GUIDE NO. AERB/NPP/SG/D-3

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GOVERNMENT OF INDIA

AERB SAFETY GUIDE

PROTECTION AGAINST INTERNALLY GENERATED MISSILES IN NUCLEAR POWER PLANTS

ATOMIC ENERGY REGULATORY BOARD

AERB SAFETY GUIDE NO. AERB/NPP/SG/D-3

PROTECTION AGAINST INTERNALLY GENERATED MISSILES IN NUCLEAR POWER PLANTS

Atomic Energy Regulatory Board
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Orders for this Guide should be address to:

The Chief Administrative Officer
Atomic Energy Regulatory Board
Niyamak Bhavan
Anushaktinagar
Mumbai-400 094
India

FOREWORD

Activities concerning establishment and utilisation of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the provisions of the Atomic Energy Act 1962. In pursuance of the objective of ensuring safety of members of the public and occupational workers as well as protection of environment, the Atomic Energy Regulatory Board has been entrusted with the responsibility of laying down safety standards and enforcing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety codes, safety standards and related guides and manuals for the purpose. While some of documents cover aspects such as siting, design, construction, operation, quality assurance, decommissioning of nuclear and radiation facilities, other documents cover regulatory aspects of these facilities.

Safety codes and standards are formulated on the basis of nationally and internationally accepted safety criteria for design, construction and operation of specific equipment, structures systems and components of nuclear and radiation facilities. Safety codes establish the objectives and set minimum requirements that shall be fulfilled to provide adequate assurance for safety. Safety guides elaborate various requirements and furnish approaches for their implementation. Safety manuals deal with specific topics and contain detailed scientific and technical information on the subject. These documents are prepared by experts in the relevant fields and are extensively reviewed by advisory committees of the Board before they are published. The documents are revised, when necessary, in the light of the experience and feedback from users as well as new developments in the field.

Consistent with the accepted practice, 'shall' and 'should' are used in the Guide to distinguish between a firm requirement, and a desirable option, respectively. Appendices are an integral part of the document, whereas annexures, footnotes and references are included to provide information that might be helpful to the user. Approaches for implementation, different to those set out in the Guide, may be acceptable, if they provide comparable assurance against undue risk to the health and safety of the occupational workers and the general public, and protection of the environment.

This Guide deals with the protection against internally generated missiles in nuclear power plants. The guide applies only for facilities built after the issue of this document. However during periodic safety review, a review for applicability of current guide for existing facilities would be performed.

For aspects not covered in this Guide, applicable national and international standards, codes and guides acceptable to AERB should be followed. Non-radiological aspects such as industrial safety and environmental protection are not explicitly considered. Industrial safety is ensured through compliance with the applicable provisions of the Factories Act, 1948 and the Atomic Energy (Factories) Rules, 1996.

This Guide has been prepared by specialists in the field drawn from the Atomic Energy Regulatory Board, Bhabha Atomic Research Centre, Nuclear Power Corporation of India Limited and other consultants. It has been reviewed by the relevant AERB Advisory Committee on Codes and Guides & Associated Manuals for Safety in Design (ACCGD) of Nuclear Power Plants and the Advisory Committee on Nuclear Safety.

AERB wishes to thank all individuals and organisations who have prepared and reviewed the document and helped in its finalisation. The list of persons, who have participated in this task, along with their affiliations is included for information.

(S. S. Bajaj)
Chairman, AERB

DEFINITIONS

Acceptable Limits

Limits acceptable to Regulatory Body for accident condition or potential exposure.

Accident conditions

Substantial deviations from operational states, which could lead to release of unacceptable quantities of radioactive materials. They are more severe than anticipated operational occurrences and include design basis accidents as well as beyond design basis accidents.

Anticipated Operational Occurrences

An operational process deviating from normal operation, which is expected to occur during the operating life of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety, nor lead to accident conditions.

Atomic Energy Regulatory Board (AERB)

A national authority designated by Government of India, having the legal authority for issuing the regulatory consent for various activities related to the nuclear and radiation facility and to perform safety and regulatory functions, including their enforcement for the protection of site personnel, the public and environment against undue radiation hazards.

Critical Target

A target that, if hit by a missile, could result in primary or secondary effects with safety significance.

Design

The process and the results of developing the concept, detailed plans, supporting calculations and specifications for a nuclear or radiation facility.

Design Basis Accidents (DBAs)

A set of postulated accidents which are analysed to arrive at conservative limits on pressure, temperature and other parameters which are then used to set specifications to be met by plant structures, systems and components, and fission product barriers.

Design Basis Missile

A missile for which the designer is required to take appropriate measures in the design.

Documentation

Recorded or pictorial information describing, defining, specifying, reporting or certifying activities, requirements, procedures or results.

Earthquake

Vibration of earth caused by the passage of seismic waves radiating from the source of elastic energy.

Environmental Conditions

Parameters such as pressure, temperature, humidity, chemical spray, flooding, and radiological conditions associated with operational states and accident conditions.

Inspection

Quality control actions, which by means of examination, observation or measurement, determine the conformance of materials, parts, components, systems, structures as well as processes and procedures with predetermined quality requirements.

Item

A general term covering structures, systems, components, parts or materials.

Items Important to Safety

The items which comprise:

(i) those structures, systems, equipment and components whose malfunction or failure could lead to undue radiological consequences at plant site or off-site;

(ii) those structures, systems, equipment and components which prevent anticipated operational occurrences from leading to accident conditions;

(iii) those features which are provided to mitigate the consequences of malfunction or failure of structures, systems, equipment or components.

Maintenance

Organised activities covering all preventive and remedial measures, both administrative and technical, to ensure that all structures, systems and components are capable of performing as intended for safe operation of plant.

Missile

A mass that has kinetic energy and has left its design location.

Normal Operation

Operation of a plant or equipment within specified operational limits and conditions. In case of nuclear power plant this includes start-up, power operation, shutting down, shut down state, maintenance, testing and refuelling.

Nuclear Facility

All nuclear fuel cycle and associated installations encompassing the activities from the front end to the back end of nuclear fuel cycle processes and also the associated industrial facilities such as heavy water plants, beryllium extraction plants, zirconium plants, etc.

Nuclear Power Plant (NPP)

A nuclear reactor or a group of reactors together with all the associated structures, systems, equipment and components necessary for safe generation of electricity.

Nuclear Safety

The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of site personnel, the public and the environment from undue radiation hazards.

Operation

All activities following and prior commissioning performed to achieve, in a safe manner, the purpose for which nuclear/radiation facility is constructed, including maintenance.

Operational States

The states defined under normal operation and anticipated operational occurrences.

Physical Separation

A means of ensuring independence of equipment through separation by geometry (distance, orientation, etc), appropriate barriers or a combination of both.

Prescribed Limits

Limits established or accepted by the regulatory body.

Quality Assurance

Planned and systemic actions necessary to provide the confidence that an item or service will satisfy given requirement for quality.

Quality Control

Quality assurance actions, which provide means to control and measure the characteristics of an item, process or facility in accordance with established requirements.

Records

Documents which furnish objective evidence of quality of items or activities affecting quality. They include logging of events and other measurements.

Redundancy

Provision of alternate structures, systems, components of identical attributes, so that any one can perform the required function, regardless of the state of operation or failure of the other.

Reliability

The probability that a structure, system, component or facility will perform its intended (specified) function satisfactorily for a specified period under specified conditions.

Residual Heat

The sum of the time-dependent heat loads originating from radioactive decay and shutdown fission and heat stored in reactor related structures and heat transport media in a nuclear reactor facility.

Safety Function

A specific purpose that must be accomplished for safety.

Safety System

Systems important to safety and provided to assure that under anticipated operational occurrences and accident conditions, the safe shutdown of the reactor followed by heat removal from the core and containment of any radioactivity, is satisfactorily achieved. (Examples of such systems are shutdown systems, emergency core cooling system and containment isolation system).

Single Failure

A random failure, which results in the loss of capability of a component to perform its intended safety functions. Consequential failures resulting from a single random occurrence are considered to be part of the single failure.

Site

The area containing the facility defined by a boundary and under effective control of the facility management.

Specification

A written statement of requirements to be satisfied by a product, a service, a material or a process, indicating the procedure by means of which it may be determined whether the specified requirements are satisfied.

Structure

The assembly of elements which supports/houses the plants, equipment and systems.

Surveillance

All planned activities, viz. monitoring, verifying, checking including in-service inspection, functional testing, calibration and performance testing carried out to ensure compliance with specifications established in a facility.

Testing (QA)

The determination or verification of the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental or operational conditions.

SPECIAL DEFINITIONS
(Specific for the present 'Guide')

Local Missile Effects

Missile effects on a target (a structure, system or component), which are largely independent of the overall dynamic characteristics of the target and are limited to local response such as scabbing, penetration, perforation, spalling etc.

Overall Missile Effects

Those effects which depend to a large extent on the dynamic characteristics of the target (a structure, system or component) subjected to impact and are therefore not limited to the immediate area of impact.

Primary Missile Effects

All effects on targets by both direct strikes and ricochet strikes from missiles which originate from the initial equipment failure.

Scabbing

Effect of a missile impact, causing ejection of irregular pieces of that face of the target opposite to the face of missile impact.

Secondary Effects

All subsequent effects due to the consequences of Primary Missile Effects.

Spalling

Effect of a missile impact, causing ejection of target material from the face on which the missile impacts.

CONTENTS

1. INTRODUCTION

1.1 General

To perform the intended functions without undue risk to the plant personnel and public at large, nuclear power plants (NPP) are required to be designed to withstand the effects of various natural and man-induced events. Among others, one needs to consider the effects of missiles resulting from failure of plant equipment, earthquake or wind-induced missiles and site-proximity missiles. The hazards due to external missiles deemed credible, such as site-proximity missiles, are to be considered in design [1].

1.2 Objective

This safety guide provides guidance for implementation of design requirements in respect of 'effects associated with equipment failure', as per safety code on Design of Pressurised Heavy Water Based Nuclear Power Plants [2].

Structures, systems and components (SSC) important to safety shall be designed to accommodate the effects of, and to be compatible with the environmental conditions, associated with operational states and accident conditions of the plant. To avoid secondary failures that could increase the safety-related consequences of the primary event, these SSC shall be appropriately located or protected against dynamic effects, including the effects of missiles, pipe whipping and discharging fluids and flooding that may result from equipment failures. If these conditions are not fulfilled, other appropriate measures shall be incorporated in the design.

1.3 Scope

This guide covers guidance on protection against internally generated missiles, including their secondary effects, which may result from postulated equipment failures including piping failures within the plant, and external wind-induced missiles. Siting code [1] shall be referred with regard to protection against other external missiles. While the document is prepared specifically for Pressurised Heavy Water Based Nuclear Power Plants, the guidance contained herein should generally be applicable to all nuclear power plants. IAEA safety guides [3,4] have been used extensively in development of this guide.

2. GENERAL CONSIDERATIONS

2.1 General

To ensure safety, the following general design requirements shall be met in spite of equipment failure, missile generation and its consequential effects:

(a) Safe shutdown of the reactor and maintain it in the safe shut down condition during and after appropriate operational states of the plant and accident conditions.

