Authority for Nuclear Safety and
Radiation Protection

ANVS Guidelines on Internal Hazards other than Fire and Explosion

(revised version of IAEA standard NS-G-1.11, 2004)

1 Foreword

The ANVS (the Authority for Nuclear Safety and Radiation Protection) has published the Guidelines on the Safe Design and Operation of Nuclear Reactors “ANVS Guidelines on Design and Operation” [1] for short DSR. They are available to download from the website of the ANVS (www.anvs.nl). The DSR provide insight into the best technology available in 2015 for ensuring the safety of new nuclear reactors.

In the context of the preparation of an application for a licence for the construction of a new reactor the DSR provide insight into what the ANVS considers to be the best available technology. Although the Safety Guidelines do not have the status of (ministerial) Regulations and do not therefore define any legal requirements, licence applications will be assessed on the basis of the safety requirements described in the Safety Guidelines. A licensee of an existing nuclear installation also has a legal (and social)responsibility to continuously improve nuclear safety. That implies that, following their publication, the DSR should also be used for guidance on the best nuclear technology currently available until no later than the next periodic evaluation. Evaluation of a nuclear reactor’s safety in the light of the best technology currently available may warrant action to improve nuclear safety, insofar as such action may reasonably be expected.

So the DSR describe the best technology available in 2015 for ensuring the safety of nuclear reactors and should be used as a guidance document for new and existing nuclear reactors. The DSR are goal oriented and at level of abstraction. The document describes subjects like the fundamental safety objectives, the technical safety concepts and requirements and postulated operation conditions and event. For the application of the DSR also other documents such as guidelines of the IAEA are useful. However these IAEA documents do not use completely the same systematic and nomenclature as the DSR which are based on the Dutch legislation and for example WENRA documents. That is why ANVS decided to adept several IAEA documents to reach a better consistency with the DSR.

One of these documents is the attached IAEA safety standard NS-G-1.11 “Protection against Internal Hazards other than Fires and Explosions in the Design of Nuclear Power Plants (2004). This document provides guidance and recommends procedures for the evaluation of seismic hazards for nuclear reactors and other nuclear installations. The revised version has got the name “ANVS Guidelines on Internal Hazards other than Fire and Explosion (revised version of IAEA standard NS-G-1.11, 2010)”. These ANVS guidelines should be used in the same way indicated above for the DSR for both new as existing nuclear reactors.

Contents

2 Introduction

Background

2.1. This Safety Guide supplements the Dutch “ANVS Guidelines on the Safe Design and Operation of Nuclear Reactors” (DSR) [1] dealing with internal hazards others than fire and explosion. Examples provided in this Safety Guide pertain to light water reactor plants; however, the recommendations provided in this Safety Guide are generally applicable to other types of plant with thermal neutron reactors.

2.2. An internal hazard is an impact resulting from occurrences within the plant site (e.g. fire, plant internal flooding, etc.).

Objective

2.3. The purpose of this Safety Guide is to provide guidance relating to an assessment of the possible consequences of internal hazards in nuclear reactors. This Safety Guide provides - guidance on the methods and procedure for analyses to support an assessment of the possible consequences of internal hazards.

Scope

2.4. This Safety Guide discusses internal hazards that may occur in the different operational states of the plant as stipulated in the DSR and supplements the relevant paragraphs. It introduces the probabilistic and deterministic approaches for reviewing the following:

(a) Internal hazards, postulated in a deterministic approach, and their probability of occurrence, which is estimated in the probabilistic approach;
(b) The potential for or probability of structures, systems and components (SSCs) being affected;
(c) The potential for or probability of damaging consequences;
(d) The overall assessment of consequences, to make judgements on their acceptability.

2.5. Guidance is provided on how to analyse the consequences of internal hazards, including the analysis of secondary and cascading effects as well as the corresponding functional analysis. Means of protection against internal hazards are discussed, as well as methods and means of reducing the aforementioned probabilities.

2.6. The following internal hazards are particularly addressed in this Safety Guide: plant internal flooding, increased radiation level, chemical reactions, electrical, I&C or process related malfunctions/failures, pressure build-up, pressure differences, temperature and humidity increase, fragments (debris/missiles) flying around and falling, as well as jet and reaction forces. For each of these hazards a description of the hazard and a discussion of specific considerations relating to prevention and protection against this internal hazard are provided.

Structure

2.7. Section 3 is dedicated to general considerations in dealing with internal hazards; it covers the selection of internal hazards, considerations on acceptability, analysis of consequences (including cascading and secondary effects) and considerations for protection and safety. In section 4 the aforementioned internal hazards are reviewed. A section is dedicated to pipe failure, which is an initiating event common to pipe whip, jet effects and flooding.

3 General considerations

Acceptability considerations

3.1. According to the general principle of defence in depth, the following should be considered in the design of a nuclear reactor:

(a) The prevention or limitation of the occurrence of internal hazards;
(b) The protection of the SSCs whose availability is necessary to bring the plant into and maintain it in a safe shutdown state, or whose failure could result in unacceptable radioactive releases, against all possible effects caused by the internal hazards considered;
(c) Application of reasonable conservatism and provision of safety margins in the design;
(d) Other features, such as possible inherently safe behaviour, redundant parts of systems important to safety, diverse systems and physical separation.

3.2. Internal hazards and their effects should be included in the safety assessment of any equipment failure unless it can be shown that either:

(a) The probability of occurrence of this internal hazard (this probability is denoted P_1) is acceptably low (see para. 3.09-3.10) so as to preclude the need for considering its consequences; or
(b) The probability of a system or component being affected (this conditional probability is denoted P_2) is sufficiently low (see para. 3.09–3.10); or
(c) If a system is affected, the probability of this leading to unacceptable consequences (this conditional probability is denoted P_3) is sufficiently low (see para. 3.09–3.10); or
(d) The overall probability of unacceptable consequences (this probability is denoted *P*) is sufficiently low (see para. 3.09–3.10). *P* is conceptually equal to the product $P_1 x P_2 x P_3$. *P* should be estimated with account taken of redundancy and other favourable design features as well as the possibility of common cause failures, the assumed unavailability of certain components and other unfavourable occurrences.

3.3. These probabilities can be illustrated as follows:

(a) Conservative design is a way of reducing P_1.
(b) Provisions in the layout, such as physical separation between source and targets, are a way of reducing P_2.
(c) Comprehensive design and qualification of possible targets is a way of reducing P_3.
(d) Use of adequate operating procedures is a way to minimize *P*; for example, by minimizing the probability of inadvertent flooding (an effect on P_1) or by avoiding the spreading of a flood by taking proper actions (an effect on P_2).

3.4. In a deterministic approach such measures are deemed to preclude the occurrence of an internal hazard and/or an inadmissible impact on safety. This means that at least one of the probabilities P_1, P_2 or P_3 is deemed to be reduced to zero. In a probabilistic approach, comprehensive plant specific reliability data would preferably be used; otherwise the probabilistic approach could be used as a complement to the deterministic approach.

3.5. In order of preference, the best design approach is to practically eliminate the internal hazard (i.e. to make P_1 acceptably small); the next best approach is to separate SSCs from sources (i.e. to make P_2 acceptably small); there is also the option of making the consequences acceptable (i.e. to make P_3 acceptably small). However, to the extent possible, defence in depth should be maintained by ensuring that the second level of defence and, if necessary, the third level of defence are effective. It may also be necessary in some cases to use a combination of all three levels.

3.6. There may be groups of similar components designed according to the same principles that have comparable quality standards and conditions of operation. It may be possible to analyse the hazards associated with such components by means of a single analysis of the probability P_1.

