UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D. C. 20555

May 7, 1980

The Honorable Victor Gilinsky
Commissioner
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Dr. Gilinsky:

Your memorandum dated March 25, 1980 asks for the Committee's thoughts on the feasibility and practicality of a containment concept which could withstand a core melt. In this letter the ACRS will provide some preliminary and necessarily incomplete comments on the subject.

1. The letter dated March 7, 1980 from Albert L. Latter, President, R&D Associates, to the Nuclear Regulatory Commission does not provide a technical description adequate to determine or evaluate the approach being proposed. Limited additional information was provided by R&D Associates at their meeting of April 25, 1980 with you and Chairman Ahearne. However, in the absence of considerably more information, the ACRS is unable to comment on the technical merit of this proposal.

2. The general question of the feasibility and practicability of a containment which could withstand a core melt should be examined within the context of some broad policy guidance. What cost is justifiable? Is 100% guarantee of containment integrity being sought? If not, what frequency of an uncontrolled airborne release of a large portion of the radioactive fission product inventory is acceptable? What frequency of a sudden gross release of the noble gas inventory is acceptable? What frequency of a penetration of the core through the containment foundation (or equivalent release to the ground water) is acceptable? Do the reactor site characteristics and the nation's energy supply situation bear on the definition of acceptable frequency?

   Prior to 1966, although the regulatory process did not include consideration of the probably strong correlation between core melt and containment failure, it was clearly recognized that paths existed for a loss of containment integrity concurrent with a core melt. These included the potential for large missiles arising from sudden failure of the reactor pressure vessel or other large components, as well as the possible failure of containment isolation mechanisms. Furthermore, natural events such as earthquakes and floods were known to provide a potential for a loss of containment concurrent with an accident which seriously damaged the core.

What developed in 1966 was a better appreciation that, for the medium power LWRs then under construction, containment failure was likely to be associated with core melt from whatever cause. As you know, in September, 1966 the ACRS was dissuaded by the AEC from transmitting a letter which would have recommended the development and implementation for LWRs of measures to cope with and mitigate serious accidents, and accepted as an alternate the establishment of a task force which was supposed to develop within a few months a recommended approach to pursue the core melt problem. The ACRS recommended in October, 1966 that the AEC initiate a vigorous, high priority safety research program on phenomena related to core meltdown and on design concepts to mitigate such an accident. The Committee has reiterated that recommendation many times in the ensuing years to both the AEC and the NRC with little success until the past several months.

For example, in a letter dated January 11, 1971 from R. F. Fraley to Milton Shaw, Director of the AEC Division of Reactor Development and Technology, the ACRS stated its belief that a core retention system could provide a substantial reduction in the probability of a fission product release to the environment. In addition, the ACRS noted some then-recent studies which offered encouraging results and recommended initiation of meaningful conceptual design work.

3. The response to your question depends heavily on what safety policy the NRC decides to adopt.

   (a) If the NRC policy were to become one which requires that there is no acceptable frequency for an accident involving both core melt and a loss of containment integrity, even very low power LWRs built underground would not satisfy this policy, since one can postulate scenarios, for example, involving terrorism, very large earthquakes, or a failure in an access path from containment, which could defeat any design, in principle.

   (b) If the NRC policy were to become one which requires that the design should have a very high probability of containing all core melt accidents, including those involving large internally generated missiles and should limit the maximum extent of airborne and liquid pathway release to man, some form of underground or earth-covered reactor plant may be required, with special attention given to earthquakes, floods, and groundwater conditions, and to the design of features having a high probability of successfully retaining a molten core and of retaining most of the radioactive material in case controlled containment pressure relief were called for.

(c) If the NRC policy were to become one which requires that the design should have a high probability of containing almost all core melt accidents which do not concurrently include a loss of containment integrity due to missiles, sabotage, very large earthquakes or similar postulated causes, the issue can probably be satisfactorily addresssed in terms of LWRs constructed above ground. There would still remain a policy question concerning the acceptability of design approaches which envisage the potential for deliberate venting of noble gases to prevent containment overpressure in the event of a serious accident.

(d) The NRC policy might involve a limited or selected set of additional requirements for mitigation, for example, a filtered venting system for containment to reduce the probability of containment failure due to overpressure, but no core retention within containment, relying instead upon acceptable hydrological conditions. Or, of course, the NRC policy might involve no additional accident mitigation requirements, placing all emphasis on prevention of serious accidents beyond the current design basis.

4. Policy alternative 3(c) above is examined briefly in this section for technical feasibility. The technical questions would, of course, be more complex if accidents such as pressure vessel rupture were also to be addressed per policy alternative 3(b).

A containment designed to withstand a core melt must consider both the problem of molten core retention and cooling, and the prevention or limitation of a significant atmospheric release of radioactive material. If one establishes a reasonable reliability goal for measures intended to protect against both the atmospheric and liquid release pathways, and the potential need for pressure relief of the containment with a resultant release of radioactive noble gases through a filtered, venting system, it appears that, for the large volume, high-design-pressure type of containment, core melt retention is probably feasible. Its practicality will depend on the cost, the reliability goals sought, and the benefits assigned to the accomplishment.

The attached, recently issued documents by Messrs. I. Catton, C. Kelber, A. Marchese and T. Speis, R. DiSalvo, and A. Benjamin and H. Walling provide some current thinking on the problems, prospects and issues involved in molten core retention. These documents have not yet been reviewed by the ACRS; an ACRS subcommittee meeting on the general subject is scheduled to be held this month.

