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ANALYTICAL STUDIES RELATED TO INDIAN PHWR CONTAINMENT SYSTEM PERFORMANCE

S.K. HAWARE, S.G. MARKANDEYA, A.K. GHOSH,
H.S. KUSHWAHA, V. VENKAT RAJ
Reactor Design and Development Group,
Bhabha Atomic Research Centre,
Trombay, Mumbai,
India

Abstract

Build-up of pressure in a multi-compartment containment after a postulated accident, the growth, transportation and removal of aerosols in the containment are complex processes of vital importance in deciding the source term. The release of hydrogen and its combustion increases the overpressure.

In order to analyse these complex processes and to enable proper estimation of the source term, well tested analytical tools are necessary. This paper gives a detailed account of the analytical tools developed/adapted for PSA level 2 studies.

1.0 INTRODUCTION

The Indian Pressurised Heavy Water Reactor (PHWR) is provided with a suppression pool type of containment designed to withstand the consequences of the loss of coolant accident (LOCA) and the main steam line break accident (MSLBA). In the event of a postulated accident, the steam flashes into the containment, leading to pressure build-up. In case of a severe accident, radioactive aerosols may be released into the containment. There is also a possibility that due to metal-water reaction, hydrogen may be generated and released into the containment.

In order to analyse the performance of the containment system under accident conditions, a programme of analytical and experimental studies is being pursued at the Bhabha Atomic Research Centre. As a part of this programme, the Containment Transient Analysis code CONTRAN has been developed to analyse the pressure and temperature transients in containment, following LOCA and MSLBA. For the analysis of hydrogen mitigation phenomena in the containment using catalytic recombiners, the code HYRECAT has been developed. To analyse the complex processes of transport, growth, deposition and removal of aerosols within the containment the code NAUA/MOD5 has been adapted. For analysing the aerosol scrubbing behaviour of the suppression pool, the code SPARC has been adapted after incorporating suitable modifications.

A detailed account of the development, validation and adaption of the analytical tools for the analysis of the containment response following an accident is presented in the following sections.

2.0 THE CONTAINMENT OF INDIAN PHWRs

The PHWRs of standardised design in India use a double containment (Fig.1), the inner (primary) containment being made of prestressed concrete and the outer (secondary) containment being made of reinforced concrete. The annular gap between the two containments is maintained under partial vacuum to prevent leakage from within to the atmosphere. The primary containment can be further subdivided into two accident based volumes called V1 (drywell) and V2 (wetwell). These two volumes are interconnected by the vent system via the vapour suppression pool. The vapour suppression pool, which passively absorbs energy released during LOCA, also helps in the scrubbing of a part of fission products released, if any, in the event of accidents leading to core damage.

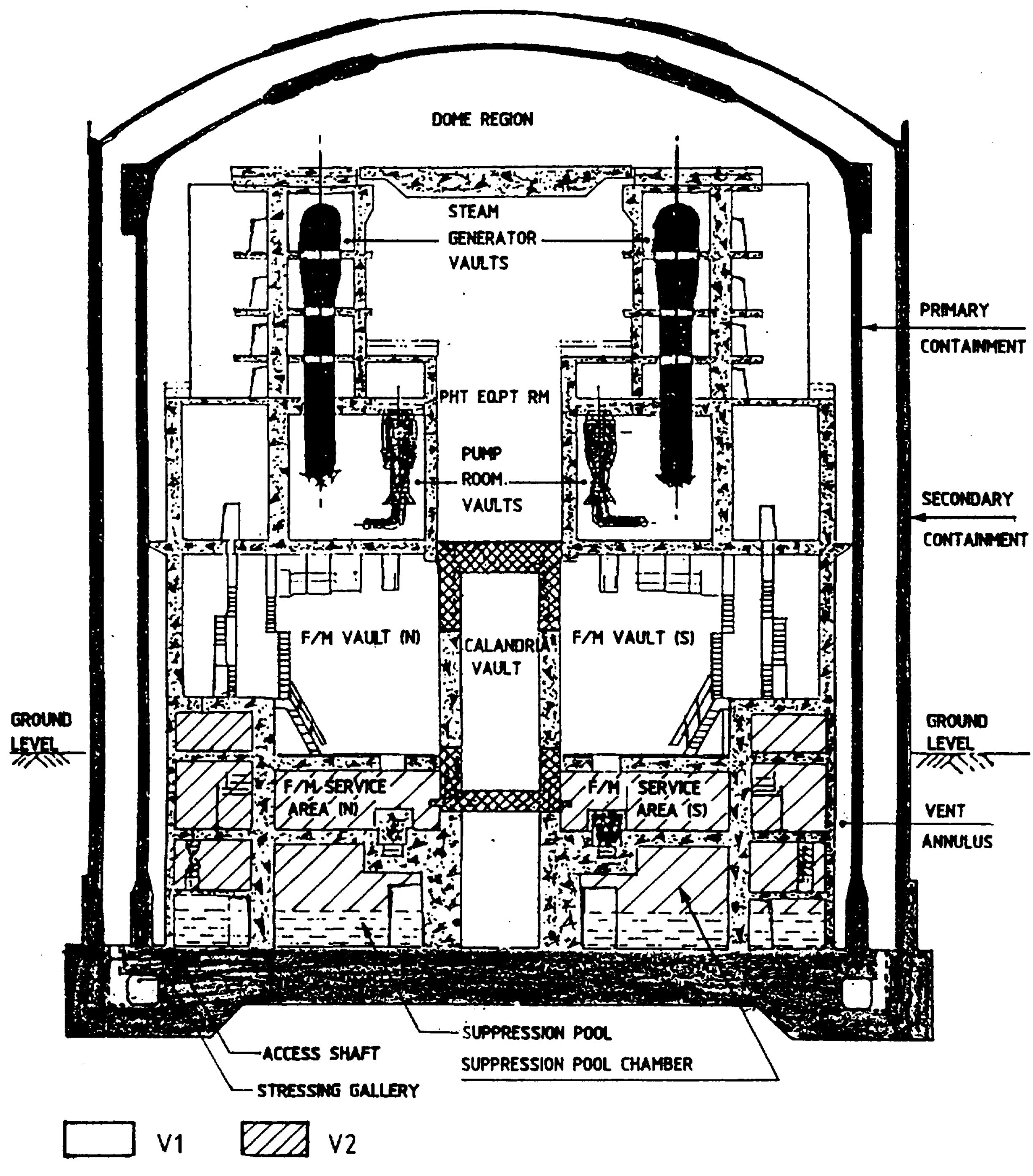


Fig.1: Typical Cross-Section of 220 MWe Indian PHWR Containment Building

3.0 CONTAINMENT SYSTEM PERFORMANCE STUDIES

The source term for the environment depends among other factors, upon the integrated over-pressure in the containment, the air-borne concentration and characteristics of the aerosols released into the containment and the leak tightness performance of the containment. The containment overpressure could be due to a LOCA or MSLBA. Release of hydrogen and its combustion could also result in further pressurisation. Various natural processes such as heat absorption by the containment structure help in reducing the containment overpressure and aerosol decay and deposition processes help in reducing the air-borne aerosol concentration in the containment, thereby reducing the source term for the environment. In addition, different engineered safety features employed in the plant help in mitigating the consequences of the accident. To analyse these complex processes and to enable proper estimation of the source term, well tested analytical tools are necessary. These tools are either specifically developed or suitably adapted for the specific reactor system and satisfactorily validated. Sensitivity analysis is required to be carried out to quantify the influence of various factors on the containment design parameters. Such validated and well tested computer codes could then be used to analyse and improve the performance of the containment system.

4.0 ANALYTICAL STUDIES ON CONTAINMENT BEHAVIOUR

4.1 CONTAINMENT THERMAL-HYDRAULIC TRANSIENT ANALYSIS

The CONtainment TRansient ANalysis code CONTRAN has been developed to analyse the pressure and temperature transients in the containment, following LOCA and MSLBA. The code has been extensively validated against data from in-house and other experiments. A large number of analyses have been carried out using the code CONTRAN for Indian PHWRs.

