COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES
IN A FULL PRESSURE CONTAINMENT
AFTER A LOSS-OF-COOLANT ACCIDENT

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SUMMARY

The object of the investigations was the verification of given computer programs explaining the thermodhapydraulic process in full pressure containments by the knowledge gained experimentally in design and review of pressure water reactors. In this paper a possibility for improvement of the existing computer programs is shown, in this case the IRS-program PREGA—as seen from the point of view of a licencing assessment organisation.

For the comparison, the calculated and measured time depending pressure—and pressure difference relationship of three main experiments of Battelle Frankfurt, were taken as basis. These experiments, called C3, C6 and C13, were performed in a sub-divided full pressure containment of a diameter of 12 m and a volume of 580 m³. The maximum pressure differences appear within the first two seconds after blow-down. Hitherto, the pressure and pressure difference relationships were greatly overestimated in most containment volumes calculated by the IRS computer program PREGA-2 which is used for reviewing of large plants.

The computer program PREGA-2 based upon a multi-point-model anticipates a thermodynamic equilibrium between gaseous and fluid phase as well as a homogeneous distribution of air, steam and water. The flow, viewed as one-dimensional and incompressible, causes the interchange of mass and energy through the overflowapertures connecting the pressure zones. For the calculations performed up to now, a nine-compartments-model corresponding to the nine pressure zones of the containment was used. In order to understand better the non-stationary flow conditions inside the pressure zones, the volume was divided into fixed sections. Doing this volume compartments either directly circulated or formed as blind alleys could be simulated in the computer program. Moreover it was now possible to assign the different primary measuring elements to the corresponding computed flows. To this end it proved reasonable to use a twenty-compartments-model.

For the review of large plants, time independent flow contraction coefficients were used. Hitherto, this assumption has proved sufficiently conservative. In order to realize the conformity of plots, which were obtained experimentally, with the calculated ones, the flow contraction coefficient \( \alpha \), was computed for each time step according to an empirical equation depending on the absolute pressure of two compartments joined by a transfer port.

Calculations with the improved program PREGA-4 showed that by extending the nine-compartments-model to twenty compartments a distinctively better conformity of theory and experiment could be achieved. Using the improved compartment-model and the flow contraction-coefficient calculated as a function of pressure difference, a still better conformity can be achieved with experimentally obtained pressure—and pressure difference relationships than in the case of a nine-compartments-model and a constant flow contraction-coefficient. Recomputing the RS 50-experiments, it expires that an essentially better conformity can be obtained by rather simple model and program amplifications. In this way the consideration of the pressure zones as stationary zones could be maintained neglecting the dynamic part of the pressure exercised up to now as well as the calculation of the mass flow through the connecting passages between the pressure zones with the orifice equation.
1. Objective

As in other countries, efforts have also been made in the Federal Republic of Germany to investigate the behavior of containments and containment structures during a loss-of-coolant accident. So far, design and licensing of containments had to rely on analytical calculations and physical assumptions and had to do without an experimental confirmation on these assumptions. In this context, the following four aspects were of particular interest:

- applicability of the computer models to pressurization in narrow compartments;
- logging of thermohydraulic flow processes between compartments;
- experimental determination of the heat transfer coefficients in case of fast transients in different compartments to which steam is admitted;
- the question of the non thermodynamic equilibrium between the phases.

For this purpose, a pilot containment was built on the premises of the Battelle Institute in Frankfurt in 1973 under a contract awarded by the Federal Minister for Research and Technology. The GRS played a prominent role in the planning and thermodynamic design of this containment and its internals as well as in the safety-related reviewing of the building. In its essential features, the pilot containment constitutes a typical full-pressure containment scaled down 1:4 in a linear way.

Its most important dimensions are:

- diameter and height of containment: approx. 2 m
- free volume: 580 m$^3$
- surface: 1400 m$^2$
- maximum excess pressure: 5.0 bar
- number of model compartments: 9

The energy required for the experiments is obtained from a high-pressure system outside the containment and supplied either through a buffer vessel that is to simulate the reactor pressure vessel or direct to the break. Care was taken to assure that the energy supply corresponded to the volumetric conditions of a PWR plant. In 5 different model compartments, single-ended or double-ended breaks of pipes of a maximum rated diameter of 150 mm can be simulated. The individual compartments of the pilot containment are connected to each other by means of overflow orifices taking the form of circular aper-
tures. Thus the influences of complicated flow geometries on the transient pressure build-up are excluded as far as possible in the first few experiments. Later experiments will include a variety of typical overflow orifices and their effects upon pressurization.

