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Distribution of Hydrogen Released within Compartmented Containment in Consequence of a LOCA - Analysis and Verification

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Hydrogen is generated and released to the containment atmosphere by different mechanisms. With respect to general safety aspects it is of some interest to avoid explosive mixtures.

Different investigations about hydrogen generation and simplified considerations of the resulting increase of concentration within an assumed homogeneously mixed atmosphere have already been reported in the first German "Hydrogen Status Report" in 1973 /1/. First results of theoretical investigations on possible local hydrogen concentrations in subcomparted containments have been presented at the 1977 Thermal Reactor Safety Meeting /2/. These preliminary calculations already had predicted the possibility of local hydrogen concentrations after a LOCA within the lower part of the containment.

Further theoretical and experimental investigations have been done /3, 4/ since that. Analysis and verification are documented now in a second German "Status Report on Hydrogen Distribution in Consequence of a LOCA" /6/. The following presentation will give a short selection of this study.

Most investigations predicted a rise of hydrogen after its release in the containment atmosphere. Some considerations also expected a stratification and locally increased hydrogen concentrations in the top of the containment dome.

All these statements are based on a couple of assumptions concerning the convection or the convection determining parameters and did not consider plant and accident specific conditions.

RALOC /3, 5/, is a variable dimensioned 4-component, 2-phase multinode containment model, which simulates

1. containment geometrie (s. Fig. 1) by using a more or less simplified discretisation (e.g. fig. 2),
2. hydrogen generation by radiolysis and metall-water-reactions ($Zr-H_2O$),
3. the transport mechanisms
   - instationary flow of atmosphere (pressure differences)
   - free convection by density lift (concentration and temperature effects)
   - diffusion of single components (local gradients of partial pressures)
   - the coolant flow path of the long time ECCS, (effect on the atmosphere temperature and transport of disolved gases).

Based on the complex simulation, the calculations show quite different results depending on accident and plant specific conditions.

Assuming homogeneous temperature the code calculates a fairly homogeneous hydrogen distribution (s. fig. 3). As the hydrogen (and oxygen) is set free at a low elevation, the hydrogen enriched atmosphere rises (concentration lift) to the containment dome. At the same time atmosphere of higher density flows downwards for compensation of (very little) pressure differences. A great convection loop is generated which passes the volumes 10, 7, 4, 2, 3, 5, 8, 9, (10) (s. scheme in fig. 3).

The existence of convection loops is typical for the distribution of hydrogen after a LOCA. Their size however is not generally fixed, but depends on plant and accident specific random parameters and may also vary with time. This has been demonstrated by further calculations and by experiments.

The above mentioned assumption of a homogeneous temperature distribution is not typical for a post LOCA containment atmosphere. More realistic RALOC calculations indicated thermal inversions. The theory has been confirmed by observations after blowdown experiments and LOCAs.

Fig. 4 presents a calculated temperature distribution under simplified assumptions, such as

- homogeneous temperature of 60 C at start of the calculation,
- no heat loss to the external atmosphere,
- heat removal by constant coolant flow with a core entry temperature of 20 C.

The resulting hydrogen distribution is shown in fig. 5. The convection loop is now limited to the lower compartments (volumes 5-10). The upper containment dome does not participate in the free convection. The increase of hydrogen concentrations in the volumes 1-4 is caused by diffusion only. The analysis is simple: The hot atmosphere at the top has a lower density than the hydrogen enriched, but cooler atmosphere at the bottom.

The RALOC calculations have been verified with preliminary experiments at the Battelle-Institute Frankfurt. The test facility used for the following described experiments (no 2 and 6) is illustrated in fig. 6. A gas mixture of 66% H_2 and 34% N_2 has been injected with a rate of about 1 m^3/h. The injection source has a sail-cloth surface to get a uniform injection with low velocity (simulation of the degasing process of dissolved gases). The facility has been subdivided by an orifice of 1 m^2, which is a restriction of about 1/10. Both compartments have been instrumented with a lot of hydrogen detectors and thermocouples to determine the time and space dependent distribution of hydrogen and temperature. The measurement was continuously recorded on tapes. Some concentrations were simultaneously reported on a online graph to stop the injection, when a local hydrogen concentration of 4% vol was reached.

The RALOC calculations of these experiments used a discretisation as shown in fig. 7. The compartments have been subdivided in 34 control volumes. The input data were the inital temperature distribution and the composition and rate of injection (to volume 33).

In accordance to the above mentioned PWR calculations, the following two tests have been selected for this presentation:
Experiment no. 2 was done under normal conditions (homogeneous temperature ~20 C). The experimental result is shown in fig. 8. Similar to the PWR-calculation, the injected hydrogen has been distributed homogeneously. Obviously a convection loop which passes the orifice in both directions (at the same time) has been mixing the atmosphere.

Experiment no. 6 has been carried out under the same conditions except the initial temperature distribution. For this test the upper compartment had been heated up by about 10 K. The effect of this comparatively low temperature inversion is remarkable but not unexpected: Both compartments are well mixed, but the hydrogen concentration rises more rapidly in the lower one (s. fig. 9). Obviously the convection loop does now not pass the orifice but is limited to the lower compartment.

The calculations, shown in fig. 10 and 11 are in good accordance with the experiments.

As the experiments confirmed the predicted phenomena, analysis and experiments already lead to some consequences. German guide lines postulate the calculation of the post LOCA hydrogen concentration and the installation of systems for passive and active control /7, 8/.

According to the calculations it is of special importance to have good measuring and mixing systems. Analytical and experimental studies may show the way of possible technical improvement. As a first attempt two more RALOC runs have been done:

The previous calculations started at a homogeneous temperature distribution of comparatively low level (60 C). The following run assumed that higher temperatures and an early inversion will exist, when the blowdown has ended. The initial values for the following calculations are
70 C in the lower part (volumes 5-10).
80 C in the upper SG compartments (volumes 3, 4),
90 C in the upper dome (volume 2).

The heat exchange between internal and external atmosphere is simulated by a heat loss coefficient K=0,1 W/m^2K (volume 1 and 2). The inlet temperature of the long term ECCS is assumed to be 30 C. (All other parameters have not been changed.)

The results of this calculation are shown in fig. 12 (atmosphere temperature) and fig. 13 (hydrogen concentrations). The analysis indicates early local concentrations above the 4% vol limit because the small convection loop (volumes 5-10) does not start before 26 days.

This means that an early and rapid atmosphere mixing will be necessary. But this might be a severe disadvantage too, if it leads to a fission product distribution over the whole containment. Probably fission products and hydrogen have some common aspects concerning their distribution and there are several reasons to leave the fission products within the central compartments (volumes 5-10).

Leaving the philosophy of conservatisms for a short best estimate consideration of design basis accidents, it probably never would be necessary to get the whole containment atmosphere mixed. Especially for the long time periode it can be assumed that radiolysis will not reach the maximum values and decrease with rising hydrogen concentrations.

Leaving the DBA philosophy and taking into account that the main hydrogen production is caused by metal water reaction, it could e.g. be unfortunate to blow air in a steam-hydrogen mixture.

At any case it would be an advantage to have some flexibility to optimise the mixing procedure. Regarding the fission product problem and considering the DBA spectrum it could be of interest to mix the atmosphere as late, limited and seldom as possible. Perhaps the following RALOC calculation, which investigates a special mixing methode, can give some new aspects.