4.1.1 Computer code CONTRAN

The multi-compartment containment geometry is modelled in the code by a network of volumes interconnected by junctions. The detailed formulation of the code is described in Ref. [1]. Salient features of the code CONTRAN are as follows:

1. Consideration of various heat sinks and heat transfer processes.

2. Vent clearing transient model for vapour suppression pool based on 1-D momentum equation [2].

3. Differential pressure driven hydrogen transportation model.

4. Hydrogen combustion model based on Adiabatic Isochoric Complete Combustion (AICC) of hydrogen.

4.1.1. Validation of the code CONTRAN

The code has been extensively validated using the test data from various sources as described below.

a. One-Tenth Scale Vapour Suppression Pool Containment Experimental (VSPE) Facility, Kalpakkam, India

The experimental facility (Fig. 2) at Kalpakkam, (India) is a one-tenth scale model of the vapour suppression pool type multi-compartment Indian PHWR containment. A large number of tests with blowdown from a PHT system model were carried out in this test facility to study the influence of various governing parameters on containment behaviour [3,4,5]. One such typical result showing comparison between code predictions and the experimental data in respect of pressure transients in V1 (drywell) and V2 (wetwell) for the test M4LO [1] is shown in Fig.3. The designated test was performed to simulate a large break LOCA in MAPS (Madras Atomic Power Station) reactor.

It can be seen from Fig. 3 that the first pressure peak of 121 kPa, corresponding to pressure buildup in the fueling machine vault till the rupture of blowout panel has been predicted correctly. The subsequent pressure transients and the value of the second pressure peak of 116 kPa (due to pressurisation of V1 until vent clearing) seem to be on the conservative side with respect to the test data. The comparison of CONTRAN predictions with data from other tests are also of similar nature and are generally found to be satisfactory.

b. Battelle Frankfurt Containment (BFC) Test Facility, Germany

The Battelle Frankfurt Containment (BFC) test facility in Germany (Fig. 4), is a one-fourth scale model concrete containment with a total free volume of about 580 cu. m. [6]. The

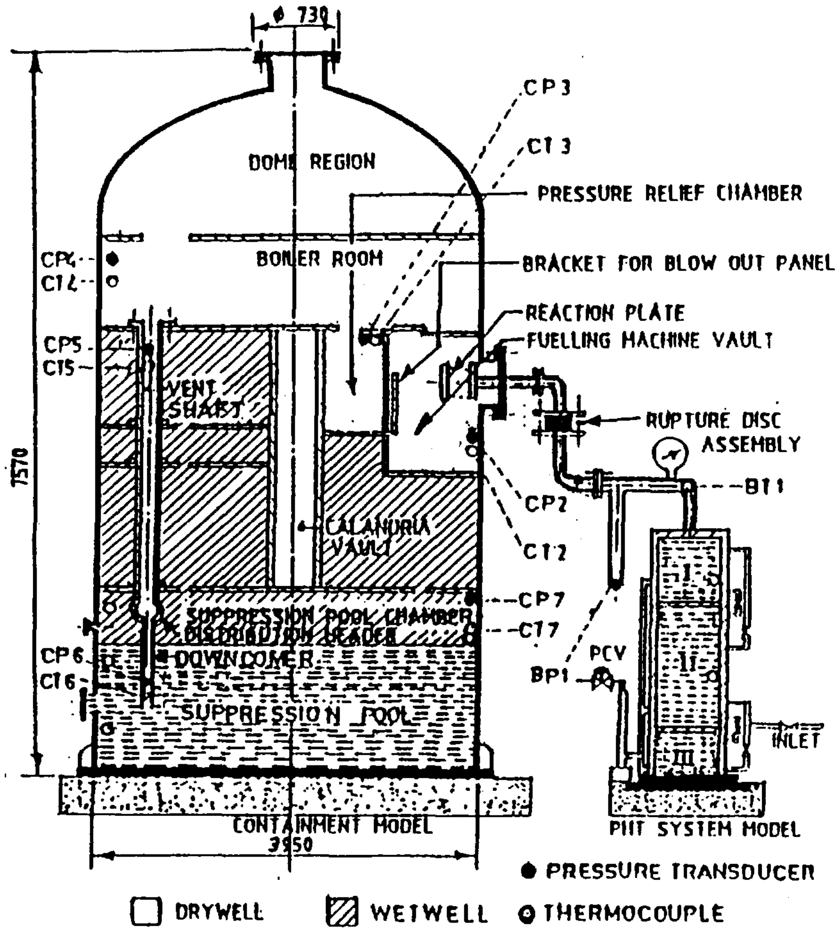


Fig. 2: One-Tenth Scale Vapour Suppression Pool Containment Experimental (VSPE) Facility

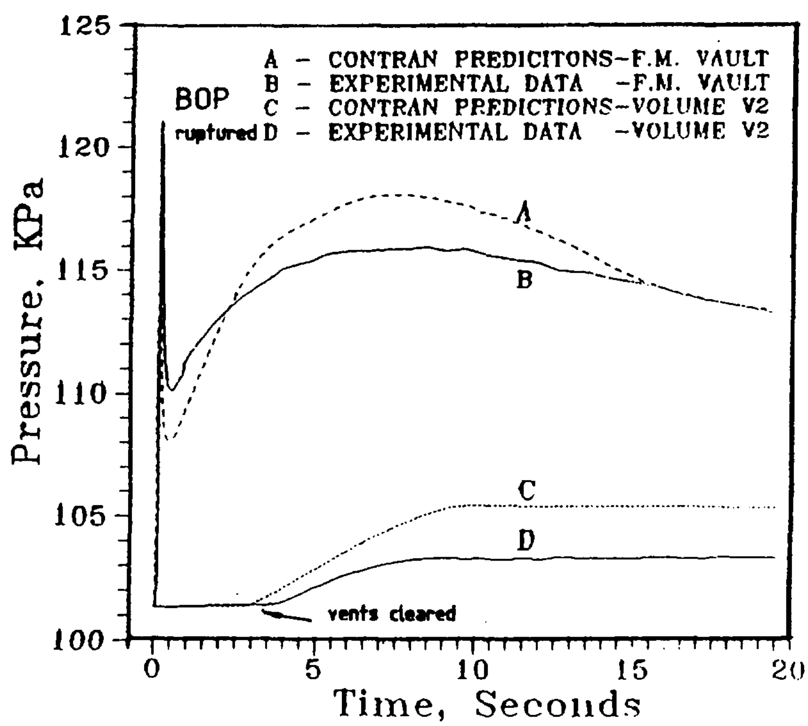


Fig. 3: Pressure Transients in V1 and V2 for Test M4L0 in One-Tenth Scale Vapour Suppression pool Containment Experimental Facility

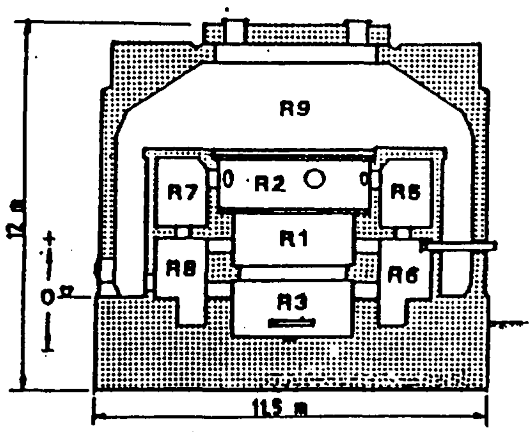


Fig. 4 ONE-FOURTH SCALE BATTELLE FRANKFURT CONTAINMENT MODEL (BFC)

containment model has several compartments with a provision to select different multi-compartment configurations. Validation of the code CONTRAN has been successfully carried out [7,1] using the data from the two blowdown tests designated as BFC Test-D1 and BFC Test-D15 [8]. The code validation results for the Test-D15 are presented in Fig.5.