All in all, the following measuring points have been provided:

- 32 pressure sensors
- 8 pressure difference sensors
- 79 temperature sensors (fast and slow)
- 2 density sensors to determine the blow-down of mass flows
- 4 drag body sensors
- 2 heat transfer sensing blocks with 8 sensors each
- 7 water level sensors.

For experiments with a fast pressurization, a containment spray system supplying 25 m$^3$/h can be used.

Until Fall 1976, as many as 16 main experiments were carried out in break compartments R1, R2, R4, R5 and R6 as indicated in Fig. 1. The breaks were single-ended and double-ended water pipe breaks. In February 1977, a new series of experiments was started concerning steam pipe breaks in connection with a greatly simplified compartment model. (I will revert to this later on).

2. Analytical model

The objective of the investigations was to review existing computer programs for logging the thermohydraulic processes in full pressure containments in the light of experimentally obtained data for the design and licensing of pressurized water reactors. The findings obtained in the model experiments were to contribute, in consideration of the necessary extrapolation beyond the model scale, to an improvement of the computer programs and their input data.

The present paper shows a possibility of improving, from the point of view of the assessors' organizations, the existing computer programs, in this case the PREGA program of the GRS. The two experiments identified as C3 and C6 serve as the basis for the comparison of experimental and theoretical data. C3 concerns a single-ended break in the relatively small (11 m$^3$) model compartment 1 (see Fig. 2) and C6 a single-ended break in model compartment 6 (40 m$^3$). The following is a presentation of the first few results of the comparison between the present theoretical logging of the physical processes and the experiments referred to before with regard to short-time behavior,
i.e. from the onset of the experiment to the time pressure equalization between the individual compartments of the full pressure containment has been obtained.

3. Computer program

The PREGA 4 program has been conceived as a multi-point model presupposing a thermodynamic equilibrium between gaseous and liquid phases and a homogeneous distribution of air, steam and water. The transient flow processes are approximated by a quasistationary flow model. For this purpose, the states in all compartments are considered as constant for a small time interval, and the steam and air quantities are calculated which flow over from one compartment to another under stationary conditions. The flow which is considered as one-dimensional and incompressible effects the exchange of mass and energy through the cross-sections connecting the pressure zones. The evaluation of earlier containment experiments has revealed that two factors have a particular influence upon the transient pressurization in the pressure zones. One is the contraction coefficient $\alpha_D$, the other the water carry-over factor $f_w$. In the assessment of large plants, different though chronologically constant values were used for the contraction coefficient and the water carry-over factor, depending on the geometric conditions. The Battelle experiments evaluated so far have always confirmed this assumption as sufficiently conservative. In previous area of two compartments connected by an overflow orifice, the relation

$$F_{\text{eff}} = F_{\text{geom}} \times \alpha_D$$

has been used where

- $F_{\text{eff}}$ is the effective area,
- $F_{\text{geom}}$ is the geometric area, and
- $\alpha_D$ is the contraction coefficient.

To improve the adaptation of the experimentally obtained curves to the theoretical curve, the contraction coefficient was first calculated for each time interval in accordance with an empirical equation (arranged upon results obtained by Schiller, Buckingham and Witte), as a function of the absolute pressures of two compartment sections connected by an overflow orifice.

Although the computer program can simulate the geometric allocation of the compartments to each other, it cannot simulate location and position of the overflow orifice inside a compartment. To achieve this, and thus an improved logging of the transient flow conditions within the pressure zones, the model
compartments were subdivided into well-defined compartment sections. It became possible now to simulate as such in the computer program, compartment areas with direct passage of flow or areas with a blind-alley configuration. At the same time, a selected allocation of individual sensors distributed all over the model compartment is possible (see Fig. 3).

A further parameter which is of considerable importance is the water carry-over factor \( \mathcal{F}_W \) referred to before. Using this factor an assumption can be made concerning the amount of water carried over to adjacent compartments.

