Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) mbH

Post-Inerting of a Large Dry Containment in Beyond-Design-Basis Accidents in PWR Plants

A Survey of Existing Studies with an Initial Assessment

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A Survey of Existing Studies with an Initial Assessment

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Abstract

The objective of this report is to present a summary of basic thoughts and concepts as described in various publications on the subject of "Post-inerting of large dry containments". The report furthermore points out the obvious advantages and disadvantages of individual strategies as well as the requirements derived from the knowledge of possible accident sequences for such a concept.

Scoping calculations on the injection of inert-gas into the containment during the progress of accidents revealed additional indications as regards e.g. the required amount of inert-gas, the injection rate, and the resulting pressure behaviour in the containment. Thereby an assessment of the effectiveness as well as of the feasibility of such measures has become possible.

From the large number of different initial conclusions, two major ones are singled out and presented here:

- In principle, the technical realisation of post-inering is possible. Thus a deflagration of hydrogen in the containment can be prevented.
- Post-inerting cannot be realised independent of the accident progress. Specific criteria for carrying out such measures will require extensive examinations.

In the course of the research and the examinations leading to this report, a number of open questions arose which need to be clarified should such a measure be further considered for implementation.

Note

This report is the translation of GRS-103 "Nachinertisierung eines Volldruck-Sicherheitsbehälters für den Fall auslegungsüberschreitender Ereignisse in DWR-Anlagen - Eine Bestandsaufnahme und erste Überlegungen". In cases of doubt, GRS-103 is the factually correct version.

Keywords
Post-inerting, pre-inerting, inert-gas, inert-gas injection, gas storage, hydrogen deflagration, nitrogen, oxygen, carbon dioxide, N_2-inerting, CO_2-inerting, RALOC, CONDRU

Contents

Page

List of Tables

List of Figures

1 Introduction

In the course of severe accidents, i.e. when the design basis has been exceeded, large quantities of hydrogen (H_2) may suddenly be released into the containment with the consequence that the measures provided for the so-called design-basis accidents, devised for the prevention of the formation of inflammable gas mixtures, become ineffective. Through a concentration of H_2, e.g. under temporally limited and steam-inerted conditions, there may be local formations of mixtures that can endanger the integrity of the containment - the final barrier for the retention of fission products - if they deflagrate under highly turbulent or detonation conditions.

In the past, various concepts and methods have been examined in order to control or prevent this hazardous situation of an early failure of the containment. After the accident in the reactor at Chernobyl, the vendor of nuclear facilities in Germany, Siemens AG, began in the summer of 1987 to develop ignitors which, contrary to those developed in the USA, were to be independent of external actuation and energy supply. The concept of a timely hydrogen deflagration was thus to be transferred onto large dry containments. GRS began relatively early to investigate an alternative solution. The evaluation of the potential for the use of catalytic devices as hydrogen counter-measure was already begun in 1984.

Various publications /1-18/ furthermore discussed or proposed concepts for post-inerting of the containment atmosphere. Such a measure is based on the injection of an inert-gas, like e.g. CO_2 or N_2, no sooner than ***after*** the onset of an accident to prevent hydrogen deflagration. While during the last 3 to 4 years the use of ignitors, of catalytic recombiners as well as of a combination of both - the so-called DUAL concept - have been increasingly examined theoretically and experimentally, the post-inerting concept found only few advocates, and therefore no investigations into its technical feasibility and its effectiveness were carried out.

This study was prepared in order to create an improved basis for the discussion, especially concerning the post-inerting concept, before the decision is taken which concept is to be used in future as H_2-counter-measure in German large dry containments. It tries to give a summary of the various post-inerting concepts described in the publications, to compile the data of the inert-gases that are considered for use, to make initial estimates about the time and the quantities needed for inerting, but also to investigate and compile basic experience with inerting procedures from nuclear and conventional technology.

In the following, the results of the various investigations are explained in detail. Chapter 2 will focus on basic considerations, while chapter 6 introduces an evaluation in tabular form of various advantages and disadvantages.