The Test-D15 involved blowdown of saturated steam for 2.92 seconds from 69.8 bar in room R6 (Break Compartment). The results comparing the CONTRAN predicted pressure transients in the break compartment R6 with the test data up to 2.5 seconds are shown in Fig.5a. The corresponding predictions of COBRA-NC for this test, reported earlier [8], are also shown in Fig.5a for comparison. The pressure transients predicted by the code CONTRAN for the other compartments viz. R8, R7, R4 and R9 are compared in Figs.5b-e, with the experimental data and the COBRA-NC code predictions. The CONTRAN predicted pressure transients are observed to be conservative with respect to the test data.

c. CSNI Numerical benchmark Test

The code CONTRAN has also been successfully validated [9] using the data from the numerical benchmark test [10] devised by the Committee on the Safety of Nuclear Installations (CSNI) of OECD. The benchmark exercise was devised to test the containment analysis computer codes for numerical accuracy and convergence errors in the computation of mass and energy conservation for the fluid and in the computation of heat conduction in structural walls.

The benchmark test model, shown schematically in Fig.6, consists of a single fluid volume into which steam and water are injected and from which heat is transferred to a single concrete wall. Based on the semi-infinite solid heat slab with a specified constant heat transfer coefficient on the inner wall surface, analytical solutions were provided to arrive at the transient wall surface temperature, total pressure and steam partial pressure in the containment. The code CONTRAN successfully predicted all the three transients with good agreement. Fig.7 shows the comparison of predicted transients for total containment pressure (Fig.7a), steam pressure in the containment (Fig.7b) and structural wall surface temperature (Fig.7c) with the test data.

4.1.2 Analysis of Indian PHWR Containment using code CONTRAN

Using the code CONTRAN, a large number of analytical case studies have been carried out to estimate the effect of variation of the following parameters on the containment pressure-temperature transients [11].

i. suppression pool bypass area
ii. surface area of the containment structure
iii. heat transfer to the structural members
iv. multi-compartment configuration
v. initial relative humidity in the containment
vi. initial temperature in the containment
vii. loss coefficient of the vent system
viii. integrated mass/energy discharge into the containment

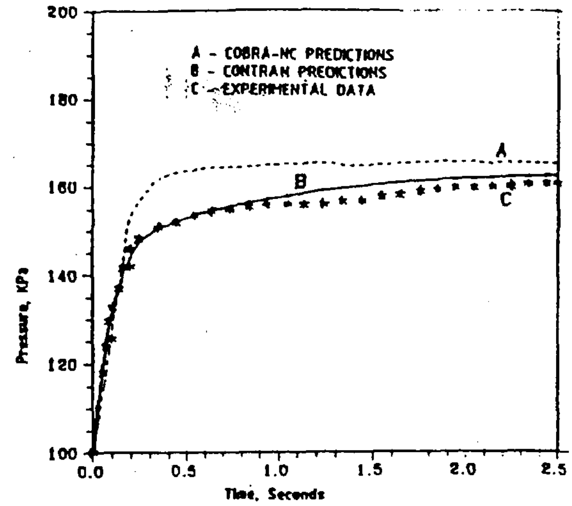


Fig. 5a: Pressure Transients in Room R6 (Break Campartment) for BFC Test D-15

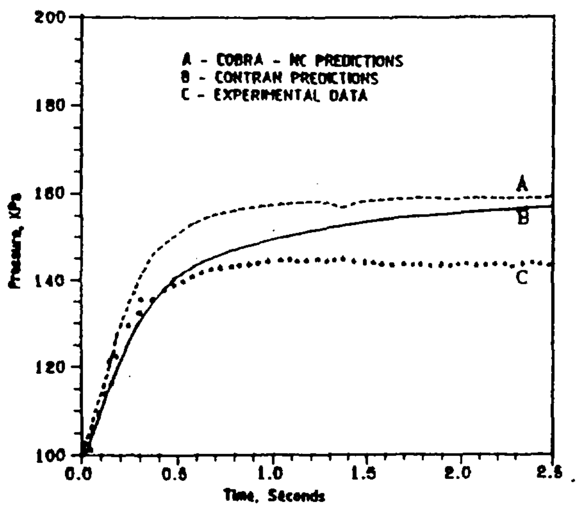


Fig. 5b: Pressure Transients in Room R8 for BFC Test D-15.

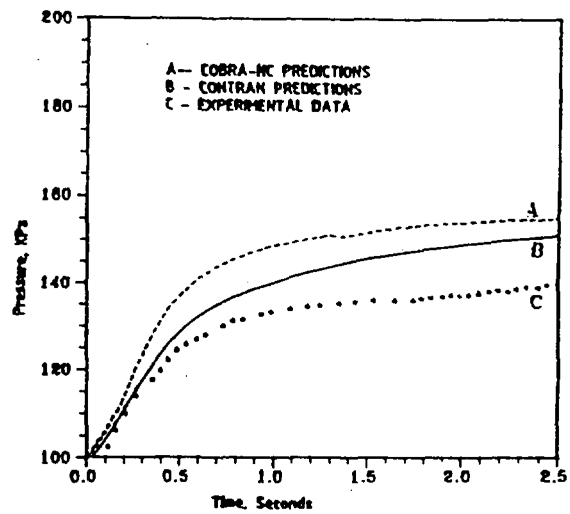


Fig. 5c: Pressure Transients in Room R7 for BFC Test D-15.

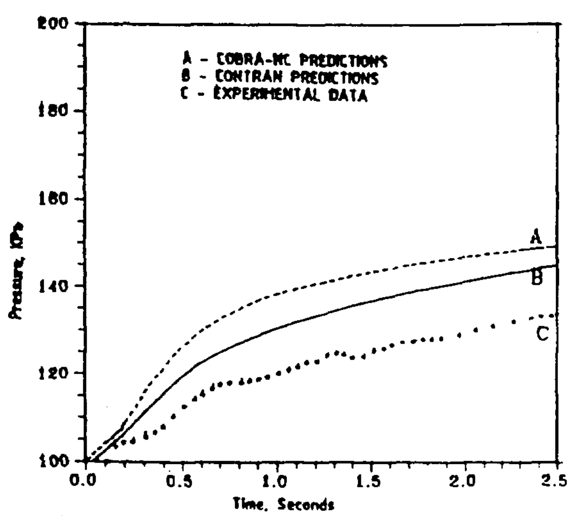


Fig. 5d: Pressure Transients in Room R4 for BFC Test D-15.

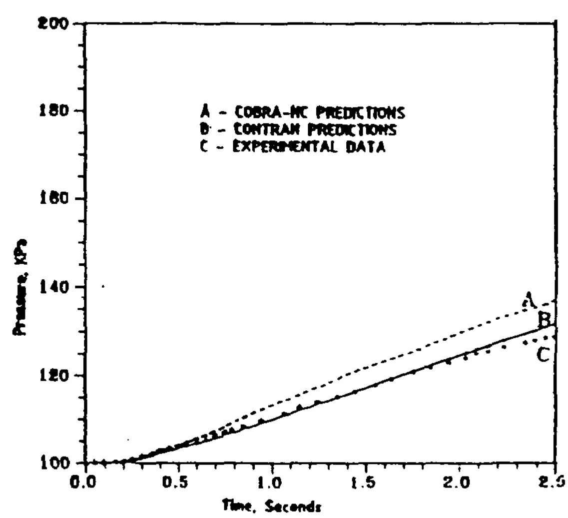


Fig. 5e: Pressure Transients in Room R9 for BFC Test D-15.