3.7. In designing a nuclear reactor, protection against internal hazards should be considered at the time of the decision making process for the layout of the plant in order to minimize P_1 (e.g. some falling objects may be eliminated as internal hazards if they can be installed on the ground floor) and/or P_2 (as in selecting an adequate location of the turbine generators in relation to the reactor building). The extent of this minimization is highly dependent on the details of the plantlayout and equipment.

3.8. In the course of the design or modification of a plant, the procedure for analysis as described here can be used as an optimization tool, and this may lead to design changes aimed at reducing one or more of the P_i factors. In a probabilistic approach, this procedure should be used for providing evidence of acceptable protection.

3.9. There is a wide variation in the level of confidence with which the frequencies and the consequences of rare events can be determined. Most reliance should be placed on those items that can be effectively controlled. This may mean in one case concentrating on the reduction of P_1 and in another case focusing mainly on P_2 or P_3. In order to cope with the uncertainty in quantifying P_1, P_2 or P_3, studies involving an appropriate combination of analytical and experimental work should be performed, to determine the worst case and to enable a conservative estimate to be made.

3.10. Where the related risks are uncertain, because of the uncertainty in quantifying the extraordinary severe consequences or the lack of confidence in the estimated probabilities, special care should be taken by providing for measures such as surveillance, monitoring, inspection, shielding and especially physical separation.

3.11. Decisions are made, either implicitly or explicitly, to give certain potential hazards very detailed and thorough consideration, while others receive only cursory review. Such decisions are based on risk. There is sometimes a limiting probability for events of certain maximum consequence, below which probability the risk is considered to be acceptable. More often, the guidelines are heuristic and the probability limits are implicit. In this latter situation decisions are made on each case separately on the basis of deterministic calculations (such as calculations for stress analysis, the analysis of fracture mechanics or impact damage) combined with qualified expert judgement. The approval of specific bases for acceptability is a matter for the regulatory bodies.

Analysis for secondary and cascading effects

3.12. Internal hazards may cause damage directly; this is termed a primary effect. In addition, they may cause damage indirectly by means of failure mechanisms that can propagate the damage. Damage caused indirectly by an internal hazard is termed a secondary effect. These secondary effects may cause damage that could exceed that caused by the primary effects. Where postulated equipment failure necessitates a safety assessment to demonstrate that the fundamental safety functions will be fulfilled, all cascading secondary effects of the failure should be included. In certain circumstances, the internal hazards addressed in this Safety Guide may be regarded as secondary effects of another internal hazard; for example, a pipe whip may result in a secondary missile.

3.13. Secondary effects are such in nature that the potential damage can vary widely. Many factors come into play that are beyond the control of a designer. Owing to these difficulties, the preferred practice should be to emphasize the means of stopping the cascading effect or, in other words, of reducing P_1 and/or P_2 rather than P_3. The prevention of a pipe break should receive special attention since it may prevent several potential internal hazards (e.g. flooding, pipe whip and jet effects).

3.14. Secondary and cascading effects induced by internal hazards should be considered in the design of the plant. The design provisions should be supplemented by verification after construction by means of a systematic and thorough approach to ensure that all the possibilities have been considered. One such approach is to use a checklist in which all possible secondary effects have been listed and space is provided to note the basis for concluding that no unacceptable indirect damage could result. This approach should be supplemented by walk-down inspections.

3.15. In this systematic analysis, among the important secondary effects the following should be evaluated:

(a) *Secondary missiles*. A missile or a pipe whip 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 characterize such secondary missiles, and the most prudent course of action is to prevent their generation or to contain them at their source. For example, spontaneous multiple pipe breaks resulting in separated pipe parts as (secondary) missiles are improbable if the ductility and the fracture toughness of piping material are sufficiently high.

(b) *Falling objects*. There may be circumstances in which a pipe whip or a missile can damage the supporting structure of a heavy object located above a safety system such that an object falls, possibly causing further damage. It may in certain cases be possible to show that the falling object cannot cause unacceptable damage. If not, either the supporting structure should be modified to withstand the missile impact or means should be provided to prevent such an impact.

(c) *Failure of high energy pipes*[1] *and components*. In case of a 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 or mechanisms: jets; high pressures; pressure waves; increasing temperatures and humidity levels; pipe whip; flooding; secondary missiles; chemical reactions; and high radiation levels. The rupture of high energy pipes or components may also give rise to a loss of coolant accident or other accidents that should be considered in the qualification of the safety systems. Unless it can be shown simply on the basis of the available energy and the location of the potential rupture, or by other suitably substantiated analytical means, that none of the above mechanisms would lead to significant damage to safety systems, means should be provided to prevent the internal hazard from rupturing the pipe or component, or possibly to minimize the likelihood of this event.

(d) *Flooding.* Where there is the possibility of an energetic missile striking pipes, tanks or pools normally filled with liquid, the potential for damage due to flooding should be evaluated. The draining of coolant from equipment or tanks by a siphoning action should also be considered in assessing the consequences of a pipe rupture. Depending on the amount and nature of the liquid concerned, indirect damage to items important to safety can result by means of such effects as an electrical short circuit, fire, hydrostatic pressure effects, wave action, thermal shock, instrument errors, buoyancy forces and criticality risk (in relation to boron dilution). If there is a potential for the significant flooding of items important to safety, in most cases the prudent course of action is to reduce P_2 to acceptable levels, since it is very difficult to predict and mitigate all the possible effects of flooding.

(e) *Radioactive release.* Release of radioactive material may result from an impact on items containing such material or on items that are necessary for its control. The release may also result from flooding. Such a release may affect the functioning of some components. (Avoiding any release of radiation that could be of radiological significance is the general nuclear safety objective as established in Ref. [1], And this would be addressed by any safety analysis; in this sense, it is not a secondary effect.)

(f) *Chemical reactions.* Missile impacts or pipe whip impacts can release dangerous chemicals, while flooding, gaseous dispersion or jet effects may result in chemical reactions. The chemical reactions of concern may include: (i) the release of flammable or explosive fluids, which can result in fires or explosions; (ii) exothermic reactions between chemicals usually kept separate; (iii) attack by acids on structures or components; (iv) reactions such as rapid corrosive attacks that can weaken important materials or can generate large quantities of gas with consequent pressure effects; (v) reactions that can release toxic materials (either as the release of a source or as a result of chemical reactions); and (vi) the release or production of asphyxiant gases. As with flooding, the possible effects of chemical reactions are many and varied and are difficult to predict. The prudent course of action is to make P_2 acceptably small. In this regard the use of any chemical substances that might support such reactions should be limited to minimal amounts and only when indispensable.

(g) *Electrical damage.* Missiles, pipe whip and flooding may damage electrical equipment or cause its malfunction (such as spurious actuation). The number and extent of items of electrical equipment and wiring in a nuclear reactor make it virtually certain that a missile traversing the plant would disable some electrical circuits. The mechanism for damage in such cases can include the severance of cables, the destruction of equipment or electrically initiated fires. In designing protection against indirect damage from impacts on electrical equipment, such techniques as the physical separation of redundant circuits, the use of fail safe circuits, the proper application of fuses and circuit breakers, adequate fire protection and the appropriate use of barriers should all be evaluated. The most appropriate course of action will be determined by the specifics of the internal hazard under consideration. For example, if a postulated missile is metallic and can introduce unintended connections between cables, this may influence the degree of reliance on fuses and may make other means of electrical protection more attractive. It should be noted that the complex potential failure modes of electronic circuits mean that it is unlikely that a full assessment of the hazard consequences can be made; a pessimistic failure mode should be assumed unless the items are protected from the effects of the hazard.