The method works by gas density lift: If a light gas, e.g. helium is injected, the density of the atmosphere will decrease and overcome the thermal blocking effect when a certain concentration is reached. In accordance to the above mentioned considerations, two periods are considered:

During a first time span (e.g. 15 days) it's intended to limit the mixing on a small central region (volumes 5-10). For this purpose it has been assumed that occasionally helium will be injected at the bottom (e.g. volume 10).

During the following period it could be necessary (assuming G (H_2)=0,44 molec. H_2/100 eV) to obtain a great convection loop (volumes 2-10). The present calculation simulates that helium is injected in volume 4 for that case.

The short term injection is assumed to have a injection rate of 50 m^3/h. It is started, when the maximum, local hydrogen concentration reaches 3,5% vol and is stopped again as soon as sufficient mixing has occured.

The resulting concentrations are plotted in fig. 14 (hydrogen) and fig. 15 (helium). The convective flowrates are shown in fig. 16 (upper region) and fig. 17 (lower containment region). The analysis indicates the possibility of an optimized atmosphere mixing.

The preliminary analytical and experimental investigations lead to some progress concerning the state of science and technology. Further analytical and experimental work will be done. A new test series with a more realistic geometry (s. fig. 18) is currently performed at the Battelle Frankfurt Institute. Pre and post test calculations will be done with RALOC. The present basic version will be further developed, e.g. to take into account the effect of heated structures.

/1/ Statusbericht 'Wasserstoffbildung bei Leichtwasser-Reaktoren' Laboratorium für Reaktorregelung und Anlagensicherung Garching, Bericht SB 2, Juni 1973

/2/ H.L. Jahn, RALOC - A New Model for Calculation of Local Hydrogen Concentrations in Subdivided Containments Under LOCA-Aspects, Thermal Reactor Safety Meeting, July 31 - August 5, 1977 / Sun Valley, ID, USA

/3/ H.L.Jahn, Zur Wasserstoffverteilung nach einem Kühlmittelverlust-Störfall in unterteilten Sicherheitsbehältern von Leichtwasser-Reaktoren, Dissertation eingereicht März 1979 bei der Technischen Universität München

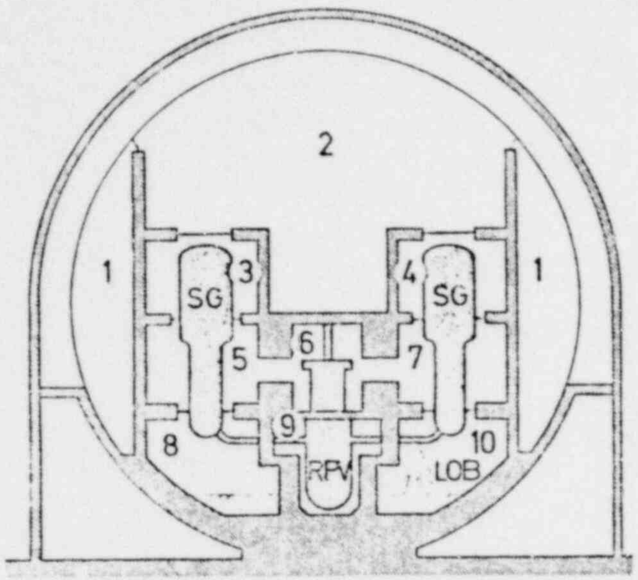
/3/ G. Langer, R. Jenior, H.G. Wentlandt, Experimentelle Untersuchungen der Wasserstoffverteilung im Containment eines Leichtwasserreaktors nach einem Kühlmittelverlust-Störfall, Bericht des Battelle-Institut e.V., Frankfurt, RS 246, Mai 1979

/5/ H.L. Jahn, RALOC-MOD 1, Ein Rechenprogramm zur Ermittlung lokaler Gaskonzentrationen in unterteilten Behältern (speziell: H_2-Verteilung nach einem Kühlmittelverlust-Störfall in DWR-Volldrucksicherheitsbehältern), Programmbeschreibung, GRS-A-263, Januar 1979

/6/ H.L. Jahn, Statusbericht zur Wasserstoffverteilung nach einem Kühlmittelverlust-Störfall, GRS-A-333, August 1979

/7/ Weisungsbeschluß 23 der TÜV-Leitstelle Kerntechnik, TdTÜV, "Verhinderung von zündfähigen Wasserstoffkonzentrationen in der Sicherheitsbehälteratmosphäre von Kernkraftwerken mit Druckwasserreaktoren nach einem Kühlmittelverluststörfall" 18. Oktober 1978

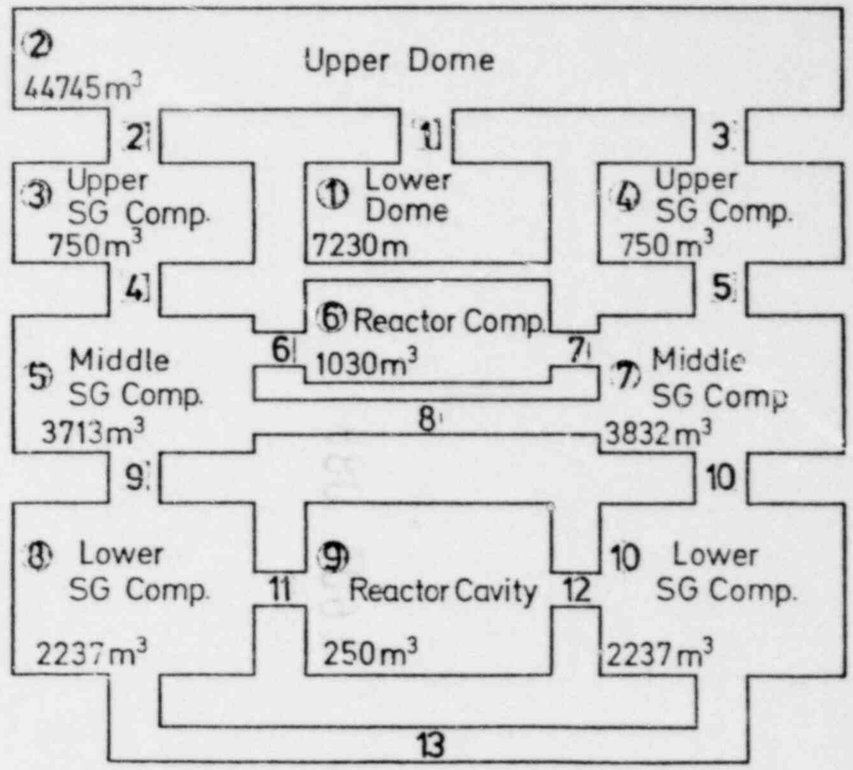
/8/ RSK-Leitlinien für Druckwasserreaktoren, 2. Ausgabe, 24. Januar 1979 (print and mail by GRS)



