PRESSURE SUPPRESSION SYSTEM CONTAINMENTS

A State-of-the-Art Report
by
a Group of Experts of the NEA/CSNI

OCTOBER 1986

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
OECD NUCLEAR ENERGY AGENCY
38, boulevard Suchet, 75016 Paris, France
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38, boulevard Suchet, 75016 Paris, France
The OECD Nuclear Energy Agency (NEA) was established on 20th April 1972, replacing OECD's European Nuclear Energy Agency (ENEA, established on 20th December 1957) on the adhesion of Japan as a full member.

NEA now groups all European Member countries of OECD and Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objectives of NEA are to promote co-operation between its Member governments on the safety and regulatory aspects of nuclear development, and on assessing the future role of nuclear energy as a contributor to economic progress.

This is achieved by:

- encouraging harmonization of governments' regulatory policies and practices in the nuclear field, with particular reference to the safety of nuclear installations, protection of man against ionizing radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;

- keeping under review the technical and economic characteristics of nuclear power growth and of the nuclear fuel cycle, and assessing demand and supply for the different phases of the nuclear fuel cycle and the potential future contribution of nuclear power to overall energy demand;

- developing exchanges of scientific and technical information on nuclear energy, particularly through participation in common services;

- setting up international research and development programmes and undertakings jointly organised and operated by OECD countries.

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operative Agreement, as well as with other international organisations in the nuclear field.
The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and co-ordinate the Nuclear Energy Agency's work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries. This is done in a number of ways. Full use is made of the traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences. Some of these arrangements are of immediate benefit to Member Countries, for example by improving the data base available to national regulatory authorities and to the scientific community at large. Other questions may be taken up by the Committee itself with the aim of achieving an international consensus wherever possible. The traditional approach to co-operation is reinforced by the creating of co-operative (international) research projects, such as PISC and LOFT, and by a novel form of collaboration known as the international standard problem exercise, for testing the performance of computer codes, test methods, etc. used in safety assessments. These exercises are now being conducted in most sectors of the nuclear safety programme.

The greater part of the CSNI co-operative programme is concerned with safety technology for water reactors. The principal areas covered are operating experience and the human factor, reactor system response during abnormal transients, various aspects of primary circuit integrity, the phenomenology of radioactive releases in reactor accidents, containment performance, risk assessment, and severe accidents. The Committee also studies the safety of the fuel cycle, conducts periodic surveys of reactor safety research programmes and operates an international mechanism for exchanging reports on nuclear power plant incidents.

The Sub-Committee on Licensing, consisting of the CSNI Delegates who have responsibilities for the licensing of nuclear installations, examines a variety of nuclear regulatory problems and provides a forum for the review of regulatory questions, the aim being to develop consensus positions in specific areas.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
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<td>CFR</td>
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<td>LOCA</td>
<td>Loss-of-Coolant Accident</td>
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<td>SOAR</td>
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</tr>
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</tr>
</tbody>
</table>
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>6</td>
</tr>
<tr>
<td>1. Phenomenology of Pressure Suppression Systems</td>
<td>6</td>
</tr>
<tr>
<td>1.1 Functions and Features of Pressure Suppression Containments</td>
<td>6</td>
</tr>
<tr>
<td>1.2 The Pressure Suppression Pool</td>
<td>9</td>
</tr>
<tr>
<td>1.3 Main Phenomena involved with Pressure Suppression</td>
<td>10</td>
</tr>
<tr>
<td>2. Commercial Pressure Suppression Containments</td>
<td>15</td>
</tr>
<tr>
<td>References Section 2</td>
<td>18</td>
</tr>
<tr>
<td>3. The Design Basis</td>
<td>24</td>
</tr>
<tr>
<td>3.1 Definition of Design Basis</td>
<td>24</td>
</tr>
<tr>
<td>3.2 Design Basis Scenarios</td>
<td>24</td>
</tr>
<tr>
<td>3.3 Regulatory Guidelines</td>
<td>34</td>
</tr>
<tr>
<td>References Section 3</td>
<td>37</td>
</tr>
<tr>
<td>4. Experimental Research</td>
<td>44</td>
</tr>
<tr>
<td>4.1 Safety/Relief Valve Blowdown Tests</td>
<td>44</td>
</tr>
<tr>
<td>4.2 LOCA Related Tests</td>
<td>46</td>
</tr>
<tr>
<td>4.3 Main Experimental Facilities and Programs</td>
<td>49</td>
</tr>
<tr>
<td>4.4 Interpretation of Selected Phenomena</td>
<td>54</td>
</tr>
<tr>
<td>4.5 Concluding Remarks</td>
<td>61</td>
</tr>
<tr>
<td>References Section 4</td>
<td>63</td>
</tr>
<tr>
<td>5. Analytical Modelling, Computer Codes and Code Verification</td>
<td>85</td>
</tr>
<tr>
<td>5.1 Introduction</td>
<td>85</td>
</tr>
<tr>
<td>5.2 Analytical Modelling of Safety/Relief Valve Blowdown Loads</td>
<td>85</td>
</tr>
<tr>
<td>5.3 LOCA-Integral Systems Behaviour Codes</td>
<td>87</td>
</tr>
<tr>
<td>5.4 Fluid-Structure Interaction Codes</td>
<td>93</td>
</tr>
<tr>
<td>5.5 Code Verification</td>
<td>96</td>
</tr>
<tr>
<td>References Section 5</td>
<td></td>
</tr>
<tr>
<td>6. Conclusions and Recommendations</td>
<td>110</td>
</tr>
</tbody>
</table>
Light water cooled boiling water reactors (BWRs) are in general equipped with a pressure-suppression containment system which acts primarily as a heat sink in the event of a loss of coolant accident. In addition, it provides retention capabilities for fission products in gas/steam mixtures should they pass through the suppression pool system. The water pool also serves as the long-term supply for the emergency core cooling system, establishing a closed cooling recirculation flow path between the core, the drywell and the suppression pool. Thus, the overall reliability of the pressure-suppression containment is of central importance for guaranteeing the entire safety of boiling water type power reactors.

Considerable research efforts have been undertaken during the last 15 years within various countries to improve the basic understanding of important phenomena observed in numerous experimental facilities as well as during operation of BWRs. In particular, the dynamic response of such a system following a hypothetical large break or anticipated small break loss of coolant accident (LOCA) has received considerable attention because of its importance for the proper design of associated containment structures. The confirmatory nature of several research projects in the BWR containment field has led to a series of additional activities to find compromises between irreversible early design decisions and the need to apply research results obtained at a later stage. It seems an appropriate time to assess the current status of the results gathered from relevant research work, which to a large extent profited from close international co-operation.

The CSNI Principal Working Group 2 on Transients and Breaks, at its first meeting in 1982 reiterated a recommendation of the former Working Group on "Water Reactor Containment Safety" to prepare a State-of-the-Art-Report (SOAR) on BWR containment pressure suppression system fluid dynamics under design basis conditions. Several countries which operate or license BWRs expressed their continuing interest in the preparation of such an SOAR at the second meeting of the Principal Working Group 2 in 1983, requesting the necessary resources to be made available to perform the task.

In general, a SOAR provides a review of selected subjects related to nuclear reactor safety research and assesses the existing state of knowledge, identifying possible gaps and giving recommendations for additional research, if necessary.

It was not the intention of the authors of this report to produce an extensive encyclopedia, compiling every single result obtained within this area. Instead, the report sets forth what is considered to be known and understood, along with some judgement of the importance of remaining uncertainties. In particular, the technical and scientific background which is available to understand governing phenomena and to extrapolate and transfer experimental observations into design and licensing decisions is illuminated.

The report is structured into various parts. A descriptive part (chapters 1, 2 and 3) illustrates the technical tasks involved in the design and construction of a containment with a pressure suppression system. Another part (chapters 4 and 5) assesses the results of a large number of experimental activities in this field, and describes the analytical tools developed to
analyse and interpret experimental evidence and to predict the behaviour of pressure suppression containment systems. The last part (chapter 6) gives general recommendations and the conclusions drawn.

A writing group of lead authors met in October 1984, February and June 1985 and in February 1986, to review the drafts and discuss the recommendations and general conclusions. Members of the writing group were:

Prof. Dr. Ing. H. Karwat
Technische Universität München
Lehrstuhl für Reaktordynamik und Reaktorsicherheit
München, FRG (Editor)

Dr. M.J. Lewis
Hauptabteilung für die Sicherheit der Kernanlagen, Schweizerisches Bundesamt für Energiewirtschaft;
Würenlingen, Switzerland

Prof. Dr. Ing. M. Mazzini
Università Degli Studi di Pisa Dipartimento di
Construzioni Meccaniche e Nucleari;
Pisa, Italy

Dr. O. Sandervaaag
Studsvik Energiteknik AB;
Nyköping, Sweden.

Several institutions:

-- Japan Atomic Energy Research Institute-JAERI (Tokai-mura)
-- Gesellschaft für Reaktorsicherheit-GRS (Köln)
-- Engieonderzoek Centrum Nederland-ECN (Petten)
-- GKSS-Forschungszentrum Geesthacht GmbH

contributed considerable parts to the draft reports. Valuable comments on the draft report were received from Kraftwerk Union AG, Offenbach-FRG, and were incorporated into the final version of the report drawn up at a meeting of the lead authors in February 1986.
1. PHENOMENOLOGY OF PRESSURE SUPPRESSION SYSTEMS

1.1 Functions and Features of Pressure Suppression Containments

The main function of a primary containment is to contain the energy and radioactivity released from the reactor coolant system during transients and loss-of-coolant-accidents (LOCA). In a pressure suppression containment this energy is absorbed in a water pool, the steam released being condensed in the pool or by some other energy sink. This reduces considerably the value of the product "maximum pressure (P_m) times volume (V)" compared to a dry containment. Containment structures and volumes can thus be smaller and lighter.

The pressure suppression containment is ideally suited for boiling water reactors (BWR). Modern BWRs have no secondary side steam generators, so that the reactor coolant system is more compact than that of a pressurised water reactor (PWR). The primary containment can be correspondingly smaller. BWRs also utilise the large heat sink inside the containment to condense steam released through safety/relief valves during reactor isolation events. During transients, which involve a loss of the main heat sink, the excess, slightly radioactive, steam cannot be released to the atmosphere.

The ice-condensing and bubbling condenser pressure-suppression containments, as used for some PWRs, are exceptions in that the suppression system has one purpose only, to reduce LOCA containment pressures. Neither of these concepts are discussed further here.

Despite the apparent variety of BWR pressure suppression containments, which are described more fully in chapter 2, they are all based on similar design principles and, as indicated in Fig. 1.1, have the following common features.

a) a pressure retaining and leak tight primary containment boundary

b) a large capacity suppression pool situated inside the primary containment structure. Pool boundaries together with the enclosed gas-space above the pool are usually designated the "wetwell"

c) a pressure retaining structure called the "drywell", which surrounds the reactor coolant system. Drywell and wetwell walls usually, but not necessarily, form the primary containment boundary

d) a vent system, which connects the drywell gas space to the wetwell below the suppression pool surface. Vent systems can have any convenient geometry. Piping networks, vertical pipes and horizontal openings have been employed.

The features b), c) and d) distinguish a BWR pressure suppression containment from its full-pressure or dry counterpart. Apart from these, other features must be considered in containment design, some of which are common to all light water reactor containments:

e) means to relieve primary system energy through safety- and relief-valves, designated safety/relief valves in this report
f) isolation of primary containment penetrations

g) systems to remove residual heat from the primary containment

h) containment spray systems to depressurise and decontaminate the drywell and/or the wetwell atmosphere after an accident

i) vacuum breakers. These are installed if the threat of structural instability exists due to the lowering of local or overall containment pressure following an accident

j) hydrogen control systems to prevent damaging the containment by hydrogen deflagration or detonation during LOCAs in which the availability of emergency core cooling is greatly reduced. Due to their design (relatively small P<sub>xV</sub>-value) pressure suppression containments are more prone to this threat

k) containment ventilation and atmospheric cooling systems.

1.2 The Pressure Suppression Pool

The large capacity suppression pool is the most important feature of a BWR pressure suppression system. It:

i) acts as a passive heat sink when the reactor is isolated from the main heat sink (condenser) or when it produces more steam than the secondary system can absorb. Primary system energy is released through safety/relief valves and transported to below the suppression pool’s surface through individual blowdown lines. The pool and containment are subjected to short term dynamic phenomena and a long term thermal transient;

ii) acts as a passive heat sink during and following a LOCA inside the drywell. Primary system coolant lost from the break is directed to the pool via the vent system. The pool and containment are again subjected to short-term dynamic phenomena and a long term thermal transient. During a small or intermediate break LOCA, coolant may also be transferred to the suppression pool manually or automatically by the opening of safety/relief valves. This depressurizes the reactor more rapidly than the break flow alone, enabling low-pressure core-coolant systems to operate;

iii) limits primary containment pressure by condensing steam released to the pool either through the relief valves or through the vent systems when performing the above functions. Wetwell pressures are thus controlled indirectly by drywell gas displacement and the pool’s thermal transient rather than by steam release;

iv) acts as a passive store or filter for radioactive material in the form of aerosols and iodine transported with the primary system coolant into the pool;

v) provides a large source of primary coolant make-up or of emergency core coolant.
1.3 Main Phenomena Involved with Pressure Suppression

The benefits of the pressure suppression capability are offset by the complexity of the phenomena involved with pressure suppression. These include the clearing of the safety/relief valve blowdown lines, the vent-clearing and gas transfer between drywell and wetwell during a LOCA, the various safety/relief valve blowdown and LOCA condensation processes in the suppression pool, a limited capacity for absorbing relieved steam, the possibility of underpressures in the drywell and wetwell and of steam bypass of the suppression pool. Within the framework of this report, only the phenomena associated with the pressure suppression processes, namely safety/relief valve blowdown and LOCAs will be considered. Brief descriptions are provided here as a foundation for details provided in later chapters.

1.3.1 Safety/Relief Valve Blowdown

To avoid overpressurisation of the reactor due to a loss of the main heat sink, or to depressurise the reactor pressure vessel in order to inject coolant from low-pressure emergency supplies, the energy generated by the reactor and stored in the pressure vessel is released to the suppression pool through safety/relief valves. A typical layout for a single valve is shown schematically in Fig. 1.2.

Safety/relief valve operation involves initial short-term (1s) clearing of the blowdown line of water and gas. The steam flow from the reactor vessel through the fast-opening valve rapidly compresses the gas in the unsubmerged portion of the blowdown line and accelerates the water column in the submerged portion. The release of steam and these accelerations cause reaction loads on the valve, on the blowdown line, and on the open end of the line. The water and gas discharges and the subsequent dynamics in the suppression pool induce a dynamic pressure field in the suppression pool.

After blowdown-line clearing, steam is discharged into the suppression pool. The steam blowdown may last for a few seconds for a mild reactor isolation event, to many minutes for a forced reactor depressurisation or a stuck open valve. Steam discharges result in dynamic condensation effects in and heat-up of the suppression pool.

1.3.2 Loss-of-Coolant-Accidents

A pipe rupture or leak inside the drywell is termed a loss-of-coolant-accident. Drywell pressure increases as high energy water and steam flow from the break, depressurising the reactor and, if the break flow is great enough, impinging on drywell structures and internal components. Water is cleared from the vent system connecting drywell to wetwell by the increase in drywell pressure. Subsequently, a mixture of steam, water and gas flows through the vents into the suppression pool. Steam condenses and, together with the hot reactor water carried over, increases the pool temperature.

If the break is large enough, the gas injection rate into the pool becomes great enough to lift a mass of water bodily upwards. This rises compressing the gas in the wetwell free-space and then disperses as the drywell gas bubble breaks rapidly through the slug of water. In containments
having small wetwell gas-spaces the slug of thrown-up water may oscillate before breaking up, thereby inducing large oscillatory loads on containment structures. The gas addition to the wetwell atmosphere increases its pressure.

Following this **short-term** (seconds) period of dynamic phenomena, steam escaping from the break, as well as steam from reactor coolant flashing in the drywell, is condensed in the pool until the reactor is depressurised and the reactor core reflooded. Depending on the steam flow into the pool, the air content of this flow and the pool's temperature, various dynamic condensation processes can occur at the vent exits or inside the vents themselves. These cause pressure variations in the drywell and in the suppression pool. The amount of non-condensable gas carried over into the wetwell and the rise in temperature dominate the containment pressure.

Decay heat and stored energy are transferred by emergency core coolant to the pool, which undergoes a **long-term** (minutes) thermal transient.

Significant short-term dynamic loads are associated with large-break LOCAs, whereas the long-term effects are evident over the complete break spectrum.

A typical loss-of-coolant-accident chronology is shown schematically in Fig. 1.3 in which all potential LOCA phenomena are identified.
Fig. 1.1 Schematic of Essential Features of a Pressure Suppression Containment
Fig. 1.2  Typical Safety/Relief Valve Discharge Line
* All potential LOCA dynamic loads are identified but not all are significant.

Fig. 1.3 Phenomenology and Typical Loss-of-Coolant-Accident Chronology
2. COMMERCIAL PRESSURE SUPPRESSION CONTAINMENTS

The various BWR pressure suppression systems which have achieved commercial status are illustrated schematically in Figs. 2.1 to 2.4. Table 2.1 provides information on typical key dimensions.

Because of the complexity of the phenomena involved with a pressure suppression system, there is no patent recipe for pressure-suppression containment sizing and load definitions. It is an optimisation process influenced by many considerations. Some general rules can be established:

--- the volume of the drywell must be large enough to accommodate the primary system components with sufficient free space and access for maintenance and in-service inspection. For reactors with external recirculation loops, adequate radiation protection may be difficult to achieve if space is limited. This was one reason for Japanese modifications to the General Electric Mark I and Mark II designs, shown in Fig. 2.2;

--- the wetwell must be large enough to hold the required mass of suppression pool water, and have sufficient free space above the water to avoid excessive pressure from drywell gas displacement;

--- the required mass of suppression pool water is governed by the need to guarantee effective condensation, and to limit temperatures below allowed maximum values during a LOCA as well as during other thermal transients imposed on the pool. Containment heat removal system capacity also plays an important role in this respect;

--- wetwell dimensions and layout have a major influence on the safety/relief valve loadings imposed on the wetwell structures;

--- drywell, wetwell and vent dimensions strongly influence dynamic loads experienced during a LOCA, the larger the volumes the smaller these loadings tend to be;

--- the height of the reactor pressure vessel above the foundation mat significantly affects earthquake dynamic loads.

The design approach becomes one of choosing some basic constraints to establish approximate dimensions. The resulting preliminary structure is analysed for its behaviour and loadings under steady state, transient and accident conditions to determine strength requirements and thus structural details. Ease and costs of construction then control the choice of materials and layout. Within these engineering restraints any shape of containment structure may be utilised.

Since the first development of the pressure suppression containment design in the late 1950's /2.1/, there has been an evolution of designs, reflecting this optimisation process, to meet growing technical requirements and cost limitations. The major contributors to this evolution were the General Electric Company (USA), Kraftwerk Union (FR Germany), and ASEA-ATOM (Sweden).
The General Electric Company (GE) developed three generations of commercial designs shown in Fig. 2.1/2.2/. The first was the Mark I configuration with a light-bulb shaped drywell, a toroidal wetwell and a complicated ring-header and vertical vent system. In the second and third generations, the Mark II and Mark III designs, larger drywell working space, as well as ease of construction were sought. The latter was achieved by simpler shapes and the use of free-standing steel structures and/or prestressed or reinforced concrete.