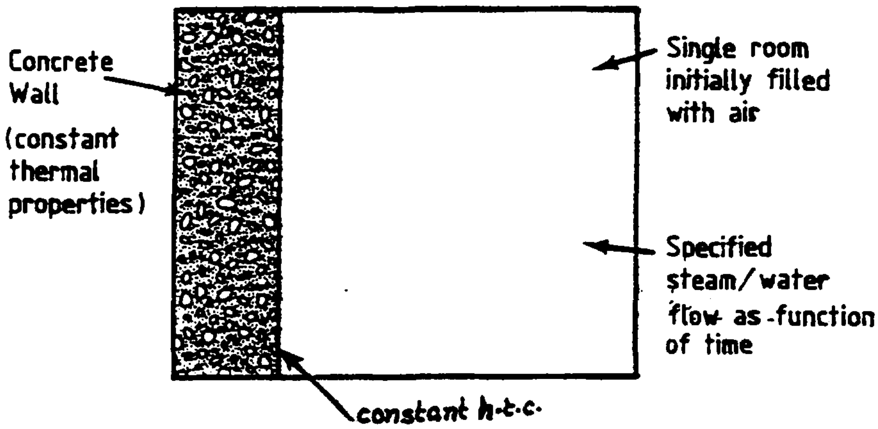


Fig. 6: CSNI Numerical Benchmark Test Model

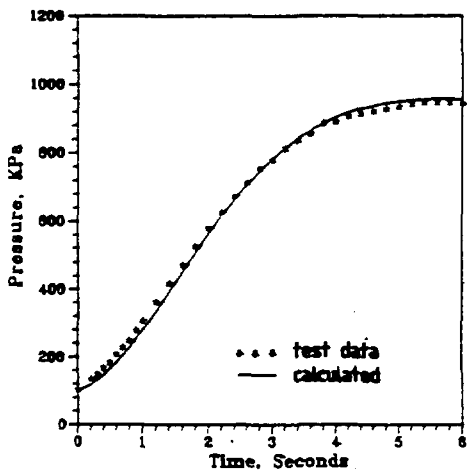


Fig. 7a: Total Pressure in Containment of CSNI Benchmark Test Model

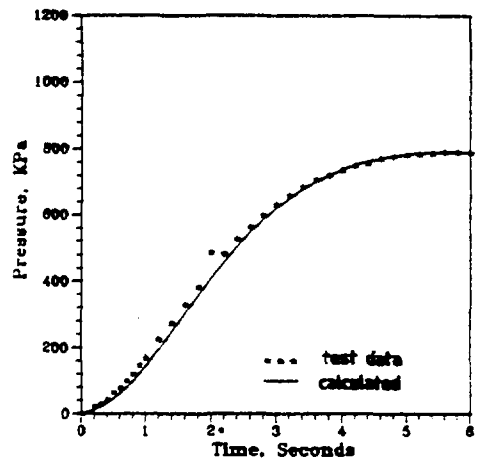


Fig. 7b: Steam Pressure in Containment of CSNI Benchmark Test Model

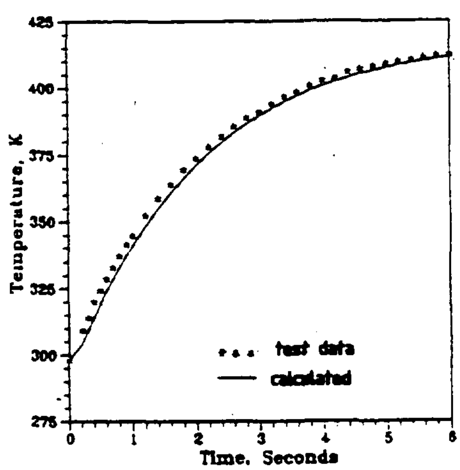


Fig. 7c: Wall Surface Temperature of Containment of CSNI Benchmark Test Model

Results of some of the analyses, e.g. the effect of variation of the suppression pool bypass area (Fig.8a), surface area of the containment structure (Fig.8b), heat transfer to the structure (Fig.8c) and multi-compartment configuration (Fig.8d) on the containment peak pressure are presented.

It has been observed that, the containment peak pressure increases with increase in suppression pool bypass area and decreases with increase in the heat transfer coefficient and surface area of structural heat slabs.

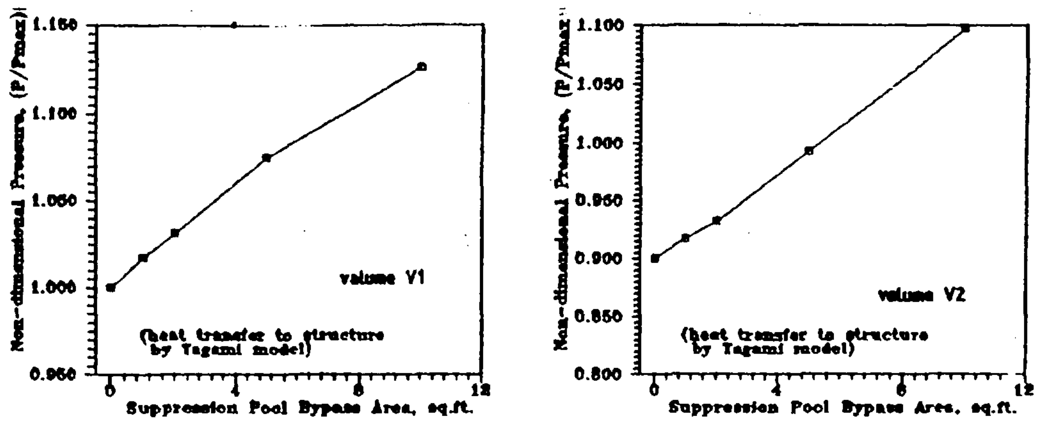


Fig. 8a: Variation of Containment Peak Pressure with Suppression Pool Bypass Area following MSLBA in 220 MWe Indian PHWR

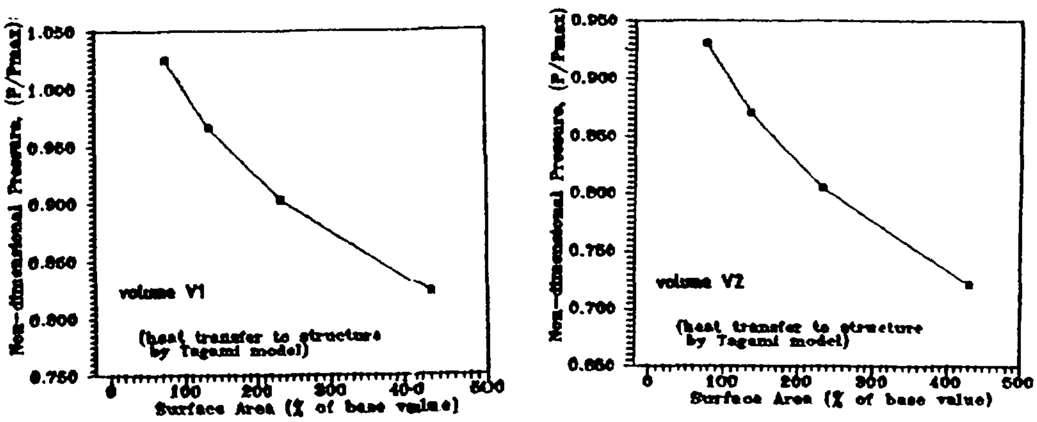


Fig. 8b: Variation of Containment Peak Pressure with Surface area of Structure following MSLBA in 220 MWe Indian PHWR

Fig. 8c: Effect of Suppression Pool and Structural Heat Transfer on Containment Peak Pressure following MSLBA

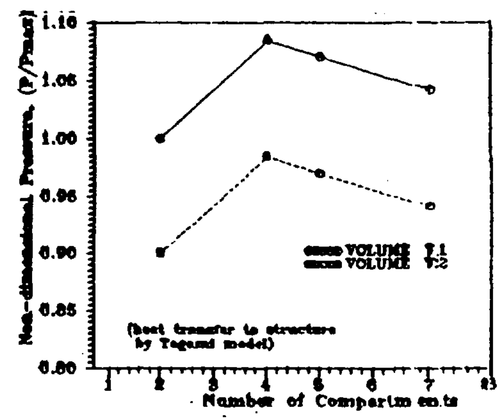


Fig. 8d: Effect of Multi-compartment geometry of Containment on Peak Pressure following MSBLA

The code CONTRAN, is extensively used for studying the performance of the containment of IPHWRs for various LOCA/MSLBA scenarios [11].

4.1.3 Experience gained during validation of the code CONTRAN

Heat and mass transfer processes play an important role in the estimation of the design pressure and temperature of the containment of a Nuclear Power Plant. While using a particular model for the condensation heat transfer processes, the conservativeness of the model should be ensured. The conduction heat transfer in the structure is better modeled by using logarithmic grids, with the grid size increasing from inner to outer surface. The use of uniform grids may result in under-estimation of the containment design pressure. Lower initial relative humidity and lower initial temperature in the containment result in higher design pressure. Sensitivity analysis helps in assessing the influence of various parameters in arriving at a conservative estimate of the containment design pressure.

