SCALING OF CONTAINMENT EXPERIMENTS

(SCACEX)

CO-ORDINATOR

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CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

ATHERMIP	Benchmark on containment penetration sealing areas behaviour
CEC	Commission of the European Communities
CESA	Containment evaluation under severe accident
CFD	Computational fluid dynamics
COTINCO	Condensation inside tube with incondensable
DABASCO	Common experimental data base for the development of physical models and correlations for thermal-hydraulic containment analysis
DBA	Design basis accident
EFFE	Evaporating film flow experiments
FLIPPER	Simplified liquid structure impact experiments
H2TS	Hierarchical Two-Tiered Scaling
LISSAC	Limit Strains for Severe Accident Conditions
NICE	Naturally-induced convection experiments
NPP	Nuclear power plant
PASCO	Passive containment cooling
PIRT	Phenomena identification and ranking table
RPVSA	On the prediction of the reactor vessel integrity under severe accident loadings
SCACEX	Scaling of containment experiments
U.S.NRC	Unites States Nuclear Regulatory Commission
VOASM	Validation of a simulation methodology for hydrogen mixing, catalytic recombination and deliberate ignition

Arr	Arrhenius number
Bo	Buoyancy number
Gr	Grashof number
Nu	Nusselt number
R	Richardson number
Re	Reynolds number
Pr	Prandtl number
Sh	Sherwood number
Sc	Schmidt number
A	area
c	heat capacity
d	characteristic length
D	diameter
e	wall thickness
E	activation energy
g	gravitational acceleration
G	mass flow rate
h	heat transfer coefficient; height
ID	inner diameter
k	reaction rate
L	length
q	heat flux
Q	heat flow
t	time
T	Temperature
p	pressure
r	radius
R	ideal gas constant
u	velocity
V	volume
w	crack width
x	space co-ordinate
z	space co-ordinate
α, β	thermal expansion coefficient
ζ	flow resistance coefficient
λ	thermal conductivity
ν	Young’s modulus
ν	kinematic viscosity
Π	dimensionless number
ρ	density
σ	stress
ω	noncondensable gas mass fraction

EXECUTIVE SUMMARY

Nuclear safety technologies are in many cases based on information obtained from scaled experiments. In such cases it is necessary to show how the experimental results can be transferred or applied to real, prototypical reactor conditions. The SCACEX Thematic Network was created with the aim to perform such transfer by application of scaling methods in a selected area of nuclear reactor safety research related to the reactor containment. The acronym SCACEX stands for SCAling of Containment EXperiments. A group of European experts was asked to conduct and document scaling analyses for reactor safety experiments done or planned in their laboratories. The network activities included a compilation of scaling methods as theoretical background, consulting for individual scaling analyses, and a number of meetings to promote information exchange and monitor progress in the group of network participants.

The scaling analyses presented in the final project report cover the following fields:

- Turbulent and radiative heat transfer
- Heat transfer by steam condensation and evaporation
- Containment spray systems
- Bubble condenser containment thermal hydraulics
- Natural convective flow processes in the containment atmosphere
- Cable ageing
- Containment penetration sealing
- Cracking and leakage through concrete walls
- Steel structures under dynamic loads

The analyses demonstrate that the existing methods of scaling and similarity analysis have an almost universal range of applicability. They require a good knowledge of the phenomena associated with the individual experiments, which is conveniently documented in a simplified Phenomena Identification and Ranking Table (PIRT). Several ways to establish dimensionless numbers were taken, and it was found that this can be a more challenging task where no straightforward recipes are available, especially in areas where scaling methods are not well established. The SCACEX report is intended to serve as a reference for future scaling analyses in similar applications.

As result of the work, common features of scaling in different application fields can be identified as follows:

- Identification and ranking of relevant phenomena (simplified PIRT)
- List of relevant parameters associated with the phenomena
- List of dimensionless numbers derived from the relevant parameters
- Interpretation taking into account the geometric (or time-related) scale ratios.

Network participants agreed that scaling analysis is a very useful approach to show how experimental data can be transferred to the prototype. The method reveals the limitations to this transfer, it helps to get a more complete understanding of the investigated processes, and it can be used to specify more effective and less costly experiments. It is suggested to extend the work to other fields of nuclear safety research, like primary system or core melt behaviour, in order to establish a more comprehensive reference of scaling analysis for nuclear engineers.

A OBJECTIVES AND SCOPE

Scaling analysis is a theoretical procedure to make sure that experimental results are applicable to prototype conditions. Many experimental investigations in nuclear reactor technology can only be performed under conditions that deviate considerably from reactor typical, e.g. by geometric dimensions or materials involved. In such cases scaling may be applied to establish proper ways for transferring experimental results to real reactor conditions, and to avoid incorrect extrapolation of data (which may be relevant to safety issues). Scaling must be considered in the design of experimental facilities and procedures, in the interpretation of results, as well as in the construction of mathematical models.

Since the establishment of the Buckingham Π theorem, scaling has been applied in many fields of research. The method is generally successful for simple technical systems. For complex systems where many interactions are involved, the method must be extended by a systematic treatment of simplifications. For application in nuclear reactor safety, a comprehensive methodology was developed by a Technical Program Group of the U.S. NRC under the chairman N. Zuber [1]. This work provides a theoretical framework and systematic procedures for carrying out scaling analyses.

While scaling considerations have been discussed in several projects of the past and present CEC Framework Programmes, a systematic and regular application of the methods is not part of the general practice. Instead, many experimental investigations are accepted on the basis of common expert understanding. The reason for this situation is that systematic application of scaling methods is relatively recent and may be complicated in practice, and there are hardly any suitable guidelines for engineering needs. Problems in predicting real plant behaviour can be caused by the small geometric scales of experiments, by the use of different materials (helium instead of hydrogen), different time scales (accelerated thermal ageing), or different loads (gamma irradiation instead of neutrons) etc.. Geometry scaling methods of thermal hydraulics may be transferred to material scaling by dimensional analysis of the Arrhenius law. The solution of the scaling issues is also especially important for accident management, e.g. the startup behaviour of passive autocatalytic recombiners or the performance of containment sprays while deinerting the atmospheric hydrogen mixture.

The general objective of the Thematic Network SCACEX is to establish a European network of experts that work together on a systematic approach for the use of scaling methods in nuclear reactor technology and safety and their application to problems where the need for proper scaling is evident. This approach shall go beyond the level of theory and methodology, by performing scaling analyses for a selected number of experiments, with the following particular objectives in mind:

- Identify the applicability, requirements, difficulties and shortcomings of the existing scaling theory
- Document case studies of scaling analysis as reference for future applications
- Find out the common features and rules of scaling analyses in different application fields
- Identify the significance of scaling for experiments and modelling
- Assess the applicability of the methodology to new areas and problems
- Assess the needs, potentials and benefits of a Scaling Handbook in nuclear reactor technology

A number of scaling case studies is conducted on existing experiments in a limited area of research, i.e.

- phenomena related to plant life extension and management,
- ageing of containment components,
- containment phenomena during normal operation and DBA (Design Basis Accident) transients, including decay heat removal in innovative reactor concepts,
- material behaviour and thermal hydraulic processes.

The cases documented in the project shall be made available to the nuclear engineering community as guidance to support similar scaling analyses in other applications. This shall also support efforts of quality assessment when new research projects are to be launched. The scope of the proposed Thematic Network is limited to containment-related aspects. SCACEX shall lay the basis for a potential larger research activity in the 6th Framework Programme that may be established to write a comprehensive Scaling Handbook, covering more areas of application by a wider network of experts. Scaling considerations may then be extended to primary system, core melt and severe accident phenomena.

B WORK PROGRAMME

The project work is directed to produce as main result a final report, prepared from contributions of all project members, that summarises the theoretical background, presents scaling analyses of a major number of diverse containment-related topics, and provides conclusions on the general achievements and open issues. The scaling analyses address the question how experimental results can be transferred to prototype conditions if differences exist in respect to geometric dimensions and shapes (e.g. small scale experiments), the choice of materials (e.g. helium instead of hydrogen in the atmosphere, artificial aerosols), time scales (e.g. accelerated thermal ageing), or material loads (e.g. artificial irradiation sources). Experimental results are mostly taken from previous projects conducted in the CEC Framework Programmes; in addition, some project members supply own data.

For transferring experimental results to prototype conditions, experimental data are often condensed to form a correlation for use in a numerical code. In this case, the structure of the code variables must be taken into account. Generally, codes are formulated in terms of local interactions; this means that introduction of non-local interaction terms (like e.g. thermal radiation or heat transfer correlations with local coordinate dependency) are difficult to be implemented. Correlations for lumped parameter codes may be quite different from corresponding correlations for CFD codes.

Frequently, a major product of a scaling analysis is a scale-independent correlation that is derived from experiments and often implemented in a computer code for simulating complex and interacting containment phenomena. The main emphasis of the project is to critically examine various correlations and to establish their scaling invariance. An important part of this work is the assessment of interactions in the experiment and in the prototypic containment that may introduce scale-dependent effects and prevent the correlation from being transferable. The questions discussed in each scaling analysis are:

- What are the most important processes investigated in the experiments?
- What are the corresponding processes in a prototypic containment?
- What are the correlations describing the experimental results?
- What are the averaged or neglected lower-order interactions?
- What are the changes of first and lower order effects with changing scale?

Answers to these questions are elaborated by evaluation of experimental trends and comparison with theoretical expressions, derived from basic conservation laws where possible.

While numerical code application is an important issue related to scaling analysis, there are other applications outside the numerical simulation field that are also addressed in the project, especially in respect to ageing investigations, where important results can be derived from experiments more directly.

The work programme structure follows the requirements for setting up the report. Individual chapters are prepared in corresponding work-packages under the guidance of task leaders. The structure of the final report shows the individual work packages as follows:

1. Introduction
2. Theoretical framework
3. Scaling of thermal hydraulic processes
3.1 Turbulent and radiative heat transfer
3.2 Heat transfer by steam condensation and evaporation
3.3 Containment spray systems
3.4 Bubble condenser containment thermal hydraulics
3.5 Natural convective flow processes in the containment atmosphere
4. Scaling of materials related processes
4.1 Cable ageing
4.2 Containment penetration sealing
4.3 Cracking and leakage through concrete walls
4.4 Steel structures under dynamic loads
5. Conclusions
5.1 Design and evaluation of experiments
5.2 Design and evaluation of code models
5.3 Extensions of the work, Scaling Handbook

The analyses focus on a number of previous and present experimental series performed under CEC Framework Programmes, like

- DABASCO thermal-hydraulic containment data base, with the experimental series PASCO, NICE, EFFE, COTINCO
- VOASM simulation methodology for containment calculations,
- ATHERMIP containment penetration sealing,
- CESA leakage of prestressed concrete containment,
- RPVSA and LISSAC size effect in deformation and fracture of steel specimens

supplemented by other experiments e.g. on cable ageing or bubble condenser blow-down. The selection of cases follows the criteria

- broad spectrum of phenomena,
- thermal hydraulics, structural mechanics and material behaviour are addressed,
- relevant to operational safety of existing reactors.

Thematic network operation and communication between partners was supported by three progress meetings.

C WORK PERFORMED AND RESULTS

C.1 Theoretical framework

The classical methods of dimensional analysis aim at producing the non-dimensional numbers that control a given situation or phenomenon. These methods are usually applicable to relatively simple situations or single phenomena (such as heat transfer or frictional pressure loss) where the length and time "scales" of the problem are rather unique and well defined. Such methods are e.g.

- Use of the Buckingham Pi theorem, i.e. combination of all relevant variables to form dimensionless groups
- Dimensionless numbers from known governing equations
- Dimensionless numbers as ratios of "competing quantities" like force balances
- Dimensionless numbers as ratios of characteristic times for exchange of mass, energy and momentum over specified areas and volumes

In analysing complex systems, however, where several phenomena interact at different spatial and time scales, one faces difficulties in applying the classical methods, since the multiplicity of scales results in too many non-dimensional numbers that cannot be assigned identical values; all the similarity conditions cannot be satisfied simultaneously. Some method is then needed to decide which scales are controlling the processes of greatest importance for the correct simulation of the system. The recent Hierarchical Two-Tiered Scaling (H2TS) approach of Zuber [1] attempts to provide guidance in these cases and has been applied successfully to the scaling of nuclear safety experiments and, in particular, containment related tests.

According to H2TS one must establish first the hierarchical architecture of the system, i.e. decompose the system in interacting:

- subsystems (e.g., containment compartments)
- modules (e.g., part of a compartment)
- constituents (different materials) (e.g., air, steam)
- phases (e.g., liquid and gas)
- geometrical configurations (e.g., liquid film, liquid droplets).

Each configuration must be described by the three field equations (conservation of mass, momentum, and energy). In relation to each field equation several processes can take place. For example, in relation to the energy equation, we can have heat transfer by convection, radiation, etc. Spatial and temporal scales need to be established at each level.

