ORNL
MASTER COPY

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

DATE ISSUED: SEP 12 1968

ORNL-NSIC-22
UC-80 — Reactor Technology

MISSILE GENERATION AND PROTECTION IN LIGHT-WATER-COOLED POWER REACTOR PLANTS

Richard C. Gwaltney

NUCLEAR SAFETY INFORMATION CENTER

NSIC

Printed in the United States of America. Available from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.65

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

November 6, 1968

To: Recipients of ORNL-NSIC-22

Report No.: ORNL-NSIC-22 Classification: Unclassified

Author(s): Richard C. Gwaltney

Subject: Missile Generation and Protection in Light-Water-Cooled Power Reactor Plants

Request compliance with indicated action:

Please refer to page 34, equation (34) where "(ft/sec)" appears on lines beginning with V_r, V and V_{xn} - change to read "(in/sec)"

also

Please refer to page 35, seventh line from top beginning η = functions related to dynamic shear strength of the plate material, assumed to be constant - change (1.76×10^6 psi) to (1.76×10^5 psi).

Thank you for your cooperation.

N. T. Bray, Supervisor
Laboratory Records Department
Technical Information Division

NTB:dbp

ORNL-NSIC-22

Contract No. W-7405-eng-26

Nuclear Safety Information Center

MISSILE GENERATION AND PROTECTION IN LIGHT-WATER-COOLED POWER REACTOR PLANTS

Richard C. Gwaltney

SEPTEMBER 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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:

Title	Author	ORNL-NSIC No.
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 Containment 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.

J. W. Michel
Coordinator, Discussion Papers
Oak Ridge National Laboratory

Wm. B. Cottrell
Director, Nuclear Safety Program
Oak Ridge National Laboratory

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
19. Bibliographies

Computer programs have been developed that enable NSIC to (1) produce a quarterly indexed bibliography of its accessions (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) cooperation 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

J. R. Buchanan, Assistant Director
Nuclear Safety Information Center
Oak Ridge National Laboratory
Post Office Box Y
Oak Ridge, Tennessee 37830
Phone 615-483-8611, Ext. 3-7253
FTS 615-483-7253

CONTENTS

Page

ABSTRACT xi

1. INTRODUCTION AND SUMMARY 1

2. BACKGROUND 3

2.1 Past Practice for Prototype and Experimental Reactors 3

2.2 Practice in Other Industries 4

2.3 Examples of Analyses of High-Pressure-System Accidents 4

3. TYPES OF MISSILES CONSIDERED IN THE DESIGN OF NUCLEAR POWER PLANTS 6

3.1 Equipment Missiles 6

3.2 Whipping Pipes 9

3.3 Rotating Machinery 9

3.4 Jet Forces 10

3.5 Missiles Generated by Natural Phenomena 10

3.6 Aircraft Accident Missiles 11

4. CALCULATIONS OF THE EFFECTS OF MISSILES 12

4.1 Sources and Energies 12

4.1.1 Piston-Type Missiles 12

4.1.2 Jet-Propelled Missiles 13

4.1.3 Self-Propelled Missiles 22

4.1.4 Missiles from Rotating Machinery 22

4.1.5 Missiles That Can Be Generated by Stored Strain Energy 23

4.1.6 Whipping Pipes 24

4.1.7 Missiles Generated from Ruptured Vessels 25

4.2 In-Path (Air) Resistance to Missiles 27

4.3 Impact and Penetration 28

4.3.1 Concrete Penetration and Perforation Formulas 29

4.3.2 Steel Penetration and Perforation Formulas 32

5. POSSIBILITY OF RUPTURE OF PRIMARY SYSTEM PRESSURE VESSELS AND EFFECTS OF RESULTING SHOCK WAVES 36

5.1 Vessel Rupture 37

5.2 Shock-Wave Effects 39

5.2.1 Generation of Shock Wave 41

5.2.2 Classical Shock Waves 42

5.2.3 Reflection of Shock Waves 44

5.2.4 Importance of Shock Waves in Reactor Accidents 45

5.2.5 Calculations of Maximum Deflections and Stresses 46

5.2.6 Effects of Shock Waves on Concrete Structures 48

5.2.7 Effects of Shock Waves on Objects That Can Become Missiles 50

5.2.8 Shock-Wave-Resistant Design 50

6. DESIGN FOR MISSILE RESISTANCE 53

6.1 Reinforced-Concrete Protective Structures 53

6.2 Methods to Control Spalling 54

7. CONCLUSIONS AND RECOMMENDATIONS 55

7.1 Vessel Rupture 55

7.2 Missiles 55

7.3 Penetration and Perforation Formulas 56

7.4 Present Design Philosophy 57

7.5 Handbook 57

REFERENCES 58

APPENDIX A. REVIEW COMMITTEE AND CONSULTANTS 65

ABSTRACT

The state of current technology of missile generation and protection in relation to the capability of meeting the relevant design criteria for nuclear power plants is presented. As part of the current technology, practices in other industries are discussed, and the available calculational techniques and their bases and deficiencies are described. A general description is also included of the cause and nature of shock waves, the various kinds of missiles that could be generated in the event of rupture of a primary system vessel, and the considerations involved in designing to protect against the harmful effects of shock waves and missiles. A summary of the current practice for nuclear power reactor designs is given, gaps in the relevant current technology are discussed, and recommendations are made for further research and development in this field.

1. INTRODUCTION AND SUMMARY

The generation of missiles from explosions or equipment failures in industrial operations is a rare event, but allowance is commonly made for this possibility as an integral part of the original plant design and operating procedures. This is particularly true in operations involving large quantities of stored energy and in those in which large or high-speed rotating equipment is employed. Both these conditions exist in commercial light-water-cooled power reactor plants, and consideration of such events is required in the proposed AEC General Design Criteria. The most specifically related criterion, No. 40, states that "...Protection for engineered safety features shall be provided from dynamic effects and missiles that might result from plant equipment failures." Also, criterion No. 49 on containment design applies to the extent that missiles resulting from credible energy releases could violate the containment structure, and criterion No. 2 on performance standards (including loads imposed by natural phenomena) applies from the standpoint of external missiles generated from such natural phenomena as tornadoes.

It is current design practice to assume that items such as valve stems, bolts, valve bonnets, and instrument thimbles are the most probable missiles. Because of their small masses, they would be unable to perforate concrete shielding around reactors or concrete containment structures. Less probable but possible missiles are large valve bonnets, turbine rotor pieces, and other rotating masses. These could perforate the containment structures, but when possible in practice, they are directed away from the containment structure and other engineered safety features if the risk is considered significant. Finally, there are massive external missiles such as aircraft and objects accelerated by windstorms to be considered.

The present methods used to analyze missile generation and missile effects are discussed in this report, and their deficiencies are pointed out. Also, missile accidents that are not presently considered in public documents are discussed, and their probable effects are reviewed. In general, the analytical techniques used to calculate the velocities of presently postulated missiles can be considered conservative because of

the assumptions made in the derivations of the equations. One exception is the method used to analyze propulsion of the missile by jets, which is a complex phenomenon. Experimental studies should be undertaken to develop more realistic and accurate equations for evaluating this type of missile.

The penetration and perforation formulas presently used for reinforced concrete were derived for military applications in which the missiles considered were of masses and shapes quite unlike those to be expected in reactor plant accidents. Therefore, these formulas may not be entirely applicable to light-water reactors. The modified Petry formula is the least conservative of the commonly used concrete-penetration formulas, and its use is not recommended. Other formulas, which give better results, are offered.

The steel-perforation formulas were empirically derived for small-diameter long-length cylindrical missiles and very thin targets. Here, both the target and the missile may be unlike those which exist in a nuclear-reactor accident, except for the case of the ejection of a control rod, and the formulas should be used with great care.

Manufacturers consider failures of the primary pressure vessels to be incredible and do not design against this event in present-day reactors. Should the primary cooling system rupture, however, this accident could cause the destruction of the containment structure by either the shock wave produced or the large missiles generated or both. If such a failure were considered credible, designs would need to be significantly modified. This would imply the development of better analytical techniques, as well as design innovations.

A handbook on missile generation and protection is needed to allow intercomparison of techniques and effectiveness of missile-protection designs and to set the basis for standardization of such design. The analytical and experimental studies necessary to produce such a handbook should be initiated immediately.

2. BACKGROUND

2.1 Past Practice for Prototype and Experimental Reactors

The primary dictum of nuclear power plant design is to provide engineered safety features, including containment, so that in the event of the complete spectrum of accidents up to the design-basis accident, the activity release to the surroundings will be less than prescribed limits. The necessity of this is being underscored by the present trend to locate reactors nearer load centers, that is, near the large cities with high population densities. To maintain adequate safety, careful attention must be paid to the containment structure and the possible damage it might undergo.

In the past the containment structures of some experimental and prototype reactors were designed to withstand an explosion of a calculated magnitude.[1-9] The energy of the explosion was based on the maximum energy that could be released under any type of accident. Three sources of energy were considered to be available for the explosive accident: nuclear, chemical, and stored. An examination of energy levels and modes of release provided the designer with an estimate of the maximum amount of energy that could be released under the worst accident case. The missiles that could be generated under accident conditions were also studied, and calculations were made to estimate the damage that could be caused by these missiles.

Some tests were actually performed on containment cells or their models to see whether they could sustain the equivalent TNT blast of an accident.[4,8] By such tests, better designs were conceived to withstand the blast and missile effects of assumed accidents. In some cases the effects of shock waves on the structures in the reactor plants and on containment walls were also theoretically analyzed,[3,5] and the possible generation of missiles by shock waves was investigated. Some of the postulated missiles were blast-wave-generated spalls from the walls; others were parts of the structure that could be propelled by the shock waves. Another method of containment design was simply that of assuming a certain equivalent TNT explosion and constructing walls to withstand

the pressure and impulse that would be caused.[9] The pressure and impulse data were obtained from empirical relations based on explosive test data,[10] while the dynamic response and stress analysis of the walls were based on empirical and tested formulas used in connection with hardened structures.[11]

2.2 Practice in Other Industries

Analyses similar to those conducted for nuclear reactors have been made in the chemical industry, where hazardous exothermic reactions or uncontrolled pressure may rupture vessels and cause damage to surrounding structures or to the operators. Here again, the containment cells are designed to withstand a TNT explosion equivalent to the maximum amount of energy that can be released in an accident.[12,13] However, use is made of openings in containment walls, frangible blowout walls, and vents. These practices are not acceptable in the nuclear industry because of potential fission-gas release. In nuclear reactor plants, even missiles that in other plants might be intercepted by external blast mats must be contained because perforation of the containment envelope might allow excessive amounts of fission products to escape.

In spite of the more stringent requirements of nuclear safety, some of the design methods used in the chemical industry can be very useful to the designers in the nuclear field.[12,13] For example, design techniques have been derived for the containment of explosions in piping and pressure vessels.[14-16] Reference 17 presents a simple design procedure and charts for analyzing hazardous pressure systems, calculating the velocities of missiles that can be generated from pressure systems, and calculating the blast pressure from the rupture of a vessel containing saturated water at high pressures.

2.3 Examples of Analyses of High-Pressure-System Accidents

One of the most complete analyses of a high-pressure system is described in Refs. 18, 19, and 20. In this analysis a gas autoclave containment system is designed to withstand the blast that would be generated by a brittle fracture of the pressure vessel. In addition, the containment

cell is designed to contain missiles generated by the rupture of the vessel, which is postulated to fail in any of three modes: a blowout of the top plug, a blowout of the bottom plug, or a longitudinal split along one side. A large mass of concrete is placed above the vessel to contain the blown-off top. By adding the massive weight of the roof to the top plug, the height to which the plug can rise is reduced to within the design limits. The containment cell can withstand the other two modes of failure without any added safety features. The same type of analysis was done for the Fermi reactor.[6,7] An analysis by Horvay[21] of an exploding hydraulically loaded pressure vessel indicates a very sophisticated method for calculation of the velocities of the missiles generated.

3. TYPES OF MISSILES CONSIDERED IN THE DESIGN OF NUCLEAR POWER PLANTS

Information on analyses of missile hazards and designs for protection against missiles was acquired for this review through personal visits to the manufacturers of reactors and by reviewing the preliminary and final safety analysis reports submitted to the AEC's Division of Reactor Licensing. Heavy reliance was placed on the information obtained directly from the manufacturers because the safety analysis reports do not contain detailed calculations. Three sample calculations were acquired. Additional information was obtained from documents published by the Defense Documentation Center for Scientific and Technical Information, architect-engineering firms, and miscellaneous topical reports.

Table 1 lists typical missiles discussed in safety analysis reports. These missiles and designs for protection against them are discussed first in this report without direct reference to reactor systems, and then methods for protecting reactors from missiles are analyzed.

3.1 Equipment Missiles

Small items (i.e., small compared with the system), such as valve stems, valve bonnets, thermowells, valves, piping, and reactor bolts have become missiles in some conventional power plants.[22] Pipes carring high-pressure fluids have exploded and sent out small fragments as missiles. In principle the velocity of a missile can be computed from the mass of the missile and the net force-time history. However, in only a few cases can a net force-time history be predicted; an example is that of a valve stem. When the exit velocity of a fluid propelling the missile can be estimated, it is frequently conservative to assume that the velocity of the missile is the same as that of the fluid. The velocity of bolts can be estimated by converting the strain energy into kinetic energy. This method is very conservative because no losses such as friction, relaxation, etc. are considered in this type of calculation. With the velocity of the missile, its weight, and a shape factor known, the damage done by the missile can be calculated from empirical formulas for penetration and

Table 1. Missiles Discussed in Preliminary Safety Analysis Reports and Amendments

Plants	Small Missiles	Large Missiles	External Missiles	Rotating Machinery	Whipping Pipes	Massive Vessel Failure
Dresden-2	Valve bonnets Valve stems Thermowells	Large valve bonnets		Rotating components of coolant recirculation pump motors Main turbines	All large pipes that penetrate the containment vessel have anchors to limit movement	Not considered
Quad Cities			Tornado-carried utility pole Tornado-carried compact car	Main turbines		Not considered
Millstone	Valve bonnets Valve stems Recirculation-pump flange joints Thermowells Small flanges	Large valve bonnets		Main turbines Rotating components of coolant recirculation pump motors	Recirculation piping has constraints to limit movement	Considered incredible, but circumferential and longitudinal breaks discussed briefly
Browns Ferry	Valve bonnets Valve stems Small flanges Thermowells Recirculation-pump coupling bolts High-horsepower pump retaining bolts	Large valve bonnets	Tornado-carried utility pole Tornado-carried compact car	Main turbine Feedwater pump turbines RCIC turbine		Not considered
Monticello	Valve bonnets Valve stems Thermowells Recirculation-pump flange	Large valve bonnets		Main turbine		Not considered
Palisades			Tornado-carried long wooden plank Tornado-carried passenger auto		Restraints are added to limit the amount of distortion and movement	Considered incredible, but circumferential and longitudinal breaks discussed briefly
H. B. Robinson-2	Control-rod drive-shaft housing		Tornado-carried long wooden plank	Flywheel of the main coolant pump		Not considered
San Onofre	All valve stems All valve bonnets All valves All instrument thimbles Various nuts and bolts Pieces of pipe	Large valve bonnets Large valves Pieces of pipe up to 10 in. in diameter Complete control-rod drive mechanism				Not considered

Table 1. (continued)

Plants	Small Missiles	Large Missiles	External Missiles	Rotating Machinery	Whipping Pipes	Massive Vessel Failure
Indian Point No. 2	Valve stems Valves Valve bonnets Instrument thimbles Various nuts and bolts Reactor vessel head bolts	Large valve bonnets Large valves Complete control-rod drive mechanism			Restraints are added to limit the movement of main primary components because of a coolant pipe rupture; auxiliary piping is not provided with any special supports	Not considered
Point Beach	Valve stems Valve bonnets Instrument thimbles Various nuts and bolts Reactor vessel head bolts	Large valve bonnets Complete control-rod drive mechanisms				Not considered
R. E. Ginna	Valve stems Valves Valve bonnets Instrument thimbles Various nuts and bolts Reactor vessel head bolts	All large valves Large valve bonnets Complete control-rod drive mechanisms			No problem exists	Not considered
Oconee	All valve stems All valve bonnets All instrument thimbles Various nuts and bolts Reactor vessel head bolts	Large valve bonnets	Tornado-carried 12-ft-long piece of wood 8 in. in diameter with a velocity of 225 mph	Main steam turbines		Not considered
Turkey Point Units 3 and 4	All valve stems All valve bonnets All instrument thimbles Various nuts and bolts Reactor vessel head bolts	Large valve bonnets Complete control-rod drive mechanisms	Commercial aircraft			Not considered
Dresden-3	Valve stems Small valve bonnets Thermowells and other small items of instrumentation	Large valve bonnets		Recirculation-pump motors Main turbines	All large pipes that penetrate the containment structure have anchors or limit stops located outside the vessel to limit movement Recirculation lines inside the containment vessel have a system of pipe supports to limit pipe motion	Considered incredible, but circumferential and longitudinal breaks discussed briefly

perforation of the surrounding structures. Usually, in the case of missiles of this size, the damage is slight because the velocities are low (around 500 ft/sec) and the masses small. The shielding structures are usually thick enough to have the structural strength to protect the primary system or the containment structure. The greatest danger from these missiles is that they may hit or destroy some of the more vulnerable engineered safety features, such as core cooling systems, although present design criteria require these systems be protected at all times.

