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MASTER

ORNL-NSIC-27
UC-80 — Reactor Technology

REVIEW OF METHODS OF MITIGATING SPREAD OF RADIOACTIVITY FROM A FAILED CONTAINMENT SYSTEM

NSIC Staff

NUCLEAR SAFETY INFORMATION CENTER

NSIC

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Nuclear Safety Information Center

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SEPTEMBER 1968

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FOREWORD

The recent surge in the building of large nuclear power plants, particularly with the projected desirability of using urban sites for such installations, has focused attention on many aspects of the AEC's responsibilities for licensing reactors and insuring the public safety. Since the industry is "young," meaningful, long-term operating experience is sparse and the definition of the possible accident spectrum, as well as a set of firm design requirements, is subject to a largely analytical approach that necessarily involves conservative judgments. As plant designs become standardized and operating experience on the newer large reactors is gained, the inevitable process of refinement and of acquiring confidence in the operation of the plants will occur. This relatively slow evolutionary approach to acquiring firm design standards and criteria is not felt to be conducive to achieving the great national benefits of atomic energy within a reasonable time, in terms of the conservation of resources, combating air pollution, and the multitude of gains resulting from low-cost electricity.

As part of the effort to improve on this approach, the Regulatory Review (Mitchell) Panel recommended the formation by the AEC of a Steering Committee on Reactor Safety Research to coordinate the needs of the Regulatory Program with the direction of the safety research and development programs. This committee, in turn, recommended that several studies be undertaken to provide guidance for the research and development projects, and this was, in turn, implemented by the AEC Division of Reactor Development and Technology into the series of discussion reports herein described. It was intended that these reports provide a comprehensive assessment of the present status of specific aspects of nuclear safety and, by identifying accepted technology and the technology needing further experimental verification, that they enhance the understanding and confidence in this new industry.

Accordingly a number of the safety aspects of large light-water power reactors were selected by the AEC* as subjects for detailed study to

*Letter from Milton Shaw (Director, AEC Division of Reactor Development and Technology) to ORNL, March 28, 1966.

ascertain whether gaps in knowledge exist and where a research and development program could be of benefit. The subjects selected cover many of the areas for which inadequate factual bases exist and in which research that duplicates expected conditions is very difficult to perform. In general the subjects are in areas considered critical in the safety analysis of power reactor installations. Eight subjects were identified and a state-of-technology type of discussion report was prepared on each. The reports, which are directed primarily toward a technical-management audience, generally compare existing or planned plant applications with what is capable of being done at this time. Such comparisons have helped to identify inadequacies in assumptions, available data, or general basic knowledge so that, together with the opinions of experts in a particular field, areas of meaningful research and development have been identified.

This report is one of the series of eight companion reports listed below:

<u>Title</u>	<u>Author</u>	<u>ORNL-NSIC No.</u>
Missile Generation and Protection in Light-Water-Cooled Power Reactor Plants	R. C. Gwaltney	22
Potential Metal-Water Reactions in Light-Water-Cooled Power Reactors	H. A. McLain	23
Emergency Core-Cooling Systems for Light-Water-Cooled Power Reactors	C. G. Lawson	24
Air Cleaning as an Engineered Safety Feature in Light-Water-Cooled Power Reactors	G. W. Keilholtz, C. E. Guthrie, and G. C. Battle, Jr.	25
Testing of Containment Systems Used with Light-Water-Cooled Power Reactors	F. C. Zapp	26
Review of Methods of Mitigating Spread of Radioactivity from a Failed Con- tainment System	R. C. Robertson	27
Earthquakes and Nuclear Power Plant Design	T. F. Lomenick and C. G. Bell	28
Protection Instrumentation Systems in Light-Water-Cooled Power Reactor Plants	C. S. Walker	29

Although not specifically one of this series, a related discussion report on reactor pressure vessels, ORNL-NSIC-21, edited by G. D. Whitman, G. C. Robinson, and A. W. Savolainen, has also been prepared at ORNL.

The general approach in the preparation of these reports was to select a primary author-investigator knowledgeable in the subject area and to establish committees of experts to review the work at several stages during its preparation. Review groups were formed both from within ORNL and outside. The external review committee members were drawn principally from other national laboratories, universities, and private research institutes - in all, 52 individuals participated and are identified in the reports. In some cases, part of the material used was developed and/or written by a subcontractor, who is similarly identified. In all cases, correspondence and/or visits were made to many sources of information, particularly to reactor operators, suppliers, architect-engineers, and public utilities, as well as to the appropriate national laboratories. This wide use of acknowledged experts was made in an attempt to include their opinions and knowledge toward the ultimate goal of achieving, through intensive research and development programs, well-defined design criteria to insure the public health and safety and to maintain a viable nuclear power industry. However, in all instances the authors have expressed conclusions and recommendations that reflect their own judgment and not that of any particular group, such as the AEC, reactor designers, or utilities.

In most subject areas more information was developed than it has been possible to include in the body of the reports prepared in this series. In some instances, such information has been included in the appendices and in other instances this information will be included in more technically oriented reports to be published in the near future. In addition, it is expected that additional discussion reports will be written on some of the many other safety aspects of large water-cooled reactors, as well as other types of reactors as they come into wider usage.

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Director, Nuclear Safety Program
Oak Ridge National Laboratory

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PREFACE

The Nuclear Safety Information Center was established in March 1963 at the Oak Ridge National Laboratory under the sponsorship of the U.S. Atomic Energy Commission to serve as a focal point for the collection, storage, evaluation, and dissemination of nuclear safety information. A system of keywords is used to index the information cataloged by the Center. The title, author, installation, abstract, and keywords for each document reviewed is recorded on magnetic tape at the central computer facility in Oak Ridge. The references are cataloged according to the following categories:

1. General Safety Criteria
2. Siting of Nuclear Facilities
3. Transportation and Handling of Radioactive Materials
4. Aerospace Safety
5. Accident Analysis
6. Reactor Transients, Kinetics, and Stability
7. Fission Product Release, Transport, and Removal
8. Sources of Energy Release Under Accident Conditions
9. Nuclear Instrumentation, Control, and Safety Systems
10. Electrical Power Systems
11. Containment of Nuclear Facilities
12. Plant Safety Features
13. Radiochemical Plant Safety
14. Radionuclide Release and Movement in the Environment
15. Environmental Surveys, Monitoring and Radiation Exposure of Man
16. Meteorological Considerations
17. Operational Safety and Experience
18. Safety Analysis and Design Reports
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Computer programs have been developed that enable NSIC to (1) produce a quarterly indexed bibliography of its acccssions (issued with ORNL-NSIC report numbers); (2) operate a routine program of Selective Dissemination of Information (SDI) to individuals according to their particular profile of interest; and (3) make retrospective searches of the references on the tapes.

Other services of the Center include principally (1) preparation of state-of-the-art reports (issued with ORNL-NSIC report numbers); (2) co-operation in the preparation of the bimonthly technical progress review, Nuclear Safety; (3) answering technical inquiries as time is available, and (4) providing counsel and guidance on nuclear safety problems.

Services of the NSIC are available without charge to government agencies, research and educational institutions, and the nuclear industry. Under no circumstances do these services include furnishing copies of any documents (except NSIC reports), although all documents may be examined at the Center by qualified personnel. Inquiries concerning the capabilities and operation of the Center may be addressed to

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ACKNOWLEDGMENTS

The problems of control of radioactivity from a failed containment system were discussed with more than 50 nuclear scientists and engineers. All showed interest and gave freely of their advice and suggestions. Their helpfulness is gratefully acknowledged.

Appendix A contains a list of essentially all who gave assistance, but a few are mentioned here as having perhaps contributed more significantly than others. These include the ORNL internal review committee members W. E. Browning, Jr., W. R. Gall, C. C. Webster, and B. R. Fish; and the external review committee members F. J. Viles of the Harvard Air Cleaning Laboratories, C. R. McCullough of the Southern Nuclear Engineering Company, and K. Downes of the Brookhaven National Laboratory. Others contributors were W. B. Cottrell, J. W. Michel, and S. E. Beall of the Reactor Division, ORNL; I. F. Stuart of the Atomic Products Division, General Electric Company; N. Sowards of the Phillips Petroleum Company at the Nuclear Reactor Testing Station in Idaho Falls; P. Litteneker of the Idaho Operations Office of the AEC; R. Wieseman of the Westinghouse Atomic Power Division; and R. Griffen of the Bechtel Corporation.

Letters of comment that were particularly helpful were received from W. P. Johnson of the Yankee Atomic Electric Company, G. Wehmann of the AEC Idaho Operations Office, J. V. A. Longcor of the Stone and Webster Engineering Company, J. C. Russ of the General Electric Company, P. Matthew of the Pacific Gas and Electric Company, L. C. Schwendiman of the Battelle Memorial Institute, T. R. Wilson of the Phillips Petroleum Company, F. Schroeder of the Water Reactor Safety Program Office (currently with AEC Division of Reactor Licensing), and B. C. Rusche of the Savannah River Laboratory.

It soon became evident in writing this report that it would be very difficult to ascribe credits for specific information or ideas developed in the many conversations. There was considerable overlapping of thoughts, and shades of meaning were subject to interpretation. The references given therefore, in the most part, apply only to information available in the printed literature.

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ABSTRACT

This preliminary survey explores measures that could be taken on the reactor site to mitigate the spread of radioactivity to highly populated areas in the unlikely event of failure of the containment system of a large nuclear power station at the time of a major reactor accident. It is pointed out, however, that the fact that the study was undertaken does not suggest a lack of confidence in containment systems nor does it imply a weakening of the present emphasis on the need for sound, reliable containment vessels; rather, to enhance safety, consideration is given to what could be done in even the most improbable situations.

This subject has received relatively little attention, and essentially no state of the art exists. Brief reviews of the possible causes of containment failure, some selected past nuclear incidents, and the nature of the fission-product release serve as an introduction to the problems.

Of the 14 control methods suggested, releases of water sprays and foams (with chemical additives to promote iodine absorption) inside the containment vessel appear to have the best chance of success in reducing the amount of activity that would escape from the site. Control measures applied outside the containment vessel are considered to have less chance of being effective because of the problems of escaping gas velocity, the difficulty of finding a leak, the possibly adverse wind and other meteorological conditions, and the excessive levels of radioactivity likely to be present near the breach in the system. Of the methods used outside, again sprays and foams appear to have the most promise. A means of "directed failure," or pressure relief, for the containment system is judged to have value over uncontrolled release in the event of pressurization above the design value. Tall stacks for the venting of contaminated gas or thermal columns generated by the burning of fossil fuels could provide dilution and dispersion that would be preferable to ground-level release in certain situations.

It is recommended that the studies now under way on sprays and foams for use inside the containment vessel be extended to consider types and other factors relating to outside use. More thought could be given to pressure relief and to use of tall stacks and thermal columns. Methods

of quickly detecting and finding a leak in the containment system are needed. The administrative and technical problems attendant to making decisions at the time of an accident need to be analyzed, and means of obtaining the necessary meteorological data quickly and reliably should be studied. Preplanning is recognized as a most important means of reducing the consequences of a serious nuclear accident.

1. INTRODUCTION

The purpose of this study was to review methods that could be used to mitigate the spread of radioactivity from a large power reactor in the event of a major nuclear accident accompanied by failure of the containment system. Only measures that could be applied within the boundaries of the reactor site were considered. In reporting the results of this study it must be made clear at the outset that high-quality engineering and construction of critical components, engineered safety features, primary cooling system, etc., and the integrity of the containment system are the assured lines of defense against the uncontrolled release of activity from the reactor to the environment. This defense is backed up by the emergency core-cooling system, which is designed to prevent all but a small release of fission products from the fuel. The containment system forms a second backup defense in depth. Nothing to be found in this report or the fact that the study was undertaken suggests that this line of defense is not adequate or that continuing efforts to assure system integrity, reliability, and testability of engineered safety systems should be diminished.

Although reactor containment systems and engineered safety features are designed to confine most of the activity in any reactor accident, the consequences of the potential resultant activity release if the containment were to fail could be so serious¹⁻³ that there is continuing interest in methods that might be used to retard or reduce the escape of contamination. In order to be prepared to react sensibly in an emergency, deliberate study of possible courses of action is needed.

If effective activity controls could be developed they might also be useful in the event of significant accidental releases due to any cause, such as, for example, an intact containment vessel with a normal leakage rate but with a source strength greater than anticipated. There could also be speculation as to whether effective activity controls could affect the siting of reactors near metropolitan areas, could allow relaxation of containment requirements at certain special installations, or could have added value at times of threats of war and sabotage. These aspects perhaps explain in part the interest in activity control measures,

but further discussion and conjecture in these areas is not pertinent to this report.

The activity control methods considered here could be considered as "consequence limiting" and at this stage of development are not to be ranked with the engineered safety features used to protect the reactor system. Even though not capable of coping with many accident conditions, some of the activity control measures could, however, have a measure of success in many situations. Even limited mitigation of the spread of activity from the reactor site could be important to those who might receive a near critical tolerance level of exposure to radiation.

In any event, it is clear that it is consistent with the Commission's reactor safety policies to investigate all avenues that may lead to better protection of the public. Accordingly the objectives of this study were to (1) explore the nature of the need for activity controls once the containment is assumed to have been breached following an accident which releases significant quantities of fission products, (2) survey the possibilities for developing effective methods of mitigating the spread of activity beyond the site boundaries, and (3) indicate whether future study and development could be recommended for some areas.

It is to be noted that the first step was to establish the premise that the containment system had failed. It is therefore extraneous to discuss methods of reducing the chances of failure or to speculate on the likelihood of its happening or on the probabilities of one type of opening occurring rather than another. The study was designed to consider, without regard to credibility, all types of possible failures, regardless of the size of opening, where located, and whether caused by internal or external events. It was assumed that the failure had occurred in conjunction with the fission-product release associated with a major accident.

To give a frame of reference it was decided that the activity control measures would be studied in terms of the current designs of pressurized- and boiling-water reactor stations, although in general the reference plant used is not critical to the discussion. The Palisades Plant⁴ of the Consumers Power Company and the Indian Point Plant of Consolidated Edison of New York were taken as typical of the PWR designs,

and the Browns Ferry Station⁵ of the Tennessee Valley Authority was assumed to be typical of the BWR plants.

A further assumption was that the study should give emphasis to the activity control methods that appeared to be the most practical. This was judged to mean those that were testable and maintainable, were versatile over a broad range of accident conditions, were capable of being initiated even under difficult and unusual situations, and for such a seldom-needed device, would require reasonable investment and upkeep costs. Obviously, a control measure must not constitute a hazard to normal safe operation of the reactor. It appears unlikely that a single method could completely satisfy all these characteristics.

Since little work has been done on activity controls for this specific application, it was decided that the review should emphasize exploratory new approaches to the problem. Rather than make quick judgments as to the value of some suggestions, it was decided to mention even those of less apparent value in the hope that this might stimulate new ideas. A word of caution is also needed at the other end of the scale in that an activity control should not be prematurely rated as having value before the experts in the nuclear industry largely agree as to its merits.⁶ Based on this background, this report has several unique characteristics that should be noted.

1. In general, little state of the art exists on this subject because the nuclear industry has correctly concentrated first on preventing situations of containment failure rather than on measures to take if a system should fail.

2. Since little formal investigative work has been done and an imaginative approach was considered desirable, it was difficult to identify experts qualified to serve as reviewers and consultants.

3. Mathematical analyses of this subject would depend on empirical data which, in general, do not exist. Situations would have to be arbitrarily assumed, perhaps one favoring one control method and one another, and the estimates could be so strongly influenced by personal viewpoint that they would be of limited technical value. This report is therefore qualitative and generalized, with little presentation of data and calculational techniques.

4. Recommendations for future study and development are limited to noting those measures that appear to have promise and to recommending them for more detailed investigation.

This report first briefly reviews the possible causes of breached containment, the nature of the radioactivity release, and some selected past nuclear incidents in order to introduce the problems that might exist in connection with application of the activity control measures. Some desirable characteristics of the control methods are briefly reviewed. The activity control measures are listed and discussed in more or less a descending order of practicality, as judged by the writer, although the differences in many cases are not great. Also some related measures are discussed that would not directly mitigate the spread of activity but are judged to have significant value in reducing the consequences of an accident.

2. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Power reactors and their safeguards are now considered to be so carefully designed and regulated that a significant release of radioactivity to the surrounding area is extremely unlikely. For a release to take place, it would be necessary to have concurrent failure of the fuel element cladding, failure of the reactor primary system, and complete or partial failure of the many engineered safety features, including the containment system itself. However, it is in line with the Commission's safety policies to investigate all possible avenues that might lead to better protection of the public. Accordingly the study reported here was concerned with one relatively unexplored area - emergency equipment at each reactor station to mitigate the spread of activity from the plant site in the unlikely event that the containment system failed at the same time the reactor suffered an accident which released significant quantities of fission products.

A survey was made of all the methods considered feasible at this time for controlling the escaping activity. While better measures may be devised in the future, it is concluded on the basis of the present technology that none of the activity control methods, or combinations of them, can be considered to be sufficiently effective over the broad range of accident conditions that can be postulated to rank them equally with the other engineered safety features now required at reactor installations. This substantiates the widespread opinion that the reactor containment system and the associated engineered safety features that make the system operable are the last assured line of defense against a major release of fission products to the environment and that the integrity of the containment system and the reliability of the associated equipment are of utmost importance. Nothing found in this study suggests a weakening of programs directed toward achieving greater reliability of containment systems and other safety features.

While not to be compared with engineered safety features for coping with a major accident, some of the activity control methods considered might be of benefit in some circumstances, such as in the occurrence of a design basis accident during rare but adverse meteorological conditions.

The extent of protection has not been evaluated, but even some small reduction in the off-site exposure level could be important in certain circumstances.

It is clear that effective and reliable means of mitigating the spread of activity from a reactor site would have value to the nuclear industry and to the general public. Such effective and reliable control measures are not easily attained, however. Some of the reasons for this are (1) the very broad range of accident and meteorological conditions that must be considered in the designs, (2) gas escaping under pressure from a containment vessel would be very difficult to trap or to reduce in radioactivity and the high-velocity flow could continue for several hours, (3) after a major release the high local radioactivity level could severely limit effective action, particularly in such aspects as locating the source and the nature of the leak in the containment system, and (4) an accident situation severe enough to have caused simultaneous failure of all the in-depth safety aspects of the reactor system could also have made the emergency activity control measures inoperative.

To cover the assigned subject, "control of activity from a failed containment system," it was necessary to start with the premise that the containment system had been breached. This was done for this study without speculation as to the probability of any particular cause of containment failure or means of preventing it. Most readers will recognize that by beginning the report at this point an area is bypassed that has always been of serious concern to the nuclear industry and one for which generally satisfactory solutions have been found.

It will also be recognized that this study was unique in many respects. There is little state-of-the-art technology to report, and there was no cadre of experts to consult. Mathematical treatments would depend largely on empirical data which, in general, are not available. This study therefore was exploratory and emphasized an inventive approach to the problems. Since the treatment of the subject could not be precise, the report necessarily includes some generalized comments, and it is not surprising that there is a lack of unanimity of opinion in several areas that reflects the several facets of responsibility in the nuclear industry.

If there were a promise that effective activity control measures could be developed, there would tend to be speculations as to whether such equipment could affect the siting of large power reactors near metropolitan areas, whether they would be useful backups at times of threat of enemy action, or even that containment requirements might be abridged at certain special locations. These subjects are not within the scope of this report, although the comment can be made that it seems highly doubtful that any of the control methods reviewed in this study would serve as a sound basis for future changes in licensing requirements.