(b) Remove residual heat from the core after reactor shutdown, and during and after appropriate operational states and accident conditions.

(c) Reduce potential for the release of radioactive materials and to ensure that any releases are below prescribed limits during operational states and below acceptable limits during accident conditions.

Where equipment failure requires safety assessment to demonstrate that the general design requirements can be met, all cascading effects of the failure such as missiles, pipe whip, discharging fluids and flooding, chemical sprays, radiation environment and humidity shall be included. All SSC required to perform safety functions shall be assessed for compatibility with the plant environmental conditions. Necessary protection shall be designed and implemented on the basis of the outcome of the assessment. This safety assessment shall include both the plant effects resulting from the initial equipment failure and the plant effects resulting from any missile produced by the equipment failure. In this guide emphasis is placed on designing to preclude the creation of missiles and on protection methods.

2.2 Missile Protection

A good approach to missile protection should address this issue as early as at plant layout stage. By suitably locating and arranging potential missile generating equipment and components, risk of items important to safety becoming primary missile targets should be minimised.

The best design approach is to virtually eliminate the generation of missiles, the next best is to separate targets important to safety from missile sources, and then there is the option of making the consequences acceptable. It may also be necessary in some cases to use a combination of approaches where none of the individual factors can by itself solve the problem. Missiles and their effects on safety functions shall be included in the safety assessment of any equipment failure unless it can be shown that either:

(a) the probability of generating a missile (P1) is less than 10^{-6} per reactor year; or

(b) the probability of assumed missile striking a target important to safety (P2) is sufficiently low; or

(c) the probability of producing primary or secondary damage with unacceptable consequences (P3) is low either due to the energy of the assumed missile is too low to be an appreciable risk of damage to items important to safety or the target items can be deterministically demonstrated to be safe for assumed missile hit. or

(d) the overall probability of unacceptable consequences (product of P1,P2 and P3) is sufficiently low (10^{-6}).

Where the related risks cannot be estimated with a reasonable amount of certainty, special care shall be taken in design.

In the screening process, sources with sufficient energy to produce a missile shall be identified. In case of doubt, the component in question should not be excluded but rather put on the list of potential hazards which have to be analysed in more detail.

One part of the analysis process is the determination of situations which give rise to the need for safety systems to operate and the other part of this analysis is the determination of operability of those safety systems.

The situations that may place demands on safety systems to operate are:

(a) the equipment failure itself,

(b) the damage due to a missile striking a target (primary missile effects),and

(c) the subsequent damage, if any, caused by secondary effects.

The situations that reduce the number of available safety systems are:

(a) the equipment that has failed is itself part of a safety system

(b) missiles generated by the initial equipment failure damage targets that are components of safety systems, thus making these components unavailable, and

(c) components of safety systems become unavailable owing to damage caused by secondary effects.

In addition to the above three, there could be another situation arising out of an assumed unavailability of components of a safety system (component of a safety system is assumed to have a single failure, or it is in the test or maintenance mode).

The number of operable safety systems (after missile impact) is compared to the number of required safety systems to determine whether there is sufficient capability to meet the general requirements given in clause 2.1. If the answer is negative, then either additional missile protection shall be provided or the redundancy of the safety systems shall be increased or a combination of the two could be used until such time as the question can be answered affirmatively.

2.2.1 Secondary and Cascading Effects

Missiles, in addition to the direct damage they may cause, called primary missile effects, may cause indirect damage by means of failure mechanisms that can propagate the damage beyond the initial missile impact. This indirect damage is referred to as a secondary effect. The secondary effects may cause damage that could exceed that caused by the primary missile effects. Where postulated equipment failure necessitates a safety assessment to demonstrate that the general design requirements of 2.1 are fulfilled, all cascading secondary effects of the failure should be included.

Because of wide variation of potential damage and other factors associated with secondary effects that are beyond the control of designer, preferred practice is to emphasize means of stopping the cascading effect or in other words reducing P1 and/or P2 rather than P3. The prevention of a pipe break should receive special attention since it may prevent several potential secondary and cascading effects.

3. ORIGIN OF MISSILES AND DESIGN CONSIDERATIONS

3.1 General

Potential sources of missiles include high pressure systems, rotating machinery, gravitational missiles and secondary missiles. Sources and events considered capable of producing missiles due to certain failures/incidents include main turbine generator, building structures and filler walls, overhead cranes, pressure vessels, pumps, motors, diesel engines, flywheels, fans, compressors, valves, control rod drive mechanisms or parts thereof, some portions of instrumentation (e.g. thermo wells) etc.

3.2 Missiles Resulting from Plant Related Failure or Incident

3.2.1 Loss of Integrity of Equipment with High Energy Content

3.2.1.1 Pressure Vessels

In NPP, pressure vessels important to safety should be analysed to demonstrate that stress levels are within acceptable limit under all design conditions and probability of brittle fracture is negligible. All phases of design, construction, installation and testing should be monitored in accordance with approved procedures to verify that the design specifications are met and the final quality of the vessel is acceptable. A surveillance programme during commissioning and operation, as well as a reliable system for overpressure protection, should be used to demonstrate that the vessels remain within their design limits. The gross failure of such vessels is generally considered to be sufficiently improbable and consideration of rupture of these vessels to form a missile should not be necessary.

A pressure vessel can fail in a wide variety of failure modes depending on its material characteristics, shape, weld positions, support conditions, nozzle designs, construction practices and operating conditions. A prudent approach in case of other vessels (not important to safety) containing fluid at high internal energy is that the system should be designed, constructed and tested as per standard norms following standard quality assurance programme and they should undergo ISI and surveillance as per standard program during the service life. In such cases, P1 generally can be considered as acceptably small and missile generation need not be postulated.

Where it is determined that P1 is not low enough, then it is necessary to assume a spectrum of missile sizes and shapes to cover the possible range and analyse them in a parametric study to determine the maximum severity.

Vessels shall be designed such that they cannot as a whole become a missile. For this purpose, analyses shall be made for various rupture locations and break sizes to ensure that the resultant vessel blow down forces are less than the strength of the supports.

3.2.1.2 Valves

Valves in fluid systems, which operate at high internal energy, shall be evaluated as potential sources of missiles. Removable parts of the valves such as valve stem or valve bonnet bolts are examples of failures generating potential missiles.

Consideration should be given to the shock loads for their potential to generate missiles, for example the relief valves.

Valve bodies are usually constructed in such a manner that they are substantially stronger than the connected piping. For this reason it is generally accepted that the generation of missiles resulting from the failure of valve body itself is sufficiently unlikely in most cases and that it need not be considered in plant design and/or evaluation. Appendix-A provides further design considerations for missiles generated due to valve stems.

3.2.1.3 Bolts

Failure of one bolt shall not lead to the generation of a missile other than the bolt itself. This requirement applies to valves, pressure vessels and other bolted components with high energy content.

3.2.1.4 Piping

High energy piping[1] qualified for leak before break[2] (LBB) including provisions for leak detection are precluded from the requirements given hereinafter.

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1. A high energy pipe is the one with an internal operating pressure equal to or exceeding 2.0 MPa or an operating temperature equal to or exceeding 100°C in the case of water. Other limits may apply for other fluids [4].

2. Design based on LBB should meet the following requirements:

   (a) The piping material meets the ductility requirements.

   (b) Fracture mechanics evaluations are carried out with postulated flaw sizes as per the applicable norms and required safety margin is demonstrated with respect to crack growth and instability.

   (c) Elimination of protective devices against rupture (For example; snubbers, supports, restraints) should be based on the evaluation that water-hammer, corrosion, creep, fatigue, erosion, environmental conditions and indirect sources (i.e. failure of supports etc.) are remote causes of pipe rupture.

   (d) Leakage size crack is defined

   (e) Leak detection systems are sufficiently reliable, diverse and sensitive, and requirements on margin to detect the through-wall crack used in fracture mechanics evaluation exists.

Depending on the characteristics of the pipes under consideration, the following types of failures should be postulated:

(a) For high energy pipes: circumferential rupture or longitudinal through wall crack.

(b) For low energy pipes[3]: leak with limited area.

A limited leak (not a break) postulation is acceptable if it can be demonstrated that the piping system considered is operated under high energy parameters for a short duration (less than 2% of the total operating time) or if its nominal stress is low (less than 50 MPa) [4].

The postulated failure locations should be determined as follows:

(a) At the terminal ends (fixed points, connections to a large pipe or to a component) and at intermediate points of high stress for a piping system designed and operated as per the rules for systems important to safety;

(b) In all locations for other pipes.

For piping of nominal diameter less than 50 mm, breaks should be postulated at all locations [4].

Piping carrying high energy fluid shall be evaluated for pipe whip forces, jet impingement forces, and possible missiles due to ejection of masses within or attaches to pipes such as valves, pipe fittings and instrument wells. Appendix-A provides further design considerations for pipe whip forces and jet impingement forces.

3.2.2 Jet Impingement Analysis

In addition to pipe restraints, barriers and layout are used to provide protection for vital equipment from pipe whip and blow down jet forces arising from postulated piping breaks. Some typical methods used to determine jet impingement loads [5] on components and supports are given in Annexure-I.

3.2.3 Pipe Whip Analysis

For breaks where pipe whip protection is not provided by means of restraints, a detailed study shall be conducted to evaluate the effects of the whipping pipe on safety related SSC. When pipe whip restraints are provided, these shall be designed to withstand pipe rupture thrust load, which includes a dynamic load factor appropriate for the gap between the pipe and the restraint. Some typical methods for pipe-whip analysis [5] are given in Annexure-I.

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3. Those pipes which do not qualify as high energy pipes.

3.2.4 High-speed Rotating Equipment

Nuclear power plants contain large number of equipment having parts that rotate at high speed during operation, such as the main turbine generator set, the steam turbines, large pumps (such as the main coolant pump) and their motors, and fly wheels. These rotating parts can attain a considerable energy of rotation, which in the event of their failure can be converted into translational kinetic energy of rotor fragments. Such failures can arise either from defects in the rotating parts or from excessive stresses due to over speed. An acceptable method of minimising the potential for failure of the flywheels of reactor coolant pump motors, based on ref [6], is described in Annexure-II.

Since rotating machinery usually has a heavy stationary structure surrounding the rotating parts, some consideration should be given to the energy loss after failure due to the energy absorbing characteristics of the stationary parts. Energy loss in the penetration of such structures is invariably a complex process, owing to the configuration of the structure. For the sake of simplicity, a conservative approach is often used in which it is assumed that no energy is lost in the interaction of the missile and the stationary casing of rotors.

There are historical examples that show that fragments of many sizes and shapes can be ejected in the event of the failure of rotating equipment. Test data indicate that for a simple geometry such as a disc, the failure process tends to result in a number of roughly equal segments [4]. However, stress concentrations, structural discontinuities, defects in materials and other factors can all affect the failure process in such a way as to influence the type of fragments formed. Missiles from the failure of rotating machinery should be characterised on the basis of their potential for doing damage and should be included in the evaluation of possible primary and secondary effects.