4.2 HYDROGEN BEHAVIOUR IN CONTAINMENT

Since the accident at Three Mile Island (TMI) Nuclear Power Plant, there has been a great deal of interest regarding the behaviour of hydrogen in the containment. In the event of highly unlikely occurrence of a severe accident in nuclear reactors, a large quantity of hydrogen could be generated. The hydrogen so generated will be confined within the containment. Due to the very large volume of containment of IPHWRs, the global hydrogen concentration is estimated to be lower than the deflagration limit of hydrogen-air mixture. Depending upon the distribution characteristics of hydrogen in a multi-compartment containment system, there could possibly be a formation of local pockets of high concentration. If the deflagration limit is exceeded, it can cause combustion. This exothermic reaction may cause further overpressurisation of the containment. To mitigate the consequences of such a situation, there are currently four approaches being investigated worldwide, viz.

* inertisation of the hydrogen-air mixture,
* deliberate ignition of combustible mixtures,
* catalytic recombination of hydrogen with oxygen [12].
* combination of deliberate ignition and catalytic recombination [13] or simultaneous inertisation and catalytic recombination [14]

Among these, the catalytic recombination method offers promising potential due to its hydrogen removal efficiency even at low hydrogen concentrations and in presence of steam, as has been demonstrated by the reported experimental studies [12].

4.2.1 Computer code HYRECAT

For the analysis of hydrogen mitigation phenomena in the containment using catalytic recombiners, the code HYRECAT has been developed [15,16]. The model is based on the solution of equations for mass and energy conservation within a homogeneously mixed hydrogen-air-steam mixture undergoing oxidation of hydrogen on the catalyst surface. The salient features of the code HYRECAT are as follows.

4.2.2 Salient Features of code HYRECAT

1. The kinetics of catalytic oxidation of hydrogen is described by Arrhenius type empirical rate equation, (on the basis of unit mass of catalyst or unit area of the catalyst coated surface) [17,18].
2. Appropriate heat transfer mechanisms are modelled for the dissipation of the heat of reaction from the catalyst to the surroundings.
3. The code can analyse the deliberate ignition mode of hydrogen recombination and also the dual mitigation system involving catalytic recombiners and igniters together. The transient containment pressure and temperature consequent to the combustion is evaluated by using (a) AICC and (b) laminar burning velocity models [19] alongwith various thermal hydraulic processes.

4.2.3 Validation of code HYRECAT

Bhabha Atomic Research Centre (BARC) has successfully developed a special type of activated platinum catalyst and the laboratory tests have demonstrated its satisfactory performance. Further tests on this catalyst system are planned on an engineering scale test facility (see Fig.9). The validation of the code HYRECAT has been carried out [15] using data from two of the several laboratory tests performed at BARC. The test was performed in a 22 litre stainless steel vessel with a catalyst coated substrate of known dimensions and known catalyst loading (i.e. mass of catalyst per unit area), with initial hydrogen concentration of 5.1 % (v/v). The variation of the total pressure in the vessel was recorded continuously.

Excellent agreement has been observed between the predictions of HYRECAT and the measured total pressure in the vessel as seen from Fig.10. More detailed results of validation are presented elsewhere [15].

4.2.4 Analysis of planned experiments using code HYRECAT

Large scale experiments are planned on a 22 cu.m. vessel to examine the behaviour of the catalytic recombination system on engineering scale (see Fig.9) and to test the performance of the device [20]. The test facility consists of hydrogen injection and monitoring system, catalytic recombiner device, steam and air injection provisions, various instrumentations and the safety devices installed on the model containment vessel. The code HYRECAT was used to analyse these tests to be conducted at BARC and predict (pre-test) the performance of the catalytic recombiner system. The predicted behaviour for a typical test, in terms of the containment pressure, temperature, hydrogen concentration, relative humidity and reaction rate etc. are presented in Figs.11a-f. These tests would generate a data bank useful for further validation of the code.

4.3 AEROSOL SOURCE TERM ANALYSIS

To enable a realistic assessment of the source term, the complex processes of transport, growth, deposition and removal of aerosols within the containment are required to be analysed. The codes NAUA/MOD5 [21] and SPARC [22] have been adapted for this purpose.

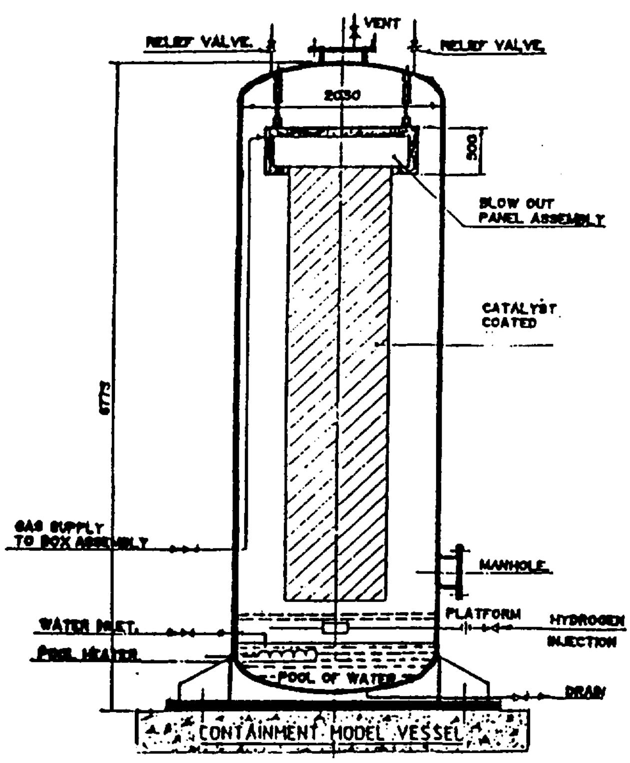


Fig. 9: Experimental Setup for Hydrogen Mitigation Studies using catalytic Recombination

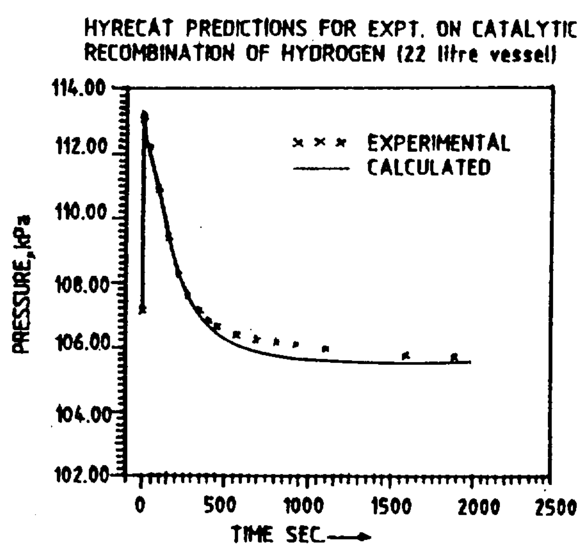
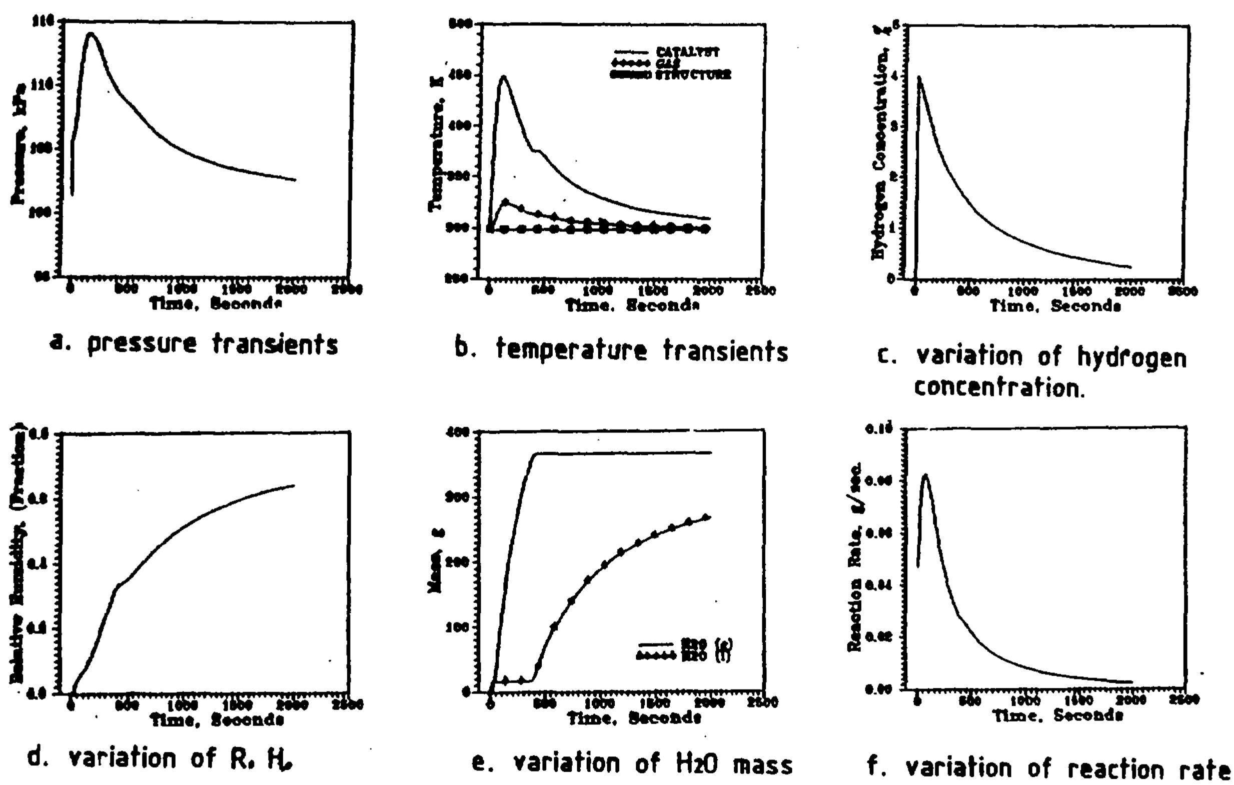


