AERB SAFETY GUIDE NO. AERB/SG/D-22

VAPOUR SUPPRESSION SYSTEM
(POOL TYPE)
FOR
PRESSURISED HEAVY WATER REACTOR

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FOREWORD

Safety of the public, occupational workers and protection of the environment should be assured while activities for economic and social progress are pursued. These activities include the establishment and utilisation of nuclear facilities and use of radioactive sources. They have to be carried out in accordance with relevant provisions in the Atomic Energy Act 1962.

Assuring high safety standards has been of prime importance since the inception of the nuclear power programme in the country. Recognising this aspect, the Government of India constituted the Atomic Energy Regulatory Board (AERB) in November 1983, vide Statutory Order No. 4772 notified in the Gazette of India dated December 31, 1983. The Board has been entrusted with the responsibility of laying down safety standards and framing rules and regulations in respect of regulatory and safety functions envisaged under the Atomic Energy Act of 1962. Under its programme of developing safety codes and guides, AERB has issued four codes of practice in the area of nuclear safety covering the following topics:

Safety in Nuclear Power Plant Siting

Safety in Nuclear Power Plant Design

Safety in Nuclear Power Plant Operation

Quality Assurance for Safety in Nuclear Power Plants

Safety guides are issued to describe and make available methods of implementing specific parts of the relevant codes of practice as acceptable to AERB. Methods and solutions other than those set out in the guides may be acceptable if they provide at least comparable assurance that nuclear power plants can be operated without undue risk to the health and safety of the plant personnel, general public and the environment.

Codes and safety guides may be revised as and when necessary in the light of experience as well as relevant developments in the field. The annexures, footnotes, references, and bibliography are not to be considered integral part of the document. These are included to provide information that might be helpful to the user.

The emphasis in the codes and guides is on protection of site personnel and the public from undue radiological hazards. However, for aspects not covered in the codes and guides, applicable and acceptable national and international codes and standards shall be followed. In particular, industrial safety shall be assured through good engineering practices and compliance with the Factories Act 1948 as amended in 1987 and the Atomic Energy (Factories) Rules, 1996.

The Code of Practice on Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants (AERB/SC/D, 1989) states the minimum requirements to be met for assuring safety in the design of a thermal neutron reactor based power plant. This Safety Guide provides guidance for designing the Vapour Suppression System (VSS). While elaborating on the requirements stated in the Code of Practice, it provides necessary information to assist personnel and organisations participating in the design of the VSS.

The safety guide has been prepared by the staff of AERB and other professionals. In drafting the guide, the relevant International Atomic Energy Agency (IAEA) documents on Nuclear Safety Standards have been used. The guide has been reviewed by experts and vetted by the Advisory Committees before issue. AERB wishes to thank all individuals and organisations who have contributed in the preparation, review and finalisation of the safety guide. The list of persons, who have participated in the committee meetings, along with their affiliation, is included for information.

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DEFINITIONS

Acceptable Limits

Limits acceptable to the Regulatory Body.

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 and severe accidents.

Design Basis Accident (DBA)

Design basis accidents are a set of hypothesized accidents which are analyzed to arrive at conservative limits on pressure, temperature and other parameters which are then used to set specifications that must be met by plant structures, systems and components, and fission product barriers.

Items Important to Safety

These items comprise:

(a) those structures, systems, equipment and components whose malfunction or failure could lead to undue radiological consequences at plant or outside the Plant;

(b) those structures, systems and components that prevent anticipated Operational Occurrences from leading to Accident Conditions;

(c) those features provided to mitigate the consequences of malfunction or failure of structures, systems or components.

Loss of Coolant Accident (LOCA)

It is an accident resulting from the loss of coolant to the fuel in a reactor due to a break in pressure retaining boundary of primary coolant system.

Operating Basis Earthquake (OBE)

The “Operating Basis Earthquake” (OBE) is that earthquake which, considering the regional and local geology and seismology and specific characteristics of local sub-surface material, could be reasonably expected to affect the plant site during the operating life of the plant; it is the earthquake that produces vibratory ground motion for which the features of Nuclear Power Plant (NPP) necessary for continued safe operation are designed to remain functional.

Postulated Initiating Events (PIE)

It is a hypothetical event that could lead to Anticipated Operational Occurrences and Accident Conditions, their credible failure effects and their credible combinations.

Safe Shutdown Earthquake (SSE)

The "Safe Shutdown Earthquake" is that which is based on an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local sub-surface material. It is the earthquake that produces maximum vibratory ground motion for which certain structures, systems and components are designed to remain functional. These structures, systems and components are necessary to assure;

(a) the integrity of the coolant pressure boundary, or

(b) the capability to shutdown the reactor and maintain it in a safe shutdown state, or

(c) the capability to prevent the accident or to mitigate the consequences of accidents which could result in potential off-site nuclear exposures higher than the permissible limits specified by the Regulatory Body, or

(d) the capacity to remove residual heat.

Single Failure

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

Surveillance

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

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1. INTRODUCTION

1.1 General

In the unlikely event of an accident in a nuclear reactor involving a rupture of a high-energy circuit, there would be a discharge of water, steam and possibly radioactive fission products.

Nuclear power plants are designed to include features which mitigate the consequences of postulated accident conditions that could release radionuclides into the environment. These features include, among others, a containment structure, a pressure suppression system, and clean-up systems. The reactor core and the reactor cooling system are placed within the containment, which provides the final barrier to the release of radioactivity into the environment.

Vapour Suppression System (VSS) with the containment system includes, among other things, the following features:

(a) energy management features provided to limit pressure, temperature and mechanical loadings on and within the containment envelope, and

(b) radionuclides management features provided to reduce the release of radionuclides to the external environment.