Typical missiles postulated to be caused by the failure of high speed rotating equipment include:

(a) Fan blades;

(b) Turbine disc fragments or blades;

(c) Pump impellers;

(d) Flanges;

(e) Coupling bolts.

To determine P1 for such rotating equipment the following steps should be taken:

(a) The design of the rotating machine itself should be evaluated for the selection of materials, speed control features and stress margins for all plant states considered in the design basis, including anticipated operational occurrences and design basis accidents.

(b) The manufacturing process for the rotating machine should be evaluated for conformance with the design intent, for the adequacy of the nondestructive examination and other testing to detect possible defects, and for the adequacy of the quality control measures taken to ensure that the equipment as installed meets all specifications.

(c) Means of preventing destructive over speed should be evaluated for reliability. This will include equipment for the detection and prevention of incipient over speed, associated power supply equipment and instrumentation and control equipment, as well as the procedures involved in the periodic calibration and readiness testing of all these.

A balance between the input energy and the output load determines the speed of rotating equipment. A sudden reduction in the output load or a sudden increase in the input energy can result in over speed. Where there is a significant possibility of unacceptable damage due to missiles, additional redundant means of limiting the rotational speed may be provided by such features as governors, clutches and brakes and by a combination of systems for instrumentation, control and valving to reduce the probability of over speed occurring to an acceptable level.

It should be noted that while engineering solutions are available to limit speed and to prevent missiles due to excessive over speed, these provisions by themselves may not make the probability of missiles being generated from rotating equipment acceptably small. Besides the failure caused by over speed there is the possibility of a flaw in the rotor resulting in missiles being generated at or below normal running speed. These missiles should be dealt with by other means, such as conservative design, high quality manufacturing, careful operation, appropriate monitoring of parameters (such as vibration) and comprehensive in-service inspection. When all these means are properly used, the probability of missiles being generated through the failure of rotating machines can be significantly reduced.

3.2.5 Storage of Explosive Gases and Compressed Gas Cylinders

The storage and inspection of such vessels, cylinders, containers shall be in accordance with the requirements of the Atomic Energy (Factories) Rules [7] and other national regulations such as Explosives Act, 1884, Explosive Rules, 1983 (as amended in 2008) and Gas Cylinders Rules 1981 (as amended in 2004).

3.2.6 Operator Errors

Erroneous operation of equipment for control of pressure or speed may result in overpressure or over speed failure accompanied by the generation of missiles. For example, operator error can cause a loss of load to the turbine generator that can lead to an over speed condition in the event of coincident failure of over speed protection. Adequate training shall be undertaken and appropriate procedures shall be formulated and applied to reduce the probability of operator errors that can result in overpressure or over speed. Highly reliable over speed or overpressure control equipment should be used to reduce effects of these operator errors. If the probability of producing a missile by operator error (P1) cannot be made acceptably small, then it is necessary to reduce P2 and/or P3.

3.2.7 Collapse of Structures and Non-Structural Elements

Safety related structures in NPP are designed to withstand extreme loads arising from design basis natural and man-induced events. Collapse of these structures due to internal missiles (except turbine missile) is considered to be unlikely. However, failure of non-structural elements, such as filler walls, should be assessed for both the design basis external events and internal missiles including their secondary effects and consequences for SSC should be evaluated in these cases.

Non-safety related structures that are designed as conventional structures may not be safe against collapse during all postulated design basis events considered in the design of safety class structures. Such structures shall be examined to determine whether their collapse can jeopardize safety of nearby SSC important to safety. If the answer is in affirmative, these structures shall be designed and built such that their probability of collapsing can be shown to be negligible; otherwise the consequences of their collapse shall be assessed.

Characterisation of the shape, size, and composition of missiles resulting from the collapse of building-like structures is sensitive to assumptions. There can be a wide range of missile properties and the missiles cannot be assumed to always fall straight to the ground. A good approach in such cases is to avoid such failures or to minimise the potential damage to SSC by means of proper location, physical separation of SSC so that no single collapse could affect all redundancies, and lastly by adequate barrier design.

3.2.8 Dropping of Heavy Equipment

Preferred approach to ensure no dropping of load is by means of design and/ or administrative control. It may be achieved by applying single failure criterion in design of cranes (as defined in NUREG-0554 [8]). Where heavy items of plant equipment are located at significant height, an evaluation shall be made of the possible missile hazards due to dropping of such equipment if the probability of dropping is not negligible.

The nature of the object and the cause of its dropping should be analysed in order to characterise the direction, size, shape, and energy of the missile or missiles created, and their safety implications.

As a good practice, handling of heavy objects should be limited to reactor shutdown periods.

Protection against drop load hazard in spent fuel storage facility is covered in AERB safety guide titled 'Design of Fuel Handling and Storage Systems for Pressurised Heavy Water Reactors', AERB/SG/D-24.

3.3 Missiles Generated due to Natural Phenomena

Site specific design basis natural phenomena for NPP are to be identified following AERB safety code titled 'Site Evaluation of Nuclear Facilities', AERB/NF/SC/S (Rev. 1), including determination of design basis parameters of these phenomena. Tropical cyclone (extreme wind) is the only phenomenon that needs to be considered for wind-induced missiles. Structural design should take care of such missiles. For other natural phenomena like tsunami, it is assumed that proper protective barriers are built.

In case of a warning of an impending cyclone, the plant site should be cleared of loose objects that can become source of wind-induced missiles.

4. DESIGN CONSIDERATIONS FOR SECONDARY EFFECTS

4.1 General

Important cascading secondary effects which need to be considered following a primary missile effect are as follows:

(a) Radiation release

(b) Secondary missiles

(c) Fire

(d) Flooding

(e) Chemical reactions

(f) Electrical damage

(g) Damage to Instrumentation & Control lines

(h) High energy pipe failures and consequent effects of jets, whipping pipes, secondary missiles, pressure, temperature, humidity, flooding and radiation, as applicable.

(i) Falling objects

(j) Personnel injury

A systematic approach to evaluate secondary effects is given in Annexure-III.

It should be ensured that safety related functions of SSC are not jeopardized due to secondary effects.

4.2 Important Secondary Effects

4.2.1 Radiation Release

The release of radioactive material may result from the impact of a missile on items containing such material or items required for its control. Where there is a potential for such releases in excess of acceptable limits, protection shall be provided.

4.2.2 Secondary Missiles

The design missile may produce secondary missiles such as pieces of concrete or parts of components, which may do unacceptable damage. In general, it is very difficult to characterise such secondary missiles and the prudent course of action is to prevent their generation or to contain them at their source by providing barriers.

4.2.3 Fire

Missiles may result in fires, for example if by their impact they produce a source of ignition energy such as electrical spark in the proximity of flammable materials. The possibility of missile impact that can produce fires shall be evaluated. Fire protection is covered in AERB safety guide titled ‘Fire Protection in Pressurised Heavy Water Reactor Based Nuclear Power Plants’, AERB/SG/D-4.

4.2.4 Flooding

Where there is the possibility of an energetic missile striking pipes, tanks or pools normally filled with liquid, the potential for damage from flooding shall be evaluated. Flooding can cause electrical short circuit, hydrostatic pressure effects, sloshing effects, thermal shock, instrument malfunctioning, and buoyant forces.

The prudent approach is to avoid flooding by appropriate design like keeping liquid filled medium and large capacity tanks out of internal missile zone by layout considerations.

4.2.5 Chemical Reactions

The possibility of missile impacts that can release dangerous chemicals shall be evaluated. Chemical reactions of concern may include:

(a) release of flammable or explosive fluids, which can result in fire or explosions,

(b) exothermic reactions between chemicals normally kept separated,

(c) acid attack on structures or components,

(d) reactions such as rapid corrosive attack which can weaken important materials, and

(e) reactions that can release toxic materials.

The prudent course of action with regard to chemical reactions is to make P2 acceptably small.

4.2.6 Electrical Damage

The possibility of missile damage to electrical equipment shall be evaluated. The mechanism of damage can include severance of wires, destruction of equipment, or electrically initiated fires.

In designing protection against indirect damage from impact on electrical equipment, such techniques as physical separation of redundant circuits, proper application of fuses and circuit breakers, adequate fire protection, and appropriate use of barriers should all be evaluated. The course of action will be dictated by the specifics of the missile under consideration. A pessimistic failure mode should be assumed incase of electronic circuits unless the items are protected from the secondary effects.

4.2.7 Damage to Instrumentation and Control Lines

Some air or fluid operated equipment as well as some instrumentation lines needed for the monitoring or control of technical parameters may be damaged owing to the phenomena of missiles, pipe whip or jet effects. This could lead to the spurious actuation of systems or to inadequate information reaching to the operator. In designing protection against the above effects, the approach for protection against electrical damage described in clause 4.2.6 should be adopted for these lines also.

4.2.8 Failure of High-Energy Pipes and Components

Where a missile can result in the rupture of a pipe or component containing fluid with significant stored energy this fluid energy may be released in such a way as to cause further damage by any of the following means:

(a) Jets, sprays

(b) Whipping pipes

(c) Secondary missiles

(d) Pressure

(e) Temperature

(f) Humidity

(g) Flooding

(h) Radiation

Rupture of high energy piping or components may also involve a loss of coolant accident (LOCA) or other core-related accidents which may expand the scope of the required safety systems. This should be prevented. Unless it can be shown simply on the basis of the available energy and the location of the potential rupture that any one of the above mechanisms will not significantly damage required safety systems, means should be provided to prevent the missile from rupturing the pipe or component.

Where the effects mentioned above cannot be precluded, appropriate measures shall be taken. Jet impingement and pipe whip analyses are to be carried out as per Appendix-A and Annexure-I. Other effects are to be considered as per this section.

Sub-compartment pressure analysis shall be carried out for differential pressure loading resulting from high energy pipe breaks, wherever applicable.

Flooding analysis is necessary for the effects of flooding resulting from postulated piping failures. If all safety related equipment are protected by elevation, flooding analysis may not be necessary.

Release of fluid from rupture of a pipe or component containing fluid may change the environment within the plant by locally increasing the humidity, temperature, and/or pressure. It may be possible to utilise equipment that can perform their safety functions in this environment. Otherwise mitigatory measure has to be provided.

4.2.9 Falling Objects

The possibility of missile damage due to falling objects shall be evaluated. There may be circumstances where the design missile can damage a supporting structure of some heavy object located above a required safety system such that a falling-object secondary missile is created with possible further damage.

It may in certain cases be possible to show that the falling object cannot result in unacceptable damage. If not, either the supporting structure should be modified to withstand the missile impact or means should be provided to prevent the impact.

4.2.10 Personnel Injury

Missiles may directly or indirectly cause injury to plant personnel. In areas normally occupied by plant personnel performing a required safety function, the probability of missile impact shall be made acceptably small (P1 P2 P3).