Another feature of H2TS is that it makes use of both Top Down and Bottom Up approaches. The Top-Down or System approach is used to derive scaling groups (expressed in terms of characteristic time ratios) that combine the process and system points of view. The characteristic time ratios are used to establish a scaling hierarchy which has two important functions:

1. to provide a technically justifiable rationale for establishing the order/hierarchy in which similarity between test and plant should be preserved; and
2. to identify important processes which need to be addressed in greater detail by a bottom-up or process analysis.

The Bottom-Up or Process approach focuses on the important processes in detail.

The basic premise in the H2TS methodology is that a hierarchy (organisation) can be established from the differences in temporal and spatial scales and that the processes and their importance can be classified and ranked according to their scales. If scales are sufficiently distinct,

processes can be decoupled; this results in a hierarchical organisation: if processes operate at different scales, it becomes possible to establish their relative importance.
Lower levels in the hierarchy of processes communicate only average values to the higher levels and less detailed information is needed at these higher levels. Overall system behaviour is controlled by the higher levels (the large scales).

The Phenomena Identification and Ranking Table (PIRT) method can also be used to identify the phenomena of greatest importance in a given situation of transient scenario. In this method, a table is prepared which lists the components, the processes and the phenomena of potential relevance. Then, a group of experts is asked to make an importance assessment of the listed phenomena, which is evaluated in terms of a ranking scale. Further analysis can then concentrate on the important phenomena, thus reducing the complexity of scaling studies based on engineering expert judgement in a systematic way.

In a number of scaling analyses computer codes were also used. This may yield useful results in certain cases, but a clear definition of the aims of the exercise is needed. For example, a well validated code capable of spanning a range of scales could conceivably be used to simulate the behaviour of scaled facilities, verify the adequacy of scaling and quantify the distortions. However, if one had sufficient faith in the predictions of a code at different scales, then tests at reduced scales and scaling analyses would not be needed. More objectionable are dual-purpose code applications where validation of a code is combined with a scaling study.

C.2 Scaling of thermal hydraulic processes

C.2.1 Turbulent and radiative heat transfer

Heat transport by combined turbulent convection and thermal radiation is of importance in innovative systems for passive cooling by buoyancy-driven airflow of the containment of nuclear reactors such as the Westinghouse AP600 and the German Composite Reactor (Figure 1). In each case, buoyant air is induced upwards in the annular space between steel containment vessel and an external wall (the steel baffle in AP600 and the concrete outer shell in the case of the Composite Reactor). Heat is re-moved directly from the containment surface by convection to the air and by thermal radiation to the surface opposite (and also to the surfaces of the steel panels which divide the annular space in the case of the Composite Reactor). This heat is then removed from those surfaces by convection to the air.

The naturally-induced cooling experiment (NICE), which formed part of the EU Project DABASCO, was initiated at the University of Manchester to provide basic information on turbulent convective heat transfer in a containment cooling system such as that employed in the AP600 reactor design. The main aim was to investigate whether the effectiveness of heat transfer in buoyancy-influenced flow in a vertical passage is dependent on the nature of the thermal boundary condition, which in the case all the previous studies had been uniform heating but in the nuclear reactor containment cooling application is uniform temperature. As can be seen from Figure 2, the NICE facility had a test sec-tion consisting of a long circular tube which could be heated either uniformly or non-uniformly so as to achieve uniform temperature. Local values of heat transfer coefficient were obtained with pumped flow covering a range of conditions from forced convection (negligible influence of buoyancy) to mixed convection (with very strong influences of buoyancy) by varying the flow rate and heating. Experiments were also performed with buoyancy-driven flow through the open test section (i.e. with the entry box absent). As can be seen from Figure 3, it was found that for large values of x/D, where a fully developed flow and heat transfer condition was achieved, the experimental results correlated satisfactorily when presented in terms of Nusselt number ratio (mixed convection to forced convection) and a dimensionless parameter which combines Grashof, Reynolds and Prandtl number in a particular manner dictated by an established semi-empirical model of mixed convection so as to characterise the strength of the buoyancy influence. With increase of this number strong impairment of heat transfer developed and then, above a certain threshold of buoyancy influence, recovery of heat transfer occurred followed by enhancement. The results for buoyancy-driven flow mapped onto those for pumped flow and were in the impaired heat transfer region. The NICE work package produced valuable experimental data of a fundamental nature which highlight the need for influences of buoyancy on heat transfer to be taken account of in the design of nuclear reactor containment cooling systems of the kind under consideration here. However, the results cannot be used directly to predict the performance of such cooling systems because of the choice of the simple circular tube geometry for the test section. Fortunately, however, experimental results from a subsequent study at Manchester with air flowing through a plane passage having one surface heated so as to achieve uniform wall temperature and the opposite one adiabatic, can be used instead. The test facility for this experiment (which has been given the acronym PACE) is shown in Figure 4. As was the case with NICE, impairment of heat transfer developed with onset of buoyancy influence and was again followed by recovery and enhancement of heat transfer, see Figure 5. However, in this case, the onset of impairment was delayed and the maximum impairment was reduced because only one surface of the pas-sage was heated.

Utilising the data from PACE a strategy has been developed for predicting the rate of heat removal by passive means from the containment of a nuclear reactor such as AP600 under dry conditions (i.e., without cooling by means of a falling water film). The correlation of the convective heat transfer data from PACE has to be used conjunction with procedures for calculating radiant heat transfer between the containment and baffle. Iterative numerical procedures are needed to determine the distribution of temperature on the baffle and the rate at which air is induced through the system.

The passive containment cooling experiment (PASCO) which was carried out at the Research Centre Karlsruhe also formed part of the EU project DABASCO. The test facility (see Figure 6) was de-signed to simulate a cooling channel in the Composite Reactor formed by segments of the annular space between the containment and outer shell and side panels (see Figure 1). The test section consisted of a vertical channel of rectangular cross section having dimensions similar to those of the cooling channels in the reactor cooling system. It was electrically heated on one side so as to achieve a uniform temperature and was well insulated on the other three (unheated) sides so as to achieve an adiabatic condition. The flow passage was open at the bottom and the top so that a buoyancy-driven flow of air was induced through it when heating was applied. It could be operated either with or without an air filter present. The test section walls were comprehensively instrumented with thermo-couples to enable their temperature distributions to be measured and traversing probes were installed at five different elevations for the purpose of measuring profiles of velocity and temperature. In addition, the electrical power supplied to each of the heaters was measured and also the pressure, temperature and humidity of the ambient air. In order to study the influence of thermal radiation, experiments were performed with the inside surfaces of the test section having an emissivity of 0.4 and with the emissivity increased to 0.9. The main difference between the PASCO experiment and the reactor containment cooling channel was in terms of height. Because of space limitations the test section height was only 5 m as compared with the full scale height of 50 m. Because of this, direct scale up of the experimental results to predict the prototype performance was not possible. Instead, other approaches had to be adopted.

A computer code FLUTAN was developed and validated against the detailed measurements made in the PASCO experiments. It was then used to predict the heat removal from the reactor containment by a full scale cooling system. Secondly, the PASCO measurements were processed to determine the coefficients of heat transfer by convection from the heated surface and the data were correlated using dimensionless parameters similar to those used in the case of NICE and PACE (Nusselt number ratio and Buoyancy number). This correlation is shown on Figure 7, where it can be seen that the results obtained from the experiments with the two different values of wall emissivity lie on a single distribution which indicates that the effectiveness of heat transfer improves systematically with increase of buoyancy influence and is generally enhanced in relation to that for forced convection. By making a number of simplifying assumptions an analysis was developed to assess the contribution of thermal radiation from the heated surface. This provided a framework for an empirical equation relating radiant heat transfer to convection. A strategy for predicting the rate of heat removal from the containment of the reactor by the passive cooling system using the two empirical correlations has been developed.

C.2.2 Heat transfer by steam condensation and evaporation

Similar to Figure 1, the AP600 reactor containment has an outer gap for heat removal by natural circulation. In addition, water can be sprayed on the hot metallic surface of the containment envelope to form an evaporating film enhancing the heat removal capacity. A scaled experiment to investigate the heat transfer by a falling water film under countercurrent air flow was conducted under the name EFFE (see Figure 8).

The main objectives of the research were:

- to collect experimental data on falling film evaporation in the range of parameters characterising practical applications in the nuclear field (e.g., AP600);
- to study the fluid-dynamic characteristics of liquid films and their effect on heat and mass transfer;
- to compare the present available models for the considered phenomena with experimental data.

Forced convection (“dry”) and falling film evaporation (“wet”) tests were performed with different boundary conditions (air velocity, plate inclination, film flow rate, plate and film temperature) to compare heat and mass transfer rates in similar conditions. Specific tests were also run for measuring the statistical characteristics and wave velocity in free falling films with different temperatures.

Due to the reduced size of the test section (e.g., 2 m in height as compared to about 40 m for the prototype) scaling considerations are necessary. A review of the different formulations available for the analogy between heat and mass transfer has been made to identify the common forms of the involved dimensionless groups which establish the similarity among systems having different sizes and fluid conditions. Evaporation experimental data have been processed in accordance, providing Sherwood numbers from the “wet” tests to be compared with the corresponding Nusselt numbers obtained from the “dry” tests in similar conditions.

The obtained data on heat transfer by film heating, evaporation and convection were then discussed. The dominant process is the film evaporation, which is related to convection by the heat and mass transfer analogy. Classical forced convection correlations with a correction multiplier for entrance effects, depending on the particular channel geometry, were found to reasonably represent the observed trends. In particular, the experimental data of the Sherwood number for evaporation mass transfer are close to the values obtained by the relationship

$$Sh = f(channel\ geometry)\ 0.023\ Re^{0.8}\ Sc^{0.33}$$

As indicated in Figure 9, the experimental results can be well correlated in terms of the relevant dimensionless numbers for heat transfer, and a good comparison with standard literature correlations is found for turbulent conditions in the air/steam mixture. Conclusions on the applicability of the obtained experimental information to reactor applications were finally drawn.

Experiments on steam condensation inside inclined tubes were conducted in the COTINCO test series [2], with the following aims:

- To investigate the physical phenomena involved in condensation of steam within tubes.
- To study the influence of the geometry (namely, the tube inclination) on the heat transfer rate, also in presence of high concentration of noncondensable gases.
- To develop models and heat transfer correlations for the given conditions.
- To produce a database for modelling in-tube condensation with high percentage of noncondensables.

This research was undertaken mainly to support development and qualification of passive containment cooling systems like the one shown in Figure 10 (MARS Reactor) and can provide useful data for other Passive Cooling Systems like the Isolation Condenser, Figure 11, where the process diagram of the ESBWR is reported.

In the MARS reactor the condenser tubes (externally air cooled) are 12 mm ID and they are 45° inclined. The ESBWR employs vertical tube condensers immersed in a pool, and the tube inner diameter is 50 mm. In the COTINCO facility, Figure 12, the condensing tube (22 mm ID) is externally cooled by water at ambient temperature; the Reynolds number of the inlet mixture ranges between 4300 and 6200, and the tube can be inclined between 0° and 45° with respect to the horizontal. Noncondensable gases mass concentrations have been analysed in the range 0 % - 72 %.

The COTINCO experiments provide information on the influence of tube inclination and completes other available experimental data bases for condensation inside vertical tubes. The results can be useful to identify the order of magnitude of the effect of noncondensable gases high concentration in a condensing steam flow, with respect to the overall heat transfer coefficient. These have allowed to identify the preliminary design requirements for inclined-tube, atmospheric-pressure operating, high noncondensable gas concentration steam condensers, to be used for totally passive emergency cooling and heat removal systems.

In Figure 13, results from the complete set of experimental data in steady-state conditions are reported as the ratio of the air-steam heat transfer Nusselt number and the value for pure steam condensation. In the figure, the following regression curve is also shown, valid for gas mass concentrations $\omega > 0.01$:

$$\frac{Nu_c}{Nu_{c0}} = 0.0118 \cdot \omega^{-0.86} \tag{1}$$

where Nu_{c0} is the Nusselt number for pure steam condensation and ω is the mass fraction of non-condensable gases. The effect of inclination angle is included in a correlation for Nu_{c0}.

Similar to the case of steam evaporation, condensation can be modelled by the analogy of heat and mass transfer. Conditions are different from the evaporation case because the condensation is strongly affected by the concentration of noncondensable gas in the pipe and flow regimes are quite different. Scaling aspects are associated with the diameter of the condenser pipe.