SG - Steam Generator
RPV - Reactor Pressure Vessel
LOB - Location of Break

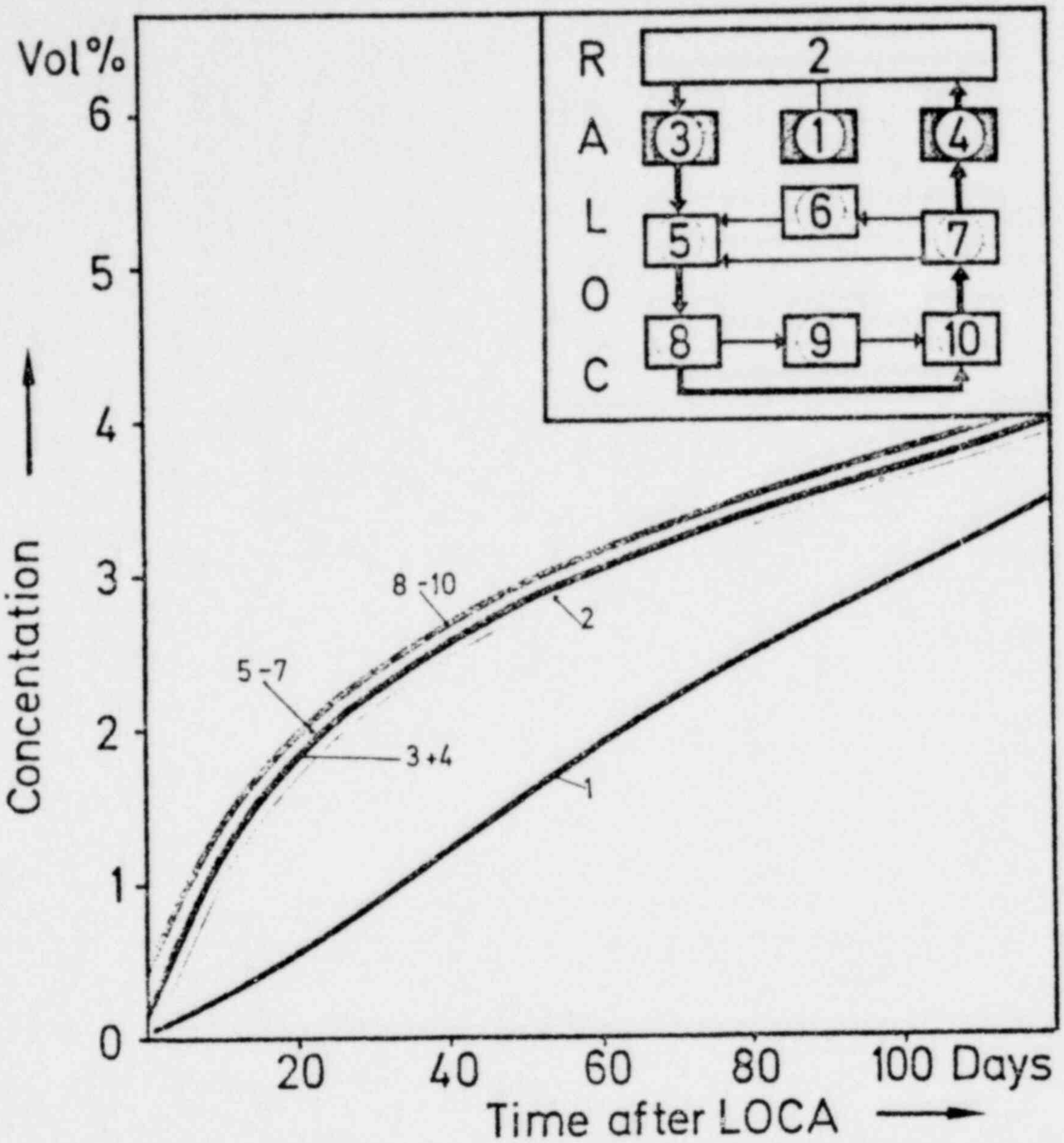
SCHEME OF A PWR CONTAINMENT

Figure 1



RALOC
DISCRETISATION OF A PWR

Figure 2



HYDROGEN DISTRIBUTION WITH ASSUMED
HOMOGENOUS TEMPERATURE

KW 19

Figure 3

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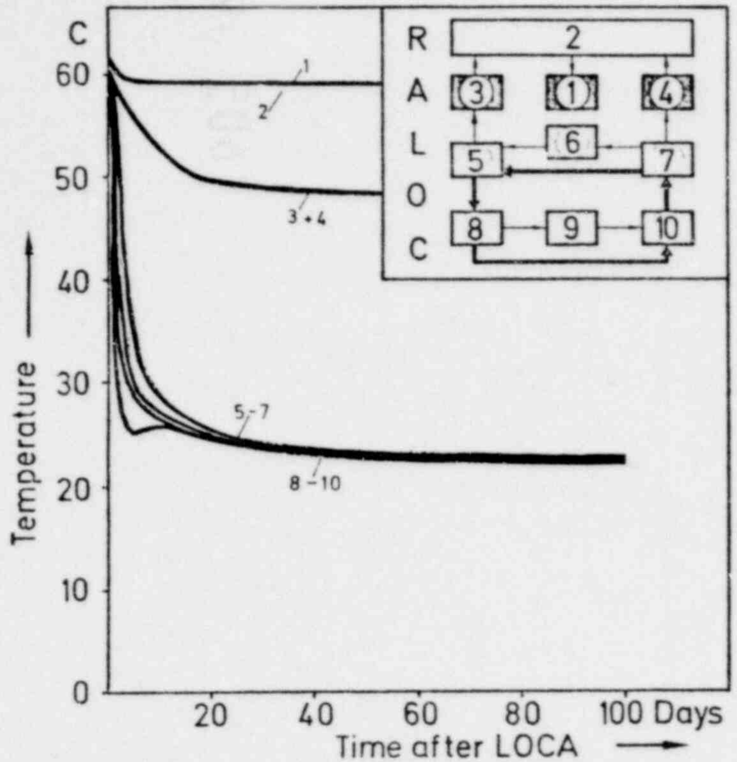
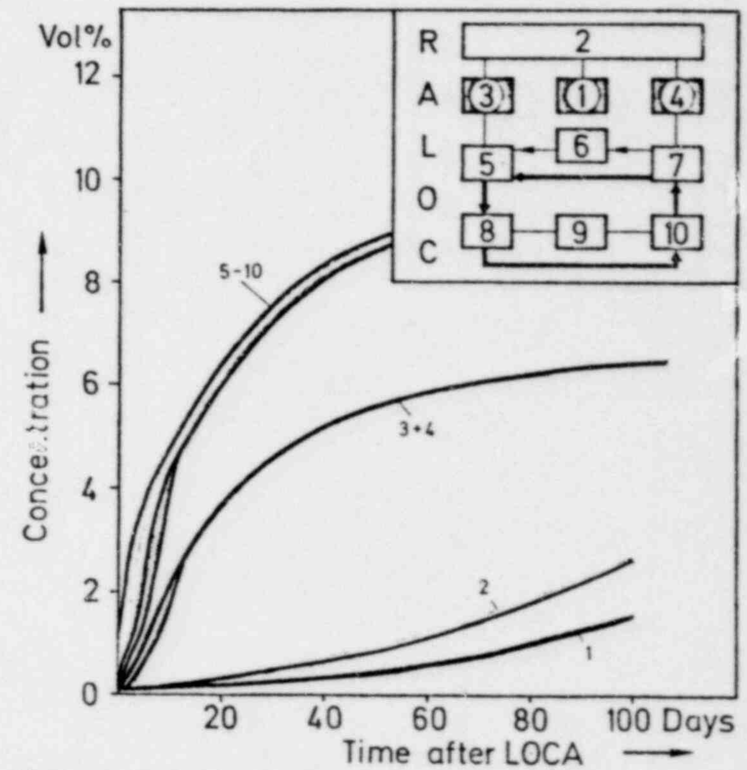
POOR ORIGINAL