Large items of equipment, such as large valve bonnets and control rods and their drive mechanisms, could possibly be ejected with missile force by the same phenomena as small vessels.

3.2 Whipping Pipes

The force of fluid escaping from a broken pipe can cause the pipe section to move, but the elastic stiffness of the pipe tends to return it to its original position. The resulting oscillatory motion is termed "pipe whipping." A whipping pipe could cause considerable damage by knocking loose other pipes and equipment and by hitting the wall of the containment structure. Another type of behavior considered is the development of a plastic hinge at a support with the result that the moving pipe would strike an object close by with considerable force. In the present designs of nuclear power plants, pipe hangers are strategically located and the piping is routed to minimize possible damage to the main components and engineered safety equipment in the event of pipe failure.

3.3 Rotating Machinery

The turbines and generators of a power plant are the largest pieces of rotating equipment in the system and are considered the most probable source of high-energy missiles. There have been some serious accidents caused by brittle fractures of rotating machinery as a result of overspeed (reaching the bursting speed), failure of control equipment, and failure of defective parts. Repairs on machines after installation have also led to component failure and the generation of missiles. Since there have

been accidents in which over half the rotor has been converted into a high-energy missile, the design for protection against such occurrences must be considered very carefully. One manufacturer conducts a very complete analysis of all possible missiles that can be generated from a postulated accident. Afterward he draws a "missile map" showing the trajectories, velocities, masses, and final positions of all possible projectiles originating at the turbine-generator. By a careful study of past accidents, the "worse-case" missiles for each section of the plant can be selected, and the proper design against such missiles can be undertaken.

3.4 Jet Forces

Reactor primary pressure systems are designed to withstand the jet forces of the design-basis accident, which is considered to be the double-ended failure of a large coolant pipe in a light-water-cooled power reactor. This means that the reactor vessel, steam generator, pressurizer, and main coolant pumps are designed to withstand the maximum jet force from one severed pipe and do not translate, rotate, deflect, nor suffer structural damage to the internal or outer surfaces of vessels. It is not considered credible that the main vessels must withstand the jet forces from two or more simultaneously severed pipes.

3.5 Missiles Generated by Natural Phenomena

Missiles generated by natural phenomena, such as hurricanes, tornadoes, and floods, are in a class by themselves and are not generally considered by the designers of nuclear plants. It has been assumed in some instances (see Table 1) that utility poles and small compact cars could become missiles during tornadoes, but there seems to be little information on the velocity of a projectile that has been picked up by a wind or on how this velocity can be calculated. The missiles are usually assumed to travel at a somewhat lower velocity than the maximum wind velocity of tornadoes experienced in the site area. Also, the containment structure is designed to take the assumed wind load produced by a tornado. Hurricanes

are studied in much the same manner, but the assumed wind velocity is usually smaller than for tornadoes. In tornadoes the maximum wind velocity can be in the range of 500 to 600 mph, while for hurricanes it rarely exceeds 200 mph.

The plant is assumed to be designed to withstand an earthquake without damage, and therefore no missiles should be generated during an earthquake if the assumed earthquake intensity is not exceeded. No consideration of missiles generated by other forms of natural phenomena was found in the design reports of nuclear plants.

3.6 Aircraft Accident Missiles

Aircraft accidents involving nuclear power plants have been considered in some cases.[23] The data used for the assumed projectiles were obtained from discussions with the Civil Aeronautics Board. Since the CAB has stated that piston or jet engines would usually stay intact during a crash, aircraft engines were the basic missiles considered in the calculations. It was shown by the calculations that the postulated missiles would not breach the reactor containment structure.[23] Unfortunately, only commercial jet aircraft (passenger) were considered in the studies, although it was stated that aircraft cargo could comprise a missile that would readily penetrate a 4-ft-thick-reinforced concrete structure.

In another study, Kennedy[24] considered a C5A military transport aircraft carrying two M60 tanks. Since the two tanks would be set one behind the other in the aircraft, there would be a tendency upon impact for both tanks to act as a single projectile and strike the containment wall at the same location. The thickness of reinforced concrete needed to prevent perforation was calculated to be 16 ft. Obviously, most reactor containment structures could not withstand this type of impact. Small military jet aircraft, which attain speeds greater than 600 mph, might also penetrate the containment structure when traveling at those speeds. Kennedy[24] pointed out that the overall effects of impact should be considered along with the penetration studies, since the overall structure might fail under the kinetic loading at some point other than that of impact.

4. CALCULATIONS OF THE EFFECTS OF MISSILES

The effects of missiles depend on their physical characteristics (such as mass, shape of the impinging cross section, and length) and on the constraints acting on the component hit by the missile. The effect of the missile, that is, the damage done, depends also on the velocity, the flight path, and whether or not the projectile rotates or tumbles. Therefore it is necessary that these factors be calculated or assumed with reasonable accuracy. Needless to say, for design purposes, it is safer to overestimate the velocity of the missile than to underestimate it. Simple conservative methods for calculating the velocities of missiles are presented here to provide insight into the assumptions that must be made and the difficulties that are encountered in attempts to make more sophisticated types of analysis.

4.1 Sources and Energies

4.1.1 Piston-Type Missiles

In the case of a missile, such as a valve stem, that is acted upon by a constant-force stream of fluid for a certain distance in a piston-type action, the work-energy principle for calculating the velocity gives

$$V = \left(\frac{2PAL}{m}\right)^{1/2} , \qquad (1)$$

where

V = the initial velocity at the end of the piston stroke (ft/sec),
P = pressure of the fluid (psi),
A = cross-sectional area of the piston (in.^{2}),
L = length of the stroke (ft),
m = mass of the missile (lb-sec^2/ft).

In this simple formula, the true length of the stroke is not always known, and usually a value for L is derived from past experience.

4.1.2 Jet-Propelled Missiles

After a missile has been expelled from a pipe or chamber, the missile may continue to be propelled by a jet of the escaping fluid and continue in that jet for a significant distance. The jet, which has mass and velocity, imparts an impulse to the missile.

The fluid expands into the atmosphere and quickly reaches a peak velocity. The expansion process depends on the state of the fluid in the container before rupture. If the fluid is in a gaseous state, it will expand very rapidly and be dispersed quickly throughout the surrounding atmosphere. Thus, it will not be able to act upon the missile very long. Data obtained from the U.S. Department of Defense indicate that the advancing front of a jet of air suddenly released from an orifice expands at angles up to 70 deg in going from the orifice pressure to atmospheric pressure.[25]

Fluid in the liquid state, that is, well below the saturation temperature (subcooled), will also expand quickly to atmospheric pressure but will not disperse to such a great angle. If the pipe or vessel contains a liquid at saturation or supersaturated temperature, the fluid will expand into the atmosphere and become a two-phase fluid, with both vapor and liquid phases.

The velocity of the fluid in the jet must be known before the energy transferred to the missile can be calculated. For a liquid jet impinging on a missile, Bernoulli's equation can be used to calculate the velocity if it is assumed that there is steady flow in the container that is the source of the fluid.[26] The pressure inside the liquid jet can be assumed to be atmospheric, and the velocity at the throat can be estimated by

$$V_T = \left[V^2 + 2g\left(\frac{P}{w} - H_L\right)\right]^{1/2} , \qquad (2)$$

where

V_T = velocity of the liquid in the jet at the throat (ft/sec),
V = velocity of the liquid in the container of pipe (ft/sec),
g = gravitational constant (32.2 ft/sec^2),
P = pressure in the container or pipe (psf),

w = specific weight of the liquid (lb/ft^3),

H_L = energy lost by the expansion of the liquid inside the nozzle (ft).

The energy loss, H_L, is usually assumed to be zero in making missile calculations. The velocity of the jet will change as the liquid expands into a larger stream. The maximum velocity is, of course, the throat velocity and is used to make upper limit missile velocity estimates. The velocity reduction due to the expansion of the jet with distance while it is impinging on the missile is disregarded.

The velocity of a gas jet can also be calculated by Bernoulli's equation when the jet issues from a container wherein the fluid is undergoing adiabatic steady flow. In this equation, absolute pressures must be used because ideal gas conditions are assumed. Accordingly, the jet throat velocity can be estimated by

$$V_T = \left[V^2 + 2g\left\{\left(\frac{K}{K-1}\right)\frac{P}{w}\left[1 - \left(\frac{P_T}{P}\right)^{(K-1)/K}\right] - H_L\right\}\right]^{1/2}, \qquad (3)$$

where

P = pressure in the container (psf abs),

P_T = pressure in the throat of the jet (psf abs),

w = specific weight of the gas (lb/ft^3),

K = adiabatic exponent.

Again, the energy loss, H_L, is usually assumed to be zero, and the decrease in velocity of the jet as it expands is neglected for calculating missile velocities. The conservatism involved depends on the distance traveled from the throat and the type of expansion of the gas, because all the state properties change at each point in the expansion process.

At the point of minimum cross-sectional area, the velocity of the gas is limited to the acoustic velocity at the temperature and pressure of the gas at that point. Therefore, when a gaseous fluid flows through a convergent section, the jet velocity will be correspondingly limited. The ratio between the pressure at the minimum cross-section point and the pressure in the vessel or pipe is called the critical pressure ratio

and, neglecting losses, it is given by[27]

$$\frac{P_T}{P_0} = \left(\frac{2}{K + 1}\right)^{K/(K-1)} , \tag{4}$$

where P_0 is pressure in the container (psf) and K is the adiabatic exponent. The acoustic velocity is calculated from

$$V_C = \left(\frac{KP_T g}{w_T}\right)^{1/2} = (gKRT)^{1/2} , \tag{5}$$

where

V_C = acoustic velocity (ft/sec),
w_T = specific weight of the gas at the throat (lb/ft^3),
R = gas constant,
T = absolute temperature at throat.

Equation (5) can be derived from Eq. (3) if the velocity in the container is zero or small compared with the acoustic velocity, the velocity of the throat is assumed to be the acoustic velocity, and losses are neglected. Since the container velocity will be small in most cases, Eq. (5) can be used without serious error. The same equations for gaseous flow from a container can be derived from the laws of thermodynamics or by compressible fluid-flow methods.[28]

In a flashing jet, the two-phase expansion of the fluid makes it very difficult to calculate the velocity or pressure because of the many unknowns, including, at any given point, the quality of the vapor and almost all other thermodynamic properties. The blowdown of saturated fluids has received much analytical and experimental study and probably will continue to be studied for many years to come. Some experimental work has been done on model blowdown studies for light-water reactors. Also, a very limited number of experiments has been done on missile generation by a two-phase fluid expansion at the National Reactor Testing Station.[29] It is hoped that this work will help solve some of the complex problems related to missiles generated by two-phase fluids.

The only method found for calculating the velocity of a two-phase fluid without the use of a complex computer program is given in Ref. 25. It is based on experimental data and should be accurate within the limits of that data. The method is outlined below.

For a given length-to-diameter ratio (L/D) of a short circular tube, Fig. 1 gives a value of V/V_0, where V is the actual velocity and V_0 is the average velocity of two-phase fluid flowing out of an orifice of the same size as that of the tube; V_0 can be calculated from the following equation once a critical exit pressure is assumed:

$$V_0 = C_d \left[\frac{2g}{\rho_i} (P_i - P_e)\right]^{1/2} , \tag{6}$$

where

C_d = discharge coefficient or Euler number, EU,
ρ_i = initial density of the fluid in the vessel (lb/ft^3),
P_i = initial pressure of the fluid in the vessel (psf),
P_e = exit pressure (psf).

The assumed value for the exit pressure is used to calculate the quantity

$$\Delta P = P_i - P_e ,$$

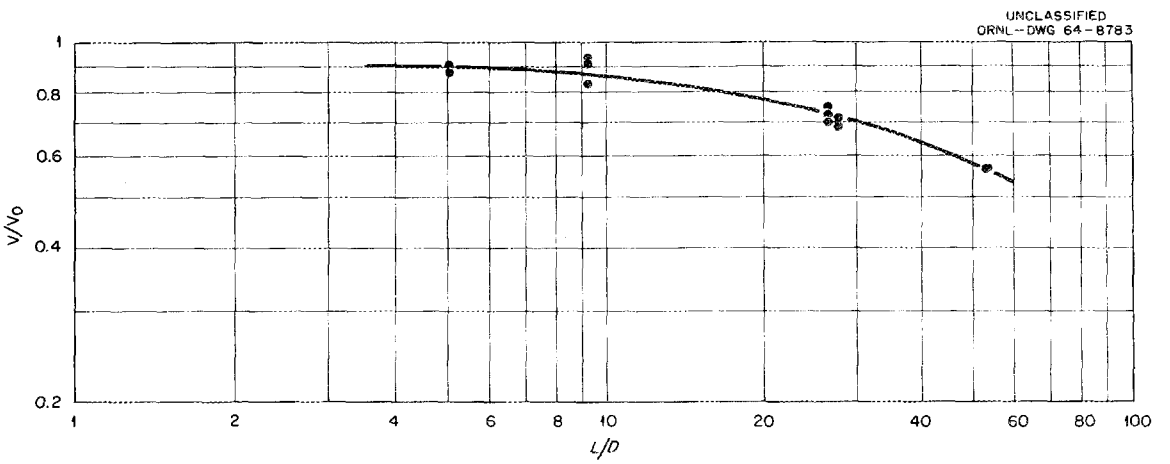

Fig. 1. Correlation of Dimensionless Velocity and Length-to-Diameter Ratio of Short Tubes.

and a value for C_d is then selected from Fig. 2. From these values, a unique value for V_0 is determined. Thus, the quantity V can be obtained from the value of V/V_0 given by Fig. 1.