2 Containment Inerting in Nuclear Power Plants

2.1 Basic Issues

Through partial or complete inerting of the atmosphere of a containment with non-condensable gases, the consequences of an uncontrolled deflagration of hydrogen during or after a beyond-design-basis accident leading to partial or complete core destruction (core meltdown) can be mitigated or excluded. This prevents the endangering of the containment integrity. In principle, there are two methods of inerting that can be considered:

a) complete replacement of the oxygen in the containment atmosphere with an inert-gas, or reduction of the oxygen content (purging)

b) additional inert-gas injection for a reduction of the relative oxygen content in the containment atmosphere.

Method a):
A partial or complete replacement of the containment atmosphere with a non-condensable inert-gas should only be carried out if there are no radioactive materials above the normal operational amount in the containment atmosphere or if there is an immediate danger of such materials being released. It is the objective of such a measure to reduce the oxygen in the atmosphere to a level below 5 % by volume in order to prevent the formation of flammable gas mixtures. This does not involve any pressure increase in the containment.

A measure of this kind is normally used for relatively small containments during normal power operation. This method is called pre-inerting.

During the course of an accident, the interruption of the isolation and consecutive opening of the containment for the replacement of the atmosphere with an inert-gas is a countercurrent measure from a safety-related point of view because there may be a possible fission-product release from the containment. This will be discussed later.

Method b):

If there has been an accident with the possibility of developing into a beyond-design-basis accident with considerable core damage up to core meltdown, there is the possibility of a late injection of inert-gas (post-inerting) into a containment atmosphere that has not been pre-inerted.

Such an injection of inert-gas into an isolated containment leads to a pressure increase in the containment. A high percentage by volume of the inert-gas in the gas mixture leads to a reduction of the percentages by volume of the other gases existing in the containment, therefore also of oxygen and hydrogen. Thus, the flammability of the mixture can be reduced by a correspondingly high rate of injection of inert-gas.

Contrary to method a), where hydrogen deflagration is prevented by ***removal*** of the oxydant oxygen, the quantities of hydrogen and carbon monoxide as well as of oxygen remain the same in the gas mixture when method b) is applied.

In principle, the objective of accident management is the safe retention of the fission products which have been released into the containment during an accident. This goal should not be jeopardised by an additional injection of inert-gas into the containment - at least not during the phase in which there is a high percentage by volume of aerosols in the containment atmosphere due to the accident progress. This means that any additional pressure increase caused by the inert-gas should not lead to a situation where the so-called "vent criterion" for the containment is reached at a considerably ***earlier*** stage.

This objective may be realised in particular by doing without ***complete*** post-inerting. Experiments /19, 20/ have shown that already at ***partial*** inerting of a hydrogen-air mixture with about 20 % by volume of CO_2-inert-gas, the possible flame-acceleration rate is sharply reduced so that highly-turbulent deflagration and detonation in this gas mixture are not to be expected. When compared with complete inerting, partial post-inerting furthermore leads to a lesser pressure increase in the containment during the accident progress; it does, however, not prevent the deflagration of hydrogen. Even at a relatively slow deflagration of large quantities of hydrogen, the corresponding energy influx may endanger containment integrity. Thus, partial inerting is only practicable in combination with a measure for limiting and reducing the hydrogen concentration in the containment atmosphere, e.g. by using catalytic recombiners.

In principle it becomes clear that method b), unlike method a), cannot be considered independent of the specific type of accident. For different accident sequences it will make sense to consider different ***times*** of injection (start of post-inerting), different injection ***rates*** and different injection ***quantities***, taking into account the pressure distribution resulting from the accident (for examples cf. chapter 4.3).

Steam (H_2O), nitrogen (N_2), carbon dioxyde (CO_2) and Halon 1301 can principally be considered as possible inert-gases. However, Halon 1301 must be excluded from the list as it is no longer available for reasons of environmental protection (cf. chapter 3.1). Steam, which due to the accident contributes considerably to the pressure increase in the containment and already has an inerting effect, is not appropriate as an effective long-term inerting measure because it can condense. Under these conditions, the only non-condensing gases that remain for further consideration are CO_2 and N_2.