It is clear that problems remain, for example, from the potential for an excessively large, sudden pressure rise within containment due to hydrogen deflagration or a very rapid thermal energy exchange between the molten fuel and water. Measures appear to be possible to cope with these and similar questions, but comprehensive and sufficiently detailed studies to evaluate and choose from various design approaches are not available.

Recent work suggests that steam explosions are not a likely source of a loss of containment integrity in a large, high-design-pressure containment. However, steam explosions may be locally disruptive to features intended to help retain a molten core. The decision as to whether it would be better to keep the region below the vessel dry or flooded with water cannot be readily made with the limited design and risk evaluation information now available.

The ACRS believes that, given reasonable reliability goals, goals which do not pose so unrealistic a demand that they cannot be confirmed either experimentally or theoretically, it should be technically feasible to design an LWR containment to withstand a core melt.

The Committee wishes to note that whatever policy the NRC adopts, thought has to be given to the approach which would be taken to recover the site and dispose of a nuclear plant which had been subjected to a core melt accident.

5. The ACRS believes that the issue of what protection is to be required to contain or mitigate accidents involving core melt in LWRs yet to be designed and constructed should be decided expeditiously. The NRC Staff has recently augmented its previously modest research efforts related to this issue. However, in view of the essential nature of this issue to any decision process regarding the design of future LWRs, the ACRS believes that the current efforts by the Staff are inadequate.

   If the NRC concludes that future LWRs will require protection to contain or mitigate serious accidents involving core melt, the Committee believes that the DOE should be requested to undertake, as soon as possible, the necessary research and development work. The DOE effort should be adequately funded from the very start in order to develop an effective and reliable protection system within a time frame that will not delay the design of future plants which would incorporate this system.

6. The ACRS believes that resolution of this general issue should be given high priority by the Commissioners themselves. The Committee believes that such a policy decision should be part of an overall NRC safety philosophy. The safety philosophy should also provide siting guidance for future reactors and reliability goals for design measures intended to prevent core melt accidents. It should also provide risk-based guidance to both the Staff and industry for the wide spectrum of possible accidents.

The ACRS believes that such a policy decision by the Commission should be made with recognition of the comparative risks from other energy sources and from other technologies, and in the light of the societal, economic, and political factors which bear significantly on the complex issues involved.

Sincerely,

Milton S. Plesset

Milton S. Plesset
Chairman

Attachments:
1. I. Catton, ACRS consultant, memo to D. Okrent, ACRS, dtd. 4/25/80 re. Breach of Containment by a Core Melt

2. C. Kelber, RSR, memo to G. Quittschreiber, ACRS, dtd. 4/22/80 re. Input to Response to Commissioner Gilinsky's Questions on Core Melt

3. A. Marchese and T. Speis, NRR, memo to D. Okrent, ACRS, dtd. 4/25/80 re. "General Feelings on Containing a Core Melt"

4. R. DiSalvo, RSR, memo to G. Quittschreiber, ACRS, dtd. 4/24/80 re. Request for Input to Commissioner Gilinsky's Questions on Core Melt

5. A. Benjamin and H. Walling "Development and Analysis of Vent-Filtered Containment Conceptual Designs," SAND80-0887

cc:
Chairman Ahearne
Commissioner Kennedy
Commissioner Hendrie
Commissioner Bradford

Api 25, 1980

TO: D. Okrent

OM: I. Catton

SUBJECT: Breach of Containment by a Core Melt

REFERENCE: Letter from Ivan Catton to David Okrent dated 6 March 1980

The question posed is whether or not it is feasible and practical to design a containment that can withstand a core melt. It is my opinion that to do so is both feasible and practical. Of course there will be a number or hurdles to overcome in arriving at a design. I will attempt to substantiate my opinion in the following paragraphs by first addressing existing plants and then give my ideas about new plants.

Before discussing LWRs, however, I would like to call your attention to previous work in this area for LMFBR's. Designs for core catchers were proposed for FFTF and CRBR. A number of crucible materials were evaluated and both passive (time delay) and active systems were considered. The German reactor SNR 300 will have an actively cooled crucible using depleted UO_2 as a sacrificial material. Several ideas for core retention have come out of efforts of the GE advanced reactor group. A firm in Germany was found that would make standard size bricks out of depleted UO_2 for what I remember to be a reasonable cost. The depleted UO_2 was needed to absorb the thermal shock from the melt and protect the active cooling system. The designs were not ılly evaluated but had potential for being successful. When one considers hat the fuel melt from an LMFBR has an energy density that is an order of magnitude greater than an LWR one sees that the design of a core catcher for a LWR will be less difficult.

A number of aspects of a core melt accident were discussed in the above referenced letter, which dealt with Indian Point and Zion. They are repeated here in part.

1. Steam explosions will probably not occur in-vessel if the pressure is above 7-10 bars. Even if a steam explosion were to occur in-vessel, recent SANDIA work shows that there is little chance of a missle that could penetrate the containment. The only missile that might be of concern was the control rod drive. Some plants have missile shields for this already and plants without could install one. An ex-vessel steam explosion will only occur if water is in the reactor cavity before the vessel is penetrated or enters shortly thereafter (before the molten pool solidifies and while gas is still being generated by concrete decomposition). The ex-vessel steam explosion will probably not do much damage and it appears that acceleration of missiles that will penetrate the containment is unlikely. Further confirmation of this opinion is needed to assure that damaging the shield wall, moving the vessel or some other aspect will not lead to containment penetration. High steam generation rate will occur if water precedes the melt and the resultant high steam generation rate needs to be a factor considered in seeking mitigation measures.