The objectives of the study were to (1) explore the nature of the need for activity controls if it is assumed that the reactor has suffered a major accident and that the containment has been breached, (2) survey the possibilities for developing effective methods of mitigating the spread of activity beyond the site boundaries, and (3) indicate whether future study and development in some areas would be profitable.

2.1 Nature of the Need for Activity Controls

Even though a relatively large amount of literature exists on such subjects as containment design and testing, descriptions of past nuclear accidents not associated with power reactors, the nature of fission-product releases, etc., brief surveys in these areas yielded few suggestions for methods of controlling the spread of contamination from the plant site. The sampling of the literature did point out, however, the extremely broad range of accident situations that might exist, the considerable magnitude of the problems to be encountered in a major accident, and the need for advance emergency planning.

In examining the circumstances of hypothetical accidents and of putting activity control measures into effect, it became apparent that one of the major problems would be quick determination of the location and character of the leak in the containment system. Since most agree that with present equipment it would often be very difficult to find the leak in sufficient time to affect the extent of a release, the conclusions were reached that the most practical of the activity control measures would be those not dependent on knowing the precise location of

the fault and that methods for determining the location of leaks could be recommended for future study and development.

For the purposes of this study "failed containment" was defined as having occurred if, due to changes in the containment integrity, radioactivity release to the environment exceeded that which was assumed in the calculation of the siting requirements. This definition states that primary and secondary containment structures, multilayered containment vessels, or additional confinement buildings are all considered part of the containment system that is considered to have failed as a premise of this study.

Since the siting requirements are based on the existence of relatively leakproof containment systems to confine the maximum credible accident, it is evident that if the above definition is applied, a system of containment can be considered to have failed even if only small openings develop, say, ones of an equivalent diameter of 1/8 in. or less. In other words, it is not necessary to assume catastrophic damage of the vessel in order to have failed containment as defined here.

Control of fission-product activity escaping through small openings would involve difficulties because of the high velocity of escape and the long time durations; for example, flow could persist for one day through a 4-in.-diam hole (see Chap. 3, Fig. 1). Assessment of the difficulties that would be encountered in retarding or reducing the spread of activity from a breached containment vessel while it was still pressurized leads to interest in methods for quickly reducing the pressure. These measures would be taken in addition to the use of pressure-suppression sprays which, as a premise of the study, might not have functioned effectively. A related aspect is that almost all the activity control measures considered in this report would have a better chance of success if the location of the failure in the containment system could be predicted in advance.

2.2 Suggested Activity Control Measures

The activity control measures suggested as a result of this study are summarized in Table 1, which lists the control methods considered,

Table 1. Summary of Suggested Activity Control Measures^{a*}

VG = Very good P = Poor
 G = Good VP = Very poor
 F = Fair NA = Not applicable

Suggested Method of Activity Control	Effectiveness on Small Holes ^b	Effectiveness on Large Holes ^b	Suitability for All Reactor Sites ^c	Adaptability to Remote Operation ^d	Self-Sufficiency ^e	Independency of Need to Know Exact Location of Hole ^f	Dependability and Simplicity of Initiation ^g	Maintainability ^h	Testability ⁱ	Reasonableness of Cost ^j
Inside sprays ^k	VG	G-F	VG	VG	G	VG	G	F	F	/ G
High-expansion inside foams ^m	VG-G	F	VG	VG	G	VG	G	F	F	G
Outside sprays	G	F	G	G	G	G	G	VG	VG	G
Foams										
High-expansion, outside	G	F	G	G	G	G	G	VG-G	VG-G	G
Dense, outside	G	F	G	G	G	G	G	G	G	G
Permanent, outside	G	P	G	F-G	G	P	F-P	G	G	G
Directed failure of containment vessel ⁿ	G-F	F	G-F	G	G	VG	G	F	P	G
Discharge from tall stacks ^o	G-F	P	F	G	G	VG	G	G	G	F-P
Underground disposal of gases ^p	G	F-P	VP	G	F	VG	F	F	F-P	P
Storage of contaminated water ⁿ	NA	NA	P	F	G	G	G	G	G	F
Patching of holes ^q	G	P	G	P	G	VP	F	G	G	VG
Plugging of openings ^r	P	F	G	F	G	VP	F	G	G	G
Transfer and storage of gases ^p										
Gas holders	C	F	F	G	F	VG	F	G	G	F
Underground	G	F	VP	G	F	VG	F	G	F	P
Flooding of containment vessel ⁿ	F-P	P	P	G	G	G	F	F	VP	F
Contaminated-gas pickup ^s	C	VP	G	F	G	VP	F	G	G	G
Retentive coatings ⁿ	P	VP	G	G	G	G	VG	F	VP	G
Remote discharge ^p	G	P	VP	G	F	VG	F	G	F	P-VP

*See following page for footnotes.

Footnotes for Table 1

^aThis table is intended primarily as a summary and not necessarily to point out control measures recommended for additional study. The ratings in the table are largely based on the opinions of the writer and on the assumed conditions given in these footnotes. The suggested control methods are arranged somewhat in a descending order of practicality, but the differences are usually not distinct. A typical accident condition for the purposes of this table is that the radioactivity release is essentially that resulting from the maximum credible accident, that the containment is initially pressurized to about 3 atm, and that the leak in the containment vessel can be fairly quickly found and is accessible. It is also assumed that there is not sufficient wind to make outside sprays or foams unusable.

^bEffectiveness is considered to be efficiency of the control measure in reducing the offsite dose rate and the accumulated dosage in the critical population areas. In considering effectiveness for large openings, large holes are assumed to have defined edges rather than to consist of total wreckage and destruction.

^cSome measures would be applicable at essentially any reactor location or for any site conditions, while others are strongly influenced by the local conditions and would be considered poor in this respect.

^dA desirable feature of the control measures is that they could be arranged for use of remotely operated tools or equipment.

^eSelf-sufficiency implies independence from local power and water supplies, controls systems, or similar facilities that might not be available under accident conditions.

^fA control measure would have limited usefulness if the exact location and size and character of the hole had to be known and the hole had to be accessible.

^gDependability and simplicity are related terms reflecting a very generalized opinion as to what would be the chances of the measure working as planned if used in an emergency.

^hMaintainability, as used in this table, relates to whether the important portions of the control measures are outside shielded areas and are accessible for periodic inspection and repair.

ⁱTestability refers to whether the control method could be tested regularly during normal reactor operation or, if tested during regular shutdowns, would not be damaging to materials or equipment.

^jReasonableness of cost is based on broad judgments, without benefit of cost estimates, as to whether a measure would involve high or low capital investment costs.

^kIt is assumed that water sprays, used either inside or outside the containment vessel, would have the benefit of chemical additives to make them more effective in iodine absorption.

^mIt is also assumed that foams would include chemical additives to make them more effective absorbers or retainers of fission products. In the case of the dense foams, it is assumed that the necessary physical properties could be developed to make the foam long lasting, cling to surface, etc.

ⁿStorage of contaminated water, flooding of the containment, and retentive coatings all might reduce the radioactivity escaping from the site, but all have serious limitations or do not act against the main body of airborne fission products.

^oTall stacks are assumed to be those greater than, say, 500 ft. Fairly favorable meteorological conditions are assumed, or, at least, it is assumed that the situation is not such as to prohibit use of the stacks.

^pUnderground disposal and remote discharge of contaminated gases were downgraded because of the heavy dependence on particular reactor site conditions.

^qPatches are considered to be rather low-grade, not completely tight closures such as might result from working under very difficult conditions.

^rPlugging is assumed only in terms of inflatable bags inserted in the opening and inflated by hose from a protected area.

^sA gas-pickup system is assumed that can suck up the gases and deliver them to a simple filter system to catch the larger particles and possibly to charcoal beds, water pool, or other absorbers to make some reduction in the iodine, but high efficiency of the containment air cleanup system is not implied.

the attributes considered desirable for the measures, and, in the footnotes to the table, a summary of some of the pertinent conditions relating to application of the methods of control. The qualitative ratings are perhaps less significant in that they are largely intuitive and based on assumptions, which, if changed, could appreciably affect the comparisons in some cases.

Control methods used inside the containment vessel are considered to have a somewhat better chance of success than those used outside, but other than for this distinction between the measures, the descending order of importance of the listing in Table 1 is primarily a matter of the writer's personal opinion. If a serious program of study and development of activity control measures were undertaken, a first step would be to establish a more complete basis of comparison of the methods.

2.2.1 Water Sprays Inside Containment Vessel

Water sprays used inside the containment vessel are considered to have the best chance of making important reductions in the amount of activity escaping from the site if containment integrity is lost. The sprays not only could possibly make a significant reduction in the escaping activity but would help lower the pressure in the containment vessel as an important aid in gaining control over the escaping gases.

Currently designed water-cooled reactor power stations include sprays inside the containment vessel. Originally the spray systems were designed principally for emergency heat removal and the accompanying reduction in containment pressure, but they are now also recognized as important for fission-product absorption. These internal spray systems are fairly simple in concept, and the spray water is collected in sumps and recirculated. The sprays can be initiated quickly and automatically, and the system is, in general, testable and maintainable. An assured supply of water is required, preferably with the reliance placed on a positive-head supply rather than on use of pumps.

Of the fission products, iodine is of perhaps greatest concern because it is one of the more abundant sources of activity and because of its large biological effect. In absorbing the elemental iodine in water drops, the temperature effect is more controlling than diffusion rates,

and the warmer the mixture the greater the difficulty in concentrating the iodine in the water. Absorption is enhanced by smaller water drop sizes and by longer contact times.

Chemical additives are employed in the spray water to improve the effectiveness in removing both elemental iodine and methyl iodide. Significant contamination factors have been reported for spray water to which borated sodium hydroxide or borated alkaline sodium thiosulfate has been added. Studies are continuing at ORNL in this area.

Fission-product particulates are also removed by the spray water. Condensation of steam helps carry particulates to the cold droplets, and under supersaturated conditions the particulates may become condensation nuclei for droplets that will settle out by gravity.

2.2.2 Foams Inside Containment Vessel

Foams could be released inside the primary or secondary containment vessel to absorb iodine chemically and to encapsulate the noble gases and particulates. Depending on the location of the hole in the containment vessel, the foam might also cover the opening to retard diffusion of the fission-product gases to the outside.

Foams, in general, however, are not durable at high temperatures and tend to be collapsed by condensing steam or water sprays. Foams generated by a gas coming from outside the containment barrier would tend to displace the containment atmosphere. If the containment gas were used for the foam generation, either the foaming equipment would have to be located inside the vessel, or, even less satisfactory, the containment gas would have to be taken outside and returned.

Investigation of foams is in preliminary stages, but encouraging decontamination factors have been reported. The results of one series of tests of foam with sodium thiosulfate reactant added indicate equilibrium concentrations of iodine to be about one-third those obtained without the foam, and the foam reduced the particulates by about 90% in a few minutes. Apparently when the foam is collapsed by a water spray, the iodine usually transfers to the liquid phase with relatively little of it becoming airborne.

2.2.3 Water Sprays Outside Containment Vessel

In contrast to sprays used inside the containment vessel, for which the effectiveness is not particularly dependent upon knowing the location of the leak in the vessel, the meteorological conditions, or the pressure inside the vessel, the performance of activity control measures used outside the containment structure is closely related to all three of these factors. Therefore the chances for making significant reductions in the spread of activity over the broad range of accident conditions to be considered is much less when the sprays are used outside rather than inside the vessel.

The comments made above regarding chemical additives, spray droplet size, etc., also apply to sprays used outside the containment vessel. The time of contact between the spray droplets and the once-through flow of the airborne contaminants would be much less, however, particularly if the gas were escaping at appreciable velocity, a stiff breeze were blowing, or if the outside spray nozzles were not positioned effectively. Another factor in the use of an outside spray is that provisions must be made for handling the contaminated runoff water.

An outside spray system, on the other hand, would not be as likely to be damaged at the time of a reactor accident as an inside system; the operating temperature would be lower and thus there would be more favorable retention of the iodine; the system would be completely testable and maintainable; and a simple, low-cost arrangement would probably be practical. Hose-fed nozzles could be positioned at the time of the accident and, indeed, might be an extension of the fire-fighting system. Chemical additives could also be considered for spray water used outside, but unless the water was recirculated, the volume of chemicals and the equipment to feed or mix them might become undesirably complicated.

2.2.4 Foams Outside Containment Vessel

High-expansion foams could be used outside the containment vessel to fill large but still-enclosed volumes, such as hallways, pipe tunnels, etc., where the exact location of the leak is not known. A more dense foam, less easily collapsed and blown by the wind, might be useful for

blanketing cracks, holes, or contaminated areas where particulates could become airborne. A more permanent foam might be hosed over an opening to restrict further diffusion of gases to the outside. Even though the foam would be largely ineffectual in confining gases having appreciable pressure, temperature, or velocity, less stringent conditions can be visualized where they might be helpful, particularly in encapsulating airborne particulates.

Only a relatively small amount of investigation has been done on foams for this special application. Development is needed for each of the three types of foams mentioned and also for the foam-generating equipment.

2.2.5 Directed Failure of Containment Vessel

"Directed failure" is a term used to describe the deliberate release of the contaminated gases at a location and in a manner that would be preferable to an uncontrolled release through an accidental opening in the containment. Automatic or manual arrangements might be used for this purpose.

Deliberate release in a controlled manner is much to be preferred to uncontrolled release from a failed vessel. Contaminated gas would preferably be directed through an efficient filter and absorption cleanup system and then discharged from a stack, but less sophisticated arrangements, such as passage through a pool of water or through chemical sprays, foams, rough filters, or even untreated discharge from the stack, could all possibly result in less off-site exposure than an uncontrolled ground-level release.

The relief arrangement would permit quick reduction of the containment pressure in emergency situations where the activity escape from the fuel had not peaked or would continue for an extended time and would thus permit attempts to restrict the hole to retard further flow or diffusion. The release mechanism could be designed for reclosure, but of course any such device would require detailed study to be sure that the mechanism itself did not constitute a threat to the integrity of the containment vessel.

2.2.6 Discharge from Tall Stacks

A "tall" stack might be defined as one that is higher than normally used for routine off-gas discharge. Such tall stacks might be, say, 500 to 1500 ft in height. The advantages to be gained with an elevated discharge point result from the effects of dilution and dispersion, getting above inversion layers, or the higher wind velocities aloft, and can vary markedly for different reactor sites and for hour-to-hour atmospheric changes.

This measure should not be judged on the basis of the worst possible conditions but, rather, on consideration of the frequency with which favorable factors would tend to exist at a particular site. Estimates of plume rise, dispersion, etc., at the present time are largely based on empirical data and are not claimed to be precise. A continuing program of such investigations by the Environmental Sciences Service Administration is sponsored by the USAEC. Study of dispersion by tall stacks can also be justified on the basis that such stacks could be useful for more routine discharge of gases from the plant, as well as in accident situations.

Transfer of the contaminated gas from a breached containment system to the stack involves ducting, valves, blowers, filters, etc., of the type already provided for the containment-air cleanup systems in some reactor designs, and the system is subject to much the same possibilities of failure to function properly at the time of an accident. Natural draft could be used in drawing gases from the containment vessel, but the stack would have to have a column of heated air inside to get the flow started. Burners in the base of the stack have been suggested for supplying the necessary heat. If the size of the hole in the containment vessel were relatively small, the gas flow rates might not be sufficient for effective self-induced flow up the stack.

2.2.7 Underground Disposal of Gases

Pumping of contaminated gases into subsurface geological formations is technically feasible at some reactor sites, and substantial benefits due to absorption and decay could be attained. Each reactor site could be substantially different as to the potential for adopting this method.

Testing with actual gas injection would probably be required, since the gas transport would be a function of channels and fissures that might not be disclosed by borings. The discharge pressure and the displacement requirements of the gas-injection system are substantial, and, again, reliance is placed on mechanical equipment and its power supply.

Since this method of activity control is limited to those sites where the geological substrata favor it, underground disposal was not ranked high as a broadly applicable solution to the problem. As with several of the other activity control methods, however, there is sufficient interest in underground disposal for more routine discharge of gases or to serve smaller reactor installations to justify continued study and investigation.

2.2.8 Storage of Contaminated Water

Large volumes of contaminated water may be created during a major reactor accident as a direct or indirect consequence of the accident. A containment system failure that permitted the escape of primary or emergency coolant would release significant activity. Postaccident sprays for heat and fission-product removal are other sources of contaminated liquid.

Storage of contaminated water from a reactor site after a major accident is, of course, technically feasible. The volumes required for storage could be quite large if past nuclear incidents can be used as an indicator, perhaps 2 to 5 million gallons as a minimum. Obviously, not all reactor sites favor construction of retention basins of the required capacity or have suitable terrain.

While storage of contaminated runoff water is an important aspect in mitigating the spread of activity, it is not ranked as a major activity control measure because the airborne activity, in general, constitutes a much greater hazard. Movement of runoff water is slower and its course can be predicted sufficiently for the public to largely avoid it.

2.2.9 Patching or Plugging of Holes

It is possible that a breach in the containment vessel could be sealed or restricted by patching, such as with a sprayed-on thick coating, or the opening could be plugged, say, by an inflatable bag. Patches and plugs

of these types would not retain any appreciable pressure, but the total fission-product release could be reduced by retarding the diffusion of gases or drifting of particulates through an opening.

The problems of locating a leak in the containment vessel, particularly when the local radioactivity level is rapidly becoming excessive, and the chances that once located it would be inaccessible, lead to the conclusion that this method of mitigation of the spread of activity might have relatively little chance of successful application. The costs involved could be so small, however, that the cost could largely overcome the arguments against having such equipment on hand.

2.2.10 Storage of Contaminated Gases

It has been suggested that the contaminated gases remaining in the breached containment structure or being evolved could be withdrawn and stored in underground chambers, gas storage tanks, etc. There could be some initial self-pressurization to cause the transfer flow, but after this subsided it would be necessary to rely on other means, such as blowers or displacement. If the storage volume was essentially at atmospheric pressure, as is probable, the volume required could be quite large, particularly if the containment vessel were initially pressurized to, say, 2 or 3 atm. Any circulation of air through the opening in the vessel would produce additional contaminated gas that would also have to be handled.

The storage containers would have to be leaktight and reliable and could present a serious biological shielding problem. The suggestion that a complex of several reactors could share a common emergency contaminated-gas storage facility may have some future merit provided the reactor plants are not too widely separated.

Transfer and storage of the gases is considered to be one of the less practical of the measures considered because of the relatively great expense, the reliance that must be placed on valves, pipes, blowers, etc., and the fact that all these components are subject to the same failures as the containment system itself.

2.2.11 Flooding of Containment Vessel

There would possibly be some value in flooding the containment vessel to cool the primary system and thus perhaps retard continued gas evolution, to absorb iodine, and to trap fission-product particulates. One disadvantage is that the flooding water would displace contaminated gases from the vessel. The flooding water storage tank might be interconnected to serve as storage for some of the displaced gas, but unless oversized, it could be only partially adequate and of itself would present a storage and shielding problem. Flooding is considered to be of greater interest as an accident-recovery measure than as a method of activity control in the event of breached containment.

2.2.12 Contaminated-Gas Pickup

A suction system with a flexible hose could be used to collect gases escaping from small leaks. The contaminated gas mixture could be discharged through the containment air cleanup system or through a separate filter system or the stack. The difficulties in locating the leak, its accessibility, the problems of placing the suction system intake nozzle at the right location, the fact that the gas-pickup system would itself become highly radioactive, and the limited size of the leaks that could be handled, all lead to the conclusion that this method has limited application.