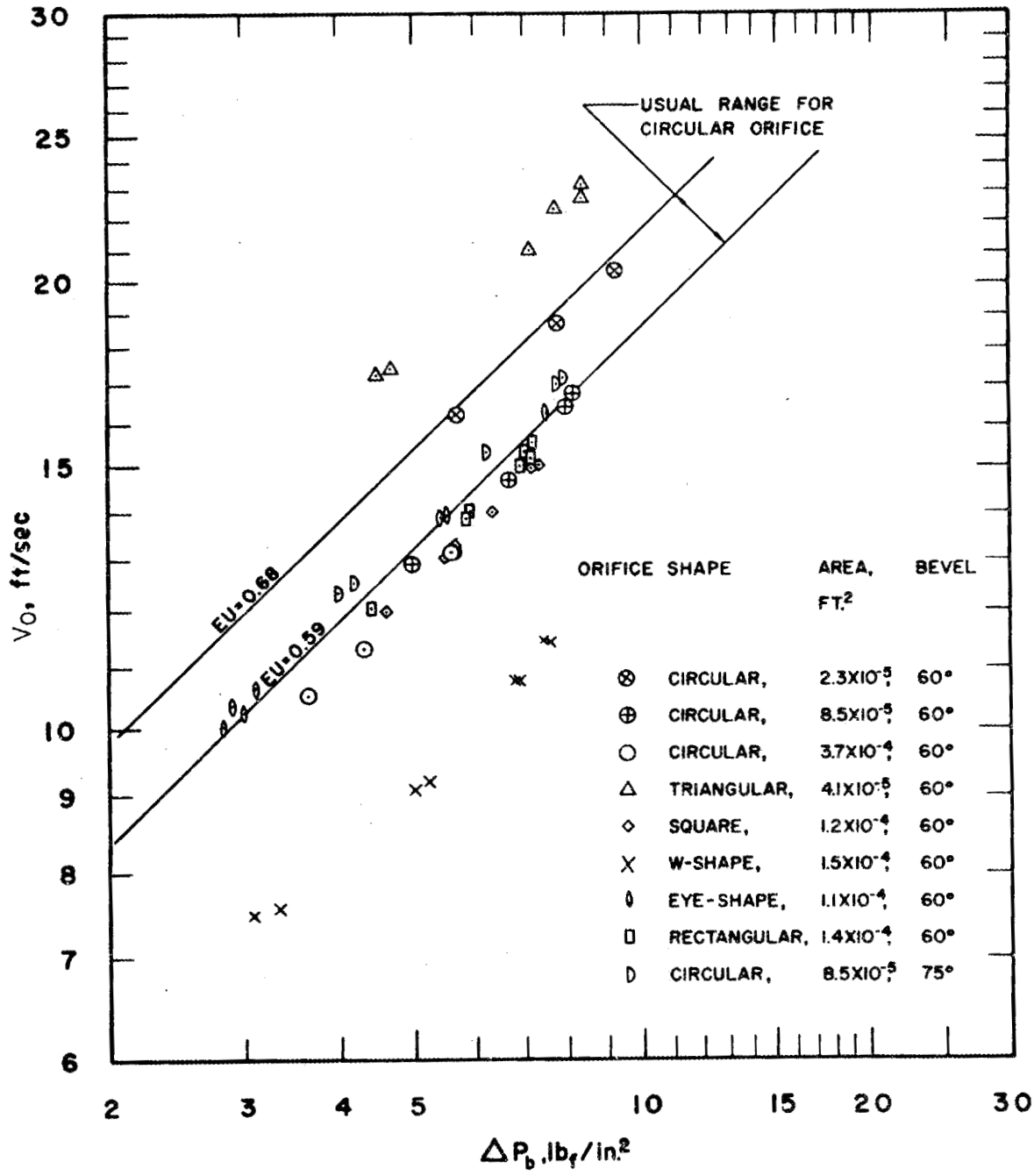

Fig. 2. Euler Number Variation for Various Apertures. (From Ref. 25)

Once V is determined, the Reynolds number can be calculated by the following formula:

$$Re = \frac{DV\rho_i}{\mu_i g} , \tag{7}$$

where μ_i is absolute viscosity (lb-sec/ft^2). A modified cavitation number, C_a, corresponding to the calculated Reynolds number may be obtained from Fig. 3. Comparison can then be made between the assumed critical exit pressure and the exit pressure given by the following equation for C_a:

$$C_a = \frac{2g(P_i - P_e)}{\rho_i V^2} \frac{L}{D} , \tag{8}$$

where L is length of the tube (ft) and D is the diameter or equivalent diameter (ft).

If the assumed critical exit pressure does not correlate with the calculated value, a new critical exit pressure is chosen and the procedure is repeated. When the correct value of critical exit pressure is found, the correct velocity is also known.

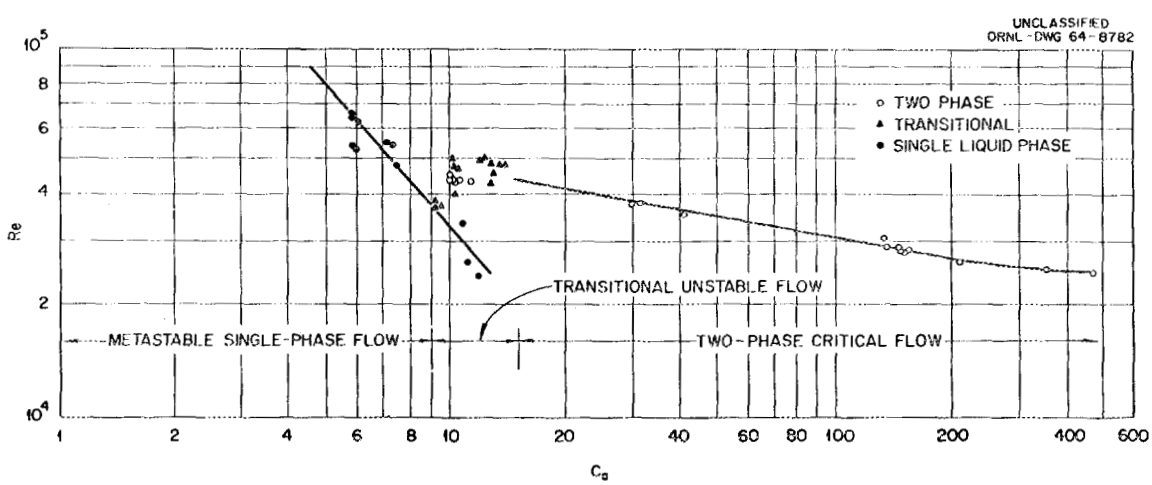

Fig. 3. Dimensionless Correlation Determining the Occurrence of Single-Phase and Two-Phase Flow Regimes and the Critical Discharge Flow Rates from Short Tubes.

Calculating the velocity of a jet impinging on a missile is thus complicated by the unknown energy losses due to shape, friction, and expansion processes and other unknowns such as the angle at which the jet expands and the state properties of the fluid as a function of distance from the jet throat. In partial effort to overcome the difficulties, the conservative assumption that the jet velocity is constant and equal to the throat velocity is introduced into the calculations.

After the velocity of the jet is calculated, assumed, or measured, the velocity of the projectile can be calculated by Newton's second law. With the assumption that the jet expands with the angle 2β, the velocity equation becomes[25]

$$\frac{dV}{dt} = \frac{d^2X}{dt^2} = \frac{\rho_f A_0 V_f}{m} \frac{A_m}{A_j} (V_f - V) , \tag{9}$$

where

X = distance traveled (ft),
t = time (sec),
ρ_f = density of the jet fluid (lb-sec^2/ft^4),
A_0 = throat area (ft^2),
V_f = jet velocity at the throat (ft/sec),
A_m = cross-sectional area of missile (ft^2),
A_j = jet area at X distance (ft^2)
= $\pi(r_0 + X \tan \beta)^2$ for circular jet,
r_0 = radius of throat (ft),
V = missile velocity (ft/sec).

The velocity of the jet is assumed to be constant and equal to V_f, independent of distance from the throat. The solution for Eq. (9), which gives the velocity of the missile as a function of distance traveled, is[25]

$$\left(1 - \frac{V}{V_f}\right) - \ln \left(1 - \frac{V}{V_f}\right) = K_1 - \frac{K_2}{r_0 + X \tan \beta} , \tag{10}$$

where

$$K_1 = \left(1 - \frac{V_0}{V_f}\right) - \ln\left(1 - \frac{V_0}{V_f}\right) + \frac{K_2}{r_0} ,$$

$$K_2 = \frac{\rho_f A_0 A_m}{m\pi \tan \beta} ,$$

V_0 = initial velocity of the missile at X = 0.

Equation (10) shows that the weight of the fluid striking the missile decreases as the jet expands, starting with a maximum at the point of rupture and decreasing as the missile moves farther and farther away. For constant conditions (variables in the equation that do not change with distance), Eq. (10) can be used to directly calculate the velocity of the missile for any distance X. In reality, however, the angle β and the density of the fluid change with distance, which means that Eq. (9) must be numerically integrated. Rather than to do this, a constant β and ρ can be assumed for a small interval in X, and Eq. (10) can be used to calculate the velocity change over the interval. Then the next assumed values for β and ρ in the next interval of X can be used to calculate the velocity change in that interval. This method can be repeated until the missile has traveled the complete distance. A major difficulty is that of properly selecting the changes of the angle β and the density of the fluid with distance, and much analytical and experimental work must be done before these changes can be assumed correctly.

A value for the distance over which the jet acts on the missile must be known or assumed. For a particular missile, a plot of distance versus velocity might be drawn and the plot used to help the designer estimate the distance over which the jet will act on the missile.

Another method* that can be used to calculate the velocity of a jet-propelled projectile is to compute the force on the projectile by multiplying the stagnation pressure of the fluid relative to the missile by the drag coefficient. The calculation of the stagnation pressure can be based on Bernoulli's equation, and for an incompressible fluid can be

---

*A similar method is used by General Electric; letter to J. W. Michel, ORNL, from J. C. Russ, Oct. 4, 1967.

estimated by

$$P_s = P + \frac{V^2\rho}{2} , \tag{11}$$

where

P_s = stagnation pressure (psf),

P = pressure of the fluid in the jet (psf),

V = relative velocity of the missile with respect to the fluid (ft/sec),

ρ = density of the fluid (lb-sec^2/ft^4).

For a compressible fluid, under adiabatic conditions, the stagnation pressure can be estimated by

$$P_s = P + \frac{V^2\rho}{2}\left[1 + \frac{1}{4}\left(\frac{V}{V_c}\right)^2 - \frac{K-2}{24}\left(\frac{V}{V_c}\right)^4 + \ldots\right] , \tag{12}$$

where V_c is the acoustic velocity (ft/sec). Equation (12) applies to all compressible fluids for ratios of V/V_c (mach number) less than unity. Since shock-wave and other phenomena occur for ratios greater than unity, the adiabatic assumption is not sufficiently accurate, and the formula no longer applies. However, the velocity of a jet will not exceed V_c, and Eq. (12) will be valid. Equations (11) and (12) are concervative because no losses are included. In either case, the stagnation pressure of the fluid relative to the missile can be approximated by the equation

$$P_s \approx \frac{V^2\rho}{2} . \tag{13}$$

The force acting on the missile can be calculated with the equation

$$F = C_D A P_s , \tag{14}$$

where F is the force acting on the missile (lb) and C_D is the drag coefficient. With the assumption of a constant force, the velocity of the missile is given by

$$V_m = \left(\frac{C_D A V^2 \rho X}{m}\right)^{1/2} , \tag{15}$$

where V_m is the relative velocity of the missile with respect to the fluid (ft/sec) and X is the distance traveled by the missile (ft). Since the density of the fluid can vary with distance and the drag coefficient varies as the relative velocity, Eq. (15) must be solved numerically or by a method similar to the one discussed for Eq. (9).

Many simplifying assumptions have been made to arrive at Eqs. (10) and (15), and it is assumed that the calculational methods outlined are conservative. As mentioned before, however, no experimental data have been found to compare with the results obtained from the equations. Therefore, it must be recommended that these equations be used with care.

4.1.3 Self-Propelled Missiles

Self-propelled missiles can be generated from pipes, valves, or other hollow structures that contain fluid at the time of rupture and are driven by expansion of the fluid they contain. In order to calculate the final velocity the missile may attain, detailed knowledge of the expansion process and the critical discharge is required. A simple calculation, in which the fluid in the missile is assumed to expand isentropically to the ambient pressure and in which the kinetic energy of the missile is assumed to equal the change in enthalpy of the fluid during this expansion, yields quite conservative results, since the energy of the fluid is considered to be transferred into kinetic energy of the missile at 100% efficiency.

4.1.4 Missiles from Rotating Machinery

In nuclear power reactors the turbines, coolant pumps, and other rotating machinery have the definite possibility of generating missiles under several accident conditions. Overspeed could lead to overstressing of the rotating parts and therefore to failure, or overspeed might cause the rotating equipment to reach the critical speed, which would result in resonance of the system and possible generation of missiles. Of course, brittle fracture and the presence of preexisting flaws would be more likely causes of failure. For example, even though turbines are designed against brittle fracture, it does not necessarily follow that no fracture can take place in a turbine; therefore the generation of missiles by turbines should be considered.

In analyzing missiles from rotating machinery, it must be decided what part might become a missile. Missiles that have been generated with a particular piece of equipment can be studied, but if there is not sufficient empirical information on the generation of the missile, the designer must study the equipment and assume the worst possible missile-generation accident for the piece of equipment.

After the volume and mass of a postulated projectile have been assumed, the next information needed is the maximum velocity that can be attained under any conditions, accident or otherwise. After this, the trajectory of the projectile can be calculated by using the standard dynamic formulas.[30] The energy lost by the perforation of the outer structural shells of the rotating equipment by the projectile must be calculated with empirical perforation formulas, which are discussed in Section 4.3. After the perforation of the outer structural shells, the continuing trajectory of the projectile can be calculated to determine whether it constitutes any danger to vital equipment in the reactor system.

4.1.5 Missiles That Can Be Generated by Stored Strain Energy

Reactor pressure vessel head bolts, other bolts, and tendons for prestressed-concrete should be thought of as potential missiles. Large amounts of strain energy are stored in these structural components and can lead to high velocities in case of failure.

If all the strain energy is converted to kinetic energy, which is a conservative assumption because no losses from friction or relaxation are considered, the velocity can be calculated with the formulas

$$V = \left(\frac{gE}{W}\right)^{1/2} \epsilon$$

and (16)

$$V = \left(\frac{g}{EW}\right)^{1/2} \sigma ,$$

where

V = velocity of projectile (ft/sec),

E = modulus of elasticity (psf),

W = specific weight of projectile (lb/ft^3),

ϵ = strain in the bolt or tendon before the accident (in./in.),

σ = stress in the bolt before the accident (psf).