The Mark III differs considerably from the Mark I and Mark II configurations:

-- the drywell does not form a part of the primary containment boundary;

-- the vents are horizontal and completely submerged in the suppression pool. A weir wall prevents flow of suppression pool water to the drywell;

-- the wetwell free volume is very much larger than the drywell free volume;

-- access to the primary containment is allowed during normal reactor operation;

-- the reactor pressure vessel is mounted low down inside the containment.

Nevertheless, it in no way diverges from the pressure suppression concept illustrated in Fig. 1.1

The Japanese BWR industries developed modified Mark I and Mark II configurations, shown in Fig. 2.2/2.3/, which gave more working space in the drywell and wetwell than the original designs. Although the larger volumes were provided primarily to reduce occupational radiation exposure associated with inspection and maintenance work, they also reduce the magnitude of LOCA hydrodynamic loads:

-- increasing the drywell volume reduces the rate of initial drywell pressurisation, which reduces the pool swell loads induced by transient gas injection;

-- larger drywell volumes decouple condensation events at the individual vent pipes, thus desynchronising condensation induced loadings on the suppression pool boundaries;

-- large drywell gas volumes increase vent flow gas fractions over a longer time period, which tend to stabilise condensation oscillation phenomena;

-- larger suppression pool volumes (see Table 2.1) contribute to reducing pool boundary loads by increasing attenuation path lengths.

Kraftwerk Union's Baulinie 69, Fig. 2.3, was an AEG-Telefunken design /2.4/ developed from the GE-Mark I concept. A need to simplify construction and reduce costs led to the Baulinie 72 configuration /2.5/, which is very similar to the GE-Mark II. Both the Swedish concepts, Fig. 2.4/2.6 and 2.7/
are similar to the GE-Mark II. The earlier design accommodated reactors with external recirculation pumps, the later design is for reactors with internal pumps.

Except for the GE-Mark III, these pressure suppression systems have vertical vent pipes partially submerged in the suppression pool. They are all subject to the phenomena and associated dynamic loads discussed in chapter 1. Individual construction details vary considerably. Examples of free-standing steel structures or reinforced concrete structures with steel liners may be found in nearly all configurations, the choice is largely dictated by civil engineering costs.

Currently, an advanced boiling water reactor is being developed for the Japanese market. This is a joint effort between GE and Japanese industry with additional input from Kraftwerk Union and ASEA-ATOM. The containment retains the pressure suppression concept with an optimal configuration developed from the experience gained by all the BWR vendors. It is similar in appearance to a Mark II containment, but with "L"-shaped vents running vertically down the reactor pedestal then horizontally into the suppression pool.
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<table>
<thead>
<tr>
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<th>GE-Mark I USA</th>
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<td>3100</td>
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<td>410</td>
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<td>N.A.</td>
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<td>23</td>
<td>30</td>
<td>20</td>
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</tbody>
</table>

**TABLE 2.1** COMPARISON OF TYPICAL CONTAINMENT CHARACTERISTICS
FIG. 2.1  GENERAL ELECTRIC PRESSURE SUPPRESSION SYSTEM DESIGNS

1 = PRIMARY CONTAINMENT
2 = DRYWELL
3 = WETWELL
4 = SUPPRESSION POOL
5 = VENT SYSTEM
FIG. 2.3 KRAFTWERK UNION PRESSURE SUPPRESSION SYSTEMS
3. THE DESIGN BASIS

3.1 Definition of Design Basis

A design basis is a specification which envelopes all phenomena for which the containment system is designed. In practice it becomes a series of specifications for components of the containment system. To establish a design basis, the first concern is to conservatively define loading histories for a spectrum of postulated initiating events. Loadings may be forces, pressures, temperatures, vibrations, impacts, etc. They may arise from the static or dynamic effects associated with postulated internal initiating events (for example, LOCA, safety/relief valve actuation, fuel handling accidents, fires, etc.) or external initiating events (earthquake, gas explosion, hurricane, airplane crash, flood, etc.). The spectrum of initiating events covers all normal plant operating conditions and all transients and accidents expected to occur with a given approximate range of probabilities.

Each loading history, for a specific load occurring during a specific postulated event, is usually provided in a load definition report as a function of space and/or time. A classic example is Fig. 3.1, which shows conservative containment pressure histories calculated for a large-break LOCA. During the same event loads are combined pragmatically with other loadings occurring at the same location and at the same time. A chart such as Fig. 1.3 may be used to identify all potential loading conditions for the LOCA, and load combinations for these conditions may be established, as indicated in Fig. 3.2. By this means, for each structure or component, bounding design parameters may be specified for the spectrum of initiating events.

Finally, to establish the design basis for the structure or component, sums of individual load envelopes are combined for independent events according to defined load cases. Examples of such combinations are large-break LOCA plus safety/relief valve actuations, or LOCA plus earthquake. It is noteworthy that, even though the primary system is designed for earthquake loads so that a LOCA is not expected to occur as a result of an earthquake, the combination of these two essentially independent events is often very conservatively included in the design basis.

3.2 Design Basis Scenarios

The key to a design basis lies in defining and determining the phenomena and loading histories for postulated initiating events. Two such events, safety/relief valve actuation and LOCA, are particularly significant for pressure suppression systems. They are discussed in detail here to illustrate which phenomena need to be considered. The NRC has carried out detailed reviews of these phenomena, /3.1 to 3.4/ for example, and the reviews themselves contain comprehensive literature sources.
3.2.1 Safety/Relief Valve Dynamic Loads /3.1 and 3.2/

a) Safety/Relief Valve Short-Term Line Clearing

A safety/relief valve line is illustrated schematically in Fig. 1.2. The valve may be opened by an actuator or by the medium pressure. Pressure increases in the line until the water column is blown clear and gas and steam enter the suppression pool. Jets of water caused by the discharged column may produce local acceleration and pressure fields near the pipe exit. These are known as water-clearing spikes. Discharged steam is condensed, but the compressed discharged gas forms one or more bubbles in the pool, depending on line exit geometry. These expand and contract under the pool's inertia causing pool water accelerations and pressure oscillations, typically at frequencies 5 - 10 Hz, which attenuate away from the source but are transmitted to submerged components and wetwell structures. The bubbles rise and in a short time (seconds) break through the pool surface. Surface disturbances are minimal because of the relatively small gas-bubble volume. A typical pressure variation in the suppression pool during short-term safety/relief valve line clearing is shown in Fig. 3.3.

Depending on the line exit geometry, water clearing spike pressures can be larger or smaller than air-bubble pressures but they attenuate very rapidly away from the source, because of the efficiency of water-jet break-up and mixing mechanisms. This attenuation may be larger than that associated with the air-bubble pressure field so that, depending on the distance from the source to the containment boundary, the water clearing spike may not always be seen at this boundary.

It is an important design task to define adequately these short-term dynamic loads /3.1/, since they have a relatively high frequency of occurrence and the loads can be significant. A completely analytical description is difficult to achieve because the line-clearing and pool phenomena are coupled, see section 5.2. Plant transients, the set-points of the safety/relief valves and possible malfunctions of the valves or actuation systems control the number of valves which can open simultaneously and the number of cycles these perform. The latter may be a fatigue concern. Safety/relief valve actuations, because of the individual variations in valve and blowdown characteristics, are a significant source of asymmetric loadings on suppression pool structures. Uncertainties in safety/relief valve containment-loading specifications have led to confirmatory test programmes being performed on most types of pressure suppression containments, see section 4.1. Pipe and pool loads depend strongly on the maximum clearing pressure in the pipe which, in turn, depends strongly on the valve opening time.
Redundant vacuum breakers are usually installed on the blowdown lines inside the drywell, not to assure piping integrity against underpressures, but to prevent too high a water column from being sucked back into the line after the valve closes. An excessive water leg length delays line clearing, which increases line pressures and water clearing dynamic thrust loads.

b) Condensation Stability During Long-Term Safety/Relief Valve Blowdown

The steam water interface, or condensation front, remains in the neighbourhood of the blowdown-line exit during steam discharge. Condensation dynamics and the stability of this front depend strongly upon the geometry of the blowdown line, upon the rate of steam flow and upon local subcooling in the suppression pool, see Fig. 3.4. Local subcooling depends on pool mixing, which may be influenced by natural convection, forced convection and thermal stratification /3.5/.

Pressure pulses and water accelerations caused by the condensation dynamics attenuate as they are transmitted throughout the suppression pool. They induce pressure loadings on pool boundaries and drag loads on submerged structures. Where sufficient local subcooling is available these loadings are not severe, which is the case for the usual condensing mode during relief valve operation, region 4 in Fig. 3.4. If saturation is approached, coupled with high steam discharge rates and poor pool mixing, large steam bubbles may form and travel well into the pool before collapsing rapidly on reaching subcooled regions. Weak shock waves, similar to "water-hammer", arise from such steam bubble implosions. This has been experienced /3.2/ with simple open-ended pipe exits when operating in region 6 of Fig. 3.4. These regions or modes are discussed in more detail in section 3.2.2.b).

Special devices attached to the submerged pipe exit, sometimes called "quenchers", are commonly installed to improve the condensation characteristics, as well as to reduce blowdown-line air clearing loads, see Fig. 1.2. These special devices have a configuration and multiple exit holes, which improve local and overall pool mixing, and thus have a much more stable condensation performance than simple open-ended pipe-exits. Indeed, with a quencher, operation in region 6 with local pool temperatures approaching saturation has been achieved without excessive condensation loads.

Current practice in containment design is to avoid any drastic changes in condensation mode by specifying an upper-limit to suppression pool bulk temperatures such that local temperatures at the blowdown line exit are always below saturation /3.2/. This upper limit may be the controlling suppression pool temperature for the containment. Condensation induced loads still have to be assessed for the complete range of blowdown conditions up to this prescribed pool temperature limit. The complexities involved with the condensation processes and the line exit geometries are such that these loads are determined nearly always by tests at full or near full scale. If high pool temperatures are avoided condensation loadings on the piping, on pool boundaries and on components in the pool tend to be relatively unimportant.

c) Suppression Pool Heat-Up During Isolation Events

The sizing of the suppression pool is normally based on the requirement for effective condensation of steam during design basis LOCA situations, as well as the need to avoid high pool temperatures and thus high containment
temperatures and pressures, see sections 3.2.2. b) and c). The latter requirement is also important during reactor safety/relief valve blowdown events. To assess possible pool temperature excursions, time dependent thermal balances are performed over a spectrum of reactor transient scenarios. Due account should be taken of reactor and pool initial conditions, of suppression pool mixing, of systems to scram the reactor or cool the pool automatically, of failure criteria, operator intervention and time limits on their actions.

3.2.2 LOCA Dynamic Loads /3.3 and 3.4/

a) Short-Term LOCA Dynamic Loads

The short-term behaviour is complicated because the drywell pressurisation, vent-clearing and wetwell phenomena are coupled:

1) -- Drywell pressure and temperature histories depend strongly on break flow, drywell and wetwell volumes, the vent-clearing transient, the two-phase, two-component, compressible, flow of gas, steam and water through the open vents, as well as on conditions in the wetwell due to thermodynamic coupling through the vents. Break flow is specified by break area, pipe geometry, pipe inventory in the broken line and reactor pressure vessel conditions. Typical, predicted, LOCA pressure histories are illustrated in Fig. 3.1

Vent-clearing is a water acceleration problem controlled by the water column length to be expelled, the pressurisation rate in the drywell and wetwell boundary conditions. Vent-flow is significantly affected by water de-entrainment occurring in the drywell. If the vent-flow approaches choked conditions, it becomes less dependent on the wetwell's thermodynamic state. Dynamic forces acting on the vents during vent-clearing and vent flows must be assessed.

Drywells often have a rather complex gas-space geometry, so that a break flow into one area is redistributed to other areas through restricted passages. An assessment must be made of compartmental pressure differences generated by such restrictions. Typical examples are breaks postulated to occur inside the biological shield wall or in the vessel upper-head regions. Stagnant regions containing gas not available for carryover to the wetwell also need to be assessed.

ii) -- Suppression pool swell depends on vent-geometry, vent submergence, the rates at which gas and steam flow from the drywell into the pool and the condensation of the steam in the pool. Vent flows are strongly influenced by the drywell pressurisation rate. Typical behaviour for a General Electric Mark III horizontal vent bubble is shown in Fig. 3.5. Vertical-vent pool-swell is similar but tends to be symmetric around the vent exit except when influenced by pool boundaries. The very large gas-bubble generated in the pool leads to pressure loadings on suppression pool boundaries. Upward motion of the water slug above the gas bubble compresses the wetwell gas-space, induces drag loads on structures submerged in the pool as well as impact and drag loads on structures above the suppression
pool surface. These loads depend on the geometry of the affected structure, on pool swell velocity and on the compactness of the thrown-up water. At some height above the undisturbed pool surface, gas breaks through the rising water slug, which disintegrates into a foamy spray. This changes the impact and drag loadings above the breakthrough height. The thrown-up water falls back as droplets or spray under the influence of gravity.

--- Wetwell pressurisation depends firstly on the compression of wetwell gas as a result of pool swell. This is of less importance in a wetwell having a very large free volume but the possibility of local loads, in restricted volumes above the rising pool surface, should be considered. Secondly, the gas carried-over with the vent flow from the drywell to the wetwell makes a mass and energy contribution, which can be large in containments having relatively small wetwell free volumes compared with the drywell volume. Thirdly, in containments with small wetwell volumes, compression of wetwell gas from a pool level increase after a LOCA, e.g. due to continued feedwater supply to the vessel, has to be considered. Finally, over the long term, the suppression pool's thermal transient heats up the wetwell gas space and increases its partial vapour pressure.

In order to specify the thermodynamic conditions and loadings arising during the above processes, a dynamic analysis which couples the drywell and the wetwell is desirable. Due consideration must be given to the two-phase, two component nature of drywell and vent-flow conditions and the compressible nature of the vent-flow. A lack of homogeneity of the steam fraction flowing through the vents into the pool must also be considered, since it can strongly influence the pool swell dynamic loads on containment structures. Pool swell drag and impact loads depend very strongly on gas breakthrough which is very difficult to predict analytically. Individual drywell, wetwell and vent geometries play an important role. Two or three dimensional effects, for example asymmetric distribution of gas and steam to the vents and resulting asymmetric pool swell dynamics, must be assessed. Very complex analyses are often avoided by using demonstrably conservative assumptions or boundary conditions. However, this has the drawback of conservative load predictions and heavier structures.

Finally, these large-break, short-term, LOCA dynamic loads are not usually combined with safety/relief valve line-clearing loads, because no reactor pressure increase is to be expected during a large steam or recirculation line break situation and such LOCAs do not require additional depressurisation through these valves. In addition, adding the compressed gas from the safety/relief valve lines to the LOCA gas-bubble in the suppression pool would neither significantly change the LOCA dynamic loads, nor produce the characteristic safety/relief valve loads at the suppression pool boundaries. In practice, such combinations are nevertheless conservatively specified. Safety/relief valve actuations are expected to occur during an intermediate or small-break LOCA, when the reactor is isolated or as a result of an automatic forced reactor depressurisation. The short-term LOCA dynamic loads are then no longer severe. These different loading conditions are illustrated in Fig. 3.2
b) Condensation in the Suppression Pool During a LOCA

To guarantee primary containment integrity during a LOCA, it is important that all steam directed to the suppression pool through drywell-to-wetwell vents be effectively condensed. A first requirement is that the vents remain covered at all times when steam is being released from the primary system into the drywell. Steam can be released both during and following vessel blowdown. It is important to have an initial vent depth deep enough to ensure vent coverage, when due account is taken of the possible diversion of suppression pool water to core cooling systems, to the reactor pressure vessel and to the drywell plenum below the vessel. On the other hand, too deep an initial vent depth aggravates LOCA vent-clearing and pool swell slug impact loads.

A second requirement is that pool temperatures in the neighbourhood of the vents should not approach saturation, because of the threat of steam bypass if the pool boils, and the large dynamic loads associated with the sudden collapse of large steam bubbles as they move from near saturated to sub-cooled regions. Pool mixing strongly influences the rate of collapse of steam bubbles and the resulting dynamic loads.

Steam condensation dynamics are very complex unsteady phenomena. They depend upon the geometry of the vents and vent exits, upon the rate of steam flow into the vents, upon local subcooling of the suppression pool and upon the gas fraction in the vent flow. The condensation dynamics produce loadings on the vents, on other submerged structures and on pool boundaries. In addition, depending on vent geometry, they may induce resonant acoustic waves inside the vent system.

The complexity of the condensation process is illustrated by an example of a condensation mode diagram for steam blowdown, shown in Fig. 3.4. A typical blowdown sequence, in which some modes occur, is shown in Fig. 3.6.

Briefly:

Mode 1 -- If energy transfer to the structures is large enough, and the steam flow rate low enough, the water inside the vent system remains subcooled. If then the rate of condensation of steam equals the mass flow of steam to the drywell, the drywell pressure stays constant so that water remains inside the vent system. This condensation mode occurs with very small break LOCAs, or after vessel blowdown and core reflood when steam production is very low.

Mode 2 -- As steam flow increases the front is expelled from the vent system by the corresponding increase in drywell pressure. Rapid mixing in the subcooled pool ensures that the steam bubble collapses at or near the vent exit causing a local pressure spike. The now subcooled front moves quickly back into the vent system until equilibrium between steam production and condensation is momentarily achieved. As the front saturates the cycle begins again. This cycling of the condensation front in and out of the vent system is known as vent chugging. A typical chugging period may be about 1 s. Chugging is experienced during small break LOCAs, or towards the end of vessel blowdown during intermediate or large break LOCAs.
Mode 3 -- If steam flow is increased further the condensation front is unable to re-penetrate the vents. It collapses and reforms outside the vent system, near the vent exit. The condensation surface oscillations induce pressure oscillations in the pool typically at 5 - 10 Hz. These are known as condensation oscillations. Such oscillations occur during intermediate and large LOCAs, as the reactor vessel depressurises. Local pressure spikes from steam bubble collapse also occur in this mode.

Mode 4 -- At still greater steam flows, the mass flow of condensed steam moving into the suppression pool plus natural convection creates enough circulation of subcooled water to the condensation front that the front stabilises in the neighbourhood of the vent system exit. Such high steam flows occur during safety/relief valve blowdowns and during the first period of a large LOCA blowdown, see Fig. 3.6. Note that in the Marviken experiments "pressure spikes" were experienced under these conditions, which were not experienced at other facilities, see section 4.4.3.

None of the above condensation modes produce severe condensation loads, except at or near the vent exits where localised bubble collapse occurs. Nevertheless, they must all be assessed as they can vary in relevance from containment to containment. As pool bulk temperature increases, local temperatures in the neighbourhood of the condensation front increase. Greater condensation front motion is necessary to produce the required degree of steam interactions with subcooled water. Thus, as pool temperature increases, oscillatory behaviour tends to become more pronounced, and it is difficult to define separate modes of condensation. This is the transition region 5 in Fig. 3.4, which is bounded by vaguely defined transition lines. Eventually, large steam bubbles may be formed, which either escape from the pool, or collapse violently in subcooled regions, if these exist, at some distance from the exits of the vent system. Thus, region 6 is one to be avoided in pressure suppression containments during the blowdown phase of a LOCA.

It is worthy of note that, during safety/relief valve steam blowdown, operation in region 6 without evidence of severe condensation loads has been demonstrated with quencher exit devices. With their multiple small exit holes, these avoid the formation of large steam bubbles and produce good pool water mixing.