1 A high energy pipe is defined as a pipe 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. In some States pressurized gas piping systems are regarded as high energy systems regardless of the pressure.

(h) *Damage to instrumentation and control lines*. Some air or fluid commanded 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 being provided to the operator. A similar pessimistic assumption applies as for electrical damage.

(j) *Fire*. Internal hazards may result in fires; for example, if an impact produces a source of ignition energy such as an electrical arc in the proximity of flammable material. Chemical reactions or electrical short circuits may also result in fires. The potential for damage due to fires and possible further actions should be evaluated in accordance with Ref. [2].

(j) *Personal injury*. Internal hazards may directly or indirectly cause injury to plant personnel. In areas usually occupied by plant personnel performing a safety function, the probability of an impact due to an internal hazard should be made acceptably small. The internal hazard may also render areas inaccessible to personnel. If intervention by personnel is required in such areas, a means of rendering them safe should be established or else the need for such actions should be removed.

3.16. In the event that an internal hazard can be regarded as leading directly to an anticipated operational occurrence, it should be demonstrated that the design is capable of preventing escalation to a design basis accident. Similarly, in the event that an internal hazard can be regarded as leading directly to a design basis accident, it should be demonstrated that the design is capable of preventing escalation to postulated multiple failure events or postulated core melt accidents. For the analysis of these internal hazards, the single failure criterion will apply to the corresponding safety group, whereas, for the analysis of other initiating events, the components that are not affected by the event may be regarded as available [3].

3.17. The plant specific list of PIEs should include PIEs initiated by internal or external hazards. It should cover a complete set of probable breaks for the systems important to safety as well as for auxiliary systems whose failure could affect safety systems.

3.18. The procedure for analysis will best be performed in a stepwise manner. In the screening process, candidate components for internal hazard sources should be identified. This screening process should be followed with due caution, and in case of doubt the component in question should not be excluded but rather put on the list of potential hazards that have to be analysed in more detail. Probabilistic safety assessment may be useful for this purpose.

3.19. The screening process should describe the situations that give rise to the need for safety systems to operate. These situations are the PIE itself (if, for example, the PIE consists of a loss of coolant accident), the damage due to primary effects and the subsequent damage, if any, caused by secondary effects.

3.20. Further on, this process should be used to determine the systems that are operable. A system may be unavailable either because of the PIE from an internal hazard or because a component of a safety system may be unavailable for reasons that lie beyond the scope of this Safety Guide. For example, a component of a safety system is assumed to have sustained a single failure or to be in the test or maintenance mode, or an operator error is assumed. Possible common cause failures should be taken into account.

3.21. It should be determined whether the remaining (intact) capacity of the safety systems is still sufficient for dealing with the situation that has occurred (i.e. the internal hazard together with the induced effects and cascade failures). If the adequate performance of the safety systems cannot be demonstrated, then either additional protection should be provided or the redundancy of the safety systems should be increased, or a combination of the two could be used, provided that adequate performance of the safety systems can be demonstrated.

3.22. In practice, protection against internal hazards will involve a great deal of engineering judgement and use of pragmatic rules. Therefore, as far as practicable, an experimental background should be provided in support of the theoretical analysis.

3.23. In placing reliance on special devices or features designed to cope with the consequences of an internal hazard, precautions should be taken to ensure that the special device is qualified for the internal hazard under consideration and that it will not itself become the source of a new PIE.

Considerations for protection and safety

Methods and means to prevent internal hazards

Design

3.24. A conservative design, with rigorous design limits, establishes the first level of defence against the failure of components and should be executed in order to reduce P_1. Careful analysis of static, dynamic and thermal loads, and combinations thereof, applied to the equipment, the application of adequate safety factors and thorough pre-service control of material properties, and the application of adequate quality assurance measures in fabrication, are commonly practised. The use of safety devices or systems to limit the maximum pressure or the rotational speed, for example, should also be considered as a way of reducing P_1. To the extent possible, the effects of ageing should be taken into account in the design of the components.

3.25. In cases in which the consequences of an equipment failure would jeopardize safety, the aforementioned design approach should be combined with inspection or surveillance at least, or with other methods of reducing P_1.

Inspections (see also Ref. [4])

3.26. Periodic non-destructive examination of the piping and components in reactor pressure circuits, as well as of their supports, should be required to detect flaws in the material that may have become enlarged during operation. The sensitivity of the inspection techniques that are used should be set to detect and characterize flaws substantially smaller than those that could cause severe failure. Care should be exercised to ensure that ongoing inspections do not increase P_1 by the thinning of pipework (or by other means).

3.27. Flaws caused in manufacturing should be identified during the manufacturing process. If decided to build in the component, these flaws should be observed and analyses should be made to predict their growth. Inspections should be made frequently enough to provide an adequate margin of time between the detection of growth and possible rupture. Periodic non- destructive examinations may be supplemented by surveys. An example is a survey for evidence of movement such as might be indicative of water hammer or other unintended loadings. Factors such as fatigue, corrosion or creep that can accelerate the growth of flaws should be thoroughly investigated.

3.28. In the event that an unexpected defect or plant malfunction is identified that challenges a given SSC, the possible implications for similar items in the plant, and possibly in similar plants elsewhere, should be considered.

3.29. Such in-service inspection in combination with other measures for reducing the probability of failure and with studies in depth, as, for example, in the leak before break acceptance procedure, can provide an acceptable basis for not postulating the gross failure of certain pressure vessels and piping as well as certain rotating equipment, so that no additional design measures are necessary to provide protection against certain types of internal hazard (missiles and pipe whip). However, the consequences of leaks such as jet impingement, flooding, humidity, increased temperatures, asphyxiant effects and radioactive releases should be considered.

Monitoring systems

3.30. In cases in which it is desired to reduce P_1, one technique of surveillance is to monitor the conditions that may give an indication of incipient failure. This technique is based on the experience that most failures, especially failures in ductile metal components, develop gradually, permitting corrective action to be taken in due time before a dangerous situation arises. Of all the methods used for reducing P_1, effective monitoring results in the least perturbation to the design or operation of the plant. It should be recognized that monitoring provides only a warning and does not prevent failures. Furthermore, the surveillance systems may provide information useful for maintenance planning. See also Ref. [4].

3.31. Applications of monitoring in nuclear reactors should include leakage detection systems for pipes and pressure vessels, monitoring for vibration on large rotating equipment and monitoring for loose parts; other examples of monitoring are directed at, for example, low and high cyclic fatigue, displacements, water chemistry, vibrations and thermal stratification effects, ageing effects, wear detection and the chemistry of lubricating materials.

3.32. In the design of a monitoring system, feedback of operational experience, including ageing effects, should be taken into account. Systems for vibration monitoring in rotating machines, for leak detection in high pressure water systems and for the detection of loose parts have been in use for these applications on a wide scale and for a long time. There have been many recorded instances in both nuclear and conventional power plants of vibration monitors alerting the plant operators to the deterioration of equipment in time to prevent major damage. In most nuclear reactors multiple systems based on humidity and temperature, radiation levels, pressures or sump water levels, among other things, have been installed to detect leaks of various sizes and in various locations. Here, too, there have been many cases in which small leaks were detected by installed monitors or routine plant inspections and major failures were thereby avoided.