Fig. 10: Comparision of HYRECAT Predictions with experimental data on Laboratory Scale Test.



a. pressure transients
b. temperature transients
c. variation of hydrogen concentration.
d. variation of R. H.
e. variation of H_2O mass
f. variation of reaction rate

Fig. 11: Analytical results for the proposed experiment for hydrogen mitigation studies using catalytic recombination on model containment.

4.3.1 Computer code NAUA MOD 5

NAUA is an advanced multi-compartment aerosol behaviour analysis code for use in reactor containments following core-melt accidents. It models the physical aerosol phenomena occurring naturally in the containment. It models gravitational deposition, diffusional plate-out and diffusio-phoresis as removal mechanisms. Among the interaction processes, the code considers Brownian coagulation, gravitational agglomeration and aerosol growth by steam condensation. The code is not integrated with the containment thermal hydraulics. NAUA can take into account the build-up of upto 50 nuclide species on a size-dependent basis.

4.3.2 Assessment of code NAUA MOD 5 with the Falcon Aerosol Test

The Committee on the Safety of Nuclear Installations (CSNI) of OECD organised during 1992-94, the International Standard Problem Exercise no. 34 (ISP-34) on aerosol behaviour in the primary circuit and the containment of a nuclear reactor. The exercise involved carrying out specific experiments in the Falcon Test Facility at Winfrith Technology Centre, U.K. and analysis of these experiments using different computer codes [23].

The tests were performed in the small scale Falcon test facility shown schematically in Fig.12. The facility comprised of core region, primary circuit piping and the containment. Simulant fuel samples clad in zircaloy-4 were placed in a silica vessel simulating the core region. Heating of the fuel was achieved in a 40 kW induction furnace. Helium gas as a carrier medium was admitted at the bottom of the silica vessel and aqueous boric acid solution could be introduced on the heated sample. The thermal gradient tube and the stainless steel pipe simulated the primary circuit. The containment was a 0.3 cu.m stainless steel chamber connected to the primary circuit.

Containment analysis of these tests was carried out at BARC using the computer code NAUA MOD5. The code calculations for one of the experiments, viz. FAL-ISP-1 are presented and compared with the experimental data in Figs.13a-d [24,25]. Many of the code predictions were found to be in reasonably good agreement with the experimental results. The containment floor deposits are predicted closely, whereas the wall deposits are underpredicted. However, the