The above condensation modes are further influenced by the gas fraction in the vent flow. An increase in gas concentration will tend to dampen chugging, and will also stabilise condensation oscillations at lower steam flows.

Pressure pulses and water accelerations from condensation processes are transmitted throughout the suppression pool, attenuating rapidly away from the source. They can interact and resonate with pool structures. The condensation dynamics also cause pressure and temperature fluctuations to occur within the drywell and vent system atmospheres. These appear as acoustic waves resonating within the available volumes, when the frequency of the condensation front oscillations matches a natural frequency of the vent system.
Loads and structural or acoustic resonances are difficult to predict analytically with any confidence, so they are normally assessed from full or near full-scale experiments on individual or multiple vents over a range of steam-flows and pool temperatures. The occurrence of random multiple condensation loads on a multiple vent system and the possibility of vent interactions must be considered. Also, the asymmetric distribution of condensation forces on vent-piping needs to be assessed for its influence on vent and support integrity.

How deep the vent coverage needs to be to guarantee effective condensation and how large a margin from local saturation is required to avoid severe condensation loads, depends on vent and drywell geometry, pool mixing and thermal stratification. The mode separation lines of Fig. 3.4 depend strongly on the above parameters. They are not well defined and serve solely a qualitative purpose. A method /3.12/ has been developed for establishing some of these boundaries analytically. The models are based on stability considerations of the acoustic phenomena in the vent and drywell and on the dynamics of the water slug at the vent and vent exit. Temperature gradients in the suppression pool and non-condensables in the vent system, are not considered in the models, which thereby predict definite boundaries.

c) Suppression Pool Temperature History During LOCA Events

It is clear that the pool's thermal transient during the LOCA is an important boundary condition for the condensation processes, which can occur.

The transient is controlled by:

i) -- the rate of energy addition to the pool. This is dependent on the postulated break size and sources of energy. Due allowance must be made for safety/relief valve assisted blowdowns during intermediate or small-break conditions. All possible sources of energy: stored energy, fission and decay heat, chemical reactions, heated feedwater, back pressure steam from auxiliary steam turbines, etc., must be taken into account;

ii) -- the mass of pool water. Water added to or drawn from the pool must be considered;

iii) -- the number of pool cooling and reactor residual heat removal systems available and the time at which they operate;

iv) -- the initial pool bulk temperature;

v) -- energy lost to structures or other heat sinks inside the containment. These are often conservatively ignored in the energy balance;

vi) -- thermal gradients in the pool water. Careful attention must be paid to the problem of thermal gradients, if good mixing is not guaranteed by pool cooling systems or by other mechanisms /3.5/;

vii) -- wetwell back pressure. This controls the subcooling of the pool water relative to the wetwell gas-space.
A LOCA may be postulated to occur during any normal reactor operating condition, which includes start-up, shut-down and standby conditions, with the suppression pool at its technical specification limits. An energy balance model similar to that for the isolation event may be employed but, when calculating wetwell pressures for the LOCA case, due account must be taken of drywell gas carryover into the wetwell.

It is a characteristic of large suppression pools that, because energy sources and sinks are almost identical during small or large LOCAs and during worst-case reactor isolation events, peak pool temperatures predicted for these events are generally very similar.

d) Underpressures, Pool Dynamics and Structural Stability

In any pressure suppression containment structure experiencing dynamic loads or steam condensation, structural problems, in particular instabilities generated by underpressures or pool dynamic forces, need to be considered. Possible sources of such phenomena include:

-- safety/relief valve clearing gas bubble oscillations in the suppression pool;

-- oscillating condensation loadings in the pool during safety/relief valve operation or during a LOCA,

-- pool swell compression of the wetwell free-space and reaction loads on wetwell and drywell structures,

-- drywell and wetwell temperature changes during reactor start-up and shut-down. (Normal atmospheric pressure changes, caused by temperature changes inside the drywell or containment, are slow [minutes to hours] and are usually mitigated by opening ventilation or other penetrations).

-- gas displacement by steam inside primary containment sub-volumes, followed by steam condensation, and

-- pipe ruptures outside the primary containment.

The first three types of loading may be mitigated, respectively, by fitting quenchers on the end of the safety/relief valve lines, by controlling pool temperatures and by optimising wetwell volumes, vent areas and vent depths. Pool swell compressions of the wetwell gas-space can lead to opening of vacuum breakers in plants with wetwell to drywell breakers.

Steam condensation in primary containment sub-volumes may be rapid, particularly if containment sprays are in use. Such condensation can lead to underpressures, which must either be incorporated into structural design loads or be mitigated by re-distributing displaced gas through vacuum breakers. Two cases serve as illustrations, the first is common to all commercial pressure
suppression containments, the second is peculiar to the General Electric Mark III design:

-- gas is displaced to the wetwell by steam during the vessel blowdown period of a LOCA. Subsequently the steam is condensed on drywell internals by subcooled coolant flowing out of the broken line or by drywell sprays. This induces drywell to wetwell underpressures.

-- gas may be displaced from the wetwell through ventilation or other openings, following a pipe rupture or leak in the wetwell atmosphere. After isolation of the break, steam is condensed on wetwell internals or by wetwell sprays inducing an underpressure in the wetwell.

Pipe ruptures or leaks outside the containment are a containment isolation concern. Depending on their location, they may impose an external pressure on the primary containment. Effects of such breaks may be mitigated by guard pipes, by blow-out panels or by other pressure relieving devices. It is usually necessary to employ transient analyses to size vacuum breakers, blow-out panels or such other devices.

e) Suppression Pool Bypass

Due to the small $P_{max}V$-value of pressure suppression containments a potential danger exists that following an accident high containment pressures may be reached due to steam bypassing the suppression pool. All possible steam bypass paths must be evaluated. These include, but are not limited to:

-- cracks or other leakage paths in the structures separating the drywell and the wetwell atmospheres. These may leak steam to the wetwell atmosphere during a LOCA;

-- piping penetrations connecting the drywell to the wetwell atmosphere. Such penetrations may be vacuum breakers, ventilation lines or combustible gas control system lines, which may be open when a LOCA occurs. Isolation of drywell-to-wetwell penetrations is just as important as isolation of the primary containment penetrations;

-- any lines in the wetwell free-space which transport high energy fluid. Examples depend on containment type but include, safety/relief valve blowdown lines, control rod drive lines, reactor vessel instrumentation lines, reactor water clean-up lines. These themselves may break and inject steam directly into the wetwell free-space.

It is not practical to make an absolutely leak-tight separation between drywell and wetwell atmospheres. What is essential is to assess by analysis the admissible leak rates during a LOCA. These serve as a basis for structural design requirements, manufacturing tolerances and leak rate specifications. Careful construction and leak-testing prior to plant operation then ensure that the leak tightness requirements are met. Wetwell sprays can greatly influence these leak tightness requirements.
3.3 Regulatory Guidelines

Regulatory guidelines for light water reactor containments specify that a containment with supporting containment systems is required, that system failures are to be accommodated and that particular postulated events and associated phenomena are to be addressed. Very general statements are made, and how design parameters for postulated events are to be established is not normally defined. Conservative boundary conditions, as well as safety addition factors for analysis uncertainties, are commonly prescribed.

The most comprehensive containment guidelines are the 10 CFR 50, U.S. Code of Federal Regulations, Appendices A and J. Their application to pressure suppression containments, specifically the GE Mark I, II and III designs, is described in the USNRC Standard Review Plan, NUREG-0800. American guidelines have served as a basis for most countries where GE reactors have been built, or where American technology provided the foundation for a national reactor programme. Over the years some countries have issued modifications or additions to the American guidelines reflecting individual national requirements. An example from Switzerland is the containment system guideline /3.6/, currently in draft form. The F.R. of Germany has its own comprehensive guideline for boiling water reactors /3.7/, also in draft form.

a) The relevant criteria in Appendix A of the U.S. Regulations /3.8/ are:

<table>
<thead>
<tr>
<th>Appendix A Criterion</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-- Design of structures, systems and components to accommodate normal, transient and accident conditions both inside and outside the plant, including dynamic effects such as jets, missiles and pipe whip</td>
</tr>
<tr>
<td>16</td>
<td>-- Containment and systems to provide an essentially leak-tight barrier</td>
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<tr>
<td>38-40</td>
<td>-- Containment heat removal systems; redundancy, single failure, inspection and testing</td>
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<tr>
<td>41-43</td>
<td>-- Containment atmosphere cleanup systems; redundancy, single failure, inspection and testing</td>
</tr>
<tr>
<td>50</td>
<td>-- Containment design basis LOCA</td>
</tr>
<tr>
<td>51</td>
<td>-- Fracture prevention of containment pressure boundary</td>
</tr>
<tr>
<td>52-53</td>
<td>-- Capability and provisions for leak rate testing</td>
</tr>
<tr>
<td>54-57</td>
<td>-- Isolation of containment penetrations</td>
</tr>
<tr>
<td>13 and 64</td>
<td>-- Instrumentation for normal, transient and accident conditions</td>
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</table>
b) Appendix J /3.9/ prescribes primary containment leakage testing requirements. Three types of tests are defined:

Type A  -- Containment overall integrated tests
Type B  -- Local leak rate tests on penetrations, seals, doors, air-locks, etc.
Type C  -- Containment isolation valve leak rate tests.

c) The USNRC Standard Review Plan /3.10/ defines what is to be reviewed. The relevant paragraphs for pressure suppression containments are 6.2.1 to 6.2.6:

<table>
<thead>
<tr>
<th>Standard Review Plan Paragraph</th>
<th>Review Areas</th>
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<tbody>
<tr>
<td>6.2.1.1.C</td>
<td>-- Drywell and wetwell pressures, temperatures and pressure differences, suppression pool dynamics, break locations, steam bypass, external pressures, containment heat removal, subcompartment pressure differences, suppression pool temperature limits</td>
</tr>
<tr>
<td></td>
<td>-- LOCA and safety/relief valve events are considered together with analytic modelling and tests</td>
</tr>
<tr>
<td></td>
<td>-- Appendices A and B deal specifically with steam bypass and Mark II LOCA dynamic loads, respectively.</td>
</tr>
</tbody>
</table>

Other paragraphs deal with particular aspects of the above, or with additional topics:

6.2.1.2  -- Subcompartment analyses
6.2.1.3  -- Mass and energy release during a LOCA
6.2.1.4  -- Mass and energy release for breaks outside the containment
6.2.2    -- Containment heat removal
6.2.4    -- Isolation of containment penetrations
6.2.5    -- Combustible gas control
6.2.6    -- Containment leak testing
d) The German Guideline /3.7/ combines both criteria and review aspects. Chapter 5 is relevant to the pressure suppression containment:

<table>
<thead>
<tr>
<th>Paragraph</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>5</td>
<td>-- Containment and its enclosure</td>
</tr>
<tr>
<td>5.1-5.2</td>
<td>-- Design of structures, systems and components to accommodate normal, transient and accident conditions</td>
</tr>
<tr>
<td></td>
<td>-- Pressures, temperatures, pressure differences, reactions, jet loads and missiles</td>
</tr>
<tr>
<td></td>
<td>-- Boundary conditions for analyses, such as initial reactor state, decay heat, internals' energy, metal water reaction</td>
</tr>
<tr>
<td></td>
<td>-- Margins for uncertainties</td>
</tr>
<tr>
<td></td>
<td>-- System separation and redundancy</td>
</tr>
<tr>
<td></td>
<td>-- Secondary containment, sabotage protection, hydrogen control</td>
</tr>
<tr>
<td>5.3-5.4</td>
<td>-- Steel containment materials, design specifications, manufacture and quality control</td>
</tr>
<tr>
<td>5.5</td>
<td>-- Containment overall integral leakage testing</td>
</tr>
<tr>
<td>5.6</td>
<td>-- Containment penetrations, design and isolation</td>
</tr>
<tr>
<td>5.7</td>
<td>-- Containment heat removal</td>
</tr>
<tr>
<td>5.8</td>
<td>-- Pressure suppression system functions and dynamic loads, including LOCA and safety/relief valve events</td>
</tr>
<tr>
<td></td>
<td>-- Steam bypass from penetrations, vacuum breakers and leakage</td>
</tr>
<tr>
<td></td>
<td>-- Tests, inspections</td>
</tr>
<tr>
<td>5.9</td>
<td>-- Pipe breaks outside the containment</td>
</tr>
</tbody>
</table>

Both the American and German guidelines could be applied, in principle, to any pressure suppression containment type. They reflect the current state-of-the-art of containment design, being revised from time to time as improvements in the understanding of pressure suppression phenomena occur. International safety guides are in preparation by the IAEA. A guide for light water reactor containments /3.11/ was published in 1985.
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/3.3/ NUREG-0808

/3.4/ NUREG-0978
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/3.5/ NUREG-CR 3471

/3.6/ HSK Draft Report R-33
"Richtlinie für das Containment-System von Leichtwasserreaktoren" Dec. 1985

/3.7/ GRS Draft Report E.9.80
"RSK-Leitlinien für Siedewasserreaktoren" Sep. 1980

/3.8/ 10 CFR 50 US Code of Federal Regulations
Appendix A: "General Design Criteria for Nuclear Power Plants"

/3.9/ 10 CFR 50 US Code of Federal Regulations
Appendix J: "Primary Containment Leakage Testing for Water Cooled Power Plants"

/3.10/ NUREG-0800, USNRC Standard Review Plan Section 6.2.1 "Containment Functional Design"

/3.11/ IAEA Safety Guides, 50-SG-D12
"Design of the Reactor Containment Systems in Nuclear Power Plants", 1985

/3.12/ Topical Meeting on Nuclear Reactor Thermal Hydraulics
a) GENERAL ELECTRIC MARK II CONTAINMENT

b) GENERAL ELECTRIC MARK III CONTAINMENT

FIG. 3.1 TYPICAL LOCA PRESSURE HISTORIES AS DETERMINED BY A SAFETY ANALYSIS
LOADING CONDITIONS FOR LARGE BREAK LOCA

LOADING CONDITIONS FOR SMALL-BREAK LOCA

FIG. 3.2  TYPICAL LOADING CONDITIONS FOR LARGE AND SMALL-BREAK LOCA
FIG. 3.3 SUPPRESSION POOL DYNAMIC PRESSURE
VARIATION ABOUT THE LOCAL HYDROSTATIC PRESSURE
FOR TYPICAL SHORT-TERM SAFETY/RELIEF
VALUE LINE CLEARING
Fig. 3.4: Schematic of typical regions for condensation modes during safety/relief or LOCA blowdown.

1. Steam condensation within transition region
2. Chugging vents or blowdown pipes
3. Condensation oscillations
4. Quasi-steady condensation
5. Transition region
6. Incomplete condensation
FIG. 3.5 TYPICAL POOL SWELL BEHAVIOUR IN A HORIZONTAL VENT (GE-Mk III) SYSTEM

POOL RADIAL LOCATION
FIG. 3.6 CONDENSATION OSCILLATION AND CHUGGING IN A PRESSURE SUPPRESSION TEST DURING BLOWDOWN. POOL PRESSURE HISTORY NEAR THE VENT EXIT.
4. EXPERIMENTAL RESEARCH

4.1 Safety/Relief Valve Blowdown Tests

Preliminary tests in the GE Mark I torus at Quad Cities /4.1/, and later at Monticello /4.2/, were carried out by GE. Both plants had rams-head discharge line exits (see Fig. 1.2) at that time. Test data indicated that the short-term, gas-bubble induced, pressure oscillations in the pool, discussed in section 3.2.1 a), were quite large. Depending on discharge line conditions prior to opening the safety/relief valve, pressures in the neighbourhood of the exits varied between approx. + 0.17 MPa and - 0.11 MPa, relative to the local hydrostatic pressure. Applying such loads, together with adders to cover uncertainties in data and correlations used at that time, led to overconservative containment loading specifications. These, in turn, gave rise to unrealistic dynamic responses of the containment and of structures or components attached to the containment.

Early operating experiences /4.3 to 4.5/ in European BWRs, having straight-down discharge exits, also showed that, during an extended steam blowdown, unstable condensation oscillations occurred in the suppression pool at local pool temperatures above about 70oC. Such condensation effects are discussed in section 3.2.1 b). Steam blowdowns in US plants indicated that higher threshold temperatures were possible with rams-head exits. Nevertheless, as a result of this early experience, restrictive technical specification limits were imposed on suppression pool temperatures.

With the objectives to reduce short-term line clearing loads and to improve the pool temperature operating margins, a series of scaled and full-scale prototype discharge devices were tested in Germany by KWU (Table 4.1, /4.5/, /4.6/ and /4.7/) and in the US by GE /4.8/. These tests led to the development and world-wide adoption of the multiple-hole quencher devices sketched in Fig. 1.2. Both two-arm T-quenchers as well as four-arm X-quenchers have been installed in suppression pools. Because of space limitations the T-quencher is more suited to the GE Mark I suppression pool.

After installation of the quenchers, a whole series of in-plant tests were carried out on a containment generic basis to confirm the design-data extrapolation from the small scale testing:

<table>
<thead>
<tr>
<th>Containment Type</th>
<th>In-Plant Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE Mark I</td>
<td>Monticello /4.9 and 4.10/</td>
</tr>
<tr>
<td>GE Mark II</td>
<td>Caorsio /4.11 to 4.13/</td>
</tr>
<tr>
<td>GE Mark III</td>
<td>Kuosheng /4.14/</td>
</tr>
<tr>
<td></td>
<td>Leibstadt /4.15/</td>
</tr>
<tr>
<td>KWU (Baulinie 69)</td>
<td>Brunsbüttel /4.16/</td>
</tr>
<tr>
<td></td>
<td>Phillipsburg /4.17/</td>
</tr>
</tbody>
</table>

The very comprehensive nature of the measurements taken during these tests may be appreciated from Fig. 4.1, which shows the number and distribution of pressure transducers in the suppression pool for the Leibstadt tests /4.15/.

Pressure inside the discharge line, pool temperatures, strains and accelerations of the containment, attached piping and components, gas/water interface motion inside the discharge line, vacuum breaker flows and safety/relief valve opening times were typically also measured.
The test programme normally involved single valve actuations, sequential actuations of a single valve and simultaneous multiple valve actuations. Extended blowdowns to investigate pool thermal response were also carried out.

Some important conclusions may be drawn from these tests:

-- The fluid dynamic response inside the discharge line and the resulting loads are well understood. They are well predicted by the classical, one-dimensional, unsteady analyses discussed in sections 5.2.1. Water clearing reaction loads on line supports can be very large at bends.

-- Quencher devices markedly reduce the short-term, gas-bubble, pressure variations in the pool. Peak pressures in the neighbourhood of the quencher are typically + 40 KPa and - 35 KPa. Such pressures, their history and distribution are well predicted by the current analytic models, described briefly in section 5.2.2.

-- Water clearing spikes are apparent in X-quencher but not in T-quencher data. Although spike pressures can be very much greater (factor 2 to 3) than the bubble induced pressures, they are of very short duration (≈0.1 s) and they attenuate rapidly away from the discharge exit.

-- It is important to mount large, redundant, vacuum breakers on each discharge line. After safety/relief valve closure these ensure that excessive overshotting of normal water level, as the line refloods, does not occur. High initial water leg lengths for subsequent valve actuation can significantly increase discharge pipe water clearing and pool dynamic loads.