22 M HEAT REMOVAL WITH ECCS

Figure 4



24 M HYDROGEN DISTRIBUTION WITH TEMERATURE INVERSION

Figure 5

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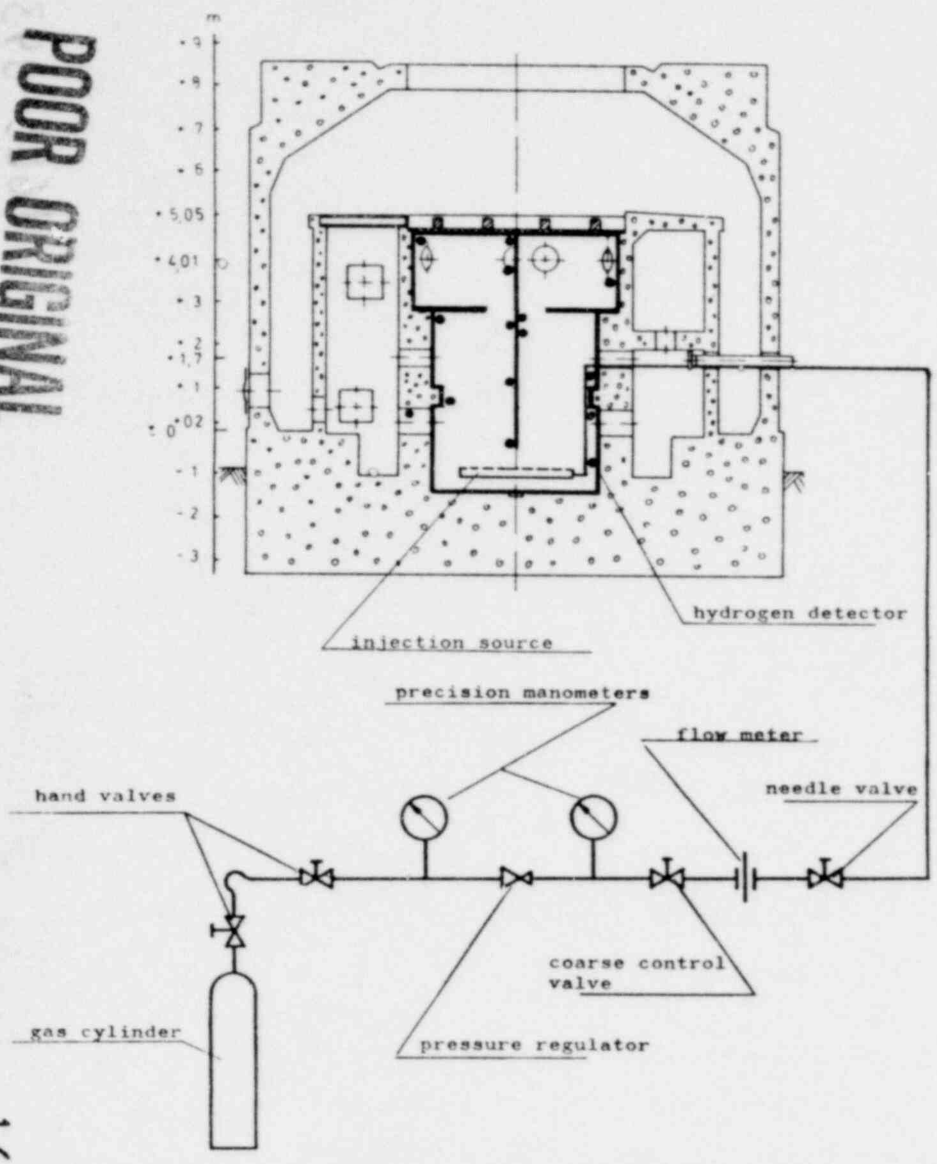
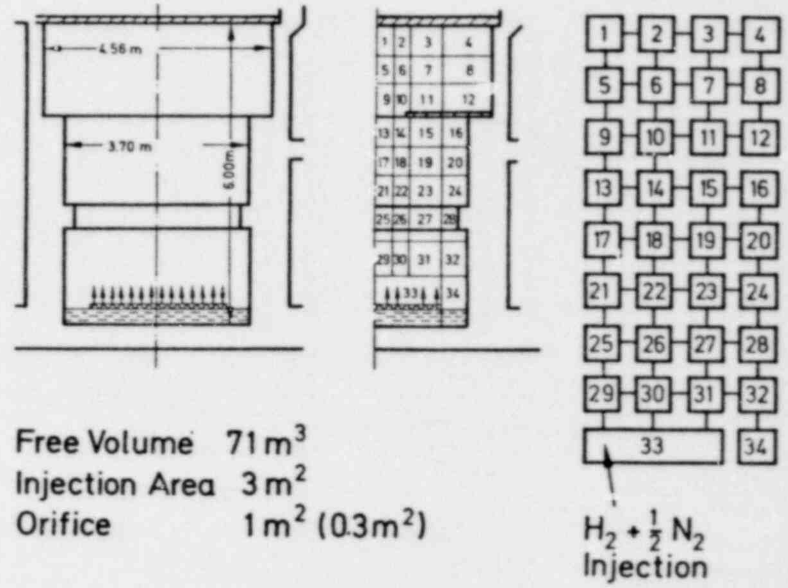


Figure 6 Test Facility



Free Volume $71 \, m^3$
Injection Area $3 \, m^2$
Orifice $1 \, m^2$ $(0.3 \, m^2)$

