other research might involve bench-scale experiments to answer questions of feasibility and effectiveness, including the testing of proposed filters (see Section 4.1) and the testing of proposed hydrogen explosion control methods (see Section 5.3).

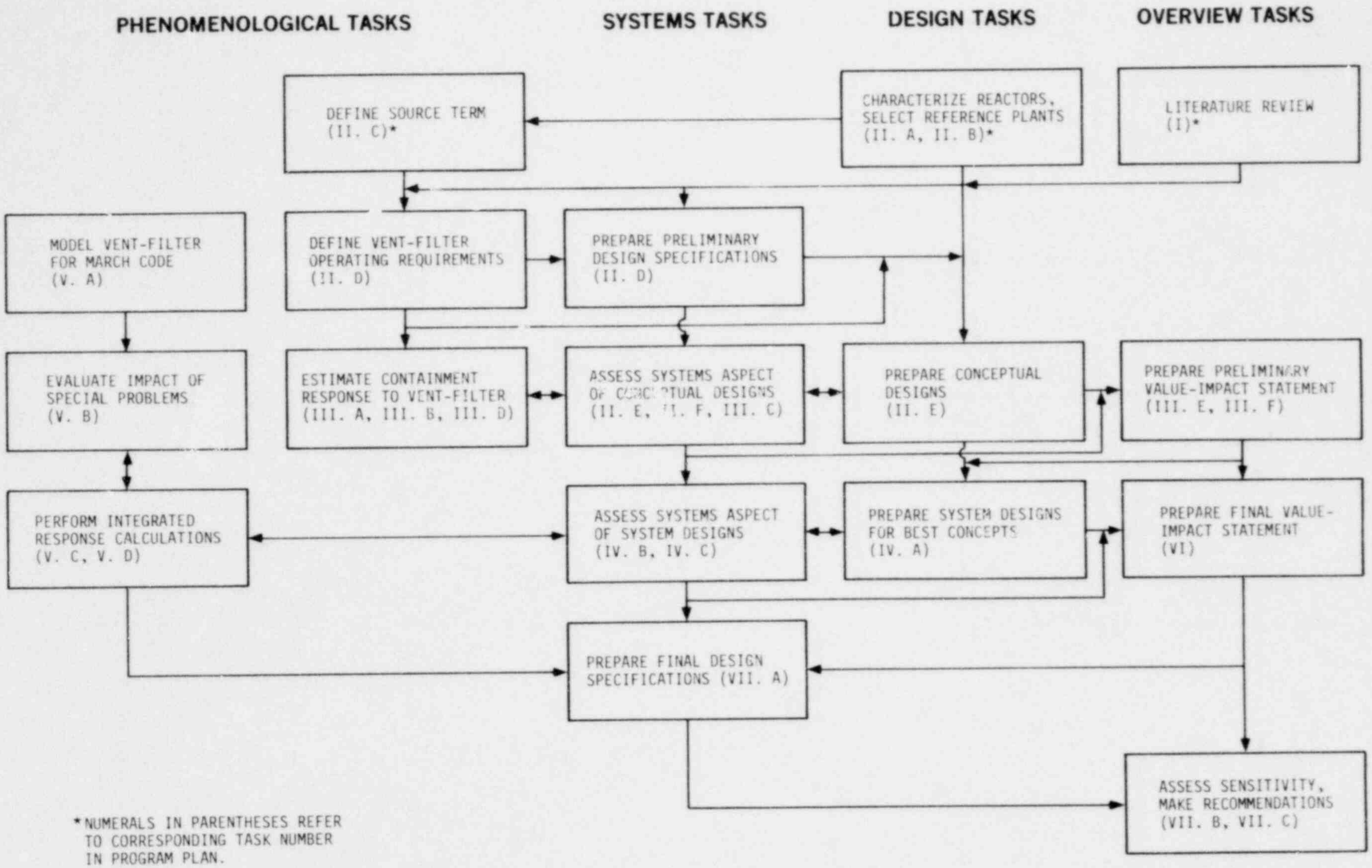

Figure 7. Program Flow

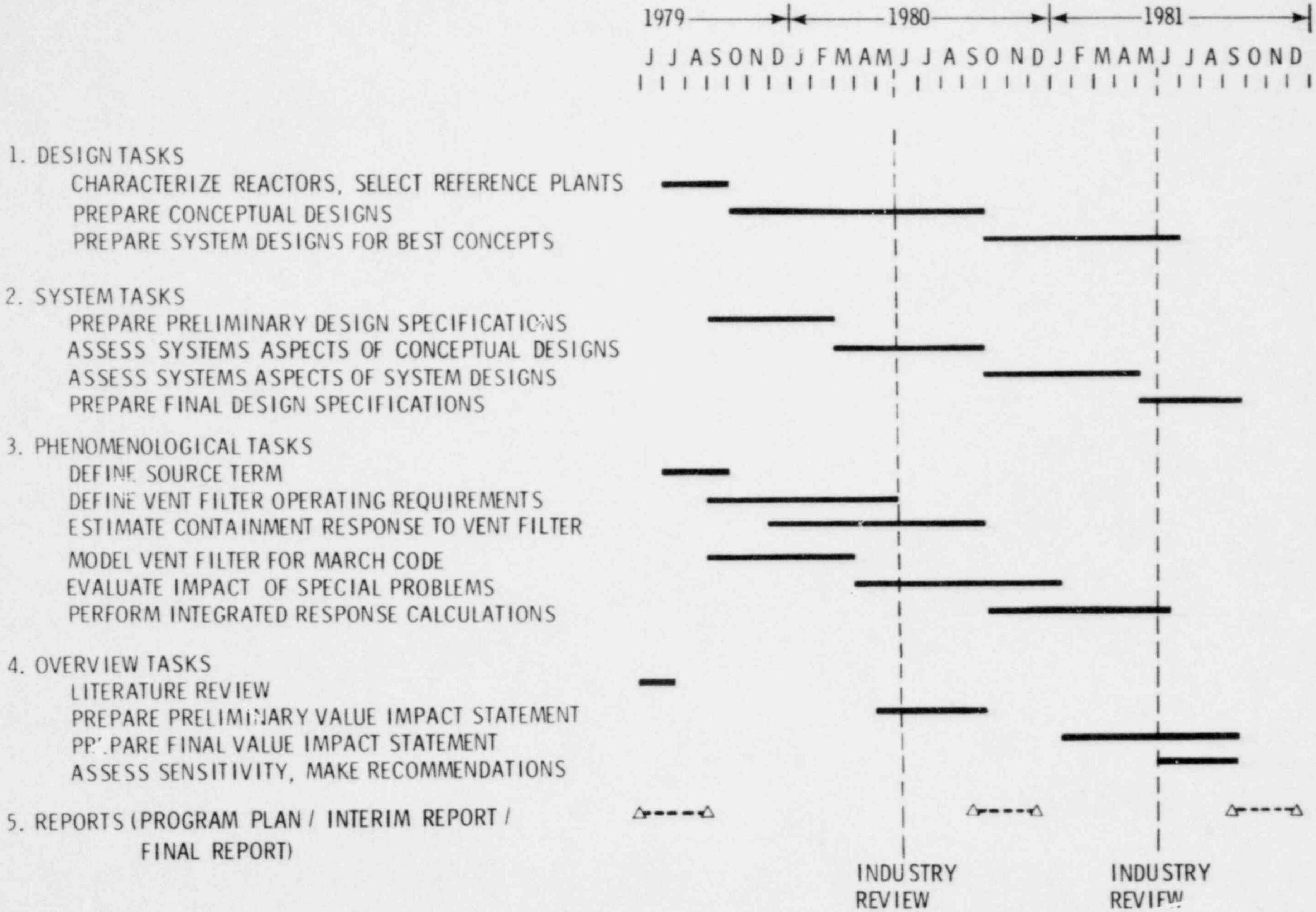

Figure 8. Program Schedule

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UNLIMITED RELEASE DISTRIBUTION:

R. Di Salvo (50)
Probabilistic Analysis Staff
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

R. S. Denning
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201

D. Okrent
Nuclear Engineering Department
University of California, Los Angeles
Los Angeles, CA 90024

N. C. Rasmussen
Nuclear Engineering Department
Massachusetts Institute of Technology
Cambridge, MA

H. W. Lewis
Department of Physics
University of California, Santa Barbara
Santa Barbara, CA

F. von Hippel
Center for Environmental Studies
Princeton University
Princeton, NJ

E. E. Cramer
Southern California Edison Co.
P. O. Box 800
Rosemead, CA 91770

F. C. Finlayson
Aerospace Corporation
2350 E. El Segundo Blvd.
El Segundo, CA 90245

J. E. Ward
S & L Engineers
6151 W. Century Blvd., Suite 920
Los Angeles, CA 90045

B. Gossett
ANCO Engineers, Inc.
1701 Colorado Avenue
Santa Monica, CA 90404

R. A. Haarman
Science Applications, Inc.
200 Lomas Blvd., N.W., Suite 600
Albuquerque, NM 87102

W. E. Kastenberg
c/o U.S. Nuclear Regulatory Commission
Advisory Committee on Reactor Safeguards
1717 H Street
Washington, DC 20555

1767	H. C. Walling
4400	A. W. Snyder
4410	D. J. McCloskey
4414	G. B. Varnado
4414	A. S. Benjamin (10)
4420	J. V. Walker
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