5. PROTECTION METHODS AND MEANS AGAINST MISSILE EFFECTS

5.1 Reduction of the Probability of Generating a Missile (P1)

5.1.1 Design

A conservative design with rigorous design limits establishes the first level of defence against failure of components. Careful analysis of static, dynamic and thermal loads, and combinations thereof applied to the equipment, application of adequate safety factors and thorough pre-service control of material properties, and application of adequate quality assurance measures in fabrication are common practices in reducing the failure probability of the equipment.

5.1.2 In-service Inspection

In-service inspection in combination with other measures for reducing the probability of failure can provide an acceptable basis for not postulating gross failure of certain pressure piping/vessels and certain rotating equipment so that no additional design action is required to provide protection against missile generation. Design aspects of in-service inspection are covered in AERB safety guide titled 'Design for In-service Inspection', AERB/SG/D-17 (under preparation) and operational aspects in AERB safety guide titled 'In-service Inspection of Nuclear Power Plants', AERB/SG/O-2.

5.1.3 Surveillance System

The use of surveillance systems should be considered as a supplement to other means rather than a sufficient measure on their own. AERB safety guide titled 'Surveillance of Items Important to Safety in Nuclear Power Plants', AERB/SG/O-8 should be referred for details of surveillance systems.

5.1.4 Special Features to Limit the Speed of Rotating Equipment

Where there is a significant possibility of unacceptable damage from missiles, additional redundant means of limiting rotational speed may be provided by such features as governors, clutches, brakes, and a combination of instrumentation, control, and valving systems to reduce the over speed probability to an acceptable level. Details of over speed phenomena and protection measures against these are described in clause 3.2.4.

5.1.5 Other Methods and Means

Operational procedures aimed at controlling thermal and other mechanical stresses, monitoring of material characteristics, environmental conditions such as water chemistry and provision of pressure relief valves and safety features activated by the protection system to ensure that anticipated operational occurrences will not result in accident conditions are examples of other methods and means of controlling failures leading to missile generation.

5.2 Reduction of the Probability of a Missile Striking a Target Important to Safety (P2)

5.2.1 Analysis for Missile Trajectory

A first step in any approach involving the postulation of missiles from equipment failure is the analysis of the failure to determine, among other things, where the missiles may go upon being ejected. It may be possible, from study of the fracture mechanics involved, to narrow the area of investigation. For example, the maximum range of the missiles may be limited by the available energy and the mass of possible missiles.

Where the driving energy for translation is unidirectional, it is helpful in locating potential targets and deciding on appropriate design action. Examples of such missiles are valve stems, falling objects, instruments driven by jets, or whipping pipes.

In other cases there may be a most probable plane or angular sector such as in rotating machine missiles where the evidence is that energetic missiles usually start out within a very narrow angle of the plane of rotation unless there is deflection by something at the source. In this latter case tests or analysis are required in order to estimate the limits of the directions of travel.

The use of rupture mechanics may make it possible, either by review of the layout or by reorientation of equipment, to conclude that no impact on critical targets is likely to occur.

5.2.2 Special Features for Retaining or Deflecting Missiles Near Their Source

The possible need for features that can retain energetic missiles resulting from the failure of equipment, or which will deflect such missiles into a harmless direction, should be considered in the design and/or evaluation. It is also possible in some cases to add such features, as for rotating equipment. It can often be shown that the heavy steel casings of pumps and the heavy stators of motors and generators may retain or deflect the fragments that may result from a disruptive failure of the rotor.

P2 can often be reduced by means of a judicious orientation of the valve in the system. Unless this is precluded by other considerations, valve stems should be installed in such a manner that the ejection of the stem or of related parts would not result in an impact of a missile on critical targets.

5.2.3 Layout Provisions

Layout is one aspect of plant design where early consideration can be of value in reducing the overall hazard of missiles from equipment failure provided the missile characteristics including the trajectory has been determined. It is frequently possible to make P2 small by layout provisions.

A particularly instructive example is the main turbine generator. Exclusion of SSC important to safety from low trajectory turbine missile strike zones constitute adequate protection against low trajectory turbine missiles [9] (see Annexure-IV). Where there are no other constraints of overriding importance, the layout should be such that potential critical targets lie inside the area least susceptible to direct strikes from the missile generating turbine. This area constitutes a cone with its axis along the axis of the turbine shaft, formed outside 25^o of the plane of rotation. This arrangement takes account of the fact that large sections of rotors, if ejected, will tend to be expelled within 25^o of the plane of rotation.

It is often possible to lay out valves, pumps, motor generators and high pressure gas containers in locations where the only likely impact zone for a potential missile is an adequately strong concrete structure. However, provisions must be made for required maintenance and inspection of equipment.

5.2.4 Enclosures for Pipes

The provision of an unpressurised guard pipe around certain sections of piping carrying high pressure fluids can be used for containing the possible effects of rupture of a pressurised pipe or to mitigate the consequences associated with loss of the fluid in a pressurised pipe.

Guard pipes may in some circumstances be useful for missile protection too. Design of such guard pipes against missile forces from the outside adds to complications in construction, interference with in-service inspection and monitoring of inner pipe. Therefore use of enclosures of pipes for protection from missiles are reserved for cases where other engineering measures are not practical.

5.2.5 Barriers

A design approach to reduce P2 is to provide barriers between the source of missiles and the target. Barriers are also used to reduce certain secondary effects such as scabbing or even ejection of concrete blocks from concrete targets. As a special case, restraints are often provided to absorb the energy of whipping pipes where ruptures are postulated.

Evaluation of the adequacy of barriers, whether they are structures provided for other purposes or as special missile barriers, requires consideration of both local and overall missile effects on the barrier. Small missiles such as valve stems will have mainly local effects, while large slow missiles such as those possibly arising from structural collapse will have mainly overall effects. Large fast missiles as from rotating machinery may exhibit both local and overall effects. Generation of possible secondary missiles by spalling or scabbing or the ejection of blocks is to be prevented because of the unpredictable nature of the secondary missile characteristics. Some barrier design procedures against missile impact, based on ref [10], are given in Annexure-V.

5.3 Reduction of the Probability of Producing Primary or Secondary Damage with Unacceptable Consequences (P3)

In case product of P1 and P2 cannot be proven in a particular case to be acceptably small, the next approach is to make P3 acceptably small. This can be done by making a detailed analysis of the potential target impact and demonstrating that the impact and potential secondary effects do not preclude meeting the general design requirements.

5.3.1 Physical Separation of Redundant Safety Systems

If it is not possible to eliminate the generation of missiles or to layout the equipment so that possible missiles do not strike critical targets, it may be possible where redundant safety systems are involved to make use of physical separation to ensure that the general design requirements are met even if missiles damage parts of the safety systems.

It is a matter of case-by-case evaluation to determine for a particular source of missiles whether multiple safety systems can be damaged. The problem becomes even more complex when there are potential secondary effects and a missile could damage one component and the secondary effects damage its redundant mates.

In cases such as rupture of pressure vessels, explosions or over speeding of rotating machines, where possibility of spectrum of missiles exist, much more careful examination is required of any reliance for protection on target separation.

6. DOCUMENTATION

6.1 General

The evaluation of a nuclear power plant for protection against internally generated missiles shall be documented in a manner suitable for review. As a minimum, the documentation should identify the sources of energy considered, the missiles postulated, the targets evaluated, and the basis for determination of adequacy for each case.

The document should clearly state the method of analysis and the criteria used to qualify the design of relevant structures, systems and components against the postulated missile hazards.

APPENDIX-A

DESIGN CONSIDERATIONS FOR VALVE GENERATED MISSILES, PIPE WHIP FORCES AND JET IMPINGEMENT FORCES

A.1 Valve Generated Missiles

The simplest and preferred design approach for valves is to make the probability of generating a missile (P1) acceptably small. This can be achieved through appropriate valve design. Valve stems should be provided with back seats having a demonstrable capability to preclude valve stems from becoming missiles in the event of failure.

If it is found necessary, the probability of the assumed missile striking targets important to safety (P2) can also be reduced by judicious orientation of the valve in the system. Unless precluded by other considerations, valve stems should be installed in such a manner that ejection of the stem or related parts will not result in missile impact on critical targets. Proper application of the available measures to reduce P1 and P2 should result in a plant design with acceptable protection against valve missiles.

A.2 Pipe Whip Forces and Jet Impingement Forces

A broken pipe whipping under the influence of an expelling fluid can exert large impact loads similar in nature to a missile on nearby structures or components. Fluid jet emerging from a ruptured pipe and impinging on nearby structures or components can impart large impulse load. Additionally, operating experience shows that whole valves can be ejected upon pipe failure. Consequently, the possible generation of missiles due to the ejection of masses within or attached to pipes (including such items as pipe fittings and instrument wells) that have failed, constitute another design consideration.

The energy available to propel a broken pipe end is derived from the internal energy in the fluid contained in the system. A detailed analysis of the system transient is necessary to quantify the forces with precision. If pipe deflections are kept small by physical restraints, designs of pipe restraints based on equivalent static loads are usually adequate.

The characteristics of the broken pipe come directly from the system design and the location and type of postulated rupture. In case of pipe whip it is usually conservative to assume a full circumferential rupture and to assume the pipe will form a hinge at the nearest rigid restraint.

Although the probability of severe pipe rupture in NPP piping systems is generally accepted to be low, it is usual practice to restrict the motion of broken pipes at selected locations by the use of physical restraints and to include jet impingement in the design loadings for structures and components located near high energy piping.

The following design bases should be considered in determination of the dynamic effects associated with the pipe rupture (not applicable to piping qualified for LBB).

(a) The assumptions used in conducting pipe break analyses should be compatible with various postulations made in safety evaluation, for example, unavailability of offsite power, single active component failure, feasibility of operator action, redundant systems, etc.

(b) An unrestrained whipping pipe shall be considered capable of rupturing impacted pipes of smaller nominal pipe sizes, and developing through-wall leakage cracks in equal or larger nominal pipe sizes with thinner wall thickness.

(c) Jet impingement forces from a given pipe of specified nominal pipe size and wall thickness shall be considered capable of rupturing targeted pipes of smaller nominal pipe size, and developing through-wall leakage cracks in pipe of larger nominal pipe size and thinner wall thickness.

(d) The functional capability of systems and equipment required to fulfil the requirements of clause 2.1 after a given break must not be impaired by the pipe whip, jet impingement or environmental conditions resulting from that break.

(e) Damage to any structure, directly caused by the pipe whip, jet impingement or environmental consequences of a given break, must not impair the function of any system or equipment required to fulfill the requirements of clause 2.1.

(f) The effects of a postulated failure, including radiation and environmental conditions do not preclude habitability of the control room or any location where manual action is required to fulfil the requirements of clause 2.1. The structural integrity of these areas shall be preserved.

(g) The design leak-tightness integrity of the containment is preserved.

ANNEXURE-I

ANALYSIS OF PIPEWHIP AND JET IMPINGEMENT FORCES FROM PIPEBREAKS

I.1 Dynamic Analysis Criteria

An analysis of the dynamic response of the piping should be performed for each longitudinal and circumferential postulated piping break. The loading condition of the piping, prior to the postulated rupture, in terms of internal pressure, temperature, and inertial effects should be used in the evaluation for postulated breaks.