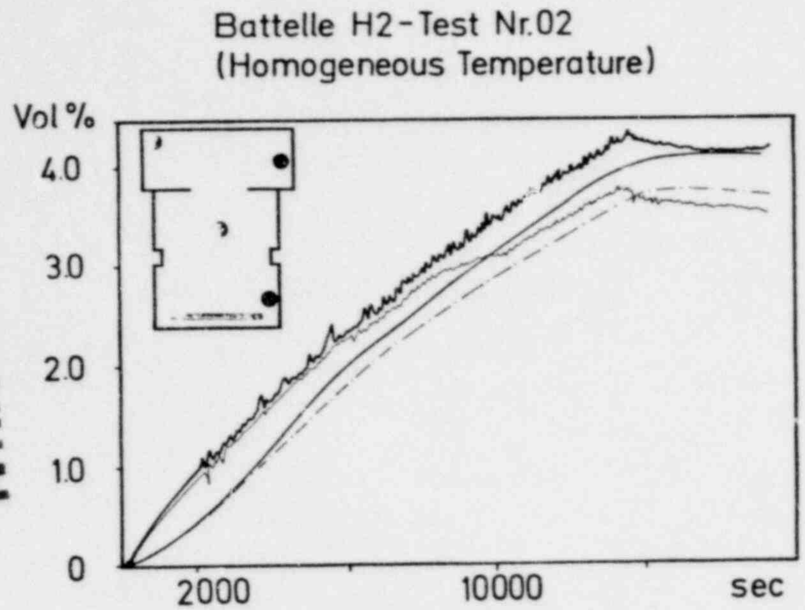
469M

RALOC DISCRETISATION OF
THE TEST FACILITY

GRS

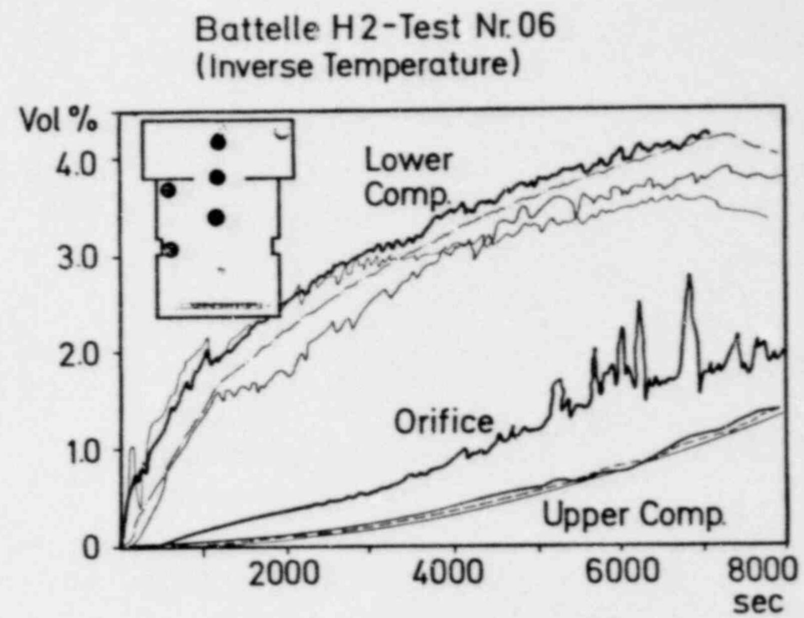
Figure 7

Battelle



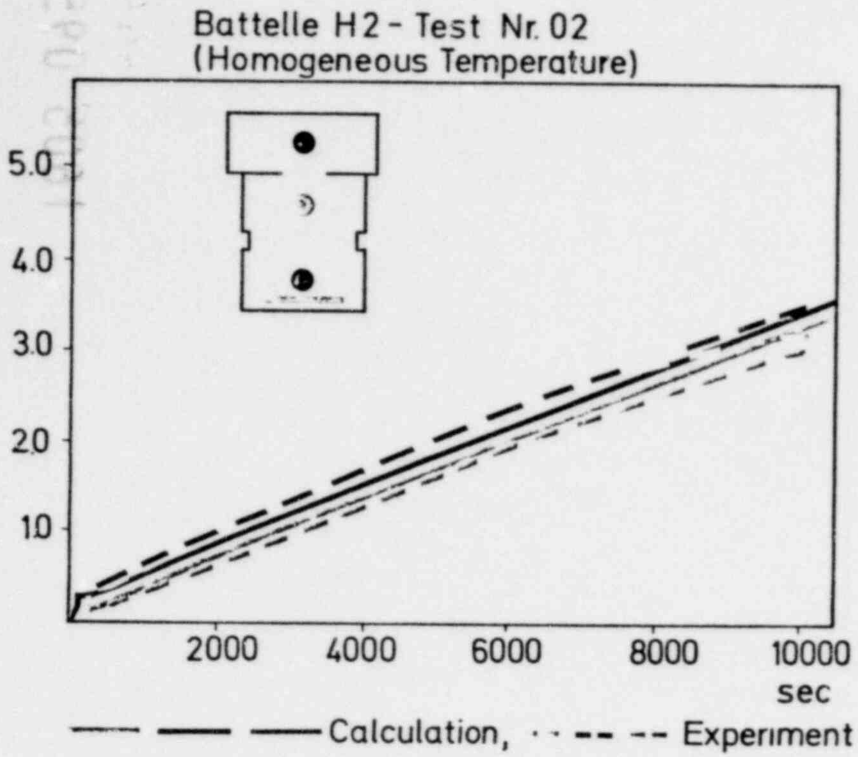
470 M EXPERIMENTAL HYDROGEN DISTRIBUTION Battelle GRS

Figure 8



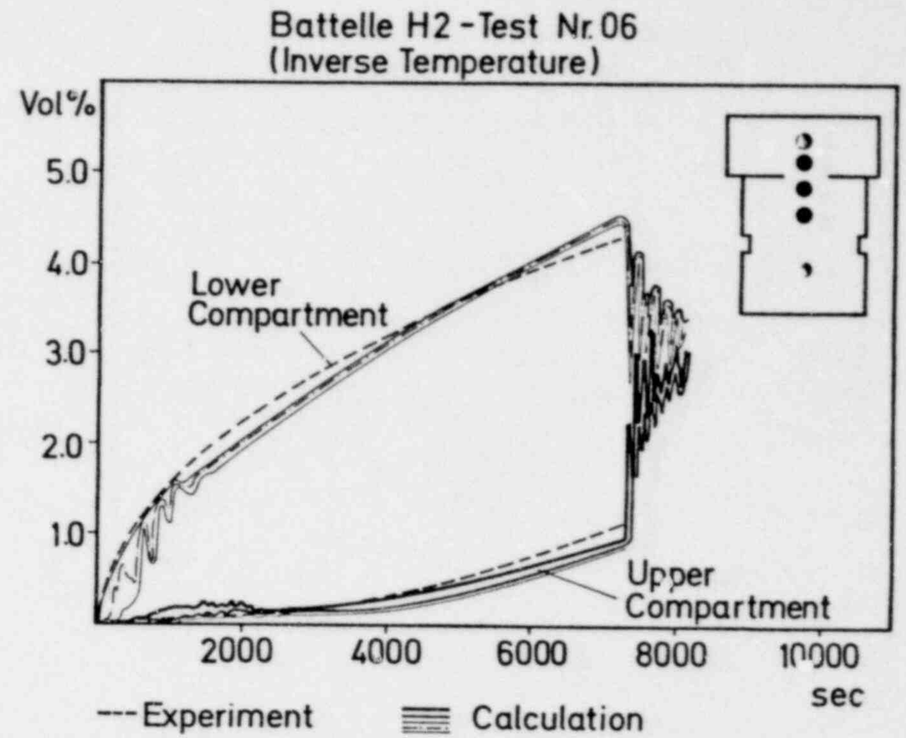
471 M EXPERIMENTAL HYDROGEN DISTRIBUTION Battelle GRS