ATTACHMENT 1

2. In-vessel core coo ..bility is presently not well e ugh understood to fully describe the core meltdown process. Programs presently underway in Germany and the US may yield sufficient information at some time in the future to describe the process. At this time one can only bound the problem and must assume that penetration of the vessel occurs early in the worst way. It should mentioned that it is not really clear what the worst way is. For example t of fuel resulting from a hole in the bottom of the vessel might erode a nole in the base mat with subsequent erosion of the hole being greater than if the entire vessel lower dome failed dumping all the molten fuel at one time.

3. Ex-vessel core debris coolability will depend strongly on whether or not water is in the cavity. If water is in the cavity in sufficient quantity before the vessel is penetrated, the core debris will be quenched as it enters. A sufficient quantity of water is a pool deep enough to prevent erosion of the base mat. It is not clear how deep this is. SANDIA programs underway, however, could help answer this question. If a reflux path is available the core debris will probably not dry out and re-melt. This opinion is based on past work at TREAT, UCLA, ANL and SANDIA that shows that $\varepsilon = 0.45$ is a reasonable void fraction and that an average particle size of 500 μm is to be expected. For $\varepsilon = .45$ and 500 μm particle sizes the entire core and a great deal of steel (125 tons of fuel and steel) will remain coolable.

If vessel penetration occurs when no water is in the reactor cavity, a great deal of penetration of the base mat may occur. The amount of penetration occurring during the period when the core debris is molten is predictable. Once it freezes a complicated process occurs and the amount of penetration is not predictable. Again, studies are underway in Germany (their strong interest results because they do not allow water into the reactor cavity) that will answer this question within the next couple of years. Use of a er in the cavity could buy time for plant personnel to get water into the cavity.

The debris could enter the dry cavity and become particulates. The gas flow from the decomposing concrete might block water added later from entering the bed. It is not known whether the cooling by the gases from the decomposing gases will be sufficient to preclude re-melting. This sequence needs further study if it cannot be shown that water will always pr ede the melt.

To summarize, in existing plants where water precedes the melt in sufficient quantities and can be resupplied, penetration of the base mat will most likely not occur. Under these conditions an ex-vessel steam explosion will probably take place with the possibility of a great deal of steam generation that must be accommodated. The possibility of damage of the biological shield or shifting of NSSS components leading to containment damage needs to be further assessed. When water is not available, the chances of base mat penetration are much greater. The conclusion is that a water supply needs to be assured. A cavity liner of depleted UO_2, Al_2O_3, MgO or some similar refractory or sacrificial material should be considered.

A containment building could be designed based on present information to preclude molten core penetration. A conceptual design that has redundant cooling capability as well could include the following features:

1. Concrete that minimizes gas generation on decomposition and has the best possible refractory characteristics.

Several courses of depleted UO_2 bricks actively cooled at the concrete-UO_2 brick interface similar to the SNR 300 core catcher. The heat sink could be an existing plant system.

3. A steel liner to protect the UO_2 bricks.

4. A cavity flooding capability and a method of refluxing to insure that the cavity stays flooded.

Such a system requires very little new technology and depends on no new research. It should also be relatively inexpensive.

APR 22 1980

MEMORANDUM FOR: G. Quittschreiber, ACRS

FROM: C. Kelber, RSR

SUBJECT: INPUT TO RESPONSE TO COMMISSIONER GILINSKY'S QUESTIONS ON CORE MELT

Pursuant to your memo of April 18, 1980 I have called Dr. Okrent to relay these thoughts:

1. The Zion/Indian Point study emphasizes the need to review the systems interactions of containment systems taking into account the probable state of the core and coolant systems at and following the time the threat to containment arises. From this review a risk based balance of the effects of system failures should be used as a major factor in deciding what systems to put in place.

2. Once a risk based balance is accepted as part of the decision system, many options are available to resolve the questions. Options include, for example, filtered, vented containment systems, highly reliable power and water supplies for containment cooling, active and passive core catchers, either sacrificial or refractory, or strong containments that are externally coolable, as the Byblis B plant.

3. Another factor in the decision process is the political factor: an inadvertant release of all the nobles through a filtered vented containment system is without health effects, but a deliberate release is probably politically impossible to permit at this time. Thus, such a system might be without merit in the next few years simply because permission to use a filtered vented containment system would probably be denied if it were ever requested in advance.

4. The Zion/Indian Point study revealed these problems to be most troublesome:

   The steam spike arising from sudden mixing of a molten core with water. Sprays or an ice condenser will ameliorate this problem if they are available. The trouble with a passive system such as the ice condenser is that it will probably be used up by the time the steam spike arises.

   The pressure from a massive hydrogen burn. Satisfactory hydrogen control methods appear to be available, but, of course, they have to be used.

   If the molten core is not cooled rapidly, radiation from the core may cause failure of massive components such as the pressure vessel, and such failures might lead to extensive damage to neighboring systems.

ATTACHMENT 2

5. It is likely to be necessary to by-pass the containment through the let down line or similar systems to maintain vital plant functions. The release through such bypasses does not appear to be substantial.

Charles N. Kelber, Assistant Director
Advanced Reactor Safety Research
Division of Reactor Safety Research

cc: T. Murley, RSR
D. Okrent

Marchese/Speis Input

to Dr. Dave Okrent, ACRS

"General Feelings on Containing a Core Melt"

Re: Memo from Quittschreiber, "Request for Input to Commissioner Gilinsky's Questions on Core Melt," dated April 18, 1980

April 25, 1980

ATTACHMENT 3

1. Refractory materials exist (e.g., MgO) which are considerably more benign than concrete is in terms of interactions with molten core debris and which would significantly reduce the associated production of water vapor, non-condensible and combustible gases generated by melt-concrete interactions.