A dimensionless formulation has been used to correlate the air-steam mixture Nusselt number (Nu_g), including sensible (s) and latent (c) heat transfer from the mixture bulk (b) to the interface (i), to the Sherwood number (Sh_g) for condensation mass transfer in the following equation:

$$Nu_g = Nu_c + Nu_s = Sh_g \cdot \left[\left(\frac{\omega_i - \omega_b}{\omega^{lm}} \right) \cdot \frac{Pr_g}{Sc_g} \cdot \frac{1}{Ja_g} + \left(\frac{C_s}{C_m} \right) \cdot \left(\frac{Pr_g}{Sc_g} \right)^n \right] \tag{2}$$

where the Prandtl (Pr_g), Schmidt (Sc_g) and Jacob (Ja_g) numbers are calculated for the air-steam mixture and ω^{lm} is the gas concentration logarithmic mean between the mixture bulk and the interface with the liquid film. The ratio C_s/C_m , expressing the potential effect of augmented sensible heat transfer with respect to the mass transfer, has been assumed equal to 7, as suggested in [3].

Following the heat and mass transfer analogy, the Sherwood number has been correlated to the mixture Reynolds and Schmidt numbers, as shown in Figure 14, where selected COTINCO results for condensation heat transfer in a 15° inclined pipe are reported.

The correlation is quite good for $Re_g > 2000$ (corresponding to the axis variable $0.023\ Re_g^{0.8} = 10$), taking into account the uncertainties in the evaluation of the liquid-mixture interface temperature profile, based on the assumption of a modified Chato's correlation [4] for pure steam condensation inside the tube. As expected, a wide spread of data occurs in the laminar region, where the Sherwood number has to be correlated to *Re* and *Sc* numbers using suitable correlations, and where the experimental errors are large.

C.2.3 Containment spray systems

During the course of a hypothetical severe accident in a Pressurised Water Reactor (PWR), hydrogen can be produced by the reactor core oxidation and distributed into the reactor containment according to convection flows and wall condensation. In order to assess the risk of detonation generated by a high local hydrogen concentration, hydrogen distribution in the containment has to be known. However, during such kind of accident, spray systems can be used in French PWR in order to reduce the total pressure, cool down the containment walls, assure a mixing of the atmosphere and wash-out the eventually existing fission products present in the air.

The use of this spraying system can lead to several contra-phenomena concerning the gas distribution (effects on hydrogen combustion is not considered in this report) and summarised by these two questions:

- Can the hydrogen risk be reduced by a high mixing level of the gas mixture when the spray droplets are injected?
- Can the hydrogen risk be enhanced due to the local reduction of steam, leading to higher local concentration of hydrogen due to condensation of steam on the spray droplets?

The TOSQAN facility (see Figure 15) will be used in order to bring some information and answers to these questions, by evaluating the importance of these two contradictory phenomena.

The approximated volume of a French PWR containment is ~50000 m³ (900MWe PWR) or ~75000 m³ (1300 MWe PWR). The dome volume is estimated as ~47000 m³ for the 1300 MWe PWR. The steam is generally at saturation conditions; the hydrogen concentration in case of an accident can be between 7 % and 16 %. The spray system is automatically activated when the total pressure reaches 2.6 bar.

The French containments have generally two series of 253 nozzles placed in circular rows (see Figure 16), with a total water mass-flow rate of about 560 kg s^{-1}. It can be assumed that there is one ring at height 54.5 m of a radius of 6 m and another ring at height 51 m of 13 m radius. The type of nozzles used in the French containment is a SPRACO 1713A type at which an injection pressure of 3.5 to 5.25 bar is applied. The temperature of the injected water is 20 °C or 60 - 100 °C, depending on the kind of process (the 60 - 100 °C process is the so-called recirculation mode for which the water of the spray is collected in the sump and recirculates up into the nozzles). The nozzle orifice diameter is 9.5 and 11.1 mm (French 900 MWe PWR and 1300 MWe PWR).

The variation of the flow-rate with the pressure supply has been measured under standard pressure and temperature conditions (1 bar, 20 °C). From these measurements, it can be verified that the flow-number of the real-scale nozzle is constant for different pressure levels. This is an important result since it means that the SPRACO nozzle has the same hydrodynamic behaviour as many nozzles used for general spray studies in the open literature. The spray obtained from a single nozzle is a full-cone spray having a half-angle of about 33 °. An important parameter of a spray is its mean droplet size. An experimental study has been performed leading to droplet diameters between 25 and 1000 µm. Care has to be taken with these results, since the aim of this study was not to characterise precisely the spray, but to have an estimation of the size-distribution. Considering the reduction of the droplet diameter at higher pressure and temperature (using empirical correlations), the Sauter mean diameter of the real-scale spray that has been deduced from these measurements and that are considered in the scaling analysis is 500 µm.

A first literature survey on large-scale facilities concerned with spray systems (NUPEC, CVTR, CSE) has shown that no obvious scaling laws exist. Therefore, the H2TS method has been used in order to determine the conditions of the scaling analysis for sprays in containment vessels. Three relevant phenomena have been selected: depressurisation of the containment, gas mixing by entrainment, and light gas mixing, which have been described by simple equations leading to three scaling rules. Other scaling criteria, not associated to a transfer process, are also given. They are all summarised in Table I.

The gaseous mixture material properties are taken as prototypical. Spray systems are simplified by the use of one single nozzle. Some geometrical scaling criteria are proposed. The first one (criterion C2, see Table I) consists of keeping the ratio of ‘spray occupied area’ to the horizontal cross-sectional area of the vessel constant, in order to have the same kind of space available for air recirculation. The second geometrical consideration (criterion C3) consists of keeping constant the ratio of the stopping distance of the droplets (based on the mean diameter) and the vessel total height. The third one (criterion C4) consists of considering the same injection height relative to the total height.

Concerning the scaling rules relative to transfer phenomena, the first rule (scaling rule S1) governs the heat and mass transfer processes: the scaling rule is to keep the same depressurisation rate. The scaling parameter is a frequency, consistent with the H2TS scaling method, since the gaseous mixture material properties are the same in the model and in the prototype, i.e. the pressure is the same.

The second scaling rule (scaling rule S2) leads to the definition of a second frequency, based on the ratio of the total entrainment flow-rate on the total volume of the vessel: A semi-empirical correlation is used for the entrainment flow rate. The maximum spray radius is reached when particles are at their stopping distance (diffusion and turbulence neglected). The total entrainment flow-rate for the real case is taken as the sum of all the entrainment flow-rates calculated for each single spray. Derivation of the entrainment flow-rate is more extensively described in the long version of the final report, and the assumptions that can lead to scaling distortions are given there.

The last scaling rule (scaling rule S3) consists of keeping a Froude number constant, the latter one being based on the mean flow occurring when the spray shape can be considered as constant, and considering that the light gas is initially at the top of the vessel and idealised as ‘pure bubble’.

The approach used here is proposed for the definition of spray tests in model facilities (not only for the TOSQAN experiments), but it does not pretend to be a scaling method of all phenomena occurring in the real containment during spray injection. Using the limited information available on real-spray containment systems together with the proposed scaling rules leads to the determination of the TOSQAN experimental conditions for spray tests. Comparison of the scaling ratios of the experimental and the large-scale facilities shows that they do not respect all the proposed scaling criteria.

The applicability of the scaling rules and the validity of the associated approximations will be examined once the first spray test results from the TOSQAN facility will become available. Some of the scaling rules or scaling criteria can be evaluated in TOSQAN by changing boundary conditions (especially for the spray characteristics); however, it may turn out that experiments in a test facility larger than TOSQAN are desirable to remove unwanted effects from scaling distortions.

C.2.4 Bubble condenser containment thermal hydraulics

Containment pressurisation by steam blowdown from a primary system break is currently investigated for the Russian VVER 440/213 reactor containments that have a bubbler condenser tower to provide a large water body for steam condensation. Downscaled tests are conducted in the EREC facility, and the task of the scaling analysis is to estimate suitable steam blowdown rates for the experiment that lead to representative pressure loads. The test facility is scaled down volumetrically and has a simplified arrangement of rooms, but the units of the bubbler condenser tower are in a 1:1 scale. It is well known that in a volumetrically downscaled facility the steam condensation at the walls is overestimated because of the scaling-induced change in the ratio of surface area over volume. This effect can be partly compensated by adding thermal insulation to the walls and by enhancing the blowdown rate. The scaling analysis is more complicated due to the nonlinear flow and heat transport processes in the bubbler condenser.

C.2.5 Natural convective flow processes in the containment atmosphere

During an accident transient, the mixing status of the containment atmosphere is of relevance in respect to the occurrence of combustible hydrogen concentrations or the distribution of fission products in case of containment leakage or venting. The mixing is largely determined by natural convection flow loops that have been investigated in numerous downscaled experiments. Natural convection is also important for the operation of passive autocatalytic hydrogen recombiners that have recently been installed in many plants to reduce hydrogen concentrations in the atmosphere during accidents. The heat generated inside these recombiners from the hydrogen oxidation process contributes to the buoyancy forces that may enhance or reduce the natural convection flow. Simplified (lumped parameter) models and reduced scale experiments are available. In order to support the model predictions of natural convection in prototypical containments, a scaling analysis is conducted to evaluate the contribution of recombiners to global natural flow. In addition, the contributions of heat released by distributed fission products are evaluated in a similar approach.

Natural convection flow is generated by distributed heat sources in the containment. The average atmospheric heat release in the scaled experiment should be the same as in the prototype in order to preserve realistic temperature levels. In order to establish realistic convection flow velocities in the experiment, the relative distribution of the heat sources with respect to elevation and horizontal position must be similar. The mass flow rate G of a global natural circulation flow loop can be estimated by

$$G^3 = \frac{2\beta\rho_0^2 A_0^2 g}{\zeta c_p} \int_0^h \int_0^z q(x)\,dx\,dz$$

where q(x) is the distribution of heat sources along the flow path (co-ordinates x and z), β the thermal expansion coefficient of the atmosphere, ρ_0 the reference density of the atmosphere, A_0 a representative flow cross section, h the containment height, g the gravitational acceleration, c_p the specific heat of the atmosphere and ζ an effective flow resistance coefficient. This relation can be used as basis of the scaling analysis. For the distribution of heat sources, two cases are considered:

- Homogeneous distribution of heat inside a subcompartment $q(x) = \frac{Q}{h}$, e.g. radioactive suspended aerosols
- Local heat sources at certain elevations $q(x) = \sum_i Q_i \delta(x - h_i)$, e.g. deposited aerosols on a subcompartment floor or catalytic recombiners (at elevation h_i)

From the mass flow rate G and the containment volume V, an effective mixing time t_{mix} due to natural convection can be estimated for both experiment and prototype. The ratio of these two mixing times, denoted by the expression $(t_{mix})_R$, is in the first case (homogeneous sources)

$$\left(t_{mix}\right)_R = \left(\frac{\zeta}{A_0^2}\frac{V^2}{h}\right)_R^{1/3}$$

and in the second case (discrete heat sources Q_i)

$$\left(t_{mix}\right)_R = \left(\frac{\zeta}{A_0^2} \frac{V^3}{\sum_i Q_i \left(h - h_i\right)} \right)_R^{1/3}$$

From these relations it can be seen that the mixing time scales approximately proportional to $(\zeta\, h)^{1/3}$.

The local acceleration of buoyant flow due to heat addition in a subcompartment with height h is governed by a local Richardson number R

$$R = \frac{gh\beta\Delta T}{u^2} = -\frac{gh\Delta\rho}{\rho u^2}$$

where u is a characteristic local flow velocity, and ΔT the local temperature rise. In order to have the same relative flow changes of the model and prototype configuration, the scaling condition

$$\left(1 - \frac{\rho\zeta}{\rho_0 R}\right)_R = 1 \text{ or } \frac{\zeta_M}{R_M} = \frac{\zeta_P}{R_P}$$

should be fulfilled (M denotes model or experiment, P prototype).

For autocatalytic passive recombiners operating under natural flow conditions, the same relations can be applied. The box-type recombiner modules used in the experiments often differ from those in the real containment by their flow cross-sectional area only, while all other characteristics (height, packing density of catalytic surfaces, flow resistance etc.) are the same. To a first approximation, the recombiner capacity can be scaled proportional to its flow cross section. Scaling distortions arise from the heat losses at the box surfaces. The relative heat losses are scaled proportional to the ratio of recombiner box surface over volume A/V, so a smaller test box has relatively larger heat losses.

The start of natural convective flow through the recombiner box is governed by the thermal inertia of the structural materials. The characteristic time to establish equilibrium conditions for the recombiner flow rate is proportional to the product of the structural mass and its heat capacity.

The average rate of hydrogen consumption by recombiners is roughly proportional to the installed recombination capacity or the total area of catalytic surfaces A. Therefore, the characteristic time t for reducing the average hydrogen concentration is proportional to the ratio of total hydrogen mass over catalytic area, or

$$t \sim p\, V / A$$

where p is the pressure and V the containment volume. This is the suitable time scaling relation to compare hydrogen concentration transients in experiment and prototype.

A numerical simulation of an accident transient in a Konvoi PWR (Figure 17) was done to assess the hydrogen related safety issues. For comparison, results of recombiner experiments in the Battelle Model Containment (BMC, Figure 18) are available. Transient hydrogen concentration data from the experiment and the prototype simulation are shown in Figure 19. The time scale of the experimental data was adjusted in this figure according to the scaling rule given above. The comparison shows roughly comparable transient behaviour. Differences are mainly related to the inhomogeneous hydrogen distribution in the PWR model which cannot be taken into account in the scaling analysis. It can be concluded that the hydrogen injection rates and the recombiner capacities applied in the experiment are scaled in a suitable way.