In the GRS PREGA 4 computer program, the water carry-over factor is defined as the ratio between the homogeneous water quantity distributed in the compartment atmosphere and the total water quantity in the pressure zone in question. In reference cases, \( \mathcal{F}_W = 0.9 \) is used for the break compartment and \( \mathcal{F}_W = 0.4 \) for all other compartments. To evaluate experiment C3, the water carry-over factor \( \mathcal{F}_W \), the contraction coefficient \( \varphi_D \) and the compartment model are varied. For experiment C6, however, only the last two factors were treated as variables.

Condensation and heat transfer processes are not taken into account for the verifications in the short-time interval of 2 sec. Their influence on pressurization in the model compartments is relatively small, as could be proved by comparative calculations.

4. Evaluation of the experiments

Of particular interest for the evaluation of the containment experiments is the question with which degree of accuracy the pressure and pressure difference maxima between two adjacent compartments can be simulated analytically. For this purpose, the assumptions for the computer model and the decisive influencing parameters must be as realistic as possible. Among the essential factors are the mass flow and the associated enthalpy, fixed quantities which are given by the course of the experiment. For the verification of the C3 experiment, the following three parameters were varied:

- compartment model
- contraction coefficient
- water carry-over factor.

Fig. 2 shows that the break compartment for this experiment is a small annulus with a volume of 11 m³ in the middle of the containment; it is connected to the independent high-pressure system via the feedwater pipe. Fig. 3 is a diagrammatic representation of the 9-compartment model depicting the overflow cross-sections on a true scale. The evaluation of the C3 experiment revealed
that meaningful results were only obtained for break compartment R1 and the immediately adjacent compartment R3. Due to the volume ratios to the following compartments, these acted only as buffers with measured data so small that they came into the category of uncertainties. Fig. 4 shows the setup of compartments for a 20-compartment model, as it was chosen because of the better allocation of the overflow cross-sections and the corresponding sensors. In this model, compartment 1 is subdivided into two sections whose only big connection leads to compartment 3 which is also subdivided. The verification of the absolute pressure in the break compartment of experiment C3, using input data such as they are customary in the licensing of large plants, is depicted in Fig. 5 (Curve 1). An overestimation of the experimental values by approx. 70 % is clearly visible.

When using the 20-compartment model and all the other input data, the absolute pressure in the break compartment takes practically the same course as depicted in Curve 1.

This shows that the influence of a compartment setup aiming at obtaining more realistic results can be neglected for a small break compartment such as R1, since pressure equalization across the compartment is too fast. This is why the further parameter calculations for this experiment could be done without an extended compartment model.

However, if the contraction coefficient, which has hitherto been assumed to be constant, is now calculated as a function of pressure in each time interval for each of the 18 connecting lines between the compartments, Curve 2 in Fig. 5 results. We find a noticeable improvement as compared with the pressure curve discussed before. Even if the result is not yet satisfactory it represents a distinctive approximation of the measured data.

While the influence of the calculated pressure-dependent contraction coefficient leads to higher values and thus, as anticipated, to a faster pressure equalization and lower pressure differences between the compartments, the influence of the water carry-over factor shows an opposite tendency. A growth of $f_w$ is equivalent to an increased share of liquid in the orifice flow and leads, because of the assumption of a homogeneous two-phase flow, to a decrease in the steam/gas mass flow which is not justified physically. The overestimated evaluation of the water transport results in a steeper pressure increase. Similarly, a decrease of the water carry-over factor will result in an essential improvement and pressure reduction. Thus, Curve 3 in Fig. 5 was calculated with values of $f_w = 0.4$ for the break compartment as opposed to $f_w = 0.9$ before and $f_w = 0.4$ for the following compartments. Curve 4 in Fig. 5 was even calculated with $f_w = 0.01$ for all compartments. Although this case shows the best coincidence with the experiments, it cannot
be inferred that the entire liquid is already precipitated in the break compartment. On the contrary, water level measurements in the following compartments have shown that a considerable amount of water is carried over from the break compartment and only precipitated in the following compartments. The obvious contradiction involved in this finding cannot yet be resolved, and thus an exact statement on the influence of the water carryover factor cannot yet be made on the basis of our present knowledge. However, it seems to have been overestimated in a conservative way in the past as a result of the physically wrong representation referred to before. Further work in this field is still necessary.

For the evaluation of the C6 experiment, which concerns a single-enden break in compartment R6 (40 m$^3$), the following two parameters were varied:

- contraction coefficient
- compartment model.