-- With best-estimate dynamic pressures applied to suppression pool boundaries, the calculated structural response of containment shells, even when taking credit for fluid structure interactions, can be an order of magnitude greater than that measured.

-- Quencher devices markedly improve the condensation behaviour during extended safety/relief valve blowdowns. Unstable condensation oscillations do not occur even with local suppression pool temperatures approaching saturation. This is due to the improved local mixing of the small steam jets issuing from the quencher holes, as well as the global pool mixing induced by the thermal gradients in the pool. Suppression pool temperature limits have accordingly been raised to ~ 93°C /4.3/.

-- Below this local pool temperature limit, condensation induced pressure variations in the pool tend to be small ~ ±5 KPa.
4.2 LOCA Related Tests

4.2.1 General Remarks

Experiments were carried out by GE during the period 1958-1963 for the Humboldt Bay and Bodega Bay reactors. These were the main source of data on the behaviour of pressure suppression containment systems (PSCS) during a LOCA /4.18 to 4.22/ up to 1971.

The aim of these experiments was the validation of PSCS designs so most if not all of the attention was focussed on steam condensation and on loads acting on the containment.

The main objectives of these early test series were:

-- to demonstrate that effective condensation of steam can be obtained during a steady state flow of steam simply by submerging a straight pipe in a water pool;

-- to investigate the effect on the condensation efficiency of the following parameters: vent pipe diameter and submergence, steam flow-rate, outflow direction, interactions between vents, geometry of the suppression pool;

-- to evaluate the maximum values of pressure and temperature in the PSCS during the LOCA transient.

Most tests were performed on an experimental facility representing a full scale sector of the actual containment corresponding to one vent pipe. However, other tests were performed on small scale multi-vent facilities, corresponding to a π/4 or π/6 angular sector of the real plant /4.19 to 4.21/.

These experiments led to the design of the Mark I containment system, which is used in all GE BWR-2 and BWR-3 and in some BWR-4 plants. At the end of the sixties new pressure suppression configurations were studied by GE /4.23/. This led to the adoption of a Mark II containment system for BWR-4 plants and then to the Mark III configuration, with horizontal vents, at the beginning of the seventies. Over the same period other PSCS designs were developed in Germany and Sweden for domestic BWR plants. The behaviour of the European pressure suppression containments is similar to that of the Mark II, due to the similarity in configuration and the use of straight vent pipes.

The design approach previously adopted for the Mark I design was also used for the later containment types:

-- small scale tests, to validate the analytical models used for the design of the system;

-- full scale tests on a sector of the containment, corresponding to one or more vent pipes, to confirm the analytical predictions or to supply full-scale empirical data.
The experimental research was first carried out on the Mark III concept, due to the innovation of horizontal vent pipes. They revealed dynamic phenomena not considered in previous designs and led to the establishment of new research programs on this and other containment types.

New research programs on PSCS were set up in the US by GE and the BWR plant owners, in Europe at Marviken in Sweden, at GKSS and KWU in F.R. Germany, and in Japan at JAERI laboratories. Because Mark II containment configurations dominate, most of the work was carried out on this type.

4.2.2 Scaling Considerations

The main LOCA experiments referenced in this report were performed on test facilities which were equipped with one or more full-size vent pipes. A large number of additional basic experiments were also conducted to get better insight into the fundamental problems of vent clearing, pool swell and steam condensation behaviour. These tests were performed on small scale test facilities and, to a certain extent, served as the basis for code verification. It is appropriate here to review aspects of the scaling of the test rigs and the proper interpretation of the test results.

The term "scaling" must be understood in a broad sense to cover all differences between a real full-size prototype BWR pressure suppression system and a corresponding experimental facility.

It involves differences in geometric dimensions and component arrangements as well as differences in operating and boundary conditions between prototype and test rig. Such differences have the potential to distort an experimentally observed parameter precluding its direct and immediate application to the design or operation of the prototype plant. Analytical tools (e.g. codes) are applied to understand and extrapolate experimental evidence for design purposes and to elaborate on possible differences in the behaviour of test rigs and prototype plants. These tools are often assessed against tests which were performed with a full-size vent pipe diameter, but within test vessels which exhibit little or no geometric similarity with the prototypes.

Main parameters of interest in this context are:

-- vent submergence depth
-- eigenfrequencies of the test vessel structures
-- operating pressure and temperature
-- vent pipe arrangements, etc.

Several studies have been published which discuss the scaling problems in connection with envisaged or performed experimental activities /4.24 to 4.33/.

Scaling laws and modelling studies for the early dynamic blowdown phenomena have been described by EPRI /4.24/ in connection with experimental activities performed for the Mark II Owners' Group. Scaling requirements were identified to be different for pool swell, wetwell pressurisation and vent discharge processes and led to compromises in the envisaged mode of operation of a 1/13 linearly scaled replica of a Mark II pressure suppression system.
It was concluded that a linear reduction in dimensions would require an equivalent, proportional, reduction in gas pressure and the application of orifices to compensate for flow resistance distortions /4.24, 4.25/. This kind of scaling respects the Froude number.

Similar findings have been obtained by an extensive experimental and analytical study, performed at the Massachusetts Institute of Technology (MIT), to assess the usefulness of small-scale modelling of pressure suppression processes /4.26 to 4.28/ for vertical vent pipe arrangements. Vent clearing and pool swell were recognized as requiring certain minimum scaling requirements. Reduced scale tests do however give rise to difficulties:

-- In a sufficiently small-scale room temperature test, the effect of water vapour in the wetwell airspace may modify the pool swell compression history.

-- Fluid structure interaction may be influenced by the presence of small air bubbles.

-- Condensation oscillations and chugging may be strongly distorted by a reduction of linear dimensions in combination with the required reduction of the system operating pressure /4.28/.

Some experiments were conducted to investigate the accuracy of distorted-geometry testing of pool dynamics in the horizontal vent Mark III containment. Distorted-geometry testing in this context was defined as testing in systems where the dimensions in the main flow-direction are full-scale, but all dimensions transverse to the main flow-direction are reduced. This is a departure from geometric similarity. It was concluded that for horizontally vented systems /4.29/ geometric distortions can have a significant effect on pool swell under LOCA-representative conditions.

The scaling-related research work at the Lawrence Livermore National Laboratory and the University of California (UCLA) /4.30, 4.31/ was consistent with the above referenced observations at EPRI and MIT.

Moody /4.32/ formulated a general procedure for the design of scale model experiments to study heat, thermodynamic and fluid phenomena in nuclear containments. Dimensionless parameter groups enable an estimate to be made of which physical effects must be preserved and which can be neglected in scale model design. Scale-modelling of coupled systems (e.g. pool response from steam relief valve operation) is discussed as an application of the procedures.

To avoid most of these scaling-related problems, tests have been conducted in single or multiple vent pipe arrangements with full-sized pipe diameters. The so-called "single cell" hypothesis was applied to determine the proper dimensions of the associated drywell and wetwell volumes. The "single cell" hypothesis is based on the expectation that dynamic similarity of transient processes will be obtained if the test rig consists of drywell and wetwell volumes which are proportional to the corresponding volumes of the prototype plant, divided by the number of available vent pipes in the prototype. The same proportionality is retained for the involved water volume within the wetwell of the suppression system. With full size vent pipe dimensions (diameter, length and pool submergence) a consistent experimental
set-up may be obtained. With a representative pool surface and geometric volumes vent clearing, pool swell and pool dynamics associated with condensation oscillations and chugging effects may be properly studied. Overall dynamic similarity of an experiment was expected, if the LOCA-related energy addition rates were proportional to the number of vent pipes involved, e.g. the specific energy addition rate per vent pipe had to be identical for experiment and prototype. To warrant proper fluid-structure interaction, one suggestion was to design the wetwell pool confinement with an eigenfrequency behaviour similar or identical to that of the prototype plant of interest.

What remains uncertain is the simultaneous interaction of a large number of vent pipes, in particular with respect to loads on the prototype structures caused by condensation oscillations and steam chugging. This uncertainty was overcome in the design of the 7-vent pipe test arrangement at the Japanese JAERI-test facility, which consists of a \( \pi/9 \) sector of a full-size Mark II wetwell with an appropriate portion of the corresponding drywell of a Japanese BWR-containment. Great care was devoted to a correct distribution of structural masses of the entire system to simulate as closely as possible the proper fluid-structure interactions and the overall structural response /4.34/. A similar approach was used in the design of the General Electric Full-Scale Test Facility (FSTF) for the Mark I containment. Both of these test rig design concepts may be considered as the most advanced means to minimise speculation on the multi-vent interpretation and extrapolation of condensation processes, presently not amenable to direct measurement nor to convincing analytical simulation.

4.3 Main Experimental Facilities and Programs

Table 4.2 summarises the characteristics and the scaling ratios of the main facility parameters, which control pressure suppression phenomenology.

4.3.1 General Electric (GE) Facilities

The General Electric Company performed extensive confirmatory test programs on all its PSCS (Mark I-III), to provide a comprehensive data base for design purposes.

The overall objective of the test programs was to provide LOCA thermodynamic and system response data for: (1) qualification of the related pressure suppression analytical models, (2) understanding of pressure suppression phenomena, and, (3) defining containment dynamic loads. Specific objectives were:

-- to determine the clearing characteristics of the vent systems
-- to demonstrate full mass flux steam condensation through the vents
-- to determine pool swell response characteristics, including velocity, elevation, and breakthrough height
-- to determine pool swell impact loads
-- to quantify dynamic loads on the pool and vent system boundaries, due to condensation of steam at the vent exits.

Hundreds of full and near full-scale tests were performed for each containment type. Most of the results are however proprietary and have not been published.
Pressure Suppression Test Facility (PSTF) /4.35/

The facility consists of three main pressure vessels: a reactor simulator (flash boiler), a drywell, and a combination of suppression pool and wetwell air-space. Appropriate piping, heaters and a comprehensive data acquisition system are also included. Its arrangement for the Mark III confirmatory test program is shown in Fig. 4.2.

The three vessels of the PSTF facility form the basis for a 1/1000 volumetric scale model of a BWR-6 Mark III containment system. The flash boiler is a 5 m³, electrically heated, pressure vessel rated at 8 MPa. The dip tube within the pressure vessel is removable, so that either saturated liquid or saturated vapor breaks may be simulated. A range of break sizes from 2.5 cm to 11 cm in diameter is possible. These simulate full-scale steam line breaks up to 200 per cent of the nominal break area.

The drywell is a 67 m³ pressure vessel, rated at 0.5 MPa. It may be preheated or purged with steam to remove air. It is connected to the suppression pool building via a 2 m diameter vent duct. In some Mark III tests the drywell volume was increased to 124 m³.

The suppression pool building simulates both the pool and the wetwell air space and has a total volume of 400 m³. The building is a pressure vessel rated at 70 kPa. The pool may be preheated to 85°C prior to a test.

The large suppression pool building gives considerable flexibility with respect to vent and pool geometry. Three different pool simulators were used during the development of the test program, (Fig. 4.3):

-- a full-scale simulation of a "single pool cell", consisting of one column of three full-size vents, the vent annulus and pool volumes associated with these vents;

-- a 1/3 area scale simulation of the above single pool cell. All flow areas were reduced by a factor of 3 (i.e. 1/3 linear scale factor) but vent submergence was held at full scale. This pool simulator was scaled like the rest of the facility by 1/100 volumetric factor;

-- a 1/9 area scale, three column, 9 vent, simulator. In this model, each cell had all its flow areas reduced by a factor of 9 from the single cell case (i.e. 1/3 linear scale factor) and vent submergence was held at full scale, but three cells were used. Thus, the volumes and flow areas for all three cells were the same as for the 1/3 area scale single cell case, and the pool was likewise correctly scaled with respect to the rest of the facility.

Temporary Tall-Tank Test (4T)

For the Mark II confirmatory test program GE modified the PSTF to reproduce in full scale a part of the Mark II containment corresponding to one vent pipe, i.e. a "single pool cell" (Fig. 4.4).

The research program on this facility named "4T" was devoted to the study of pool swell, condensation phenomena and associated containment loads /4.36, 4.37/. 23 tests were performed initially, followed by 28 tests devoted to condensation oscillations and chugging.
Full-Scale Test Facility (FSTF)

For the study of condensation oscillations and chugging phenomena in Mark I containments, GE built a full-scale facility corresponding to a π/8 sector of the prototype plant, Fig. 4.5. This is known as the Full-Scale Test Facility (FSTF) /4.38, 4.39/.

A total of ten tests were performed in the FSTF facility to investigate the effects of break size, steam or liquid blowdowns, downcomer submergence, torus temperature and pressure.

4.3.2 Marviken Containment Program

Two multinational experimental programs on PSCS behaviour have been carried out in Sweden, utilising the decommissioned nuclear power plant Marviken /4.40/.

The objective of the first series of experiments, comprising 16 blowdowns, was to investigate the overall containment behaviour, in order to identify important physical phenomena and to create a large scale data base for code verification.

The second program, consisting of nine blowdowns, was devoted to the dynamic response of the containment. Emphasis was placed on pressure oscillations in the containment and sharp pressure excursions of short duration ("chugging") which occurred near the outlet of the vent pipes as a result of rapid steam condensation.

The first series of experiments was aimed at providing information about the influence of the following factors on the pressure and temperature build-up in the drywell and wetwell.

-- amount of energy stored initially inside the pressure vessel
-- size and location of the break
-- wetwell pool temperature
-- vent pipe submergence (by varying the water level in the pool)
-- effects of containment spray.

During the second series of experiments the influence of the following parameters on the pressure oscillations was investigated:

-- vent pipe area
-- submergence depth (by varying the pool level)
-- pool surface area (reduced by a partition wall)
-- pool mass (by varying the pool level and the pool surface area)
-- vent flow path geometry
-- pool temperature
-- vent mass flow rate
-- fraction of air in the vent flow.

The test facility, Fig. 4.6, consists of a containment, a pressure vessel and a discharge line connecting the vessel to the containment.
The drywell consists of several sub-compartment. It has a total air volume of 1980 m³, which includes the vent system down to the normal (initial) water level inside the vent pipes. The normal depth of the wetwell water pool is 4.5 m, giving a water volume of 560 m³ and an air space column of 1580 m³.

The vent system consists of four large pipes of 1.2 m inside diameter, connecting the lower drywell to a header located in the wetwell air space. From this header a total of 58 vent pipes, of 0.3 m inside diameter, run vertically down to the wetwell water pool. The normal submergence depth is 2.8 m.

The design pressures are 410 kPa for the drywell and 330 kPa for the wetwell. The maximum pressure difference between the drywell and the wetwell is limited to 120 kPa. One-way spring loaded valves prevent the pressure in the wetwell from exceeding the drywell pressure by more than about 25 kPa.

The pressure vessel has a 5.22 m inside diameter and a height of 24.55 m. The net volume of the vessel is 420 m³. The vessel is designed for a pressure of 5.75 MPa and a temperature of 545°K.

Pipe ruptures may be simulated in the upper part or the lower part of the drywell. In order to provide for two-phase discharges, a siphon connects the water in the vessel to the discharge location. The lower drywell discharge location uses the original main steam line. In some of the tests the upper break location was used to pre-purge the containment in order to simulate the occurrence of a large leak prior to a pipe rupture.

4.3.3 JAERI Full-Scale Mark II Containment Response Test Program

From April 1979 to March 1982, the Japan Atomic Energy Research Institute (JAERI) conducted an experimental program on LOCA hydrodynamic loads in the General Electric Mark II containment system.

Both vent clearing and pool swell loads as well as steam condensation loads were studied. Particular emphasis was placed on experimental confirmation and evaluation of multivent effects on the steam condensation loads. A total of 28 tests were conducted for a wide variety of initial and break conditions. Data from 12 tests, conducted in the earlier part of the program, have been published /4.41/.

At JAERI the effects due to the following parameters in particular were studied:

-- break diameter
-- blowdown of liquid or of steam
-- pool temperature
-- prepurging of drywell atmosphere.

Fig. 4.7 is a schematic drawing of the test facility /4.34/, which consists of a test containment and an external pressure vessel. As illustrated in Fig. 4.8, the lower portion of the containment vessel is a full-scale, π/9 sector, representative of a Mark II wetwell annulus. The vent system comprises seven full-sized (0.6 m o.d., 14 m long) vent pipes.
The pool boundaries are formed from steel-lined concrete. The drywell and the pressure vessel volumes are scaled by a factor of 1/18.

4.3.4 GKSS Experimental Research

At the GKSS-Forschungszentrum Geesthacht GmbH a co-operative experimental program was established with German institutions and the USNRC. This program focused on understanding pressure suppression containment response to a postulated LOCA, and the generation of full scale experimental data useful to advanced code development and licensing requirements /4.42, 4.43/. It was also used to investigate chugging mitigators to reduce dynamic loads.

The design, the boundary conditions and the large scale of the test facility enabled LOCA induced pressure suppression loads, affecting both the KWU-69 and Mark II containment system designs, to be investigated.

Fifteen multivent steam blowdown experiments were performed with the objective of investigating the influence of:

-- mass and energy flow rate
-- pool initial temperature
-- pool back pressure
-- vent pipe submergence
-- number of vent pipes and vent pipe geometry.

Reproducibility of test results was considered important in defining the test matrix. This was achieved by changing only one parameter from test to test, so as to identify its influence alone on the pressure suppression processes.

The test facility was a pressure suppression containment research apparatus, originally developed to design a suppression system for a container ship with nuclear propulsion. The configuration and arrangement of the facility are shown in Fig. 4.9. It consists of a pressure vessel to simulate steam blowdown, a drywell, a wetwell and an expansion room. The latter provides a capability to enlarge the wetwell air space to simulate pool back pressure variations. Drywell and wetwell are connected by 3 vent pipes. Key full-scale parameters are: vent diameters of 0.61 m, vent submergence of 2.8 m, pool area per vent pipe of 5.4 m², mass and energy release into the system, and full-scale pressure and temperature transients during the LOCA simulation.

4.3.5 KWU Research

Kraftwerk Union (KWU) performed a broad series of tests on PSCS behaviour related to LOCA in many test facilities /4.44/. Table 4.3 summarises the test series.

Fig. 4.10 shows a sketch of the GKM II M test facility /4.44/; which represents, full-scale, a single cell of the pressure suppression system of a Mark II plant. The experiments simulated LOCAs from main steam and recirculation line breaks under various conditions of break size, pool temperature, back pressure, etc.
The instrumentation enabled comprehensive measurements to be made of pool pressures, lateral loads on the vent pipe and loads on submerged structures, as well as measurements of the various physical quantities and conditions during the blowdowns: temperature, steam flux, air content, phase boundaries, etc.

4.4 Interpretation of Selected Phenomena

4.4.1 Vent Clearing

In a large break LOCA the drywell is pressurised at a rate of 100 kPa/s or more, and vent clearing is complete within a second or so after the break. During a small break LOCA the drywell pressurisation is less rapid (< 10 kPa/s) and vent clearing occurs when the drywell pressure exceeds the vent's hydrostatic head.

The first peak in the drywell pressure history, Fig. 3.1, is caused by the inertia of the water in the vent pipes, which delays their clearing. The maximum drywell and wetwell pressures are controlled by gas carryover in a Mark I or II type containment. In the Mark III maximum drywell pressure is governed by vent flow, and the wetwell peak pressure by the long-term pool heat-up transient.