With reference to fission product decay heat effects in the containment, the following scaling rules were established:

- Equal volumetric decay heat releases
- Equal relative positions of decay heat sources and steam sources
- Similar mixing times

Table II summarises the requirements for experiments that follow from these rules, together with some indication of magnitudes in the reactor case.

The only containment experiments with radioactive aerosols were done in the Phebus facility, Figure 20. In Table III the characteristic parameters of the Phebus experiment FPT1 are compared to reactor conditions in order to assess the scaling of decay heat effects. Obviously these effects are not adequately represented in the experiment. It can be concluded that containment experiments sensitive to decay heat effects are presently not available.

C.3 Scaling of material behaviour

C.3.1 Cable ageing

In addition to the scaling studies mentioned above that are related to thermal hydraulics, fluid and structural mechanics, experiments related to material ageing were analysed. As an example, the reliability of safety-related cable in the containment must be assured until the end of the plant lifetime including a potential DBA and post DBA. The cable polymeric materials are exposed to enhanced temperature and radiation doses to simulate an accelerated ageing process. In this case the scaling is done on the time axis. The parameter which describes the quality of the cable material is the elongation at break which decreases with increasing thermal and radiation ageing. The change in the elongation at break is related to polymer degradation. The thermal ageing can be modelled by the Arrhenius equation

$k(T) = k_0 \exp\text{-}(E/RT)$,

where k is the parameter change rate, E the activation energy (a material specific parameter), R the ideal gas constant and T the temperature. According to this equation, a scaled acceleration of the rate of thermal ageing can be achieved by exposure to an enhanced temperature. The dimensionless number for this process is the Arrhenius number Arr = E/RT. A scaled acceleration of the rate of radiation ageing can be achieved by exposure to higher dose rates than operational. Laboratory experiments are conducted to determine reliable dose rates of gamma radiation to simulate operational NPP ageing which is characterised by homogeneous oxidation of the cable polymeric material. The homogeneous oxidation means that the rate of oxygen consumption is comparable to the oxygen diffusion from the surrounding atmosphere. The characteristic dimension is the thickness of the cable material L, which leads to the scaling relation $L = (a/b)^{1/2}$, where a is the oxygen diffusivity and b the oxygen consumption rate by thermal and/or radiation ageing.

In DBA and post DBA conditions, the thermal and radiation ageing is accompanied by interactions with high pressure of water steam and chemicals, forming a very complex environment which makes the scaling of the cable ageing difficult. The scaling analysis is therefore directed to specification of experimental procedures for reliable simulation of the cable ageing under these conditions.

C.3.2 Containment penetration sealing

Material ageing is also involved in the ATHERMIP experiments where the tightness of gaskets for containment airlocks was tested. When the containment atmosphere is pressurised during an accident transient, the gaskets are exposed to high mechanical stress and enhanced temperature levels which lead to plastic deformation. When the pressure decreases during later stages of the transient, the gasket should expand sufficiently to maintain leaktightness. The ability to fulfil this requirement will decrease with increasing material age and embrittlement.

C.3.3 Cracking and leakage through concrete walls

The French reactors have containments built from prestressed concrete. The CESA experiments were conducted on a downscaled concrete building to investigate the behaviour of potential cracks under internal pressure loads and associated leakage flow. The geometries of model and prototype are shown in Figure 21.

In addition to pressure loads, a time-dependent temperature load at the inner surface was applied. Scaling distortions occur between horizontal and vertical stresses due to their interrelation by the applied pressure load. Radial displacements in the experiment are strongly reduced in comparison to the prototype. An analysis to determine dimensionless numbers was based on the relevant parameters shown in Table IV. The matrix manipulations to derive dimensionless numbers from this table are described e.g. in [5], the results are:

$\Pi_1 = r_i / w = e / w$

This number requires geometric similarity of radius r_i, wall thickness e, and crack width w.

$\Pi_2 = \rho_s = \rho_p$

The same fraction of reinforcement steel in axial and circumferential direction should be used.

$\Pi_3 = \rho C w^2 / (\lambda t)$

This number gives the reduction of time scale due to heat conduction.

$\Pi_4 = h_e (T_m-T_{se}) t / (\sigma w) = h_i (T_m-T_{se}) t / (\sigma w) = \lambda (T_m-T_{se}) t / (\sigma w e)$

This is the interrelation of heat transfer, thermal conductivity and time.

$\Pi_5 = E_c \alpha (T_m-T_{se}) / [\sigma (1-\nu)]$

This number relates thermal and elastic stresses.

$\Pi_6 = f_{ctm}/ p_i = E_s/ p_i$

Elastic properties are related to the containment pressure.

$\Pi_7 = p_i / \sigma$

Relation between pressure and stresses.

Time dependent temperature profiles in the wall were determined by heat conduction calculations for the model and the prototype, in order to establish the basis for estimating thermal stresses.

It can be concluded from the dimensionless numbers that the product of containment radius and heat transfer coefficient r_i h_e should be invariant, a condition which is closely fulfilled in the

CESA experiment by suitable enhancement of the external heat transfer coefficient h_e. The wall thickness e is scaled 1:1 in the experiment, but the radius is not. This means that scaling distortions are present in the experiment.

Pressure, stresses and crack width are strongly interrelated in the CESA facility. Due to the scaling distortion, the pressure boundary condition for the leakage rate is distorted in a similar way. In other tests discussed in the project, crack width and pressure can be adjusted separately, thus giving more controlled boundary conditions for the leakage flow rate measurement.

C.2.4 Steel structures under dynamic loads

Under postulated reactor accident conditions, a steam explosion in the pressure vessel may accelerate core materials which could damage the vessel by impact and generate missiles in the containment. In the FLIPPER experiments, impact loads of accelerated water plugs were investigated in a downscaled facility shown in Figure 22.

The impact effect is measured in terms of the deflection angle φ of the target plate which is related to the plastic deformation of the bending joints indicated in Figure 22. Test with different scaling were conducted to investigate a potential scale dependency. The results in the lower part of the figure show that the results are nearly scale independent, a slight variation is attributed to small creep effects (viscous effects). It can be concluded that a scale extrapolation from the test section diameter of 0.25 m to the prototype pressure vessel diameter of 5 m (factor 20) should be possible.

The theoretical scaling analysis is based on the differential equations that describe the force balance of the elastic-plastic structures and the momentum conservation of the liquid water. The equations are invariant under scaling if

- length and time co-ordinates are scaled by the same factor, and
- materials are the same.

This implies that the impact velocities should be invariant.

CONCLUSIONS

From the experience with the analysis of a wide variety of scaled experiments in the SCACEX project, the following conclusions can be drawn. While a number of different methods for conducting scaling analysis is available, in practical application several difficulties show up.

First, scaling considerations are not always a normal generic component of an experimental investigation. In some cases, this may reflect, to a certain extent, the traditional separation between experimental and theoretical work, which could be considered as a lack of interdisciplinary co-operation. On the other hand, in some fields like, e.g., heat transfer research, scaling based on dimensionless numbers has a well established tradition, while in other areas, scaling analysis has not been established, and its feasibility or usefulness are not obvious. This is especially true when small scale, separate-effects tests are designed to investigate specific mechanisms. In this case, scientists postpone questions of applicability to prototypical conditions and prefer to concentrate efforts on revealing the subtle aspects of the underlying physics.

Second, processes in the containment are characterised by complex interactions of multiple phenomena. Scaling analysis necessarily involves a simplification step aiming at ranking the relative importance of the phenomena, which is difficult to take. The scientist can never be very sure about the justification for leaving out phenomena that are considered to be less important.

Intuitively, the experimentalist would be more interested in discovering unexpected details in his results, instead of going to the simplification step.

Third, generating practical results by conducting a scaling analysis is not straightforward in fields where no such routine practice exists. Finding and interpreting the proper dimensionless numbers, formulating the correct simplified differential equations, or setting up simple but meaningful analytical solutions can be a challenging theoretical task, which cannot be resolved just by taking textbook information. Available methods of scaling analysis describe very fundamental and general approaches, but their transformation into a practical application requires substantial extra effort. Big collections of application examples exist, like, e.g., [Szirtes 1998], giving the impression of almost universal applicability, but the search for an example that can be used as easy guidance for the actual problem fails in many cases.

Fourth, scaling analysis can lead to unexpected results, whenever it was not explicitly considered at the beginning of the study. In the best case of success the applicability of the downscaled experimental results to the prototype can be firmly established; however, it may also turn out that the transfer to prototypical conditions is completely or partly impossible. The latter conclusion may be anyway useful for two purposes:

- to show to what extent the obtained experimental data can still be useful for evaluating prototype behaviour and providing limits for their applicability;
- to suggest the way for planning further experimental activities aimed at collecting data more representative of prototypical conditions.

Fifth, in order to avoid such unexpected results, scaling analysis should be applied in the planning phase of experimental programmes. However, successful completion of such analysis requires a good understanding of the phenomena and parameter ranges. Often this understanding can only be achieved after having executed the experimental work. This difficulty is very common in science, and it is generally overcome by cyclic iteration of experiment and analysis.

Sixth, often experiments are intended to generate data for validation of computer models and codes. Application of a validated computer code to predict prototypical conditions does not automatically resolve the scaling issue, and may even introduce additional complexity due to numerical and modelling approximations. Scaling analysis may be supported by computer simulation if the calculation can be carefully controlled and understood, but it cannot be replaced by computer simulation alone.

Project partners initially found difficult to apply the PIRT technique because of some of the above mentioned reasons. It must be recognised that previous PIRT projects in nuclear reactor technology were large undertakings, involving dozens of engineers and many man-years of work. Moreover, the character of separate-effects tests of some investigations implied a previous identification and ranking of phenomena at the prototype level, leaving only the possibility of more detailed phenomena consideration. After some discussion, a “downscaled” application of PIRT was anyway undertaken by most partners, by setting up a table of phenomena and adding a set of rankings individually. It was generally concluded that even this oversimplified application of the method turned out to be a highly beneficial tool for improving the structure and completeness of the analysis.

The SCACEX results confirm the power, elegance and usefulness of the scaling methodology in the area of nuclear reactor containment research, but also demonstrate problems associated with practical application of the theory. The collection of examples in this report may provide a useful reference for supporting future analyses in related fields.

The SCACEX project work has extensively taken benefit from the co-operation of several European institutions. Because of the wide scope addressed in the scaling analyses, the necessary expertise to conduct such work can hardly be found on a national level. The information exchange between the partners has lead to substantial enhancements of the scaling studies, some of which resulted in innovative treatments of important topics in reactor safety research. This is a clear evidence of a European added value to the outcome of the Thematic Network.

The network participants have agreed to maintain the network connection in future. The SCACEX activities were restricted to containment applications in order to find out the feasibility and usefulness of a multi-partner project on scaling methods. In view of the success achieved by the project work, it appears highly desirable to extend the work to other important reactor safety areas like primary system and core melt behaviour. Especially, scaling analyses related to the use of non-prototypical materials should be added. Such extension may be done by enlargement of the existing network and systematic additions of new scaling analyses to the present collection from the SCACEX project. The ultimate goal of such activity would be to establish a comprehensive reference on scaling analysis for nuclear engineers.