4.1.6 Whipping Pipes

The whipping of a pipe can be described as a complex elastic-plastic multidegree-of-freedom motion; however, the following simple approximations to the equations of motion yield reasonably good results. First the motion can be described as a simple one-degree-of-freedom elastic vibration. The equation for this is

$$\frac{d^2y}{dt^2} + W_n^2 y = \frac{F(t)}{m} , \tag{17}$$

where

W_n = natural frequency of the system (first fundamental mode) = $\frac{k}{m}$,

y = displacement,

t = time,

k = spring constant of the system,

m = mass of the system,

$F(t)$ = forcing function (force caused by jet action).

Another possible equation for the motion of the pipe is that for simple one-degree-of-freedom rigid plastic vibration:

$$\frac{d^2y}{dt^2} + \frac{R_e}{m} = \frac{F(t)}{m} , \tag{18}$$

where R_e is resistance against movement. The resistance function R_e depends on where the plastic hinge develops, which in turn depends on the assumed boundary conditions of the pipe.

An elastic-plastic analysis can be made when a nonlinear spring constant is used in Eq. (17), and a technique similar to the Runge-Kutta method can be used for obtaining the solution for this case. Since the forcing function is caused by the jet action of the fluid issuing from the ruptured pipe, the velocity of the fluid jet must be known or assumed.

The problem of determining the fluid velocity was discussed above. Once a (conservative) value for this velocity has been obtained, it is considered constant. Hence, the force acting on the pipe is constant, and Eqs. (17) and (18) can be solved. The damage done by the whipping pipe is estimated through the use of the penetration formulas discussed in Section 4.3.

4.1.7 Missiles Generated from Ruptured Vessels

The rupture of a vessel operating at high pressure can lead to some very massive high-velocity missiles[31] and can produce shock waves that can, in turn, generate missiles and cause structural damage. Missiles generated by a vessel rupture can be either random fragments of unknown mass and cross-sectional area or certain whole parts of the vessel. In the case of a cylindrical vessel, whole parts might be such things as the top head, the bottom head, a longitudinal segment from the side wall, etc.

Accurate calculation of possible random fragment velocities and masses is very difficult. Moore[17] proposed the following formula for the velocity of such projectiles:

$$V = 1.092\left(E_f R\right)^{1/2} , \tag{19}$$

where for cylinders

$$R = \frac{\frac{C}{M}}{1 + \frac{C}{2M}} ,$$

and for spheres

$$R = \frac{\frac{C}{M}}{1 + \frac{3C}{5M}} ,$$

and

E_f = available energy released by isotropic expansion of pressurized fluid to one atmosphere for one mass unit (ft^2-lb/lb-sec^2),

C = mass of the fluid (lb-sec^2/ft),

M = mass of vessel (lb-sec^2/ft),

V = velocity of projectile (ft/sec).

Note that the mass of the entire vessel is used. This equation is an extrapolation from the Gurney equation,[32,33] which has been verified by the detonation of high explosives in cylinders with wide ranges of diameters and thicknesses.

The use of Gurney's formula in the form given by Eq. (19) for the much slower and lower-pressure explosions characteristic of pressure vessels is, of course, without sound theoretical foundation. Moore compared velocities predicted by Eq. (19) with velocities calculated from distances of travel of fragments of exploded pressure vessels reported in the literature. The results indicated that the modified Gurney formula was conservative. However, the data that Moore used in his correlation came from fire tube boilers and may not fit all cases. For example, if the vessel rupture produced a few large missiles instead of many small ones, the method might not give very good results.

The method described above was used to calculate the velocity of a 2-ton missile generated in an accident in England.[31] In that case liquid in the vessel was subcooled, and only a few large missiles were generated. Moore's method in this case did not give very good results in that the calculated velocities gave distances of travel much less than those observed. Since Gurney's equation was derived from weapons data to predict the velocity of small fragments from bomb cases that were designed to rupture into many small projectiles, it is believed that, if the pressure vessel had ruptured into many small fragments, Moore's equation would have given fairly good results.

The equivalent TNT method can be used to calculate the velocity of the missile of the English accident with fair accuracy. In this case, the stored energy is converted into a TNT equivalent explosion, and the momentum of the missile is calculated from the corresponding impulse. From the momentum, the velocity of the missile is easily calculated. Another method that gives conservative results is based on the assumption that all the stored energy is converted into kinetic energy of the largest

missile. The velocity of the missile is then calculated from the kinetic energy.

In the case where a pressure vessel ruptures into two parts that become missiles, the energy must be partioned among the parts according to masses of the parts, as shown in the formula[34]

$$\frac{E_1}{E_2} = \frac{M_2}{M_1} , \tag{20}$$

where

E_1 = energy of part 1,
E_2 = energy of part 2,
M_1 = mass of part 1,
M_2 = mass of part 2.

Thus, the energy imparted to each fragment is inversely proportional to its mass. The energy of each part is, in turn, converted into kinetic energy of the missile.

In the calculations described, all the energy is assumed to be transferred to the projectiles, with losses ignored. Fluid losses would depend upon the type of fluid and the configuration of the parting masses. These losses could range from very large in some cases to very small in others. Hence, the missile velocity calculations, in any case, are conservative.

4.2 In-Path (Air) Resistance to Missiles

In the above discussion the resistance of the surrounding atmosphere to the movement of the projectile was not considered. Since the air resistance would lower the final velocity of the missile, conservative velocities are calculated when this resistance is neglected. In addition, the velocity computations are simplified. However, the drag force can be calculated by the formula[35]

$$F = C_D \rho A \frac{V^2}{2} , \tag{21}$$

where A is some characteristic area (ft^2), usually the area projected on a plane perpendicular to the relative motion of the fluid, and V is the relative velocity of the fluid with respect to the body (ft/sec).

If the drag force is included in the missile equations, iterative-process computer solutions will probably be required, and some of the equations will be nonlinear. A further complicating factor is that drag coefficients have been experimentally derived for only a few common shapes and may not be applicable to most of the assumed missile shapes. Therefore it is recommended that the drag forces be included in the calculations only if less conservatism is required.

4.3 Impact and Penetration

Once the velocity is known or assumed, estimates can be made, based on existing formulas, of the damage the accident-produced missile can do. Most of the formulas that are used today to calculate the penetration and perforation of structures or targets have been empirically derived. There have been attempts to derive theoretical formulas for penetration, but these have not been too successful.[36]

The study of missile penetration, which is called terminal ballistics by the military, is one of the oldest technologies, with experimentation dating back to the early 1800's.[37] In spite of this there are no handbooks on terminal ballistics commercially available.* Even for the well-defined physical situation of a projectile of known material properties, size, shape, and velocity striking a plate with known properties, the data are extremely scattered and often contradictory.

Combined projectile and target behavior can be classified in one of three regimes: low-speed impact regime, transition impact regime, and hypervelocity impact regime. The projectile velocity corresponding to the breakup threshold on impact determines the lower velocity of the transition region.[38] Since projectile deformation depends on both target strength and projectile strength, it is understandable that the extent of

*There are classified handbooks that were compiled by the military.

the transition region depends on the physical properties of both the projectile and target.

Most of the recent experimental work[38] has been done for the transition regime. In the hypervelocity range, quite reproducible experimental results can be expected, since the materials behave as fluids under the very high pressures and temperatures that exist.[38]

Most of the postulated missile-target combinations for light-water reactors fall in the low-speed impact regime, except for cases where wooden missiles are generated. Since the structural components for light-water reactors are concrete or steel, only penetration formulas for these materials are discussed here. All the present formulas are empirical and cover only limited ranges. Characteristics of impact not included in these formulas, such as shape factors, are not discussed because the available data are not adequate to make useful quantitative correlations.

4.3.1 Concrete Penetration and Perforation Formulas

The unclassified equations for the penetration of concrete are listed below, together with the limits of applicability when they are available. The first equation is the modified Petry formula[39-41] and is the most commonly used:

$$D = KA_p \log_{10}\left(1 + \frac{V^2}{215,000}\right), \tag{22}$$

where

D = depth of penetration into an infinite thickness (ft),

A_p = sectional pressure $\left(\frac{\text{missile weight}}{\text{maximum cross-sectional area}}\right)$ (psf),

V = terminal or striking velocity (ft/sec),

K = experimentally obtained material coefficient for penetration.*

Equation 22 calculates the penetration into an infinite slab.

---

*These coefficients can be obtained from Refs. 39, 40, and 41.

The formula derived[40] to calculate penetration into a reinforced-concrete slab of finite thickness is

$$D' = D\left\{1 + e^{-4[(T/D)-2]}\right\} , \tag{23}$$

where

D' = actual depth of penetration (ft),

D = depth of penetration for an infinite slab (ft),

T = thickness of the slab (ft).

When D is calculated from Eq. (22), the lower limit of thickness of reinforced concrete for which this equation holds is[40]

$$D' = 2D . \tag{24}$$

Equation (23) is also referred to as the Petry, or the modified Petry, formula. The Ballistic Research Laboratories formula for reinforced concrete of finite thickness is[41,42]

$$P = 7.8 \frac{W}{D^2} D^{1/5} \left(\frac{V}{1000}\right)^{4/3} , \tag{25}$$

where

D = diameter of missile (in.),

P = thickness of concrete slab that will be perforated (in.),

W = weight of missile (fragment) (lb),

V = striking velocity (ft/sec).

The Army Corps of Engineers' formula for reinforced concrete of infinite thickness is[43]

$$X = \frac{222}{(S_u)^{1/2}} \frac{W}{A} D^{0.215} \left(\frac{V}{1000}\right)^{1.5} + 0.5D , \tag{26}$$

where

X = penetration in infinite concrete (in.),

W = weight of missile (lb),

A = area of the missile (in.^{2}),

D = diameter of the missile (in.),

V = striking velocity of missile (ft/sec),

S_u = compressive strength of concrete (psi).

Limit case companions to Eq. (26) are also given.[43] To calculate the thickness that can just be perforated, the formula given is

$$e = 1.35D + 1.24X \ , \tag{27}$$

where e is the thickness in inches. Also, the thickness for which a projectile will just scab the back side can be calculated from the formula

$$S = 2.2D + 1.35X \ , \tag{28}$$

where S is thickness just to scab (in.). The limits on Eq. (26) are

$1 \text{ in.} \leq D \leq 16 \text{ in.}$,

$0.4 \text{ lb} \leq W \leq 2500 \text{ lb}$,

$1500 \text{ psi} \leq S_u \leq 8000 \text{ psi}$,

$500 \text{ ft/sec} \leq V \leq 3000 \text{ ft/sec}$.

These indicate that Eq. (26) is very limited in its application. Reference 43 contains nomographs a designer may use to calculate the thickness required to prevent perforation.

The military's most documented formula for an infinite slab was only recently declassified. It is[44]

$$X = \frac{282}{(S_u)^{1/2}} \frac{W}{D^2} D^{0.215} \left(\frac{V}{1000}\right)^{1.5} + 0.5D \ , \tag{29}$$

where the symbols are those described above. Equation 29 is the same as Eq. (26), because $A = \pi D^2/4$; however, in this case,[44]

$$e = 1.23D + 1.07X \tag{30}$$

and

$$S = 2.28D + 1.13X \ . \tag{31}$$

The limits on Eq. (29) are the same as for Eq. (26).

Equations (23), (25), (27), and (30) for calculating the thickness just to perforate are plotted in Fig. 4 for a 6-in.-diam cylindrical

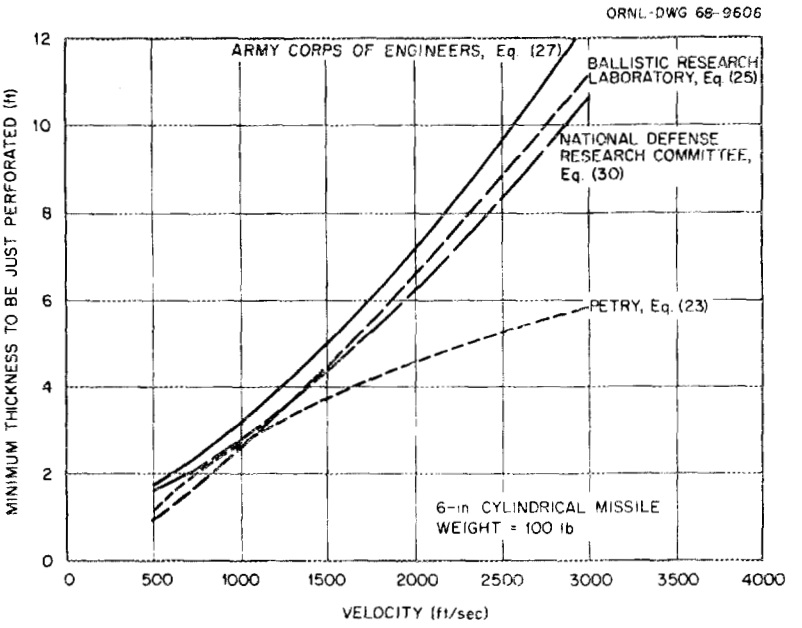

Fig. 4. Comparison of Results Obtained with Formulas for Calculating Perforation of Reinforced Concrete by a Small Missile.

missile weighing 100 lb and in Fig. 5 for a 16-in.-diam missile weighing 2500 lb. As may be seen in the figures, the Corps of Engineers' formula is more conservative than any of the others for the small missile, while the Ballistics Research Laboratories' formula is the most conservative for the large missile. The Petry formula, Eq. (23), is the least conservative of all the equations for both missiles. This may be due to the fact that the formula was derived earlier (1939) than the others.[39] It is recommended that this formula not be used for penetration calculations.

There are no known penetration or perforation formulas for prestressed or posttensioned concrete.

4.3.2 Steel Penetration and Perforation Formulas

The unclassified equations for the penetration or perforation of steel are listed below with the known limits for each. The first formula is the Stanford equation,[45] which is the most commonly used steel penetration formula:

$$\frac{E}{D} = \frac{S}{46,500}\left(16,000\ T^2 + 1,500\ \frac{W}{W_S}\ T\right) , \qquad (32)$$

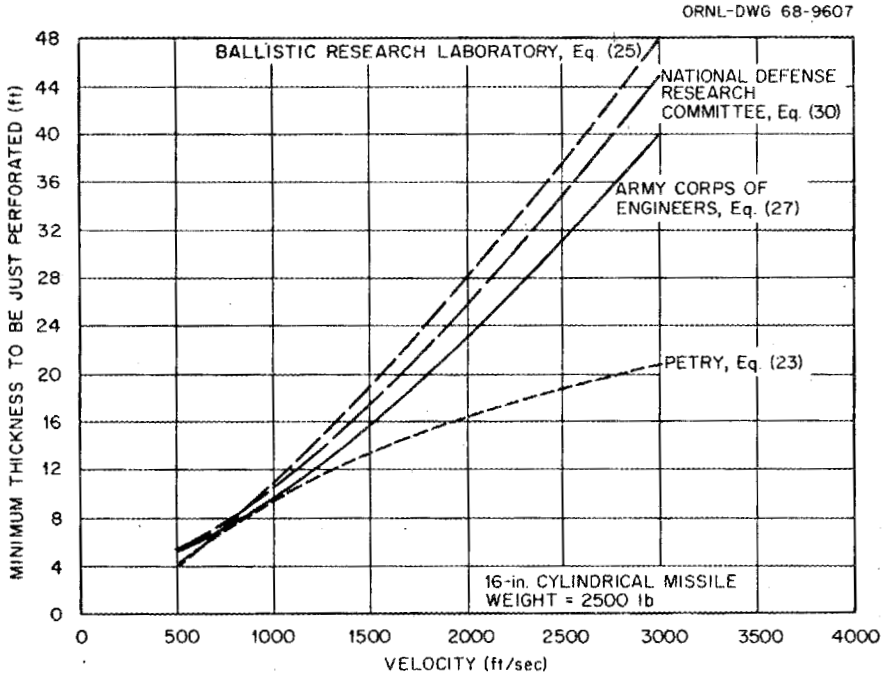

Fig. 5. Comparison of Results Obtained with Formulas for Calculating Perforation of Reinforced Concrete by a Large Missile.

where

E = critical kinetic energy required for perforation (ft-lb),

D = missile diameter (in.),

S = ultimate tensile strength of the target (steel plate) (psi),

T = target plate thickness (in.),

W = length of a square side between rigid supports (in.),

W_S = length of a standard width (4 in.).