2. A core retention device could not only prevent failure of containment via preventing melt-through of lower basemat, but could have a significant mitigating effect on the upper containment loading conditions by decreasing the pressure, hydrogen, aerosol and activity transients.

3. We believe that a core retention device will mitigate significantly core meltdown accident consequences by:

   a. reducing both the airborne releases caused by sparging of activity out of the core melt (thus reducing the vaporization fraction of the atmospheric releases) and the higher containment pressure when core melt material interacts with concrete; and

   b. reducing the likelihood of containment basemat penetration, thereby reducing the likelihood of ground water contamination via melt-through.

4. If containment fails prior to the melt contacting the core retention device, the major value of such a device in this case (insofar as airborne releases are concerned) would be to reduce the driving forces for leakages caused by non-condensible gas generation and sparging of activity out of the core melt debris.

5. An actively cooled core retention device would have the added advantages of (a) permanently retaining the core melt debris within the confines of the containment building, and (b) dissipating the core melt decay heat to the atmosphere, rather than retaining the heat of the melt inside of the containment building.

6. The value of minimizing the sparging phenomena and the vaporization releases extends broadly across the core melt spectrum but would have greatest importance to the risk dominating sequences. This value would be achieved primarily through reduction of the sparging induced release of tellurium and to some lesser extent it would reduce other isotopes. Since tellurium may be one of the dominant contributors to the health risks (from airborne releases), a core retention device could have a significant value in reducing the health risks from airborne releases.

7. For those nuclear plant sites located on soils of high permeability and in close proximity to major water resources, the use of a core retention device would be of greater relative value insofar as liquid pathway releases are concerned. Also, the use of a passive core retention device would have some value in terms of providing added time for interdictive measures to be taken against ground water contamination, thus further reducing the probability of such contamination.

8. If a controlled-vent-filter containment system proves desirable, a core retention device would significantly reduce the gas, vapor, aerosol, and activity loadings on such a system.

9. A core retention device could eliminate the water vapor evolved by melt-concrete interactions, thereby reducing melt-water reactions and the associated H_2 production in the region of the core retention device.

10. Conceptual designs of core retention systems for each of the reactor containment types should be undertaken; studies should be of the integrated, system type.

11. Need to consider special backfit problems associated with installing a core retention system in existing plants.

12. Those existing plants that either have a poor liquid pathway situation (with respect to rapid transport of core melt activity) or are located in areas of high population density should be given special emphasis.

13. Need to decide on whether to delay the melt-through penetration of the basemat or whether to permanently retain the core debris within the confines of the containment building.

14. In connection with Item 13, both passive and actively cooled core retention systems should be examined. Studies of passive systems should also consider natural circulation cooling around the extremities of a refractory bed of material.

15. After conceptual design studies are completed, the required R&D can be better focused to support the final design of the most promising of the core retention systems.

16. Primary problems which will require core melt R&D are in areas of materials interactions, heat transfer and fission product behavior.

17. For future plants, we believe that it is both technically feasible and practical to incorporate a core retention system into the reactor containment building that will significantly mitigate the consequences of core melt accidents.

18. For existing plants, we feel that the feasibility and practicality has to be examined on a case-by-case basis, including but not limited to considerations of high population density sites, liquid pathway problems, and containment types. The practicality of installing a core retention device in the lower reactor cavity region should be examined in terms of space availability, access, shielding, radiation levels and costs.

19. Besides NRC and its contractors, Reactor Manufacturers and A&E firms need to take this problem seriously and perform actual conceptual design studies of real core retention systems.

20. The combination of a stronger containment (i.e., higher design pressure) coupled with containment heat removal and core retention systems is a very desirable concept for future plants to preclude the need for venting in order to relieve pressure following a core melt accident. Public acceptance of nuclear power would be greatly enhanced if we could claim that we can contain the worst of the nuclear accidents.

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

APR 24 1980

MEMORANDUM FOR: Gary Quittschreiber, Senior Staff Engineer
Advisory Committee for Reactor Safeguards

FROM: Raymond DiSalvo,
Probabilistic Analysis Staff,
Office of Nuclear Regulatory Research

SUBJECT: REQUEST FOR INPUT TO COMMISSIONER GILINSKY'S QUESTIONS ON CORE MELT

REFERENCE: Your Memorandum, same subject, April 18, 1980

I am not sure whether you have requested comments on the specific proposal offerred by Mr. Latter or on the more general issue his letter addresses as raised by Commissioner Gilinsky. Mr. Latter's letter is short on technical substance. Nevertheless, I will frame my comments within the context of his letter and trust that they will be applicable to the more general issue.

COMMENTS ON RATIONALE

1. Latter recommends changing regulatory policy to require "containment of all accidents" without defining acceptability criteria. Does "containment" mean zero release, a release less than TMI-2, a release giving doses less than those in 10 CFR 100, no release to groundwater, or what? Does "all accidents" include low probability externally initiated events which could destroy the containment building, or sabotage or human error which could reduce the effectiveness of any containment design? Feasibility of retaining a molten core is a red herring. The real issue is acceptability.

2. If the technology of containment is "well understood and reliable" enough to base changes in currect policy on, why are we bothering to study containment response during accidents within and beyond design basis?

3. The sentence "If the probability of a containment failure were estimated to be low..." is puzzling. To what "empirically determined data" does it refer; containment leak tests? Their applicability to the questions at hand is suspect at best.