Dynamic analysis methods used for calculating piping and restraint system responses to the jet thrust developed following the postulated rupture should adequately account for the following effects:

(a) Mass inertia and stiffness properties of the system

(b) Impact and rebound

(c) Elastic and inelastic deformation of piping and restraints, and

(d) Support boundary conditions

I.2 Dynamic Analysis Models for Piping Systems

Analysis should be conducted of the postulated ruptured pipe and pipe whip restraint system response to the fluid dynamic force.

Acceptable models for the analysis of high energy piping systems include the following:

(a) Lumped Parameter Analysis Model: Lumped mass points are inter-connected by springs to take into account inertia and stiffness properties of the system, and time histories of responses are computed by numerical integration, taking into account clearances at restraints and inelastic effects. In the calculation, the maximum possible initial clearance should be used to account for the most adverse dynamic effects of pipe whip.

(b) Energy Balance Analysis Model: Kinetic energy generated during the first quarter cycle movement of the rupture pipe and imparted to the piping and restraint system through impact is converted into equivalent strain energy. In the calculation the maximum possible initial clearance at restraints should be used to account for the most adverse dynamic effects of pipe whip. Deformations of the pipe and the restraint should be compatible with the level of absorbed energy. The energy absorbed by the pipe deformation may be deducted from the total energy imparted to the system. For applications where pipe rebound may occur upon impact on the restraint, an amplification factor of 1.1 should be used to establish the magnitude of the forcing function in order to determine the maximum reaction force of the restraint beyond the first quarter cycle of response. Amplification factors other than 1.1 may be used if justified by more detailed dynamic analysis.

(c) Static Analysis Model: The jet thrust force is represented by a conservatively amplified static loading, and the ruptured system is analyzed statically. An amplification factor can be used to establish the magnitude of the forcing function. However, the factor should be based on a conservative value obtained by comparison with factors derived from detailed dynamic analyses performed on comparable systems.

(d) Other models may be considered if justified.

I.3 Dynamic Analysis Models for Jet Thrust

(a) The time-dependent function representing the thrust force caused by jet flow from a postulated pipe break or crack should include the combined effects of the following:

(i) The thrust pulse resulting from the sudden pressure drop at the initial moment of pipe rupture

(ii) The thrust transient resulting from wave propagation and reflection

(iii) The blow down thrust resulting from buildup of the discharge flow rate, which may reach steady state if there is a fluid energy reservoir having sufficient capacity to develop a steady jet for a significant interval.

Alternatively, a steady state jet thrust function may be used, as outlined in I.3 (d) below.

(b) A rise time not exceeding one millisecond should be used for the initial pulse, unless a combined crack propagation time and break opening time greater than one millisecond can be substantiated by experimental data or analytical theory based on dynamic structural response.

(c) The time variation of the jet thrust forcing function should be related to the pressure, enthalpy, and volume of fluid in the upstream reservoir, and the capability of the reservoir to supply a high energy flow stream to the break area for a significant interval. The shape of the transient function may be modified by considering the break area and the system flow conditions, the piping friction losses, the flow directional changes and the application of flow limiting devices.

(d) The jet thrust force may be represented by a steady state function if the energy balance model or the static model is used in the subsequent pipe motion analysis. In either case, a step function amplified as indicated in I.2 (b) or I.2 (c) above is acceptable. The function should have a magnitude not less than

$$T = KpA$$

where

T = Steady state function for jet thrust force

p = System pressure prior to pipe break

A = Pipe break area, and

K = Thrust coefficient

To be acceptable, K values should not be less than 1.26 for steam, saturated water, or steam-water mixtures, or 2.0 for subcooled, nonflashing water.

I.4 Jet Impingement Forces

Analyses of jet impingement forces should show that jet impingement loadings on nearby safety-related structures, systems, and components will not be such as to impair or preclude essential functions as stated in clause 2.1.1. Assumptions in modeling and analysis should be defined and justified.

ANNEXURE - II

REACTOR COOLANT PUMP FLYWHEEL INTEGRITY

II.1 Introduction

During operation at normal speed, a flywheel has sufficient kinetic energy to produce high-energy missiles and excessive vibration of the reactor coolant pump assembly if the flywheel should fail. Over speed of the pump rotor assembly during a transient increases both the potential for failure and the kinetic energy of the flywheel.

If the flywheel of the reactor coolant pump is conservatively designed and made from suitable materials with closely controlled quality, if adequate design review of new configurations is provided, and if adequate in-service inspection is provided, the probability of a flywheel failure is sufficiently small that the consequences of failure need not be protected against.

Materials for pump flywheels should be manufactured by processes that minimise flaws and result in adequate fracture toughness in both the transverse and longitudinal rolling directions. Materials produced by vacuum melting and degassing or the electroslag remelting process are shown to have improved cleanliness and toughness.

Quantitative estimates of the margins against fracture or excessive deformation during overspeed, as described below, coupled with adequate provisions against overspeed, provide the best basis for assurance that the probability of failure under normal and transient conditions is sufficiently small that the consequences of failure need not be protected against.

II.2 Protection Measures

II.2.1 Material and Fabrication

(a) The flywheel material should be of closely controlled quality. Plates should conform to ASTM A20 and forgings should conform to ASTM A508 Grade 4N, Class 1 or Class 2.

(b) Fracture toughness and tensile properties of flywheel material should be checked by tests that yield results[4] suitable to confirm the material properties used in the fracture analyses of the flywheel called for in II.2.2(c), (d) and (e).

4 These results should be included as part of the Final Safety Analysis Report (FSAR).

(c) All flame-cut surfaces should be removed by machining to a depth at least 12 mm (1/2 inch) below the flame-cut surface.

(d) Welding, including tack welding and repair welding, should not be permitted in the finished flywheel unless the welds are inspectable and considered as potential sources of flaws in the fracture analysis.

II.2.2 Design

(a) The flywheel assembly, including any speed-limiting and anti rotation devices, the shaft, and the bearings, should be designed to withstand normal conditions, anticipated transients, the design basis loss of coolant accident, and the Safe Shutdown Earthquake loads without loss of structural integrity.

(b) Design speed should be at least 125% of normal speed but not less than the speed that could be attained during a turbine over speed transient. Normal speed is defined as the synchronous speed of the A.C. drive motor at 50 Hz.

(c) An analysis should be conducted to predict the critical speed for ductile fracture of the flywheel. The methods and limits of paragraph F-1323.1 (b) or corresponding paragraph of latest edition in Section III of the ASME Code are acceptable. If another method is used, justification should be provided. The analysis should be submitted for evaluation[5].

(d) An analysis should be conducted to predict the critical speed for non ductile fracture[6] of the flywheel. Justification should be given for the stress analysis method, the estimate of flaw size and location, which should take into account initial size and flaw growth in service,

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5 The analyses outlined in II.2.2(c), (d) and (e) should preferably be submitted in topical reports rather than on a case-by-case basis for those flywheel designs that will have multiple applications.

6 The non-ductile fracture analysis should be based on appropriate conservative assumptions for stress level, flaw size, temperature, and fracture toughness at the location of interest. The non-ductile fracture criterion used to predict the critical fracture speed should be based on initial instability of the flaw as defined in ASTM E-399. The justification for the stress analysis method used in the fracture analysis should describe the treatment of stresses arising from interference fits and thermal stresses when they are superimposed on the stresses caused by rotational forces. Justification for the flaw size estimate should consider it to be the maximum expected size of flaw that could conceivably escape detection, and should consider material thickness, method and frequency of nondestructive inspection, and analysis of flaw growth in fatigue if that is significant. The effect of cracks emanating from such structural discontinuities

and the values of fracture toughness assumed for the material. The analysis should be submitted for evaluation[5].

(e) An analysis should be conducted to predict the critical speed for excessive deformation[7] of the flywheel. The analysis should be submitted for evaluation[5].

(f) The normal speed should be less than one-half of the lowest of the critical speeds calculated in II.2.2(c), (d) and (e) above.

(g) The predicted LOCA over speed should be less than the lowest of the critical speeds calculated in II.2.2(c), (d) and (e).

II.2.3 Testing

Each flywheel assembly should be spin tested at the design speed of the flywheel.

II.2.4 Inspection

(a) Following the spin test described in II.2.3 above, each finished flywheel should receive a check of critical dimensions and a nondestructive examination as follows:

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as keyways and bolt holes should be evaluated. Justification for the fracture toughness assumed for the material should describe the properties to be measured transverse to the rolling direction in the tests of each plate of material. The range of fracture toughness test temperatures should include the lowest service temperature at which overspeed could occur. If not, the basis used for any extrapolation should be justified.

In doing the fracture analysis, engineering judgment should be used to select for analysis only those locations that appear to have the most severe sets of conditions. Severity is a function of stress level, flaw size, and fracture toughness at the location of interest. Comparison of perhaps three or four cases in terms of K_1/K_{1C}, the ratio of the imposed stress intensity factor at some nominal speed to the material toughness, should locate to most severe sets of conditions. Evaluation of the critical speed for fracture, which may require techniques that go beyond linear elastic fracture mechanics, may then focus on one critical location.

7 Excessive deformation during over speed of the flywheel is of concern becaus e damage could be caused by separation of the flywheel from the shaft. For the purpose of this guide, excessive deformation means any deformation such as an enlargement of the bore that could cause such separation directly or could cause an unbalance of the flywheel leading to structural failure or separation of the flywheel from the shaft. The calculation of deformation should employ elastic plastic methods unless it can be shown that stresses remain within the elastic range.

(i) Areas of higher stress concentrations, e.g. bores, keyways, splines, and drilled holes, and surfaces adjacent to these areas on the finished flywheel should be examined for surface defects in accordance with paragraph NB-2545 NB-2546 of Section III of the ASME Code using the procedures of paragraph NB-2540. No linear indications more than 1.6 mm (1/16 inch) long, other than laminations, should be permitted.

(ii) Each finished flywheel should be subjected to a 100% volumetric examination by ultrasonic methods using procedures and acceptance criteria specified in paragraph NB-2530 (for plates) or paragraph NB-2540 (for forgings) of Section III of the ASME Code.

(b) In-service inspections[8] should be performed for each flywheel as follows:

(i) An in-place ultrasonic volumetric examination of the areas of higher stress concentration at the bore and keyway at approximately 3 to 4 years intervals, during the refueling or maintenance shutdown or planned shutdown, as applicable, coinciding with the in-service inspection schedule as required by Section XI of the ASME Code.

(ii) A surface examination of all exposed surfaces and complete ultrasonic volumetric examination at approximately 10-year intervals, during the plant shutdown coinciding with the in-service inspection schedule as required by Section XI of the ASME Code.

(iii) Examination procedures should be in accordance with the requirements of Sub article IWA-2200 of Section XI of the ASME Code.

(iv) Acceptance criteria should conform to the recommendations II.2.2(f).

(v) If the examination and evaluation indicate an increase in flaw size or growth rate greater than predicted for the service life of the flywheel, the results of the examination and evaluation should be submitted to regulatory body for evaluation.