The ultimate tensile strength is directly reduced by the amount of bilateral tension stress already in the target. The equation is only good within the following ranges:

$0.1 < T/D < 0.8$,

$0.002 < T/L < 0.05$,

$10 < L/D < 50$,

$5 < W/D < 8$,

$8 < W/T < 100$,

$70 < V_C < 400$,

where L is missile length (in.) and the missile is assumed to be cylindrical; V_C is velocity (ft/sec).

The Ballistic Research Laboratories' formula for steel is[41]

$$T^{3/2} = \frac{0.5MV^2}{17{,}400K^2D^{3/2}} , \tag{33}$$

where

T = steel wall thickness (in.),

M = mass of the missile (wt/g) (lb-sec^2/ft),

V = velocity of the missile (ft/sec),

K = constant depending on the grade of the steel and is usually $\cong 1$,

D = diameter of the missile (in.).

Recht and Ipson[46] derived a completely theoretical equation that appears to be accurate within the limits tested. (This equation is not used by reactor designers.) The equation is

$$V_r = \frac{(V^2 - V_{xn}^2)^{1/2}}{1 + \Omega \left(\frac{D}{d}\right)^2 \frac{T}{L}} , \tag{34}$$

where

V_r = residual velocity (ft/sec), that is, velocity of the missile after perforation,

V = initial striking velocity (ft/sec),

V_{xn} = minimum perforation velocity (ft/sec),

Ω = ratio of steel plate (target) to missile material density (steel missile),

D = plug diameter or hole diameter (in.) (since D is usually not known, a value of 1 can be used for D/d),

d = missile diameter (in.) for a cylindrical missile,

T = steel plate thickness (in.),

L = missile length (in.).

The minimum perforation velocity, V_{xn}, is given by

$$V_{xn} = \frac{4\Omega T^2 \psi \eta}{Ld} \left\{ 1 + \left[\frac{L + \Omega T}{\Omega T} \left(1 + \frac{d}{4\rho_S T \eta \psi^2} \right) \right]^{1/2} \right\} , \tag{35}$$

where

$$\psi = \frac{\rho_p C_p + \rho_s C_s}{\rho_p C_p \rho_s C_s},$$

ρ_p = missile density (steel),

ρ_s = plate material density,

C_p = longitudinal acoustic-wave velocity in missile material,

C_s = longitudinal acoustic-wave velocity in plate material,

η = function related to dynamic shear strength of the plate material, assumed to be constant (1.76×10^6 psi).

The limits of the equation are $T/L < 1/2$ and $T/D < 1/2$, and reasonably correct results are obtained when the missile deformation is not severe.

As can be seen, all the penetration and perforation formulas for steel were derived for small-diameter long-length cylindrical projectiles and very thin targets. There does not seem to be any data for larger missiles or thicker targets.

All these penetration and perforation formulas for concrete and steel are based on normal impact. When the missile strikes the target at an angle, the penetration depth is naturally reduced. In case of oblique impact, the designer must exercise care to insure that he is using the most conservative method.

5. POSSIBILITY OF RUPTURE OF PRIMARY SYSTEM PRESSURE VESSELS AND EFFECTS OF RESULTING SHOCK WAVES

The reactor vessel is one of the major components in a nuclear facility in that it performs the very critical functions of housing the radioactive core and provides a pressure-tight membrane to retain the coolant. Pressure vessel technology per se is not new, and vessels have been designed and fabricated that have good performance records of many years duration. This was not always the case. In the early 1900's, as a result of catastrophic failures of boilers, the ASME undertook the task of providing a minimum set of standards for the design, materials, and construction of a class of these devices. The first Boiler Code was published in 1914. Through the intervening years, additional codes have been written and published, with today's accepted standard for nuclear reactor vessels being Section III of the ASME Code. The primary intent of these codes is to establish levels of safety, and when applied within the bounds of good engineering judgment and the limitations set forth, a new product of adequate quality should be produced.

It is important to emphasize that it is not now possible to arrive at an absolute position on many aspects of vessel design and construction, and furthermore, in order to evaluate the incredibility of failure of a pressure vessel when incorporated into a system such as a power reactor complex, limits must be specified for the environmental conditions. The nuclear systems designer specifies a set of service conditions, including abnormal events, that form the basis for design input. The vessel designer provides analyses that demonstrate the adequacy of the structure for these specified service conditions, and fabrication is performed with considerable quality control so that there is no apparent reason for poor performance within the design limits specified. A system of checks and balances is invoked throughout the course of a project that establishes multiple review of the design, material, fabrication, and quality control. Checks are made on the completed vessel that insure its capability to withstand overpressure loading, and measurements are made to check deflections and displacements of the loaded vessel to back check the design predictions.

The net result is that all evidence[47] indicates that the industry is producing high-quality vessels in terms of the standards set forth and required by the Code, since these requirements are generally exceeded in all phases of the manufacturing process. This practice has evolved because of the recognized importance of vessel integrity to safety and plant availability.

5.1 Vessel Rupture

Failures of the primary system pressure vessels, such as the reactor, steam generator, and pressurizer vessels, are not, as most manufacturers state, incredible, but rather of low probability, even though this cannot be stated with any mathematical precision. The manufacturers are not concerned with rupture of such vessels because they are convinced that these vessels can be designed to prevent brittle fracture under hydrostatic loading. Since only simple, brief discussions of this type of accident are given for some reactor plants, the public documents, such as the preliminary safety analysis reports, leave the impression that this kind of accident is not considered. Further the designs of containment structures do not provide for the consequences of rupture of high-pressure components.

Considerable confidence has been developed in techniques for designing to prevent crack initiation. However, design techniques based on insuring crack arrest are less certain, especially in the case of pneumatic loading. An up-to-date discussion of the state of the art in the United States and Great Britain is given in Ref. 47.

The large amount of damage that can be done by brittle fracture of a vessel under hydrostatic loading was demonstrated on December 22, 1965, when a large thick-walled nonnuclear pressure vessel failed during proof testing in England.[31] A general view of the ruptured vessel is shown in Fig. 6. The vessel was a long cylinder with end closures, one welded and the other bolted, and was intended for use in an ammonia plant. The cylindrical part of the vessel was 52 ft 8 1/2 in. long, 5 ft 7 in. in diameter, and had a wall thickness of 5 7/8 in. Failure occurred by brittle fracture at a proof test temperature of 50°F and an internal pressure of 5000 psi. Several heavy fragments separated completely from

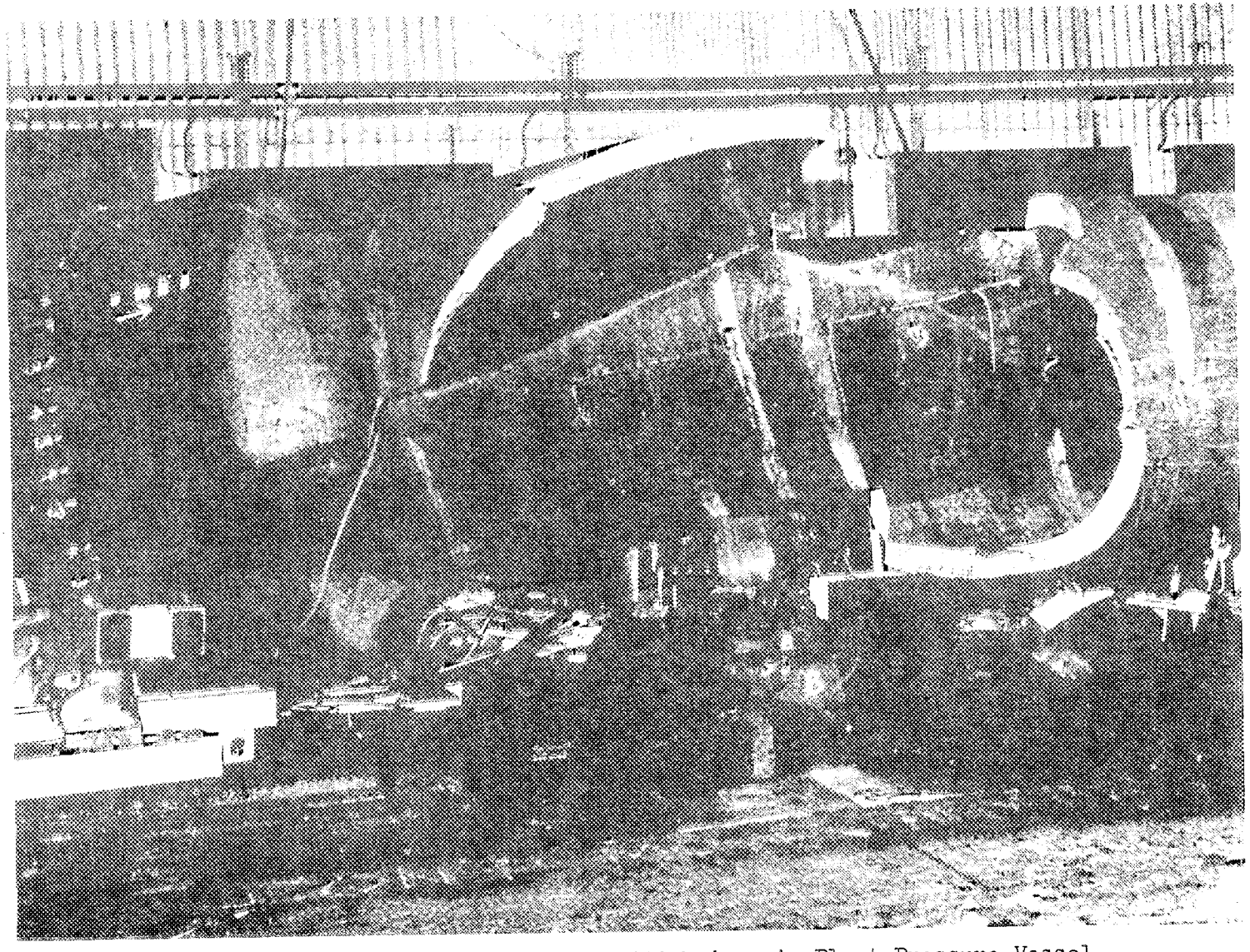

Fig. 6. General View of the British Ammonia Plant Pressure Vessel That Failed by Brittle Fracture at a 5000-psi Internal Pressure During Hydraulic Proof Testing. (From Ref. 31)

the vessel, including one that weighed two tons. This large piece passed through the workshop wall and traveled a total distance of 152 ft (see Fig. 7). A detailed study of this case is given in Ref. 47.

In the case of a vessel filled and pressurized with water at high temperature, or gas,[48] the consequences of failure would be much more severe. British studies[49-51] have indicated that under conditions where a part of the volume (20%) is gas filled, the failure behavior would be the same as if the vessel were entirely gas filled. Also, a blowdown study performed in Japan[52] on a water-filled vessel with temperature and pressure of 535°F and 1000 psig confirmed that the behavior of the system during blowdown was similar to that of a steam-pressurized vessel. This means that the destructive potential of high-pressure water systems is not greatly different from that of pneumatically loaded systems.

Analytical and experimental investigations, such as the Heavy Section Steel Technology Program* (HSST) at Oak Ridge National Laboratory for developing information on fracture mechanics, the AEC-PVRC Program for studying nozzles and reinforced openings in pressure vessels,* the AEC-PCRV Program for investigating piping, pumps, and valves for nuclear service,* and the pipe rupture studies at Battelle Memorial Institute and General Electric Company, are expected to make the design of pressure systems to prevent fracture more accurate and reliable.

5.2 Shock-Wave Effects

The only shock wave (pressure wave) considered in the preliminary safety and analysis reports is the pressure pulse in the loss-of-coolant accident. There are no discussions of the effects of shock waves that would be generated by the rupture of a main vessel, and it is assumed that containment structures are not designed for this type of shock loading. Shock waves are, however, of interest in this report because not only can they generate missiles but the shock wave itself can be considered a missile.

---

*See progress reports from ORNL Nuclear Safety Program for reports of current developments on these projects. The most recent is USAEC Report ORNL-TM-2230, May 30, 1968.

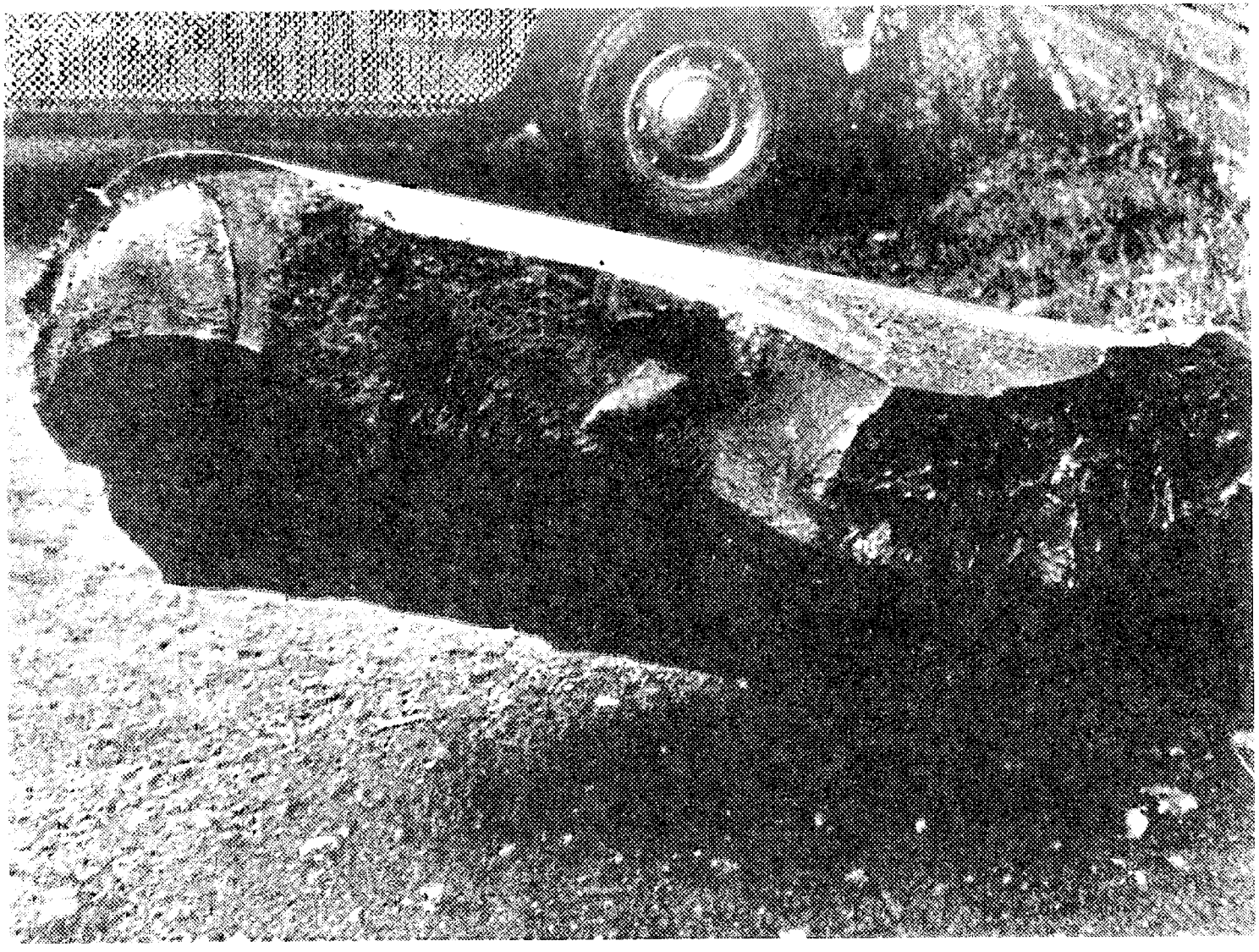

Fig. 7. Two-Ton Segment of Vessel Shown in Fig. 6 That Was Thrown 152 ft on Failure. (From Ref. 31)

5.2.1 Generation of Shock Wave

An explosion* implies a process by which a pressure wave of finite amplitude is generated in a fluid by a rapid release of energy. Widely different types of energy sources can be classed as explosives under this definition. The stored energy in a compressed gas or vapor, either hot or cold, can be such a source, as well as the failure of a high-pressure gas storage vessel or steam boiler and the muzzle blast from a gun. Electrical discharges, rapid vaporization of fine wire, and metal-water reactions can also produce strong pressure waves in a fluid. The more usual energy sources for explosions are, however, either chemical or nuclear materials that are capable of producing violent reactions.