3.33. The degree of reliance placed on monitoring systems in reducing equipment failures varies in practice. According to the principle of defence in depth, the use of monitoring systems should be considered a supplement to other means of reducing equipment failures rather than a sufficient measure on its own. For example, in the case of the prevention of primary circuit ruptures, leak detection systems and acoustic monitoring systems are considered adjuncts to conservative design and manufacturing, non-destructive examination and several other factors. However, even all of these measures together may be insufficient to obviate the need to postulate a pipe rupture for design purposes for higher order safety features or structures and components. An appropriate maintenance programme should be conducted for the monitoring system.

3.34. To preclude or to reduce the probability of large pipe breaks, and with them the consequences of missiles, pipe whip and jet impingement, for example, a comprehensive procedure should be performed to qualify certain piping systems.

3.35. Adequate operational procedures may also contribute to reducing the probability of generating a PIE. Examples include: the prevention of excessive thermal stresses in metal pressure vessels and the monitoring of vessel material for radiation embrittlement; the limitation of plant transients by the use of pressure relief valves and safety features activated by the protection system; prohibitions or restrictions during the conduct of dangerous operations; the use of seismic instruments to provide data for the assessment of the condition of the plant for continued operation following an earthquake; and the control of the water chemistry in the primary circuit and the secondary circuit to inhibit corrosion and corrosion assisted initiation of cracks.

Methods and means of protection of SSCs against possible effects

Provisions in the layout

3.36. Provisions in the layout should be made early in the process of plant design as a valuable way of reducing P_2. In this regard, feedback of experience from similar installations should be taken into account. Decisions on layout are of particular importance in relation to missiles and flooding hazards, and these considerations are addressed in the corresponding sections of this Safety Guide.

Barriers and physical separation

3.37. If the general layout of the plant is not sufficient for reducing P_2 to an acceptable level, it is possible to provide barriers between the source of the internal hazard and the candidate affected component. The barriers should preferably be placed close to the source of dynamic effects (missiles, pipe whip and other impacting masses). This covers the protection of all potential targets in the case of a missile and eliminates possible concerns about scattering. Additionally, where the postulated impacting mass can continue to gain energy during its travel, as in jet driven missiles or whipping pipes, the design requirements for the barrier are least severe nearest the source. However, it may be that the existing structure provides adequate protection for all but one or two small targets in some particular case, and then a special barrier might best be placed at the targets. In the case of postulated flooding, barriers should be provided in the form of appropriate doors, thresholds, platforms and retention walls. However, due consideration should be given to aspects of testing and maintenance; for example, weld seams should be kept easily accessible from the outside of vessels and pipes.

3.38. Physical separation should be provided between redundant items important to safety or of different safety trains (including power supplies, instrumentation cables and any related systems) on the basis that the multiple components should be independent and their separation will help to limit the consequences of internal hazards to one safety train.

Methods and means of avoiding unacceptable consequences

3.39. Wherever possible the design of SSCs should be a failure tolerant design. That is, should these items fail, their failure would tend to move the plant towards a safe plant condition. This technique has broader application to areas other than protection against internal hazards, but where valid it may help in mitigating the effects of postulated internal hazards.

3.40. As already discussed, internal hazards may result in PIEs which may result in a subsequent release of fluid, which may change the environment in the plant by locally increasing the humidity, temperature, pressure and radiation level. Equipment should be used that can perform its safety functions in this environment and that is accordingly qualified. If a component is not qualified for such an environment, it should be deemed not available or it should be protected by means of encapsulating, shielding or another appropriate measure. However, an enclosure complicates maintenance activities and necessitates that the seal be restored upon the completion of each maintenance action.

3.41. The provision of an unpressurized guard pipe around certain sections of piping carrying high pressure fluids has been used in various cases as a well established technique for mitigating the possible effects of a rupture of the pressurized pipe. The disadvantage of such a solution would be the possible difficulty in conducting inspections of the internal pipe.

4 Review of Internal Hazards

Missiles

4.1. In the design and evaluation of nuclear reactors, internally generated missiles arising from internal hazards (such as the failure of pressure vessels and pipes, the failure of valves, the ejection of a control rod and the failure of high speed rotating equipment) should be considered. The potential for secondary missiles should also be evaluated. Measures to prevent the initiation of internally generated missiles should be undertaken if such measures are practicable. Otherwise, protection of SSCs against internally generated missiles should be provided by using the methods described in the following. Analyses of missile hazards and of the design of the plant to protect against them are usually performed by a combination of deterministic and probabilistic methods. Some missiles are postulated on a deterministic basis and their effects on the SSCs in terms of strikes and damage are also evaluated either deterministically or probabilistically. In a few cases, all aspects of the missile hazard — initiation, strike and damage — are treated probabilistically.

Prevention of the generation of missiles

Failure of pressure vessels

4.2. In nuclear reactors, pressure vessels that are important to safety are designed and constructed by means of extremely comprehensive and thorough practices to ensure their safe operation. Analysis is performed to demonstrate that levels of stress are acceptable under all design conditions. All phases of design, construction, installation and testing should be monitored in accordance with approved procedures to verify that all work is carried out in accordance with the design specifications and that 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 determine whether the vessels remain within their design limits. The gross failure of such vessels (such as the reactor pressure vessel) is generally believed to be sufficiently improbable that consideration of the rupture of these vessels as a PIE should not be necessary.

4.3. Other vessels in nuclear reactors may not undergo such stringent design, quality assurance and surveillance. Failures of such vessels containing fluids of high internal energy should be evaluated, as they may become sources of missiles if they rupture. The failure of a pressure vessel can result in a wide variety of failure modes depending on such factors as material characteristics, the shape of the vessel, the positions of welds, the design of nozzles, construction practices and operating conditions. Metal vessels composed of materials that behave in a brittle manner are more likely to produce missiles.

4.4. Further measures to reduce P_1 include the use of ductile material and additional anchoring or supporting of the vessel. Where it is determined that P_1 is not low enough, or if the vessel can possibly fail in a brittle manner, a range of missile sizes and shapes to cover the range of possibilities should be postulated and analysed to identify the design basis missiles. Alternatively, a simplified conservative approach is acceptable in order to determine the missiles to be considered.

4.5. A vessel, because of its unpredictable behaviour and the potential for severe damage, should be designed so that it cannot as a whole become a missile. If it is judged that the vessel as a whole could become a missile, an analysis should be made of the various locations of ruptures and break sizes to determine whether the resultant vessel blowdown forces would be sufficient to separate the vessel from its retaining supports (restraints). If a vessel could be separated from its restraints, the design of the vessel should be modified to prevent this type of failure.

4.6. For reactors equipped with vessel closure plugs to retain the fuel in position, special design features should be provided to ensure that the probability of ejection of the closure plug is low. In the absence of such special features, the consequences of the failure or the ejection of a single closure plug should be evaluated as for a missile.

Failures of valves

4.7. Valves in fluid systems that operate at high internal energy should be evaluated as potential sources of missiles. Valves are typically designed with various parts that are removable for maintenance purposes. These removable parts present the most significant potential for failures that lead to the production of a missile. The failures of valve stems or the valve bonnet or of retaining bolts are examples of failures that should be taken into consideration as good engineering practice even if such failures have not been observed. 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 the valve body itself is sufficiently unlikely in most cases and that it need not therefore be considered in the design and/or evaluation of the plant.

4.8. The simplest and the preferred approach to the design of valves is to make P_1 acceptably small; there are several features that can conveniently be incorporated into the design of valves to achieve this. Valve stems should be equipped with appropriate devices having a demonstrable capability to prevent valve stems from becoming missiles in the event of their failure. Valve bonnets frequently have bolted closures. As a design rule, no failure of a single bolt should lead to the generation of a missile other than the bolt itself. This recommendation applies to valves, pressure vessels and other bolted components with a high energy content. However, consideration should be given to the potential for multiple bolt failures due to corrosion or stress corrosion in the event of the leakage of fluid contents past gasketted joints.