2.2.13 Retentive Coatings

Special paints and coatings that have an affinity for iodine depend on chemical processes which are considered too slow to have much value as an activity control measure inside the containment vessel.

2.2.14 Remote Discharge

It has been suggested that contaminated gases might be piped underground to a discharge stack located in a remote area, off-shore, or at a higher elevation. Acceptable discharge points would be difficult to obtain, however, and the transport pipe itself would require much more property investment than the usual right of way. Valves, blowers, and other

mechanical equipment would be needed. This method is judged to have little to recommend it at this time.

2.2.15 Related Measures

There are some emergency measures and equipment that would not directly limit the spread of radioactivity but nevertheless would be very useful in reducing the hazards of a nuclear accident. One of the most important of these is a program of preplanning for emergency conditions. Plans of action and training programs are needed. Emergency evacuation of the threatened areas will still be the best answer to some situations. Warning systems, special hospital facilities, etc., and a continuing program of preparedness could also be of great importance.

Since no one activity control method would be best for all contingencies, more effective action probably could be taken if the reactor operators were given some freedom of choice at the time of the accident as to the best procedures to follow. An example might be a choice between continuing a slow ground-level release through a breach in the containment vessel or venting the pressure more quickly by discharge from a tall stack. As a practical matter, however, such decisions would probably be too far-reaching to be made quickly. Sufficient information and authority for making the selections probably would not be available until it was too late to affect the course of the accident greatly. It would probably be necessary, even at the expense of maximum effectiveness in some cases, to establish and approve beforehand specific courses of action for all emergency conditions.

Construction of reactors underground or underwater does not eliminate all escape routes for the activity but would undoubtedly offer a greater measure of protection. It is believed that this possibility will receive more attention in the future as the economic patterns continue to shift and change. This paper, however, is limited to additional measures applicable to conventional containment systems.

2.3 Recommendations

The recommendations are divided into three groups for further study and investigation and a fourth group which lists the concepts that do not merit further consideration.

Group I. The first group of actions are recommended as measures that should be considered in current planning by nuclear power plant operators. Except for the first item, they would require little if any experimental or hardware development work.

1. A method is needed for quickly indicating a leak in the containment system. Indications of a change in containment pressure or the presence of radioactivity outside the containment vessel would probably not be sufficiently early warning.

2. The whole question of directed failure or pressure relief for containment vessels should be kept open and thought given to how various equipment arrangements might satisfy containment integrity requirements.

3. Reactor stations need essentially continuous input of meteorological data and its analysis to allow quick evaluation of an accident situation and use of activity control measures. Prediction of the weather conditions likely to exist during the full course of the activity release is needed.

4. There is considerable opinion that preplanning for emergency conditions, including operator training, plans of action for the community, etc., would be one of the most important means of reducing the seriousness of a major activity release from the containment system. The work already done in this area could be extended, and the Civil Defense Program might be made a more intimate part of emergency planning. On the other hand, the administrative and technical problems attendant to operators' decisions as to the best courses of action in a particular accident situation also need analysis and study. Speed would be essential, and yet the consequences could be so great as to demand reliable accident analysis information, meteorological reports, and communication with higher authorities.

5. A significant amount of work has been done and is still in progress on the use of water sprays, both with and without chemical additives,

to absorb or entrap fission-product gases and particulates under conditions likely to exist inside the containment vessel. Investigations should also be made under conditions that might exist outside the vessel. Such factors as spray drop sizes, spray densities, thickness of spray curtain, design and placement of nozzles, etc., would be of interest.

Group II. The second group of recommended actions would probably require substantial developmental or experimental work before applications could be made. There is a reasonable expectation that after this development, effective measures would be produced. Thus these techniques are further removed from successful application than those in Group I and the incentive for their development is somewhat contingent on the performance and acceptability of the higher ranked techniques.

1. Some work has been done on high-expansion foams as they might be used inside the containment vessel. The investigation should be extended to foams as they might be used outside and should cover development of higher density and more permanent types of foam, as well as the high-expansion type. Studies are also needed of foam-generating equipment.

2. While some studies have been made of tall stacks, cloud buoyancy, etc., a study to relate these specifically to use as activity control measures would probably be meaningful. A wide range of meteorological conditions, fission-product releases, and distances from the stack should be considered.

3. Flooding of the containment vessel would provide both (a) a large heat sink for afterheat and sensible heat and (b) a fluid envelope that would absorb, or at least confine, the fission products once boiling was suppressed. Although several of the accepted emergency core-cooling techniques accomplish these ends from within the reactor pressure vessel itself, containment flooding techniques would not be subjected to the restraints of core or pressure vessel integrity. The effectiveness and problems concerning the use of this technique merit further consideration.

4. As population densities and the number of nuclear power stations increase, there will probably be increasing interest in underground and underwater nuclear plants. Studies of safety features, costs, and additional problems associated with such sites should be undertaken as the basis for encouraging the construction of such plants.

5. The release of colored smoke or an olfactant inside and/or outside the containment vessel needs to be investigated both as an aid to locating leaks and as a means for tagging a radioactive cloud crossing the site boundary.

Group III. The third group of actions consists of those that need further study before a decision is made either to enter into their development or to discard the concepts.

1. The problem of storage of large quantities of contaminated water should be evaluated and emergency plans established for such storage at every nuclear facility.

2. Contaminated gas storage systems are technically feasible, but detailed engineering design would be required to evaluate their cost and performance. Such work would not appear justified unless several of the more promising techniques such as directed failure and tall stacks are ruled out.

3. Retentive coatings within the containment vessel might be effective in some situations but would have limited effectiveness in the event of a large containment vessel failure that occurred simultaneously with the loss-of-coolant accident. Perhaps it should be further developed for the former situations although it cannot be regarded as a satisfactory solution to the general problem.

Group IV. Of the many techniques considered for the control of activity in the event of a failed containment vessel, the following do not appear to have sufficient merit to warrant their further consideration:

- (1) underground disposal of gases, (2) patching or plugging of an opening, (3) gas-pickup system, and (4) remote discharge of gases.

3. NATURE OF CONTAINMENT FAILURES

While methods of preventing failure of the containment system are not pertinent to this report, the possible causes of failures, the effect of the hole size, the nature of the released activity, and past experiences in nuclear accidents are all of interest because they have a bearing on the problem of retarding the spread of activity beyond the site boundaries.

3.1 Definition of Failed Containment

For the purposes of this report, failure of the reactor containment system can be defined as having occurred if, due to changes in the containment integrity, a radioactivity release to the environment significantly exceeds that assumed in the calculation of the exclusion area requirements. This definition states that primary and secondary containment structures, multilayered containment vessels, or additional confinement buildings are all part of the containment system considered to have failed as a premise of the study.

3.2 Possible Causes of Breached Containment

In the preparation of this report the principal methods by which containment vessels could be breached were considered in order to determine whether there were characteristic features associated with each that would have a bearing on the activity control measures that could be employed. The results are summarized in Table 2. (There is no significance to the order of listing.) It may be noted that all the possible causes, except acts of war, are taken into account in the design. The following comments are not, as is obvious, a comprehensive review of these broad subjects.

3.2.1 Missiles

Both pressurized- and boiling-water reactor designers have investigated whether missiles could be generated within the containment vessel that would have sufficient energy and direction of flight to violate the vessel integrity. In fact, some opinion exists that the inside missile

Table 2. Possible Causes of Breached Containment

Cause of Breached Containment	Probable Hole Size	External Appearance of Hole	Probable Location	Ease of Location and Detection	Probable Accessibility	Probable Immediate Radioactivity Level Outside Hole
1. Missiles - interior	Small to medium	Cracks, fissures, jagged openings	Upper half of vessel	Poor for smaller holes and cracks	Variable over wide range	Variable over wide range
Missiles - exterior	Small to massive, essentially complete destruction	Variable over wide range	Upper half of vessel	Relatively easy for large holes	Relatively easy	Delay of few minutes possible - amount could vary over wide range
2. Overpressure	Small to massive	Cracks, jagged openings, blown seals and fittings	Variable over wide range	Variable over wide range	Variable over wide range	Variable over wide range
3. Isolation valve, seals, or piping	Fixed by dimensions of parts and number that fail	Fixed by geometry of parts	As fixed by design	Variable - control room indications could help	Could be poor	Variable over wide range of possibilities
4. Operational errors	Variable over wide range	Generally unknown and variable over wide range	Unknown	Variable over wide range	Variable over wide range	Unknown
5. Design, manufacture, inspection, and installation deficiencies						
6. Tornadoes, hurricanes, and tsunamis						
7. Earthquakes						
8. War and sabotage	Large	Immaterial	Bottom of vessel	Immaterial	Impossible	Unknown
9. Reactor core melt-through						

risk has been reduced to the point where the danger from outside missiles is the greater of the two. The present technology with regard to missile damage to the containment vessel has been reviewed by Gwaltney.⁷

An interior missile could strike the containment shell of a pressurized-water reactor and possibly cause appreciable leakage without necessarily making a well-defined hole easily located from the outside. Missiles striking the outer surface of the confinement building associated with a boiling-water reactor would meet relatively little resistance to penetration until they passed through it and struck the primary containment structure. Small missiles could make clearly defined and fairly easily located holes. On the other hand, missiles striking the outer surfaces of heavy-walled concrete containment structures would meet such high resistance to penetration that it has been estimated that only the largest of airplanes or armored military missiles could reach the inside. For concrete vessels, complete penetration of 4 or more feet of thickness seems unlikely, although it is possible to visualize fractured and splayed concrete, twisted reinforcing steel, and many cracks and fissures covering a broad area through which the escaping gas would follow a devious path. Examination from the outside might give only a fair indication of the total damage.

In the unlikely event that a large missile struck the containment vessel of either a boiling- or a pressurized-water reactor in such a way as to rupture the vessel and also to cause a loss-of-coolant accident, the massive activity release through a large, irregular opening, perhaps accompanied by fire and explosion, would create a most difficult situation for the application of activity control measures.

3.2.2 Overpressure

The containment vessels for pressurized-water reactors⁴ are typically designed for an internal pressure of 55 psig and those for boiling-water reactors⁵ for 62 psig. The design and test pressures for several power reactor containment systems are summarized in Table B.1 of Appendix B. The secondary containment or confinement building used with boiling-water reactors is a sealed structure with relatively little pressure-containing capability.⁷

A loss-of-coolant or nuclear excursion type of accident can be postulated, however, that fills the containment vessel with a mixture of gas, hydrogen, air, steam, and fission products. If a defect in the design, material, or workmanship is postulated, the pressure might exceed the strength of the structure and failure would ensue.

Some believe that if a containment vessel were pressurized to the point of failure, breaching would probably occur by blowout of seals, ruptured pipes or fittings, or cracking of the vessel, rather than by a massive splitting open and sudden release of the contents. The point of failure would possibly not be the same even for vessels of the same design. As will be discussed subsequently, it would be advantageous from the standpoint of activity control measures to be able to predict the mode and location of the failure.

3.2.3 Isolation Valve, Seal, or Piping Failures

Failure of the process piping penetrating the containment wall, the seals or valves on this piping, or seals at access openings into the containment structure would not necessarily release activity to the uncontrolled environment but, under certain conditions, could constitute a breach of the containment system.

These types of failures could take a great many forms and involve leaks of a variety of sizes, particularly if several points in the piping system failed simultaneously. The general location of the leaks would obviously be in the vicinity of such equipment or openings, but the exact location could be in a pipe tunnel or at another inaccessible point and thus make direct approach for inspection and repair extremely difficult.

3.2.4 Operational Errors

Despite control interlocks, alarms, checklists, etc., there is always concern that misoperation may lead to an unlikely chain of circumstances. Operator errors are perhaps most likely to be a threat during reactor shutdown or at other times when the normal protective control measures are inactivated and more than normal reliance is placed on administrative procedures.

It would have little meaning to speculate on the broad range of accident situations that could be postulated as a result of operator errors. Some of these could cause failures, such as overpressure, etc., that have already been listed. One type of operator error frequently mentioned as a possibility is the failure to close and seal containment access openings properly. In the event the "door were left open," so to speak, the corrective action would be apparent, although not always possible due to high activity levels. Operator errors that perhaps pose a more difficult problem in prediction of the consequences are those resulting from activating the wrong controls or using poor judgment during emergency situations.

3.2.5 Design, Manufacturing, Inspection, and Installation Deficiencies

Responsible management in the design and construction of the reactor, its associated equipment, or, for that matter, the activity controls that might be applied at the time of a containment failure, is basic to the industry and is mentioned only to emphasize its importance. The range of difficulties that could result from lapses of management in these areas is so great that speculation would add little to this discussion.

3.2.6 Tornadoes, Hurricanes, Tsunamis, and Floods

The violence and unpredictability of tornadic winds are well appreciated. Hurricanes, tidal waves, and floods can be anticipated farther in advance but are nevertheless violent and of concern. While reactor designs must take cognizance of these hazards, they can still be listed as possible causes of failure of the containment.

It has been pointed out that storms or events that caused failure of a reactor would also probably disrupt the electric power, communication, and transportation facilities and could affect the availability of emergency cooling water, either from storage tanks or reservoirs. The same disturbances could also strike nearby population centers to create disastrous conditions. A major activity release that would threaten the population under these disturbed conditions could be of particularly serious consequence.

The extent and nature of the containment failures that could result from these forces of nature could be postulated as covering the entire spectrum from essentially the smallest to the largest openings. It is hard to conceive of any of the activity control measures being effectively applied during the course of a tornado, hurricane, tidal wave, or flood, but they could be of value afterward, particularly since the activity release from a major nuclear accident could continue for many days or even weeks. On the other hand, it is most unlikely that a disastrous natural phenomenon and a reactor failure that would release fission products could occur simultaneously with sufficiently high probability as to warrant serious consideration from the standpoint of activity control unless the same natural phenomenon were to simultaneously cause both the accident and the containment failure.

3.2.7 Earthquakes

Reactor designs include consideration of seismic loads, and Bell and Lomenick⁸ have reviewed the present technology as related to nuclear structures. As with the other natural occurrences mentioned above, the range of possible failure modes of the containment system is rather large, and normal conditions could be so disrupted that few specific conclusions can be drawn with regard to application of the control measures.

3.2.8 Acts of War and Sabotage

It is evident that a reactor containment vessel located above ground would be subject to direct hits from large explosive-head missiles. As has been pointed out, however, penetration of or damage to the containment structure would not necessarily trigger a chain of events leading to a release of fission products.

Sabotage is of concern because it is difficult to defend completely against it. However, many acts of sabotage would probably be guarded against by the reactor control interlocks and safety systems in much the same manner as other accident situations, and the threat to reactor safety and containment integrity is not necessarily a great one.

Speculation on the range of accident conditions that could result from enemy action is considered to be outside the scope of this report.

3.2.9 Reactor Core Melt-Through

The mechanisms of the core melt-through accident are still under discussion, but for the purpose of this report the accident can be simply described as a loss-of-coolant situation accompanied by failure of the emergency core cooling system. It can then be postulated that this causes the reactor core to become a molten mass and to melt through the primary system vessel and then through the bottom of the containment vessel. Kolb and Samuels⁹ made preliminary studies of this situation, and Lawson¹⁰ has reviewed the technology on emergency in-core cooling. McLain¹¹ has made a similar review of the metal-water reaction that bears on this problem. An AEC task force, under the chairmanship of Ergen,¹² has reported on this subject.

This type of postulated accident is of interest here because it represents a somewhat different failure of the containment vessel. An opening formed near the bottom of the vessel, well below grade level, would cause escaping gases to find their way to the surface by devious routes. Particulates and other contaminants could be transported by movement of ground water or through drainage systems. Flooding of the containment vessel in such an emergency could release additional amounts of contaminated water into the ground, but whether this would be a desirable or an undesirable expedient would depend on the accident conditions, the ground water movement at the particular site, etc. The extent to which the ground materials would trap particulates and volatile fission products is a matter of conjecture, but some feel that, with perhaps the exception of the noble gases, the earth would be an effective barrier.

3.3 Effect of Hole Size

If the containment vessel is pressurized at the time it is breached, the resulting gas velocity through the opening could make effective external application of activity control measures difficult or impossible. The gas flow could continue for minutes, hours, or days, depending on the size of the hole. It is thus of interest to calculate the effect of hole size on the time required for a containment structure to bleed down

to essentially atmospheric pressure. The results of such calculations are given in Fig. 1, and the calculations are described in Appendix C.

The blowdown time is of course a direct function of the initial pressure, which was assumed to be 55 psia. This arbitrary value may be compared with typical test pressures for a PWR containment vessel of 55 psig and for a BWR vessel of 62 psig, as listed in Appendix B.

For 1,000-Mw(e) nuclear power stations the free volume of the containment vessel associated with boiling-water reactors⁵ is about 300,000 ft³.

Fig. 1. Time Required for Blowdown of Containment Volume. Pressure from 55 to 14.7 psia.

and that for pressurized-water reactors⁴ is roughly 2,000,000 ft³. It was arbitrarily assumed that the interior temperature was 150°F and that this remained constant throughout the expansion; thus a factor was allowed for continued heat release within the vessel. The value of the temperature or the fact that it remains constant do not, however, have a critical effect on the estimates of blowdown times. If, for example, the interior temperature remained constant at 250°F rather than 150°F, the estimated time to bleed down would be decreased by only about 3%. Other assumptions used in making the estimates are given in the footnotes to Table 1 and in Appendix C.

The time estimates given in Fig. 1 would be greater if there were continued steam generation or blowdown of the primary system inside the vessel, or they could be shorter if the spray cooling or pressure-suppression systems operated as planned. The values illustrate, however, that for smaller holes there could be an extended period over which there would be appreciable gas velocities through the opening. This velocity could be well over 1000 fps initially and in the range of more than 100 fps even at residual pressures of a few inches of water. It should be appreciated, also, that even at low flow rates, the quantity of radioactivity escaping could still be such as to prohibit direct approach to the vicinity of the leak. To effectively control escaping activity it is clear that one must first reduce the pressure in the containment vessel.

3.4 Released Activities

3.4.1 General

A discussion of activity control measures necessarily involves some consideration of the nature and quantity of radioactivity that could escape from the containment system and the effect this could have on the off-site dose rates. Some of these aspects are briefly reviewed here because they have a direct bearing on the need for activity controls and possibly suggest the chances for success in significantly mitigating the spread of activity. It is also of interest to have an appreciation of the analytical methods involved in estimating the off-site dose rates and the degrees of pessimism involved.

Many consider that the design basis accident for a water-cooled reactor would be caused by loss of coolant. While it is generally agreed that this is an unlikely situation, if it is assumed that the emergency core-cooling system does not function properly, the events that take place in this type of accident are rupture of the primary cooling circuit, loss of coolant, pressurization of the containment vessel, core heating by decay heat, melting of the cladding, fuel melting, fission-product release, and fission-product dispersal within the containment vessel. It may be noted that for large amounts of fission-product activity to escape from the reactor site it is necessary to assume (1) rupture of the fuel-element cladding, (2) failure of the reactor primary system, (3) failure of the emergency core-cooling system, and (4) failure of the containment system.

The engineered safeguards and the containment system are designed to meet the contingencies of the maximum credible accident. In addition, the lack of precise information in some aspects has led to very conservative assumptions, particularly in the calculations used to evaluate the safety of potential reactor sites.