While the influence of the model variation was almost insignificant with regard to the break of a reactor coolant pipe in the small compartment R1, the C6 experiment reveals a distinctive difference to the comparable calculations with the 9-compartment model. Thus, for example, the 9-compartment model provides a wrong verification of the tendency of the differential pressure course between compartment 4 and compartment 1 (Curve 1). The cause is the calculation of the pressure for compartment 4 which is used as reference compartment for all pressure difference measurements. This compartment has opposite orifices so that the flow takes a relatively short way. This cannot be simulated by the computer program in case of the 9-compartment model. With the 20-compartment model, the experimental course of the curve can be correctly verified (see Fig. 6). The combination of 20-compartment model and pressure-dependent calculation of the contraction coefficient leads to a satisfactory result (Curve 2). A similar effect can be observed in the pressure difference course from R4 to R6. In Fig. 7, the uppermost curve depicts the verification on the basis of the 9-compartment model and a constant contraction coefficient (Curve 1). In Curve 2, the influence of the change from the 9-compartment to the 20-compartment model is clearly visible. The combination of extended compartment model and pressure-dependent calculation of the contraction coefficient leads to Curve 3 and thus to a clearly improved coincidence with the experimental values.

The pressure peak which is recognised during the first 10 milliseconds after blowdown onset cannot be dealt with by the computer program. It is a pressure wave which is reflected on the rear wall of compartment 6.

The steam pipe experiments referred to at the beginning are a consistent continuation of the previous feedwater pipe experiments. The obvious advan-
tage of the new series of experiments is that, at least for the first few experiments, a compartment model was chosen that has been greatly simplified as compared to the one presented before. Moreover, one of the parameters, the water carry-over factor \( f_w \), is eliminated right away, since steam pipe breaks are investigated. Thus, a well-founded statement can be expected with regard to the remaining influencing quantities. The evaluation of these experiments is still under way at present.

5. Conclusion

It can be inferred from the results presented that it will be reasonable, irrespective of the size of the compartment, to introduce in the calculations the pressure-dependence of the contraction coefficient. On the other hand, the effectiveness of a compartment subdivision depends on the compartment volume. As the licensing of large plants concerns above all relatively large compartments, a corresponding extension of the model seems to be recommendable here as well.

The influence of the water carry-over factor has not yet been clarified in a satisfactory way as far as the previous evaluations of the available containment experiments are concerned. It is suspected that the differences, some of which are still considerable, between the calculated and the experimental curves are not only due to the insufficient logging of the water separation processes. An exacter description of the flow processes in and between the compartments and the determination of the flow resistances as well as improved determination of the blowdown mass flow is the objective of further theoretical and experimental investigations.

The aim of the verifications presented here, however, was to achieve a clearly better coincidence between theory and experiment by means of relatively simple program and model extensions. Furthermore, the comparative calculations contributed to a closer quantification of the conservativeness of previous safety analyses.
6. References

/1/ Battelle, Technischer Bericht RS 50 Vorläufiger Versuchsbericht C3

/2/ Battelle, Technischer Bericht RS 50 Vorläufiger Versuchsbericht C6

/3/ Seipel, H.G. und Meinhardt, D. Köln
Differenzdrücke zwischen Räumen eines Sicherheitsbehälters nach einem Primärkreisbruch
AKT 13-68 (401-407) 1968

/4/ VDI-Durchflussmeßregeln DIN 1952
6. Ausgabe November 1948

/5/ Witte, R.
Durchflußzahlen von Düsen und Staurändern.
Techn. Mechanik und Thermodynamik 1)1930), 3, 113-120

/6/ Buckingham, E.
Beitrag zur Berechnung der Kontraktionszahl
Forschung 2 (1931), 5, 185 - 192

/7/ Busemann, A.
Die Expansionsberichtigung der Kontraktionsziffer von Blenden
Forschung 4 (1933), 4, 186 - 187

/8/ Buckingham, E.
Zur Berechnung der Kontraktionszahl
Forschung 4 (1933), 1, 25-26

/9/ Schiller, W.
Überkritische Entspannung kompressibler Flüssigkeiten
Forschung 4 (1933), 3, 128 - 136
VERTICAL CROSS SECTION OF THE BATTELLE CONTAINMENT

HORIZONTAL CROSS SECTION OF THE MODELL AT ELEVATION 1.7m

FIG. 1

FIG. 2