The water jets exiting the vent system induce drag loads on pool internal structures and transient pressure loads on the pool boundary. Small-scale visual experiments have demonstrated the significant decay of jet velocity before impingement onto the pool boundary. The observed jet decay mechanism includes formation of starting vortices at the front of the jet /4.45, 4.46/. These observations are consistent with the almost uniform spatial distribution of the pool boundary pressure load measured in subscale and large-scale facilities /4.47/.

4.4.2 Pool Swell and Associated Loads

Pool swell results from the upward differential pressure between the expanding gas bubbles and the wetwell free-space. Higher pool swell velocity, and hence greater pool swell loads, are induced by faster drywell pressurisation and transfer of the air through the vents caused by the larger pipe ruptures. Accordingly, most tests included simulation of the postulated maximum pipe ruptures.

Pool swell has been investigated in specific plant geometries, since it is strongly influenced by vent and pool configurations.

4.4.2.1 GE Mark I Containment

The pool swell induced loads of primary concern to the Mark I design include the torus down load due to the initial bubble growth following vent clearing, wetwell upload due to free-space gas compression and, most importantly, the impact load on the ring-shaped vent header which is located above the initial pool level. The magnitude of the header impact load depends on the pool surface configuration as well as on the surface velocity at the time of impact. The pool surface becomes distorted before it impacts the ring header, because of the relatively small initial vent submergence (~1 m) and the complex pool geometry.
Tests were performed on facilities with linear scales of 1/4, 1/5, 1/10 and 1/12 /4.48 to 4.50/. Both two-dimensional (with one pair of main-vent downcomers) and three-dimensional (with multiple pairs of downcomers) facilities were used. The test conditions, including the drywell pressurisation rate, were determined by scaling based on the Froude number. The initial drywell pressurisation was simulated by discharging air rather than steam into the drywell to avoid scaling uncertainties arising from steam condensation in subscale systems. Small-scale tests were conducted for detailed investigations of the scaling laws governing the vent clearing and pool swell phenomena, e.g. /4.51, 4.52/.

The time-dependent three-dimensional behaviour of the pool surface, as well as the wetwell and ring header loads, were measured and were extrapolated to actual plant scales /4.39/. Favourable comparisons of test results at different scales verified the adequacy of the scaling theory with respect to pool surface behaviour and wetwell pressure loads.

Mitigation of wetwell pressure loads by altering vent exit geometry, and mitigation of the header impact load by installing deflectors, has been studied /4.39/. Calculations /4.71/ have indicated the importance of the steam condensation within the wetwell air bubble for its effects on pool swell, and on the download and upload on Mark I types of containment.

4.4.2.2 GE Mark II and European BWR Containments

Pool swell on Mark II designs has been studied using full-scale (GE, JAERI, GKM) and subscale facilities. These include a 1/13-scale \( \pi/2 \) sector /4.53/ and a 1/6-scale cylindrical model /4.54/. The same scaling theory, as was used for the Mark I tests, was applied to develop the test conditions and to extrapolate test results.

The pool swell-induced loads of primary interest in the Mark II containment design are the impact and drag loads on wetwell internal structures and the possible activation of vacuum breakers. Impact loads can be much larger than drag loads. These can be evaluated knowing the pool swell velocity as a function of time.

Measurements of pool surface elevation (or velocity as its time derivative) were made, either visually in transparent facilities, or by using conductivity probes distributed in the wetwell. Since the Mark II wetwell geometry is cylindrical, pool swell observed in the tests was essentially one-dimensional. However, growing instability of the pool surface was observed as the maximum swell elevation was approached /4.47, 4.53/. Such instability caused uncertainty in pool level measurements, and also generated a spray of water which reached higher elevations than the bulk water.

Pool surface instability leads to uneven pool surface elevation and induces small loads on structures at higher elevation due to water spray impact. Surface distortion is important since a small inclination of the pool surface with respect to the impacted structure reduces the impact loads considerably. Current licensing evaluation models conservatively assume that an intact and flat pool surface impacts structures.
4.4.2.3 GE Mark III Containment

In the Mark I and Mark II containments, which have relatively small wetwell free-space volumes, pressurisation of the wetwell due to pool swell decelerates the rising water slug and limits the maximum pool swell elevation. This limiting effect is much weaker in the GE Mark III containment which has a very large free-space volume. Thus, pool swell continues until the air bubbles eventually break through the pool surface.

Pool surface velocities and breakthrough heights were measured using full-size vents (0.7 m i.d.) and $1/\sqrt{3}$ length scale models of the Mark III vent system. Based on the results of these tests an empirical correlation was developed for the breakthrough height. Impact loads on simulated structures were also measured for typical configurations /4.35, 4.55/.

4.4.3 Condensation Oscillations

During the early period of a blowdown, in which both the steam injection rate and the air concentration in steam are high, the condensation of steam at the vent exits in direct contact with subcooled pool water is a relatively smooth, although unsteady, process. Relatively regular oscillations of pressure inside and outside the vent system are driven by the oscillatory motion of the steam/water interface.

Condensation oscillations in vertical vent systems have been studied in various scaled facilities under various thermal-hydraulic conditions, e.g. /4.56, 4.57/. Scaling effects limit the applicability of small scale loading data to full-scale plants. One noticeable observation is that condensation oscillations in large-scale systems are more sensitive to the vent system geometry than in small-scale systems. This seems to be related to the fact that the bubble-to-vent diameter ratio is larger for smaller scales. In small-scale systems, with vent diameters of a few centimeters or less, the bubbles can be several times as large as the vent diameter, particularly at high pool temperatures. In full-scale systems, with 0.6 m i.d. vents, a typical penetration of the steam bubble below the vent exit is $< 0.3$ m /4.41/.

At small scales the dominant frequency of the pressure oscillation depends on many parameters, but can be correlated primarily with average bubble volume, which is dependent on vent diameter, pool temperature and steam injection rate. For a fixed system geometry and a fixed steam injection rate, the bubble volume increases with increasing pool temperature, and the dominant frequency decreases. At large-scales the dominant frequency appears to be less sensitive to pool temperature or steam injection rate, although published data at large scales are scarce. The dominant frequency as well as the spatial distribution of amplitude appear to depend on the geometry of the vent system as well as the drywell.

Unusual pressure excursions of short duration (pressure spikes) appeared in the Marviken experiments at high steam flow rates. Peak to peak pressures up to 180 kPa were recorded, with the maximum values at the exit of the vent pipes /4.40/. These are probably associated with the collapse of steam bubbles detached from the vent pipes and appear to be peculiar to the Marviken tests. They may be differentiated from chugging phenomena in that their amplitude and number increased with increasing steam flow-rate. Reducing the air concentration in the vent flow by prepurging resulted in larger and more frequent pressure spikes. Increasing the wetwell temperature had the opposite effect.
The influence of system geometry on condensation oscillations has not been investigated quantitatively, but has been recognised from comparisons of test results for different geometries. For instance, test results obtained at the JAERI full-scale, Mark II, facility /4.41/ and at the Marviken test facility /4.40/ showed weak and strong coupling between the vent pipes, respectively. In the JAERI tests the dominant measured frequency was close to the acoustic fundamental frequency of the vent pipe. The pressure oscillations in the multiple vent pipes were essentially out of phase and poorly coherent with each other. Pressure oscillations in the pool and in the drywell were much smaller than those in the vent pipes. In the Marviken tests, however, the measured dominant frequency was much lower than the vent natural frequency. At the dominant frequency, the pressure oscillations inside the vent pipes, in the drywell and in the pool were in phase and coherent with each other.

Another important parameter affecting the condensation oscillation phenomenon is poor mixing of the pool water /4.58/. The stirring effect of the buoyant air bubbles rising in the pool decreases as the air concentration in the vent flow decreases. The motion of the steam-water interface may not be large enough to induce good pool mixing by itself. Poor mixing leads to pool temperature stratification or local pool heatup in the neighbourhood of the vent exits, or to a combination of both.

4.4.4 Chugging

4.4.4.1 General Remarks

The analysis of high speed films (1000 f.p.s.) was correlated with vent exit temperature and pool bottom pressure (1 m below vent exit) measurements in the full-scale, vertical-vent, GKSS facility /4.59/. The following phases may be recognised in a chugging event, Fig. 4.11A. First, a horizontal steam front with cylindrical shape, 1, occurs at the pipe exit. This intrudes into the pool by about one pipe diameter. The steam volume grows into a conical shape, 2, which becomes hollow in the central region, 3. Partial steam collapse occurs outside the vent pipe exit, 4. The steam then forms a steam torus on the inside wall of the vent exit, 5. This steam ring collapses rapidly and the vent is closed once more by water.

The temperature measured near the vent pipe exit, Fig. 4.11B, indicates steam contact as long as the steam front penetrates into the pool. At this stage the pressure below the vent pipe shows a low frequency oscillation induced by the observed partial steam condensation outside the vent pipe. The frequency of this pre-chug oscillation corresponds to the acoustic frequency of the steam filled vent pipe. These oscillations are followed by a high frequency ring-down, initiated by collapse of the steam annulus inside the vent exit. Chugging events without pre-chug oscillation have also been observed. The second part of the chug, in particular, produces strong local pressure pulses inside the wetwell pool and lateral forces at the vent pipe exit, due to random asymmetric effects.

The bubble collapse process found in the JAERI full-scale seven-vent test facility was more straightforward than that observed in the GKSS facility. The external condensation of steam led directly to penetration of the pool water into the vent pipe, as shown in Fig. 4.12. Observed pool
pressure oscillations may be divided into three parts: initial depressurisation, high-frequency pressure spikes, followed by a period of damped oscillations of lower frequency. The initial depressurisation and pressure oscillations result from collapse of steam bubbles at the vent exit, and the damped oscillations from system response to fluid-dynamic perturbations generated by the bubble collapse process.

Pressure oscillations induce pressure loads on the pool boundaries and the pool internal structures. Bubble collapse at the vent exit induces transient loads on the vent system.

4.4.4.2 Transition from Condensation Oscillation to Chugging

Chugging occurs only at low steam injection rates coupled with very small air concentrations. The upper-threshold steam injection rate depends on many parameters, including pool temperature, facility scale, vent system geometry, the number of vent pipes and the drywell volume. For full-sized (0.6 m i.d.) vertical vent systems and moderate pool temperatures (~30°C), the threshold steam mass flux measured at JAERI laboratories ranged between 10 and 30 kg/m².s /4.60/. The threshold steam mass flux decreases with increasing local pool temperatures near the vent exit. Thus, any local pool heatup occurring during the condensation oscillation phase of the blowdown, affects the onset of chugging. Uncertainties in pool temperature uniformity lead to uncertainty in the experimental definition of the transition condition /4.60/. There also exists a lower-threshold steam injection rate, below which chugging no longer occurs and condensation stabilises inside the vent system or on the drywell walls.

Data on the threshold air concentration in steam are scarce particularly for large scales. An estimate of the threshold air concentration of < 1% by weight of steam was obtained in the full-scale multivent Mark II containment tests /4.58/. Such low air concentrations occur only during the later phase of a blowdown, when almost all the air has been expelled from the drywell.

Effects of system geometry on transition conditions are of interest, but they have not been investigated quantitatively. Qualitatively, increasing the drywell volume per vent, by blocking some of the vent pipes during the tests stabilised the condensation in both the full-scale and subscale facilities /4.54/.

4.4.4.3 Pool Boundary Loads

Chugging may induce pool boundary pressure loads of much greater magnitude than condensation oscillations. Various tests were conducted to define adequate chugging loads, upper-bound loads being of particular interest. Because of scaling and system geometry effects, the quantitative definition of chugging loads requires large scale tests on plant specific geometries.
For the Mark I containment geometry tests were conducted using a full-scale, π/8 sector, facility having four pairs of main-vent downcomers /4.38/. For the Mark II containment geometry, in addition to some small scale investigations, tests were conducted using one full-scale, π/9 sector, facility with seven vent pipes /4.41/, and two full-scale, single-cell models /4.36, 4.37, 4.43/. For Mark III geometry a full-scale, single cell model with three horizontal vents was employed /4.35/. Most of the results from the above tests are proprietary except for those of the Mark II, π/9 sector, tests which have been published in part.

It is well known that chugging exhibits a more or less random nature. Hydrodynamic perturbations generated in the pool by steam bubble collapse differ from one bubble collapse event to another, because interfacial instability and turbulence around the interface influence the bubble collapse process. Furthermore bubble collapse may not occur simultaneously at all the vents. This random behaviour implies a favourable reduction in the magnitudes of the pool boundary loads in actual plants having one hundred or more vents, relative to those loads measured in test facilities having small sections with a single or few vents. This dependence of loading magnitudes on the number of vents, designated "multivent effect", was observed in small-scale multivent tests conducted prior to the full-scale multivent tests, e.g. /4.54, 4.61/.

It is desirable to allow for the multivent effect when defining plant design loads, since experimentally measured chugging loads sometimes pose severe problems in containment structural designs. Thus, obtaining chugging test data and evaluating the multivent effect were both primary objectives of the full-scale multivent test programs.

The first objective has been met. The second objective has yet to be satisfactorily attained. To quantify the multivent effect, it is first necessary to compare in detail the test results obtained with different numbers of vents. This is possible only by comparing results obtained from different test facilities. However, the proprietary nature of the large-scale test-data has prohibited such comparisons, or prevented conducting counterpart tests within different test programs. Consequently, it is difficult to extract from the data available the individual contributions of various parameters responsible for the multivent effect. Some attempts to evaluate analytically the effect of desynchronisation among the condensation events have been made, e.g. /4.62/. Desynchronisation was statistically evaluated for the Mark II containment geometry using the results of the full-scale, seven-vent tests /4.60/. Credit for this statistical approach was given in the licensing evaluation of plant loads. The dependence of chugging induced pool boundary loads on thermal-hydraulic conditions has also been studied. Conclusions derived from different tests were rather inconsistent because many factors are involved /4.58/. The primary parameters include steam mass flux, air concentration in the vent flow and local pool temperature. In large-scale facilities none of those variables are easy to measure.

4.4.4.4 Vent System Loads

Steam bubble collapse inside and outside the vents, at or near the vent exits, induces transient internal and external loads on the vent system walls near the vent exits. These lateral loads are normally of concern for vent systems formed from unsupported vertical pipes. Because of the complicated and random nature of the bubble collapse process, experimental studies are
needed to define load histories. The measured vent lateral loads are large and impulsive, so that in weakly supported vents the peak amplitudes of the loads may depend on the rigidity of the vent system as well as on the thermal-hydraulic conditions.

Load magnitudes are also random. An exponential correlation of load magnitudes versus probability of exceeding a particular load has been developed, based on single-vent test data /4.64/, and has been used to predict the probable upper-bound loads in actual plants /4.65/.

Because of the random nature of bubble collapse, stresses in the vent system structure in actual plants are expected to be much smaller than those experienced in test facilities. Desynchronisation between bubble collapse events, as well as the random direction of the loads, are major contributors to such reductions/4.63/. To spread these loadings vent pipes are usually connected together by bracings.

4.4.4.5 Reduction of Chugging Loads

The experimental results at GKSS, concerning the steam annulus or steam ring formation inside the vent pipe exit, led to two mitigation proposals involving geometrical changes to the vent pipe outlet /4.66/. The main idea was to influence by passive methods the thermal hydraulics of the condensation process at the pipe exit in order to smooth the dynamic chugging loads.

A first proposal was an outlet collar at the end of each vent-pipe. This avoids the steam annulus growth and the subsequent collapse with its resulting sharp pressure pulse and the lateral vent pipe forces. The radius of the collar was taken roughly from the steam annulus radii observed in the TV-movies.

The outlet collar was tested very successfully, as indicated in Fig. 4.13, where the results of two tests with the same mass and energy release into the drywell are compared. It is important to note that, by this design, only the pressure pulses produced by the chugging are avoided, but not the chugging phenomenon itself. Water periodically enters the vent pipe and initiates the well-known mixing effect of cold and hot water in the pool.

A second mitigator, the vent-pipe end cut at 45°, was also tested very successfully. The basic idea of this construction is to provide a continuous steam flow path from the vent pipe to the pool to avoid the periodic steam release of the conventional pipe during chugging and so to obtain a partial stabilisation of the steam flow. During the time when chugging is expected, i.e. at relatively low steam mass flow rates, this construction shows a very distinct self-regulating effect: less steam flow through the vent pipe, less steam flow area at the vent pipe exit. In the pool the dynamic pressure loads are practically eliminated (Fig. 4.13), while in the drywell atmosphere cyclic pressure reductions of about 20 kPa occur at the beginning of chugging.

Finally, it should be mentioned that dynamic load reduction by other engineering methods is possible. An increase in initial pool temperature or final pool back-pressure reduces the dynamic loads. A distinct attenuation of pressure amplitudes during chugging may be obtained by injecting air into the vent pipes in the range of 1% of the steam mass flow /4.67, 4.68/. None of these mitigation devices or dynamic load reduction methods have actually been applied to a commercial containment design.
4.5 Concluding Remarks

Some observations about the suitability of the experimental results obtained in the various research programs for code validation may be drawn.

The limited availability of published experimental data and the large research effort spread over more than 20 years preclude a complete discussion. For each principal phenomenon an opinion is given about the relevant and main experimental results without any claim to be exhaustive.

Most tests were of a confirmatory nature, and were neither planned nor instrumented to study pressure suppression phenomena in detail. For example, visual observations were generally lacking in large scale experiments with the important exception of the GKSS tests.

As an additional complication, some measured phenomena are not fully understood. The pressure spikes evident at high steam flows in the Marviken tests do not fall into the overall pattern of steam condensation processes discussed in this chapter and in section 3.2.2. b).

4.5.1 Quasi-Steady Pressurisation and Vent Clearing

All main experimental results are significant for code validation of these parameters.

The proprietary nature of most of the GE experimental data makes the large-scale Marviken experimental results particularly valuable. By analysing these data the influence of several parameters: blowdown, flow-rates, enthalpy flow-rates, pool-temperature, pipe submergence, etc. can be assessed. The importance of air transfer from the drywell to the wetwell was emphasised by the Marviken experiments /4.40/. Similar observations may be made about the JAERI tests.

Two particular points should be noted:

-- the effect of prepurging the dry-well atmosphere
-- the full-scale demonstration that wetwell to drywell vacuum breaker valves may open in the early pool-swell phase of the transient.

4.5.2 Pool-Swell and Associated Phenomena

Again, all the experiments mentioned in sections 4.3 and 4.4 provide useful information on pool-swell.

Two observations should be made:

-- there is a lack of published full-scale experimental results for the GE Mark I and Mark III containments. This is troublesome, because these phenomena are of particular interest for these containments due to the extremes in the wetwell free-space volumes (very small in the Mark I and very large in the Mark III);

-- the JAERI experimental data for Mark II containments are of particular value.
4.5.3 Pressure Oscillations

Pressure cycling due to condensation oscillations, with dominant frequencies related to acoustic phenomena in the vent pipes, have been emphasised in GKSS tests, in JAERI tests, as well as in the Marviken experiments.

The effect of the geometry of the vent system and drywell on the characteristics of oscillation (amplitude, dominant frequencies, spatial distribution) are evident when comparing test results obtained at the JAERI Laboratory and at Marviken. The former tests show weak coupling among the vent pipes, while a strong interaction is evident in the latter.

GKSS tests are of particular value with regard to condensation chugging. The comprehensive instrumentation available and the visual examination of the phenomena have provided information particularly suitable for setting up related mathematical models and for code validation. The parametric studies on the effects of steam flow-rates, of multivent interactions, of wetwell area per vent, of features designed to reduce chugging loads, etc., are especially valuable to this latter objective.