4. Latter states, "...the critical question is whether adequate containment is technically possible and economically reasonable. On the basis of our preliminary work, we believe the answer is yes." Putting aside the lack of definition for "adequate," I have no reason to doubt the conclusion. In fact, if I substitute "improved" for "adequate," I agree with his answer. I disagree that this is the "critical question," however, preferring to think that effectiveness and necessity are more important.

 ATTACHMENT 4

APR 24 1980

COMMENTS ON CONCEPTS

1. Latter offers little technical content on which to base an evaluation. The generalities are characteristic of earlier dissertations on improved containment design except that Latter is the first soul I have found who is confident enough to predict "no releases of radioactivity."

2. Reducing static pressure may only be a partial answer to retaining containment integrity. Recent analyses by Battelle Columbus Laboratories and Sandia National Laboratories* indicate that pressure spikes from rapid generation of steam or hydrogen burning also challenge containment integrity in core melt sequences having relatively high probability of occurrence. Concepts have been proposed to overcome this potential problem.

3. Containing a molten core via a core retention device and a passive cooling system is feasible to the extent that on the order of 40 MW can be transferred from the core debris to its surroundings and an ultimate heat sink via natural circulation. In addition to being a "dense, inert, low melting point, and high thermal conductivity melting bed" (could it be lead?), it would be desirable that the material be economically available, workable into the proper configuration, and that its production and fabrication have no adverse effects on health, safety and environment.

4. In order to achieve the appearance of total containment of a core melt accident, all recognized containment failure modes must be precluded. This means eliminating failure to isolate in addition to the more spectacular failure modes Latter cites. The probability of isolation failure may put a lower limit on the feasibility of containing a core melt totally.

Please let me know if I can provide any further information or clarification of these comments.

* W. B. Murfin, "Summary of the Zion/Indian Point Study," SAND80-0617, NUREG/CR-1409, in publication.

Raymond DiSalvo

Raymond DiSalvo,
Probabilistic Analysis Staff
Office of Nuclear Regulatory Research

cc: D. Okrent, ACRS
I. Catton, ACRS

SAND80-0887

Development and Analysis of Vent-Filtered Containment Conceptual Designs

A. S. Benjamin and H. C. Walling
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

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

INTRODUCTION

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

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

1. Development of conceptual designs of vent-filter systems which have the potential to mitigate the effects of accidents (particularly core melt accidents) that are beyond the current design basis.

2. Determination of the potential reduction in radioactive releases for core-melt accidents and the resultant reduction in overall risks.

3. Determination of the effect of the vent-filter on non-core-melt accidents and on normal operations.

4. Specification of system performance and safety design requirements for vent-filter systems.

5. Quantitative analysis of values versus impacts.

ATTACHMENT 5

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

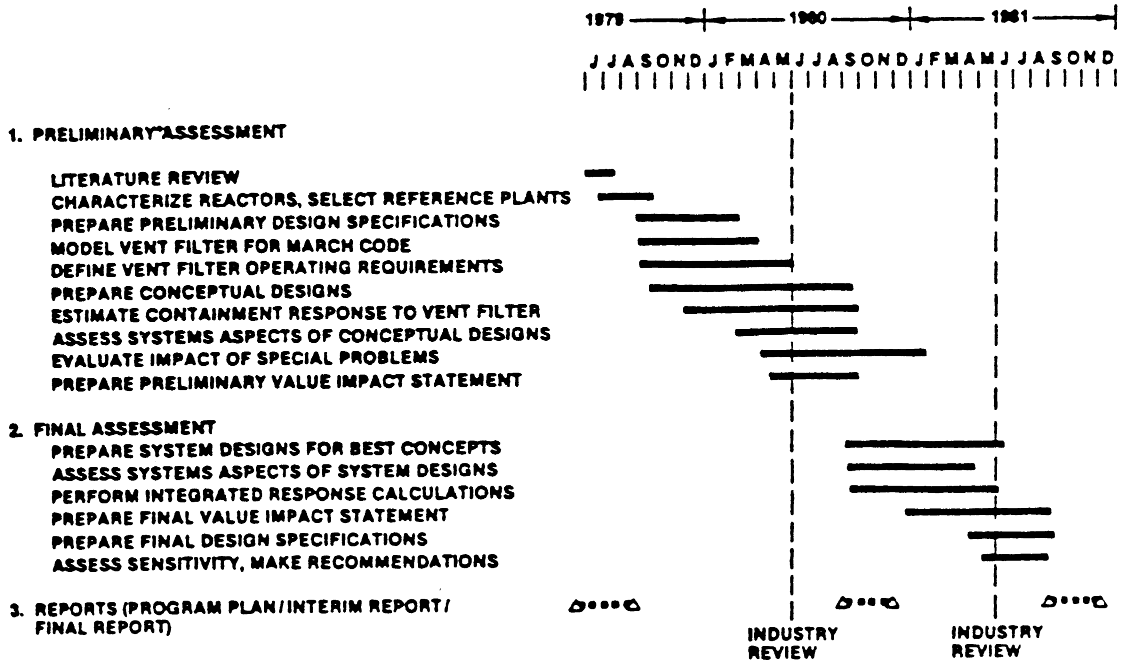


Figure 1. Program Schedule.

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

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

TECHNICAL ISSUES

Accidents that Challenge the System

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

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

Table I. Accident Scenarios Considered for Reference PWR Designs.