1.2 Objective

This Safety Guide is intended to supplement the Code of Practice on Design for Safety in Pressurised Heavy Water Based Nuclear Power Plants [1]. The main objective of detailed requirements given in the Guide is to provide guidelines to design VSS to limit the containment peak pressure and hence the release of radioactivity during and following an accident.

1.3 Scope

This Safety Guide deals with safety requirements in the design of VSS being deployed in Indian PHWRs. The Guide includes a description of the equipment and components, design bases, design parameters, requirements for surveillance and safety analyses. This Guide also describes the methodology for evaluating the various loads acting on VSS [Ref. Section- 3].

However, the Guide does not deal with aspects of structural analysis of VSS. Considerations for materials are not included in this guide. These are dealt with in the Design Safety Guide AERB/SG/D-16. Guidelines for containment design are covered in AERB/SG/D-21 and that for LOCA analysis are in AERB/SG/D-18.

Among various alternatives of VSS, e.g., Ice Condenser, Dousing, Containment Spray, Vapour Suppression Pool (VSP), this Guide deals with VSP system alone because of its prevalence in Indian PHWRs.

The requirements of the containment system in general are dealt with in some detail to focus on the specific requirements of the VSS.

2. FUNCTIONS AND DESCRIPTION OF VAPOUR SUPPRESSION SYSTEM

2.1 Functional Requirements

One of the objectives of containment is to prevent unacceptable release of radionuclides to the environment resulting from certain postulated accidents. VSS helps in achieving these objectives, through passive means, by reducing pressure and temperature in the containment, and trapping some of the radionuclides after a postulated accident.

2.1.1 VSS as an Energy Management Feature

VSS as an energy management feature should be designed to limit internal pressure, temperature and mechanical loading on and within the containment envelope to values below design values for the containment system. The equipment housed within the containment envelope should be designed to withstand accident loads and environmental conditions along with other design loads specific to that system.

2.1.2 Long-term ECCS Recirculation

In case, VSP water is desired to be used for core cooling in long-term recirculation mode during postulated accident conditions (LOCA), suitable provisions for recirculation and cooling should be made. Details may be found in Ref. [3 & 25].

2.1.3 Radiological Aspects

VSP water dissolves or entrains some radionuclides, airborne particulates and vapours. However, radionuclide management is only a secondary role for VSS. During the blowdown phase, the release of radionuclides into the containment is likely to be very small. However, depending on consequences of accident leading to fuel failure, there could be higher release of radionuclides during subsequent phases.

In the event of fission product release from irradiated fuel at a later phase, iodine is released in a number of forms including non-volatile CsI, volatile molecular I_2, and some organic iodines. Volatile forms could be released into containment atmosphere which can be controlled by maintaining high pH in pool water. High pH can have significant effect on iodine behaviour for two reasons [4][1]:

(i) it leads to hydrolysis of molecular I_2 eventually leading to the formation of less volatile species HOI, and

(ii) radiolytic oxidation of CsI, which leads to formation of I_2 (volatile), is reduced at high pH.

The release of radionuclides from the containment envelope is determined by the following factors:

- quantity of radionuclides released inside the containment envelope,
- reduction of radionuclides concentration in the containment as a result of radioactive decay and efficacy of radionuclides management features,
- release of radionuclides from the containment before isolation, and
- leakage rate of containment envelope after isolation (leakage rate depends on leaktightness and pressure rise in the containment).

VSP may also help to reduce radionuclides by scrubbing the fission products. This removal is likely to depend on factors such as chemical and physical forms of fission products, the chemical composition of water in the pool, the relative volume of pool water and non-condensible gas in the coolant release, the rates of release from system, entrained water and non-condensible gases to VSP.

2.2 System Description

The containment is divided into two volumes called V1 (drywell) and V2 (wetwell). Volume V1, containing high pressure and high enthalpy systems, is inaccessible during reactor operation largely due to high radiation fields. The remaining volume, designated as V2, contains low enthalpy systems and those areas, which are generally accessible. Typical illustration is shown in Fig.1. These are sealed from each other except that under accident conditions when the pressure in V1 is sufficiently above (equivalent to water column that is equal to the depth of submergence of vents) that in V2, steam and air are directed from V1 to the water in VSP through submerged vents and bubble through to volume V2.

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[1] In one specific study [4], a maximum partition factor of $1x10^6$ for Iodine has been reported at a pH value of 7. It is recommended that VSP water should be maintained at a pH value not less than 8. Safety analysis may be performed with a partition factor of $2x10^5$, which is considered to be conservative. However, the use of a higher value of partition factor should be justified.

VSP is generally located at the lowest elevation of the containment. The components connecting V1 to the VSP are generally vent shaft(s), distribution header(s) and downcomers. However, in a specific design, one or more of these components may be dispensed with. Typical illustrations are shown in Fig.2.

VSS shall be designed in such a way that following a postulated pipe rupture (i.e. PHT system / main steam line inside the containment) the air-steam mixture should get directed to V2 via VSP. All the steam in the steam-air mixture entering VSP should get condensed there. The cooled air subsequently gets released into V2. The leakage between V1 and V2 that bypasses submerged vents should be minimum and shall be taken into account in the design. Apart from communicating from V1 to V2, there is a need to communicate from V2 to V1 should the pressure in V2 be higher than that in V1 in the post-accident situation. Accordingly, there should be provision for pressure equalization by which a high pressure in V2 is relieved to V1.

An effective pressure suppression system requires a low dry well to wet well volume ratio and low bypass area. Some typical results of a parametric study carried out on pressure suppression efficiency and energy absorption efficiency of VSP, and pressure efficiency versus VSP bypass area are presented in Annexure-I. These results may be useful in designing the containment and VSS, in particular. However, the effectiveness of pressure suppression by VSP may get reduced due to bypass of the suppression pool under certain postulated conditions (e.g., excessive leakage through doors separating V1 and V2).