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TABLES

Table I: Summary of the proposed scaling rules and scaling criteria for spray systems in containment applications

Scaling criteria	
(C1)	gas conditions scaled 1:1
(C2)	$\left(\frac{S_{spray}}{S_{tot}}\right)_{real}=\left(\frac{S_{spray}}{S_{tot}}\right)_{model}$
(C3)	$\left(\frac{D_{stop}}{H}\right)_{real}=\left(\frac{D_{stop}}{H}\right)_{model}$
(C4)	$\left(\frac{H_{inj}}{H}\right)_{real}=\left(\frac{H_{inj}}{H}\right)_{model}$
Scaling rules	
(S1) Depressurisation	$\left(\frac{dP}{dt}\right)_{real}=\left(\frac{dP}{dt}\right)_{model}$
(S2) Gas entrainment	$\left(\frac{Q_{entr}}{V}\right)_{real}=\left(\frac{Q_{entr}}{V}\right)_{model}$
(S3) Light gas mixing	$(Fr)_{real}=\left(\frac{t_{buoy}}{t_{conv}}\right)_{real}=(Fr)_{model}=\left(\frac{t_{buoy}}{t_{conv}}\right)_{model}$

D_{stop} : particle stopping distance
Fr : Froude number
H : total height of a vessel
H_{inj} : spray injection height
P : initial total pressure (before spray injection)
Q_{entr} : gas entrainment flow-rate
S_{spray} : maximum horizontal surface of the spray
S_{tot} : total horizontal surface of the cylindrical part of the containment
t : time
t_{buoy} : characteristic time for buoyancy
t_{conv} : characteristic time for forced/induced by the spray convection
V : total volume of a vessel

Table II: Scaling requirements for natural convection decay heat experiments

Scaling rule	**Requirements for experiments**
(1) Equal volumetric decay heat release rates $\frac{\dot{Q}_{DH,E}}{V_E} = \frac{\dot{Q}_{DH,P}}{V_P}$	High volumetric decay heat release rates, e.g. $\frac{\dot{Q}_{DH,P}}{V_P} =$ 140 W/m^3 (German PWR) Also required: equal decay heat to latent heat (steam) release rate ratio $\frac{\dot{Q}_{DH,P}}{\dot{Q}_{St,P}} =$ 0,2 - 1,5 (German PWR) This ratio influences the relative humidity.
(2) Equal relative positions of heat and steam sources and sinks $\frac{h_E - h_{i,E}}{h_E} = \frac{h_P - h_{i,P}}{h_P}$	Similar partition of the decay heat releases in the containment e.g. $\dot{Q}_{DH,atm}$: $\dot{Q}_{DH,wet}$: $\dot{Q}_{DC,Str}$ = 1:5:2 (German PWR) $\dot{Q}_{DH,water}$ contains releases in sump and other water pools. This fraction may be smaller in other reactor cases. It influences rh. The relative spatial distribution of the decay heat sources especially their elevation must be similar in the experiment and the prototype.
(3) Similar mixing times $\frac{t_{mix,E}}{t_{mis,P}} = \sqrt[3]{\frac{\zeta_E \cdot h_E}{\zeta_P \cdot h_P}} \approx 1$	The mixing time ratio $t_{mix,E}/t_{mix,P}$ does not depend on $\dot{Q}_{DH}$ if the scaling rules (1) and (2) are fulfilled. This is valid for decay heat area sources (layer of settled FP or heated structures) as well as for volume sources (airborne FP) Compared to non-radioactive experiments no additional measures are required.

$\dot{Q}_{DH}$	decay heat release rate
$\dot{Q}_{St}$	steam latent heat release rate
V	volume
h	containment height
h_i	elevation of decay heat source i
ζ	flow loss
A	containment surface area

Subscripts:

E	experiment
P	prototype
atm	atmosphere
wat	water
str	structure

Table III: Comparison of Phebus and PWR characteristics

	Phebus FPT1	**Konvoi PWR**
Volume [m^3]	10	71 000
Height [m^3]	5	60
Surface/Volume [1/m]	0.23 (for wet condenser only)	0.65
Decay heat per volume [W/m^3]	5	150
Ratio of decay heat to latent heat	0.011 (during injection)	0.2 - 1.5
Wall/condenser temperature	controlled	-
Mixing time ratio, $t_{mix,E}/t_{mix,P}$	0.44	1

Table IV: List of relevant parameters for the CESA experiments

Unit	T_m-T_{se}	time t	σ	w	r_i	e	ρ C/ λ	h_e, h_i, λ/e	E_c α/(1-ν)	ρ_s , ρ_p	f_{ctm}	E_s	p_i
Mass	0	0	1	0	0	0	0	1	1	0	1	1	1
Length	0	0	-1	1	1	1	-2	0	-1	0	-1	-1	-1
Time	0	1	-2	0	0	0	1	-3	-2	0	-2	-2	-2
Temperature	1	0	0	0	0	0	0	-1	-1	0	0	0	0