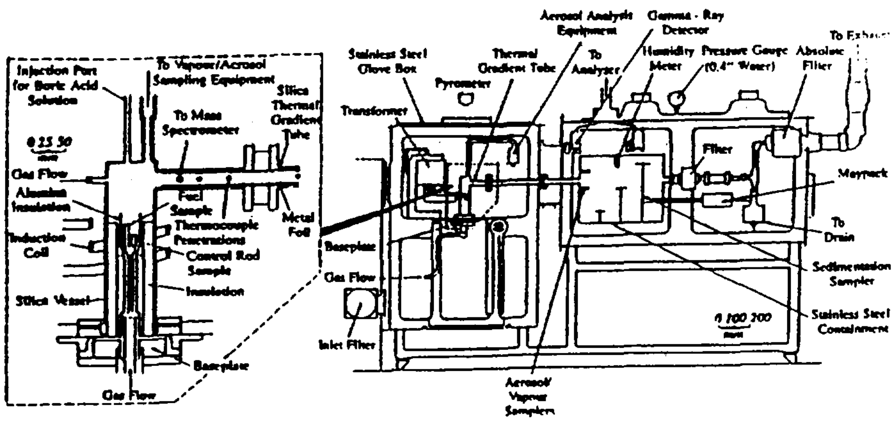


Fig. 12: Falcon test facility for Aerosol Studies

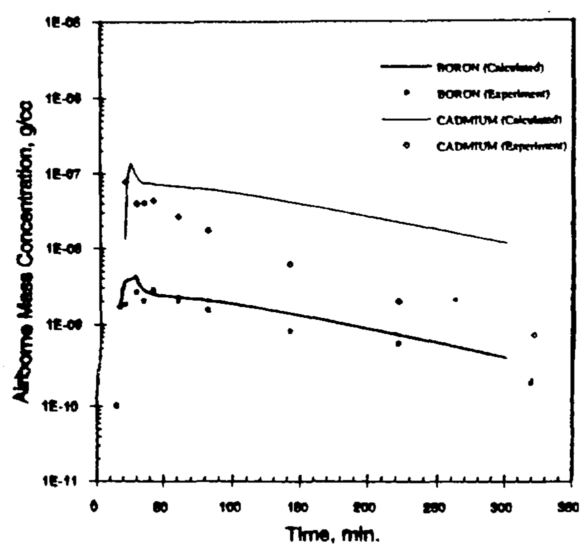


Fig. 13a: Boron and Cadmium airborne mass concentrations in containment

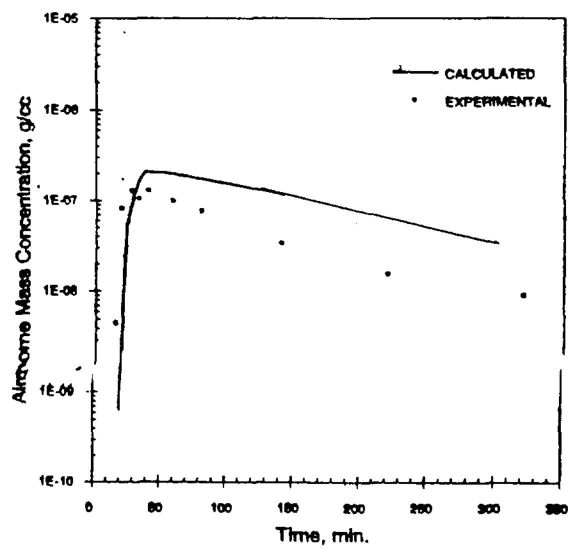


Fig. 13b: Cesium airborne mass concentration in containment

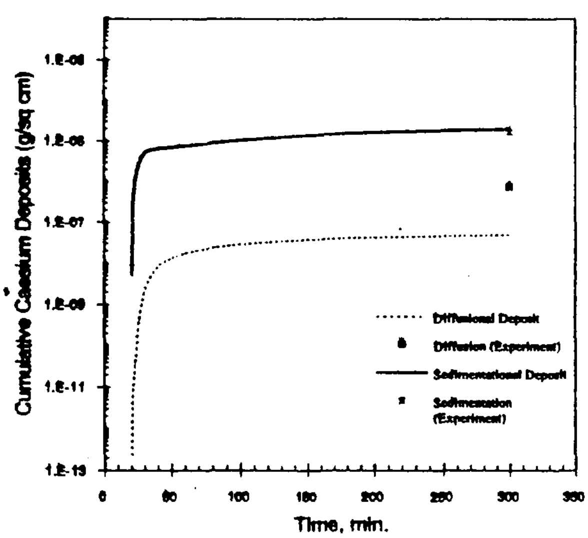


Fig. 13c: Cumulative deposition of Cesium

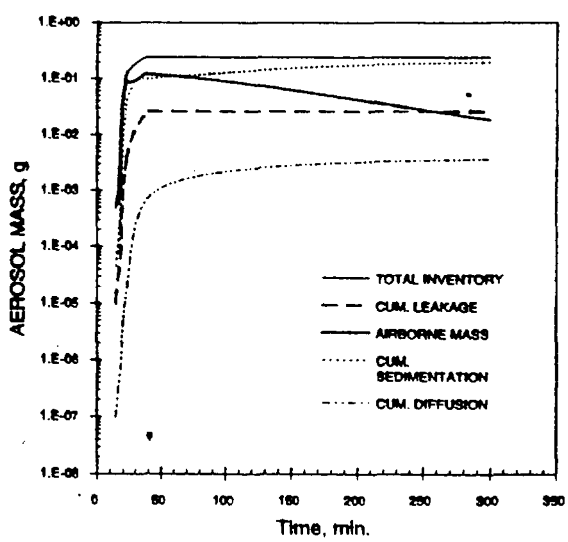


Fig. 13d: Removal of aerosols by various mechanisms.

predictions are observed to be well within the reported uncertainties in the experimental measurements. Augmentation of the code for integral thermal hydraulics and assessment of the containment behaviour of Indian PHWRs is in progress.

4.3.3 The computer code SPARC

Engineered Safety Features (ESFs) such as suppression pool are a part of the IPHWR containment system. Besides its intended function of reducing the containment pressure, the suppression pool also helps in the removal of aerosols.

In order to analyse the aerosol scrubbing behaviour of the suppression pool, the code SPARC has been adapted after incorporating suitable modifications. The code models the particle capture by condensation of steam, impaction, sedimentation, centrifugal deposition and diffusional deposition. Growth of soluble particles by water vapour absorption is also modelled. The removal of aerosols is quantified by decontamination factors (DF) defined as the ratio of concentration of aerosols in the gas entering the pool to that leaving the pool [22].

4.3.4 Validation of the code SPARC

Laboratory scale experiments were carried using a prototype bubbler unit (Fig.14). The nebuliser generates wet aerosols from aerosol solution. Compressed air is used for drying these aerosols and carry them to the pool of water. Suction produced by the pump forces the aerosol-laden air to bubble through the pool of water. Aerosols were collected on filters after passing them through the pool and compared with the case without passing through the pool to obtain the decontamination factors. Experiments with two different sized particles viz. Fluorescein (MMAD = 0.8 microns) and Silica (MMAD = 0.2 microns) were carried out. Figs.15a-b show the analytically computed DFs as a function of size classes for Fluorescein and Silica aerosols respectively. The code predictions and experimental results presented in these figures are found to be in close agreement [26].

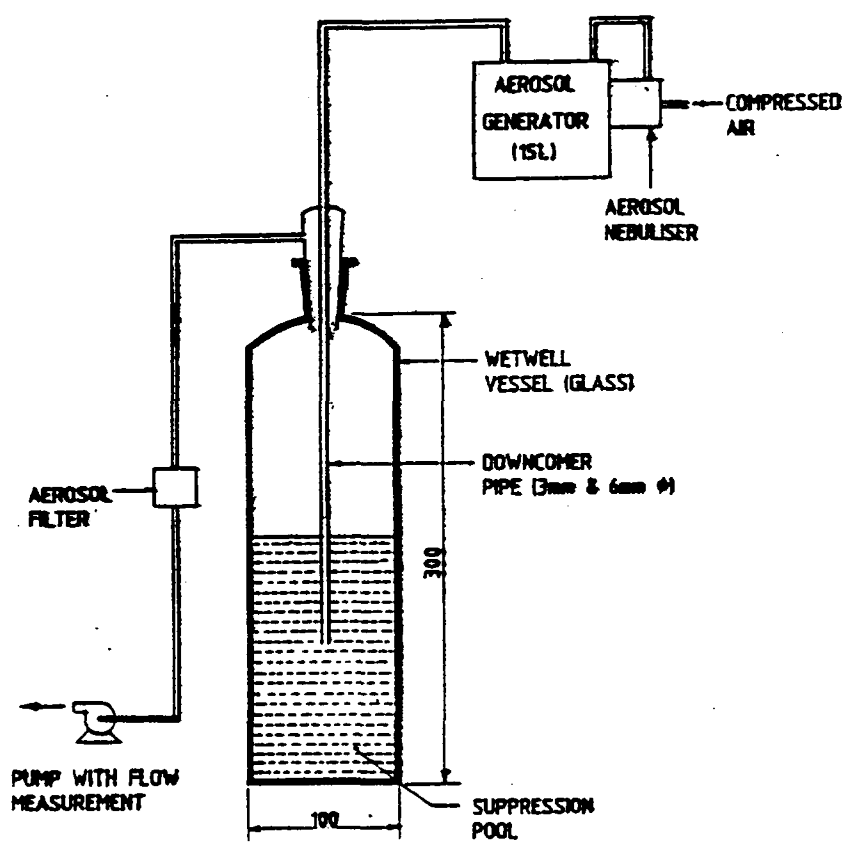


Fig. 14: Suppression pool Aerosol Scrubbing Test Facility (schematic)

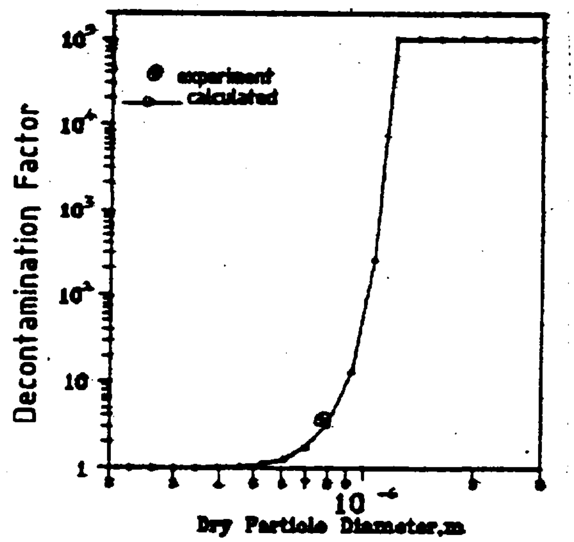


Fig. 15a: Effect of particle diameter for Fluorescein aerosols

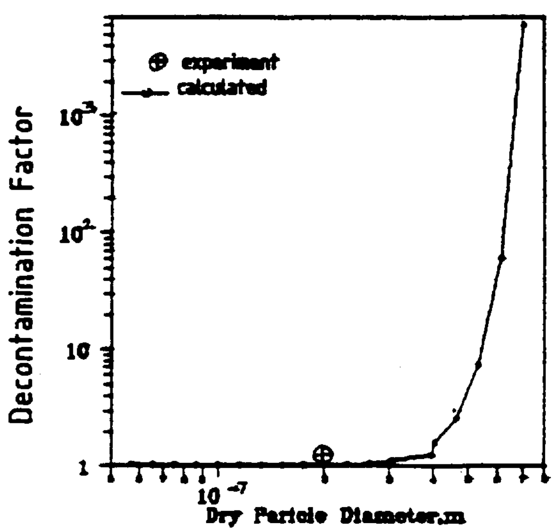


Fig. 15b: Effect of particle diameter for Silica Aerosols

5.0 CONCLUDING REMARKS

The various codes under use at BARC for analysing containment related scenario following DBA or severe accidents are briefly described. The results of the validation exercises performed to test the code capabilities are also described. The code CONTRAN for predicting thermal hydraulic transients in the containment has been validated extensively. The codes for hydrogen and aerosol behaviour have been validated to a limited extent. Augmentation of the aerosol codes for integral thermal hydraulics and assessment of the containment behaviour of Indian PHWRs is in progress.