When compared with each other, both gases have different advantages and disadvantages. Figure 2.1 compares the above-mentioned H_2O, CO_2, N_2 and Halon gases. If normal conditions are presumed in the containment (about 20 °C, 1 bar), the ordinate (abscissa value 0.0) of the diagram shows that inert-gas injection of approx. 191 t of CO_2 into a 70 000-m^3 containment is sufficient to prevent flammability of the hydrogen (> 56 % by volume, cf. Figure 2.3). The injection of this quantity of CO_2 into the isolated containment leads to a pressure increase of approx. 2.9 bar.

If inerting is carried out with N_2, the comparable quantity is approx. 230 t (> 70 % by volume, cf. Figure 2.3); at cold state in the containment, the pressure increases due to the injected nitrogen to 4.2 bar.

The comparison in Figure 2.3 with steam shows that an injection with CO_2 changes the flammability range only slightly, while N_2-injection expands it considerably. This furthermore requires a larger quantity of nitrogen - and therefore also higher containment pressure - in order to prevent a deflagration of H_2. Thus, there are some advantages of CO_2-inerting compared with the use of N_2 for inert-gas injection.

Post-inerting is mainly being discussed with a view to controlling critical situations during the first couple of hours and the first few days after the onset of an accident, i.e. in order to prevent early containment failure caused by a hydrogen detonation.

In the long-term phase following an accident, after weeks, months and maybe also years, considerable quantities of hydrogen - and possibly also oxygen - are produced due to sump radiolysis and may then be released into the containment. The important factor here is the oxygen, which in the long run leads to a de-inerting. Figure 2.2, for example, shows that 2 to 3 t of oxygen may have formed after 3 weeks. Higher formation rates than the ones considered here are possible if e.g. the melt is covered with water or if the sump water is highly polluted. Figure 2.1 shows the additional quantities of inert-gas required for keeping up the inerting process as well as the resulting total pressure dependent on the oxygen that has been produced due to radiolysis (excluding the percentage by volume of the steam from an accident).

If repeated post-inerting with inert-gas required for one of the above-mentioned reasons is carried out, the design pressure of the containment can already be reached after several months, even at cold state. Consequently, the containment will constantly be under high pressure during the process, which may lead to increased leakage from the containment.

As regards the issue of injecting inert-gases in liquid or in gaseous form into the containment, one should note that although normally N_2, for example, is stored in a deep-frozen, liquid state, an injection of nitrogen in most technical fire-fighting measures and also e.g. at the pre-inerting of BWR containments is always carried out in gaseous state (heated up to 15 - 20 °C). This is also true of large-scale transportations of N_2 in pipelines (cf. also chapter 3).

It must be taken into account that liquid-gas injection may, especially in the case of N_2, lead to considerable local problems through cold shock on components which are required for accident control.

The storing of inert-gases ***outside*** the containment does not pose a technical problem. Stock quantities up to 50 t are the standard. Larger quantities (in this case approx. 200 t) can be stored either in several standard gas tanks or in especially manufactured storage tanks. No particular problems are seen in connection with such storage methods, even though at present such storage tanks are not yet available. However, the storage in large tanks requires additional efforts because a separate storage building (bunker) is required which protects the nuclear power plant from e.g. a possible explosion of the inert-gas tank (cf. also capters 3.2 and 3.3).

The liquid storage of the quantities of inert-gas needed for post-inerting the containment (cf. chapter 3.3) ***inside*** the containment is technically very complex due to the size of the storage tank, its related protection measures (bunkering) and the necessary instrumentation (access); it requires special examination whether it corresponds with the existing safety concept. The feasibility of storing the inert-gas in gas cylinders inside the containments must be called into question because of the high number of standard gas cylinders that would be needed (cf. Table 3.2) and the technical effort regarding the connecting pipes.