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

Pressure Spikes

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

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

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

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

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

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

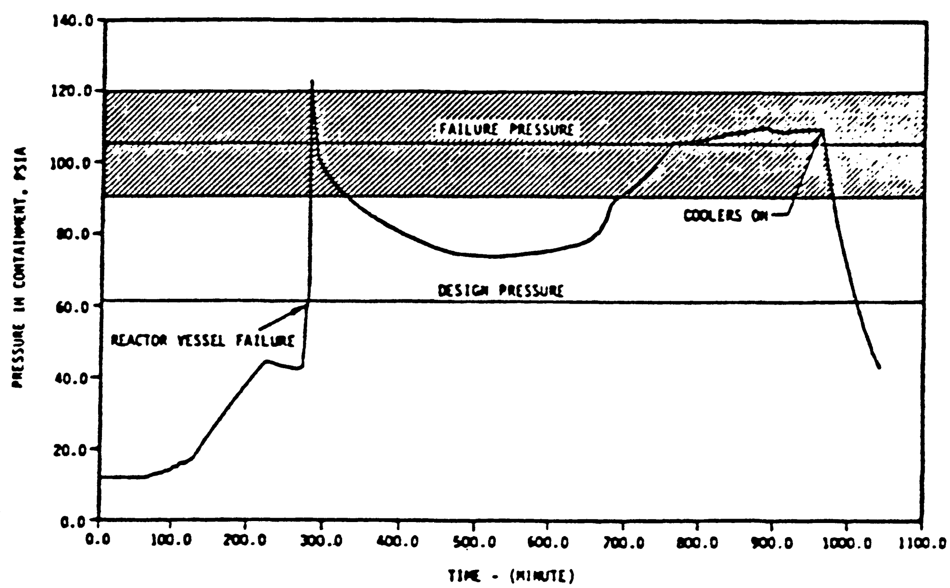


Figure 2. MARCH Code Calculation of Containment Pressure Versus Time for the TMLB' Accident in the Reference PWR.

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

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

System Interactions

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

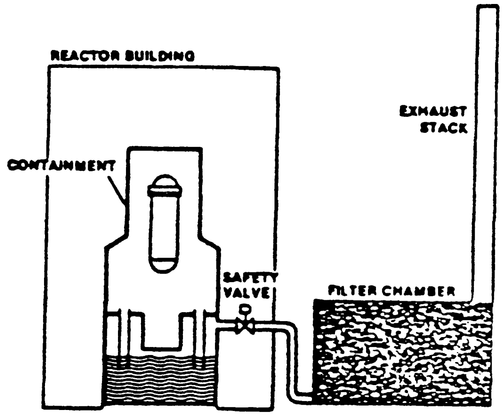
DESIGN POSSIBILITIES

Containment Vent Strategies for New Reactors

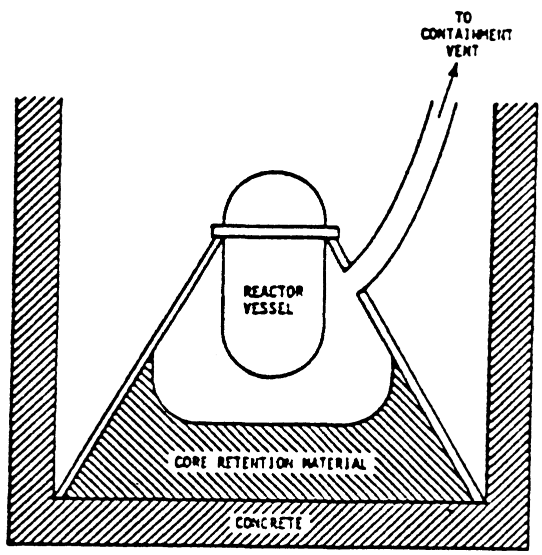
The primary challenge to a vent-filter system is its ability to mitigate the pressure spikes in containment. To accomplish this goal, it is much easier to formulate design concepts for new reactors (i.e., reactors that have not yet been built) than for reactors that already exist.

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

(a) Suppression Pool in Containment



(b) Reactor Vessel Guard Structure



(c) Vacuum Vent Building

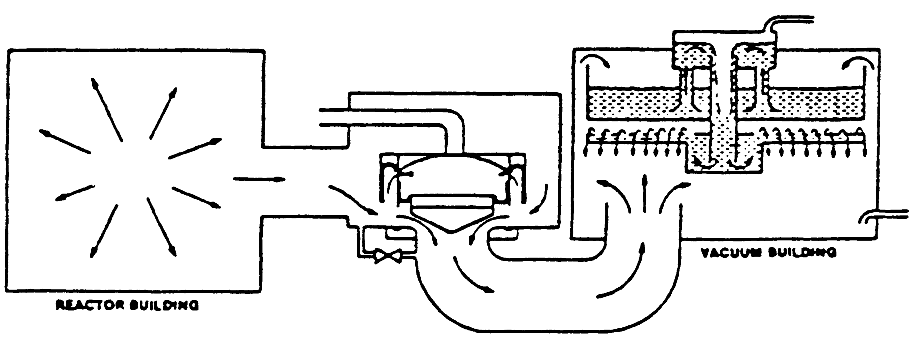


Figure 3. Schematics of Vent-Filter Design Concepts for New Reactors.