The sudden expansion of a gas, whether from a bursting pressure vessel or from heating by a lightning bolt, or some other rapid energy input, results in a pressure disturbance that moves away from the source at a velocity directly related to the peak pressure. The impingement of such a disturbance on a wall or a potential missile results in pressures that may exceed the initiating pressure, particularly if the disturbance has developed a steep front or has become a shock wave in passing through the air.

The tendency of a strong pressure wave to become a shock wave is explained simply by the fact that the speed of sound in a gas, such as air, increases as the pressure is increased adiabatically (due to the increased temperature). Thus the high-pressure peak of a sound wave always tends to catch up with the preceding low-pressure valley, much as the peak of an ocean wave catches up with the valley as the wave enters the shallow water near the shore.

Neglecting attenuation, the number of wave lengths, N, that a sinusoidal wave will travel before it forms** a shock wave is given by

$$N = \frac{P_0}{\Delta P(2K - 1)} ,$$

*Explosion here is assumed to mean a detonation type of energy release.

**Colloquially to "shock up."

where P_0 is the ambient pressure, ΔP is the wave amplitude, and $K = C_p/C_v$, that is, the ratio of the specific heat at constant pressure to the specific heat at constant volume.

Friction in the medium, on the other hand, attenuates the higher harmonic components of a complex wave more rapidly than the fundamental component and tends to reduce the wave to a simple single-mode harmonic form. Thus, ordinary low-amplitude acoustical waves may be treated as harmonic waves.

In a large pressure disturbance, the attenuation of higher components is insufficient to prevent the pressure peak from catching up with the edge of the wave front, and the result is a step increase in pressure, or a shock wave. Shock waves move at velocities that correspond roughly to their peak pressure and, hence, at greater than the sonic speed of low-amplitude acoustic waves. The transmission of shock waves is inherently a nonlinear process, whereas acoustic wave propagation can be adequately described by linear theories.[53]

5.2.2 Classical Shock Waves

The analysis of classical shock or blast waves in air is based on the assumption that the explosion that creates the waves occurs in a still homogeneous atmosphere. A pressure wave is generated by the sudden release of energy that forces the surrounding atmosphere away from the detonation point, with the peak of the pressure wave traveling faster than the rest of the wave, as shown schematically in Fig. 8, curves a and b. At some later time, curve c, the peak pressure has advanced to the front of the pressure wave and created an abrupt change in the atmospheric pressure as the wave continues to propagate. On further expansion, inertial effects produce overexpansion and a consequent rarefaction at the explosion center. The overall pressure configuration then consists of an abrupt pressure discontinuity followed by positive and negative pressure phases (curve d). This latter characteristic is maintained in further propagation of the blast wave.

The positive pressure phase is, in general, far more intense than the negative phase. Negative pressures are limited in magnitude to 1 atm.

ORNL-DWG 68-9608

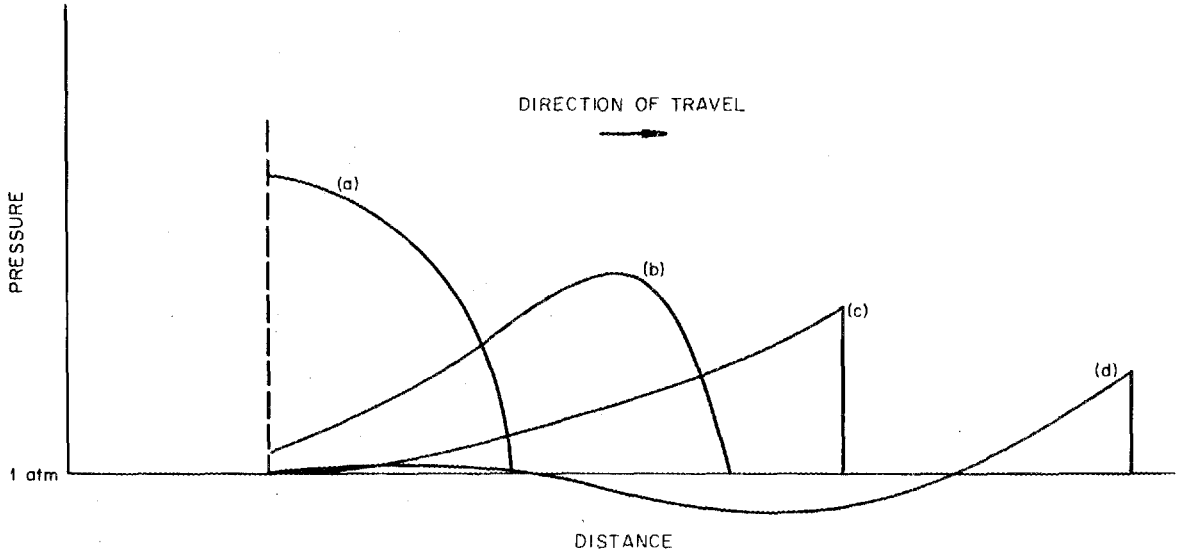

Fig. 8. Development of Explosive Shock. (a) Assumed initial pressure pulse and successive configurations. (b) and (c) Waves formed by differing speeds of shock-wave parts. (d) Typical pressure-distance curve for some time after a point-source explosion.

It may be noted that inertial effects responsible for the negative phase could give rise to additional pressure reversals and to pressure oscillations in the atmosphere. Such reversals are important in underwater explosions but are not ordinarily observed or reported for explosions in air, presumably because of the relatively low density and because dissipative processes rapidly attenuate them.

The pressure-time history of a typical blast wave as observed at a location removed from the center of the explosion is shown in Fig. 9. At an arrival time of t_x seconds after the explosion, the pressure at this removed location suddenly jumps to a peak value of overpressure. A properly oriented streamlined object at this location is then subjected to an instantaneous crushing force equal to the product of this overpressure and the surface area of the volume enveloped during passage of the blast wave. This is not a stable condition, and the overpressure immediately begins to decay following a pressure-time relation, such as that illustrated and described as quasi-exponential in character.

Descriptions of this type of blast wave require specification of three independent characteristics. One of these is the initial shock

ORNL-DWG 68-9609

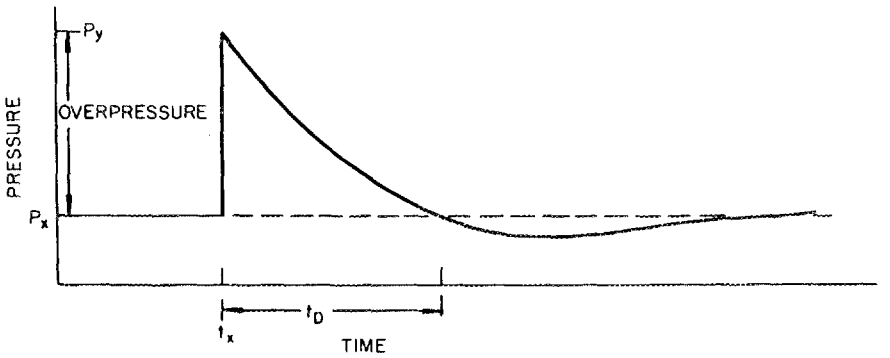

Fig. 9. Typical Pressure-Time Curve for an Explosive Blast Wave.

intensity, which is specified, perhaps, by the peak overpressure but also by any related intensity item, such as particle velocity. The second is the duration of the positive phase of the blast wave (t_D). The third is the impulse product, the area under the positive phase of the curve, for the pressure forces in the blast. An additional related parameter is the time (t_x) required for the shock front to travel from the center of the explosion to the location of concern.[54]

5.2.3 Reflection of Shock Waves

A normally reflected shock front shows characteristics different from those of the incident shock wave, for it is moving through a different medium; in reflecting, it returns through the atmosphere it has compressed. The reflected overpressure is always considerably greater than the incident overpressure. For weak shocks, it is twice as great; for strong shocks in a perfect diatomic gas it can be eight times as great; in a real diatomic gas this multiplying factor can be as high as 16 for incident shocks of 1000 atmospheres.[55] The reflected overpressure provides the force for the instantaneous dynamic load imposed on a surface of a structure whose surface is normal to the advancing shock front.

In a closed structure, a shock wave and its reflections will cause repeated transient loadings of the walls until dissipative mechanisms convert the shock-wave energy into static pressure and temperature increases. The complex reflection and refraction to be expected in an

equipment-filled containment vessel may also result in discrete regions where waves reinforce each other. However, the initial shock loading to the walls is expected to be of greater magnitude than any of the reflected loadings due to energy-dissipation processes.

5.2.4 Importance of Shock Waves in Reactor Accidents

Shock waves generated by the release of nuclear, chemical, and stored energy within a reactor system can produce two undesirable effects.[56] The shock wave itself can do structural damage, and missiles created by the shock wave may penetrate the containment structure. At present there is little experimental information on the energy released by a nuclear excursion that can be used reliably to calculate the related blast effects. Arguments are raised against using calculations based upon TNT data on the ground that the method is overly conservative. However, an analysis by Proctor[57] of the SL-1 accident showed that the TNT method predicted the damage done by this excursion accident very well. The SL-1 accident and the Borax-I and SPERT-I reactor tests indicate the manner in which energy can be released and the damage that is possible from a nuclear excursion accident.[58] The SL-1 excursion caused the entire reactor vessel to behave as a missile; it moved upward 9 ft before falling back into its cell. The physical phenomena associated with such accidents are not well understood, and there seem to be no reliable techniques for predicting the energy release and the related blast effects prior to the accident, as pointed out by Proctor.[57]

Chemical energy release in light-water-cooled reactors usually means metal-water reaction. Explosions have been caused by metal-water reaction in other industries that resulted in considerable structural damage.[59,60] Detonations of gaseous combustibles, organic liquids, and hydrogen, which were studied on a limited scale,[61,62] have been found to ignite fires and to cause much structural damage over large areas.[63] For TNT and pentolite, much experimental information has been gathered, and the data have been put into a form[10,64,65] that is very useful for designers faced with the problem of chemical energy release.

The release of stored energy from a ruptured vessel has been shown experimentally to generate shock waves.[66,67] The fact that steam will act

approximately the same as air or any other gas has been demonstrated by accidental explosions of steam boilers.[68] The rupture of hydrostatically loaded vessels can release large quantities of energy in the form of very high energy missiles.[20,31] Few tests or experiments have been done on shock waves developed from the rupture of completely hydrostatically loaded vessels, although shock-tube studies show that heated pressurized water will generate a finite compression pulse in the adjacent air.[69]

These findings indicate that the rupture of high-pressure storage vessels and other high-pressure systems could lead to creation of shock waves. Fragments generated by the brittle fracture of pressure vessels could be propelled by the shock wave of the expanding liquid.

5.2.5 Calculations of Maximum Deflections and Stresses

The impulse of the shock wave delivered to a structure will cause the structure to respond dynamically and produce at least a transient vibratory response. Since the experimental reflected-shock-wave data are probably accurate only to within about 10 to 15%,[43] most analysts represent complex structures as simple lumped-parameter systems with one degree of freedom, as shown in Fig. 10(a). A recent comparison[70,71] between the analytical method and experimental data has shown that this method is valid for engineering purposes. The dynamic equation for such a model is

$$\frac{d^2y}{dt^2} + W_n^2 y = \frac{F(t)}{m} , \tag{36}$$

where

y = displacement,

t = time,

W_n = natural frequency of the system (first fundamental mode),

$W_n^2 = \frac{k}{m}$,

k = spring constant of the system,

m = mass of the system,

$F(t)$ = forcing function.

ORNL-DWG 68-9610

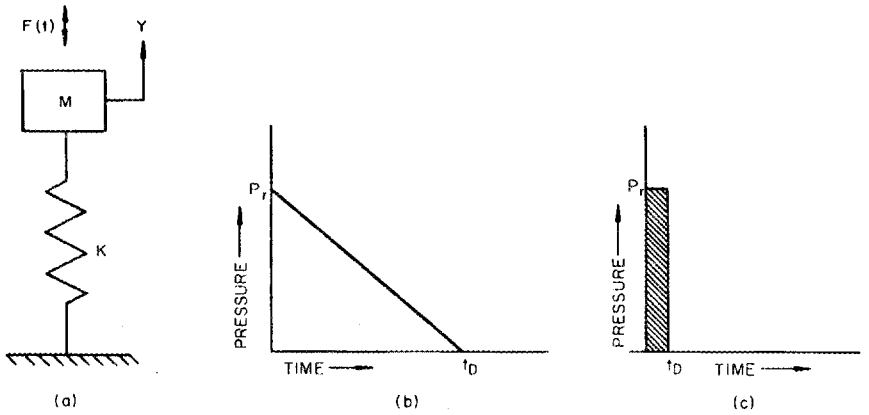

Fig. 10. (a) Lumped-Parameter Single-Degree-of-Freedom System; (b) Assumed Triangular Pulse; (c) Initial Impulse.

If the form of the forcing function or reflected pressure-time history of the shock wave is known, the deflection of the structure due to the action of the shock wave can be calculated from the natural frequency and mass of the structure. The reflected pressure-time history is usually assumed to be a triangular pulse, as shown in Fig. 10(b). A method of solution for Eq. (36) corresponding to this case was derived in Ref. 71.