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8 The geometry of the flywheel and pump motor design should facilitate pre service and in-service inspection of all high-stress regions (bore, keyway, and bolt hole regions) without the need for removal of the flywheel from its shaft and preferably without the need for removing the rotor from the motor assembly.

ANNEXURE-III

TYPICAL EXAMPLE OF AN INTERNALLY GENERATED MISSILE DESIGN CHECKLIST

III.1 General

This annexure demonstrates the use of a checklist for a typical evaluation of a postulated missile hazard for the purpose of determining the adequacy of the design. In practice all factors of the hazard and relevant plant details must be carefully considered.

This checklist is a convenient means of organizing the evaluation of the effects of internally generated missiles. The checklist is based on an assumed initial equipment failure in a valve in a steam line in a PHWR for the purpose of illustration. The checklist is not intended to convey all the information relative to the evaluation but merely to serve as an index or outline of the possibilities considered and the conclusions reached regarding each. The checklist may be supplemented by notes or reference to other material such as calculation records, reports, drawings, failure diagrams based on failure trees, etc., as may be judged appropriate.

Fig. III-1 depicts the consequences of a postulated equipment failure and the various safety features. The possibility of missile generation, and the primary and secondary effects of the missile on equipment and safety systems are also taken into account. This information helps in deciding the adequacy of protection against missile effects.

III.2 Typical Design Checklist

Table III-1 is an example of a typical worksheet that may be useful in organising and defining a specific missile problem and documenting its resolution.

The initially failed valve is listed in column 1 of Table III-1 and again in column 6. Column 2 lists the characteristics of the missile, in this case the valve stem that is generated.

For the purpose of this illustration, only the missile effects resulting from the valve stem ejection are considered. Effects of steam or steam-water jets and their associated secondary effects are not dealt with.

Various primary targets that might be struck by this valve stem missile are listed in column 3.

Columns 4 and 5 characterise the secondary effects and identify possible secondary targets.

Column 6 is a list of all the failed equipment, namely the initially failed equipment (valve in the steam line), the primary targets that fail and the subsequent failures due to secondary effects.

Columns 7 to 11 inclusive are directed at assessing the adequacy of the safety systems to cope with the failures listed in column 6.

Column 11 is a test to see whether the degree of redundancy of the safety systems is adequate. The degree of redundancy is adequate when the redundancy provided in the original design less the loss in redundancy due to various failures (column 9) and the loss due to other design assumptions (column 10) result in a number equal to or greater than one.

Column 12 describes the protection required.

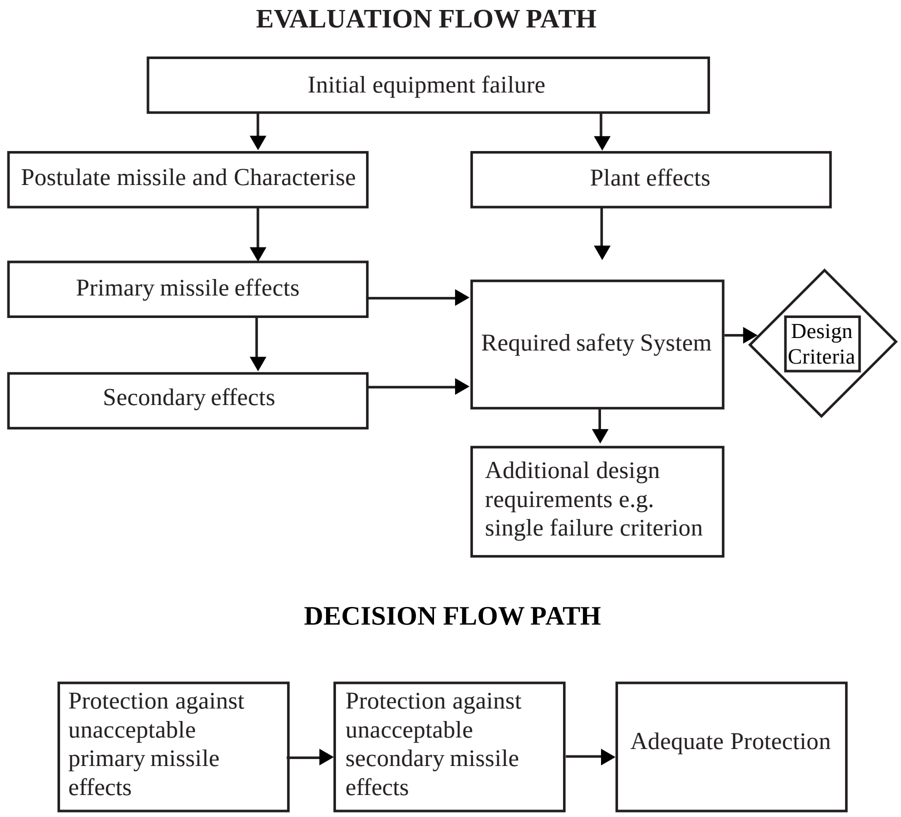

Fig. III-1 : Evaluation and Decision Flow Path in Determining Adequate Missile Protection

TABLE III.1 : MISSILE EVALUATION WORK SHEET

1	2	3	4	5	6	7	8	9			10	11		12
Identify Failed equip-ment	Characte-rise Missile (s)	Identify Primary Targets (and damage caused by missiles) if no failure occur proceed to column 6	Characte-rise Secondary effects	Identify Secondary targets (if no failure occurpro-ceed to column 6)	List failed Equipment From Columns 1,3 and 5	List Safety Equipment/ System Required to Mitigate Effects of Failures Identified in column 6	List Degree of Redundancy Provided in Design for Systems in Column 7	Identify Loss of Redun-dancy from Failures Occurring in Column 1,3 and 5			Identify loss of Redundancy from Additional Design Require-ments	Is column 8 minus columns 9 and 10 ≥ 1		Protection required
												Yes	No	
								1	3	5		Design adequate	Design inadequate	
MSIV in Steam Line (Outside R.B.)	Valve stem	Emergency Feed water storage Tank	AFW not available	None	MSIV, Emergency Feed water storage Tank	Fire Water System Pumps Valves & Piping	1 Alternate routes of supply for SG cooling provided	0 0	0 0	0 0	N.A	Yes		123 m floor opening can be provided with concrete cover
ASDV in steam line (outside R.B.)	Valve stem	Air Supply tanks for valve operation	---	---	Air Supply Tanks	---	---	0	0	0		Yes		None

ANNEXURE-IV

TYPICAL EXAMPLE OF PROTECTION AGAINST TURBINE MISSILES

IV.1 General

Turbine missiles can be broadly classified as low trajectory and high trajectory missiles. The high trajectory missiles are ejected upward through the turbine casing and may cause damage if the falling missile strikes an essential system. Low trajectory or direct missiles are ejected from the turbine casing directly towards an essential system [9]. Such missile with sufficient energy may damage the intervening structures, systems or components.

IV.2 Low Trajectory Turbine Missiles

The following specific information is necessary in order to assess the protection against low trajectory turbine missiles:

(a) Dimensioned plant layout drawings

(b) Barriers (e.g., structural wall material strength properties, thickness)

(c) Identification of safety-related structures, systems, and components in terms of location, redundancy, and independence

(d) Identification of all turbine-generator units (present and future) in the vicinity of the plant and quantitative description of the turbine-generator in terms of rotor shaft, wheels, steam valve characteristics, rotational speed and turbine internals pertinent to turbine missiles analyses. Postulated missiles should be identified in terms of missile size, mass, shape, and exit speed for design over speed and destructive over speed turbine failures. A description should be provided of the analysis used in estimating the missile exit speeds. The sense of rotation should be identified with respect to each turbine-generator under consideration.

The probability of unacceptable damage resulting from turbine missile is expressed as [11]:

$P = P1 \times P2 \times P3$

where

P = Probability of unacceptable damage resulting from turbine missiles

P1 = Probability of turbine failure resulting in the ejection of turbine rotor (or internal structure) fragments through the turbine casing

P2 = Probability of ejected missiles perforating intervening barriers and striking safety-related structures, systems, or components and

P3 = Probability of struck structures, systems, or components failing to perform their safety function, P3.

The probability of unacceptable damage from turbine missiles should be less than or equal to 1 in million per year for an individual plant (i.e., P should be $< 10^{-6}$ per year per plant).

In general, two modes of turbine rotor failure can result in turbine missile generation; (a) rotor material failure at approximately the rated operating speed and (b) failure of the over speed protection system. Failure of turbine rotors at or below the design speed (nominally, 120% of normal operating speed) can be caused by small flaws or cracks that grow to critical size during operation. Failure of the turbine rotors at destructive over speed (about 180% to 190% of normal operating speed) can result from failure of the over speed protection system.

The missile generation probability at the design speed should be related to rotor design parameters, material properties, and the intervals of in-service examinations of disks. The missile generation probability at the destructive over speed should be related to the speed sensing and tripping characteristics of the turbine governor and over speed protection system, the design and arrangement of main steam control and stop valves, the reheat steam intercept, reheat stop valves, and the in-service testing and inspection intervals for system components and valves.

The material properties of the turbine casing are of interest because secondary missiles could be generated if the casing fails or, alternatively, the casing could serve to arrest and contain missiles. The turbine casing material in its operational environment should be evaluated for fracture toughness properties.

Maintaining an acceptably low missile generation probability, P1, by means of a suitable program of periodic testing and inspection is a reliable method for ensuring that the objective of precluding generation of turbine missiles (and hence the possibility of damage to safety-related structures, systems, and components by those missiles) can be met.

The safety objective for turbine missiles (i.e., P should be $< 10^{-6}$ per year per plant) is best expressed in terms of either of two sets of criteria applied to missile generation probability, P1 (see Table IV-1) appropriate to the applicable turbine orientation. One set of criteria should be applied to favorably oriented turbines; the other should be applied to unfavorably oriented turbines.

Favorably oriented turbine generators are those that are located such that the containment and all, or almost all, safety-related SSCs outside containment are excluded from the low-trajectory hazard zone. The low-trajectory hazard zone is generally taken to be the area within 25 degrees of the first and the last low pressure stages as measured from the plane of the wheels, see Fig. IV-1[9].

The design, inspection, and operating conditions should provide assurance that the probability of turbine missile generation will not exceed those described in Table-IV-1.

This approach places responsibility on the applicant for initially demonstrating, and thereafter maintaining specified turbine reliability. Accordingly, the applicant should commit to conduct appropriate in-service inspection and testing throughout the life of the plant. Accordingly, the applicant should demonstrate the capability to perform visual, surface, and volumetric (ultrasonic) examinations suitable for in-service inspection of turbine rotors and shafts and provide reports, as required, describing the applicant's methods for determining turbine missile generation probabilities for review and approval of the regulatory body.