Figure 9



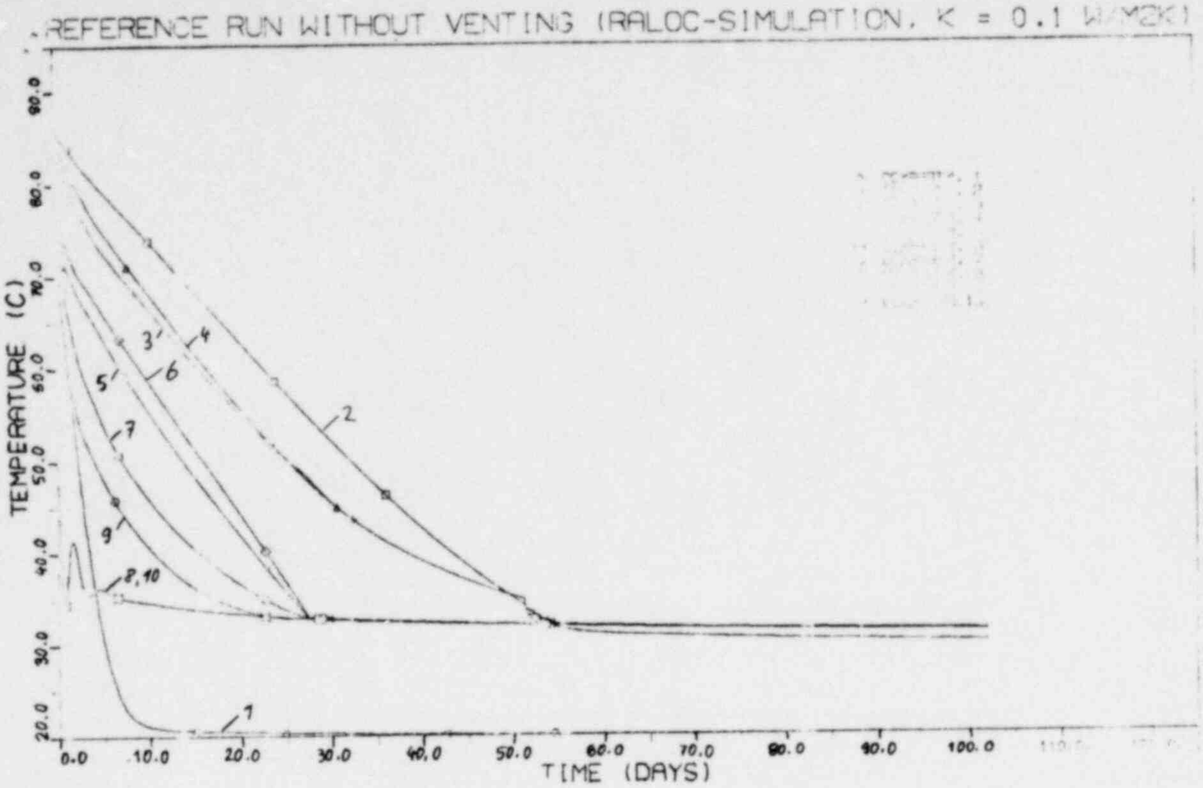
466 M EXPERIMENTAL RESULT AND RALOC CALCULATION

Figure 10

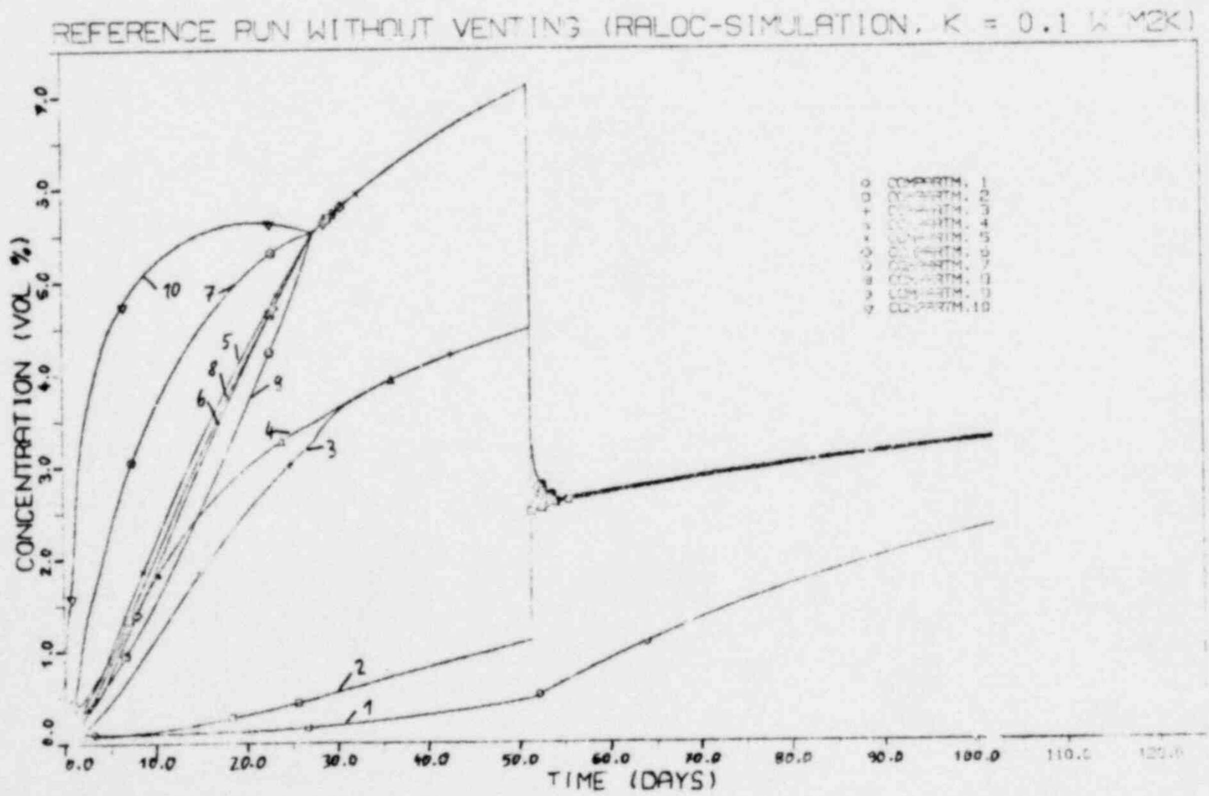


467 M EXPERIMENTAL RESULT AND RALOC CALCULATION

Figure 11



<u>Figure</u> 12 Atmospheric Temperatures



<u>Figure</u> 13 Hydrogen Concentrations

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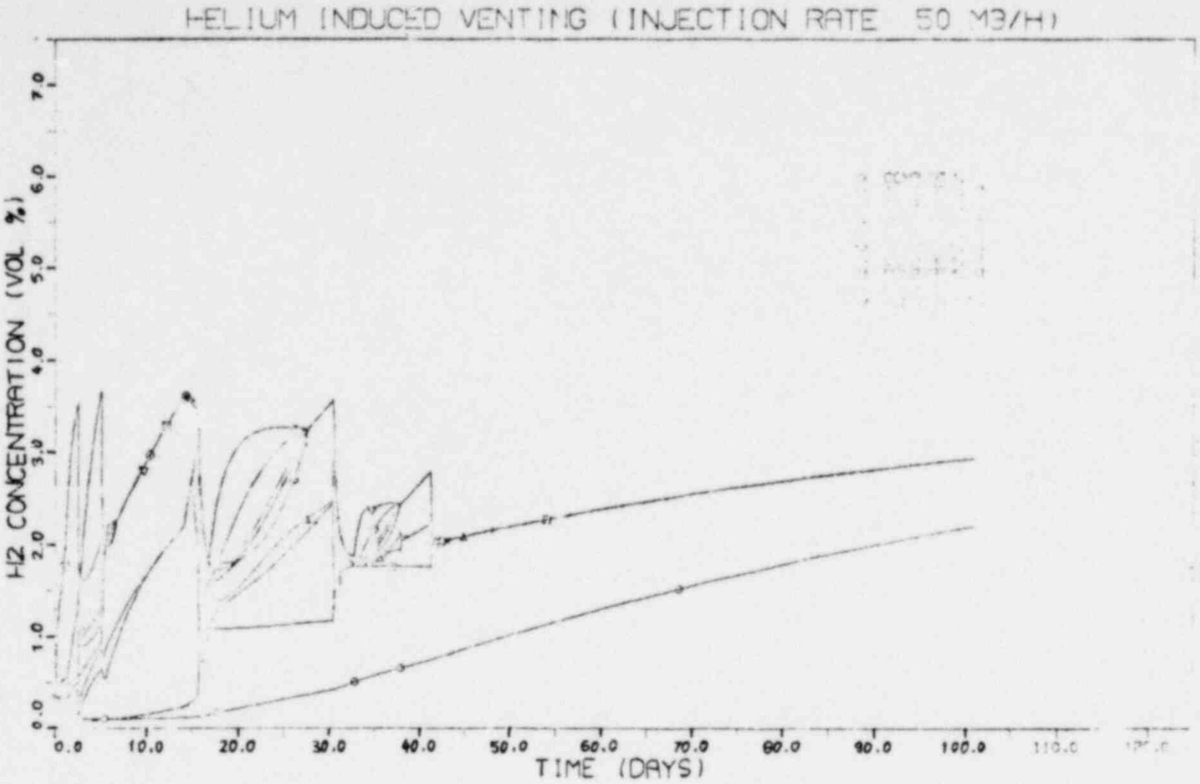