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

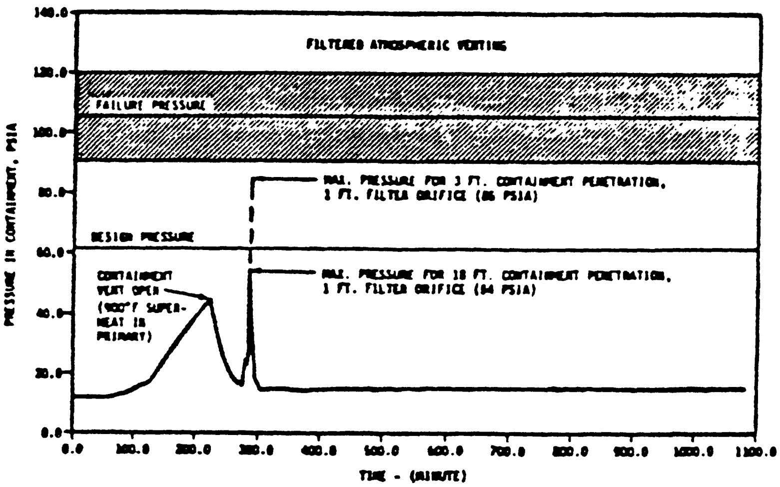
Containment Vent Strategies for Existing Reactors

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

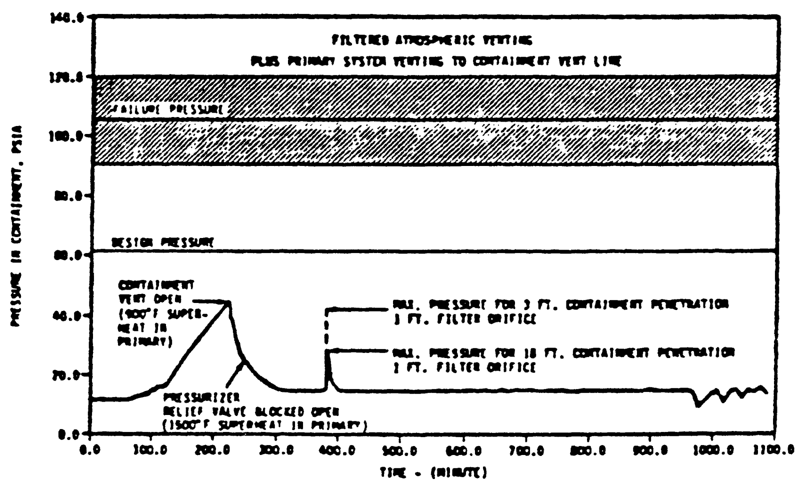
All of these strategies have implied risks, such as possible system interactions or human errors, that require a careful examination. When all the risks are evaluated, a simple vent strategy such as containment pressure relief at a setpoint above the design pressure, though perhaps less effective for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

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

(a) Filtered Atmospheric Venting



(b) Filtered Atmospheric Venting and Primary System Venting



(c) Venting to a Second Building

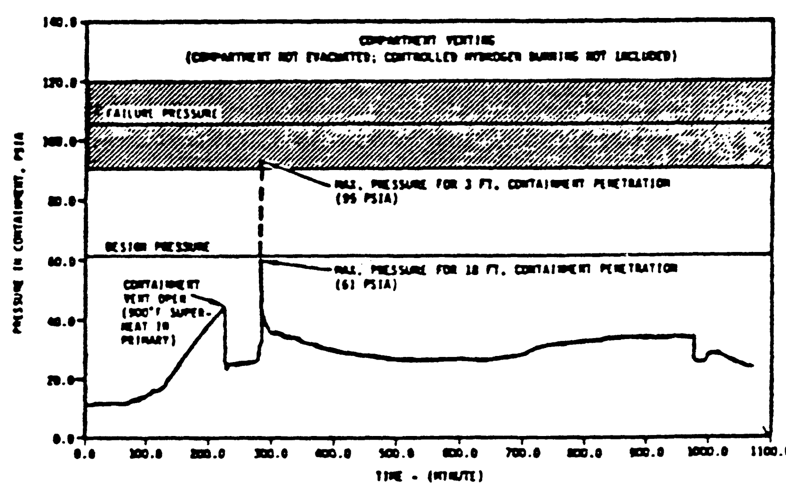


Figure 4. MARCH Code Calculations of Containment Pressure Versus Time for Various Venting Options During the TMLB' Accident in the Reference PWR.

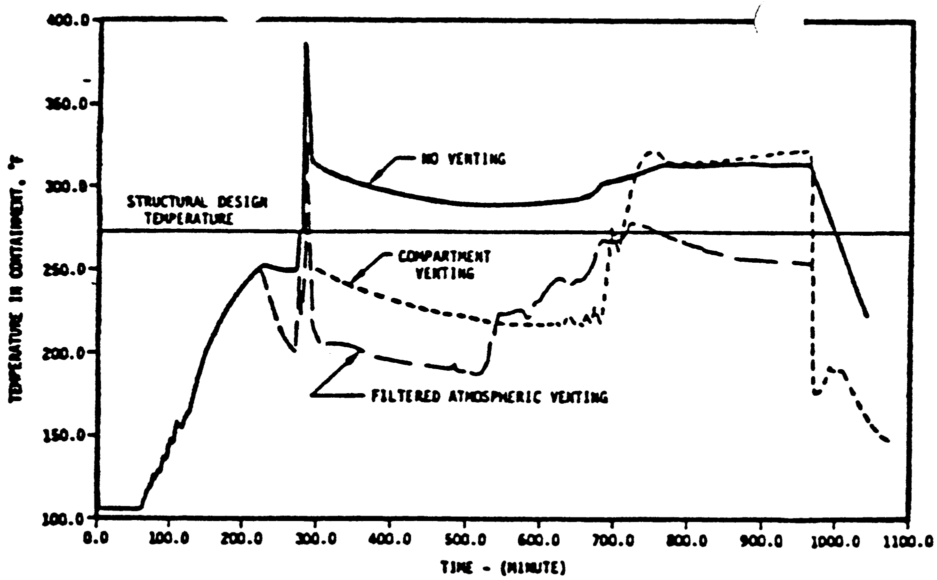


Figure 5. MARCH Code Calculations of Containment Atmospheric Temperature Versus Time for Various Venting Options During the TMLB' Accident in the Reference PWR.