VSP should be suitably painted or lined so that leakage from or into the pool is prevented.

Description of purification, make-up, draining and sampling arrangements are given below:

Purification

A filter vessel with disposable cartridge filter element should be provided on VSP water recirculation line to filter out suspended impurities. A chemical addition tank with sufficient capacity should be provided for adding a suitable chemical (e.g., lithium hydroxide) to maintain the pH of pool water at a value not less than 8.

Control of Bio-mass Growth

Recirculation should be provided for agitation of VSP water to prevent biological growth. Accordingly adequate recirculation flow by pumps should be engineered.

Make-up

If the pool water level goes down, provision for maintaining VSP level by adding demineralized water should be made. A line tapping for make-up should be provided in a nearby area inside the Reactor Building (RB).

Draining Arrangement

Provision should be made to drain the pool water if VSP water level goes up or gets contaminated. In case of VSP water contamination, provision should be made to dispose off the pool water via waste management facility (WMF). Recirculation pumps can be used for emptying the pool as and when required. For this purpose, the pumps should take suction from a pit at the bottom of the Pool. The design should be such that inadvertent draining of VSP water is precluded.

Sampling

Suitable provision should be made for sampling of VSP water under different conditions. A sampling point should be provided in the recirculation loop to monitor the pH of the pool water and also to monitor crud or bio-growth and radioactivity. Samples of VSP water should be drawn at regular intervals of time.

3. DESIGN BASES

3.1 General

VSS components should be designed to accommodate the effects of and to be compatible with the environmental conditions associated with all operational states and the postulated accidents, including LOCA/MSLBA. These components should be appropriately protected against dynamic effects including pipe whipping and external events e.g., a seismic event.

In order to prevent the spread of activity to the environment, V1 and V2 are kept at sub-atmospheric pressure during normal operation with V1 pressure below that of V2. V1 and V2 are normally sealed from each other. V1 has closed loop ventilation with small purge and V2 is ventilated.

3.2 Design Considerations

VSS helps to reduce the pressure and temperature, and the concentration of airborne vapours and/or particulates in the containment. Consequently, the results of analyses of the postulated initiating events (PIEs) are the principal considerations in establishing the design basis for VSS.

The requirements applicable to this analysis are as follows [1, 6, 27, 28 & 29]:

- Mass and energy release rates for LOCA/MSLBA shall be calculated in a manner that conservatively establishes the internal design pressure and temperature in the containment;
- The pressure and temperature transient and responses of VSS to postulated events shall be calculated in a manner that will result in a conservative prediction of responses.

To meet the general requirement regarding containment design margin, it should be ensured that suppression pool is not bypassed [7]. Ideally, the allowable leakage areas for steam bypass of suppression pool should be determined for a spectrum of postulated reactor coolant system pipe breaks so that the peak pressure does not exceed the design pressure [5]. However, for design purposes the maximum allowable bypass area between V1 and V2 may be conservatively estimated on the basis of operating experience. VSS should be designed to accommodate, for the spectrum of postulated pipe breaks, a minimum bypass area of the order of 0.09 sq.m (1 sq.ft) even if experience shows a smaller area of bypass [6]. The efficiency of VSS depends on the V1/V2 ratio and the effective vent area.

The depth of submergence[2] of the downcomers should be adequate to permit complete condensation of steam coming into the suppression pool. However, it should be noted that a higher submergence depth would increase the back pressure. The total amount of water in the suppression pool should be adequate to limit the rise in temperature of the pool water and to reduce temperature of air released to volume V2. Lower the temperature of the pool, lower is the pressure rise in V2 and higher the available net positive suction head (NPSH) for ECCS recirculation pumps. Further, with a higher depth of water below the downcomer, the divergence of the jet emanating from downcomer is also higher, resulting in reduced jet impingement load.

The number of downcomers should be selected based on total vent shaft area and vent area of individual downcomer. Vent area should be such that effective steam condensation should be achieved. Minimum distance (centre to centre) between two downcomers should be around twice the diameter of downcomer. The distance between wall and outer periphery of the downcomers should be at least equal to the diameter of the downcomer. Analysis should be carried out conservatively assuming any one of the downcomers not available.

Chemical control of the suppression pool water is required to inhibit corrosion, biological growth and to enhance radionuclide trapping.

Provision should be made to avoid choking of VSS flow path.

Suitable provision should also be made to prevent spillage of water (active/non-active) and oil from other systems to the VSP.

3.3 Safety and Seismic Classifications

Containment is the final barrier for release of radioactivity to outside atmosphere following postulated accidents involving release of activity from fuel to inside the containment. The vent shaft and distribution header systems of VSP type containment perform mitigatory safety function, so these should be classified as Safety Class-II.

Containment should be designed to retain its integrity and remain functional during and after the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE). For this reason, containment structure, vent shafts and distribution header system should be designed to be functional for both SSE and OBE [24].

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[2] In the design of current PHWRs, the depth of submergence is 1.22 m (4 ft) [20].

3.4 Design Basis for the VSS

VSP does not play any role during the normal operation of the reactor. The design basis for VSS is derived primarily from results of analyses of PIEs following relevant operational states. The events considered are:

(a) failure of the primary coolant pressure boundary,

(b) failure of the secondary coolant pressure boundary,

(c) seismicity, and

(d) seismicity and postulated pipe rupture.

For each relevant PIE, appropriate combinations of the design parameters shall be analyzed to determine the most severe demands on VSS [25].

Vent shafts shall be suitably sized and located in volume V1 to effectively communicate to volume V2 under accident conditions. Vent shafts shall be designed to withstand dynamic loading due to flow of fluid. Sealing between volumes V1 and V2 shall be such that VSP bypass is minimum.