Ejection of a control rod

4.9. In most reactor designs features are incorporated by means of which solid neutron absorbing control elements (control rods) are inserted into and withdrawn from the core in a manner such that the travel housings for these elements form appendages on the reactor pressure vessel. For reactor designs in which significant fluid pressure is contained by the reactor pressure vessel, it has been customary to postulate, for design purposes, that a failure of one of these appendages can occur in a manner permitting the ejection of the control rod due to the driving forces of the fluid contained. This postulated ejection gives rise to a reactivity transient and to a loss of coolant accident, neither of which is dealt with in this Safety Guide, as well as to the generation of a missile which may, depending on the particular reactor design, have the potential for causing significant primary or secondary damage. For example, typical matters of concern include the possible damage to adjacent control rods, to safety systems and to the containment structures.

4.10. The probability of a control rod being ejected may be reduced in some reactor types by providing special design features. These features should be confirmed by test or by analysis to demonstrate that they have the capability to retain the control rod and drive assembly in the event of a failure of the travel housing for a control rod.

Failure of high speed rotating equipment

4.11. Nuclear reactors contain large items of equipment that have 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 flywheels. 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 overspeed.

4.12. 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. To the extent practicable the calculation of the energy losses should be based on empirical relationships developed in tests of similar, carefully defined structures. 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.

4.13. 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. 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 characterized on the basis of their potential for doing damage and should be included in the evaluation of possible primary and secondary effects.

4.14. 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.

4.15. To determine P_1 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 non- destructive 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 overspeed should be evaluated for reliability. This will include equipment for the detection and prevention of incipient overspeed, 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.

4.16. The speed of rotating equipment is determined by a balance between the input energy and the output load. A sudden reduction in the output load or a sudden increase in the input energy can result in overspeed. 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 overspeed occurring to an acceptable level.

4.17. It should be noted that while engineering solutions are available to limit speed and to prevent missiles due to excessive overspeed, these provisions by themselves may not make the probability of missiles being generated from rotating equipment acceptably small. Besides the failure caused by overspeed 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.

Analysis for and protection against missiles

4.18. The next step in the analysis involving the postulation of missiles being generated as a result of equipment failure is to determine the directions and the possible targets of these ejected missiles.

4.19. It may be possible, by studying 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 mass. In certain cases, however, such as for large turbine missiles, the maximum possible range encompasses the entire plant site. Awareness of the directions in which missiles from a particular source may be ejected may often help in locating potential targets so as to avoid missile strikes. This is the case especially where the driving energy for translation is unidirectional, as for valve stem missiles. In other cases there may be a most probable plane or angular sector, as is the case for missiles from rotating machines. There is evidence from failures of rotating machines that energetic missiles are usually ejected within a very narrow angle of the plane of rotation unless they are deflected by a barrier of some kind (e.g. casing) at the source. In this latter case, tests or analyses should be performed in order to estimate the limits of the directions of travel.

4.20. 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.

4.21. P_2 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.

4.22. A particularly instructive example of layout provisions is the main turbine generator. Barring other constraints of overriding importance, the layout of the main turbine generator should be such that potential critical targets (such as the control room) lie within the area least susceptible to direct strikes from the turbine; that is, within a cone with its axis along the axis of the turbine shaft. This arrangement takes account of the fact that large sections of rotors, if ejected, will tend to be expelled within 25° of the plane of rotation. The arrangement does not eliminate the possibility of their hitting a critical target, but it significantly reduces the probability of a direct strike.

4.23. 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. While such an approach is straightforward, simple and easily understood as a means of eliminating hazards, provision should be made for the required maintenance and inspection of the equipment.

4.24. The provision of an unpressurized guard pipe around certain sections of piping carrying high pressure fluids may in some cases be useful for protection against missiles. Two protection features are obtained: protection of the surrounding structures and equipment from whipping pipes and possible secondary missiles, and protection of the inner pipe from missiles generated in the surrounding area.

4.25. Perhaps the most direct and obvious design approach to reducing P_2 is to provide barriers between the source of the missiles and the target. Barriers are also used to reduce certain secondary effects such as scabbing or even the ejection of concrete blocks from concrete targets. Both aspects of barriers are discussed in the following paragraphs.

4.26. Missile barriers have frequently been provided in nuclear reactors to absorb the energy of postulated missiles and to prevent their travel beyond the barrier. Usually missile barriers consist of reinforced concrete slabs or of steel plates. However, other means such as woven steel mats or missile deflectors could also be used. Generally the barrier should be placed at the source of the missiles, as stated in para. 3.37.

4.27. Evaluation of the adequacy of barriers, whether they are structures provided for other purposes or special missile barriers, necessitates the consideration of both local and general effects of missiles on the barrier. Depending upon the postulated missile's mass, velocity and impact area, the local or the general effect of the missile may dominate, but both should be evaluated. Local effects of missiles are penetration, perforation, scabbing or the ejection of concrete blocks and spalling, which are limited mainly to the area of impact on the target. General effects of missiles include buckling or structural failures in bending, tension or shear. Small missiles such as valve stems will have mainly local effects, while large, slow moving missiles such as those arising from structural collapse or falling loads will have mainly general effects. Faster large missiles such as those arising from rotating machinery may exhibit both local and general effects.

4.28. In analysing the local effects of missiles on missile barriers, the practice is to determine the depth of penetration of the missile into the target by using acceptable empirical equations. The equations have been derived from various experiments and are limited in the range of parameters for which test data were taken. It should be recognized that penetration depth formulas may not in all cases be adequate for determining the design of a missile barrier (e.g. the necessary thickness, strength and reinforcement of steel and/or concrete). The mass, velocity, impact area, shape and hardness of the missile, as well as the characteristics of the construction and strength of the targets, are all important parameters that should be considered. The selection of the appropriate formula needs expert engineering judgement, since there may not be a formula that is directly applicable and some extrapolation of the range of parameters may be necessary. An added factor with regard to local missile effects in considering reinforced concrete targets is the generation of secondary missiles by spalling or scabbing or the ejection of blocks. Such phenomena should be prevented wherever possible because of the scatter of the secondary missiles, which makes certain characteristics difficult to predict. The generation of secondary missiles can be prevented by making the barrier adequately thick or by providing a steel backing plate on the concrete surface.

4.29. The consideration of general missile effects on the barrier should include the possible deformation of the structure by local missile effects. If there is no major local deformation of the structure by penetration, then methods of energy balance and momentum balance can be used to predict the deflections or stresses in principal members for the purpose of determining whether the barrier can contain the missile and continue to perform its design function. If, however, local missile effects are severe, as they often are, an applied force– response time history should be developed and the structural response should be analysed as for an impulse load. The dynamic loads induced by missile impacts should be considered with due attention to the frequency response of the target structure. This is particularly important when the response of the barrier may interfere with the operability of equipment either mounted directly on the barrier or installed in the vicinity of the barrier.

4.30. In the event that the product of P_1 and P_2 cannot be proven in a particular case to be acceptably small, the next approach is to make P_3 acceptably small. This can be done by making a detailed analysis of the potential impact on the target and demonstrating that the impact and its potential secondary effects do not prevent the safety requirements from being met.

4.31. Where redundant safety systems are involved, use should be made of physical separation to ensure that the general safety requirements are met, e.g. that no more than one safety train is inadmissibly affected.