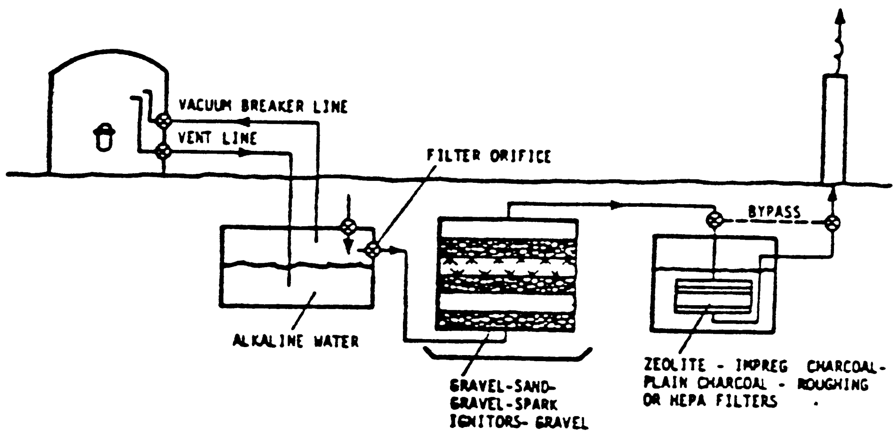
Cooler/Condenser and Filter Components

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

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

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

(a) Without AC Power



(b) With AC Power

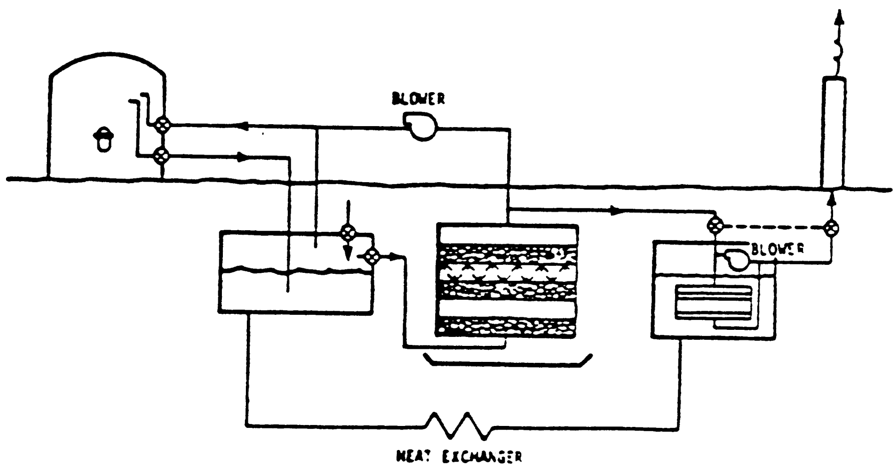


Figure 6. Filtered Atmospheric Venting Option. Estimated Collection Efficiencies: 99.98% Particles, 99.98% Inorganic Iodine, 99.95% Organic Iodine, 98% Xenon, 10% Krypton.

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

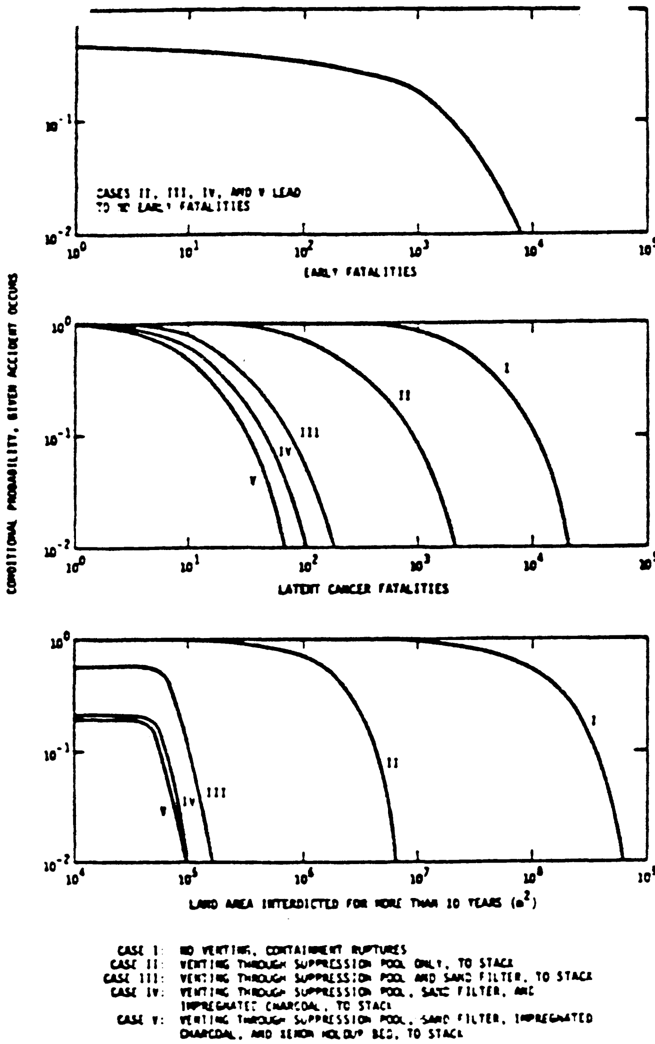


Figure 7. Probability of Early Fatalities, Latent Cancer Fatalities, and Land Interdiction for Various Filtered Venting Options, Given Occurrence of the Accident TMLB'.

CONCLUSIONS

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

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

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