An in-service inspection program should be used to detect rotor or disk flaws that could lead to brittle failure at or below design speed in the steam turbine rotor assembly. The turbine rotor design should facilitate in-service inspection of all high-stress regions, including disk bores and keyways, without removal of the disks from the shaft. The volumetric in-service inspection interval for the steam turbine rotor assembly should be established according to the following guidance:

(i) The initial inspection of a new rotor or disk should be performed before any postulated crack is calculated to grow to more than one-half the critical crack depth. If the calculated inspection interval is less than the scheduled first fuel cycle or planned shutdown, as applicable, the applicant should seek the manufacturer's guidance on delaying the inspection until the first refueling outage or planned shutdown, as applicable. If the calculated inspection interval is longer than the first fuel cycle or planned shutdown, as applicable, the applicant should seek the manufacturer's guidance for scheduling the first inspection during a later refueling outage or planned shutdown, as applicable.

(ii) Disks that have been inspected and found free of cracks or that have been repaired to eliminate all indications of cracks should be re-inspected using the criterion described in (i) above. Crack growth should be calculated from the time of the last inspection.

(iii) Disks operating with known and measured cracks should be re-inspected before the elapse of one-half the time calculated for any crack to grow to one-half the critical depth. The guidance described in (i) above should be used to set the inspection date on the basis of the calculated inspection interval.

(iv) Under no circumstances should the volumetric in-service inspection interval for low-pressure (LP) disks exceed 3 years or two fuel cycles or two planned shutdowns, as applicable, whichever is longer.

In accordance with the manufacturer's procedures, the turbine in-service inspection program should use visual, surface, and volumetric examinations to inspect turbine components such as couplings, coupling bolts, LP turbine shafts, blades and disks, and high-pressure (HP) rotors. Shafts and disks with crack(s) having depths at or near one-half the critical crack depth should be repaired or replaced. All cracked couplings and coupling bolts should be replaced.

The in-service inspection and test program should be used for the governor and over speed protection system to provide further assurance that flaws or component failures will be detected in the over speed sensing and tripping subsystems, main steam control and stop valves, reheat steam intercept and stop valves, or extraction steam non-return valves — any of which could lead to an over speed condition above that specified by the design over speed. The in-service inspection program for operability of the governor and over speed protection system should include, at a minimum, the following provisions:

(i) For typical turbine governor and over speed protection systems, at intervals of approximately 3 to 4 years during refueling or maintenance shutdown or planned shutdown, as applicable, at least one main steam control valve, one main steam stop valve, one reheat intercept valve, one reheat stop valve, and one of each type of steam extraction valve should be dismantled for examination. Visual and surface examinations of valve seats, disks, and stems should be conducted. Valve bushings should be inspected and cleaned, and bore diameters should be checked for proper clearance. If any valve is shown to have flaws or excessive corrosion or improper clearances, the valve should be repaired or replaced. All other valves of that type should also be dismantled and inspected.

(ii) At least once a week during normal operation, main steam control and stop valves, reheat intercept and stop valves, and steam extraction non return valves should be exercised by closing each valve and observing directly the valve motion as it moves smoothly to a fully closed position.

(iii) At least once a month during normal operation, each component of the electro-hydraulic governor system (which modulates control and intercept valves), as well as the primary and backup over speed trip devices (both of which trip the main steam control and stop valves and the reheat intercept and stop valves) should be tested.

The online test failure of any one of these subsystems mandates repair or replacement of failed components within 72 hours. Otherwise, the turbine should be isolated from the steam supply until repairs are completed.

Because of the uncertainties associated with calculating P2 and P3, such analyses are 'order of magnitude' calculations only. On the basis of simple estimates for a variety of plant layouts, the strike and damage probability product can be reasonably assumed to fall in a range that depends on the gross features of turbine generator orientation. For favorably oriented turbine generators, the product of P2 and P3 tends to be in the range of 10^{-4} to 10^{-3} per year per plant. For unfavorably oriented turbine generators, the product of P2 and P3 tends to be in the range of 10^{-3} to 10^{-2} per year per plant.

The regulatory body does not generally encourage calculations for P2, P3, or their product because of assumptions and modeling difficulties in these probabilistic calculations. Instead, products of strike and damage probabilities of 10^{-3} per year per plant for a favorably oriented turbine and 10^{-2} per year per plant for an unfavorably oriented turbine are considered as acceptable values.

An applicant may propose to install barriers or to take credit for existing structures or features as barriers. Such a decision could be based on the applicant's deterministic judgment that a structure, system or component is particularly vulnerable to destruction or unacceptable damage in the event of a turbine failure. The applicant should include specific details in the safety analysis report (SAR) supporting the need for such protection. If an applicant proposes to design or evaluate barriers to reduce or eliminate turbine missile hazards to equipment, the barriers should meet the applicable criteria.

IV.3 High Trajectory Turbine Missiles

High trajectory turbine missiles are characterised by their nearly vertical trajectories. Missiles ejected more than a few degrees from the vertical, either have sufficient speed such that they land offsite, or their speeds are low enough so that their impact on most plant structures is not a significant hazard.

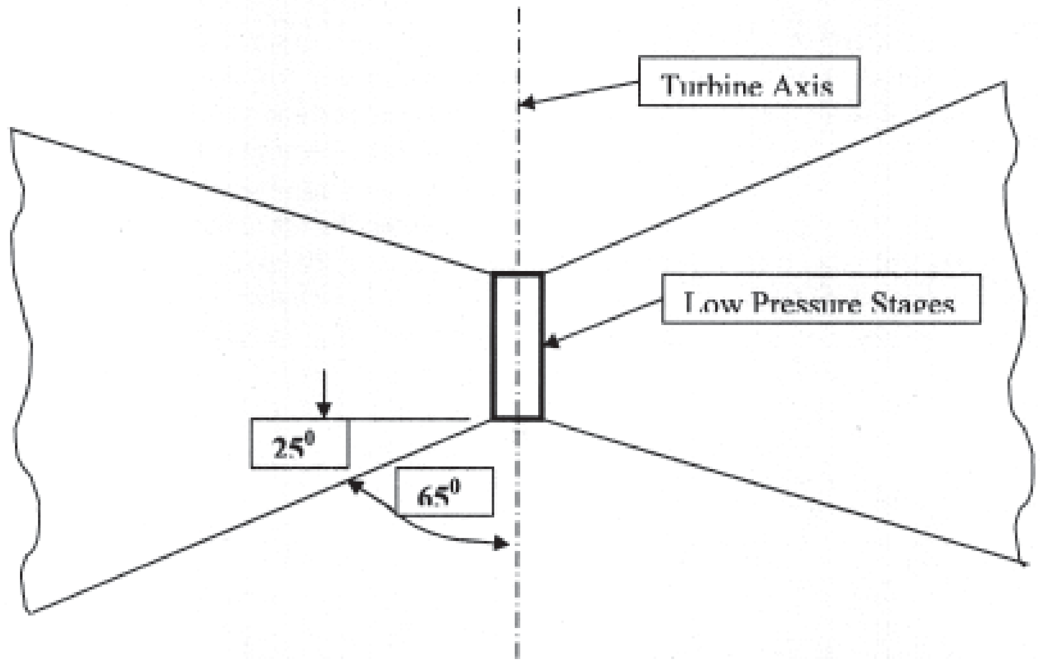

Fig. IV-1 : Low Trajectory Turbine Missile Strike Zone

TABLE IV-1

Probability of Turbine Failure Resulting in the Ejection of Turbine Rotor (or Internal Structure) Fragments Through the Turbine Casing (P1) and Recommended Actions

Case	PROBABILITY PER YEAR FOR A FAVORABLY ORIENTED TURBINE	PROBABILITY PER YEAR FOR AN UNFAVORABLY ORIENTED TURBINE	**RECOMMENDED ACTION**
A	$P1 < 10^{-4}$	$P1 < 10^{-5}$	This condition represents the general, minimum reliability requirement for loading the turbine and bringing the system on line.
B	$10^{-4} < P1 < 10^{-3}$	$10^{-5} < P1 < 10^{-4}$	If this condition is reached during operation, the turbine may be kept in service until the next scheduled outage, at which time the applicant must take action to reduce P1 to meet the appropriate Case A criterion before returning the turbine to service.
C	$10^{-3} < P1 < 10^{-2}$	$10^{-4} < P1 < 10^{-3}$	If this condition is reached during operation, the turbine must be isolated from the steam supply within 60 days, at which time the applicant must take action to reduce P1 to meet the appropriate Case A criterion before returning the turbine to service.
D	$10^{-2} < P1$	$10^{-3} < P1$	If this condition is reached during operation, the turbine must be isolated from the steam supply within 6 days, at which time the applicant must take action to reduce P1 to meet the appropriate Case A criterion before returning the turbine to service.

ANNEXURE-V

TYPICAL EXAMPLES OF BARRIER DESIGN PROCEDURES

V.1 General

Barriers are designed to withstand the effects of missile impact. The local effect of missile impact is evaluated for depth of penetration into the barriers, perforating potential, and spalling or scabbing effects caused by missile impact. The overall effects are evaluated for response of the structure or target, and portions thereof to missile impact. Missiles are assumed to strike the barriers normal to the surface, and the axis of each missile is assumed to be parallel to the line of flight. These assumptions result in a conservative estimate of missile effects on barriers.

Specific criteria necessary to meet the relevant requirements of design are described below.

V.2 Local Damage Prediction

V.2.1 Concrete Barriers

Sufficient thickness of concrete should be provided to prevent unacceptable perforation, punching shear effect, spalling, or scabbing of the barriers in the event of missile impact.

For turbine missile barriers, penetration and scabbing predictions should be based on applicable empirical equations or the results of a valid test program. Thickness resulting from such calculations should in no case be less than that necessary to protect against missiles generated by a tropical cyclone, wherever relevant, unless supported by justification including test data.

Some typical empirical formulae are described below:

V.2.1.1 Penetration and Spalling

The penetration and the spalling thickness for pipe missiles and solid steel cross section missiles, such as a 25mm steel rod are estimated by using the formulae[9]

$$x = \left[220\ KNWd \left[\frac{v_o}{12d}\right]^{1.8}\right]^{\frac{1}{2}} \qquad \text{for } \frac{x}{d} \leq 2.0 \qquad (1a)$$

or

$$x = 55\ KNW \left[\frac{v_o}{12d}\right]^{1.8} + d \qquad \text{for } \frac{x}{d} > 2.0 \qquad (1b)$$

where

N	=	missile shape factor
	=	0.72 flat nosed bodies
	=	0.84 blunt nosed bodies
	=	1.00 average bullet nose (spherical end)
	=	1.14 very sharp nose
K	=	concrete penetrability factor = $\dfrac{16.5}{\sqrt{f_{ck}}}$
d	=	missile diameter (mm). All of the experimental and theoretical work concerned with local impact effects has been developed for cylindrical projectiles. For missiles with noncircular cross-sections, "d" is the diameter of an equivalent solid cylindrical shaped missile with the same contact surface area as the contact surface area of the actual missile.
v_o	=	striking velocity of missile (m/s).
W	=	missile weight (kg).
x	=	total penetration depth (mm), the depth which a missile penetrates into an infinitely thick target.
f_{ck}	=	characteristic cube compressive strength of concrete (MPa) [assuming cylinder compressive strength ≈ 0.8 times cube compressive strength].