4.32. The effectiveness of the physical separation of redundant critical targets is strongly affected by the number and range of possible missiles. Physical separation and adequate redundancy may be sufficient for cases in which only one or two energetic missiles can result from an equipment failure. However, if the generation of multiple missiles in several directions simultaneously is possible, then the benefit of separation by distance and redundancy could be considerably reduced. The arrangements and locations of potential targets and missiles should be considered with the aim of minimizing the effects of events of this kind.

Collapse of structures and falling objects

4.33. Any structure or non-structural element or object of substantial potential energy could be considered a possible source of an internal hazard. All such structures (cooling towers, stacks and turbine buildings) should be examined to determine whether their collapse could affect SSCs. Structures classified as liable to affect SSCs in the event of their collapse should be designed and built so that the probability of their collapsing can be shown to be negligible; otherwise the consequences of their collapse should be evaluated. Similarly, the hazard posed to SSCs by falling objects (cranes and lifted loads) should be evaluated.

Structures and non-structural elements

4.34. Safety related structures in nuclear reactors are designed to withstand extreme loads such as those arising as a result of earthquakes, high winds, impacts of aircraft of certain types, external explosions, external flooding, snow and loss of coolant accidents. Collapse of these structures due to internal causes is therefore considered to be unlikely. Reference [5] covers the evaluation of structures for protection against external hazards arising from natural and human-made phenomena. Also, the practice for design in most states with nuclear power programmes is to ensure that no failure in a structure classified in a lower class will be able to propagate to an SSC classified in a higher class. If this is not the case, failure in the structure classified in the lower class should be evaluated as an internal hazard. In addition to minimizing P_1, physical separation of SSCs should be used to reduce P_2 by ensuring that no single structural collapse could affect all redundancies.

4.35. The failure of non-structural elements such as block walls, stairs and scaffolding could have consequences for SSCs. External hazards (such as earthquakes, high winds, explosions or impacts of aircraft) could be the cause of such a failure and they are usually evaluated on the basis of Ref. [5]. However, there may be situations in which the failure of non-structural elements may be caused by internal initiating events such as operator error or accidents during maintenance. The consequences for SSCs should be evaluated in these cases. Care should be taken either to avoid such failures or to minimize the potential damage to SSCs by means of proper location and adequate barrier design.

Dropping of heavy equipment

4.36. If heavy items of plant equipment are located at significant heights, an evaluation should be made of the possible hazards associated with dropping such equipment, if the probability of this event is not negligible. Generally, the cause of the dropping of heavy equipment would be an external phenomenon such as an earthquake or an aircraft impact, but it may also be human error. References [5, 6] provide methods for preventing such events and for analysing their safety significance. Following the recommendations of Refs [5, 6] will reduce the likelihood of dropping heavy equipment as a result of internally initiated events.

4.37. The nature of the object and the cause of its dropping should be analysed in order to characterize the possible direction, size, shape and energy of the missile or missiles generated and their possible consequences for safety.

4.38. Functional design requirements often govern the physical location of equipment in this category. Where it is functionally necessary to tolerate proximity between heavy equipment and critical targets, it is possible to provide sufficient design measures such as redundant cables on cranes or interlocks to reduce the probability of failure. Also, additional care should be taken in the handling of heavy loads in the vicinity of SSCs. Special attention should be paid to the periodic inspection and maintenance of cranes (e.g. their interlocks, cables and brakes), nooses, straps and shackles, and related items.

4.39. In the particular case of cranes and heavy crane loads such as fuel shipping casks, it is often functionally impractical to interpose shields or barriers between the potential missile and the target. For reactors that use a system for fuel storage in water, attention should be paid to the fuel casks because of the possible consequences if they are dropped into the fuel storage pool. This possibility is normally analysed by means of calculations to determine whether there would be a gross rupture of the pool if a fuel cask were to be dropped from the maximum operational height and by demonstrating whether the water make-up systems would have an adequate capacity to maintain the level of the pool water in the event of leakage caused by a dropped cask. Another practice that should be considered is to restrict the handling of fuel casks to an area remote from the pool itself and remote from other critical target areas.

Pipe failures and their consequences

Assumptions for PIEs

Types of failure considered and their locations

4.40. Depending on the characteristics of the pipes under consideration (internal parameters, diameter, stress values, fatigue factors), the following types of failure should be considered as internal hazards:
(a) For high energy pipes, except for those qualified for leak before break, for break preclusion or for low probability of failure: circumferential rupture or longitudinal through-wall crack.
(b) For low energy pipes[2]: leak with limited area.

4.41. It is accepted to postulate only a limited leak (and not a break) if it can be demonstrated that the piping system considered is operated under 'high energy' parameters for a short period of time (e.g. less than 2% of the total operating time) or if its nominal stress is reasonably low (e.g. a pressure of less than 50 MPa).

4.42. The locations where a failure has to be postulated 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 according to the rules applied for systems important to safety;
(b) In all locations for other pipes.

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

4.43. A circumferential pipe rupture may result from: a failure of the piping by a stochastic, spontaneous double ended guillotine break; damage by a degradation failure mechanism such as corrosion or fatigue (i.e. a crack growing over its critical size); an impact due to the rupture of other piping; or an impact of a different kind on the piping under consideration. The most probable location of such a pipe separation is any circumferential weld between the straight pipe parts and the pipe components such as pipe bends, T intersections, reducers, valves or pumps; in general, where there are changes in stiffness and vibration or fluid stratification caused by temperature differences. The frequency of a double ended guillotine break of high energy piping may be derived from operating experience and calculations of fracture mechanics. This frequency may also be available from evaluations made for the purposes of probabilistic safety assessment.

4.44. A large longitudinal through-wall crack in high energy piping resulting in a large leakage area should be considered an internal hazard, although it is less probable than a circumferential crack.

2 A low energy pipe is defined as a pipe with an internal operating pressure of less than 2.0 MPa or an operating temperature of less than 100°C in the case of water. Other limits may apply for other fluids.

4.45. Complete instantaneous breaks of high energy pipes should be postulated in analysing the capacity of the emergency core cooling system and the pressure bearing capacity of the containment. The consequences of breaks in these pipes include flooding and increases in pressure, humidity and temperature. The effects of these on the qualification of components and the infiltration of impurities into the emergency core coolant water should be taken into account in the design.

Induced phenomena
4.46. PIEs from internal hazards may have an impact on safety systems by means of local effects, such as direct mechanical contact or jet impingement, as well as global effects, such as flooding, increases in humidity, increases in temperature, asphyxiant effects and higher radiation levels. These possible effects should be analysed.

4.47. In particular, as well as a break, a leak with a limited area should be considered to be an internal hazard that could lead to an internal flooding hazard. For flange connections and for different types of sealing, the possible leak areas should be analysed case by case.

4.48. Three main phenomena that could be induced by pipe failures — pipe whip, jet effects and flooding — are discussed in the following sections.

Preclusion and prevention of pipe breaks
4.49. A pipe break need not be assumed if a successful qualification for leak before break, for break preclusion or for low probability of failure has been performed for the piping under consideration, resulting in a sufficiently low frequency of the occurrence of a spontaneous break[3]. In general, a fracture mechanics analysis should be performed to calculate the leak size. In lieu of such an analysis, a subcritical crack corresponding to a leak size of 10% of the flow cross-section should be postulated. The leak detection system should be shown to have a sensitivity that is adequate to detect the minimum leakage from a crack that is just subcritical.