The same observations are valid for the JAERI experiments, where emphasis was placed on studying multivent interactions.
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/4.67/ G.F. Schultheiss, H.R. Niemann, F. Sakkal:
"Untersuchungen zur Verminderung der dynamischen Lasten bei SWR-Druckabbau-Vorgängen"
Jahrestagung Kerntechnik 1982, Tagungsbeibericht ISSN 07209207, p. 211-214

/4.68/ E. Aust, G.G. Schultheiss, D. Seelinger, E.W. McCauley:
"Experimental Results about Dynamic Load Mitigation for BWR Pressure Suppression Containments under LOCA Conditions"

/4.69/ "The Marviken Full Scale Containment Experiments"
Description of the Test Facility, MXB-101 (1977)
4.70/ E.W. McCauley:
"A Study of the Multivent Effects in a Large Scale Boiling Water Reactor Pressure Suppression System"
GKSS 84/E/31 (1984)

4.71/ A. Woudstra:
"Influence of Steam Condensation in the Wetwell Air Bubble on the Pool Swell Height and Lift Force"
<table>
<thead>
<tr>
<th>TEST SERIES</th>
<th>NUMBER OF TESTS</th>
<th>SCALE</th>
<th>QUENCHER ARMS</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GKM</td>
<td>70</td>
<td>1:2</td>
<td>-</td>
<td>Open Pipe</td>
</tr>
<tr>
<td>KWW</td>
<td>50</td>
<td>1:1</td>
<td>-</td>
<td>Open Pipe</td>
</tr>
<tr>
<td>GKM</td>
<td>100</td>
<td>1:2</td>
<td>4</td>
<td>Tests of Prototype</td>
</tr>
<tr>
<td>KKB/KKP 1</td>
<td>148</td>
<td>1:1</td>
<td>4</td>
<td>Verification Tests of X-Quencher</td>
</tr>
<tr>
<td>Karstein Quencher</td>
<td>32</td>
<td>1:1</td>
<td>2</td>
<td>Verification Tests of T-Quencher</td>
</tr>
</tbody>
</table>

Table 4.1: Safety/Relief System Steam Discharge Tests Performed by KWU /4-17
<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>INSTITUTION</th>
<th>FACILITY</th>
<th>REFERENCE CONTAINMENT TYPE</th>
<th>VENT TYPE</th>
<th>EXPOSURE</th>
<th>VENT AREA (m²)</th>
<th>TOP VENT SUBMERGENCE (m)</th>
<th>DET WELD</th>
<th>AIR GET WELD</th>
<th>POOL</th>
<th>SCALE FACTORS</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.A.</td>
<td>CE</td>
<td>PTFP</td>
<td>BWR 6 Mark III</td>
<td>Straight Horizontal (3 Rows)</td>
<td>1.0, 0.7, 0.6</td>
<td>1.0, 0.7, 1.0</td>
<td>0.6 - 4.7</td>
<td>67 (126)</td>
<td>300</td>
<td>200</td>
<td>12.4</td>
<td>1/112</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vertical</td>
<td>0.5, 0.19, 0.6, 0.27</td>
<td>2.7 - 4.1</td>
<td>53</td>
<td>0.5 to</td>
<td>0.024</td>
<td>53.2</td>
<td>0.92</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KRT</td>
<td>BWR 4 Mark II</td>
<td>Straight</td>
<td>0.6, 0.5, 0.3, 0.3</td>
<td>2.0 - 4.0</td>
<td>0.5 to 3.0</td>
<td>0.25</td>
<td>0.024</td>
<td>0.024</td>
<td>0.116</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PTFP</td>
<td>BWR 1-3 Mark I</td>
<td>Branches</td>
<td>0.6, 0.6, 0.6, 0.6</td>
<td>0.5-1.4</td>
<td>237</td>
<td>0.6 to</td>
<td>0.18</td>
<td>0.6 to</td>
<td>0.0036</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(vertical out flow)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.018</td>
<td>0.007</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>KfK</td>
<td>CANDU</td>
<td>Straight Vertical</td>
<td>0.3, 0.6, 0.3</td>
<td>4.0</td>
<td>2.0</td>
<td>1980</td>
<td>550</td>
<td>1500</td>
<td>110.0</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GAHR</td>
<td>CANDU</td>
<td>Straight Vertical</td>
<td>0.6, 0.6, 0.6, 0.6</td>
<td>1.91, 3.3 - 3.9</td>
<td>329</td>
<td>255</td>
<td>187</td>
<td>24.8</td>
<td>1/10</td>
<td>/4-35/</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CRESS</td>
<td>SMR 69</td>
<td>Straight Vertical</td>
<td>0.6, 0.6, 0.6, 0.6</td>
<td>0.88 - 2.8</td>
<td>59.8</td>
<td>47.3 (22.5)</td>
<td>41.1</td>
<td>16.2</td>
<td>1/95</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>EUW</td>
<td>SMR 69</td>
<td>Straight Vertical</td>
<td>0.6, 0.6, 0.6, 0.6</td>
<td>0.29</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1/110</td>
<td>/4-35/</td>
</tr>
</tbody>
</table>

* - Can be changed as a parameter.

(1) - Flow, Flow / Flow Area / Vent Pipe Flow Area
(2) - SW Pool Surface Area / Vent Pipe Flow Area
(3) - SW Volume / BD Flow Area (m)
(4) - SW Volume / WW Air Volume

**TABLE 4.2: CHARACTERISTICS OF MAIN EXPERIMENTAL FACILITIES**
Fig. 4.1: Suppression Pool Pressure Transducer Locations for Safety/Relief Valve Blowdown Tests at Leibstadt 14-15

- ELEVATION VIEW
  - CONTAINMENT SHELL
  - SUPPRESSION POOL
  - RHR-B SUCTION LINE
  - X-QUENCHER

- PLAN VIEW
  - DRYWELL
  - X-QUENCHER
  - WEIR WALL
  - CONTAINMENT SHELL
  - SUPPRESSION POOL
FIG. 4.3 - PSTF POOL AND VENT SYSTEM GEOMETRIES
PLAN VIEW.
<table>
<thead>
<tr>
<th>TEST SERIES</th>
<th>PLANT TYPE</th>
<th>NUMBER OF TESTS</th>
<th>SCALE</th>
<th>NUMBER OF DOWNCOMERS</th>
<th>TEST TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GKM I</td>
<td>B1 69</td>
<td>19</td>
<td>1:1</td>
<td>1</td>
<td>Stationary</td>
</tr>
<tr>
<td>KKB</td>
<td>B1 69</td>
<td>15</td>
<td>1:1</td>
<td>1</td>
<td>Stationary</td>
</tr>
<tr>
<td>Karlstein Large Tank</td>
<td>B1 69/72</td>
<td>14, 6</td>
<td>1:2, 1:1</td>
<td>1...6, 1...2</td>
<td>Stationary</td>
</tr>
<tr>
<td>GKM II</td>
<td>B1 69/MARK I</td>
<td>71</td>
<td>1:1</td>
<td>1</td>
<td>Transient</td>
</tr>
<tr>
<td>Karlstein Concrete Cells</td>
<td>B1 69/72</td>
<td>29</td>
<td>1:7</td>
<td>1...10</td>
<td>Stationary</td>
</tr>
<tr>
<td>GKM II M</td>
<td>MARK II</td>
<td>22</td>
<td>1:1</td>
<td>1</td>
<td>Transient</td>
</tr>
<tr>
<td>GKM II S</td>
<td>B1 72</td>
<td>11</td>
<td>1:1</td>
<td>1</td>
<td>Transient</td>
</tr>
</tbody>
</table>

**TABLE 4.3 - PRESSURE SUPPRESSION SYSTEM LOCA-TEST PERFORMED BY KWU.**
FIG. 4.4 - "4T" POOL SWELL TEST
Fig. 4.5: Mark I Full-Scale Test Facility
Fig. 4.6: Marviken Containment Schematic (Pressure Transducers in the Wetwell & Lower Drywell indicated)
Fig. 4.7: Schematic of JAERI Test Facility

Fig. 4.8: Cross-Section of Test Containment Superimposed on the Mark II Wetwell

- TEST CONTAINMENT
- NOZZLE
- VALVE
- PRESSURE VESSEL
- VENT PIPE
- HEATER
- RUPTURE DISC
- DRYWELL (302 m³)
- VACUUM BREAKER
- WETWELL AIRSPACE (255 m³)
- SUPPRESSION POOL (188 m³)

- CONCRETE
- TEST CONTAINMENT
- MR II CONTAINMENT
- BRACE
- VENT PIPE
- π/9 SECTOR
STEAM SOURCE:

\[ P_o = 111 \text{ bar} \]
\[ T_o = 319 \text{ °C} \]
\[ m_o = 100 \text{ kg/s} \]

PLANT-LIKE KEY PARAMETERS

- 3 VENT PIPES
- 2.8 m SUBMERGENCE
- 0.6 m VENT DIAMETER
- 5.4 m² POOL AREA/VENT
- PRESSURE+TEMPERATURE TRANSIENTS

FIG. 4.9 - GKSS PRESSURE SUPPRESSION TEST FACILITY
(STEAM GENERATOR AND WETWELL EXPANSION ROOM NOT SHOWN).
FIG. 4.10 - SIMULATION OF SWR 69 PRESSURE SUPPRESSION SYSTEM IN GKM II M TEST FACILITY.
Fig. 4.11: Typical Chugging Event, (A) Steam-Water Interface, (B) Temperature and Pressure
Fig. 4.12: Typical Vent and Pool Pressure Transients during a Single Chug Event, as observed in JAERI Facility
Fig. 4.13: Dynamic Load Reduction by Geometric Mitigators

Test M1-5 (standard exits)

Test M1-ABC.K (collar exits)

Test M1-B.45 (45°-cut at pipe B)

Test M1-ABC.45 (45°-cut at pipes A,B,C)

All tests under the same boundary conditions
5. ANALYTICAL MODELLING, COMPUTER CODES AND CODE VERIFICATION

5.1 Introduction

In containment modelling the use of computer codes is inevitable for the prediction of physical phenomena, for the understanding of experimental results as well as for extrapolating them to support full-size plant design decisions.

The codes contain mathematical formulations of the physical events involved founded on conservation laws, constitutive equations which serve for the modelling of the transfer processes across physical boundaries and interfaces, and the material property equations. Based on experience the code user must make decisions on the nodalisation and the optimal choice of constitutive equations to obtain the analytical simulation of the physical processes of interest.

It is appropriate to distinguish between predictive analytical capability in the sense of being able to predict events which have not yet happened, and those analytical activities serving the reanalysis of previous events which are known from experimental evidence. The space-and-time averaged conservation laws used in many integral systems codes is the preferred formulation for both categories.

In general, it is not possible to describe all types of expected loads with a single code. In some situations the dynamic interaction of the fluid-dynamics and the structure mechanics may be well approximated by the simultaneous application of uncoupled codes. In other situations, coupled codes are needed to obtain a proper description of local structural behaviour.

5.2 Analytical Modelling of Safety/Relief Valve Blowdown Loads

As described in Section 3.2.1, the physics of safety/relief valve blowdown into the suppression pool may be divided into short-term clearing of the blowdown line, followed by a relatively long-term steam blowdown with condensation in and heat-up of the suppression pool. Because they generate significant loads, the short-term line clearing and gas-bubble dynamics in the suppression pool have been intensively studied. Most analytic model development with experimental confirmation has been carried out by the General Electric Company.

1) Line Clearing of water and of gas, or gas/steam mixtures, is readily handled by classical unsteady, one-dimensional analyses, such as the method of characteristics for the gaseous portion /5.1 and 5.2/ coupled to an equation of motion for the water leg /5.3/. Models must take into account the wide range of boundary conditions which can affect the phenomena. These include: reactor conditions, valve characteristics, line geometry, line exit geometry, line thermodynamic conditions (air/steam temperatures) after previous valve actuations or from leaking valve conditions, initial water leg lengths in the line, suppression pool depth and pool temperatures.

If sequential valve actuations are to be investigated, an unsteady analysis of line condensation processes, vacuum breaker flows and water leg oscillations after valve closure is necessary to provide the initial thermodynamic and water leg lengths when the valve is reopened /5.4/.
Once the unsteady pressures and flows in the line-clearing process are known, an unsteady momentum balance provides the forces on relevant portions of the line /5.5/. Water clearing reaction loads, particularly on pipe bends and at expanded pipe exits, can be very large indeed and should always be assessed.

ii) Dynamic Pressure Fields in the Suppression Pool arise from water leg clearing, and gas bubble growth and oscillations. The former is known as the water clearing spike.

The water clearing spike depends very strongly on the fluid accelerations in the neighbourhood of the pipe exit, which are controlled by the line-clearing process and exit geometry. Although simplified exit losses may be used for the overall line-clearing dynamics discussed in i) above, due account of actual geometry must be taken to calculate representative pool fluid accelerations. Such accelerations have been assessed using an energy equation and assuming a radial source flow model /5.6/. The source flow is predicted from the line-clearing model with corrections for the exit geometry. This approach is adequate if the pool water volume is very much larger than the total water-leg volume in the blowdown line, which is usually the situation. Actual spike pressure attenuation is determined empirically.

Injected gas-bubble behaviour in the suppression pool is more difficult to analyse. Allowance must be made for the pool water acceleration as a result of the water discharge, for the condensation of any steam mixed with the discharged gas, and for heat transfer from the bubble to the pool. A refined Raleigh bubble analysis /5.7/ which includes the effects of compressibility, finite pool size, bubble vertical motion and gravity has been developed by General Electric /5.6/ to determine bubble pressure oscillations. Initial bubble conditions are matched to the water clearing spike model using empirical information.

Pressure and acceleration fields in the pool, around submerged components and at the pool boundaries may be calculated once gas-bubble pressure variation is established. Potential field theory, method-of-images and electric field analogies have all been usefully employed for this purpose. An excellent overview is provided in /5.8/. When simultaneous actuation of valves is postulated, such fields must be combined, directly or statistically, with due allowance being made for the different locations of blowdown line submerged exits.

The effect of fluid-structure-interactions (see Section 5.4) on the pool pressure field adjacent to the pool boundaries needs to be considered, particularly where suppression pool walls are fabricated from unsupported steel plates /5.9/. Many two- and three-dimensional codes are currently available to perform such analyses /5.10/. These require, as input, a bubble pressure variation or equivalent source-term as a function of time. Fluid-structure-interaction analyses tend to be very expensive, but may be needed to assess adequately the transmission of vibrations through pool structures to containment structures above the pool surface. Effects of such vibrations on components attached to the containment need to be assessed.
To summarise, the modelling of short-term safety/relief valve line-clearing and pool pressure field dynamics involves a series of coupled, unsteady analyses. If reasonably accurate pool pressures are required, some empirical information is needed for the air-bubble injection model. Long-term condensation induced loadings are determined empirically. A model of the pool thermal mixing /3.5/ during the long-term steam blowdown through a "T" quencher on a Mark I containment has been developed and successfully tested.

5.3 LOCA-Integral Systems Behaviour Codes

5.3.1 Containment Code COPTA

The computer code COPTA is a multi-purpose containment code. COPTA simulates various aspects (pressure transients, temperatures, vent clearing, pool swell, etc.) of the BWR pressure-suppression-containment response under postulated water or steam line breaks.

The base version of COPTA-2 /5.11/ was released in 1975. Improvements with new options were developed and released as version COPTA-6 /5.12/ in 1979.

The following provides a brief summary of the most important features of the COPTA code:

-- The problem is formulated as a system of ordinary differential equations for control volumes, with up to ten independent variables for each volume and two for each dynamic connection.

-- Explicit or implicit integration methods may be used. The explicit method is normally used for short transients, the implicit for long-time behaviour.

-- Break flow data comes either from the built-in vessel model or from an input table based on computer or measured data.

-- An arbitrary number of volumes for drywell and wetwell modelling may be employed, the practical maximum is ten.

-- Subvolumes may be specified to be either in thermal equilibrium or in thermal non-equilibrium, i.e. different temperatures of the gas and liquid phases in a sump or suppression pool.

-- The gas phase may contain water droplets at the same temperature as the mixture of steam and non-condensable gas (normally air). Alternatively, depending on thermodynamic conditions, no water droplets are specified. Any droplets are assumed to fall to the sump or pool by gravity, unless sucked out through pipes or openings.

-- The liquid phase may contain bubbles of gas and steam (vent flow) or steam only (boiling) according to flow and thermodynamic conditions. Bubbles rising to the surface and carrying mass and energy into the gas phase are assumed to be at the same temperature as the liquid phase and rise with a constant prescribed velocity. During the vent clearing phase an optional pool swell model with more sophisticated equations may be used.
-- An arbitrary number of connections between control volumes, as well as between the volumes and the outside atmosphere, may be specified.

-- Different flow models: dynamic, compressible steady state or incompressible steady state may be chosen.

-- The generation and distribution of up to five noncondensable gases (H₂, CO₂ etc.) may be treated.

-- Multi-layer heat absorbing and conducting solid structures are represented by a finite difference approximation for linear, cylindrical or spherical geometry with variable mesh sizes. The resulting one-dimensional heat equations are solved by the implicit Crank-Nicolson method.

-- Heat transfer coefficients to solid structures, and between the gas and liquid phases may be specified either by input data tables or as a function of partial pressures according to the Uchida-correlation /5.13/.

-- The bulk condensation model is controlled by the energy of the gas phase.

-- Containment spray systems are modelled for both drywell and wetwell compartments.

-- Vacuum-breakers, fans, heat-exchangers, arbitrary heat and mass addition or withdrawal rates, etc. may be modelled.

5.3.2 Containment Code ZOCO-V

A full description of the code is given in /5.14/. ZOCO-V is a multi-control volume code. The communication between the volumes is by a one-dimensional description of the flow paths. The total model is represented by energy and mass flow balances with loss coefficients, equations of state, heat transfer correlations and a model for the wall temperatures. The volumes may contain water, steam and gas in homogeneous thermal equilibrium.

The following improvements were made to the original ZOCO-V version:

-- An automatic switch from superheated steam to equilibrium at the water thermodynamic conditions.

-- Heat transfer to walls.

-- A carry-over factor, which is defined as that part of all the water in a volume which may be present as droplets in the steam-air mixture.

-- Application of the code ZOCO-V for the calculations of temperatures and pressures in a containment is limited to pressures from 2 to 500 kPa and temperatures from 18 to 152°C.

-- The maximum number of sub-volumes is 11. The possible combinations are: one wetwell volume and 1-10 sub-volumes for the drywell, or no wetwell volumes and 1-11 sub-volumes for the drywell.
Several standard problems for full pressure containment systems were calculated with ZOCO-V. The results of these calculations were satisfactory and gave good agreement with most of the experimental results.

5.3.3 Containment Code CONTEMP-LT/26

The CONTEMP-LT/26 code is written specifically for the long-term portion of a containment transient during a LOCA. It is particularly suited to pressure suppression system analysis.

Version 26 was released in 1979 /5.15/. Further developments led to release of versions 26B and 28. Various authors have introduced improvements and new features /5.16/.

The main features of the code include:

-- The primary system, the drywell, the wetwell and the secondary containment are individually modelled by a single control volume. The code is thus not suitable for the analysis of a transient requiring a subdivided drywell. Where this is important for determining gas-carryover from a drywell with a complex geometry, a separate code such as ARIANNA 2 /5.17/, which treats multiple subcompartments, may be used. This procedure was successfully employed in ISP 17 /5.18/.