While the various accident scenarios, performance of the protective systems and engineered safety features and the behaviour of the released products decide the gross values of the source-strength and the probability of the associated event, the uncertainties can be estimated from the scatter of the values of various code predictions. The studies aimed at understanding, analysing as well as improving the containment performance being carried out at BARC are presented and discussed.

REFERENCES

1.Haware, S.K., Markandeya, S.G., Ghosh, A.K., Venkat Raj, V., "Assessment of a Multi-compartment Containment Analysis Computer Code CONTRAN With the Experiments on Containment Response During LOCA Conditions", Paper No. HMT-94-118, First ISHMT-ASME Heat and Mass Transfer Conference and 12th National Heat and Mass Transfer Conference, BARC, Bombay, Jan. 5-7, 1994.

2.Ghosh, A.K. and Grover, R.B., "Analysis of vent clearing transient in a pressure suppression type containment system", BARC/I-814, BARC, Bombay (1984).

3. Haware, S.K. and Venkat Raj, V., "Experimental Studies on One-Tenth Scale Model of Vapour Suppression Pool Containment for 235 MWe Indian PHWRs", Fourth International Topical Meeting on Nuclear Reactor Thermal Hydraulics, Karlsruhe, Germany,Oct. 10-13, 1989.

4.Haware, S.K. and Venkat Raj, V., "Experiments on One-Tenth Scale Model of Vapour Suppression Pool Containment for 235 MWe Indian PHWRs - Results of One of the Tests Simulating MAPS Conditions", 10th National Heat and Mass Transfer Conference, Srinagar, India, Aug. 23-25, 1989.

5.Haware, S.K. and Venkat Raj, V., "Experimental Studies on one-tenth Scale Model of Vapour Suppression Pool Containment for 235 MWe Indian PHWRs - Effect of Change of the Break Compartment on the Containment Transients in the Tests Simulating NAPS Conditions", National Symposium on Safety of Nuclear Power Plants and Other Facilities, B.A.R.C., Bombay, March, 1992.

6.Investigation of Phenomena occurring within a Multi-compartment Containment after Rupture of the Primary Cooling Circuit in Water-Cooled Reactors, Battelle Institute e.V. Frankfurt (Germany), Technical Report BF-R550-32-D1, May 1977, and Technical Report BF-R550-32-D15-2, November 1978.

7.Haware, S.K., Markandeya, S.G., Ghosh, A.K., Venkat Raj, V., "Computer Aided Analysis of the Transient Behaviour of Nuclear Reactor Containment", Paper No. 107, National Symposium on Computer Applications in Power Plants, BARC, Bombay, Dec.8-10, 1992.

8.Wheeler, C.L., Thurgood, M.J., Guidotti, T.E. and DeBellis, D.E., "COBRA-NC : A Thermal Hydraulics Code for Transient Analysis of Nuclear Reactor Components", Vol. 1 - 9 NUREG/CR-3262, PNL-5515, Pacific Northwest Laboratory, Battelle Memorial Institute, April 1986.

9.Haware, S.K., Ghosh, A.K., Venkat Raj, V., Kakodkar, A., "Analysis of CSNI Benchmark Test on Containment Using Code CONTRAN", 3rd International Conference on Containment Design and Operation, CNS, Toronto, Ontario, Canada, 1994.

10.Numerical Benchmark on Containment Codes, Organisation for Economic Cooperation and Development, Nuclear Energy Agency, SINDOC (80) 263, Paris, December 1980.

11.Haware, S.K., Bhartiya, S., Ghosh, A.K., Venkat Raj, V., "Analytical Studies on the Behaviour of Nuclear Reactor Containment", Paper No.HMT-95-097, Second ISHMT-ASME Heat and Mass Transfer Conference and 13th National Heat and Mass Transfer Conference, K.R.E.C., Surathkal, India, Dec. 28-30, 1995.

12.Chakraborty, A.K., "Removal of Hydrogen with Catalytic Recombiners During Severe Accident Situations", Proceedings of a Workshop on Hydrogen Behaviour and Mitigation in Water Cooled Nuclear Power Reactors, Brussels, Belgium, 1992.

13.Heck, R., "Concept and Qualification of Combined System for Hydrogen Mitigation After Severe Accidents", Proceedings of a Workshop on Hydrogen Behaviour and Mitigation in Water Cooled Nuclear Power Reactors, Brussels, Belgium, 1992.

14.Chakraborty, A.K., Markandeya, S.G., "A new Approach to Inertise the Containments During Catalytic Removal of Hydrogen", 3rd International Conference on Containment Design and Operation, CNS, Toronto, Ontario, Canada, 1994.

15.Haware, S.K., Bhartiya, S., Ghosh, A.K., Venkat Raj, V.,"Studies on Catalytic Recombination of Hydrogen in Indian PHWR Containment", Paper No. HMT-95-097, Second ISHMT-ASME Heat and Mass Transfer Conference and 13th National Heat and Mass Transfer Conference, K.R.E.C., Surathkal, India, Dec. 28-30, 1995,

16.Haware, S.K., Bhartiya, S., Ghosh, A.K., Venkat Raj, V., "Analytical Studies on the Catalytic Oxidation of Hydrogen Using the Code HYRECAT", CHEMCON-95, Kalpakkam, India.

17.Mayo, J.A. and Smith, J.M., "Catalytic Oxidation of Hydrogen-Intrapellet Heat and Mass Transfer", A.I.Ch.E. Journal, Vol.12, No. 5, Sept. 1966, pp. 845-854.

18.Markandeya, S.G., Chakraborty, A.K., "Modeling of catalytic Recombiners for Removal of Hydrogen During Severe Accidents", SMiRT-12/K, Aug. 1993, pp.73-78.

19.Liu, D.D.S., McFarlane, R., Laminar Burning Velocities of Hydrogen-Air and Hydrogen-Air-Steam Flames, Combustion and Flame, Vol. 49, 1983, pp. 59-71.

20.Jain, V.K. et.al., "Project Proposal For Development and experiments on Hydrogen Mitigation System", Internal Report, RED, BARC, 1991.

21.Bunz, H. et.al., "NAUA-MOD5 and NAUA-MOD5M - Two Computer Programs for Calculating the Behaviour of Aerosols in a LWR Containment Following a Core-Melt Accident", KfK-4278.

22.Owczarski P.C.; Schreck R.I., Postma A.K.;Technical Bases and Users Manual for the prototype of a Suppression Pool Aerosol Removal Code (SPARC): NUREG/CR-3317.

23.Williams, D.A., OECD International Standard Problem Number 34, FALCON Code Comparison Report, AEA RS 3394, Dec. 1994.

24.Haware, S.K., Ghosh, A.K., Sharma, V.K., Venkat Raj, V., "Analysis of FALCON Test FAL-ISP-1 Using Code NAUA", Fifth IASTA Conference on Aerosol Science and Technology, BARC, Bombay, Jan. 10-12, 1994.

25.Haware, S.K., Ghosh, A.K., Sharma, V.K., Venkat Raj, V., Assessment of the Computer Code NAUA MOD 5 against a small-scale Containment Aerosol Test, J. Aerosol Sci., vol.28 (to be published).

26.Venu Vinod, A., Haware, S.K., Ghosh, A.K., Venkat Raj, V., Sapra, B.K., Mayya, Y.S., Raghunath, B.R., Sawant, V.D., Nair, P.V.N. and Nambi, K.S.V., Experimental Studies on Pool Scrubbing of Aerosols, Sixth IASTA Conference on Aerosol Science and Technology, Ahmedabad, November, 28-30, 1995.