4.50. For primary or secondary piping without qualification for leak before break or for break preclusion, the probability of a pipe break can be reduced significantly if additional safety orientated measures are applied, such as surveillance measures (increased in-service inspections or monitoring for leakage, vibration and fatigue, water chemistry, loose parts, displacements, and erosion and corrosion).

Pipe whip

Phenomenon of pipe whip
4.51. The phenomenon of pipe whip in its classical form can occur only as a consequence of a double ended guillotine type pipe break in high energy piping. As the free cross-sections of the broken pipe are propelled by the forces of the discharging high energy fluid contained in the system, the adjacent free pipe branches are accelerated, which tends to move them from their installed configuration. In the case of unlimited or sufficiently large movement of the pipe branch, the increasing bending moment develops a plastic hinge at the location of the nearest pipe whip restraint or at a rigid or sufficiently stiff support. This defines the length of the pipe branch that rotates coherently about this point during the phase of free pipe whip movement.

4.52. On the impact of the whipping pipe with other equipment, structures or components, its motion is slowed down or stopped and the kinetic energy of the moving pipe branch is transferred partially or totally to the target as an impulsive loading. Such mechanical impacts on safety related targets should be prevented or, if unavoidable, should be investigated for inadmissible consequences.

4.53. In the case of a large longitudinal through-wall crack in high energy piping, no classical pipe whip occurs in the vicinity of this break since there is no separation of the pipe. However, large displacements should be considered on the basis of the assumptions that the piping forms a V shape with three plastic hinges and has the potential to affect other safety related equipment.

3 It should be noted that piping qualified for break preclusion should itself be protected from the consequences of internal hazards such as pipe breaks, missiles or the dropping of heavy loads.

Analysis of pipe whip

4.54. The whipping pipe branches should be analysed geometrically to determine possible directions of motion that might endanger target SSCs, as well as to evaluate their kinetic energy. Any possible mechanical impact on the target should be investigated by means of an appropriate dynamic analysis made on the basis of a detailed assessment of the system transient, to quantify the discharge forces and the energy of the whipping pipe as well as the fraction of the energy that would be transferred to the target (the extent of the analysis can be limited on the basis of conservative assumptions). In addition, the analysis should include an assessment of the effectiveness of the pipe whip restraints, demonstrating that pipe deflections may be kept small by the physical restraints. In the case of terminal end breaks, consideration should be given to the secondary effects on the remaining terminal ends.

4.55. The characteristics of the broken pipe should be taken directly from the design of the system and the location and type of the postulated rupture. In the case of pipe whip it is usually conservative to assume a full circumferential rupture and to assume that the pipe will form a hinge at the nearest rigid restraint. Simplified but proven engineering formulas are available for the analysis of a free whipping pipe with the formation of a full plastic hinge, and their use should be considered.

4.56. For the analysis of the consequences of an impact, it should be assumed that any impact of a whipping pipe onto a pipe of similar design but smaller diameter than the impacting pipe in general results in damage (a break) to the target pipe. Impacted target pipes of a diameter equal to or larger than the impacting pipe need not be assumed to lose their integrity. However, if an additional mass (such as a valve or an orifice plate) is present on the whipping branch, the kinetic energy of the motion is increased. In this case the target pipe may be broken even if it is larger than the whipping pipe.

4.57. In the investigation of the whipping pipe, consideration should be given to the potential for a subsequent break after an impact on a target, with the ejection of secondary missiles. Sources of missiles may be single concentrated masses within or attached to a pipe branch, such as valves and pumps or heavy form parts. If these components have separate supports by design to prevent such breaks and the formation of secondary missiles, the analysis should be extended to these anchor points. Attention should also be paid to instrumentation wells and similar attachments to the pipe as further possible sources of missiles.

Protection against the consequences of pipe whip

4.58. Although the probability of a severe pipe rupture in the piping systems of a nuclear reactor is generally accepted to be low, it is usual practice to restrict the motion of possible broken pipes at selected locations by the use of physical restraints. If piping is equipped with a sufficient number of effective pipe whip restraints at appropriate locations, the phenomenon of pipe whip may be considered to be excluded.

4.59. In addition to the prevention of pipe whip by means of a sufficiently low frequency of the double ended guillotine type pipe break, and its exclusion by means of pipe whip restraints, it may be necessary to take protective measures to reduce the probability of safety related piping or equipment being hit or inadmissibly damaged. In particular, special measures should be taken to protect isolation valves in the vicinity of a possible pipe break or a leak and to ensure the operability of these valves.

4.60. No special measures for protection against the consequences of an impact due to pipe whip need to be provided if any one of the following conditions is met:

(a) The breaking of the pipe is precluded as described in paras 4.40–4.50. This design inherently provides the necessary accessibility for improved in- service inspection.

(b) The whipping pipe is physically separated from safety important piping (such as that for the physical separation of trains) and from safety related SSCs by protective barriers or shielding or by an appropriate distance.

(c) It can be demonstrated for a whipping pipe after a double ended guillotine break that the unrestrained free movement of either end of the ruptured pipe in any possible direction around a plastic hinge formed at the nearest pipe whip restraint or rigid support cannot cause an impact on any SSC important to safety.

(d) It can be demonstrated that the internal energy of the whipping pipe is insufficient to impair to an unacceptable extent the safety function of any affected safety related SSC.

Jet effects

Phenomenon of jet effects

4.61. A jet is a stream of fluid ejected from a leak or break in a pressure retaining system, in a particular direction and with a significantly high velocity.

4.62. Jets usually originate from a broken component such as a pipe or vessel containing high energy pressurized fluid. The PIE from that hazard is then a leak or break of that pipe or vessel. Jets can be excluded for low energy systems.

4.63. Other possible sources of jets should be taken into account where appropriate. An example of such a source is a jet of gas (the possible effects of its burning are considered in Ref. [2]).

4.64. Once a high energy pipe or vessel has broken, the generation of a jet cannot be avoided. The only way to prevent the generation of a jet is to prevent the internal hazard itself. However, there are means of limiting the jet in time and/or space. For example, valves installed upstream and check valves installed downstream of the point of failure can stop the jet soon after it is initiated. Barriers around the failed pipe can limit the range of the jet (see also paras 3.37 and 3.38).

Analysis of jets

4.65. For each postulated location and size of a break, the jet geometry (shape and direction) and its physical parameters (pressure and temperature) should be evaluated as a function of time and space.

4.66. The jet's origin is usually assumed to be a circumferential break or a longitudinal leak of a vessel or pipe. The resulting jet is then limited to a particular direction. In the case of circumferential breaks, the jet may be orientated either axially or radially with respect to the pipe. Radial jets arise in the early stages of the separation of the two limbs of the pipe as a result of the counter-impingement of the two axial jets, one from each limb. The radial jet may persist for a sustained period if the motion of the limbs is arrested before they become misaligned.

4.67. If the internal hazard generates more than one jet, the possible interference of the jets should be taken into account. An example of this situation is the double ended break of a pipe without restraints, in which two jets may be generated, one from each of the broken ends of the pipe.

4.68. The influence of the motion of the jet's source (such as a whipping pipe) on the jet's geometry should be taken into account as well as other possible influences (such as objects in the vicinity of the jet's trajectory).

4.69. Either an up to date computer code or a simplified approximation on the basis of experimental data, or appropriate conservative assumptions, can be used for the analysis of the jet's shape and properties.