FIGURES

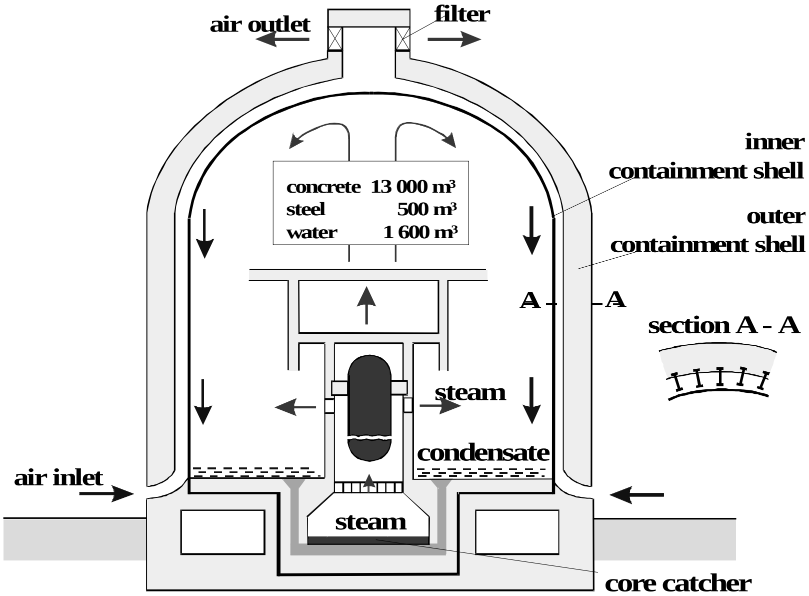


Figure 1: Composite reactor containment arrangement

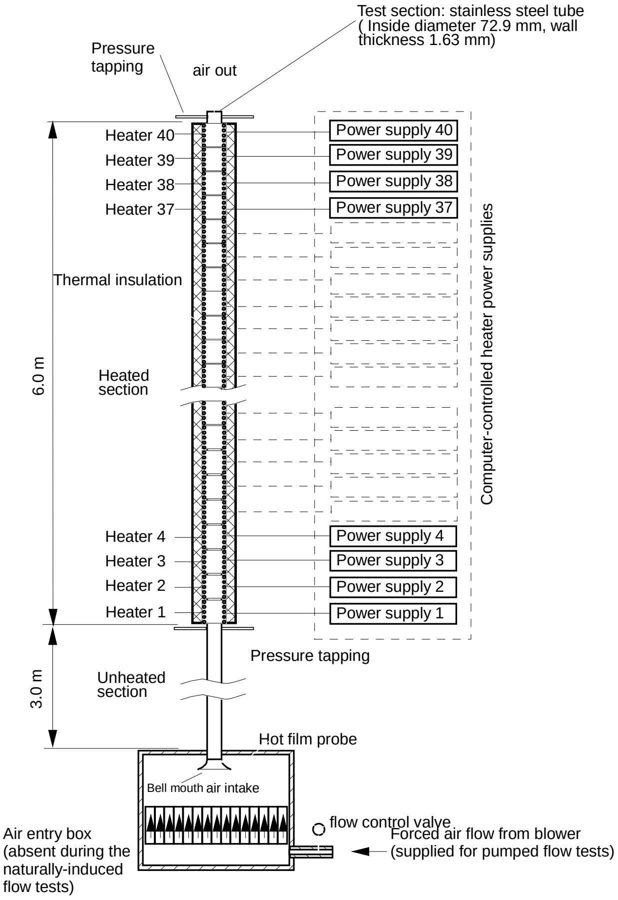


Figure 2: General arrangement of NICE

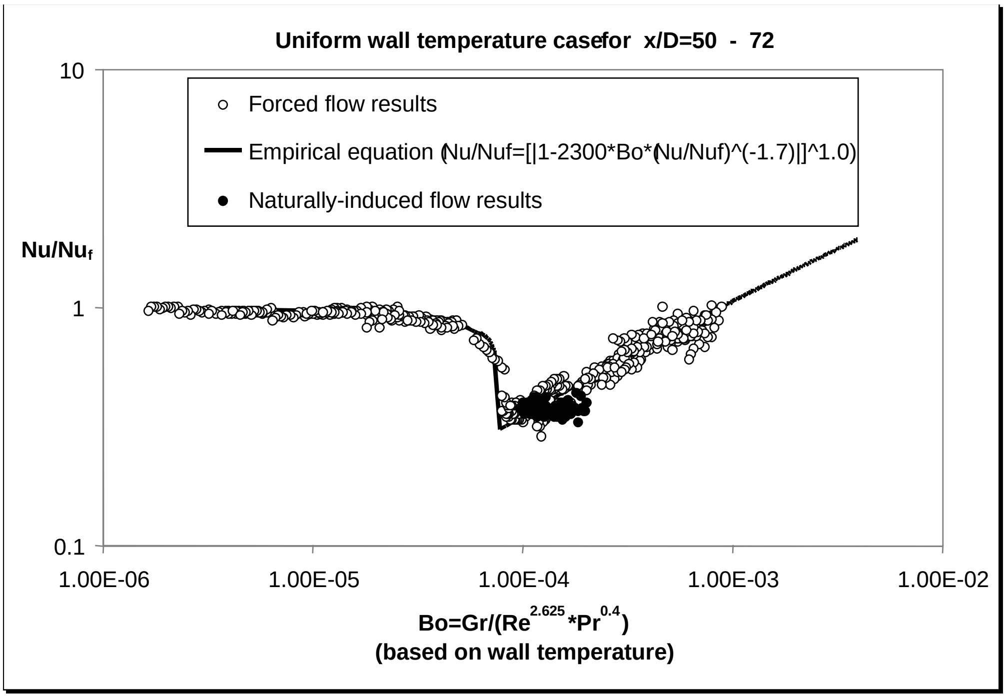


Figure 3: Heat transfer results from NICE

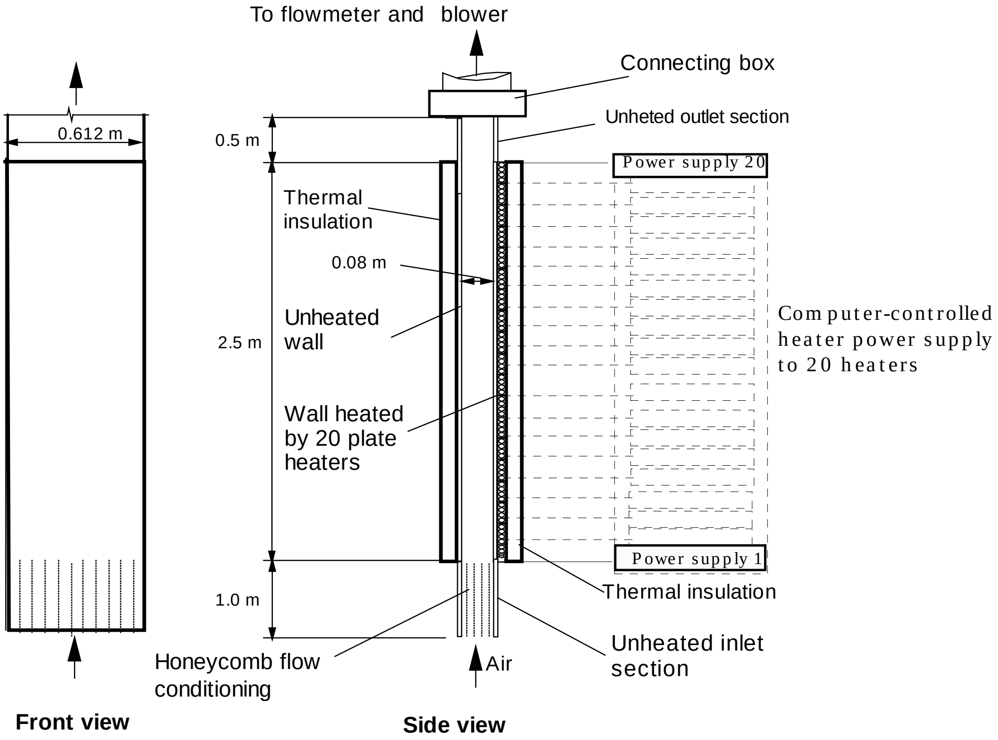


Figure 4: The PACE test section

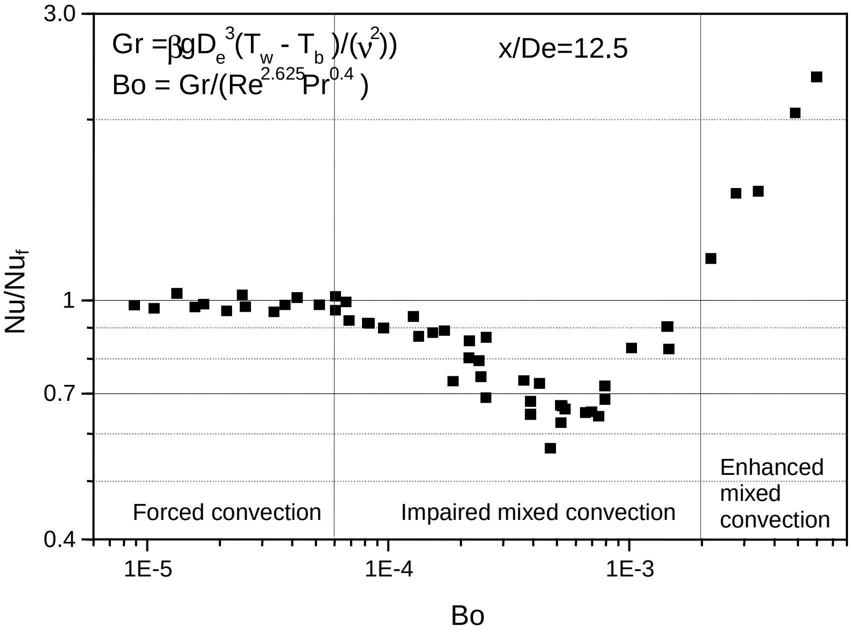


Figure 5: Correlation of PACE heat transfer data in terms of Nu/Nu$_f$ and Bo

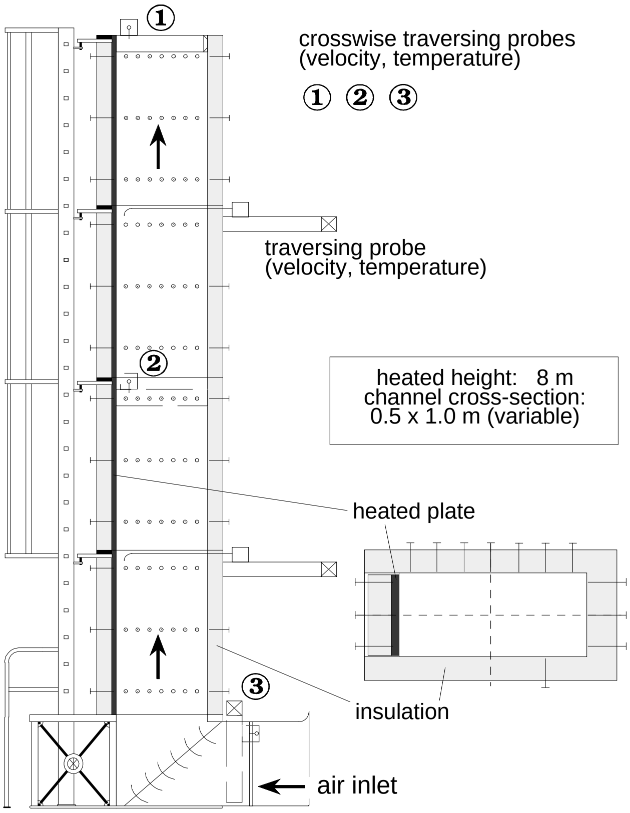


Figure 6: The PASCO experiment

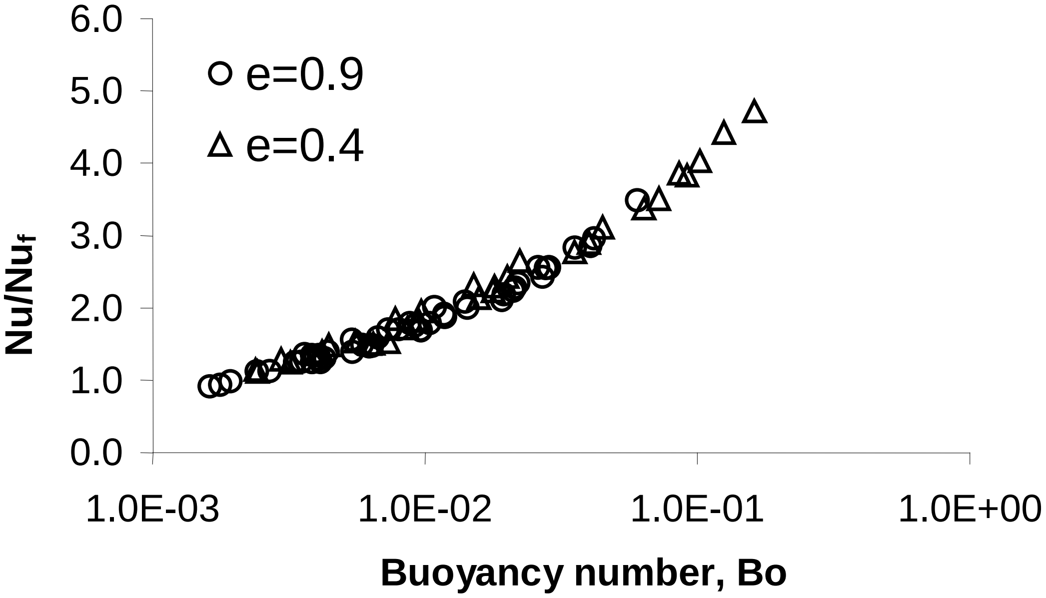
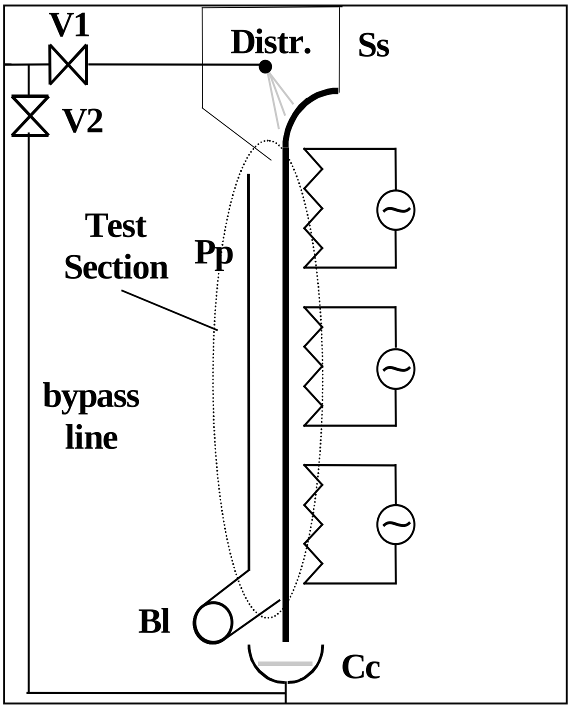


Figure 7: Ratio of Nusselt number to that for forced convection



Cc = Collecting container
Pp = Plexiglas plate
Ss = Spray system
Bl = Blower
V1, V2 = Valves

Figure 8: EFFE experiment on water film evaporation at a heated surface

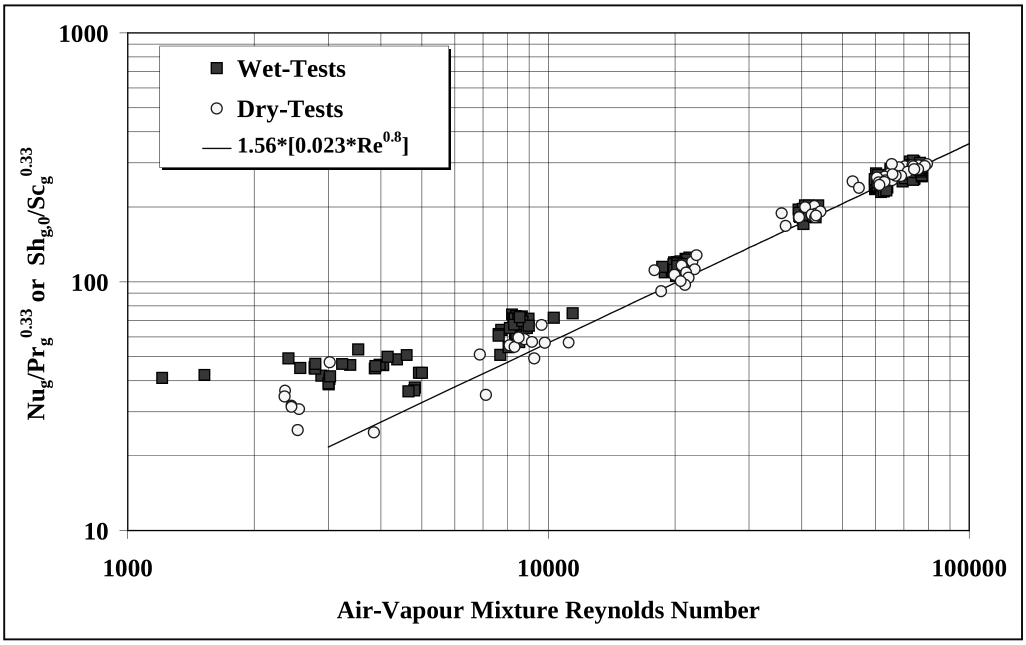


Figure 9: Results of EFFE tests for heat transfer by evaporation

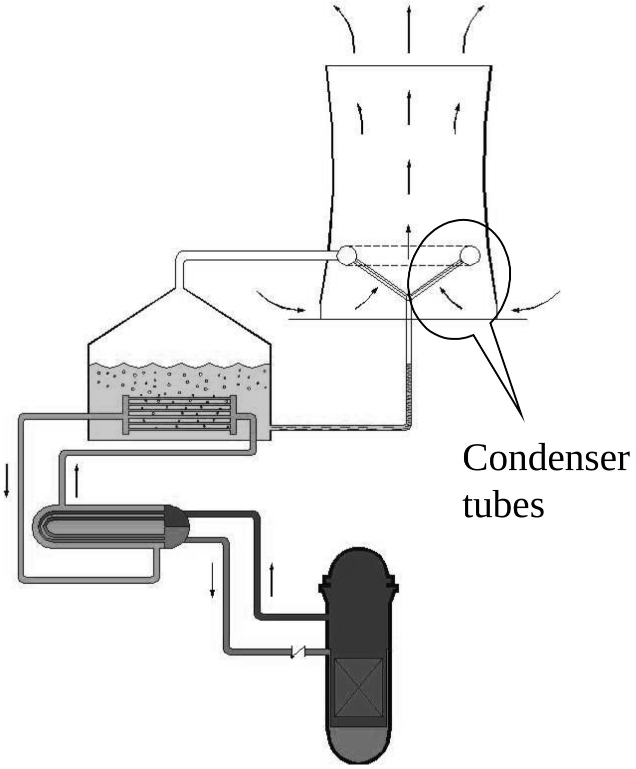


Figure 10: MARS passive containment cooling system

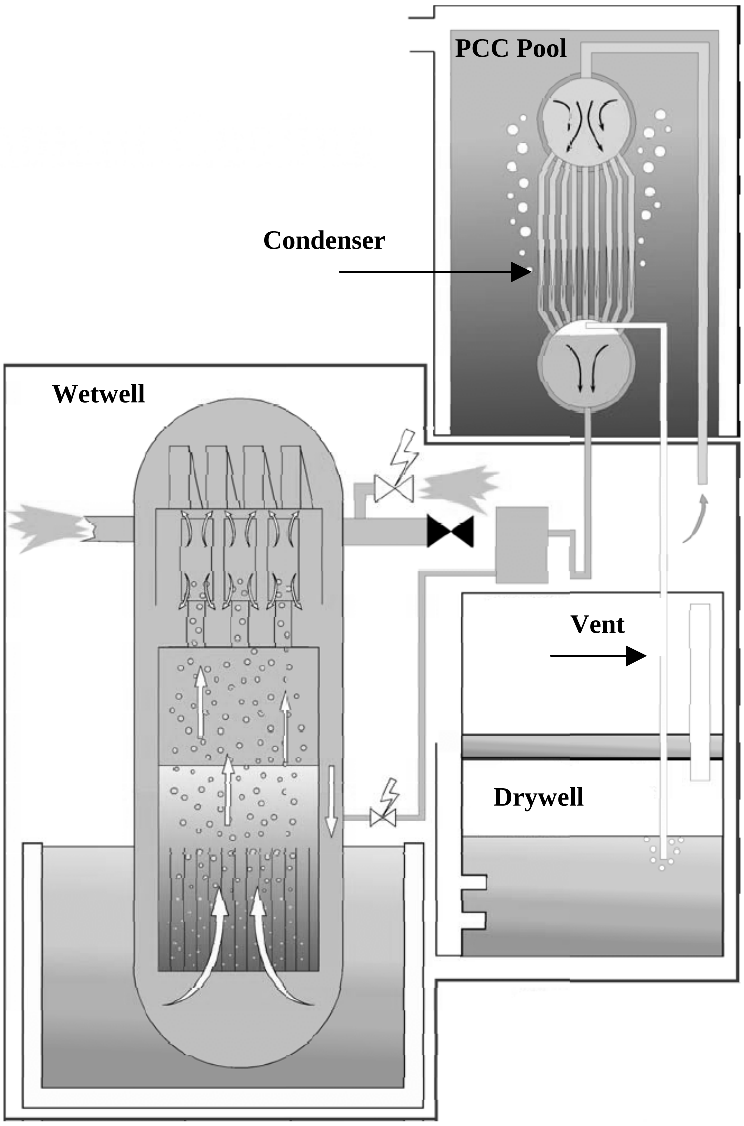


Figure 11: ESBWR Passive Containment Cooling System: pool-immersed vertical condenser