3.4.2 Nature of Release

The fission products of primary interest from a health hazard standpoint are the xenon and krypton gases, volatile methyl iodide (CH_3I), elemental iodine, tellurium, ruthenium, cesium, cerium, and strontium. The last five mentioned would probably exist as particulates, depending on the particular chemical form and isotope, its temperature, decay time, etc. These fission products exhibit quite varied chemical and transport characteristics.^{13,14}

The fission-product inventory in the reactor core can be calculated accurately as a function of the neutron flux, irradiation time, and decay time after shutdown. This is covered in detail in the literature, and Cottrell and Savolainen¹⁵ have presented an excellent summary and bibliography.

How much of the fission products would be released from the fuel upon failure of the cladding cannot be as precisely estimated, however. There are many areas of technical uncertainty and a broad range of accident conditions to be considered. There might be considerable difference

in the activity release from a reactivity excursion type of accident and that from a loss-of-coolant accident. The time sequence of events during the reactor blowdown has an important influence on the quantity and rate of release of the contaminants.

It is of interest to know how the fission products will behave on escape from the reactor vessel into the containment volume. The changing conditions could result in the formation of steam and other vapors, as well as liquid and solid aerosols in a wide range of sizes. Some of the ejected material may react with other elements to increase the volatiles and fine particulates. At the same time, certain amounts of the products are removed by deposition on surfaces and by steam condensation within the containment vessel, as discussed by Watson, Perez, and Fontana.¹⁶ The processes are complicated by decay of some of the gaseous products to solids and by condensation of some of the volatiles while cooling. These several factors make it unprofitable to attempt refined estimates of the quantities of fission products that might be available for release. It seems generally agreed, however, that the atmosphere in the containment vessel would be highly radioactive and possibly turbulent due to thermal-convection forces.

3.4.3 Dose-Rate Estimates

Because of the complexity of the conditions, the broad range of possible accident situations, and the present lack of definitive data in many areas, conservative assumptions have been used in calculations of the dose rate at the reactor site boundaries. In making the calculations, as required by the Code of Federal Regulations,¹⁷ the assumptions by DiNunno¹⁸ have commonly been used. These state that at the time of the maximum credible accident, 100% of the noble gases, 50% of the halogens, and 1% of the solids in the fission-product inventory in the fuel elements will be released into the containment volume. This represents about 15% of the gross fission-product inventory. Of the iodine released into the containment volume, 50% is assumed to remain available for escape into the environment. No credit is taken on this 50% assumption for the effects of containment sprays or air-cleaning systems. (This is not to say, however, that credit for the spray or cleanup systems will not be given

in judging the suitability of a reactor site. Culver¹⁹ discusses the credit that could be given for such safeguards in terms of apparent engineered-safeguard factors.)

In connection with the above assumptions it is interesting to note that at least some preliminary data indicate that the plateout of iodine in the containment vessel could be as high as 90%, rather than the 50% assumed.²⁰ The particularly good iodine absorption characteristics of bare concrete have been noted.²¹ Work by Morrison and his associates²² at Battelle Memorial Institute is continuing on the absorption of iodine and fission-product deposition on painted surfaces, stainless steel, and other materials found in containment vessels. It is thus possible that further investigations will disclose that the activity release is not so great as is now commonly assumed for the calculations.

From estimates of the fission-product release (based on the above assumptions), the demonstrated leak rate from the containment vessel, and the meteorological conditions at the particular site, calculations can be made of the distance required to the site boundary, the size of the low-population zone, and the required distance to population centers. The criteria for these estimates are established in Title 10 of the Federal Regulations.¹⁷ Methods of making these estimates have been summarized by DiNunno,¹⁸ Watson and Wittenbrock,²³ and others.

The dose received at the site boundary is a function of the amount of activity released, the inhalation time, and the distance from the point of leakage from the containment system. This has been illustrated by Gall,²⁴ as shown in Fig. 2. For all practical purposes, the dose at the site boundary is directly proportional to the amount of radioactivity released. For longer distances or extended release times, the wind and other meteorological conditions could change sufficiently to mask this proportional effect, however. Nevertheless, it is evident that if by use of control measures the amount of activity escaping from the site could be, say, cut in half, the dose rates in the surrounding area would also be reduced by roughly 50%.

As mentioned above, one of the important variables entering into the estimates of the dose rates at the site boundaries is the great variety of atmospheric conditions that could exist and which could change markedly during the course of a single accident. A constant wind direction is

Fig. 2. Inhalation Times to Give a Dose of 25 rem to Adult Thyroid Following 100-Mw Meltdown for Various Containment Leakage Rates. (Taken from Ref. 24)

usually assumed, but even a so-called steady wind is said to shift within a range of perhaps 10 to 30°. Watson and Wittenbrock²³ have calculated that the total body dose due to all fission products at 1.5 miles for 2-hr exposures under variable wind conditions is about one-half that for the assumed invariable case.

The most common expression of lack of variability in wind direction is persistence, which is determined by the length of time the wind direction remains in some preselected compass sector. This method fails to indicate the true hazard, however, in that a wind shift could end the instance of persistence even though the wind resumed its original direction

immediately thereafter. Brookhaven National Laboratory⁶ has examined the statistical concept of "constancy" represented by the ratio of the vector mean and scalar mean of the wind velocity. The initial results of applying this to the Brookhaven site indicated a surprising constancy at times not suggested by the persistency analyses. Further, periods of high constancy apparently often were accompanied by relatively strong winds, a condition favorable to dilution of the released activity and consequent reduction in doses.

Studies at the NARF site by Bradbury²⁵ support the thesis that the estimated dispersion factors obtained from the assumed relationships are well on the safe side when compared with measured values. The meteorology at the time of an accident thus has an important influence, a factor that has prompted several suggestions for more complete atmospheric data to be promptly available at the time of an accident.

Another factor entering into the dose-rate calculations at the site boundary is that the limiting condition is assumed to be the dose rate to the thyroid due to the iodine, principally ^{131}I . The iodine is considered to be the greatest health hazard because of the ability of the thyroid to concentrate it to a relatively high dose rate in that portion of the body. It has been pointed out, however, that while the thyroid dose may be controlling at lower levels of irradiation, in emergency situations of much higher dose rates, other contaminants may assume more importance. This is substantiated in a report prepared for the Internal Conference on Radiation Protection²⁶ in which it is suggested that thyroid tumors caused by radiation are not so great a risk to life as the less readily excisable malignancies, such as leukemia or bone tumors.

3.4.4 Leakage Rates

In translating the estimated activity level at the site boundary to the radiation effects on man at the usual distances of the site boundary from the reactor, the total exposure is more a function of inhalations from or exposure to the passing cloud than from direct gamma irradiations from the containment vessel itself. (This is true for both thin-walled steel containment shells and the thick-walled concrete vessels.) It is

thus very important to control the quantity of gas escaping from the containment system. Fortunately, it has been proved possible to build containment systems with a relatively high degree of integrity. In fact, the amount of containment leakage measured at actual installations in many cases has been less than one-half that required by the Federal Code.¹⁷ The design leakage rates and measured values at some major reactor installations have been summarized by Cottrell and Savolainen,¹⁵ and Robinson and Horton²⁷ have reviewed in some detail the design conditions, leakage, and leakage-rate testing for large U.S. reactor installations. Zapp²⁸ has reviewed the technology of containment systems testing.

It is important in this study to appreciate the low leakage requirements of the containment system in meeting the site-boundary dose-rate limitations. As shown in Table B.1 of Appendix B, in present-day nuclear plant installations the calculated "permissible" leakage rate (based on actual distances to the boundary) varies from about 0.1% of the containment volume per 24 hr for the PWR reactors to about 0.5% for the boiling-water type. If a PWR containment volume of 2,000,000 ft³ and a BWR containment volume of 300,000 ft³, leakage rates of 0.1% per 24 hr and 0.5% per 24 hr, respectively, containment conditions of 55 psia and 150°F, and the properties of steam are assumed, the amounts of leakage are represented by a hole about 0.06 in. in diameter in the PWR vessel and about 0.05 in. in diameter in the BWR vessel.

On the basis of the low leakage rates required to meet the siting criteria, it can be seen that almost any disturbance of the integrity of the containment vessel at the time of a major accident would come under the definition of a "failed" containment system, as given in Section 3.1. An appreciable hole, but by no means one constituting catastrophic failure of the vessel, could result in off-site calculated doses of serious proportions. In this connection, McCullough²⁹ states that "It is of no practical consequence whether 10%, 50%, or 90% of the fission products are released (from the core into the containment). The containment is our major engineered safeguard upon which we must rely if the integrity of the primary system has been broken and the emergency cooling system does not function. The leak rate of the containment, therefore, is of vital consequence. In the case of large reactors, if they are located

in reasonably populated sites, the leak rate is so low as to be beyond the practical measuring limit, that is, less than a tenth of a percent per day."

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It can be concluded from the above very brief review that even if fission-product behavior at the time of an accident were better known and present assumptions were perhaps less stringent, effective activity control measures would still probably be very worthwhile, even if the containment failure were due to a rather small opening. It is evident that the broad area of work in progress in the study of the meteorological and biological aspects will bring new understanding of the problems in the near future.

3.5 Past Accident Experience

Fortunately there have been no containment vessel failures associated with large reactor accidents in which significant amounts of activity have escaped. The following are generalized conclusions based on a few selected nuclear accidents or incidents involving small reactors. It must be kept in mind, however, that these small accidents are probably not typical of those that might occur in large power reactors.

In general, accident experience (e.g., SL-1,³⁰⁻³² NRX,^{33,34} NRU,³⁵ WTR,³³ Windscale,^{36,37}) has given little specific information with regard to application of activity control measures such as those described in this report. These accidents could, however, suggest the magnitude of some of the problems that could be encountered. It can be noted, also, that in any sort of incident involving the release of activity it is almost always very difficult to decontaminate the area. The cleanup usually requires considerable time, expense, and manpower, the latter because of the limited doses that can be accumulated per person.

Reactor accidents are usually the subject of wide-spread interest and concern. One of the major conclusions to be drawn from a study of past accidents is the importance of public relations and preplanning. The July 1956 Sylvania pyrophoricity incident, discussed by Eisenbud³⁸ in

terms of the inadequate program in effect for the dissemination of emergency information, was said to be followed by confusion and general hysteria in the Bayside, New York, area. The need for careful, explicit, and frequent reporting was apparent. Subsequent incidents, such as that at the Y-12 Plant in Oak Ridge³⁹ and the SI-1 accident, mentioned above, demonstrated the success of the AEC policy of giving prompt and full reports of possible hazards to the public, exposure of workers, and other circumstances likely to create rumors or exaggerated reports.⁴⁰

It seems generally agreed among those with reactor operating experience that were consulted in the preparation of this report that preplanning for emergency conditions may be one of the most important factors in reducing the effects of a major accident. With such preplanning and the use of some of the control measures suggested in this report, it is possible that the accidental releases described in the above accidents might have been mitigated, but the extent of this would be pure conjecture. One of the major difficulties to personnel taking effective action at the time of an accident is the local high radioactivity levels. With large power reactors involving activity releases of perhaps several orders of magnitude greater amounts than those involved in the above accidents, the possibilities of the operators taking activity control measures are probably considerably less than in these past experiences.

4. PROTECTIVE MEASURES FOR ACTIVITY CONTROL

It was assumed for this study that several methods of activity control might be maintained at each reactor site, since it is apparent that no one method is clearly best for all the contingencies of the broad range of accident situations that must be considered. The methods would be used as the emergency situation demanded or permitted and have been considered as relatively simple, highly flexible arrangements. This is in contrast to the philosophy of selecting the most promising of the control measures and, through sophisticated analyses and design, developing a system of equipment and controls to attempt to meet the exigencies of all anticipated conditions and have a guaranteed performance similar to that for the engineered safety systems used inside the containment vessel.

In considering the various suggestions for controlling the escape of activity from the site in terms of the situations that could possibly exist, it was apparent that the range of effectiveness for each could be very broad, and under particular postulated conditions might contribute very little. As stated previously in Section 3.4.3, the off-site dose rate would be reduced in essentially direct proportion to the percentage of the escaping fission products that an activity control measure could succeed in confining to the reactor site.

One of the basic assumptions made at the initiation of this study was that the measures to be considered were not of the accident-preventing type but rather were consequence-limiting procedures that could be applied on the reactor site to mitigate the spread of radioactivity beyond the exclusion-area boundaries. It was also decided that the study would not include off-site accident-recovery equipment and procedures, although provision for radiological surveys and monitoring, warning systems, evacuation plans, shelters, food and water regulation, medical treatment, etc., are very closely related to the subject and obviously could be of very great importance in emergency situations. (Accident-recovery procedures have been studied by Babcock & Wilcox³³ and by General Electric.⁴¹) Other similar aspects, such as the tagging of radioactive clouds, although not directly related to limiting the spread of

activity, are of interest to this report and are briefly discussed in Chapter 5.

Various methods have been proposed for the construction of containment vessels that would provide some builtin protection against leaks. These include self-sealing liners, sandwich construction, evacuated honeycomb spaces, etc. Double-wall multiple containment with evacuation of the inner space was proposed for the Ravenswood plant^{42,43} and is also proposed for the Malibu station, with the inner space filled with so-called "popcorn" concrete.⁴⁴ The features of some power reactor containment structures are summarized in Table B.1 of Appendix B, which was prepared by Denkins and Northrup.⁴⁵ However, as stated in Section 3.1, it was assumed for this report that the containment system had been breached regardless of the design of the vessel, and thus methods of construction were not of direct concern.

In order to make a summary comparison of the suggested activity control measures, they have been evaluated against assumed desirable characteristics, as briefly discussed below and listed in Table 1. It is emphasized that this qualitative evaluation is based on the writer's intuitive opinions after discussions with the various reviewers and consultants and also involves considerable speculation with which there may not be complete agreement. As explained in the footnotes to Table 1, if other equally likely conditions are assumed as a basis for the table, the relative worth of many of the measures could be changed somewhat.

4.1 Desirable Characteristics

It would be desirable that the activity control measures have as many as possible of the attributes given below. The listing is somewhat academic, however, and serves mainly as a basis for discussion, since, in the first place, few of the measures possess these virtues over a very broad range of accident conditions. It is also obvious that a few of the listed attributes are inappropriate for some of the control measures suggested.

4.1.1 Effectiveness

The primary objective is to retain as much as possible of the fission products either in the failed containment vessel or on the reactor site in order to reduce the dose rates in the low-population zones and nearby population centers.

4.1.2 Versatility

The activity control measures would possibly be called upon more in unforeseeable situations than in those that can be predicted. For this reason, it is highly desirable that the methods be effective over the broadest possible range of conditions. It is particularly desirable that they be effective over the range of all possible hole sizes in the containment, since this appears to be one of the most important variables affecting their performance. Reactor siting conditions, which can differ markedly between installations, can also place different demands on the activity control measures.

4.1.3 Dependableness

The methods should be simple and reliable and function with essentially no close attention or adjustment.

4.1.4 Adaptability to Remote Operation

The radiation level in the vicinity of a break in the containment probably would quickly mount to levels preventing direct approach. It would then be necessary to work behind shielding to apply the activity control measures through use of long-handled tools, booms, remotely operated vehicles, helicopters, etc. It would be most desirable, and mandatory in many cases, that the control method could be positioned, placed in operation, and then left unattended until the accident had run its course. A remote control center from which essential equipment could be operated might be necessary.

4.1.5 Self-Sufficiency

The activity controls preferable should operate independently of other controls systems, the local power supply, etc.

4.1.6 Independency of Knowing Precise Location of Hole

As will be discussed subsequently in more detail, quickly determining the precise location of the breach in the containment system under accident conditions would be likely to be difficult or impossible. A control measure should be effective if applied in the general area where the break in the system is thought to be, or it should be completely independent of the location of the failure.

4.1.7 Simplicity of Initiation

Because of the confusion that could attend a major accident, and the short time that might be available, the activity control procedures should be simple, easily initiated by manual means, and capable of being tested in advance of the need.

(Consideration could be given to the automatic initiation of the control measures on the grounds that immediate evacuation of the reactor area might be necessary. However, this would add complication and expense and, perhaps more importantly, could possibly endanger normal operation of the reactor through inadvertent activation of the devices. It can be argued that in many reactor accident situations that can be envisioned, the operators would have sufficient time to manually put the appropriate control measures into effect.)

4.1.8 Maintainability

The equipment should not deteriorate excessively with age, and necessary repairs and replacements should be so easy and inexpensive that they would not tend to be postponed until the system became unreliable.

4.1.9 Testability

The control measures will probably not be needed over many years of reactor operation. It should therefore be possible to routinely test the equipment.

4.1.10 Reasonableness of Cost

It is believed that to have practical application the control measures should offer some assurance of protection at a relatively low cost.

No credit could now be given for such control methods in making safety evaluations of plants, although future investigative work might eventually lead to this. There would thus be an understandable reluctance to add significantly to the investment cost of a station to buy equipment which many would argue would have a very low probability of ever being needed.

The costs should be low enough for each plant to afford to have its own equipment rather than to share it with other nuclear stations. (In general, it is believed that equipment could not be transported to a site in time to be of value in the critical stages of an accident.⁴⁶)

4.2 Locating Leaks

A problem common to the application of almost all activity control measures is the very important one of locating the source of the leak in the containment vessel. After an accident, the first reliable indication of a break in the containment vessel would probably be the annunciation of alarms by the radiation monitors located outside the vessel. This might be accompanied by obvious evidences of failure, such as visible escaping steam, noise, or control-room indications pointing to a particular trouble spot, but the chances seem good that the location of the breach in the containment vessel would not be easily or quickly determined.

Since the released activity could spread quickly, success in locating the source with radiation survey instruments would be doubtful. In addition, the mounting radiation hazard would permit only short-term occupancy of the region or, perhaps more likely, soon prohibit it altogether.

One of the methods suggested as an aid in determining leak locations was the release of a dense, distinctively colored smoke inside the breached containment vessel. This could be provided at relatively little cost, and although it can be argued that for very small leaks it might not be effective, there may be a range of leak sizes where it would be helpful.

A similar suggestion involved release of an olfactant, such as a mercaptan, in the containment vessel. This method was demonstrated in leak tests at the Homogeneous Reactor Test at Oak Ridge to have limited

usefulness, however, because the escaping odor spread so rapidly that the direction of the source often could not be detected.⁴⁷

If the gases were escaping from the containment vessel under pressure, a sudsing or foaming agent might be sprayed over a suspected area to make the point of escaping gases more evident. Whether local activity levels would permit this is open to conjecture, however.

In general, it has been concluded that activity control measures that depend on quickly pinpointing the location of a leak probably have much less chance of effectiveness than those that require knowledge of only the general vicinity of the break in the containment vessel.

4.3 Effects of Opening Size and Amount of Activity Released

In addition to the amount of activity released into the containment system, another facet of the accident situation that has a most important bearing on the chances for success in reducing the spread of activity is the size of the opening in the failed containment system. Small leaks might be briefly approached and partially or totally sealed, provided the hole was accessible and the escaping gas velocity not excessive. At the other end of the scale, a catastrophic failure could release an initial sudden "puff"; such a release is judged essentially impossible to mitigate. Given the same total amount of activity to be released, the smaller flow-rate longer-term release would be preferred, since there would be time for decay and absorption of the fission products and for evacuation of critical areas.

Postulation of the conditions attending the catastrophic type of accident leads to another aspect of the problem, perhaps academic, but of interest to this discussion. This relates to whether decisions made by the reactor operator to activate certain control measures might not be so far reaching in their possible consequences as to greatly limit the chances that the decision could be made quickly enough, if at all. An example is the decision as to whether it would be better for a ground-level release to perhaps contaminate a relatively small area and number of people or whether the lesser of the evils would be to activate control

measures that would tend to loft the radioactive cloud to higher elevations to contaminate a larger area to a lesser degree. Military and civilian authorities are empowered to make such decisions, but it is an interesting question as to whether reactor operators could assume such prerogatives.