Figure 14 Control of local Hydrogen Concentrations

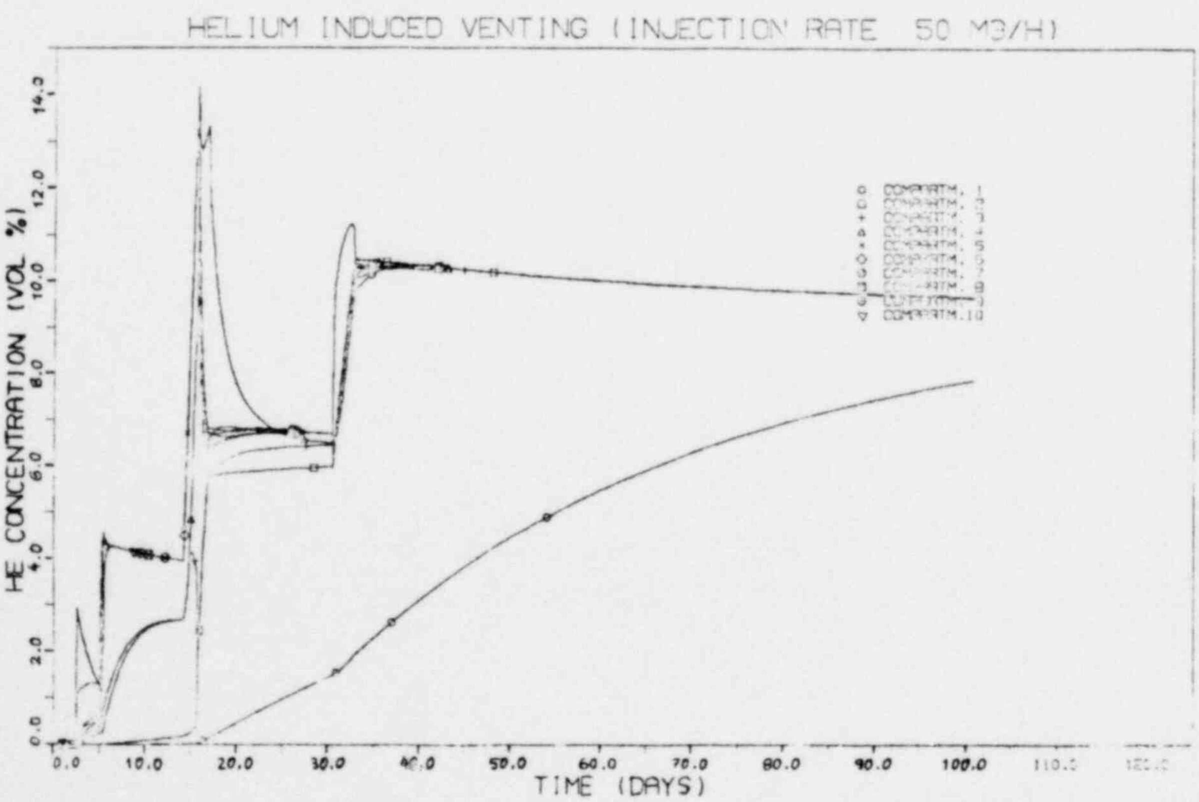
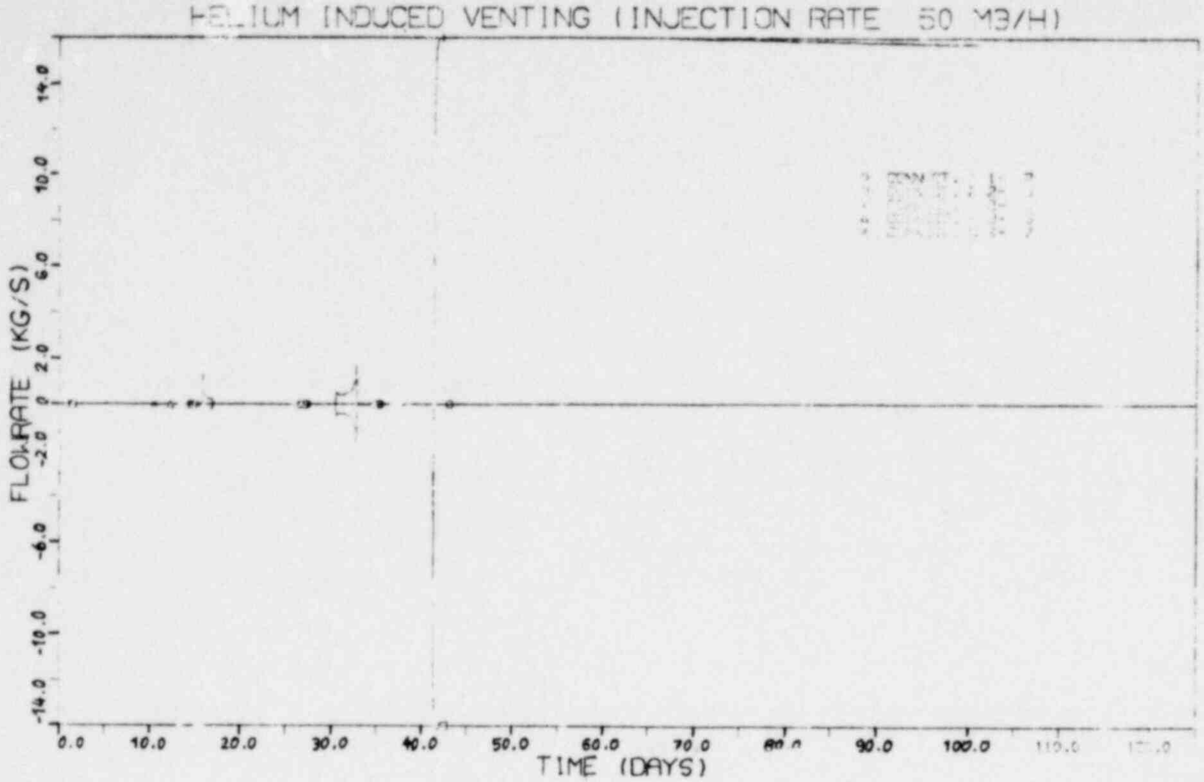
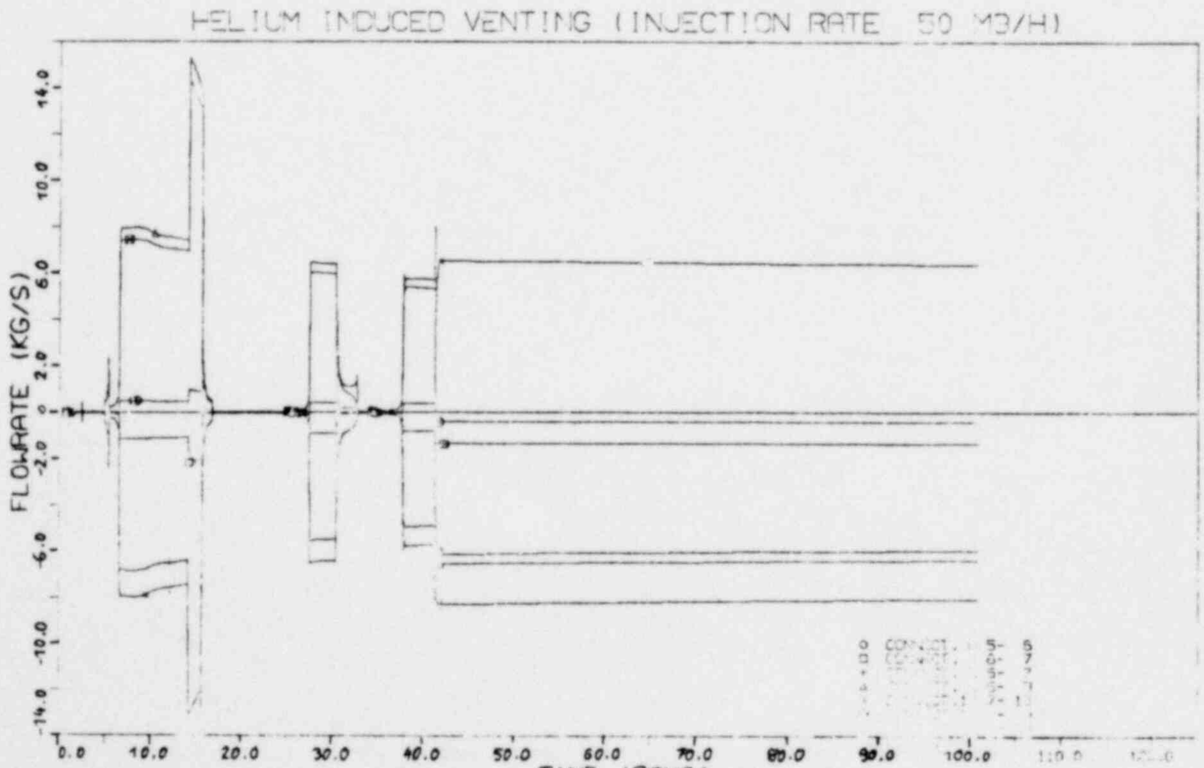