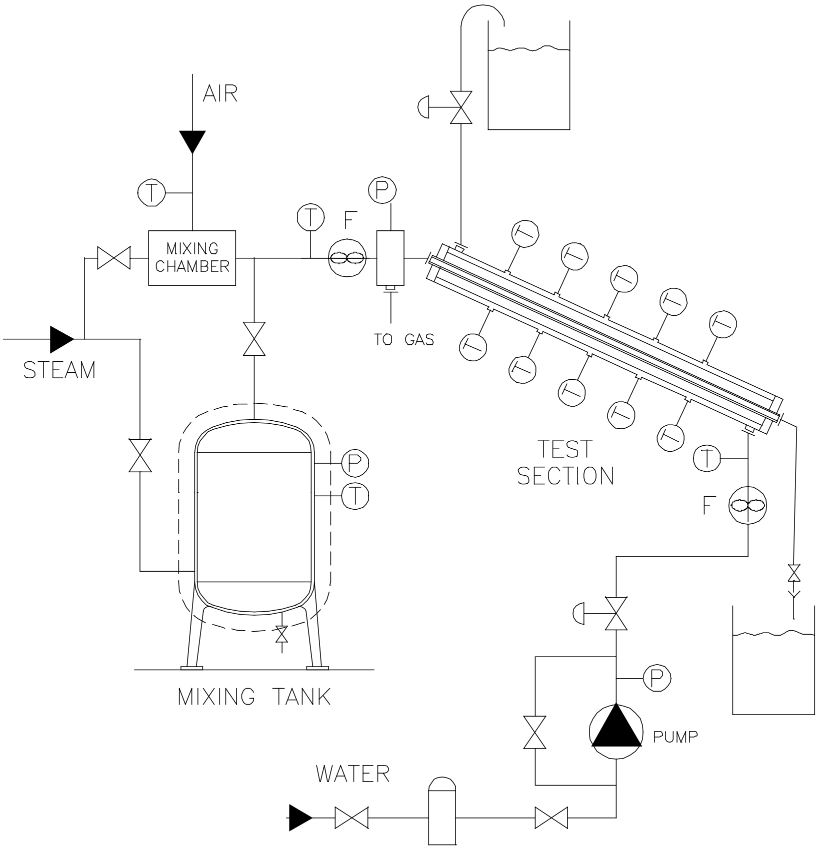


Figure 12: COTINCO facility

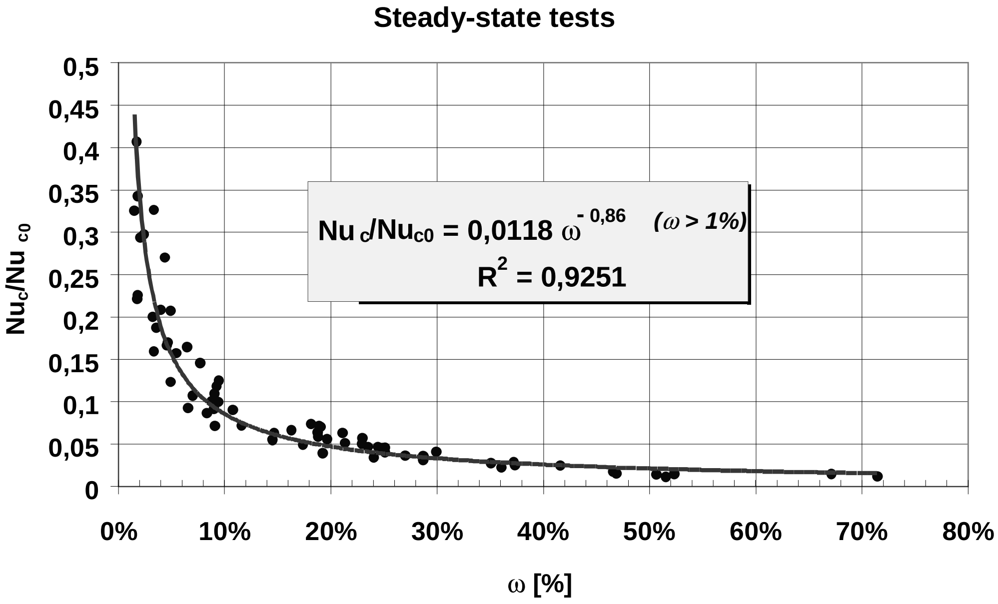


Figure 13: COTINCO results on condensation heat transfer

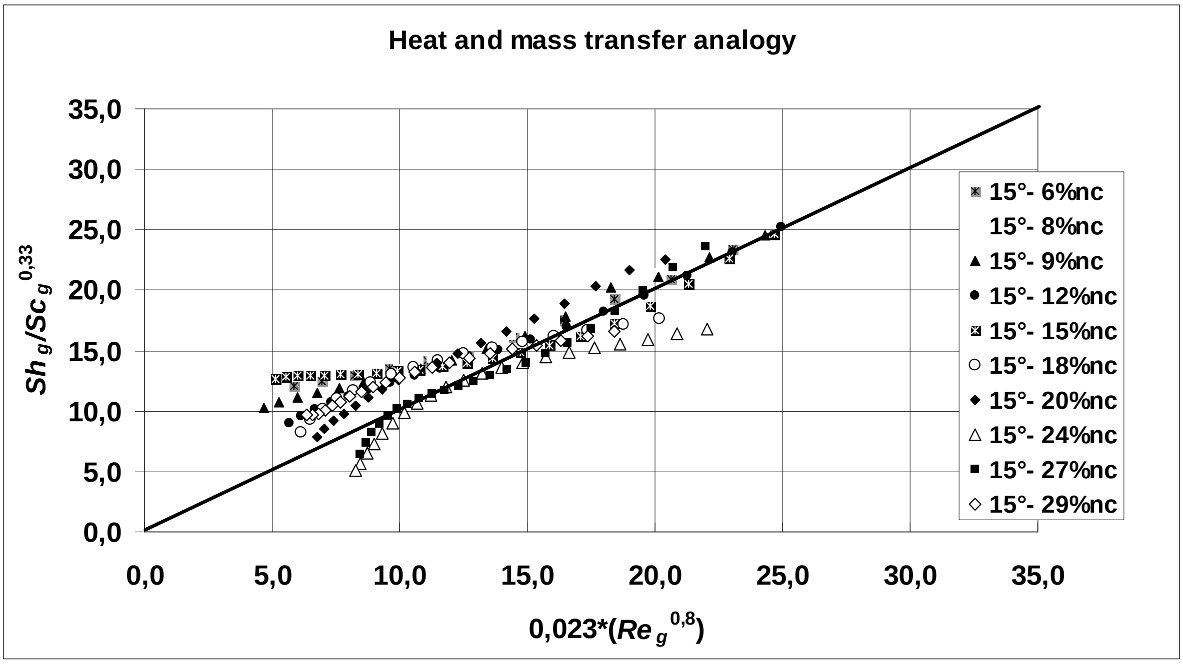


Figure 14: Heat and mass transfer analogy for in-tube condensation with air

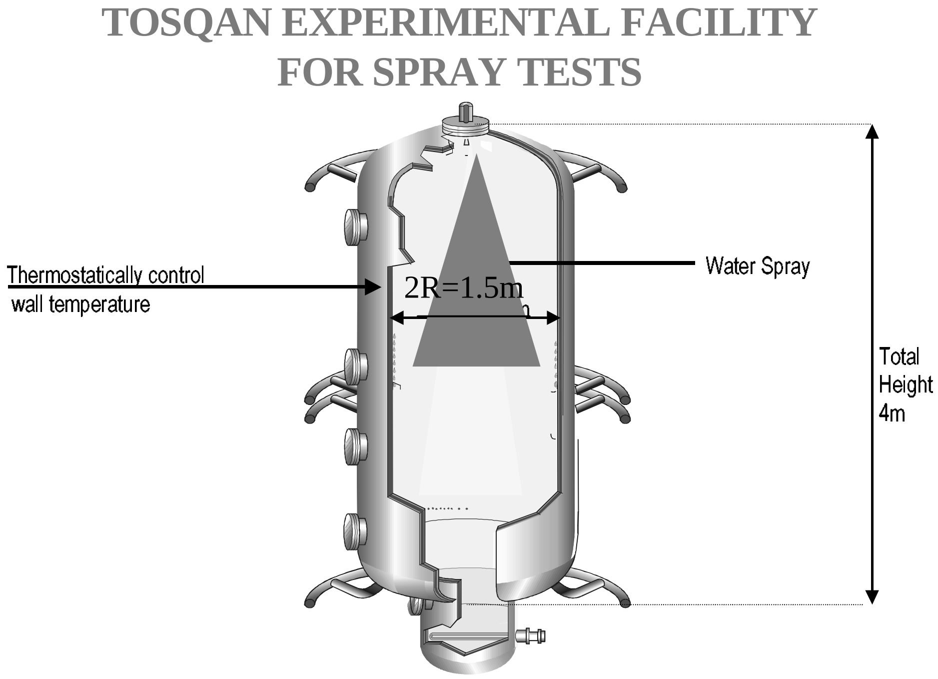


Figure 15: TOSQAN experimental facility for spray tests

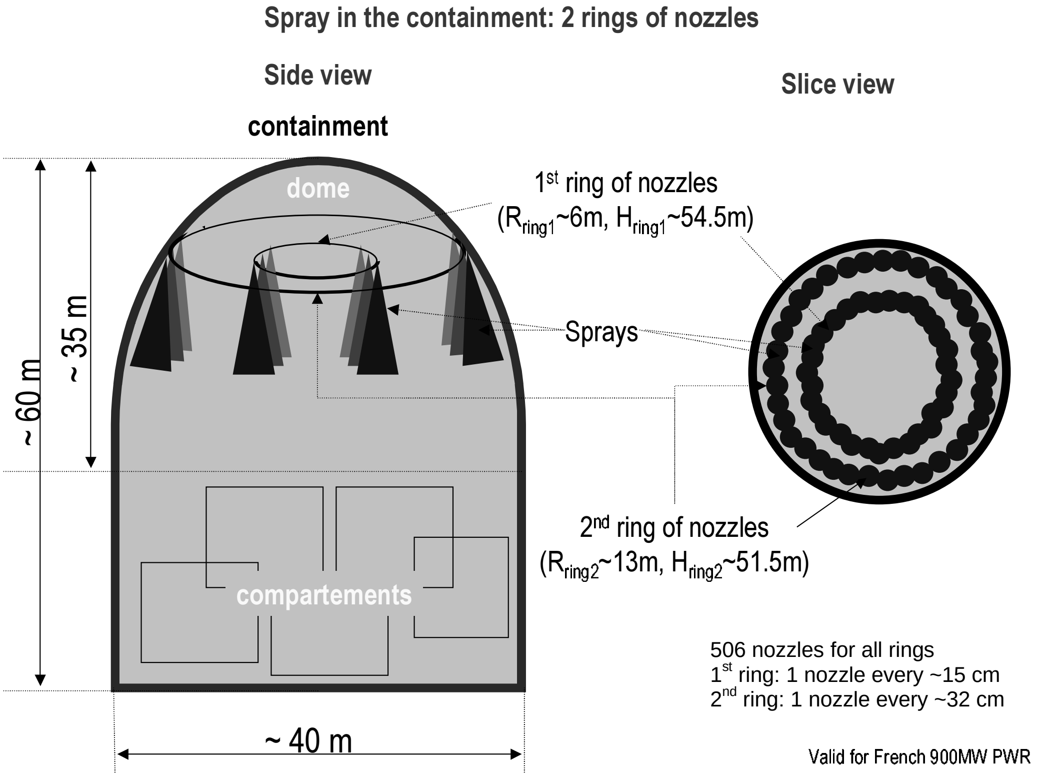


Figure 16: Spray in PWR (not at scale)