Speculations and discussions of these broad aspects point out the need for provisions to make quick assessments of accident conditions in terms of the hole size and location, the amount of activity released and likely to be released, meteorological conditions, both present and long range, other local emergency situations, etc.

4.4 Suggested Control Measures

The following control measures have been considered:

1. Sprays
2. Foams
3. Directed failure of containment vessel
4. Discharge from tall stacks
5. Thermal-column discharge
6. Underground disposal of gases
7. Storage of contaminated water
8. Patching of holes
9. Plugging of openings
10. Transfer and storage of gases
11. Flooding of containment vessel
12. Contaminated-gas pickup
13. Retentive coatings
14. Remote discharge

These control measures are discussed below in the order listed above. Those judged to be the most effective and practical are listed first, although the differences are not clear-cut and are somewhat a matter of opinion. Table 1 (Chap. 2) attempts to correlate the measures in terms of the desirable characteristics discussed in Section 4.1.

4.4.1 Sprays

Current reactor designs now include water sprays inside the containment system as an engineered safety feature for emergency heat removal. The sprays have the additional advantage of transferring a portion of the airborne radioactive contaminants that could be present in the containment atmosphere at the time of a major accident to the collected water pool, where they can be more easily contained and treated. How effective the sprays are in this respect is thus a matter of considerable interest at the present time, and studies of this are under way at ORNL.

At some stage in a major reactor accident the containment volume could be filled with gases and steam heavily laden with highly radioactive fission-product gases, particulates, and aerosols. In the event of a failure of the containment system at this time the inside sprays would probably do much to reduce the amount of airborne activity available for escape from an opening and from the reactor site. Some tests suggest that under certain conditions this could amount to orders of magnitude reductions. Sprays used outside the vessel would not be likely to be as effective but still might do much to mitigate the spread of activity. Chemicals can be added to the spray water to enhance effectiveness against particular contaminants.

Spray equipment need not be complicated or expensive, it can be activated by remote means, and to a large extent it is testable and maintainable. In the case of sprays used inside the containment vessel, the effectiveness is not particularly dependent on the inside pressure or on knowing the location of the leak in the containment system. Sprays would probably be useful even with fairly large opening sizes, depending, of course, on the velocity of the escaping gas. In general, sprays are believed to be one of the most practical of the measures considered in this report for mitigating the spread of activity from a failed containment system.

Many of the factors influencing the effectiveness of the sprays would probably apply whether the sprays were applied inside or outside the containment vessel. However, since all the studies and testing accomplished to date have been concerned with inside use, the brief discussion

of the principles involved has been given below under the heading of inside sprays. A following section discusses the practical aspects of outside spray systems, but to what extent the performance principles for inside sprays can be applied outside has not yet been demonstrated.

Sprays Inside the Containment Vessel. The effectiveness of sprays inside the containment vessel depends on many variables, such as the chemical additives used, temperature, spray liquid drop size, contact times, and the distribution and nature of the fission-products in the containment atmosphere. The interrelationships of these factors have been studied under controlled conditions, and many aspects are generally understood. However, there are several areas of uncertainty that are yet to be resolved. Also, in applying test results to hypothetical accident conditions it must be remembered that a great many aspects are involved that cover a wide range of accident situations.

It is of particular importance to retard the escape of iodine isotopes, not only because they are one of the more abundant sources of radioactivity but because the thyroid dose usually establishes the tolerance level to exposure. If the reactor fuel melted in a water-cooled reactor, most of the iodine release would be in the elemental form, as I_2 . A small amount, some say about 5%, would react with paints and other materials in the cell to form methyl iodide, CH_3I . This molecular organic form is more volatile than I_2 and is more difficult to remove by sprays. An objective would be to absorb the iodine fast enough to materially reduce the amount of methyl iodide formed, although even with relatively effective iodine removal there could still be sufficient methyl iodide present to be of concern.

The rate of transfer of elemental iodine into water drops is controlled primarily by the rate of diffusion through a gas film. Although data can be found in the literature which indicate that the partition coefficient of iodine between water and air (the ratio of iodine concentration in the water to that in air) is in the order of 10^2 at $20^\circ C$, the results obtained by several experimenters⁴⁸⁻⁵¹ indicate that the partition coefficient could be in the order of 10^4 . If the coefficient is small there is probably significant liquid film resistance, but if the coefficient indeed approaches 10^4 , the liquid film resistance is essentially

negligible. The reasons for this spread in the partition coefficient are not well understood at this time. A study by Eggleton⁵² gives some understanding of the complexity of the problem.

The above-mentioned partition coefficients are of little significance when chemical additives are used in the spray water. Borated sodium hydroxide or borated alkaline sodium thiosulfate are being proposed as additives for the spray water in power reactor containment systems now being designed. (Boron is specified because the same spray liquid may also be used in the reactor core under certain accident situations.) Either of these chemicals will apparently be effective in changing the elemental iodine to a nonvolatile form. Reasonably low concentrations are required; it has been estimated that 1% of sodium thiosulfate or about 0.4% of sodium hydroxide probably could provide more than ten times the quantity of reagent needed in a hypothetical accident situation.

Experiments and theoretical studies on removal of elemental iodine from simulated accident atmospheres by use of sprays have indicated that the effectiveness depends principally on the liquid mass flow of the spray and on the size of the droplets. Half-times for iodine removal ranging from 30 sec to 23 min have been observed in various experiments.⁴⁹⁻⁵¹ Mass flow rates and nozzle designs proposed for reactor containment systems have given half-times of less than 1 min in several experiments.⁵¹

The removal of methyl iodide from the containment atmosphere is a much more difficult problem than the removal of elemental iodine. The partition coefficient is not so favorable⁵³ and the mass transfer of the iodide is controlled by the liquid film. For example, for physical absorption in a 1000- μ drop at 30°F, the mass transfer coefficient for the methyl iodide is 0.004 cm/sec, as compared with 12 cm/sec for the iodine vapor. To achieve effective removal rates for the iodide it will thus be necessary to make use of a chemical reaction. Extensive work on removal of methyl iodide by various reagents has been reported.⁵³⁻⁵⁵ In general, the results show mass transfer coefficients one to two orders of magnitude higher than could be expected by use of water without additives.

The mass transfer rates observed for methyl iodide are appreciably faster than would be predicted on the basis of absorption and chemical

reactions in the liquid phase. This probably indicates that the rate-controlling step in the process is the decomposition of the methyl iodide while in the vapor phase.⁵⁶ The decomposition of iodide is promoted by hot surfaces, gamma irradiation, and visible light.^{55, 57, 58} The first two of these are conditions that could exist in sufficient magnitude to be of importance in major accident situations. Studies in this area are under way at ORNL.

The above discussion relates to the removal of gases, particularly iodine, from containment atmospheres. In addition, removal of fission-product particulates, and the gases absorbed on these particles, can be accomplished by fallout due to gravity, deposition on surfaces, and impaction with spray droplets. The settling of particles due to gravity depends on their size and density and the air movements within the cell. Particles of greater than $10\ \mu$ would probably drop out rather quickly. Particles which collided with each other might form larger particles, which would then settle more rapidly. This agglomeration effect is very rapid in concentrations exceeding 10^5 particles per cubic centimeter.

Particles may be rapidly deposited on walls and other solid surfaces by eddy diffusion, particularly if there are strong convection currents present. Small-sized particles will also diffuse through the air due to Brownian motion, the diffusion coefficient being inversely proportional to particle size. This mechanism is significant for particles of less than $1\ \mu$ and could be important in types of reactor accidents that produce high percentages of submicron-sized particulates. When airborne particles experience a temperature gradient more gas molecules strike the particle from the high-temperature side and thus drive it toward the cold surface. This phenomenon, termed "thermophoresis," also makes a significant contribution to the capture of particles by spray droplets.

Removal of particulates by spray water becomes less effective as both the drop size and the size of the particle decrease, with the solids tending to follow the air streamlines and move aside as the drop falls. To illustrate, but without implying particular significance to the absolute values, one experiment showed an impaction efficiency of about 70% for $5\text{-}\mu$ particles but only about 4% for $1\text{-}\mu$ particles.

When a vapor component, such as steam, flows to a cold surface to condense, it carries particulates along with it due to the concentration gradient. This is referred to as "diffusiophoresis." Perhaps more importantly, the cooling effect of the spray water in the moisture-laden atmosphere may produce supersaturation conditions. The airborne particulates may then become condensation nuclei for formation of droplets and subsequent removal by gravity.

The above very brief discussion of the mechanisms involved in removal of gaseous and particulate fission-products indicates the considerable complexity of the processes and why continuing study is needed. Even in the present state of the art, however, it seems reasonable to conclude that (1) even a failed containment system could contribute significantly to the retention of fission-product particulates by deposition and settling, and (2) internal spray systems are not only useful for heat-removal purposes but could probably significantly reduce the concentration of airborne contaminants, possibly by orders of magnitude.

Practical considerations with regard to the use of sprays inside the containment vessel are the assured supplies of large volumes of spray water, protection against freezing, and, if a positive head is not available, reliable pumps and power supplies. Storage facilities are needed for chemicals and the associated proportioning feed pumps. A method for periodically testing the spray nozzles located inside the containment vessel is needed; one suggestion is for introducing a suitable gas into the spray system and detecting flow with permanently installed hot-wire anemometers at each nozzle location.

In summary, spray systems located inside the containment vessel are believed to offer one of the most effective methods of reducing the activity that would be available for escape from the reactor site in the event of failure of the containment system.

Sprays Outside Containment Vessel. Some of the advantages to locating sprays outside the containment vessel would be that (1) the spray system would not be as likely to be damaged at the time of the reactor accident; (2) the temperature would be lower, particularly if the gas expanded through an appreciable pressure drop in leaving the vessel and

promoted a more favorable retention of the iodine in the water; (3) the system would be completely testable and maintainable; and (4) a simple manually initiated low-cost arrangement might be the most practical system. No claim is made that outside sprays would significantly cool the interior of the containment vessel.

While the outside sprays could possibly make some reductions in the activity escaping from the site, even under the best of conditions they would not be nearly so efficient as sprays used inside the vessel. This would be true because (1) the water drop size used in the outside spray would have to be larger to prevent the wind from carrying it away; (2) the contact times would undoubtedly be very much less, since in this case the gas would pass through the falling drops and escape on a once-through basis; and (3) the location of the hole in the containment vessel might be such as to prevent effective use of the sprays. The escaping gas would probably have sufficient velocity to cause it to pierce a thin curtain of water drops with relatively little decontamination.

A question raised in connection with the effectiveness of the sprays was whether the cooling effect as the containment atmosphere mixture expanded through the opening in the vessel would create a "fume-like" cloud, or fog, that would not be easily dispelled by a water spray. How much of the fission products would be absorbed on the fine droplets and how much would be washed out by the sprays under these conditions apparently needs further study.

Operation of the spray system at below freezing temperatures should not impose major technological problems, since methods of protection from freezing are well developed. The recovery of spray water for recirculation at below freezing temperatures, however, could be a problem. The efficiency of artificially produced snow in absorbing gases would need study, but it can be assumed that adsorption and impaction processes would be enhanced.

Sprays with fixed nozzles outside the containment vessel would have to provide a water curtain of sufficient thickness to prevent escaping gases from passing through it with insufficient contact. If the gas left an opening with appreciable velocity, a significant distance would be required for it to slow down sufficiently to experience effective contact

with the falling water. Care would also have to be taken that gases escaping in the vertical direction would not miss contact with the spray water. The spray density needed is not known, but if we take a value of 0.4 gpm/ft^2 , such as used for spray ponds, etc., and assume a curtain about 40 ft thick surrounding the top and sides of a 120-ft-diam containment vessel and a required pumping head of, say, 150 ft, about a 750-hp 12,000-gpm pump would be required. A one-million-gallon water-storage tank would provide about 1 1/2 hr of spray operation if the water were not recirculated. The complexity of the system and the investment required seems rather high for fixed outside sprays.

A less elaborate spray system could be considered with fewer fixed nozzles and these installed in the critical areas, such as at penetrations where failure possibly would be most likely. Without some prior knowledge as to where the containment vessel is most likely to fail (see Sect. 4.4.3), however, the effectiveness of this system would seem to be limited.

A more practical arrangement for the outside sprays would be hose-fed nozzles that could be positioned at the time of an accident at the most efficient location. This could be done manually, by booms, or by remotely operated vehicles with special equipment to hold the nozzle in the desired position. The spray system could be an extension of the installed fire-fighting system and, indeed, would offer a measure of increased fire-fighting capability. Advantage might also be taken of the head made available by a fire truck pumper and aerial nozzles to get the spray water to the top of the containment vessel, should this prove necessary.

Another consideration in the use of outside sprays is the large volume of contaminated runoff water that might result. There is the possibility that the containment vessel could be used for some of the water storage, but this is viewed with some skepticism. The fallout area for the spray water should be hard surfaced and pitched to the storm drains. These drains could lead to a retention pond or other means of selectively storing water until it could be treated or allowed to decay to safe levels for disposal.

Chemical additives can also be considered for use in spray water outside the containment vessel, but unless provisions are made for catching and recirculating the water, the expense of the chemicals and the necessary storage and feeding equipment could be significant. It is possible that the selection of the most practical chemical additive would be influenced by the cost considerations, storage life, etc., as well as by its effectiveness in absorbing the fission products.

In summary, the effectiveness of outside sprays would depend on getting good contact of the droplets with the escaping cloud of contaminants. Since the degree of success in this respect is contingent on locating the leak, its accessibility, the wind conditions, the velocity of the gas leaving the opening, and other variables, it is suggested that a flexible system with movable nozzles would be the most practical. While the effectiveness of the outside sprays is not so great as that of sprays on the inside, and, indeed, conditions can be postulated in which they would do little good, they still hold promise of making important reductions in the escaping activity in many types of accident situations. Although provisions for ample storage of spray water could be an expense at some installations, in general, the outside sprays should not be prohibitive in cost. They would meet other requirements of testability, reliability, etc., as summarized in Table 1, and appear to be worthy of additional study and development. The recommendations with respect to development are discussed more fully above.

4.4.2 Foams

Foams appear to have good promise of effectiveness in retarding or preventing the escape of fission products and, similarly to the water sprays, could be flexibly employed over a wide range of accident conditions, could be operated remotely, and are not dependent on knowing the exact location of the opening in the containment vessel.

Several kinds of foam can be considered that could be applied either inside or outside the containment vessel. For purposes of this report the foams have been classified into three types: (1) high expansion, (2) dense, and (3) permanent.

High-Expansion Foams. "High-expansion" foams are so termed because the ratio of the volume of foam produced to the volume of foaming solution is about 1000 to 1, as compared with expansion ratios of 10 to 30 for conventional fire-fighting foams. The high-expansion foams thus have relatively little water content. They are created in test equipment by spraying an aqueous solution of foaming agent against a fine mesh while forcing air or inert gas through it.

The lightness of the foams makes them susceptible to being blown about by the wind or picked up and carried into ventilation systems. Tests⁵⁹ indicate that foams drawn into filter systems tend to cause plugging and cutoff of air flow and that demisters will not arrest the flow of foam through a duct.

The foams are fairly easily collapsed with a water spray. This would be an advantage during cleanup operations but would limit the effectiveness of the foam when used outside the vessel in a rainstorm or in conjunction with water spray systems on the inside.

It is judged that this type of foam would be useful for filling large volumes where it would be partially confined, such as in the containment vessel, hall or stairways, pipe tunnels, etc. It would serve to inhibit free movement of the fission products and to reduce the amounts becoming airborne, and it would have some absorptive value. It would not be necessary to know the exact location of the leak, since the foam could be generated in great quantity in the general vicinity.

Dense Foams. Dense foams would be similar to those used for fire fighting or those generated by gas with an expansion ratio of perhaps 10 to 30. They would form a dense blanket for covering the leak site or areas from which contaminants might become airborne. They would be more suitable than high-expansion foam in less confined locations in that they would better resist being blown by the wind. Again, it would not be necessary to know the exact location of a leak, since the foam would be mounded over suspected spots and replenished as needed.

It is believed that foams of this type could be developed especially for the purpose of activity control. While it would certainly be desirable that the foams have good iodine-absorbing characteristics, this might

be secondary to good physical properties. These would include such features as the ability to stick to vertical surfaces, to bridge over fairly wide openings, and to resist collapse even in water sprays. (Chemical solvents might be used for cleanup operations.) Simple and portable equipment for generation of the foam would be desirable.

Permanent Foams. Permanent foams would be of a type that could be sprayed into openings or mounded over an area to form a rigid mass that would not need replenishing in order to form a long-lasting generally impervious barrier to escape of particulates. Such a foam would be in the nature of a patching material, as will be discussed subsequently in Section 4.3.8, but it would also be useful for covering contaminated areas.

Effectiveness of Foams. Despite the fact that foams have been proposed over a number of years as means of absorbing and containing fission products, apparently the investigations have not extended beyond the preliminary stages. The initial testing effort has been toward developing foams for good fission-product retention. Yoder, Fontana, and Silverman⁶⁰ made tests at ORNL in 1963 in conjunction with the Harvard Air Cleaning Laboratory on high-expansion foam suppression of radioactive iodine and UO_2 particles in a 6000-ft³ cell with an ether lauryl surfactant and a sodium thiosulfate reactant. The equilibrium concentration of the iodine when using the foam was about one-third less than without it, and this value was reached in about one-half the time. The foam could reduce particulates by about 90% within a few minutes. Steam injections into the cell did not deteriorate the foam excessively. The foam was readily collapsed by water, and the iodine was transferred to the liquid phase with relatively little of it becoming airborne. Dow Anti-Foam A added to the spray water effectively prevented foaming in disposal of the liquid waste. It was concluded that within a closed cell the high-expansion foam could be an effective means of collecting iodine and converting it to a nonvolatile form.

Smith⁶¹ has described tests made at Battelle Northwest Laboratories where iodine- and argon-contaminated air was discharged without filtration through a foam generator and up a stack. It was estimated that

about 85% of the two tracers was encapsulated. The high-expansion foam floated to the ground and dissipated to about 50% of the original volume in about 1 hr. About 5 gal of foaming agent and 3300 gal of water were required to generate 500,000 ft³ of foam at a rate of 45,000 cfm.

Jury⁶² made a mathematical analysis of diffusion in bubbles in static foam and in foam beds subjected to elution. His calculations showed an obvious advantage to small bubble sizes. The suggestion was made that such a foam might be generated by forcing gas through a sintered-metal sparging tube immersed in the aqueous surfactant. The study also covered the tendency of the radioactive particles to redisperse when the foam collapsed. It was concluded that in the absence of chemical reagents to reduce the vapor pressure of the organic iodine compounds, an elution process would be necessary. This would involve trickling fresh nonaerated surfactant down through the foam bed to displace the interstitial liquid onto which the radioactive components had diffused.

Taheri⁶³ is conducting a study at Pennsylvania State University on removal of small particles from gases by a dynamic foam process. This work will be presented as a Ph.D. thesis.

Application Considerations. Deleterious alteration of physical properties by irradiation is not considered a major obstacle to the use of foams because of the relatively short exposure times of interest. Foams could be used either inside or outside the containment vessel. If used inside, the emphasis would be on fission-product retention through chemical reactions with the iodine and encapsulation of the particulates and noble gases. Since the foams are not durable at high temperatures and tend to be collapsed by condensing steam or water sprays, it is possible that the sprays could be used first for cooling and condensing the steam and the foam introduced later to retard escape of activity through an opening in the containment vessel. Certainly, the spray system would have priority.