Figure 15 Convection inducing Helium Concentrations



<u>Figure</u> 16 Atmospheric Flowrates of upper Containment Part



<u>Figure</u> 17 Atmospheric Flowrates of Lower Containment Part

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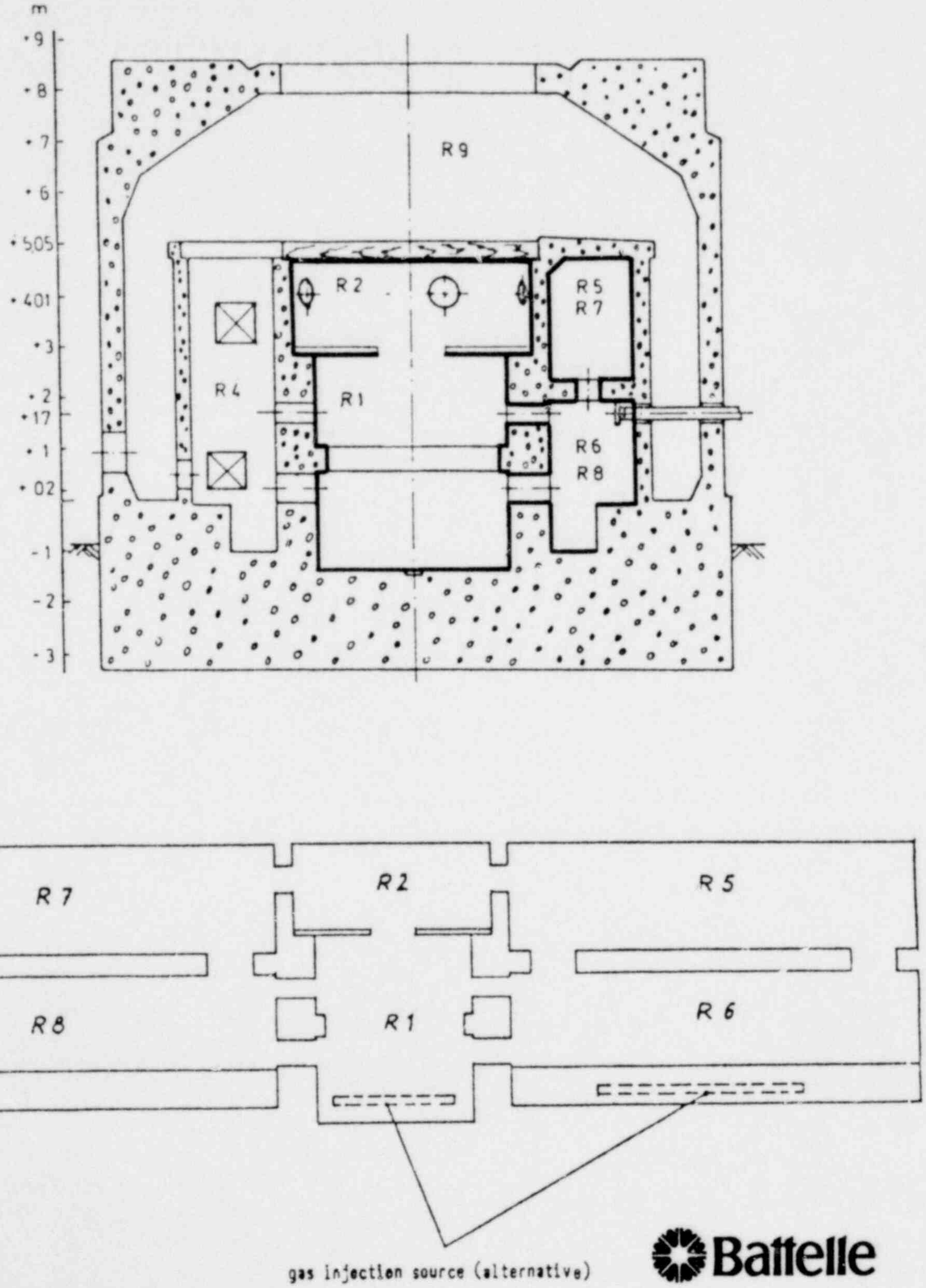

Battelle

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Figure 18 Test Facility