-- Engineered safety systems such as fan coolers and water sprays are included.

-- Control volumes are specific, the volume simulating the drywell cannot be used to represent a wetwell.

-- Each volume has two subvolumes, one for liquid the other for a liquid-vapour-gas mixture. Both are in homogeneous equilibrium. Energy and mass transfer between the subvolumes are controlled by evaporation, condensation and boiling processes.

-- Water droplets in the atmosphere are assumed to fall into the sump over a specified time.

-- Blowdown flow data are input and based on calculations or experimental data.

-- In addition to the vent flows to the suppression pool, leakages of air or gas between volumes may be modelled.

-- Up to 20 multilayer heat structures, describing three typical geometrical shapes (slab, cylindrical and spherical), may be modelled in one-dimensional form. The partial differential equations are solved by finite difference.

-- Heat transfer coefficients to the heat conducting structures may be specified as input data, according to the Uchida correlation /5.13/, as a correlation for turbulent natural convection, and as radiation heating.
-- Two different vent analytical models are available, one for vertical and one for horizontal vents.

-- Analyses are divided into three time periods:

1. vent clearing, in which water is expelled incompressibly, from the vent system;
2. a period in which quasi-steady compressible flow of a two component, two-phase water-steam-gas mixture occurs within the vent system;
3. a long term period, in which control-volume mass and energy changes occur due to mechanisms such as ECCS, leakage flows, etc.

-- The original version of the code assumes that steam condensation within the suppression pool is complete; only gas is added to the wetwell free space. A new routine has been inserted into the code /5.16/, which takes into account the possibility of direct steam flow between the drywell and wetwell free space, i.e. suppression pool bypass, either as leakage or transported with gas bubbles through the pool.

5.3.4 Pressure Suppression System Code DRASYS

The early DRASYS-code was developed /5.19/ and then improved /5.20/ to predict all LOCA related loads. The code simulates:

-- the p,T- histories in the drywell and wetwell
-- vent clearing
-- pool swell (symmetric or asymmetric)
-- gas carryover through the pool
-- condensation oscillations
-- chugging (in the subroutine KSWING V)

The main thermodynamic options of the code comprise:

-- lumped parameter models
-- two types of control volume with an arbitrary arrangement for simulation of the drywell, of the wetwell or a wetwell with a variable number of vent pipes
-- four types of connections
-- subdivision of volumes
-- thermodynamic equilibrium between steam, gas and water within each volume
-- homogeneous mixture within the volumes
-- saturated or superheated conditions
-- properties of water and steam
-- thermodynamic nonequilibrium within wetwell volumes at gas-water interfaces
-- one-dimensional, unsteady, incompressible, homogeneous, two-phase, two-component flow between the volumes
-- one-dimensional transient fluid dynamics for vent clearing.
Pool swell is modelled by a cylindrical bubble with:

-- transient, one-dimensional fluid dynamics with a cylindrical bubble
-- three options for condensation in the pool swell bubble
-- six options for simulation of gas carryover through the pool.

For condensation oscillations the water motion is calculated employing:

-- a one-dimensional equation of motion, which models the water surface whether inside or outside (spherical bubble) the vent pipe
-- six options for the simulation of heat and mass transfer at the steam-water interface.

Heat transfer to solid structures may be analysed using:

-- one-dimensional, unsteady heat transfer analysis
-- two structural geometries (plate, cylinder)
-- three materials per structure with two gaps
-- an arbitrary number of structures and structural layers
-- heat sources/sinks in the material
-- constant or time dependent heat transfer coefficients
-- inner, outer walls and walls in between the volumes.

Simultaneous solution of the system of differential equations is by the explicit/implicit integration procedure.

5.3.5 General Electric Code M3CPT04 for Mark III Type Containments

The M3CPT04 code (Mark III Containment Pressure Transient; Version 04) was developed by General Electric to simulate the Mark III type containment with horizontal vent pipes. The code is described in 5.21 and is a modification of an earlier code used for vertical vent pipes.

The model may be divided into five parts:

-- the reactor system, which models the vessel contents and provides blowdown flows
-- the drywell
-- the vent system, which includes submodels for vent system water clearing, vent flow of drywell contents to the suppression pool and a pool-swell-bubble, back-pressure model
-- the suppression pool and wetwell free-space
-- a system thermodynamics package.

The reactor system is modelled as a volume with a single pressure and temperature and a collapsed liquid level. Main steam, feedwater, and emergency core cooling system flows into the vessel are considered. Decay heat from the fuel, and heat transfer from the vessel walls and internals, to the reactor inventory are included. Break and safety/relief valve flows may either be saturated liquid, saturated vapor, or a two-phase mixture, depending upon the elevation of the collapsed liquid level relative to the break or valve elevations. Break and valve flows are functions of reactor pressure and fluid enthalpy, and may be calculated using either a Moody slip flow model or the homogeneous equilibrium model.
The drywell model is similar to the reactor model. The drywell contains a mixture of water, steam and gas, the steam may be saturated or super-heated. Mass and energy are added to the drywell by the break flow from the reactor. Following vent clearing, mass and energy leave the drywell through the vent system. The composition of the vent flows is taken as that of the drywell, which is assumed to be a homogeneous mixture in thermodynamic equilibrium.

The vent system is modelled by three relatively complex submodels. The vent clearing model determines the clearing times of the upper, middle and lower vents by mass conservation and momentum analyses of the water in the vent system. Very specific assumptions are made to simulate the sequential clearing of the horizontal vents. The vent flow model is based on the compressible flow of a two-phase, two-component mixture in a constant area duct with friction.

A pool-swell-bubble, back-pressure, model with air only as a medium simulates conservatively the effect of pool liquid inertia during the pool swell transient, which immediately follows vent clearing.

The bubble back pressure analysis assumes bubbles are created at each row of vents as the vents clear. Air, which flows into the bubbles from the drywell, is treated as an ideal gas at the drywell temperature. Water slug vertical motion is determined from the solution of a one-dimensional momentum equation. The mass of air in each bubble is calculated by integrating the mass flow at each vent exit. Bubble volumes are determined from integration of slug accelerations. With the bubble masses and volumes known, the bubble pressures are calculated from the ideal gas relations. The calculated back-pressure is used to modify the two-phase, two-component, vent flow analysis. A similar analysis is applied to the Mark II pool-swell model.

The wetwell model consists of the pool and wetwell free space. The flow of gas and steam from the drywell passes through the suppression pool before reaching the wetwell free space. All steam is assumed to condense in the suppression pool. The drywell gas passes through the pool and is assumed to emerge saturated with water vapor at pool temperature. Water from the vent system or to the emergency core cooling system is added to or subtracted from the pool. The wetwell space is assumed to be in thermal equilibrium with the suppression pool. Air can be added to the wetwell from the secondary containment building, via vacuum breakers.

5.3.5 Pressure Suppression System Code CORAN

The CORAN - (Containment Response Analysis) code has been developed /5.22/ and improved /5.23, 5.24/ by GKSS to predict LOCA related loads. The code calculates:

-- the p,T- histories in compartments for the short and long term periods

-- vent clearing

-- pool swell (symmetric)

-- air carry over through the pool.
The basic concept is:

-- lumped parameter model
-- two types of typical nodes (drywell and wetwell)
-- subdivision of a compartment is possible
-- thermodynamic equilibrium within the nodes between steam air and water
-- homogeneous mixture within the nodes
-- saturated or superheated conditions
-- thermodynamic equilibrium within wetwell nodes at gas/water interfaces
-- one-dimensional, steady, compressible, homogeneous 2-phase, 2-component flow between the nodes
-- vent clearing model with one dimensional transient fluiddynamics.

The pool model comprises:

-- transient, one dimensional fluiddynamics with cylindrical bubbles
-- simulation of air carry-over through the pool by a bubble rise model
-- instantaneous complete steam condensation within the pool.

Heat transfer to solid structures modelled by:

-- one-dimensional unsteady transfer
-- choice of three geometries of structure (plate, cylinder, sphere)
-- unlimited number of materials per structure including gaps
-- arbitrary number of structures and structure layers
-- heat sources/sinks may be specified per material
-- heat transfer coefficient-correlation based on air/steam concentration (other correlations possible by user applied subroutines)
-- simulation of inner and outer walls and walls between the nodes

Solution of the system of differential equations is by variable order integrators for the numerical solution of ordinary differential equations (VODE, Adams Corrector Predictor).

5.4 Fluid-Structure Interaction Codes

As discussed in Chapter 3, the discharge of safety/relief valves or a severe LOCA event in a BWR triggers complex processes within a pressure suppression system. These originate from dynamics and steam condensation in the large pools of water at the blowdown line or at the vent-pipe exits.

In most containment design evaluations, the dynamic loads arising from these processes are applied as wall loads. These are in some cases computed by a model, which accounts for the fluid by a hydrodynamic mass correction to the equations governing the structural response. Where loads are large and where structural resonances are evident, such uncoupled analyses may not be adequate, or may be overconservative. Then, coupled fluid-structure interaction analyses become necessary.
Several reports are available that describe the development of analytical methods for calculating the loads and the coupled structural response of pressure suppression systems. As examples, the methods applied within the computer codes, PELE-IC /5.25/ and SING-S /5.29/ are briefly described here.

The PELE-IC code couples a two-dimensional, semi-implicit, Eulerian fluid-dynamics (subroutine SOLA) algorithm to a Lagrangian finite element structure dynamics shell algorithm. The PELE-IC code uses a two-phase fluid dynamics model, it can couple to either a one-dimensional or a lumped parameter description of compressible gases. The code is written in both plane and cylindrical co-ordinates, in order to handle a variety of geometrical configurations, and is capable of following large interface motions through the calculational grid. By means of variable time steps it accommodates varying flow conditions and maintains computational stability.

The basic semi-implicit solution algorithm contained in the SOLA subroutine /5.26/ tracks the movement of free surfaces using a full donor-cell treatment based on a combination of void fractions and interface orientations. This provides great versatility to follow surface motion and water-gas interfaces for bubble definition without the use of marker techniques. The structural motion is computed from the applied fluid pressure at the fluid structure interface by a finite element code /5.27/.

The finite-element shell structure algorithm uses conventional thin-shell theory with transverse shear. The spacial discretization employs piece-wise-linear interpolation functions and one-point quadrature to conical frustra, making use of the Newark implicit time integration method implemented as a one step module. The fluid code then uses the structure's resultant position and velocity as boundary conditions. The fluid pressure field and the response of the structure are iterated until the normal velocities of the fluid and structure are equal. This results in a strong coupling between the two algorithms /5.28/.

The early fluid-structure-interaction code verification exercises performed in 1979 with the PELE-IC code indicated the need for a more rational methodology for supplying the loading functions that drive vent clearing, condensation oscillation, and chugging processes. As a result, a vent flow model was developed that coupled the drywell pressure history to the pool by treating compressibility effects (e.g. choked flow) in noncondensable gases. This model improved PELE-IC comparisons with air-blowdown experiments in both rigid and flexible water-filled containers.

Another method for analysing the dynamic stresses in spherical pressure suppression containments during steam condensation was reported in 1981 /5.29/. In their code (SING-S) the fluid dynamics of the water pool are described by a boundary integral equation method. For the structural dynamics of the thin spherical containment shell analytical solutions of Flügge's /5.30/ shell equations are applied. The effect of fluid-structure interaction is considered, because it may increase the loadings significantly in comparison to calculations without this effect. The steam condensation in the water pool is treated as a parametric time function based primarily on experimental observations.
Developmental efforts for the computation of local pressure perturbations associated with stable and unstable steam condensation events have not been undertaken. Instead, artificial pressure-time histories are prescribed to simulate steam bubble behaviour, with no attempt made to examine the heat transfer processes at the bubble surface or the inertial over-expansion of the bubble in the water pool. A modification to this approach, taking into account compressibility of the steam column in the vent pipes, reproduced the same structural frequencies observed in steam-blowdown experiments.

In /5.31/ it is proposed that the steam condensation be modelled empirically by a transient point source located at the exit of the vents. The time history of the volume $V$ fed into the water pool is qualitatively shown in Fig. 5.1. The time $t_p$ denotes one condensation period. During this time the volume grows rather slowly from zero to the maximum $V_0$. Then it collapses very rapidly within the time $t_0$:

$$V(t) = V_0 \left[ 1 - \left( \frac{t}{t_0} \right)^4 \right]^3$$

$0 < t < t_0$

Typical values are:

$t_p = 1 - 2s$, $t_0 = 0.02 - 0.1s$
Due to the sensitivity of the steam condensation process, certain stochastic effects are inevitable. Therefore, the time history in Fig. 5.1 is never exactly periodic. For the dynamic excitation of the system only the high-speed collapse process is important. Consequently, the interaction between steam condensation and the fluid dynamics of the water pool is described in a conservative manner by the above mentioned equation. Several attempts /5.32-5.35/ were made to model steam bubble behaviour under chugging conditions to supply boundary conditions for coupled codes. These models have been assessed, at least partially, by comparison with experimental observations from various test rigs.

The determination of the expansion volume $V_0$ and the collapse time $t_0$ from experiments, still represents a problem. The values obtained show a wide range because of the variability of the steam condensation process. The definition of the most unfavourable collapse to be used for design stress analysis remains a difficult task.

5.5 Code Verification

When assessing a code against experiments it is important to simulate as precisely as possible all parameters relevant to the design basis. Other physical phenomena may be of secondary interest, but they should be described correctly, to verify the ability of a code to predict total system behaviour. In Table 4.1 several of the numerous international pressure suppression system experiments are listed that may be utilised for the assessment of codes.

5.5.1 Assessment of LOCA-Integral Systems Codes

Very extensive assessment work has been performed for the DRASYS code, the COPTA code and the codes developed by the General Electric Company within the frame of the load evaluation and acceptance criteria efforts. The CONCEPT code, particularly version 2B, has also been extensively assessed by the USNRC and through International Standard Problem exercises.

COPTA was tested against the Marviken Full Scale Containment experiments /5.36/. It was also successfully applied to the OECD-CSNI dry containment standard problems CASP 1 /5.37/, and CASP 2 /5.38/, a heat soakage benchmark problem /5.39/, as well as to the pressure suppression standard problem ISP 17 /5.40/.

The code DRASYS was assessed /5.41 and 5.42/ using the following tests and test programs:

- **vent clearing** /5.41, 5.42/
  - Predictions
    - GKSS 3-vent tests M1, M5, M6, M7

- **pool swell** /5.41, 5.43, 5.44/
  - Post-test calculations
    - Marviken BD 17, GKSS-PSS-21
    - GKSS 3-vent VM2, M1, M5, M6, M7, GKM-II-tests 7, 14, 16, 18, 24, 27, 31, 49, JAERI tests 1202, 1203, 1204

- **condensation oscillations** /5.45/
  - Marviken BD 13
integral behaviour P, T
/5.41/ Marviken BD 17, GKSS-PSS-21, GKSS-M1, M7
chugging stage /5.41, 5.46/ GKM-II-Test 21, GKSS-M1

Assessment of the General Electric codes for the Mark I, II and III containments was limited to integral behaviour P, T, vent-clearing and pool-swell /5.47-5.50/. These assessments were performed mainly on the full-scale or near full-scale facilities described in Chapter 4. The codes do not have models for condensation oscillations, or bubble breakthrough. These are modelled empirically.

5.5.2 General Observations from the Work Code Assessment

The assessment of the systems codes yielded several general observations which were common to all involved simulation models. They may be summarised as follows:

5.5.2.1 Pressure and Temperature Histories of Drywell and Wetwell

The nature of the pressure and temperature transient in a pressure suppression system during a blowdown is well understood. There is no fundamental problem in the analytical description for the realistic simulation of these transients. However, the importance of some margins and initial conditions has been underestimated.

The maximum pressures in a pressure suppression system are governed by vent-clearing, vent-flow and gas carry-over in the short term, and by energy transfer in the long-term. Thus, its behaviour is somewhat different to that of a full pressure containment. The maximum pressure build-up does not necessarily coincide with the end of blowdown, but may occur at an earlier stage (less than 40 s after the occurrence of a large break). Due to its effect upon gas carryover, drywell nodalisation may influence the results of the containment pressurisation calculations in restricted drywell geometries.

For the assessment of gas carryover into the wetwell, and of the distribution of the remaining gas within a multi-compartmented drywell, Marviken tests have proved highly suitable. Within the wetwell free space, it has to be clarified whether a layer-type temperature distribution occurs resulting in a different medium temperature and thus a different pressure than calculated with a homogeneous model.

The ability of various codes to simulate the long-term behaviour of a pressure suppression system has been confirmed. A lot of post-test calculations yielded good results. For further assessment work it may be worthwhile to:

-- perform additional post-test calculations of experiments from different test programs;
-- consider temperature layers in the wetwell free-space;
-- improve the energy transfer from the water into the wetwell free-space;
-- improve the energy balance for the quasi-stationary motion of the steam/water interface in the pool.
5.5.2.2 Vent Clearing

The relevant phenomena during vent clearing are understood and can be adequately described by applying one-dimensional models in the codes. Three-dimensional effects, such as Taylor instabilities and the detailed formation of the gas/water interface, are not significant. Typically, the one-dimensional models provide predictions with the following accuracy:

-- vent clearing time (-5 per cent)
-- maximum pressure difference (+5 per cent)
-- maximum dynamic pressure (+15 per cent).

These are within the limits of measurement accuracy.

Further support for the one-dimensional approach is provided by data from the 7-vent JAERI test facility. Vent clearing proceeded almost synchronously (±10 ms).

Due to the achieved model qualification and the relevance of the loads of interest, only points of minor importance remain for further examination:

-- examination of the models for the accelerated additional water mass in the pool from tests with wide and narrow pools;
-- pressure distribution in the vent clearing jet.

5.5.2.3 Pool-swell

The phenomenology of pool swell and its related effects are well understood. To reproduce the phenomena in a facility, or to predict them adequately, requires some care.

In order to evaluate by experiment the three-dimensional behaviour of pool swell as found in a real containment, certain requirements are necessary:

-- the three-dimensional variations of the pool system must not be obstructed by a narrow geometry in the test facility,
-- the unrestricted motion of the pool surface in the vertical direction must be representative of that in a real containment,
-- the pressure transient and the maximum driving pressure must correspond to those expected in the power plant.

The capabilities of a pool swell model may be examined by tests that do not necessarily meet these requirements. Generally, precise knowledge of the following parameters affecting vent flow and pool-bubble formation is essential:

-- the initial gas mass in the drywell and the pool temperature. A representative medium temperature, a representative pressure and the initial relative humidity have to be carefully assessed;
-- the coefficient of fluid resistance of the vent pipes and the drag coefficient of the vent pipe inlet are important compared to other influences. They strongly affect the compression of the wetwell free space and the minimum pressure difference between drywell and wetwell;

-- the horizontal bubble expansion radius in connection with the one-dimensional modelling of pool swell. This empirical parameter represents an unsatisfactory approach, since it has a strong influence on the calculated results;

-- separate effects occurring during pool swell, such as bubble generation, steam condensation within the bubble, Taylor instabilities, gas breakthrough and gas carryover are impossible to predict reliably and are difficult to measure. The strong influence of steam condensation has been demonstrated analytically /4.71/.

By adjusting the bubble radius, good agreement with measured results can be achieved. Conservative predictions, particularly for the wetwell pressure, swell level and velocity are possible. Best estimate predictions can only be made in cases where the pool bubble behaviour is well-defined.