To assure system and component reliability, design measures may be used, if necessary, in combination, to achieve and maintain the required reliability commensurate with the importance of safety functions to be performed. (e.g., redundancy may be provided in terms of additional downcomer/ vent area to provide for failure of a downcomer or choking).

If plastic sheets are placed at the entrance of vent shafts to avoid mixing of heavy water and light water vapours, it should rupture at a low pressure (few mm of water column) to permit the passage of fluid from V1 to V2 under accident condition. Choking and ageing effects of plastic sheets should also be considered.

Suitable provisions may be made to monitor the corrosion of downcomers. However, if the design can ensure sufficient corrosion allowance for design life with adequate margin to account for variation in pool environment (e.g., pH) during the operating life, the inspection requirement with respect to corrosion check may be relaxed.

Layout of the system should provide easy access and sufficient headroom for carrying out required maintenance work on any of the equipment/ component (e.g., recirculation pump etc.).

3.5 Loads and Load Combinations

The following loads and load combinations as applicable to specific site should be considered for design of containment and its associated systems e.g., VSS [8].

3.5.1 Loads

(a) **Normal Loads** : Dead load, live load, equipment load, erection load, additional equipment loads (under condition of laydown during shutdown) for various floors.

(b) **Environmental Loads** : Wind load, flood load and seismic loads.

(c) **Abnormal Loads** : Accident pressure and temperature loads, piping loads due to increased temperature, reaction due to fluid discharge and hydrodynamic loads in the suppression pool chamber. In addition, effect of any potential pipe whip loads should be taken care of in design.

3.5.2 Load Combinations

VSS should be designed for simultaneous action of loads as given in the following load combinations. Wind and earthquake are considered non-concurrent. However, the peak response during OBE or SSE should be taken simultaneously with accident loads, which has a much lower probability of occurrence than individual events, but to be considered as one of the working load combinations conservatively. The following combinations of loads need to be considered (as applicable) [8]:

i) *Construction :* $D + L + F + W_c$
ii) *Normal :* $D + L + F + T_o + R_o + P_o$
iii) *Pressure test:* $D + L + F + P_t + T_t$
iv) *Severe environmental :* $D + L + F + T_o + E_o$
v) *Extreme environmental :* $D + L + F + T_o + E_s$
vi) *Abnormal:* $D + L + F + P_a + T_a' + R_a + H$ *and/or* Y_r

Or

$D + L + F + P_a' + T_a + R_a + H$ *and/or* Y_r

vii) *Abnormal-severe environmental:*

$D + L + F + P_a + T_a' + E_o + R_a + H$ *and/or* Y_r

Or

$D + L + F_a + P_a' + T_a + E_o + R_a + H$ *and/or* Y_r

viii) *Abnormal-extreme environmental :*

$D + L + F + P_a + T_a' + E_s + H + R_a$ *and/or* Y_r

Or

$D + L + F + P_a' + T_a + E_s + H + R_a$ *and/or* Y_r

where,

D = dead load from self weight of structure and material effects such as creep and shrinkage of concrete,

E_o = operating basis earthquake (OBE). [severe environmental condition (iv)],

E_s = Safe Shutdown Earthquake (SSE). [Extreme Environmental Condition (v)],

F = pre-stressing force including time-dependent variation,

H = suppression pool hydrodynamic loads,

L = live load including loads due to equipment, effect of soil and ground water pressure,

P_a = peak accident pressure inside primary containment. [abnormal condition (vi)],

P_a' = accident pressure at the time of peak temperature,

P_o = sub-atmospheric minimum pressure load during normal operation,

P_t = test pressure,

R_a = piping load due to increased temperature resulting from accident,

R_o = piping load at operating temperature,

T_a = peak accident temperature in primary containment,

T_a' = accident temperature at the time of peak pressure,

T_o = operating temperature (include ambient temperature),

T_t = test temperature,

W = wind load,

W_c = wind load during construction,

Y_r = reaction due to fluid discharge.

Load cases (vii) and (viii) correspond to the combination of abnormal and severe environmental conditions [(iv) and (vi)] and abnormal and extreme environmental conditions [(v) and (vi)] respectively.

4. DESIGN PARAMETERS

4.1 General

In order to determine the response of VSS to PIEs, appropriate analyses of the thermal hydraulics and structural response shall be performed taking into account the uncertainties in calculational models, the input data from system performance, material properties etc.[5]. The results of these analyses shall then be used to establish the design parameters [2] described in the following sections:

4.2 Process Parameters

(i) pressure and temperature transients, and

(ii) steam-air flow transients.

4.3 Structural Parameters

The hydrodynamic loads associated with LOCA or MSLBA are:

- vent clearing,
- pool swell,
- steam-air flow, and
- steam chugging.

Other loads are:

- differential pressure loadings imparted to structures and equipment, and
- structural loadings resulting from internal and external events (e.g., seismic event).

4.3.1 Hydrodynamic Aspects

4.3.1.1 Vent Clearing Transient

In the event of LOCA or MSLBA (as appropriate), pressure and temperature rise first in V1. This causes downward acceleration of water column in the downcomers and gradual clearing of water in the downcomers to VSP. Exit of water jet from downcomers causes loading of distribution header and downcomer pipes due to reaction, and the containment structure and other submerged structures in the pool due to jet impingement and drag. These loads are required to be determined for design of structures and components involved. References [7], [10], [11] and [15] present some models for analysis of vent clearing transient. Typical methodologies of calculating various loads due to vent clearing transient are given in Annexure-II.