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9 These formulae are derived from the modified National Defense Research Committee (NDRC) formulae [12,13]:

$x = [4\ KNW\ d\ (v_o/1000\ d)^{1.80}]^{1/2}$ for $x/d \leq 2.0$ or

$x = KNW\ (v_o/1000\ d)^{1.80} + d$ for $x/d \geq 2.0$

where

N	=	missile shape factor
	=	0.72 flat nosed bodies
	=	0.84 blunt nosed bodies
	=	1.00 average bullet nose (spherical end)
	=	1.14 very sharp nose
K	=	concrete penetrability factor = $180/(f'_c)^{\frac{1}{2}}$
d	=	missile diameter (in.).
v_o	=	striking velocity of missle (fps).:
W	=	missile weight (lbs).
x	=	total penetration depth (in).
f'_c	=	specified compressive strength of concrete, psi.

As defined herein, the penetration depth neglects all rear boundary effects and is applicable only when the target thickness is sufficiently great to prevent rear face scabbing.

To prevent perforation and scabbing of the concrete walls or slabs, the thickness of the concrete is determined by using the following equations:

$$\frac{e}{d} = 3.19\left[\frac{x}{d}\right] - 0.718\left[\frac{x}{d}\right]^2 \qquad \text{for } \frac{x}{d} \leq 1.35 \tag{2a}$$

$$\frac{s}{d} = 7.91\left[\frac{x}{d}\right] - 5.06\left[\frac{x}{d}\right]^2 \qquad \text{for } \frac{x}{d} \leq 0.65 \tag{2b}$$

$$\frac{e}{d} = 1.32 + 1.24\left[\frac{x}{d}\right] \qquad \text{for } 1.35 \leq \frac{x}{d} \leq 13.5 \tag{2c}$$

$$\frac{s}{d} = 2.12 + 1.36\left[\frac{x}{d}\right] \qquad \text{for } 0.65 \leq \frac{x}{d} \leq 11.75 \tag{2d}$$

where

e = perforation thickness (mm), which is the maximum thickness of a target which a missile with a given impact velocity will completely penetrate. Theoretically, the exit velocity of the missile is equal to zero. For concrete, the perforation thickness is considerably greater than the penetration depth “x” due to scabbing of concrete from the rear face of the target.

s = scabbing thickness (mm). The thickness of the target required to prevent scabbing of material from the rear face of the target for a missile with a given impact velocity.

V.2.1.2 Punching Shear

Whenever applicable, punching shear capacity of concrete barriers may be established on the basis of any international code for design of nuclear safety related concrete structures such as ACI 349 [14] or Long’s criteria for punching shear capacity [15].

Concrete barriers may also be assessed for safety against local missile effects such as perforation, penetration and scabbing due to hard missile impact following guidelines given in reference [16] with due consideration of the limitations of applicability of the empirical relations, use of appropriate safety factors to account for the scatter of experimental data with respect to the empirical relations and with additional safety margin (i.e. conservatism) to account for other uncertainties, as recommended in the reference [16].

V.2.2 Steel Barriers

Steel barriers are designed to prevent perforation of the barrier. Local damage resulting from cylindrical missile impact is predicated using the *Ballistic Research Laboratory Formula* given below:

$$T^{\frac{3}{2}} = \frac{3.5\, MV^{\,2}}{\left[K^{2} D^{\frac{3}{2}}\right]} \tag{3}$$

where

T = thickness to be penetrated (mm)

M = mass of missiles (kg-s^2/m)

V = velocity of missiles (m/s)

D = diameter of missiles (mm)

K = constant depending on the grade of steel (usually about one).

V.2.3 Multiple Element Barriers

For multiple missile barriers, residual velocity of the missile perforating the first element is considered as the striking velocity for the next element. The residual velocity is obtained from the differences between the kinetic energy of the missile before impact and the energy required to perforate the first barrier. The residual velocity is calculated as [17,18]:

$$V_r = [V_s^{a} - V_p^{a}]^{\frac{1}{a}} \qquad \text{for } V_p \leq V_s \tag{4a}$$

$$V_r = 0 \qquad \text{for } V_p \geq V_s \tag{4b}$$

where

V_r = residual velocity of missile after perforation of an element

V_s = striking velocity of missile

V_p = velocity required to just perforate an element

a = power of velocity in the equation for penetration (1.8 for a multiple element barrier where the first element is steel and 2.0 where the first element is concrete are considered acceptable values).

V.3 Overall Damage Prediction

The overall structural capacity of both concrete and steel barriers is determined to preclude structural collapse of the barrier under missile impact loading.

The response of a structure or barrier to missile impact depends largely on the location of impact (e.g., mid span of a slab or near a support), on the dynamic properties of the target and missile, and on the kinetic energy of the missile. In general, the assumption of plastic collisions is acceptable, where all of the missile initial momentum is transferred to the target and only a portion of its kinetic energy is absorbed as strain energy within the target. However, where elastic impacts are expected, the additional momentum transferred to the target by missile rebound should be included.

After it has been demonstrated that the missile will not penetrate the barrier, an equivalent static load concentrated at the impact area should then be determined, from which the structural response, in conjunction with other design loads, can be evaluated using conventional design methods.

Values given in [10] may be used for maximum allowable ductility ratios for steel and reinforced concrete barriers and other structural elements if used in the above analysis.

For all reinforced concrete or steel structural elements or systems of elements subjected to impactive loads (i.e., wind induced missiles), the structural response is determined by using one of the following methods:

(a) The dynamic effects of the impactive loads is considered by calculating a dynamic load factor (DLF). The available resistance to the impactive load must be at least equal to the peak of the impactive load multiplied by the DLF.

(b) Dynamic effects of impactive loads are considered by using impulse, momentum, and energy balance techniques, as detailed in reference [19]. For concrete barriers, strain energy capacity is limited by the ductility criteria as given in ACI 349 [14]. For steel barriers, the maximum allowable ductility is the extreme fiber strain at the onset of strain hardening divided by the extreme fiber strain at the yield point.

A simplified method based on idealisation of the actual structure to an equivalent single-degree-of-freedom system and of the impulse load time history to a simple mathematical form, is used to analyze the seismic category I structures.

The ultimate load capacity of concrete barriers is based on the yield line theory of reinforced concrete slabs. The collapse mechanism is a circular fan yield line pattern based on the impact of a concentrated load.

For a ductile missile, characterized by significant local deformation of the missile during impact (wood plank, utility pole or steel pipe), the peak of the impactive force is determined by the formula:

(5)

where

$\sigma_{crushing}$ = 25 MPa for wood missiles

= 420 MPa for solid steel missiles

= 560 MPa for steel pipe missiles

A_{net} = net cross sectional area of the missile (mm^2).

Assuming a rectangular impulse for the force function, the duration of the impulse, t_d , is determined by the formula:

$$t_d = \frac{mV_m}{F_{crushing}} \quad (6)$$

where

t_d	=	time duration of impact
m	=	mass of missile
V_m	=	striking velocity of the missile

A representative forcing function for frontal impact of an automobile striking a rigid barrier is [18],

$$F(t) = 0.625\, V_s\, W \sin 20t; \quad 0 \leq t \leq 0.0785 \quad (7a)$$

$$F_{crushing} = \sigma_{crushing} A_{net}$$

where t is in second.

$$F(t) = 0; \quad t > 0.0785 \quad (7b)$$

where

F (t)	=	amplitude of the force
V_s	=	striking velocity of the automobile
W	=	weight of the automobile
t	=	time after impact (seconds)
20t	=	(20 radians/s.) (t)

Based on the above formula, the forcing function for the automobile is approximated as a rectangular shape of magnitude:

$$F = 0.625\, V_s\, W \quad (8)$$

and total time duration, t_d, of

$$t_d = \frac{M\, V_s}{F} \quad (9)$$

where, M is the mass of the automobile.

V.4 Design of Barriers

Design of concrete barriers may be carried out as per AERB safety standard titled 'Design of Concrete Structures Important to Safety of Nuclear Facilities', AERB/SS/CSE-1.

Design of steel barriers may be carried out as per AERB safety standard titled 'Design, Fabrication and Erection of Steel Structures Important to Safety of Nuclear Facilities', AERB/SS/CSE-2.

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LIST OF PARTICIPANTS

WORKING GROUP

Dates of meeting	:	January 18, 2004 October 31, 2007

Members of the Working Group:

Dr. A.K. Ghosh (Chairman)	:	BARC (Former)
Shri G.K. De	:	AERB (Former)
Shri A.S. Warudkar	:	NPCIL (Former)
Dr. P.C. Basu	:	AERB (Former)
Shri G.K. Sharma	:	NPCIL
Shri L.R. Bishnoi (Member-Secretary)	:	AERB

ADVISORY COMMITTEE ON CODES, GUIDES AND ASSOCIATED MANUALS FOR SAFETY IN DESIGN OF NUCLEAR POWER PLNATS

Dates of meeting	:	February 6, 2005 May 15, 2005 November 27, 2005 August 22, 2008 March 31, 2010

Members of the ACCGD:

Shri V.K. Mehra (Chairman)	:	BARC (Former)
Shri S.A. Bhardwaj	:	NPCIL (Former)
Shri S.C. Chetal	:	IGCAR (Former)
Dr. S.K. Gupta	:	AERB (Former)
Shri B.B. Biswas	:	BARC (Former)
Shri P. Hajra	:	AERB (Former)
Shri K.K. Vaze	:	BARC
Shri S.G. Ghadge	:	NPCIL
Shri S.A. Khan	:	AERB
Shri S.K. Dubey (Secretary)	:	AERB

ADVISORY COMMITTEE ON NUCLEAR SAFETY

Date of meeting	:	February 23, 2012

Members of the ACNS:

Dr. Baldev Raj (Chairman)	:	IGCAR (Former)
Shri S.A. Bharadwaj	:	NPCIL (Former)
Shri S.C. Chetal	:	IGCAR (Former)
Shri.S.C. Hiremath	:	HWB (Former)
Shri A.K. Anand	:	BARC (Former)
Shri S. Krishnamony	:	BARC (Former)
Shri D.S.C. Purushottam	:	BARC (Former)
Shri. K.K. Vaze	:	BARC
Dr. D.N. Sharma	:	BARC
Prof. J.B. Doshi	:	IIT, Bombay
Shri K. Srivasista (Member-Secretary)	:	AERB

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24.	AERB/NPP-PHWR/ SG/D-23	Seismic Qualification of Structures, Systems and Components of Pressurised Heavy Water Reactors
25.	AERB/SG/D-24	Design of Fuel Handling and Storage Systems for Pressurised Heavy Water Reactors
26.	AERB/NPP-PHWR/ SG/D-25	Computer Based Safety Systems of Pressurised Heavy Water Reactors
27.	AERB/NPP-PHWR/ SM/D-2	Hydrogen Release and Mitigation Measures under Accident Conditions in Pressurised Heavy Water Reactors
28.	AERB/NPP-PHWR/ TD/D-1	Decay Heat Load Calculations in Pressurised Heavy Water Reactors

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Niyamak Bhavan, Anushaktinagar
Mumbai - 400 094
INDIA.

BCS