A particular problem associated with the use of foam inside a failed containment vessel is that introducing a foam generated by an outside gas would displace the containment atmosphere from the vessel. If the containment atmosphere were used for foam generation, either the foam-

generating equipment would have to be located inside the vessel or contaminated air would have to be taken outside. The former is considered the more desirable, but equipment located inside the vessel would require periodic inspection and maintenance and would be susceptible to damage in the reactor accident. Further study and development of suitable apparatus for generation and distribution of the foam within the vessel would be needed.

The tendency of high-expansion foams to clog the filters in the air-cleanup system, a factor which could limit their usefulness, was previously mentioned.⁵⁹ For example, if the leak developed in the containment system were small enough for the entering air not to exceed the volumetric capacity of the containment ventilation system, the fans in this system could be arranged to draw air in through the opening and to discharge filtered and decontaminated air from the off-gas stack. Use of the foam in such a situation might not be advisable. In the cases where the inflow through the opening would exceed the capacity of the fans or where the ventilation system was rendered inoperative by the accident, the foam might be used. Further study of means of preventing the foams from clogging the filters, such as centrifugal devices, would probably be productive.

Foams used inside the vessel might limit thermal air-convection currents. This factor might not be advantageous from the standpoint of cooling the vessel contents or for circulation of the air through the cleanup system. There is also a remote possibility that hydrogen evolved from a metal-water reaction could be trapped in pockets in sufficient concentration to be an explosion hazard.

Use of foams outside the containment vessel presents different problems. One of these is that high-expansion foams could be carried by the wind or could be collapsed by rain. Rain at the time of a major activity release, however, could be a fortunate circumstance from the standpoint of activity control through washout of contaminants, if this took place before the cloud reached populated areas. (Washout of contaminants from a dispersed cloud is generally considered undesirable, however, in that this would tend to concentrate the activity in a smaller area.⁶⁴) Perhaps a worst case from the standpoint of use of the foams is a succession

of short rain showers that would necessitate repeated renewal of the collapsed foam.

It is visualized that foam could be used in a variety of ways outside the containment vessel. It could be used to fill rooms, hallways, or tunnels that would be gas escape routes. It could be used to cover broad areas to retard fission products from becoming airborne. It has been suggested that foam could be introduced into the containment vessel by sticking a foam nozzle through the opening, provided, of course, that the hole was suitable for this and sufficiently approachable. If the gas were emerging from the vessel at appreciable velocity and the opening was reasonably accessible, it might be possible to manipulate foam-generating equipment over the hole to capture the escaping gas in self-generated foam.

Methods of generating and spreading the foam outside the containment vessel would have more design latitude than those installed inside. For much the same reasons discussed under water sprays, portable foam nozzles would appear to be the most practical arrangement. Movable self-contained foam generators probably could be developed for the various foam types. It would be desirable to have a means of dispensing the foam from a long boom or from a remotely operated vehicle. A survey is needed of equipment now available and the work required to develop suitable portable foam generators.

One advantage in the use of foams rather than sprays outside the containment vessel is that the foams would not create an immediate contaminated-water runoff problem. In postponing this situation more time would be gained for decay of the fission products and for setting up water-holdup and decontamination facilities.

In summary, foams have promise as versatile and reasonably inexpensive active control measures that appear to have sufficient effectiveness to make them worthwhile to have on hand. More study of foams, foam-generating equipment, and techniques of use is obviously needed. Investigation would also be desirable on procedures for capturing the fission products upon dispersal of the foam.

4.4.3 Directed Failure of Containment Vessel - Pressure Relief

It would be desirable to be able to predict where the failure of the containment vessel due to overpressure would take place. An arrangement to accomplish this might be a blowout disk that could withstand the required test pressure for the vessel but nevertheless would give way before the containment system failed. This point of directed failure could discharge through filters to a stack, or at least be advantageously located with regard to prevailing winds, height above ground, proximity to other buildings, etc. Activity monitors, spray or foam nozzles, etc., could be strategically placed at the opening.

It would be desirable that the relief opening be designed to be reclosable. It would also be advantageous to be able to trigger the device to secure quicker blowdown of pressure, should this prove desirable. It will be recognized that with these two features added, the mechanism takes on the aspects of a "pressure-relief" valve. Examples of the use of pressure relief are present in the Hanford NPR and the Canadian Chalk River NPD systems. In the NPR system, pins in a vent cap are sheared to release the pressure. After venting, a butterfly valve closes; if it should fail to operate, a balloon closure can be inflated in the vent pipe to provide a seal.⁶⁵ In the NPD system a large glass diaphragm is broken to relieve the pressure, and a gravity-actuated flapper closes after about a 10-sec interval to reseal the system.⁶⁵

Proponents of pressure-relief mechanisms for a containment vessel argue that if failure due to overpressure is imminent, it is better to relieve the pressure rather than to let the situation proceed to uncontrolled rupture. As previously mentioned, there is an obvious advantage to reducing the containment pressure as quickly as possible. The objection to pressure-relief devices is, however, that they themselves, by being subject to malfunction, constitute a threat to the containment integrity.

An interesting suggestion in connection with pressure relief is an arrangement for relieving a BWR type of containment vessel if the pressure-suppression system does not function as planned. As described by

McEwen and Kjemtrup,⁶⁶ the gas would be discharged through an annular water pool and then up the off-gas stack.

Even if pressure-relief devices as such are not acceptable, the directed failure concept appears to have merit, although it must be noted that it would be useful only in certain accident situations of overpressure or need to quickly reduce the pressure in the containment. However, the development of an arrangement that would withstand test pressures, and yet could be counted on to open up before the vessel itself failed, would involve some careful study.

4.4.4 Discharge of Contaminated Gases from Tall Stacks

It has been suggested that if large amounts of fission products must be released, it is better to do this from the top of a tall stack than to discharge the contaminants at ground level. Such a system of stack discharge would include a high-capacity containment exhaust system capable of, say, about one air change of the containment volume per hour, and stack heights of 500 to 1500 ft have been mentioned. Filtration or other cleanup of the gases to be discharged would obviously be desirable, but the discussion of this method of activity control is directed principally to the advantages of the elevated discharge point.

Tall stacks could make reductions in the off-site activity dose rates through atmospheric dilution and dispersion processes. Gifford⁶⁷ concludes that tall stacks have the advantage that the gas discharge point might be

1. high enough in most cases to prevent the plume from looping* back to the ground level,
2. above the radiation inversion layer that commonly exists at the 400- to 600-ft level,
3. elevated sufficiently to take advantage of the higher wind velocities that usually exist a few hundred feet above the surface,
4. high enough to minimize the fumigation effect wherein eddies beneath an inversion layer could bring portions of the plume back to the ground.

*Some of the terms used here, such as "looping," "fumigation," etc. are illustrated in Appendix D.

Gifford⁶⁷ cautioned, however, that local conditions of terrain and meteorology at a particular stack location could strongly influence the behavior of a stack plume. For example, the "heat island" effect of a nearby city tends to reduce the buoyancy of a cloud. In this connection, the buoyancy of the discharge gases from a nuclear plant, even in emergency conditions, is not likely to equal that from a fossil-fired plant because the temperatures are probably not in the range 300 to 500°F, as with the latter, and the self-heating effects by decay of fission products could often be of little consequence.

Although the stack might be tall enough to gain some atmospheric stability for the reasons mentioned above, the discharge point would still be below the friction inversion layer, which is the well-stirred region reaching up to the 2000- to 5000-ft level, or the subsidence inversion layer, which is due to the earth's rotation and wind movements.⁶⁷

Culkowski⁶⁸ points out that the farther one is horizontally from the stack the more likely it is that the advantages of an elevated discharge point can be subjugated or masked by the prevailing meteorological conditions. Also, the settling of airborne particles of certain size ranges could create higher intensities of irradiation several miles from the reactor than immediately adjacent to it. These conditions could differ markedly and could change significantly even during the course of a single accident, but it seems generally true that a tall stack might possibly be of more benefit to those on or near the reactor site than to those several miles downwind.

It has been postulated that the dose rate at more distant points could possibly be less under certain circumstances with a ground-level release than with elevated discharge. This would take into account the greater opportunity for deposition and absorption on intervening vegetation and other surfaces, as well as lower surface wind velocities that permit more time for decay. If further study indicated that this factor were of major importance, it would be possible to provide a diversion damper in the exhaust system to route the gases to a ground-level release point. As discussed in Section 4.3, however, this would create a necessity for a decision that could probably not be made quickly because of its importance and far-reaching effects.

In this same regard, the rapid withdrawal of contaminated gases from a failed containment structure and release from a stack could possibly assure inflow through a leak and thus benefit those nearby, but those some distance away might receive much less exposure if the fission products were allowed to stay in the containment vessel as long as possible for decay and plateout. Webster⁶⁹ found this to be substantially true in an analysis made for the LITR at ORNL, in which a point about ten miles downwind from the reactor was taken as a reference for the study.

A large enough opening in the containment structure can be postulated, however, to say that the fission products will escape in short order in any event and that, in this case, stack release is preferable.

The considerable work that has been done on the meteorological aspects of fission-product transport and diffusion cannot be fully cited here. An article by Moses⁷⁰ on stack plume rise contains a good bibliography and the U.S. Department of Commerce publication "Meteorology and Atomic Energy" is frequently used as a reference.⁶⁴ Briggs⁷¹ is completing a doctorate thesis on the subject of tall stacks.

Comparison of plume rise formulas at Brookhaven National Laboratory⁶ on ground-level distributions from the Brookhaven Graphite Research Reactor cooling air discharge showed that equations used to estimate the buoyant ascent of large volumes of stack gas, while giving good results with fossil-fired plants, gave results for the smaller BGRR plume that tended to consistently underestimate the concentrations.

Much of the published information is in the form of analytical studies made with mathematical models, but, for example, as stated by Moses,⁷⁰ none of the 15 or more formulas proposed in the U.S. for calculating plume rise is free of the need for empirical values or can be universally accepted, because it has been impossible to establish the validity of any one from the quality and quantity of available plume-rise and meteorological data. He adds that this is due in part to the difficulties inherent in making satisfactory measurements. In this same vein, Gifford⁷² has commented on the problems of forecasting dispersion in the lower atmosphere due to lack of reliable measured values. A continuing program of investigation by the Environmental Science Services Administration is

sponsored by the USAEC Division of Reactor Development and Technology.⁷³ It appears that the meteorological conditions prevailing at each reactor site would almost have to be studied separately and that broad generalizations as to the effectiveness of tall stacks could be misleading.

If a tall stack were provided at a reactor as an emergency activity control measure it would, of course, also serve as well for the off-gas stack usually provided at reactor installations. At some installations, the credit that could be taken for this could be significant, as for example, the TVA Browns Ferry plant, which will have a 325-ft reinforced concrete stack.⁵ A rule-of-thumb cost estimate for stacks of this size is about \$1000 per ft of height. For taller stacks the unit cost could be somewhat higher. For example, the TVA 800-ft Bull Run Steam Plant stack would cost about \$1.2 million to duplicate at the present time.⁷⁴ A stack for nuclear service might not require an insulated or corrosion-resistant liner but otherwise would be about as expensive as a stack for a fossil-fueled plant because the construction features are largely dictated by the wind and earthquake design-load considerations.

The emergency tall-stack discharge system suggested here would be provided in addition to the containment air cleanup system, which is of smaller volumetric capacity and incorporates efficient filtration and absorption systems. The exhaust system would obviously benefit greatly from even rudimentary filtration, scrubbing with chemical or water sprays, or absorption equipment. This type of activity control would possibly be of more benefit to distant population centers than the effect of the elevated discharge point.

The exhaust system is visualized as being one of sufficient capacity to produce inflow conditions for even rather large openings in the containment structure. It would thus not be necessary to know the exact location of a leak. Large exhaust fans provided with separate emergency power supplies, or possibly jet-engine drives, would probably be required, since a high exit velocity (say, 50 fps) would be desired at the top of the stack. Some thermal draft would be available in a tall stack after the flow was once started, and possibly this could be augmented by aspirating jets using steam from the power cycle or by combustion of fossil

fuels inside the stack base. Initially, of course, for some types of accidents there could be enough pressure in the containment vessel to force the gases from the stack.

One of the most important aspects relating to the use of tall stacks as an activity control measure, and, in fact, one which could essentially preclude their use of this purpose in the U.S. at the present time, is the method of connecting the exhaust-stack system to the containment volume. The most obvious method is through use of butterfly valves or blow-out disks. Whether such devices would in themselves threaten the integrity of the containment system, or whether the advantages would outweigh the disadvantages, is not readily apparent. This subject was discussed further in Section 4.4.3 above.

The design of very tall stacks for nuclear service has evidently received little attention, and special designs may be possible, such as the free-standing steel trylon stack briefly considered for the TVA Browns Ferry station.⁷⁴ Another suggestion is a steel stack guyed similarly to tall TV antenna towers. A suggestion that the stack be mounted on top of the containment vessel appears at first glance to be impractical because of the transfer of the stack static, wind, and seismic loads to the vessel.

The above discussion points out that use of tall stacks does not necessarily benefit those some miles distant and, in fact, could increase the radiation exposure under some circumstances. The dependence on favorable meteorological conditions for effective use of the stack is evident. The relative high cost of a stack in comparison with some of the other suggested activity control measures is also a significant factor. Before dismissing this activity control measure as impractical, however, it must be noted that under certain atmospheric conditions it could be useful and that if a fairly tall off-gas stack must be provided in any event, the cost might not be excessive. Further study possibly could discover some point of diminishing return on release height and cost versus dose rates at various distances.

4.4.5 Underground Disposal of Contaminated Gases

The pumping of contaminated gases into a subsurface geological formation is technically feasible at some reactor sites. In the petroleum industry, natural gases are often stored in underground reservoirs.

A recent review of this subject by an AEC working group has been reported by Jacobs.⁷⁵ He concluded that at the time of the maximum credible accident to a reactor, the injection of the radioactive gases into the ground rather than directly into the atmosphere would greatly reduce the hazards to the population. A few months delay time seemed quite feasible, and sorption of elemental ^{131}I , together with the decay of ^{121}I , would be sufficient for removal of almost all the iodine. It was pointed out, however, that the iodine is one of the easier fission products to remove by scrubbers or adsorption on charcoal filters. It would thus seem that a major advantage of underground discharge would exist in the case of methyl iodide or ^{85}Kr .

The time required for migration of the radionuclides back into the critical zones of man's environment would permit decay of the short half-life radionuclides to much less hazardous levels. In addition, condensation and filtration of the normally nongaseous materials that escape from the containment shell would be enhanced, and adsorption would further reduce the rate of migration of numerous radionuclides and provide even more time for radioactive decay.

The absorption of iodine and strontium in different rocks and clays is shown in Fig. 3 (from Ref. 76). Jacobs and Tamura⁷⁷ reviewed the retention and movement of liquid radioisotopes in soils and found that the behavior differs because of the differences in the chemical nature of the isotopes and because of the mineralogical nature of the soils and sediments. Whether gaseous fission products would be retained similarly is, of course, subject to question. The absorption of cesium was found to be quite dependent on the nature of the soil minerals. The iodine vapor retained by clays appears to be a mixture of condensed or physically adsorbed iodine plus chemisorbed iodine.⁷⁸ The latter can be considered essentially immobile in the ground; the velocity of desorption

Fig. 3. Absorption of Iodine and Strontium in Different Clays and Rocks. (Taken from Ref. 76.)

should be small compared with the rate of radioactive decay. The behavior of methyl iodide (CH_3I) is much different; very little adsorption takes place and it moves nearly as rapidly through the ground as the transporting air. The noble gases are also not likely to be extensively absorbed; Rees and Williams⁷⁹ found that there is only a slight tendency for krypton to be adsorbed by zeolitic materials at ambient ground temperature.

Field studies of injection of gas with helium tracer were made at NRTS.⁸⁰ Contrary to the belief that the gas would migrate faster through the coarser materials near the bottom of the formation, it was found that the flow pattern was much the same as that predicted for a homogeneous soil.

Prior to injection, the geological formation must be thoroughly tested to insure adequate containment of the radioactive gases until they have decayed to innocuous levels. It is unlikely that adequate assurance can be given on the basis of off-site analyses of samples from borings because the limiting transport does not occur as predicted from the average properties of the formation but, rather, as a function of the leaks and channels that are commonly found in natural strata.⁷⁵

The only formations considered feasible for disposal at present are those lying above the water table. It is very unlikely that geological formations would be found at a reactor site that would be suitable both for gas deposition in the ground and also for a nearby water storage reservoir. If such a formation were fortuitously available, there would be some concern for future contamination of ground water.⁷⁵ It is not known what percentage of existing and planned nuclear power stations are located on sites having suitable geological conditions for underground disposal.

The pressure required to inject the gas into the substrata would vary with the particular reactor site. If a pressure of 100 psig is assumed, although this is not represented as a typical value, and the volume of gas to be disposed of is $2,000,000 \text{ ft}^3$ at 150°F and 14.7 psia, a 5,000-cfm/1,000-hp single-stage compressor could accomplish the injection in about 10 hr. This, again, places reliance on mechanical equipment and an assured power supply.

The facts that underground disposal could probably cope with only small leaks under certain conditions of geological strata and that these conditions apparently do not exist except for some fraction of reactor sites, lead to the conclusion that this activity control measure has limited application. The costs of exploratory drillings, testing by actual ground injections, and associated pumping equipment and its emergency power supply are all important reasons for considering this measure to be less practical than some of the others suggested, but it is still worthy of more detailed study.

4.4.6 Storage of Contaminated Water

Airborne activity is the major concern at the time of a major nuclear accident, but since significant amounts could also escape in contaminated water, the storage of contaminated water as an activity control measure will be briefly discussed. The subject is also directly related to the use of water sprays and flooding of the containment, as well as to accident cleanup and recovery measures.

Escape of contaminated water from a reactor site is generally considered less catastrophic than a major atmospheric release of radioactivity. This is because the water movement is slower, the speed and direction of the flow are predictable, and the natural effects of decay, dilution, and settling aid materially. In contrast to a contaminated atmosphere, activity in water can be avoided to some extent if its presence is known. This is to say that contamination of the water supply of a city would undoubtedly be an emergency of major proportions but it need not necessarily be catastrophic.

The containment vessel might be used for storage of water, as discussed below under flooding of the containment vessel, but, in general, this would appear to be impractical for most situations. The preferred arrangement for storage of contaminated water is a retention basin that could be closed off at the time of an accident to impound the water. The review of past nuclear incidents, see Section 3.5, indicates that the storage volumes required could be relatively large. As previously mentioned in Section 4.4.1, sprays used outside the containment vessel for

activity control could generate large volumes of runoff water. Storage capacities of 2 to 5 million gallons, or more, could be in order, although many reactor sites would be limited in this respect.

4.4.7 Patching of Holes

The difficulties of finding the exact location of a leak and determining its size and character were briefly reviewed in Section 4.2. There is, of course, the chance that the leak would be in a location where booms, cranes, long-handled tools, portable shielding, remotely operated vehicles, etc., could be maneuvered only with difficulty or not at all. Certainly, the patching problem should not be thought of as one of applying a patch to an easily found, conveniently located hole.

The difficulties of placing a closure over a hole through which there was appreciable gas flow were mentioned in Section 3.3. If the pressure were not relieved in some other fashion, the gas flow through a small opening could continue over an extended period, as was shown in Fig. 1.