4.3.1.2 Pool Swell Transient

Following vent clearing, individual air bubbles start growing at exit of each downcomer (or the vent hole where there is no downcomer). They may grow to such an extent as to occupy inter-downcomer spacing following which bubbles in a particular downcomer cluster coalesce to form a large bubble that subsequently grows and rises. With the formation of bubble and its growth, the pool level swells resulting in compression of the atmosphere above VSP in volume V2. Besides, rise in pool level causes hydrodynamic load on submerged structures. If required, a suitable bubble breaking arrangement may be incorporated in the suppression pool to reduce bubble size. References [7], [11], [12], [31] and [32] present some models for analysis of this phenomenon. A methodology for calculating hydrodynamic loads during pool swell is given in Annexure-II.

4.3.1.3 Steam-Air Flow Loads

After the downcomers have been cleared of the water and air initially present in downcomers get expelled during the pool swell phase, the flow of air and steam mixture gets established. The main result of this flow is the increase in pressure and temperature in V2 (as mentioned in Section 3.2) which have to be withstood by the structure therein. This increase in pressure and temperature is also felt by submerged structures. During the steam-air flow, loads similar to those felt during vent clearing phase but less in magnitude, are also experienced by vent shafts, downcomers and other submerged structures [13]. The details of evaluation of the steam-air flow can be found in AERB Safety Guide on Containment Design [AERB/SG/D-21]. Some calculational models are available in references [14] and [15].

4.3.1.4 Steam Chugging Loads

Steam chugging is associated with intermittent condensation events which occur at low steam flow rates where steady condensation cannot be maintained. The steam flow rate under such circumstances is usually lower than condensation rate. Intermittent condensation or chugging exerts pressure on the pool wall and base and on the downcomer pipes that are higher than those found under high steam flow rates characterized by nearly steady state flow condensation.

When the steam is presented with sufficient interface surface area and cooler pool water, a condensation event takes place and steam pressure drops very rapidly. The rapid interface acceleration or deceleration causes large pressure loads on the associated structures. The interface continues to move backward up in the downcomer, till the pressure of compressed steam is high enough to move forward down the pipe into VSP. Chugging is generally reported to be reduced by the amount of non-condensable flowing with steam. Chugging may be encountered during the latter phase of the blowdown in case of nearly pure steam flow from volume V1 to the suppression pool i.e. the air concentration is relatively low [22]. If it can be demonstrated by analysis that air concentration of the steam-air mixture flowing through suppression pool throughout the transient is significantly above the threshold beyond which chugging phenomenon gets suppressed, then it will be permissible not to consider any chugging load. Typical data regarding threshold of air concentration is given in references [14], [15] and [22].

4.3.2 Seismic Loads

Besides the loads associated with LOCA or MSLBA, VSS and its associated equipment as well as containment structure and its components are required to be designed for seismic loads as well.

The seismic loads for VSS and its associated equipment and components are usually obtained through seismic analysis of containment building.

4.3.3 Missile Loading

The possibility of generation of downcomer pipe missiles or downcomer pipe whip as a result of loads described in Section 3.5 should be investigated and the design made accordingly.

4.4 Chemical Aspects

Pool water chemistry should be maintained to prevent corrosion of structural material and biological growth. A proper water chemistry can also enhance the iodine trapping in pool water such that a large fraction of iodine remains in aqueous form [19].

Chemical treatment circuit should be designed to suit system requirements e.g., selection of filter, capacity of chemical addition tanks, the required instrumentation etc.

4.4.1 Corrosion Control

Corrosion under almost stagnant water condition can be controlled by suitable protective coating and alkaline water chemistry [19]. Pool water may be dosed with a suitable chemical (e.g., lithium hydroxide or potassium hydroxide) periodically to control the pH.

Recirculation piping supports should have adequate corrosion protection (e.g. use of heavy galvanized material).

4.4.2 Control of Growth of Bio-mass

Necessary engineering should be evolved to provide means to restrict bio-mass growth in pool water. To achieve this, recirculation may be provided with sufficient agitation to avoid biological growth in pool water. A velocity of 1 m/sec has been found to be adequate to prevent the growth of bio-mass [19]. Recirculation pumps should be installed such that the locations of their suction points enable emptying the pool, if necessary. The system should contain water recirculating pumps with redundancy. Suspended impurities should be separated out by filtration. Cartridge filter of appropriate rating (typically, 10 micron) along with potassium hydroxide added periodically in pool water may be used to prevent biological growth.

4.5 Other Considerations

Environmental conditions needed for specifications of equipment and structures e.g., humidity and exposure to water including chemical additives should also be considered for design.

5. SURVEILLANCE REQUIREMENTS

5.1 General

The VSP system shall be designed to permit appropriate testing to assure structural integrity and leaktightness of containment envelope and V1-V2 leaktightness, the operability and performance of the active components of recirculating system of the suppression pool water.

5.2 Monitoring of Suppression Pool

5.2.1 Level

Water level in VSP should be maintained at a fixed value within operating tolerance. The pool water level should be continuously monitored using suitable instrumentation covering small range around normal level (say ± 100 mm) [19]. Annunciation of high and low levels of water in suppression pool should be available in the control room.

5.2.2 Sampling of Suppression Pool Water

A sampling point should be provided in recirculation loop to draw representative samples of VSP water at regular intervals of time to monitor the pH of pool water and also to monitor crud or bio-growth and radioactivity.

5.2.3 Instrumentation for Pumps and Filters

Indication of the operating pump should be available. Pressure gauges should also be provided to monitor the performance of the pumps.

A differential pressure gauge of adequate range should be mounted across the filter to ascertain the condition of filter element [19].

5.3 V1-V2 Integrity Test

Leaktightness of V1 and V2 is essential for effective performance of VSS. Leak tests during commissioning and in-service should therefore be carried out. Detailed requirements are covered in the Design Safety Guide AERB/SG/D-21.