Protection against the consequences of jets

4.70. As the next step, an analysis of the consequences of jets should be performed. The following effects of jets on targets should be taken into account: mechanical load (pressure, impact), thermal load (temperature, including thermal stresses and shocks where appropriate) and properties of fluids (such as possible short circuits in electric equipment due to the conductivity of liquid water). Possible chemical effects should also be taken into account, especially if the fluid ejected is other than water. It may be necessary to analyse the effects of jets on targets that are not SSCs also, if their damage may lead to significant secondary consequences. A typical example is damage to pipe insulation. Although the insulation is not itself important to safety, debris from insulation material could block the sump strainer of the recirculation pump for the emergency core cooling system.

4.71. In addition to the direct impingement of a jet onto targets (local effects), flowing fluid may also have a significant effect on the general environmental conditions in a room. The effects will depend, among other things, on the time duration and the parameters of the jet and on the dimensions of the room. If this is a concern, then the general environmental parameters and their influence on the functioning of SSCs should also be analysed. Such an analysis is usually performed as part of the process for the environmental qualification of equipment. However, the set pf PIEs that are considered in the process of equipment qualification are usually limited to a relatively narrow range of design basis accidents that are analysed in the safety analysis report for the plant. A larger set of PIEs should be considered in the context of internal hazards (see para. 3.17), Including the influence of pressure, temperature, humidity, water level and activity on the functioning of SSCs. For example, a break in an auxiliary system is not usually analysed among the design basis accidents, but it should be considered in the evaluation of internal hazards. It should be shown by analysis that the general environmental conditions generated by a jet are not more severe than those considered in the process for equipment qualification. If this cannot be ensured, the components concerned should be requalified or else they should be protected.

4.72. Changes in the general environmental conditions in a room may result from factors not related to internal hazards. Such changes are outside the scope of this Safety Guide and the corresponding protection measures should be considered in the qualification process for equipment.

4.73. Protection against direct jet impingement is similar to protection against missiles (see paras 4.1–4.32). Protective measures can be designed in such a way as to cope with both missiles and jets, or generally with as many internal hazards as possible.

4.74. The differences between missiles and jets that should be taken into account in designing the protection include, for example:
(a) Their time duration (missiles are generally assumed to cause instant impacts, whereas jets, in addition to their instant impact, endure for some period of time;
(b) The possible penetration of a jet through the barrier due to erosion should be investigated);
(c) The behaviour of jets and missiles after impinging on a barrier is quite different; barriers should be designed in such a way that they do not deflect either jets or missiles in unfavourable directions;
(d) Since a jet is not a compact solid, barriers such as nets, which are effective against some missiles, would not protect SSCs against jets.

Internal flooding

Phenomenon of internal flooding

4.75. Flooding can be caused by any PIE that results in the release of a liquid (usually water) and consequently leading to internal hazards that include, for example, leaks from or breaks of pipes, vessels or tanks as well as any event that can lead to the actuation of a spray system (containment spray or fire extinguisher sprays), no matter whether the actuation is spurious or desired.

4.76. In a general sense, flooding means not only the formation of pools of water on the floor of a room but also the collection of liquid in higher locations, if sufficient drainage is not assured. For example, water (arising from sprays or condensed steam) can collect in cable trays even if they are located well above the floor level. Equipment located in such a place should then be considered to be subject to flooding. In addition, water from these trays may be drained to other undesired locations.

4.77. Examples of PIEs for internal flooding hazards include:
(a) A leak or break of the primary or secondary system;
(b) Spurious actuation of the containment spray system;
(c) A leak or break of the secondary feedwater system;
(d) A leak or break of the emergency core cooling system;
(e) A leak or break of the service water system;
(f) A leak or break of the fire water system;
(g) Human error during maintenance (e.g. in leaving a valve, an access hole or a flange open by mistake).

4.78. Prevention principles are in general similar to those for other internal hazards. Since flooding can be caused by the leaking or breaking of a vessel, tank or pipe, any measure that reduces the probability of a leak or a break (P_1) also reduces the probability of flooding.

4.79. The reduction of human error is another important way to reduce the probability of flooding.

Analysis of flooding

4.80. All possible internal flooding hazards should be carefully identified. The best approach is to base the list of internal hazards on a list of SSCs and then to identify all the possible sources of liquid (water in the case of pressurized water reactors and boiling water reactors), including sources in other rooms. This identification should be supported by room by room walk-downs.

4.81. For each internal hazard, P_1 should be determined, with account taken of possible human errors.

4.82. For all internal hazards, unless P_1 is acceptably small, a liquid level as a function of time should be determined not only for the room with the source of the liquid but also for all rooms to which the liquid could spread (through doors, pipe conduits or cracks in walls or floors). In the case of breaks in pipes connected to tanks or pools, account should be taken of possible siphoning effects, which can increase the amount of liquid drained. Possible blocking of drain holes by debris should be taken into account if this would lead to more severe conditions. In determining the liquid level using a volume–height relation, the as-built status of the room should be used. The possible collection of liquid in upper parts of the room (e.g. in cable trays) should also be analysed. In some cases it may be necessary to analyse the flooding also with regard to the transport of objects and/or small particles to undesired locations. A typical example is the blockage of the strainers of the emergency core cooling system. Isolation debris, corrosion particles and even human hair can be transported by water and can block the strainers.

4.83. If the liquid is water, flooding is usually considered to be of concern mainly for electrical devices. If the liquid is in contact with a hot object, a pressure excursion is possible; this phenomenon should be considered in the design of civil engineering structures. Other possible consequences, such as those stated in para. 2.15, Should also be considered.

Protection against the consequences of flooding

4.84. Sometimes intentional flooding is a design feature, and flooding phenomena should then be given full consideration in the design (e.g. some components of instrumentation and control systems should be qualified accordingly for containment sprays, and some doors and walls should be qualified as waterproof for fire protection sprays). Being a design feature, such intentional flooding may not generally be considered an internal hazard; however, owing to its similar nature, intentional flooding should be included in the set of flooding events.

4.85. Reduction in the probability P_2 of SSCs being affected by flooding can be achieved, for example, in the layout of the plant. Effective physical separation of redundant systems may in this case mean vertical separation. The SSCs can be located on a pedestal that is higher than the maximum possible flooding level. If this is not possible, a barrier (either a wall around the component or a complete enclosure) can be used. It should also be ensured by all available means that flooding (unless it is intentional flooding as a design feature) is mitigated as soon as possible and its spreading to unfavourable regions is prevented (e.g. by means of suitable thresholds). Means that can be used to mitigate flooding include:

(a) Appropriate design (isolation valves on potentially hazardous pipes, drains and pumps);
(b) Detection systems (flood warnings);
(c) Procedures (operational and/or emergency procedures).

For all actions taken in mitigation, the likelihood of success should be carefully evaluated. In case of any doubt, their failure should be assumed in the analysis. In the deterministic approach, the most severe single failure should always be assumed.

4.86. The probability P_3 of systems or components being seriously damaged can be reduced by using equipment qualified for operation in the wet or even submerged.

4.87. If neither measure can be practically achieved, then the overall probability of unacceptable consequences can be reduced by using redundant systems or components that are physically separated. It should be taken into account that there is great potential for common cause failures since liquid can flood an entire room and even spread to other rooms.

4.88. The possible formation of waves should be taken into account and analysed, if flooding is fast enough (such as in the event of a total breach of a tank). A wave may increase the fluid level locally significantly above the value predicted on a steady state basis. Waves can also impose a large mechanical load on SSCs. If such a possibility is identified, an appropriate means of protection (such as by a barrier, an appropriate layout or the redundancy of SSCs with physical separation) should be provided.

4.89. In addition to the direct impacts of flooding as described in this section, flowing fluid may also have a significant effect on the general environmental conditions in a room. Such effects should be considered in the qualification process for equipment.

5 References

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