With regard to the radiation hazard, it must be remembered that with the containment volume filled with a highly radioactive mixture, even if no gases were escaping, direct approach to the vessel would be limited to the biologically shielded portions. If, for example, the fission-product gases had filled the secondary containment vessel, or confinement building, of the boiling-water reactor, which has essentially no biological shielding value, direct approach to the building would probably be unwise. If the contaminated gases were escaping at some point, the local activity level would soon mount to values that would permit only very short occupancy, if any. The airborne contamination level would necessitate full-face air-supplied masks and special clothing. If there was no initial positive pressure in the containment vessel or it had subsided, perhaps the locality of the hole could be sufficiently decontaminated for closer approach, but this could be time consuming. The severe radiation problems to be encountered in the patching of holes in emergency situations can hardly be overemphasized.

One criticism made of having such activity control measures as patching materials on hand is that operators might receive unnecessarily high

doses in futile attempts to apply them in hopeless situations. Again, it would be necessary to rely on good management.

A patch applied to a hole from the inside of the vessel would have a better chance of holding against a positive pressure in the vessel than a patch made from the outside. However, entrance into the containment vessel or building of either a pressurized- or boiling-water reactor after failure of the reactor in a major nuclear accident would be most inadvisable. Since the containment structures of neither reactor could be entered, consideration was given to installation of the necessary viewing equipment and remotely operated devices to make patching repairs from inside the structure. The expense of such provisions, the complexity, the lack of room for maneuverability, the probable inaccessibility of the leak, etc., all lead to the conclusion, however, that repair of the vessel from the inside is impractical.

It is believed that the only patching that could be considered would be that done from outside the vessel. Again, this could be severely limited by the location and size of the hole, the gas outflow through it, and the radiation hazard. Perhaps some pressure-retaining capability could be restored to the containment structures, but this would appear unlikely except for the smallest of leaks or for the most fortunate of circumstances.

Because of the difficulties of approach, it appears that the patching materials with the best chance of success would be those that could be hosed on. For smaller cracks and holes, the hosed-on material should be sticky and capable of bridging an opening, and it should set to a rigid or semirigid, generally airtight, waterproof mass. Ideally, the patching material should be simple and easy to prepare quickly, not require special curing, and not release toxic gases or be an extreme fire hazard.

An example of a material now commercially available is a rigid urethane foam that can be sprayed onto vertical or overhead surfaces and is highly catalyzed to give a rapid rate of rise and reduced sag. While intended primarily as thermal insulation, Pierce⁸³ at ORNL used the foam to provide a 3/4-in.-thick interior coating to successfully seal the air

leaks in a secondary containment structure maintained at below atmospheric pressure.* The two components of the foam were mixed in a special hand-held spray gun with an air-mixing turbine and were fed with six hoses. Two pairs of hoses handled the prepolymer and crosslinker, and a return line for each permitted total recycle when spraying was stopped. The fifth hose supplied 90-psig compressed air, and the sixth hose supplied the methylene chloride solvent used to purge the gun. Respiratory protection equipment and special clothing were required because methyl and toluene diisocyanate are powerful skin sensitizers and also affect respiratory functions. Some difficulties were encountered if the substrate was at a temperature below about 50°F. After some experimentation with the equipment and the training of operators, the process was judged to be a practical one, and the building was effectively sealed. The resulting foam was nonburning and had a density of about 2 lb/ft³, 95% closed cells, and a shear strength of 25 psi.

The scope of this report does not permit a complete survey and evaluation of commercially available materials that might be suitable for patching operations. Some of the suggestions drawn from the rapidly expanding field of possibilities are the epoxies, phenolics, polyurethanes, polyvinyls, etc., and of a more prosaic nature, hot asphalt, automotive undercoating, roof coatings, gunnite, etc. It appears that little extension of the technology would be required in making suitable materials available.

If the hole was too large or of a nature that the hosed-on patching materials would not be effective, it was suggested that a rigidly setting foam might be developed that could be used to fill a large opening. Special foam-generating equipment could be devised for this purpose. Another suggestion was that under certain circumstances it might be possible to place a supporting wire mesh over the opening and hose on a patching material.

*Two different brands of foam were used: (1) Hetrofoam, 414/293 D Durez Plastics Division, Hooker Chemical Corp., North Tonawanda, New York; (2) Unarco, A100/B1201A, Chembest Division, UNARCO Industries, Inc., Bloomington, Illinois. The equipment was the Unifoam System manufactured by the Lake Erie Machine Company, Toledo, Ohio (from Ref. 81).

A form of patching, or covering, that is usually mentioned in connection with a failed containment system is plastic sheeting. This is widely used at nuclear installations to prevent particulates from becoming airborne, but its limitations must be appreciated. It is easily blown by the wind, and it is not only very difficult to place but the edges must be fastened and sealed securely for it to be effective. Stud guns with special fasteners were suggested as a possible means for attaching covering materials to concrete. Sticky cements might also be used to seal the plastic sheeting over an opening. A much less sophisticated but fairly successful application of the plastic has been to simply wad it into open pipes or holes to restrict the movement of airborne contaminants.

In summary, the basic problems of patching are (1) locating the leak, (2) possible pressurization or excessive velocities through the opening, (3) the short time available if patching is to be effective, (4) the special equipment and materials that may be needed, and (5) the high levels of radiation that could exist in the vicinity. Accordingly, patching is considered practical only for small, accessible holes under a rather limited set of accident conditions. These could be important enough, however, to warrant the development of suitable materials and equipment. Patching (or plugging) is of particular interest also in that it is the only method by which the containment structure could possibly be restored to essentially its original integrity. The cost of maintaining simple patching materials on hand could be so low as to essentially eliminate the arguments against having them.

4.4.8 Plugging of Openings

Plugs are perhaps the only method of restricting flow while the gas is still escaping with appreciable velocity through the opening. With the exception of plugs for pipes, an infinite variety of shapes and sizes of plugs might be needed, and therefore preformed plugs do not appear to be practical.

Inflatable bags would seem to have the best chance of success. Even though these would be capable of sealing off pressures probably no greater than a few inches of water, they could still be a valuable asset. The

bags would be useful for closing very large openings, such as a hallway or a large opening in the vessel itself. It was suggested that a bag could be inserted through the hole in the containment vessel and inflated on the inside - an arrangement that theoretically would have good pressure-retaining qualities but is given little chance of success because of the difficulties of insertion and the interferences on the inside.

Since the walls and other surfaces against which the bags would have to bear would be likely to have equipment mounted on them, good contact could not be counted on, and the bags should be thought of as partial restrictions to flow rather than as fairly gastight plugs. It should be noted that inflation of a bag would necessarily displace its volume of contaminated gas, although this would not be of great consequence in most cases. The bags could deteriorate in storage and would require periodic testing and replacement.

A particular advantage to use of the inflatable bags would be that exact positioning would not be required, and by retreating to a safer location for the actual inflation, the radiation exposures would possibly not be great. The idea for use of inflatable bags is not a new one. Davis and his associates⁸² have described bags made of Dacron-Hypalon for use at the NPR installation at Hanford in the event of a butterfly valve failure.

Use of the bags would be limited to particular situations, but they could prove very worthwhile in these special cases. Since they are already developed to some extent, the cost of maintaining a few sizes on hand should not be excessive.

4.4.9 Transfer and Storage of Contaminated Gases

If the containment vessel was filled with a highly contaminated gas mixture at the time a leak developed in the system, it would be logical to think in terms of transferring the gas to a safer container. Once confined, the accident could be evaluated, people removed from hazardous areas, and decay, cleanup, and disposal of the radioactive gases could be effected.

Transfer. A large pipe (say, 1 to 3 ft in diameter) would be required to connect the containment vessel to the storage volume. If the

containment atmosphere was under pressure due to an accident, it would be possible to transfer a significant portion of the gas by its own pressurization. After self-flow stopped, or if there were no initial pressurization, transfer would involve a motor-driven fan or blower of relatively large size. An emergency power supply would be needed, or perhaps a jet-engine-driven axial blower could be considered.

It has been suggested that the fans in the containment ventilation system might be adapted for use in the transfer operation. It will be noted, of course, that if the containment air cleanup system was functioning properly, there would be little need for transferring the gas.

An alternative arrangement for transfer of the gas by blowers would be to introduce gas or air into the containment vessel to flush out the contaminated atmosphere. This would of course add to the volume of gases to be stored. A perhaps better arrangement would be to flood the containment vessel with water to displace as much of the gas as possible. Both these schemes have the disadvantage of pressurizing the containment structure and thus driving additional contaminated gases from the leak in the system.

It is evident that the connection of the transfer pipe to the containment volume again involves valves or rupture disks that could be considered undesirable threats to the containment integrity. Reliance would be placed on the functioning of these devices and on other mechanical equipment, such as the blowers, the power supply, etc. The storage containers would pose additional problems and expense, as discussed below.

Storage Containers. The contaminated gas could either be compressed for storage in relatively small high-pressure tanks or be stored at near-atmospheric pressure. The expense and complexity of the high-pressure system would seem to rule this out as a practical measure.

Storage of gases at low pressure emphasizes the problem of the capacity required. If a PWR containment vessel were pressurized by an accident to, say, 3 atm before the transfer had to be made, the required storage volume of 5 million ft³ or more (depending on the degree of cooling and continued gas evolution) is of impressive proportions. The

low-pressure containers might consist of (1) negative-pressure tanks, (2) commercial gas holders, or (3) underground chambers.

1. Negative-Pressure Tanks. The 500-Mw(e) Pickering Generating Station near Toronto makes use of a negative-pressure tank, or vacuum building, into which steam and gases from the reactor building can be vented through a relief-valve arrangement. The 171-ft-diam 176-ft-high concrete vessel has extensive internal supports and emergency water storage and spray systems.⁸³ Although relatively expensive, as long as the pressures in the system are subatmospheric the system offers a measure of protection against a failed containment system.

2. Conventional Gas Holders. Some of the structural disadvantages attendant to prior evacuation of a tank can be avoided by using a moving-head type of gas holder. The comments made above with regard to the large storage volumes required also apply to these containers.

A moving-top gas holder, such as those used commercially, has been studied briefly by First⁸⁴ at the Harvard Air Cleaning Laboratories. The nuclear accident application is not conventional in that the volume might be required to expand rapidly. Problems with binding, inertia, and the sealing liquid were mentioned.

It should also be noted that the leaktightness requirements desired for substitute storage would be as strict as those for the containment vessel itself. The metal tanks would require regular maintenance and testing and would be vulnerable to small missiles. Like the filled balloons, they would generate a broad area of gamma flux. To avoid the latter two problems, underground storage could be considered.

3. Underground Storage. Underground storage containers could take the forms of buried concrete structures, lined tunnels, or caverns. The foundation and earth stability conditions desirable for a reactor site unfortunately do not usually make for easy evacuation, readily available caves, and porous substrata. Construction of reinforced-concrete underground structures for the sole purpose of confining containment gases seems inordinately expensive. While it is perhaps true that some reactor sites would have natural possibilities for subsurface storage, this possibility seems too limited to make this an activity control method to be recommended for general use.

In summary, the transfer and storage of the contaminated containment atmosphere presents some major questions with regard to reliability and effectiveness, and the investment required could be excessive. The present judgment is that this measure perhaps is deserving of additional study but appears to lack sufficient practicality to be of major interest.

4.4.10 Flooding of Containment Vessel

The desirability of flooding the containment vessel at the time of a major nuclear accident would depend on evaluation of the immediate problems involved. (See Section 5.4.2 on underwater installations.) Purely from the standpoint of control of released activity, one of the major concerns in flooding of the containment vessel is that the contaminated atmosphere would be displaced and that little gas storage space would remain. An interesting suggestion in this connection is that the flooding-water storage tank and the containment vessel be interconnected so that the contaminated gas fills the water tank as it empties. The water entering the reactor containment vessel could be sprayed in to enhance fission-product absorption. A positive means of forcing the gas to the storage volume would thus be provided.

The positive transfer of the gas, by the same token, however, would increase the leakage through the opening in the containment system. Obviously, success of the flooding measure would depend on the water tightness of the containment vessel, and this would be determined by the location of the leak. It is to be noted that the lower portion of the containment structure is usually well filled with equipment and supports and contains a relatively small proportion of the total free volume. Further, if the containment gas were pressurized at the time the containment vessel failed, and the gas were to be transferred to the water tank for storage at essentially atmospheric pressure, the tank would hold only some fraction of the gas unless it were made much larger than needed for the water storage alone.

It may be noted that the provisions made for flooding of the Browns Ferry containment vessel are for possible use as a recovery measure and

are not related to mitigating the spread of radioactivity at the time of an accident.⁷⁴

Flooding would have value (1) in cooling the reactor primary system and thus possibly retard continued evolution, (2) in absorption of the more soluble of the fission-product gases, such as iodine, if they were forced to bubble through the water, and (3) as a relatively efficient means of preventing escape of particulates. Fission-product removal by bubbling gases through water pools is being studied at the General Electric Company's Atomic Power Equipment Department.⁸⁵ Flooding of the containment vessel would probably not be recommended except in situations where contaminated gas and particulates continued to escape for some time after the initial accident.

4.4.11 Contaminated-Gas Pickup

It was mentioned in Section 3.4.4 that a containment vessel leak with even a very small-volume flow rate could represent a significant fission-product release and radiation hazard. This might be mitigated substantially by using a suction nozzle outside the containment vessel to pick up a portion of the escaping gas.

The gas-pickup system could be roughly compared with a central vacuum-cleaning system with permanent piping connecting a central treatment facility to hose couplings mounted at strategic locations. The air-cleanup station would be provided with absolute filters, charcoal beds, chemical sprays, as required for retention of the iodine and particulates,⁸⁶ and possibly membrane-type barriers for the noble gases.⁸⁷ The capacity of such a pickup system might be limited to a few hundred cubic feet per minute. The discharge would preferably be made from the off-gas stack.

Several alternate arrangements were suggested. One of these is to make use of the containment ventilation system air-cleanup facilities. The present state of the art of containment-air-cleanup systems has been reviewed by Keilholtz, Guthrie, and Battle.⁸⁶ There is, of course, the possibility that the containment ventilation system could be damaged by the reactor accident. It is doubtful whether the suction developed by the containment ventilation system fans would be adequate, but even if

they were designed for such service, a positive pressure inside the containment vessel would tend to negate the suction that could be developed for the gas-pickup nozzle. A better system would consist of a separate gas-pickup suction blower discharging into the containment ventilation cleanup system. It would be desirable that this system also discharge the processed air from the off-gas stack, as was mentioned in Section 4.4.4.

A third suggested arrangement is a completely separate and portable gas-pickup and -cleanup system. This would be installed in a large trailer that could be moved by tractor on the highways or airlifted by helicopter or transport plane from a storage point central to several reactor installations. A portable rig might have some value in serving several reactors at a large complex, but it is judged that movements over great distances would be uncertain and time consuming.

Another arrangement is a gas-pickup system discharging directly to the off-gas stack without filtration. The advantage of the elevated release point for the contaminated gas could be considerable in certain circumstances. This system would be very inexpensive in comparison with the foregoing schemes that use air-cleanup arrangements, but obviously its effectiveness in reducing the activity level would not be nearly so great.

Still another variation of this system is that the leaking gas might be sucked up, if possible, and used to generate a foam to encapsulate the contaminants. Advance planning as to where to discharge this contaminated foam would be needed.

The expense of any of these gas-pickup systems and the associated air-cleanup and emergency-power supply equipment depends greatly on the complexity of the system adopted. There would be the added costs of maintenance, periodic testing, etc. Since the size of leak against which the systems would be effective is probably small and effectiveness would also greatly depend on the accessibility of the opening, the practicality of this suggestion is questionable. However, if one wishes to assume, as apparently many do, that the likelihood for small leaks is much greater than for the larger ones, this method of activity control might have some importance.

4.4.12 Retentive Coatings

Interest has been shown in paints and coatings inside the containment system that irreversibly absorb iodine gas. The AEC has initiated work at Battelle Memorial Institute in this area.⁸⁵ Also, as part of the LOFT program, paints and coatings that might have application in commercial nuclear plants will be tested to investigate the chemical state of the desorbed iodine and plateout rates of both iodine and mixed fission products.⁸⁵ Because of the affinity for iodine, relatively little decontamination of the coatings can be made by remote means. For this reason, strippable coatings are being studied.

Such materials possibly could reduce the amount of iodine available for release from a failed containment vessel, but in general the chemical processes are considered too slow to have much value as an activity control measure as considered in this study.

4.4.13 Remote Discharge of Contaminated Gases

It has been suggested that a reactor located in a metropolitan area could be provided with an underground off-gas pipe leading to a more advantageous discharge point, such as offshore, at a higher elevation, in sparsely-settled areas, etc. Several variations of the idea have been offered, such as that a multiplicity of reactors in an urban area could be served by a common off-gas line and gas-decontamination facility.

Even if a double pipe were used, with the annular space evacuated, an underground line containing highly irradiated fission products might require a right-of-way that in itself would have to be classified as a restricted area or low-population zone. Land rights for such a pipe line out of an urban area could thus be excessive.

It is not clear where a more publicly acceptable discharge point for the gases could be. If the case is presented that it is too dangerous to locate the emergency off-gas stack in the urban area, those living in the nearby rural area selected for the discharge point would understandably be perturbed. In any event, as populations increase, so-called "remote locations" become increasingly scarce. This method apparently

has little practical value and was mentioned here primarily to indicate that it received consideration.

5. RELATED MEASURES

Some of the measures that could be taken in the siting of reactors or at the time of a nuclear accident are not within the scope of this study but might be effective in reducing hazards. There was a widespread tendency to bring these related aspects into discussions of activity control methods. Some of them are briefly mentioned here primarily to indicate that these important areas were not overlooked.

5.1 Advance Planning

The need for operator training to meet emergency conditions is obvious, but for effective use of the activity controls suggested in this report, such training is imperative. Most of the methods depend on quick evaluation of the accident conditions to determine the most effective procedures. None of the measures can be initiated by the simple push of a button, but, rather, they depend on the speed, skill, and ingenuity of the reactor crew in reacting to the emergency.

It is also essential that the reactor operators be provided with the necessary emergency equipment, such as instruments for making quick evaluations of the radiation hazards, special clothing, masks, and complete health physics protection. A broad area of this subject has been discussed in studies of accident-recovery programs,^{33,41} and by Ablitt⁸⁸ in a study of incident evaluation.

Advance planning in communities in critical areas around a reactor site is equally important. Many feel that this advance preparation could make the difference between a disaster and a catastrophe. The recommended programs include plans of action for local authorities, emergency warning systems, hospital facilities for treatment of irradiated patients, emergency evacuation plans for selected areas, etc. The emergency plan for the Shippingport reactor⁸⁹ appears to be unusually thorough in some of these respects. The similarity between these measures and those of concern in the civil defense program is obvious. A very cursory investigation⁹⁰ indicates, however, that apparently more effort could be made to

coordinate the civil defense effort with emergency planning at stationary nuclear power plant installations.*

It is believed that as community living becomes more complex, there will be a demand for more, rather than less, recognition of potential hazards. The dangers of hysteria and panic due to atmospheric toxicity, contaminated water, fires, explosions, flooding, nuclear missiles, etc., all may lead to the requirement in the not too distant future that all incorporated cities have facilities for handling major disasters. The effectiveness of such programs is attested to by the remarkable improvement advance planning made in some gulf-coast communities in reducing hurricane casualties.

It is to be emphasized that a continuing program of preparedness for accidents at a nuclear reactor station would probably be as important to limiting radiation casualties as activity control measures applied on the site.

5.2 Visual or Olfactory Tagging of Clouds

It was suggested in Section 4.2 that colored smokes or olfactants might be discharged inside the containment vessel as an aid in locating leaks. These also might have value if released from the reactor site at the time of a major escape of activity.