6. SAFETY ANALYSIS

6.1 General

VSP helps to limit the rise in pressure and temperature in the containment after a postulated LOCA or MSLBA. However, its effectiveness depends, among other factors, on the flow area of downcomers, bypass of VSP, choking of the piping due to bio-fouling or presence of foreign materials. Degradation of various seals between V1 and V2, among other factors, can lead to increased bypass of the VSP.

If vent flow paths are used which are not immediately available during pipe rupture, the following criteria may apply [6]:

(i) The vent area and resistance as a function of time after the break should be based on a dynamic analysis of the sub-compartment pressure response to pipe ruptures.

(ii) The validity of analysis should be supported by experimental data or a testing programme should be proposed at the construction permit stage to support the analysis. However, if the pressure for vent opening is not significantly above the general ambient pressure, a sub-compartment analysis is not called for.

6.2 Degraded Operation of VSS

Following modes of degraded functioning need to be considered:

6.2.1 Choking of Downcomer/ Vent Holes

For obtaining a conservative estimate of containment loading, certain flow blockage shall be assumed for flow of air-steam mixture from V1 to suppression pool (e.g., one downcomer is not available) [20].

6.2.2 Suppression Pool Bypass

Leakage path between V1 and V2 bypassing suppression pool is specified as an input data to the codes used for calculating pressure-temperature transients. A parametric study should be carried out to see the effect of bypass on containment peak pressure [20]. Some typical illustrations are given in Annexure-I.

The containment should be designed to accommodate, for the spectrum of postulated pipe breaks, a minimum bypass leakage area of the order of 0.09 sq.m (1 sq.ft.)[6].

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ANNEXURES

ANNEXURE-I

EFFECTIVENESS OF VAPOUR SUPPRESSION SYSTEM [15]

An effective pressure suppression system requires a low V1 (dry well) to V2 (wet well) volume ratio and low bypass area. However, practical considerations impose restraints on these parameters. Some typical results from the studies [15] are presented in this Annexure. Fig.I.1 describes the dry well pressure transient for different V1/V2 ratios. Fig.I.2 shows the pressure suppression efficiency for two different pipe flow areas. Fig.I.3 shows the energy dump efficiency of the passive suppression system. Fig.I.4 illustrates the effect of suppression pool bypass area on pressure suppression efficiency. Nevertheless, with given restraints, using these parametric studies one could arrive at optimum containment design. It may be noted that these results are only indicative and may depend on the actual system details.

ANNEXURE-II

HYDRODYNAMIC LOADS [13], [23]

A. Vent Clearing

Initially the level in downcomer starts moving downwards as the pressure in the drywell builds up after LOCA or MSLBA. The velocity of water jet from the downcomer varies with time and it is obtained from the governing one-dimensional hydrodynamic equations.

Jet Load Calculation from Vent Clearing Velocity

The loads due to vent clearing and steam and air mixture flow are computed by the following method. (Ref. Fig.II.1)

(i) Load due to jet impingement:

Jet momentum pressure on structures close to the pipe outlet.

$$P_{jo} = \rho V^2 \cos\theta \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.1)$$

When the structure is away from jet outlet, the pressure gets reduced due to spreading of the jet. The following correction can be used for calculating the jet impingement pressure at a distance ‘r’

$$P_{jr} = P_{jo} / (1 + Kr^2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (II.2)$$

where,

V = fluid velocity
ρ = density of the fluid
θ = angle of inclination
K = geometry dependent factor (5.15x 10^{-3} observed in Mark II experiment)

(ii) Loads due to bends:

Horizontal load $F_X = Q\,(V_1 - V_2 \sin □)$ ....…….........*(II.3)*

Vertical load $F_V = Q\,(V_1 - V_2 \cos □)$ ....*(II.4)*

where,

Q = mass flow rate
V_1 = fluid velocities at upstream of the bend
V_2 = fluid velocities at downstream of the bend
□ = angle of bend.

A schematic diagram showing the loads during vent clearing is presented in Figs. II.2A & B.

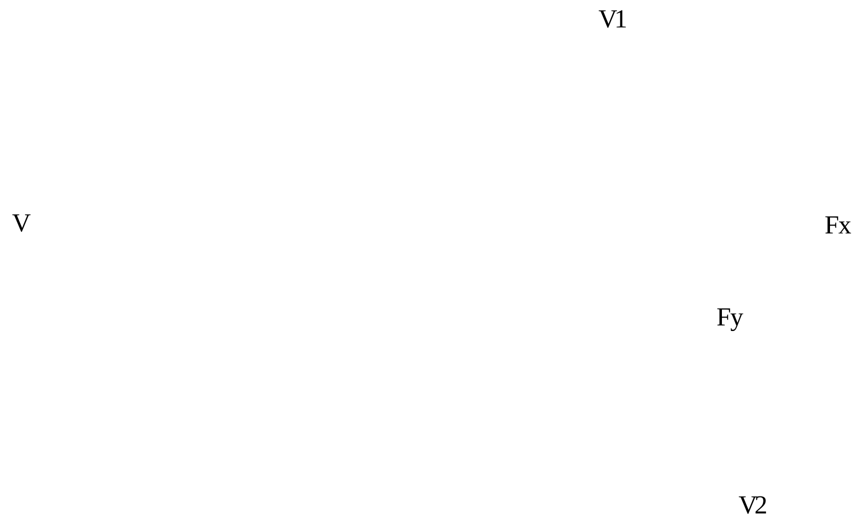

Fig. II.1 - Jet Impingement Load and Loads due to Bend

B.1 Pool Swell Pressure Load on Submerged Structures

The loading on submerged boundaries below vent exit may be taken as the maximum pressure of air bubble at the vent opening plus hydrostatic head corresponding to vertical distance from the vent exit. For the portion above the vent exit up to the maximum pool elevation, linear variation between maximum bubble pressure and maximum wet well air space pressure may be taken. The maximum air bubble pressure at the vent exit should be calculated from a suitable pool swell analytical model. Various loads associated with pool swell are presented in Fig. II.3.