The duration of the pressure pulse is sometimes very much shorter than the natural period of the structure. If it is one-thirtieth or less of the natural period of the structure, the so-called "initial impulse" method,[72] which is simple and accurate, can be used to solve Eq. (36). In this method, the maximum reflected pressure is taken to approach infinity while the duration approaches zero, but the impulse, defined as the integral of the pressure P_r over the time t_0 to t_D, is taken as a constant. If the period of the pressure wave is much smaller than the period of the structure, this is the way the structure sees the pressure pulse. A graphical representation of the initial impulse is shown in Fig. 10(c). The solution to Eq. (36) by the impulse method is[71]

$$y = \frac{AI_0}{mW_n} \sin W_n t \ , \tag{37}$$

where A is the area of the struck surface of the structure and I_0 is the initial impulse per unit area (area under the pressure-time curve).

Equation (37) gives the maximum deflection of the structural component, and from this the maximum stress caused by the shock wave can be derived. With the value of the maximum stress known the designer can determine whether the structure will survive the blast.

5.2.6 Effects of Shock Waves on Concrete Structures

Concrete walls, from which most of the present containment structures are made, can have four possible modes of failure: (1) spalling of the rear surface of the wall, which forms secondary missiles, (2) local failure due to excessive shear stresses, (3) flexural failure, and (4) total destruction of the wall, with the production of large numbers of secondary missiles. All four modes of failure are possible when a detonation is close to the wall. However, if the detonation is far from the wall, a plane shock wave is formed, and only the latter two modes of failure can occur.[73] The occurrence of any one of the failure modes will depend on the configuration and strength of the wall, the energy release of the shock wave, and the location of the energy release relative to the wall.

The stresses induced by a shock wave are transmitted through concrete at velocities of thousands of feet per second in the form of a stress wave. Two predominant types of waves are encountered. The primary or longitudinal wave travels parallel to the direction of shock-wave propagation at what is called the dilatational velocity. The particle motion in the compression wave also travels in this direction. The secondary or distortional wave is formed by the shear distortions and moves in the same direction as the primary wave, but its particle motion is perpendicular to the direction of the shock-wave propagation. The shearing stresses are of lower intensity than the compression stresses and move with a velocity less than that of the longitudinal wave. In simple practical analyses, only the effects of the compressional stresses are considered.

A material is said to spall when one or more segments are displaced from the main body. As the longitudinal wave propagates through the wall

and impinges upon the rear free surface, reflection occurs in the form of a tension wave that is identical in shape and magnitude to the compression wave. At some point, the tension strains exceed the compressive strains, and the preexisting microcracks in the concrete grow until the tensile capacity is exceeded. The spalled sections trap a portion of the stress wave and eject from the main body with a higher velocity.

Simple formulas for calculating the initial velocity and thickness of a spall are[73]

$$T = \frac{C_s t_D f'_t}{2P_r} = \frac{C_s I_r f'_t}{P_r^2} , \tag{38}$$

$$V = \frac{144}{mC_s} (2P_r - f'_t) , \tag{39}$$

and

$$C_s = \left[\frac{E(1 - \nu)}{m(1 + \nu)(1 - 2\nu)}\right]^{1/2} , \tag{40}$$

where

T = thickness of spall in ft,
C_s = dilatational velocity in ft/sec,
t_D = pressure pulse duration in msec,
f'_t = tensile strength of concrete in psi,
P_r = reflected pressure at the wall in psi,
I_r = reflected impulse of the shock wave acting on the wall in lb-msec/in.^{2},
V = velocity of spall in ft/sec,
m = mass per unit volume in lb-sec^2/ft^4,
E = Young's modulus of concrete in psi,
ν = Poisson's ratio of concrete.

To find the total weight of a spalled body, it is assumed[73] that the spalled area on the free rear wall corresponds to the base of a cone that has an included angle of 80 deg and an altitude equal to the normal

distance between the rear of the wall and the center of the source of the shock wave. The thickness is calculated from Eq. (38). (For more complicated spalling, such as multiple spalling, see Ref. 73.)

5.2.7 Effects of Shock Waves on Objects That Can Become Missiles

A shock wave striking a free object, such as a piece of pipe or a valve, can produce a missile with the velocity[25]

$$V = \frac{P_r tA}{m} = \frac{I_r A}{m} , \tag{41}$$

where A is the cross-sectional area of the missile normal to the direction of the shock wave and m is the mass of the missile.

Additional information on shock waves of more complex nature, such as spherical or two-dimensional shocks, may be found in Refs. 55, 74, 75, and 76.

5.2.8 Shock-Wave-Resistant Design

5.2.8.1 Determining the Energy of the Shock Wave. The design of a structure for protection from a blast or shock wave is principally a dynamics problem in which the blast wave acts as the forcing function. In light-water-cooled reactors the source of the shock wave could be the rupture of main vessels, such as the reactor, steam generator, and pressurizer vessels. Metal-water reaction or a nuclear excursion could add to the energy of the shock wave, but in present-day commercial light-water-cooled reactors, the stored energy of the system would be the primary source of energy. There is no known method for accurately calculating the shock wave from a ruptured vessel containing saturated water at a high pressure.[17] However, it is well known that[29,69,77] saturated water will flash into steam in an explosive manner when the pressure is suddenly released. The designer can therefore make a conservative estimate of the shock-wave energy based on the change in enthalpy during an isentropic expansion. The explosion could then be treated as an equivalent TNT explosion.

5.2.8.2 Dynamic Model of the Structure. When a value for the shock-wave energy has been established, the mathematical model to be used for analyzing the containment structure can be selected. As noted previously, a lumped-parameter dynamic model is normally used, and the containment structure is assumed to have a single degree of freedom. A more accurate model is not usually justified because of the approximate description of the shock wave. It is not the intent here to go into details on the modeling of structures for dynamic analysis; rather, reference should be made to available literature.[78-80]

In order to model a structure by a single-degree-of-freedom system, it is necessary to know the first fundamental natural frequency of the structural component, which can be derived. Reference 81, however, contains tables and graphs of this frequency for many standard structural components. After the natural frequency of the structure and pulse shape of the shock wave have been assigned, the fundamental vibration response of the structure can be calculated. The maximum amplitude can then be found, and the maximum elastic stress can be calculated. Such a technique is discussed in detail in Ref. 71. Static stresses already present due to the design loads can be added for making the failure evaluation.

5.2.8.3 Effects of the Dynamic Loading on the Structure. When a pressure wave strikes the front surface of a wall, the wall bends and deflects. If the shock is not sufficiently large to cause failure, the wall responds elastically and returns to its initial position after the disturbance has decayed. If the stresses exceed the elastic limit, the wall deforms plastically and may fail. Failure will depend on the magnitude of the load and the load-carrying properties of the wall, such as the moment of inertia and shear capacity. A reinforced-concrete wall may experience only minor cracking.

5.2.8.4 Design of Concrete Walls for Accommodating Dynamic Effects. There are several methods for designing a reinforced-concrete structure to withstand shock loading (Refs. 11, 71, 73, 79, 80, 81) based on the known dynamic or elastic properties of reinforced concrete. It is suggested that designers of containment structures use several of these methods to obtain comparisons for analyzing their designs. The design of prestressed-concrete structures, however, is less well established

for shock loadings beyond the elastic limit. Failure criteria based on the elastic yield stress may be overly conservative, and additional research in this area is needed.

5.2.8.5 Effects of Missiles Generated by the Shock Wave. Even when the stress level in the structure has been found to be acceptable for shock-wave loadings, there is still the problem of possible missiles generated by the shock wave. This problem can be very complex and must be studied carefully; its severity depends upon the physical characteristics of the containment structure and the vibration response of the system. Possible missiles are spalls from the back surface* of the containment walls, as well as from internal walls within the containment structure. Any object that is not rigidly fixed in place can also become a missile.

---

*When reviewing the literature, it should be remembered that military designers define spalling as the ejection of fragments from the front surface and scabbing as the ejection of fragments from the back surface.

6. DESIGN FOR MISSILE RESISTANCE

The first step in the design of missile-resistant structures is to define the possible missiles and to calculate their mass, velocity, cross-sectional area, direction, and structural properties. Structural properties greatly influence the penetrating ability of the missile. With these factors known, barriers can be designed to control the missiles in any given direction.

6.1 Reinforced-Concrete Protective Structures

Two basic design premises for the ultimate containment of a nuclear plant accident are preservation of leaktightness and protection of engineered safety features. Most protective structures used for commercial light-water-cooled reactor plants are made of reinforced or prestressed concrete, which is strong in compression but weak in tension, and when overstressed, fails in a brittle manner. Reinforcement tends to supply tensile strength and to reduce the consequences of brittle cracking, such as mass cracking, splintering, scabbing, and spalling that would result from a direct impact. The added resistance to penetration offered by the steel is too small, however, to warrant any large increase in percentage of steel for this purpose.[43,44]

Studies of the use of specialty concrete to improve the resistance to projectile penetration did not indicate sufficient increase in resistance to justify their use.[43,44] Results of small-projectile tests and some evidence from tests of larger projectiles show that resistance to penetration is enhanced by increasing the compressive strength of the concrete, as measured on standard test cylinders. For a given projectile at a given striking velocity, the penetration in concrete is approximately proportional to the inverse of the square root of the compressive strength. There is also some evidence that penetration is decreased somewhat by an increase in maximum aggregate size, especially if the aggregate size is greater than the diameter of the projectile. The penetration of concrete under impact is considered to be principally a crushing action on which the reinforcement has little effect.

Thus thickness, compressive strength, and stress levels are the most important parameters that affect the ability of concrete structures to withstand missile penetration. Reinforcement should be based primarily on the overall design loads, such as the static loads, shock-wave loads, and the general effects of the projectile impact. The walls should be designed specifically to withstand the effects of the projectile impact only if the impact will greatly increase the stress level in the structure. The response of the structure to impact, however, should be studied to insure that even if the projectile does not perforate the structure the overall effects will not cause failure at some other point.[39]

6.2 Methods to Control Spalling

Projectile-produced front and back face spalling of concrete structures can also generate dangerous missiles. If a concrete wall cannot be designed to prevent back face spalling, a cover plate can be attached to prevent damage from flying spalls. Steel antispall plates must be tied to the concrete by strongly welded lugs or heavy bolts at frequent intervals. Tests[43,44] have shown that the shock from deep penetration is enough to cause antispall plates welded directly to shear steel to fail over a large area and thus make the plate a potential missile. A very strongly attached plate adds up to about 10% to the perforation resistance of a concrete slab. Spall plates can also be attached to the front surface to reduce front spalls and to add to the projectile penetration resistance of the structure.

Blast mats, which are woven mats of steel cable or manila rope, have been used by other industries during blasting operations and around hazardous pressure vessels to stop missiles. Unfortunately, there are no rational methods for quantitatively estimating the effectiveness of these mats.[17]

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Vessel Rupture

It was not the intent of this review to assess the credibility of reactor pressure vessel rupture. However, if the rupture of the main vessels were considered a credible accident, it would be necessary to consider the large amounts of energy that would be released. The containment structures would have to be designed to withstand both the dynamic effects of shock waves and the impacts from missiles generated by the vessel rupture.[82]

The energy that would be delivered to fragments, or pieces, of the primary vessel if it ruptured would be estimated by using Eq. (20), with the total energy being equal to the change in enthalpy of the fluid for an isentropic expansion process to ambient pressure. If a less conservative estimate were desired, data on the rupture processes would have to be gathered.

The limiting of motions and stress levels of components inside the containment structure is, of course, essential to reducing the possibility of missile generation from nonpressurized components. Therefore, if catastrophic pressure vessel failure were considered credible, complete dynamic analyses would be required for all components in possible paths of shock waves. Since there are few data[83] on the fluid expansion process during the rupture of a pressure vessel containing high-pressure water at the saturation temperature, the energy stored in the vessel should be assumed to give an equivalent TNT type of explosion, and the impulse delivered to possible missiles generated by the shock wave and to the containment structure should be calculated on this basis.

7.2 Missiles

Designers must calculate the effects of missiles generated by other credible mechanisms. Conservative velocities for jet-propelled missiles can be calculated without knowing the true expansion processes that cause the acceleration. This type of calculation is suitable for small

missiles, but for large missiles the conservatism may be too great. Additional research in this field will be needed to develop accurate equations. The jet-propelled missile tests being done at the National Reactor Testing Station[29] are examples of the research needed.

The effects of jet forces from an unrestrained pipe rupture could turn one of the primary components into a large missile that might seriously damage the containment structure. Piping should be designed so that whipping action cannot take place, or a structural barrier should be placed between the piping and any equipment it might damage. All pipes that penetrate the containment structure should have constraints, both on the inside and the outside of the structure, to prevent movement so that the containment barrier will not be violated.

A complete analysis of all missiles that can be generated by the failure of a piece of rotating equipment should be conducted with existing techniques, and a missile map should be drawn to show trajectories, velocities, masses, and final position so that equipment can be protected. There seem to have been no detailed studies of missiles from equipment, such as coolant, feedwater, or recirculation pumps that turn at fairly high rates of speed (~1200 rpm).

7.3 Penetration and Perforation Formulas

Most of the penetration or perforation formulas for concrete and steel were derived empirically by military designers for bullets, artillery shells, bombs, etc. The ranges over which these formulas can be used are limited, and the projectiles used in the tests were always long narrow cylinders with ogival noses designed especially for maximum penetration of comparatively thin targets. Since the missiles that would be generated in nuclear reactor accidents, in general, would be rough fragments not designed for penetration, use of the military formulas should give conservative results. However, large fragments from failed turbines and other heavy equipment and possible missiles from aircraft accidents are outside the limits of the formulas. The modified Petry formula, the most commonly used concrete-penetration formula, is the least conservative

of those available. The formulas of the Ballistics Research Laboratories, the National Defense Research Committee, and the Army Corps of Engineers give better results but are still unsatisfactory for the larger missiles.

There are no formulas available that are specifically for use with prestressed- or posttensioned-concrete structures. Whether or not the formulas developed for reinforced-concrete structures are adequate and/or conservative has not been experimentally determined. Fundamental engineering research will be required to develop adequate penetration formulas for the range of possible missile generation accidents postulated for light-water-cooled reactors.

7.4 Present Design Philosophy

The structural protection against missiles presently designed into reactor containment systems is that provided by the 4 or 5 ft of reinforced concrete used for biological shielding. This would offer adequate protection against small missiles, but it might not be adequate for protection against the more massive missiles generated by a failed turbine rotor, a ruptured pressure vessel, a natural disaster, or a commercial aircraft accident. Present design philosophy is to consider such missiles as incredible and therefore outside the design requirements of the plant.

7.5 Handbook

There is no one document or collection of documents with which to compare the methods of analysis currently in use for missiles that might occur in light-water-cooled reactors. The present discussion is based largely on personal communications with manufacturers, because there were relatively few documents available for reference. A handbook for missile analysis in light-water-cooled reactors should be assembled as a joint effort between the manufacturers and the AEC. Such a handbook would fill gaps in the present state of the art and lead to better techniques than those currently used.

REFERENCES

1. P. M. Wood, A Study of Possible Blast Effects from Vessel Rupture, USAEC Report ORNL-CF-54-12-100, Oak Ridge National Laboratory, Dec. 14, 1954.

2. Alco Products, Inc., Hazards Summary Report for the Army Package Power Reactor, USAEC Report APAE-2, July 27, 1955.

3. F. B. Porzel, Design Evaluation of BER (Boiling Experimental Reactor) in Regard to Internal Explosions, USAEC Report ANL-5651, Armour Research Foundation of Illinois Institute of Technology, January 1957.

4. W. E. Baker and J. D. Patterson, II, Blast Effects Tests of a One-Quarter Scale Model of the Air Force Nuclear Engineering Test Reactor, BRL Report No. 1011, Ballistic Research Laboratories, March 1956.