Colored smoke could be quickly dispersed under certain meteorological conditions but, in more favorable situations, might be visible for miles to serve as a warning and provide information as to wind directions aloft. A distinctive color might be standardized. Some feel that there would be less panic on the part of the public if the cloud movement could be more clearly seen; others feel just as strongly that it could add to the panic. It would have to be emphasized, however, that there could be little quantitative relationship between the intensity of the smoke color

*The preplanning programs and studies made in connection with ports-of-call of the N.S. SAVANNAH⁹¹ are of some interest, but as pointed out by McCurdy,⁹² the protection in this case emphasizes the mobility of the reactor. In California, each reactor facility must develop an emergency plan in cooperation with the State Disaster Office.⁹³

and the radiation dose level at a given point, and, in particular, that a hazard could exist even if no smoke were visible.

Olfactants, such as the mercaptans, could serve a similar purpose and would have the advantage that their observation would not be limited to the day-light hours, as would the smoke. The odor would be detectable in much smaller concentrations and thus could carry to greater distances. It has been pointed out, however, that although it is possible to detect the odor of ethyl mercaptan in very minute concentrations of less than 0.01 ppm, fine distinctions cannot be made between relative intensities and the direction of the source.⁴⁷ As with the smoke, there would not necessarily be a direct numerical relationship between the intensity of the odor and the radiation hazard. Despite these drawbacks, the release of a distinctive odor would appear to have advantages in serving as a warning to move across wind to a safer location and possibly to report for a medical examination.

5.3 Thyroid Saturation

Ingestion of iodine to saturate the thyroid before exposure to radioactive iodine has been frequently suggested as a precautionary measure. There would probably be some exchange of the iodine in any event, but the practical aspects of quick distribution and use of pills, even if effective, would pose very serious problems. A suggestion that elemental iodine gas be released at the time of an accident to dilute the radioactive iodine was viewed with some skepticism, because iodine is considered to be a toxic gas, and selection of the lesser of the evils at the time of an accident could be very difficult.

5.4 Underground and Underwater Siting of Reactors

5.4.1 Underground

Underground installation of reactors has long been recognized as a means of protection from military action and a means for providing biological shielding. In countries where the purchase of exclusion areas is extremely expensive the scheme has received particular attention, and

the Halden nuclear plant in Norway was actually built in a rock excavation.⁹⁴ It has proven practical to build several hydroelectric power plants underground.

As pointed out by Fontana,⁹⁵ underground construction has the advantages that explosive forces would be taken up by the rock, the possibilities of destruction of the plant from without would be decreased, and fission-product gases and aerosols would have to seep through the rock and soil before reaching the surface.

Although the cost of underground installations might be competitive at certain sites in foreign countries, this is thought to be less true in the U.S. at the present time. The condensing-water supply is an important consideration, and since very few instances would probably exist where the condenser could economically be located underground, the arrangement considered most likely involves piping the steam from the underground reactor to a turbine-generator and condenser located on the surface at the available condensing-water supply.

While it is true that location of a reactor underground could lessen the hazards due to a failed containment vessel and the spread of activity, this could not be offered as a panacea for the problem because escape routes for the activity might still be present. More study is also probably needed on the problem of removing decay heat from underground reactors.

5.4.2 Underwater

Underwater installation again provides better shielding and protection against exterior missiles. Whether the surrounding water pressure would reduce the outleakage of contaminated gas at the time of a containment vessel failure would depend on the size and location of the hole, the relative pressures, etc. A catastrophic type of failure of the containment vessel would probably allow large gas bubbles to rise to the surface.

In connection with investigations of earthquake-resistant structures, ORNL and Bechtel Corporation made studies of the feasibility of reactors located in caissons beneath the water surface.^{96,97} The reactor design used as a reference was a 700 to 800-Mw(e) Dresden-type

boiling-water reactor located in water 30 ft deep and 1/2 mile offshore. A natural-circulation system removed heat from the drywell and the suppression pool.

The main advantages cited for the design were the following:

1. External sea pressure opposed outleakage.
2. The caisson provided double containment.
3. Cooling could be provided without reliance on pumps and valves.
4. The "land" cost for the site would probably be lower and in some cases there might be greater flexibility in choices of sites. Greater exclusion distances perhaps could be provided.
5. There would be better protection against earthquakes.
6. The danger from external missiles would not be as great.

The chief disadvantage found in the use of caissons was that the estimated construction costs were high as compared with the costs of land-based plants, although this would perhaps be offset by the lower land costs. Further, accident-recovery measures for an underwater reactor could be more difficult than those for a land-based plant.

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APPENDICES

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Appendix A

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Appendix B

Table B.1. Summary of Data for Some Power Reactor Containment Structures^a

NAME, LOCATION, OWNER AND OPERATOR	TYPE	POWER		STARTUP DATE	SCHEME	VOLUME ($\times 10^6 \text{ FT}^3$)		DESIGN PRESSURE (PSIG)	DESIGN TEMP (°F)	LEAK RATE CRITERIA (% NET VOL / 24 HRS AT DESIGN PRESSURE)	TEST PRESSURE		MAJOR DIMENSIONS (FT)	REMARKS AND CONFIGURATION		
		MW (1)	MW (e)			GROSS	NET				DESIGN	LEAK				
1. DRESDEN GRUNDY COUNTY, ILL COMMONWEALTH EDISON CO	BOILING WATER	700	208	SEPT. 1959	SEALED ENVELOPE SYSTEM	3.60	2.88	29.5	325	<0.5	37		D = 190 t _s = 1.40 IN.	SPHERICAL STEEL SHELL ON A CONCRETE FOUNDATION AND STEEL COLUMNS. CODES: ASME		33
2. BODEGA BAY BODEGA HEAD, CALIF. PACIFIC GAS AND ELECTRIC CO	BOILING WATER	1008	325	PLANT CANCELLED	PRESSURE SUPPRESSION SYSTEM WITH CONVENTIONAL BUILDING	0.142	0.115	62 DRYWELL 35 CHAMBER	150	<0.5 <0.3	62 35		D ₁ = 26 H = 100 D ₂ = 60 T = 93 D ₃ = 26	STEEL SPHERE-CYLINDER DRY WELL AND TOROIDAL SUPPRESSION CHAMBER SURROUNDED BY REINFORCED CONCRETE. CODES: ASME, CONCRETE UNKNOWN.		33
3. SAN ONOFRE NUCLEAR GENERATING STATION SAN CLEMENTE, CALIF. SOUTHERN CALIF EDISON CO	PRESSURIZED WATER	1210	375	JAN. 1967	SEALED ENVELOPE SYSTEM	1.44	1.115	44 100 MPH WIND PLUS SEISMIC FACTOR	90	<0.1	50.6	CLOSE TO DESIGN PRESSURE	D = 140 t _s =	SPHERICAL STEEL SHELL ON CONCRETE FOUNDATION. CODES: ASME, UNIFORM BUILDING CODE.		33
4. CONNECTICUT YANKEE HADDAM NECK, CONN CONNECTICUT YANKEE ATOMIC POWER CO	PRESSURIZED WATER	1473	490	1967	SEALED ENVELOPE SYSTEM	2.26	2.057	40 150 MPH WIND	260	<0.1	46	20	D = 135 t ₁ = 4.5 H = 113 t ₂ = 5.5 R = 67.5	REINFORCED CONCRETE CYLINDER, MAT AND DOME WITH INTERIOR 1/4 IN. STEEL MEMBRANE LINER. CODES: ACI, LINER UNKNOWN.		33
5. MALIBU NUCLEAR PLANT CORRAL BEACH, CALIF. CITY OF LOS ANGELES DEPT OF WATER AND POWER	PRESSURIZED WATER	1473	490	JAN. 1968	SEALED ENVELOPE SYSTEM	2.26	2.193	40 20 PSF WIND PLUS SEISMIC FACTOR	260	<0.1	46	15 BOTH MEM- BRANES	D = 135 t ₁ = 2.5 H = 113 t ₂ = 3.2 R = 67.5 t ₃ = 4.2	REINFORCED CONCRETE CYLINDER, MAT AND DOME WITH TWO 1/4 IN. STEEL MEMBRANE LINERS: ONE ON INTERIOR SURFACE AND ONE BETWEEN EXTERIOR CONCRETE AND POROUS INTERIOR CONCRETE. CODES: ACI, LINER UNKNOWN.		33
6. RAVENSWOOD NEW YORK, NEW YORK CONSOLIDATED EDISON CO. OF NEW YORK	PRESSURIZED WATER	2025	1000	CANCELLED BY CON ED.	SEALED ENVELOPE SYSTEM	2.508		40 HURRICANE WINDS	120	<0.1 AT 15		15	D = 150 t ₁ = 2.0 H = 92 t ₂ = 5.0 R = 75 t ₃ = 5.0	REINFORCED CONCRETE CYLINDER, MAT AND DOME WITH TWO 1/4 IN. STEEL MEMBRANE LINERS: ONE ON INTERIOR SURFACE AND ONE BETWEEN EXTERIOR CONCRETE AND POROUS INTERIOR CONCRETE. CODES: ACI, LINER UNKNOWN.		33
7. NINE MILE POINT OSWEGO, NEW YORK NIAGARA MOHAWK POWER CORP	BOILING WATER	1538	500	NOV. 1968	PRESSURE SUPPRESSION SYSTEM WITH CONVENTIONAL BUILDING			62 DRYWELL 1 35 CHAMBER PLUS SEISMIC FACTOR	280	<0.1 <0.1	71.3 40.25	62 35	D ₁ = 33 D ₃ = 27 D ₂ = 70 H = 120 T = 123.33	STEEL SPHERE-CYLINDER DRY WELL AND TOROIDAL SUPPRESSION CHAMBER SURROUNDED BY REINFORCED CONCRETE. CODES: ASME, ACI, REF 45, AND 46, AISC, N.Y. BLDG CODE.		33
8. OYSTEN CREEK OCEAN COUNTY, NEW JERSEY JERSEY CENTRAL POWER AND LIGHT CO	BOILING WATER	1600	515	1967	PRESSURE SUPPRESSION SYSTEM WITH CONVENTIONAL BUILDING	0.212	0.170 0.129	62 DRYWELL 2 35 CHAMBER PLUS SEISMIC FACTOR	150	<0.5 <0.5		62 35	D ₁ = 32 D ₃ = 29 D ₂ = 70 H = 120 T = 101	STEEL SPHERE-CYLINDER DRY WELL AND TOROIDAL SUPPRESSION CHAMBER SURROUNDED BY REINFORCED CONCRETE. CODES: ASME, CONCRETE UNKNOWN		33
9. INDIAN POINT INDIAN POINT, NEW YORK CONSOLIDATED EDISON CO OF NEW YORK, INC.	PRESSURIZED WATER	585	151	1962	SEALED ENVELOPE SYSTEM	2.14	1.8	25 -1.25	225	<0.1	34.4	25	t _s = 0.9 IN. H = 107 D _s = 160 t ₁ = 5.5 D _c = 182 t ₂ = 2.75	SPHERICAL STEEL SHELL ON A CONCRETE FOUNDATION AND STEEL COLUMNS ENCLOSED WITHIN A REINFORCED CONCRETE BUILDING WITH ELLIPTICAL DOME. CODES: ASME, CONCRETE UNKNOWN.		33
10. OLDBURY NUCLEAR POWER STA. SOUTH OF BERKELEY, ENGLAND CENTRAL ELECTRICITY GENERATING BOARD	GAS COOLED (CO ₂)	1668 (TWO REACTORS)	560 (TWO REACTORS)	1966	PRIMARY VESSEL WITH CONVENTIONAL BUILDING	0.560 (TWO REACTORS)		385	131 CONCRETE 149 LINER	<5.0	443	VACUUM	D = 77 t ₁ = 15 H = 60 t ₂ = 22	VERTICAL CYLINDER OF PRESTRESSED CONCRETE WITH 1/2 IN. MILD STEEL LINER. RAFT-TYPE FOUNDATION (ONE FOR EACH REACTOR). THE CONCRETE IS COOLED WITH WATER. CODES: UNKNOWN, REF 50, MODEL TESTS.		4
11. WYLFA ENGLAND CENTRAL ELECTRICITY GENERATING BOARD	GAS COOLED (CO ₂)	3751 (TWO REACTORS)	1180 (TWO REACTORS)	1968- 1969	PRIMARY VESSEL WITH CONVENTIONAL BUILDING	0.926 (TWO REACTORS)		400	122	<5.0	460	VACUUM	D = 96 t = 11	PRESTRESSED CONCRETE SPHERE WITH 3/4 IN. STEEL LINER AND RIBBED OUTER SURFACE FOR PRESTRESSING ANCHORS. RAFT-TYPE FOUNDATION (ONE FOR EACH REACTOR). THE CONCRETE IS COOLED WITH WATER. CODES: UNKNOWN, REF 50, MODEL TESTS.		5
12. EDF 3 CHINON, FRANCE ELECTRICITE DE FRANCE	GAS COOLED (CO ₂)			1963	PRIMARY VESSEL WITH CONVENTIONAL BUILDING			400	149	<5.0	500	VACUUM	D = 62.3 H = 69.4 t = 13.8	PRESTRESSED CONCRETE EXTERIOR CUBE, INTERIOR CYLINDER. RAFT-TYPE FOUNDATION. THE CONCRETE IS COOLED WITH ORGANIC LIQUID. CODES: UNKNOWN, MODEL TESTS.		5

^a Taken from Ref. 45.

Appendix C

TIME REQUIRED FOR A PRESSURIZED FAILED CONTAINMENT VESSEL
TO LEAK DOWN TO ESSENTIALLY ATMOSPHERIC PRESSURE

It is of interest to roughly estimate how long it might take a pressurized failed containment vessel to bleed down to essentially atmospheric pressure, since it would probably be very difficult to retard the escape of radioactive gas mixtures as long as even a small pressure difference existed across the hole. The estimates are based purely on the flow characteristics through an opening and do not take into account any probabilities of one hole size or type occurring instead of another, etc. Holes ranging in size from 0.1 to 14 ft² were assumed. Containment free volumes from 300,000 to 2,700,000 ft³ were studied, since these sizes span the range of interest of present-day large BWR and PWR reactors.

An accident situation was assumed in which there was no continued steam generation within the vessel. To include a factor for continued heat release, it was assumed that the interior temperature remained at a constant 150°F throughout the blowdown process.*

At the time of the failure the containment vessel could be filled with a mixture of air or the containment atmosphere, steam, fission-product gases, products of a metal-water reaction, etc. To obtain an appreciation of the effect of the mixture properties, the blowdown times were estimated in one case by using the properties of air and in another by using the properties of steam. The results are reported in Table 1 (see Summary, Conclusions, and Recommendations) as a time range, with the lower times those obtained from the properties of steam and the longer values those resulting from the use of the properties of air.

A leak in the containment vessel could take the form of a crack, crevice, jagged hole, etc. It does not seem likely that the hole would be a neat round one of the type usually associated with orifice flow

*This temperature assumption is not critical in making the estimates. If the interior temperature were held constant at, say, 250°F rather than 150°F, the estimated blowdown times would be increased by only about 3%. This was verified by estimating a few of the cases on the basis of 250°F.

calculations. For want of better information, however, the usual relationships for an orifice were assumed to apply.

If the hole behaved as a sharp-edged orifice, the mass flow rate would not be limited by the sonic velocity at the "throat." In this case the discharge coefficient would probably be lower than that usually applied to an orifice, and a coefficient of 0.55 was arbitrarily assumed. If the hole behaves as a rounded-edge orifice, both the sonic and subsonic regimes must be considered, and a discharge coefficient of 0.60 is a conventional assumption. Both of these modes were investigated, but the difference between the two was so small as to be of no significance in the broad evaluation of the time estimates. The latter case, in which consideration is given to the sonic velocity, is the one reported here.

The initial pressure in the containment vessel was assumed to be 55 psia. This arbitrary value may be compared with typical test pressures for a PWR containment vessel of 55 psig and for a BWR of 62 psig. It is obvious that the estimated times for blowdown would be even longer if the failure occurred at values exceeding 55 psia. However, it is not necessary to fix this value precisely in order to make the point that the time required for many postulated accident situations would be a matter of hours rather than minutes.

The general flow relationships were assumed to apply. The velocity through an opening can be expressed, in fps, as

$$V = F_c \left\{ 2Jg_c c_p T_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{(k-1)/k} \right] \right\}^{1/2},$$

where

F_c = correction for approach velocity, assumed to be 1.0,

p_2 = atmospheric pressure, assumed to be 14.7 psia,

p_1 = upstream pressure, initially assumed to be 55 psia,

T_1 = upstream temperature, assumed constant at 150°F,

c_p = specific heat, 0.24 Btu/lb·°F for air and 0.47 Btu/lb·°F for steam,

k = exponent for isentropic expansion, 1.4 for air and 1.31 for steam,

J = Joule's equivalent, 778.3 ft-lb/Btu,

g_c = gravitational constant, 32.2 ft/sec².

This can be reduced to

$$V = 2708.9 \left[1 - \left(\frac{p_2}{p_1} \right)^{(k-1)/k} \right]^{1/2}$$

for air and to

$$V = 3790.8 \left[1 - \left(\frac{p_2}{p_1} \right)^{(k-1)/k} \right]^{1/2}$$

for steam.

The mass flow rate is:

$$m = CVA/v_2 ,$$

where

C = discharge coefficient, assumed to be 0.6 (see discussion above),

V = velocity at "throat," fps,

A = hole area at "throat," ft²,

v_2 = specific volume at p_2 , ft³/lb.

By assuming perfect gas relationships and noting that the term $C(p_2)^{1/k}/RT_1$ is a constant for the assumed conditions, this can be reduced to

$$\begin{aligned} m &= \frac{C(p_2)^{1/k}}{RT_1} AV(p_1)^{(k-1)/k} \\ &= 0.01814 AV p_1^{0.2857} \end{aligned}$$

for air and

$$= 0.01285 AV p_1^{0.2366}$$

for steam.

Starting with the initial volume, the mass flow during a finite time, say 1 min, was calculated. This was subtracted from the original mass of gas in the containment to give a new specific volume and a new pressure:

$$p_1 = 226 \left(0.2434C - \sum m \right) = \text{psia}$$

for air and

$$p_1 = 363.5 \left(0.1513C - \sum m \right) = \text{psia}$$

for steam. This process was repeated until the containment pressure was reduced to atmospheric. Since p_1 could theoretically approach but never reach atmospheric pressure, the process was considered complete when a pressure within about 0.1 psia of atmospheric was reached. Again, it was not necessary to determine this point exactly to achieve the purpose of the estimates.

A critical pressure ratio of 0.528 was assumed for air flow and 0.545 for steam. The latter value, which is the value usually used for superheated steam, was considered reasonable since wet steam would tend to superheat during expansion to the pressure in the "throat." During the initial sonic regime, if $14.7/p_1 < 0.528$,

$$V = 1106.3 \text{ fps}$$

for air, and if $14.7/p_1 < 0.545$,

$$V = 1386.5 \text{ fps}$$

for steam. These velocities were used until the flow became subsonic.

A CEIR time-shared computer was used for the step-by-step analysis, with 30-min intervals for the small holes, 1-min intervals for larger ones in the large vessels, and 1/4-min intervals for the large holes in the 300,000-ft³ vessel. The results are tabulated in Table 1 and are illustrated in Fig. 1.

Appendix D

Fig. D.1. Schematic Representation of Behavior of Stack Effluents Under Various Conditions of Vertical Stability (Taken from Ref. 64).