B.2 Pool Swell Impact and Drag on Other Internal Structures

The impact and drag loads for internal structures above the suppression pool (except the vent header, downcomers and vent header deflectors), shall be modified such that the structures are classified as either cylindrical (e.g. pipes), exposed flat surfaces (e.g. 'I' beams), or gratings. The following load specifications for each of the three structural classifications shall be used. Any structure that can not be classified as one of these geometries will be reviewed on a case-by-case basis. The longitudinal velocity distribution shall be based on the main vent "EPRI pool swell tests". It has been observed that gratings do not experience any significant impact load. Results for cylindrical and flat targets are given below:

B.2.1 Cylindrical Structures

For cylindrical structures, the pressure transient which occurs upon water impact and subsequent drag is depicted in Fig. II.4. The parameters in Fig.II.4 shall be defined as follows:

1. The maximum pressure of impact P_{max} will be determined by,

$$P_{max} = 7.0 * \frac{1}{2}\left[\frac{\rho V^2}{144g}\right] \text{ .... } (II.5)$$

where P_{max} is the maximum pressure averaged over the projected area (psi) ρ is the density of water (lb_m/ft^3), V is the velocity (ft/sec) and g is the acceleration due to gravity (ft/sec^2).

2. The hydrodynamic mass per unit area for impact loading shall be obtained from a correlation for cylindrical target. A margin of 35% should be added to this value to account for data scatter.

3. The impulse of impact per unit area shall be determined by,

$$I_p = \frac{M_H}{A}\left[\frac{V}{144g}\right] \quad \text{.......... (II.6)}$$

where I_p is the impulse per unit area (psi-sec), M_H/A is the hydrodynamic mass per unit area (lb_m/ft^2) and V is the impact velocity (ft/sec).

4. The pulse duration will be determined from the following equation:

$$\tau = 2* \frac{I_p}{P_{MAX}} \quad \text{.......... (II.7)}$$

5. The pressure due to drag following impact shall be determined by,

$$P_D = \frac{C_D}{2}\left[\frac{\rho V^2}{144g}\right] \quad \text{.......... (II.8)}$$

where P_D is the average drag pressure acting on the projected area of target (psi), C_D is the drag coefficient.

B.2.2 Flat-Surface Structures

For flat surface structures, the pressure transient which occurs upon water impact and subsequent drag is depicted in Figure-V.2. The parameters in the figure shall be defined as follows:

1. The pulse duration (τ) is specified as a function of impact velocity,

τ = 0.0016*W for $V \leq 7$ ft/sec

τ = 0.011* W/V for $V > 7$ ft/sec

where W is the width of the flat surface (ft) and V the impact velocity (ft/sec).

2. The pressure due to drag following impact shall be determined by,

$$P_D = \frac{C_D}{2}\left[\frac{\rho V^2}{144g}\right] \quad \text{.......... (II. 9)}$$

where P_D is the average drag pressure acting on the projected area of target (psi), C_D the drag coefficient.

3. The hydrodynamic mass per unit area for impact loading shall be obtained from a correlation for flat target. A margin of 35% should be added to this value to account for data scatter.

4. The impulse of impact per unit area shall be determined by,

$$I_p = \frac{M_H}{A}\left[\frac{V}{144g}\right] \quad \text{..} \quad (II.\ 10)$$

where I_p is the impulse per unit area (psi-sec), M_H/A the hydrodynamic mass per unit area (lb_m/ft^2) and V is the impact velocity (ft/sec).

5. The maximum pressure P_{max} shall be calculated from the impulse per unit area and the drag pressure as follows:

$$P_{max} = 2*(I_p/t) + P_D \quad \text{..} \quad (II.11)$$

Other calculation methods are also available in Ref.[23].

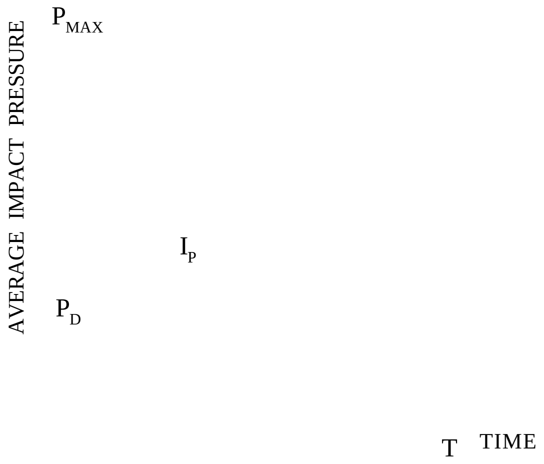

Fig. II.4 - Pulse Shape for Water Impact on Cyclindrical Target

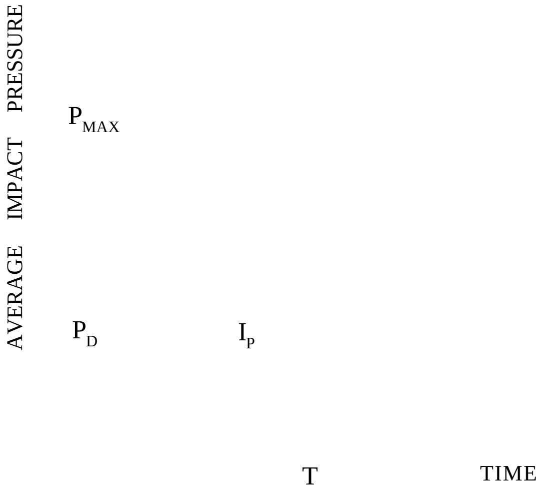

Fig. II.5 - Pulse Shape for Water Impact on Flat Target

ANNEXURE-III

ARRANGEMENT OF VENT SHAFT AND DOWNCOMERS IN VARIOUS PHWRs

1. MAPS-1&2

The vent system of MAPS has been provided with two vent shafts connected with a single distribution header situated in the west side of the suppression pool area. The distribution header of MAPS is of circular cross-section and 54 downcomers are connected to this to communicate with suppression pool water. The downcomers are submerged in suppression pool water by 1.2 m. The vent shafts and distribution headers are metallic.