5. D. H. Asire, Containment of a Nuclear Power Excursion in the Air Force Nuclear Engineering Test Reactor, Report USAFIT-TR-58-12, Air Force Institute of Technology, Wright-Patterson Air Force Base, March 1958.

6. W. McGuire and G. P. Fisher, Report on Containment Studies of the Enrico Fermi Atomic Power Plant for Power Reactor Development Company, Inc., May 1959.

7. W. McGuire and G. P. Fisher, Containment Studies for an Atomic Power Plant, J. Power Div., Proc. ASCE, June 1960.

8. W. R. Wise, Jr., J. F. Proctor, and L. P. Walker, Response of Enrico Fermi Reactor to TNT Simulated Nuclear Accidents, Report NOLTR 62-207, United States Naval Ordnance Laboratory, Nov. 13, 1964.

9. W. Y. Kato, G. J. Fischer, and L. R. Dates, Safety Analysis Report Argonne Fast Critical Facility (ZPR-VI), USAEC Report ANL-6271, Argonne National Laboratory, December 1963.

10. A. J. Hoffman and S. N. Mills, Jr., Air Blast Measurements About Explosive Charges at Side-On and Normal Incidence, BRL Report No. 988, Ballistic Research Laboratories, July 1956.

11. Air Force Design Manual, Principles and Practices for Design of Hardened Structures, Report AFSWC-TDR-62-138, December 1962.

12. H. C. Browne, H. Hileman, and L. C. Weger, Barricades for High Pressure Research, Ind. Eng. Chem., 53(10): 52A–58A (October 1956).

13. R. L. Porter, P. A. Tobo, and C. M. Sliepchich, Design and Construction of Barricades, Ind. Eng. Chem., 45: 841–846 (May 1956).

14. P. R. Alvy, Design of Pressure Vessels and Piping Containing Explosive Mixtures, Holmes & Narver, Inc., 1957.

15. J. F. Proctor, Explosion Containment for Nuclear Reactor Vessels, Nucl. Safety, 7(4): 459–468 (Summer 1966).

16. W. R. Wise, Jr., and J. F. Proctor, Explosion Containment Laws for Nuclear Reactor Vessels, Report NOLTR 63-140, United States Naval Ordnance Laboratory, Aug. 16, 1965.

17. C. V. Moore, The Design of Barricades for Hazardous Pressure Systems, USAEC Report KAPL-M-6446, Knolls Atomic Power Laboratory, Feb. 5, 1965.

18. W. E. Baker and R. R. Mills, Jr., Evaluation of Shock and Missile Hazards from a Bursting Pressure Vessel, Report AAI ER-3192, Aircraft Armaments, Inc., August 1963.

19. W. E. Baker, R. Mills, Jr., and T. G. Stastny, Addendum to Report AAI ER-3192, Evaluation of Shock and Missile Hazards from a Bursting Pressure Vessel, Report AAI ER-3192A, Aircraft Armaments, Inc., October 1963.

20. C. E. Muzzall (Ed.), Compendium of Gas Autoclave Engineering Studies, USAEC Report Y-1478, Union Carbide Corporation, Nuclear Division, Nov. 2, 1964.

21. G. Horvay, Blowout of the Flat End of a Hydraulically Pressurized Pressure Vessel, Nucl. Eng. Design, 4: 61–82 (Mar. 4, 1966).

22. W. S. Gibbons and B. D. Hackney, Survey of Piping Failures for the Reactor Primary Coolant Pipe Rupture Study, USAEC Report GEAP-4574, General Electric Company, May 1964.

23. T. M. Dahl, Effects of Aircraft Impingement on Reactor Containments, Jackson and Moreland Division, United Engineers and Constructors, Inc., Sept. 20, 1966, unpublished information.

24. R. P. Kennedy, Effects of an Aircraft Crash into a Concrete Reactor Containment Building, Holmes & Narver, Inc., July 1966.

25. W. B. Cottrell and A. W. Savolainen (Eds.), U.S. Reactor Containment Technology, USAEC Report ORNL-NSIC-5, Chapt. 6, Oak Ridge National Laboratory, August 1965.

26. J. H. Perry (Ed.), Chemical Engineers' Handbook, McGraw-Hill, New York, 1950.

27. J. S. Doolittle and A. H. Zerban, Engineering Thermodynamics, International Textbook, Scranton, Pennsylvania, 1964.

28. J. H. Kennan, Thermodynamics, Wiley, New York, 1948.

29. Letter from Teo. J. Finnegan, Staff Engineer, Engineering and Test Branch, Atomic Energy Division, Phillips Petroleum Company, National Reactor Testing Station, to R. C. Gwaltney, ORNL, Jan. 10, 1967, subject: Missile Velocity Equations.

30. F. P. Beer and E. R. Johnston, Jr., Mechanics for Engineers, McGraw-Hill, New York, 1957.

31. R. Weck, Brittle Fracture of a Thick-Walled Pressure Vessel, British Welding Research Association Bulletin, 7(6): 149–178 (June 1966).

32. T. E. Sterne, A Note on the Initial Velocities of Fragments from Warheads, BRL Report 648, Ballistic Research Laboratories, Sept. 2, 1947.

33. R. W. Gurney, Velocity and Range of Fragments from a Bursting Gun, BRL Report 563, Ballistic Research Laboratories, Aug. 28, 1946.

34. W. T. Smith, Hazards Pertaining to the Converted Thirty-Inch Pressure Vessel, Part 1 of Compendium of Gas Autoclave Engineering, edited by C. E. Muzzall, USAEC Report Y-1478, Union Carbide Corporation, Nuclear Division, Nov. 2, 1964.

35. H. Rouse and J. W. Howe, Basic Mechanics of Fluids, Wiley, New York, 1958.

36. W. Goldsmith, Impact, Edward Arnold, Ltd., London, 1960.

37. F. Holié, Portions of Traite de Balistique Experimentale, NOTS-TM-RRB-75, U.S. Naval Ordnance Test Station, Inyokern, California, May 1, 1950.

38. M. Kornhauser, Structural Effects of Impact, Spartan, Baltimore, Maryland, 1960.

39. F. J. Samuely and C. W. Hamann, Civil Protection, The Architectural Press, London, 1939.

40. A. Amirikian, Design of Protective Structures, Report NP-3726, Bureau of Yards and Docks, Department of the Navy, August 1950.

41. C. R. Russell, Reactor Safeguards, MacMillan, New York, 1962.

42. Letter from W. E. Baker, Manager, Engineering Dynamics Section, Southwest Research Institute, to R. C. Gwaltney, ORNL, Nov. 4, 1966, subject: Missile Penetration and Damage Literature Search.

43. Fundamentals of Protective Design, Report ATI207821, Army Corps of Engineers, Office of the Chief of Engineers, 1946.

44. National Defense Research Committee, Effects of Impact and Explosion, Summary Technical Report of Division 2, Volume 1, Washington, D.C., 1946.

45. R. W. White and N. B. Botsford, Containment of Fragments from a Runaway Reactor, Report SRIA-113, Stanford Research Institute, Sept. 15, 1963.

46. R. F. Recht and T. W. Ipson, Ballistic Perforation Dynamics, J. Appl. Mech., 30: 384–390 (September 1963).

47. G. D. Whitman, G. C. Robinson, Jr., and A. W. Savolainen (Eds.), Design of Nuclear Pressure Vessels, Chapter 6, pp. 282–429 in Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors, USAEC Report ORNL-NSIC-21, Oak Ridge National Laboratory, December 1967.

48. E. C. Miller, The Integrity of Reactor Vessels, USAEC Report ORNL-NSIC-15, Oak Ridge National Laboratory, May 1966.

49. W. A. Irvine, A. Quirk, and E. Bevitt, Fast Fracture of Pressure Vessels: An Appraisal of Theoretical and Experimental Aspects and Application to Operational Safety, J. Brit. Nucl. Energy Soc., pp. 31–48, January 1964.

50. E. Bevitt, A. Cowan, and A. L. Scott, Failure Tests on Cylindrical Steel Vessels Containing Axial Faults, J. Brit. Nucl. Energy Soc., pp. 16–30, January 1964.

51. R. W. Nichols, Prevention of Catastrophic Failure in Steel Pressure Circuit Components, Nucl. Eng., pp. 369–373, May 1966.

52. T. Tagami, Interim Report on Safety Assessment and Facilities Establishment Project in Japan for Period Ending June 1965 (No. 1).

53. Letter from W. E. Baker, Manager, Engineering Dynamics Section, Department of Mechanical Sciences, Southwest Research Institute, to R. C. Gwaltney, ORNL, Oct. 27, 1966, subject: Discussion Paper on Missile Generation and Protection.

54. G. F. Kinney, Explosive Shocks in Air, pp. 75–77, MacMillan, New York, 1962.

55. W. Doering and G. Burkhardt, Contributions to the Theory of Detonation (translated from the German as Tech. Rep. No. F-TS-1227-1A, GDAM A9-T-46), Wright-Patterson Air Force Base, Ohio, May 1949.

56. W. E. Baker, The Response of Containment Structures to Transient Pressures Caused by Nuclear Reactor Runaway, Progress in Nuclear Energy, Series IV, Technology, Engineering, and Safety, Vol. 5, pp. 581–599, Pergamon Press, London, 1963.

57. J. F. Proctor, Adequacy of Explosion-Response Data in Estimating Reactor-Vessel Damage, Nucl. Safety, 8(6): 565–571 (November–December 1967).

58. G. R. Warren and T. W. Rice, An Assessment of Reactor Safety Modeling Techniques Based on the Accident to the SL-1 Boiling Water Reactor, British Report AWRE R-3/65, United Kingdom Atomic Energy Authority, August 1965.

59. G. Long, Explosions of Molten Aluminum in Water – Cause and Prevention, Metal Progr., 71: 107–112 (May 1957).

60. W. Nelson and E. H. Kennedy, What Causes Kraft Dissolving Tank Explosions, Reprint from the Paper Trade Journal.

61. D. G. Pearce, D. L. Ward, and P. Hayes, Liquid-Hydrogen Explosions in Containment Vessels, British Report AERE-R 4584, United Kingdom Atomic Energy Authority, February 1966.

62. T. H. Pigford, Explosion and Detonation Properties of Mixtures of Hydrogen, Oxygen, and Water Vapor, USAEC Report ORNL-1322, Oak Ridge National Laboratory, Aug. 14, 1952.

63. U.S. Atomic Energy Commission, The Study of Missiles Resulting from Accidental Explosions, A Manual for Investigators, AEC Safety and Fire Protection Bulletin No. 10, pp. 34–35, March 1966.

64. W. D. Kennedy and E. T. Bunce, Air-Blast Measurements on Pressed and Cast High Explosives in Service Use, Report NAVORD 98–46, United States Naval Ordnance Laboratory, November 1946.

65. H. J. Goodman, Compiled Free-Air Blast Data on Bare Spherical Pentolite, BRL Report 1092, Ballistic Research Laboratories, February 1960.

66. R. J. Larson and W. Olson, Measurement on Air Blast Effects from Simulated Nuclear Reactor Core Excursions, BRL Memorandum Report 1102, Ballistic Research Laboratories, September 1957.

67. D. W. Boyer, H. L. Brode, I. I. Glass, and J. G. Hall, Blast from a Pressurized Sphere, UTIA Report No. 48, University of Toronto, January 1958.

68. P. M. Wood, A Study of Possible Blast Effects from HRT Pressure Vessel Rupture, USAEC Report ORNL-CF-54-12-100, Oak Ridge National Laboratory, Dec. 14, 1954.

69. E. A. Brown, Experiments on the Explosive Decompression of Water, Report ARF-4132-9, Armour Research Foundation of Illinois Institute of Technology, November 1959.

70. J. P. Weber, J. Savitt, J. Krc, and H. C. Browne, Detonation Tests Evaluating High Pressure Cells, Ind. Eng. Chem., 53(11): 129A–133A (November 1961).

71. R. C. Gwaltney, Blast Resistant Design, Part 2 of Compendium of Gas Autoclave Engineering Studies, edited by C. E. Muzzall, USAEC Report Y-1478, Union Carbide Corporation, Nuclear Division, Nov. 2, 1964.

72. J. N. MacDuff and J. R. Curreri, Vibration Control, McGraw-Hill, New York, 1958.

73. Industrial Engineering Study to Establish Safety Design Criteria for Use in Engineering of Explosive Facilities and Operations, Wall Response, Report AD-411445, Picatinny Arsenal, April 1963.

74. H. A. Bethe et al., Blast Wave, USAEC Report LA-2000, Los Alamos Scientific Laboratory, Mar. 27, 1958.

75. I. B. Zeldovich and A. S. Kompaneets, Theory of Detonation, Academic Press, New York, 1960.

76. R. H. Cole, Underwater Explosions, Dover, New York, 1965.

77. R. Meyer, Facts You Should Know About Water Heaters, Family Safety, 25(4): 20–22 (Winter 1966).

78. C. M. Harris and C. C. Crede (Eds.), Shock and Vibration Handbook, Vol. 2, McGraw-Hill, New York, 1961.

79. C. H. Norris et al., Structural Design for Dynamic Loads, McGraw-Hill, New York, 1961.

80. J. M. Biggs, Introduction to Structural Dynamics, McGraw-Hill, New York, 1964.

81. C. M. Harris and C. C. Crede (Eds.), Shock and Vibration Handbook, Vol. 1, McGraw-Hill, New York, 1961.

82. W. E. Baker, S. Silverman, E. M. Briggs, and A. G. Pickett, Engineering Feasibility of Contained Detonation (title unclassified), Report AFWL-TR 65-96, Air Force Weapons Laboratory, October 1965 (Secret).

83. D. L. Hunt and F. J. Walford, An Experimental Investigation into the Failure of a Pressure Vessel Containing High-Temperature Pressurized Water, British Report AEEW-R 97, United Kingdom Atomic Energy Authority Reactor Group, September 1961.

Appendix A

REVIEW COMMITTEE AND CONSULTANTS

Review Committees

USAEC Review Committee

R. R. Newton, RDT
R. R. Maccary, DRS

ORNL Internal Review Committee

H. A. Nelms
J. G. Merkle
D. A. Canonico

External Review Committee

W. E. Baker, Southwest Research Institute
J. F. Proctor, U.S. Naval Ordnance Laboratory
W. McGuire, Cornell University

Other Reviewers

USAEC Germantown

S. Lanes, RDT
G. Arlotto, DRS

ORNL

J. W. Michel
J. Buchanan
W. B. Cottrell
R. N. Lyon
S. E. Beall

Phillips Petroleum Company, NRTS

J. Waage
C. S. Miller
H. D. Curent
N. Anderson
L. J. Linnegan

Argonne National Laboratory

S. Fistedis

Manufacturers Consulted

Combustion Engineering

V. C. Hall
J. R. Parrette
W. K. Wilhelm
L. M. Johnson
J. M. West
R. L. Hoover
P. C. Zmola
J. R. Dietrich
W. Nelson

Babcock & Wilcox

R. Luken
H. F. Flora

Westinghouse Electric Corporation

T. Paxson
R. A. Wiesemann
G. R. Taylor
R. Salvatori
J. D. Macado
E. S. Beckjord

General Electric Company

S. W. Taggart
L. K. Liu
J. E. Corr
T. Brown
I. Kohsa
T. Judge