Due to the complex character of pool swell and the interaction of the correlations involved in its prediction, the correlation of physical events, such as the minimum pressure difference to a single parameter, e.g. drywell volume per vent pipe, may be misleading.

Improvements in the following areas are desirable for best-estimate predictions:

-- a bubble radial expansion model, to provide a representative horizontal radius for the one-dimensional analyses;

-- a description of condensation in the pool swell bubble, possibly by introducing a type of boundary layer capable of storing heat;

-- drywell gas carryover;

-- gas breakthrough.

5.5.2.4 Chugging

None of the computer codes, except DRASYS, has the capability to analyse condensation phenomena occurring in pressure suppression systems. The subroutine KSWING V does present a chugging model, but a series of questions remains to be answered. A more detailed evaluation of the GKSS experimental data may close the gaps in knowledge.

The chugging model in KSWING V is based upon the "lumped-parameter" concept. It represents the thermodynamic instabilities at the initiation of an external bubble collapse and spontaneous condensation at one vent pipe.

The resulting hydrodynamic instabilities are described parametrically. Despite a series of simplifying assumptions, qualitative and even quantitative agreement with experimental results has been achieved. The model was assessed against the GKSS 3-vent-test M1, GKM-II test 21 and the GKSS 1-vent and 2-vent-tests.
Parameter and sensitivity studies demonstrate that:

-- the tendencies and dependencies of the system parameters found by experiment were essentially reproduced by the model KSWING-V;

-- the model KSWING-V, when related to the reference case GKSS-M1, yielded numerically stable results for a wide range of parameters, such as pool temperature, drywell and wetwell pressure and geometry;

-- the model parameters had a small influence on the calculated result.

The frequency of chugging initiation and the resulting mean pressure fluctuations in the drywell, vent pipe and wetwell free space can be predicted. The determination of the chugging amplitudes still requires improvement.

Not included in this chugging model are:

-- an analytical description of the so-called internal chug;

-- a module for the computation of fluid structure interactions.

The internal chug arises from the formation of a steam torus during the backflow of water into the vent pipe. The collapse of the steam torus inside the vent pipe results in higher pressure spikes than those from an external chug. To simulate the internal chug further analysis development is necessary. With regard to fluid-structure coupling, KSWING-V can basically serve as a so-called source term for such calculations. The fluid-structure calculations have of necessity a field-equation character. In that case no feedback coupling between the fluid-structure analysis and the chugging analysis is possible. This feedback is not essential in large suppression pools.

5.5.3 Fluid-Structure Interaction Code Assessment

There is very little available literature on successful and generally valid verification of fluid-structure interaction codes. Information was found on the assessment of the PELE-IC codes, based on a number of 1/5-scaled Lawrence Livermore Laboratory tests for the Mark I torus pressure suppression system, and on a certain number of proprietary GE chugging experiments on the 4T facility. Some results of the reanalysis efforts were reported in /5.25 and 5.28/.

From the analysis of the 1/5-scaled torus experiments it was concluded that three-dimensional vent clearing and pool swell hydrodynamics may be successfully calculated with two-dimensional models by proper consideration of two effects:

(i) the geometric decay of fluid velocity near the downcomer for 2-dimensional plane or axisymmetric calculations, and

(ii) the ratio of the initial fluid mass in the downcomer to the total fluid mass in a tributary volume of the torus.
Two-dimensional models can be substantially in error on both counts, because of the out-of-plane restraint against fluid motion and because of downcomers being treated as long channels.

Axisymmetric models with downcomers on the axis, or with downcomers treated as equivalent annuli, proved to be successful in analysing vent clearing times and peak bottom center pressures. As a result, it was suggested that a combination of two-dimensional (early time) and three-dimensional (structural response time) fluid-structure analyses could accurately and economically provide vent clearing and pool swell evaluations without recourse to a fully-coupled, three-dimensional, treatment. It has been shown that uploads are neither dependent on the stiffness of the torus shell nor on the stiffness of the supports, but are a consequence of wetwell liquid being accelerated vertically by the growing LOCA gas bubble. Wetwell structural geometry can control upload magnitudes. The greatest limitation of PELE-IC when performing Mark I analyses was the code's inability to calculate three-dimensional fluid-structure problems. On the other hand, great care must be taken in attempting to substitute for PELE-IC other computational devices (e.g., acoustic models) which may be able to treat the three-dimensional aspects of the problem but at the expense of neglecting bubble dynamics and other non-linear fluid phenomena. Such phenomena control both the download and upload histories.

From the reanalyses of the GE tests on the 4T facility, it is interesting to note that most conclusions and recommendations are related strictly to the structural properties of the test rig.

It was observed that the fluid-structure interaction for the 4T tank is seen by the reduction of the frequency of the dry 4T cylinder from about 800 Hz to 63 Hz, and the frequency of the bottom plate from about 190 Hz to 39 Hz. This reduction in frequency was demonstrated using an incompressible representation of the wetwell liquid. Liquid (wetwell) compressibility effects, introduced through entrainment of noncondensables, have a potential for a significant reduction of the effective liquid wave speed. Such compressibility effects can reduce the computed incompressible fluid-structure frequencies even more.

As expected, the 4T system was found to be sensitive to downcomer vent acoustic effects and to the prescribed vent exit pressure-forcing functions. The reason for this sensitivity is that the reflected acoustic pressure pulse traversing the downcomer has a strong frequency component only slightly below the dominant fluid-structure natural frequency of the 4T system. Shortening the 4T downcomer to a prototypical Mark II length, and decreasing the 50-to-55 ms duration of the pressure source, produces a near resonant condition in the 20-to-30 Hz range when wetwell liquid compressibility effects are included in the calculations.

Because of the system sensitivity to this resonant or potentially near resonant condition, it was concluded from the reanalysis of the experiments that the envelope of experimental response spectra obtained from 4T tests is heavily influenced by the particular 4T system characteristics: downcomer length, thickness and radius, entrained noncondensables and all the other Mark II non-scaleable parameters. Therefore, the use of such an envelope response spectra may not necessarily be conservative unless near prototypical
test configurations and conditions are obtained. Further work on a more
generic, mechanistically derived source function for condensation events is
recommended in /5.25/ to reduce the existing uncertainty about the Fourier
spectra of the driving source functions. These quantitative findings should
not be generalised, but they may be considered as indicative of the
sensitivity of the integral behaviour of the coupled fluid-structure system to
the specific properties of the test rigs as well as to the prototype structure.

A more recent attempt to develop a source function is described in
publication /5.51/. The model was verified against some UCLA and GKSS
chugging experiments. The authors demonstrated the complexity associated with
the analytical simulation of the chugging source function driving the
fluid-structure interaction. The care needed to predict the collapse
mechanisms, through proper characterisation of the vapour-liquid interface,
was emphasised. Along with the dependence on system thermodynamics and
transport properties, the validity of the computed chugging source function
was found to depend upon the spatial resolution required to model the unstable
interface and the resulting calculated maximum vapour region volumetric
growth. It is this system dependent maximum growth which determines the
initial conditions for subsequent calculations of the rarefaction pressure
pulse and the resulting containment loading.

Great efforts to simulate chugging events on a probabilistic basis were
undertaken by EPRI, the results are described in /5.52/. Based on an earlier,
purely deterministic approach /5.53/, probabilistic methods have been
introduced to simulate the randomness of condensation events. The approach
was developed, calibrated and tested against small-scale experimental test
data (vent diameter 4-10 cm). The main intent is to understand the basic
mechanisms and to assess their relative importance in connection with the
empirical evidence from the experiments. Additional efforts to generalise the
empiricism obtained from these studies for full-size prototype BWR application
are recommended by the authors.

5.5.4 The International Standard Problem (ISP) 17

A proposal made by Sweden for a standard problem based on one of the 25
Marviken full-scale containment experiments /5.54/ was approved as a candidate
for ISP-17 by the CSNI Principal Working Group No. 2 in October 1982. The
test No. 18 was finally chosen for the standard problem, to be performed as an
"open" exercise, i.e. the participants were requested to reanalyse known test
results. The specification /5.55/ for ISP-17 was distributed in June 1983 and
a workshop related to the standard problem was held at Marviken on August 18,
1983.

The standard problem exercise covered the integral hydraulic portion of
the experiment. Dynamic oscillations caused by condensation phenomena were
not addressed because, in general, containment codes are not capable of
handling these phenomena. Also, uncertainties existed with respect to
thermalhydraulic boundary conditions within the vent pipes during the
oscillatory period of the experiment.
Submittals were obtained from four participants: ECN (Energy Research Centre, Netherlands), University of Pisa (Italy), VTT (Technical Research Centre, Finland) and STUDSVIK (Sweden). Italy and Sweden contributed two different submittals each, so altogether there were six results submitted, together with some additional parametric studies from Italy, Finland and Sweden.

The aim was to reanalyse, as realistically as possible, the time histories measured in the experiment: pressure, temperatures, masses in the containment compartments and the pressure differentials between the containment compartments.

The codes used for the submittals were: ARIANNA-1 (Italy), CONTEMPT-LT/26 (Italy), CONTEMPT-LT/28 (Finland), COPTA-7 (Sweden), and ZOCO-V (Netherlands).

ARIANNA-1 was the only dry containment code participating, and as such could produce sensible results for the time to the vent clearing only, which occurred around 1.4 s after the start of blowdown. This run was valuable since the many drywell nodes (17 compared to 4 or 1 for the other codes) supplied detailed information on drywell pressure differences and flow paths.

All the other codes had wetwell models and could produce integral results for the whole blowdown period. Two of these codes (COPTA and ZOCO) allow subdivision of the drywell into a fairly large (around 10) number of subcompartments, the two CONTEMPT versions did not have that possibility.

The following summarises the results and findings of this ISP exercise as presented in /5.40/.

The evaluation of the results was split into two different timeframes, short-time cases covering the first 4.4 s (0-1.4 s for the ARIANNA-1 code), and long-time cases covering the period 0-220 s (0-75 s for the ZOCO-V code).

For the short-time cases the most important parameters are differential pressures, the vent clearing transient and the pool-swell phenomena. The differential pressure between drywell and wetwell, as well as the vent clearing transient were predicted quite well by most of the codes. The differential pressures within the subcompartmented drywell were fairly well described by those codes having this capability (ARIANNA-1, COPTA-7 and ZOCO-V).

Only two of the codes, COPTA-7 and ZOCO-V, performed pool swell analyses. These gave a roughly correct prediction of the pool swell integral behaviour.

In the long-time cases, the parameter of main interest was the pressure build-up. This is influenced by mass transport to the wetwell, by heat-up of the pool and by heat soakage into solid structures such as the concrete confines and the large number of metal structures inside the containment. The pressure levels after roughly 50 s were to a large extent controlled by the total mass of air transported from the drywell to the wetwell through the vent pipes. Most participants used knowledge of measured air flow rates. One of the submittals (ZOCO-V) tried to avoid this by using a 4-compartment subdivision of the drywell throughout the transient. Italy ran ARIANNA and CONTEMPT successively, transferring wetwell pressure from CONTEMPT to ARIANNA and vent flow composition from ARIANNA to CONTEMPT.
On the whole, the modelling procedures were found to be satisfactory, and useful experience was obtained.

Differences in analytical approach, which varied from licensing to best-estimate assumptions, and system representation, which varied from many to a small number of compartments, served to illustrate the relative importance of various parameters in the models.

The following observations were made:

-- In view of the accuracy of the measurements, the calculated drywell pressures, the differential pressures in the drywell and the drywell-to-wetwell differential pressures agreed well with the experimental data.

-- Drywell temperatures were well described by the analyses. The wetwell airspace temperature history was well reanalysed when the airspace was modelled explicitly.

-- The time to vent clearing was somewhat underestimated, but in reasonable agreement with data.

-- Good simulation of vent flow composition into the suppression pool is important for obtaining good results.

-- Heat transfer to drywell heat sinks was underpredicted in most submittals due to the low heat transfer coefficients applied. Experimental data show that heat conduction in the material soon becomes the governing phenomenon.

-- In general, the use of a small number of sub-volumes in the drywell gave adequate results. More volumes improved the results for the rather complex Marviken geometry.

In areas where differences existed between data and calculations, the reasons for the differences were understood. The participants concluded that the modelling capabilities in the area covered by the exercise are sufficiently accurate for adequate safety evaluation of a containment design, and that a further open exercise of this nature is not required.

It was however noted that some phenomena which could be of importance in pressure suppression systems were outside the scope of the ISP-17 exercise. These include, for example, phenomena associated with pool swell loadings, extremely long-time containment behaviour, condensation-induced periodic oscillations and chugging and thermalhydraulic events of sequences beyond design basis accidents.
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- 109 -
6. CONCLUSIONS AND RECOMMENDATIONS

In this chapter an attempt is made to relate the research and design objectives of pressure suppression containment systems to the current state-of-the-art. Preceding chapters also contain observations and conclusions on the various topics discussed. Where relevant, particularly important points are repeated here.

The primary function of a containment is to prevent release of radioactivity to the environment. Containment designers have focussed on providing a leak-tight barrier during loss-of-coolant accidents, as well as during reactor transients involving a loss of the main heat sink. This report has dealt with processes which may occur during the spectrum of such design basis LOCA and transient scenarios. Beyond design basis situations, for example, involving core-meltdowns, have not been discussed.

Pressure suppression, by condensing in a large heat sink the steam released during an accident, considerably reduces the required containment pressure times volume compared to dry containments. Because of their compact designs, modern boiling water reactors are well suited to this concept. However, the benefits of pressure suppression are offset by the complexity of the phenomena involved. Penalties have been paid in terms of the development of new or modified designs, which reflected improved understanding of pressure suppression phenomena, the ensuing increase in requirements and the need for economical solutions in compliance with these requirements.

Pressure suppression systems differ in design and much developmental effort has been devoted to verification of these designs. Experiments have been carried out at various scales, the complexity of the processes often requiring full or near full-scale testing. Experimental data have also been used for the validation of analytical models built into computer codes. Much effort has been devoted to the development of such computer codes. The codes are used to help understand the observed results and to predict the behaviour of real systems. They aid in the translation of experimental results, which may suffer from atypicalities, into evidence valid for actual designs.

An overall objective of the experimental and analytical investigations is to verify that sufficient, but not excessive margins exist against failure of structures and components. Acceptable safety margins are largely controlled by how well loads and margins can be predicted and with what confidence.

Predictive capabilities very between phenomena and from application to application. Differences in the level of understanding are clearly dependent on the nature of the phenomena involved. For example, quasi-static processes, which occur during the immediate post-LOCA containment pressurisation as well as over the long-term, are generally adequately predictable. For the period immediately following a break, such processes include the drywell pressurisation, flow between drywell subcomponents and from drywell to wetwell, vent clearing dynamics and wetwell gas space compression. Important processes for the long term behaviour are flow composition and flow rate between drywell and wetwell, heat transfer to structures, temperature history of the wetwell pool, spray cooling, leaks between drywell and wetwell and the influence of vacuum breakers.
Phenomena associated with the immediate pressurisation and the long-term quasi-static behaviour of a containment are sufficiently well understood to allow basic design and licensing predictions, addressing these topics, to be made with some confidence. This does not mean that every detail involved is predictable, but rather that sufficient knowledge exists about the sensitivity of the parameters to be able to choose prudent upper bound parameter values and models, which generate conservative results with acceptable and definable safety margins. Qualitative comparisons of predictions with large-scale data indicate that many of the simplifications and idealisations normally applied in analytical modelling have the effect of giving conservative results.

In summary, the analysis codes describing overall containment behaviour are sufficiently developed and assessed, and are adequate for design purposes. Further activities in this area could be motivated by the need to maintain a basic competence on how to use the analysis codes and how to evaluate the calculated results.

On the other hand, processes which are dominated by rapid dynamic phenomena are less well understood. Examples of such processes are pool swell and the dynamics of steam condensation in the suppression pool. Predictions of pool swell behaviour generally have large uncertainties because of the difficulties involved in predicting bubble-size and break-through. The one-dimensional analyses often employed need empirical information about these parameters.

Unsteady condensation phenomena in the suppression pool, both during a LOCA and during safety/relief valve discharge, are a source of complex dynamic loads acting on wetwell structures. They were first encountered during safety/relief valve blowdowns where, in several events, loadings were excessive. Quenchers have been installed on safety relief valve lines in nearly all plants. These have largely eliminated concerns about unstable condensation. Although a great deal of progress has been made in the analytical modelling of safety/relief valve line-clearing, both safety/relief valve and LOCA condensation loads remain almost wholly empirical.

Most of the research on unsteady condensation has been devoted to anticipated behaviour during a LOCA. Research has categorised the condensation phenomena into condensation modes: condensation oscillations, chugging, transition, etc. These appear as regions on a condensation mode diagram, having suppression pool average temperature and vent steam mass flux as independent variables. Mode boundaries are by no means well defined on such a diagram.

Condensation oscillations have been investigated experimentally in many containment geometries. At high and medium steam mass fluxes the condensation processes give rise to acoustic waves, which correlate with vent length or with overall containment geometry. Potential oscillation frequencies can be predicted, but analytical methods are not sufficiently developed to predict amplitudes with confidence.

Chugging may occur at low steam flow rates. The steam flow from the drywell is not high enough to sustain the phase boundary, which quickly withdraws into the vent pipe. Eventual expulsion gives rise to rapid condensation. Chugging produces large pressure pulses in the wetwell pool.
followed by damped oscillations at high frequencies. Chugging occurs in a stochastic manner. Favourable conditions for formation of chugs have been identified, but the determination of amplitudes and the stochastic behaviour are empirically based. Successful chug mitigators have been tested in part based on visualisation of the flow processes involved.

A phenomenon similar to chugging, referred to as condensation "pressure spikes", was observed in the Marviken facility at high steam flow rates. This has not been experienced elsewhere and may need further clarification.

Loads exerted by condensation induced pressure pulses do not challenge overall containment integrity. However, local loads may be high and should always be assessed. The main difficulty is their determination as a function of space and time with confidence.

In some situations, fluid structure interaction analyses may be necessary to analyse adequately containment structural response to condensation or other dynamic loads. Accurate load specifications, or source terms, are then mandatory if realistic responses are desired. Fluid structure interaction analysis rests on well established formulations of basic equations, but a need remains for full-scale experimental data to validate current codes.

Although most research on pressure suppression containment behaviour has addressed dynamic condensation effects, with appreciable progress as far as understanding the mechanisms is concerned, the ability to predict these phenomena in a general manner is limited. The reasons for this are partly that the available data base often contains contradictory information, for example, on the functional dependence of important parameters such as pool temperature gradients and gas content of the vent flow. In addition, the data base usually contains information which is strongly facility dependent and which has been obtained with limited measurement techniques or which may have been incorrectly interpreted. Another major barrier is that such information is seldom published in sufficient detail, or is often retained as proprietary information.

It is recommended that the data base for condensation phenomena, consisting of data from many facilities, be subjected to a thorough technical review. The objective of the review should be to generate a standard data base, which would support the current, empirically based calculation procedures, or provide some foundations for assessing new analytical tools as these become available.

The state-of-the-art in pressure suppression systems may be summarised by the following example. Assuming that we were required to-day to assess a completely new pressure suppression design, we would recommend that the overall design be verified using existing analysis codes, which we have judged to be adequate for design purposes. We would further recommend that designs in which pool swell or dynamic condensation effects play a decisive role should be avoided. If this is not possible, experimental verification, either from relevant parts of the existing data base or from new experiments, would be required.

- 112 -