Section - B B

Vent
Shafts

Fig. 2B - One Distribution Header, Vertical Exit from Downcomers (MAPS)

2. NAPS-1&2

The vent system of NAPS has been provided with two vent shafts, each connected with distribution header of rectangular cross-section and located in east and west sides of the suppression pool. Each distribution header is connected with 60 downcomers. Each downcomer has vertical exit and submerged in suppression pool water by l.2 m.

Section - D D

Fig. 2D - Two Distribution Headers, Vertical Exit from Downcomers (NAPS)

3. KAPS-1&2

The vent system of KAPS has been provided with two vent shafts located in the east and west sides of the suppression pool. Each vent shaft is connected with one distribution header in East and West sides of the suppression pool. These distribution headers of east and west sides are connected with 10 and 15 Nos. of downcomers respectively. These downcomers communicate with suppression pool water through vent holes provided in horizontal direction. The submergence depth of downcomer from the top of vent hole is 1.2 m.

Section - C C

Fig. 2C - Two Distribution Headers, Horizontal Exit from Downcomers (KAPS)

4. KAIGA-1&2 and RAPP-3&4

In Kaiga, the annular space between structural wall and IC wall is used as vent shaft as well as distribution header. Since the Structural Wall is distributed all over the periphery, the downcomers (10 in east side and 15 in west side) are directly connected to this wall. The downcomers communicating vent shaft/ distribution header with suppression pool water by horizontal vent holes are submerged in suppression pool water by 1.2 m from the top of vent holes.

Section - E E

Fig. 2E - Annular Vent Shaft, Horizontal Exit from Downcomers (KAIGA)

5. TAPP-3&4 [500 MWe REACTOR]

The vent system of 500 MWe reactors has four vent shafts and two distribution headers. Each distribution header is connected with two vent shafts. The east distribution header communicates with suppression pool water through 38 horizontal vent holes. Similarly, the west distribution header has 40 vent holes to communicate with suppression pool water. The submergence depth from the top of vent hole is 1.2 m. The vent shafts and the distribution headers are R.C.C. structures.

Vent Shaft

ICW

Distribution Header

Vent Holes

Section A A

A

Fig. 2A - No Downcomer (500 MWe)

LIST OF PARTICIPANTS

WORKING GROUP

Dates of meeting:	October 31, 1995	August 23, 1996
	May 10, 1996	January 03, 1997
	June 4 & 12, 1996	June 25, 1997
	July 5, 1996	July 28, 1998

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Shri S.K.Haware	:	RSD, BARC
Shri Nalini Mohan	:	NPCIL
Shri R.N. Bhawal	:	NPCIL
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Shri V.R.Dhotre (Invitee)	:	DRI&E, AERB
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ADVISORY COMMITTEE FOR CODE, GUIDES AND ASSOCIATED MANUALS FOR SAFETY IN DESIGN OF NUCLEAR POWER PLANTS (ACCGD)

Dates of meeting : January 20 & 21, 1997
August 26 & 27, 1997

Members and alternates participating in the meetings:

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Shri S. Damodaran : NPCIL (Formerly)

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Shri Ch. Surendar : Executive Director (Operations), NPCIL

Dr. U.C. Mishra : Director, H&SE Group, BARC (Formerly)

Shri S.K. Sharma : Director, RG, BARC

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Shri S.P. Singh : Head, NSD, AERB (Formerly)

Shri G.K. De : Head, NSD, AERB (Formerly)

Shri K. Srivasista (Member-Secretary) : NSD, AERB

PROVISIONAL LIST OF SAFETY CODE, GUIDES & MANUAL ON DESIGN OF PRESSURISED HEAVY WATER REACTOR

Safety Series No.	Provisional Title
AERB/SC/D	Code of Practice on Design for Safety in PHWR Based Nuclear Power Plant
AERB/SG/D-1	Safety Classification and Seismic Categorisation
AERB/SG/D-2	Application of Single Failure Criteria
AERB/SG/D-3	Protection Against Internally Generated Missiles and Associated Environmental Conditions
AERB/SG/D-4	Fire Protection
AERB/SG/D-5	Design Basis Events
AERB/SG/D-6	Fuel Design
AERB/SG/D-7	Core Reactivity Control
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AERB/SG/D-9	Process Design
AERB/SG/D-10	Safety Critical Systems
AERB/SG/D-11	Electrical Power Supply Systems
AERB/SG/D-12	Radiation Protection in Design of PHWR
AERB/SG/D-13	Liquid and Solid Radwaste Management
AERB/SG/D-14	Control of Air-borne Radioactive Materials
AERB/SG/D-15	Ultimate Heat Sink and Associated Systems
AERB/SG/D-16	Materials Selection and Properties
AERB/SG/D-17	Design for In-Service Inspection
AERB/SG/D-18	LOCA Analysis Methods
AERB/SG/D-19	Hydrogen Release and Mitigation Systems under Accident Conditions in PHWR
AERB/SG/D-20	Safety Related Instrumentation and Control
AERB/SG/D-21	Containment Systems Design
AERB/SG/D-22	Vapor Suppression System
AERB/SG/D-23	Seismic Analysis Methodology
AERB/SG/D-24	Design of Fuel Handling and Storage Systems
AERB/SG/D-25	Computer Based Safety Systems
AERB/SM/D-1	Decay Heat Load Calculations

NOTES