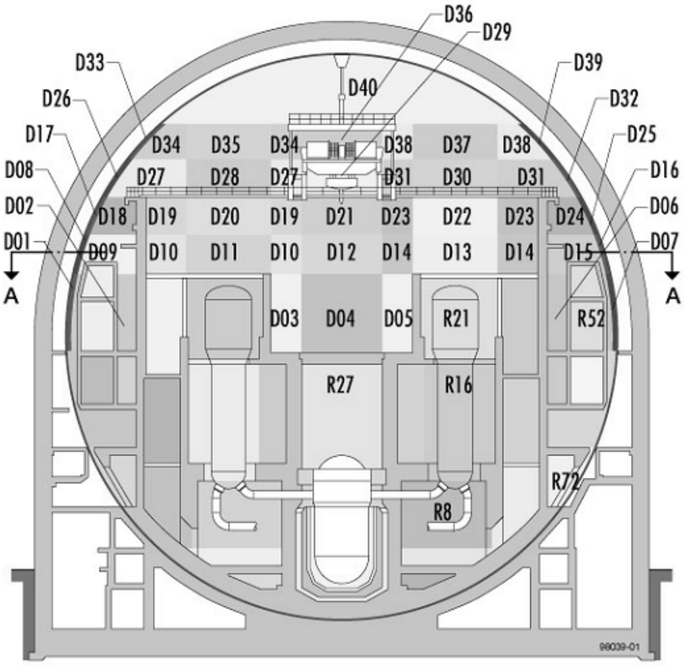


Figure 17: Simulation model of Konvoi PWR

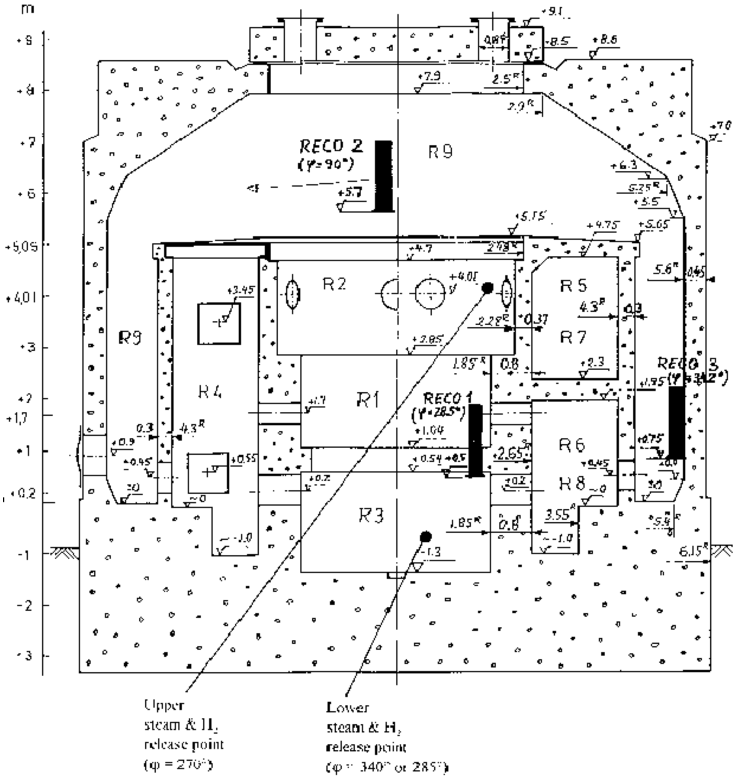


Figure 18: Battelle Model Containment with recombiners

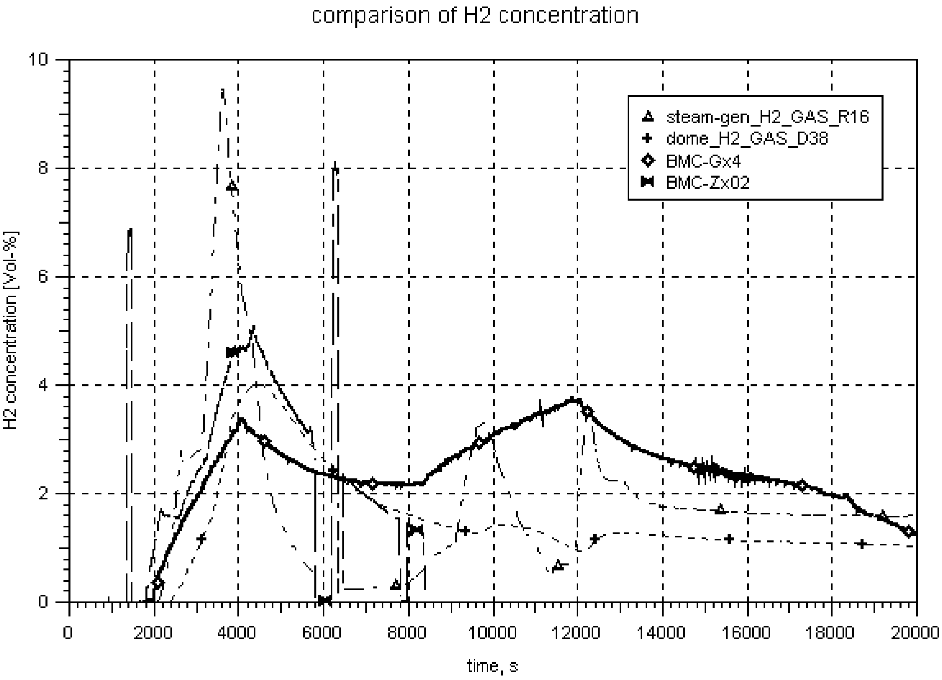


Figure 19: Hydrogen concentration transients in experiment and PWR simulation

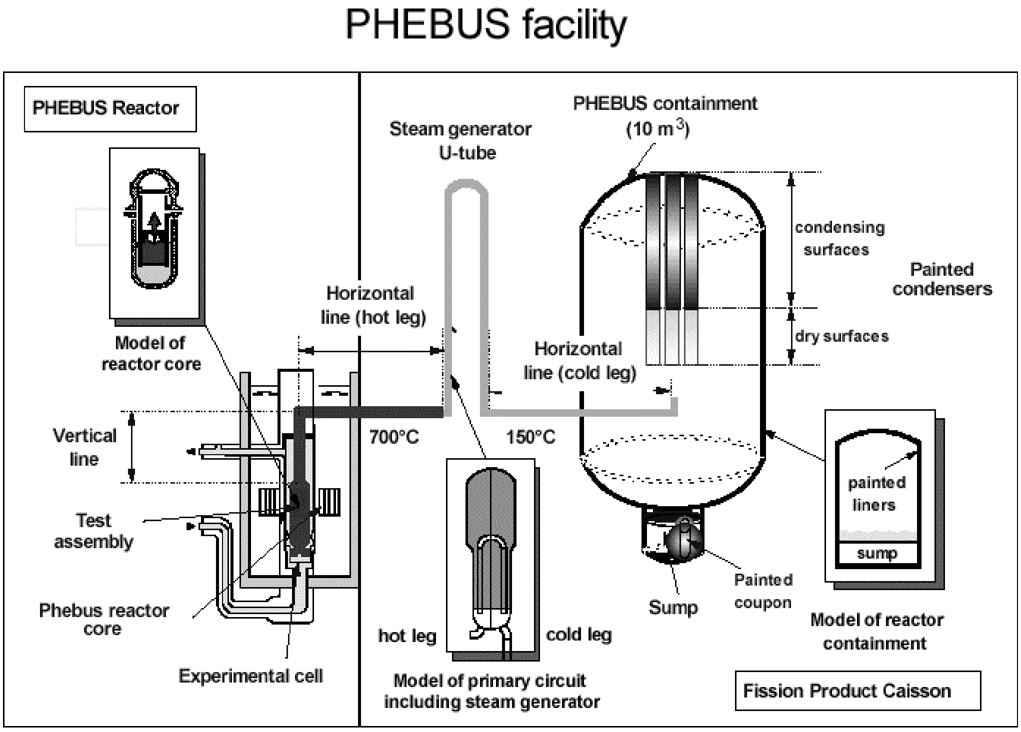


Figure 20: Phebus FP test facility scheme

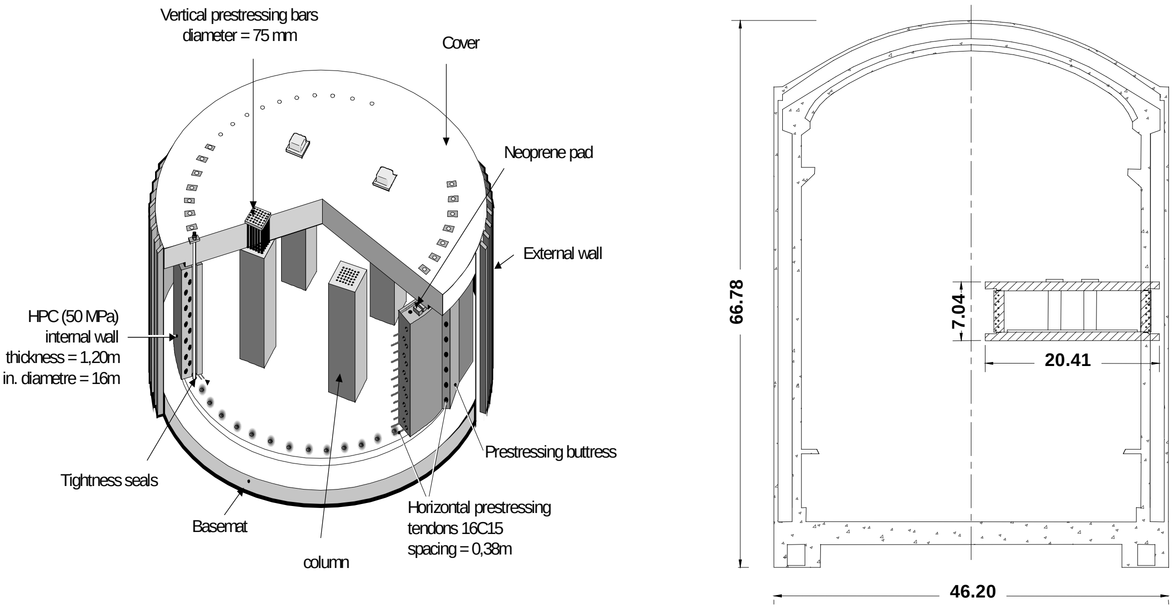


Figure 21: CESA experiment (left) and containment (right)

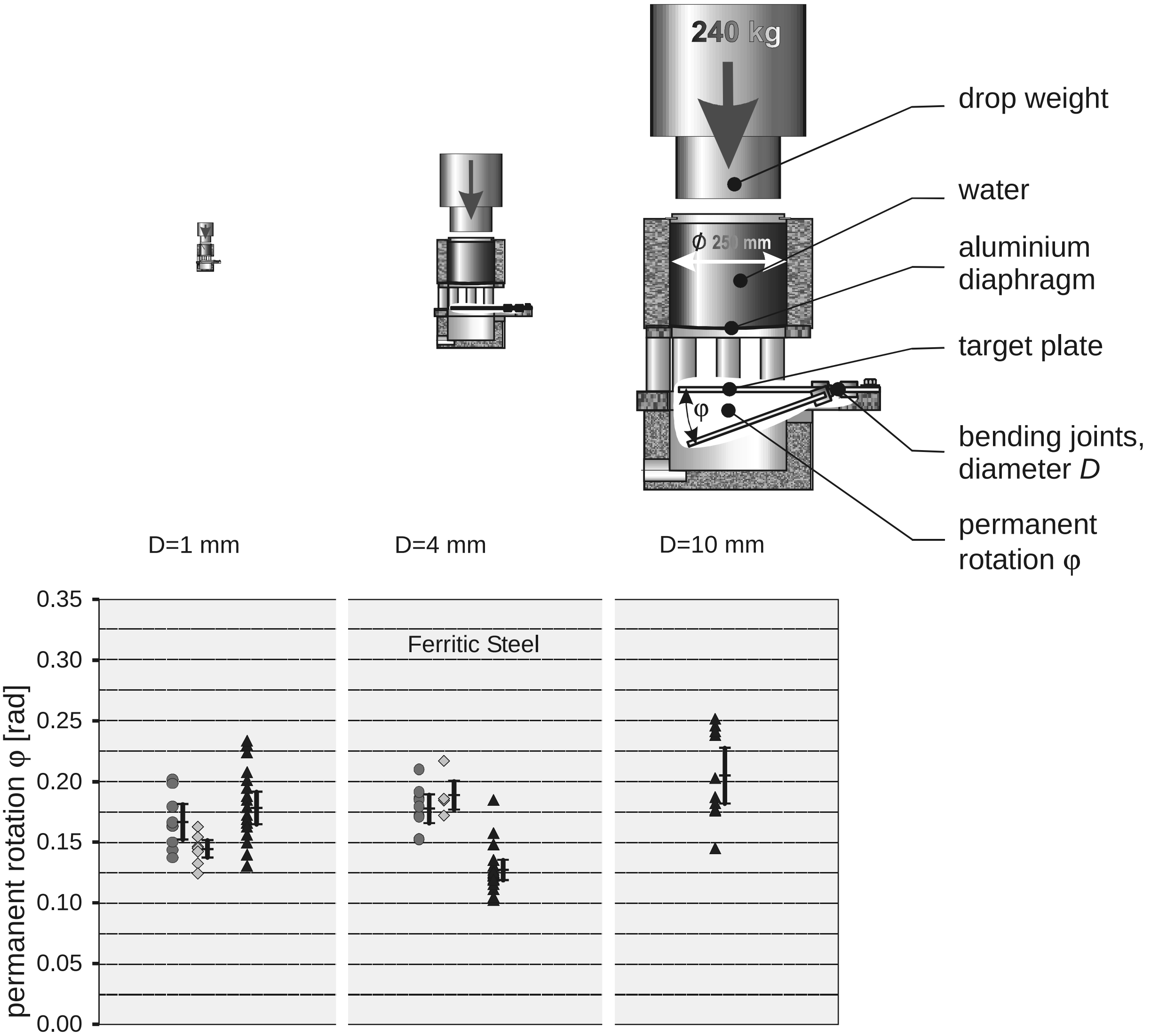


Figure 22: The FLIPPER experiments