The following chapters will examine the problematic items outlined above in more detail.

2.2 Present Considerations on the Post-inerting of Large Dry Containments

Investigations on the post-inerting of the containment atmosphere during severe accidents have been carried out with different objectives since the early 1980s. The dominating basic issues were the selection of appropriate inert-gases, required injection quantities and times, effects on the accident progress, and possible inadvertent actuations. Initial studies /1, 4, 5, 6, 8/ were already begun in 1979 and looked systematically at the potential of different kinds of measures for H_2-removal or for the prevention of H_2-deflagration. In this context, experience gathered by industry, NASA and others with H_2-accidents was taken into account. Without considering individual technical solutions concerning post-inerting in detail, /1, 4, 5, 6, 8/ present the basic principles and discuss their appropriateness for PWR-1300 plants with large dry containments. N_2, CO_2 and Halon are named as appropriate gases. The investigated methods are the exchange of the containment atmosphere for inert-gas or the addition of inert-gas. Table 2.1 shows the relevant results concerning injection times and quantities of gas as well as the appropriateness of various gases for post-inerting.

Almost at the same time a study was published in the USA /3/ which makes similar considerations on post-inerting of a low-pressure containment (Mark III) and compares these measures with a spark-plug concept. This study bases its ideas on an injection of cold CO_2-gas and points at a number of problems that arise in principle with post-inerting (accident detection, timely injection, irreversible decision of injection, additional operator actions during stressful accident phase, direct injection into the water reservoir of the pressure-suppression system, long-term pressurisation, inadvertent injection - also especially during tests and maintenance - with the possible consequence of more difficult accident conditions). This study gives indications to necessary actions for the injection, reliability and redundancies of the necessary valves, required electricity supply, and possible examination methods. It also shows up calculations regarding the pressure and temperature distribution for various injection rates. A post-inerting concept is rejected in particular because of the uncertainties of the accident progress to be expected at the time of the injection and because of the possible consequences of inadvertent injection of cold gas.

A more recent study /7/ than the one just mentioned investigates the use of Halon for the post-inerting of a large dry containment. The positive assessment at the time of the study has become irrelevant due to the ban on Halon production.

In /9/, a test programme is suggested for the HDR with regard to the problem of the inert-gas distribution during injection into the equipment compartments or into the dome compartments under accident conditions; this test programme is based on the idea of an inerting system for a PWR plant. The specific details are shown in Table 2.1. The injection of liquid gas could take place after> 15-20 min after the onset of the accident. In the further course of accidents the containment is to be vented via the vent-pipe and the filters.

A further study /17/ deals with the risks of an ignition device in German steel containments and recommends the purging of the containment at the time when there are clear criteria that core meltdown is to be expected and when there are only small quantities of fission products in the containment. The timings and the quantities indicated are also given in Table 2.1. The follow-up study /18/ continues with the arguments of /17/ and presents initial calculations on gas stratification and temperature distribution at an injection of liquid gas with simultaneous venting and supplementary outer spraying. The results show that all compartments are completely inerted.

Research-programme results given in /19/ show up the influence of the percentages by volume of nitrogen and carbon dioxide in a hydrogen-air mixture on the deflagration process. According to this study, only 20 % by volume of CO_2 in the gas mixture is sufficient to limit the propagation of the flames to such an extent that there is neither a highly-turbulent deflagration nor a detonation. The extensive basic experiments were carried out in a laboratory. After the findings of /19/ more investigations are necessary, especially concerning the transferability of the results onto real conditions in PWR plants. These results form the basis for considerations regarding partial post-inerting of an accident atmosphere.

In /32, 33/ possible advantages and disadvantages of pre- and post-inerting measures for PWR plants are presented and discussed. Table 2.1 gives the technical data on which these investigations are based. In /33/ post-inerting on demand is not recommended since e.g. in some cases the decision for or against it needs to be taken within half an hour when there are complex decision criteria to be considered which may possibly be insufficient. Also, the arguments are put forward that gaseous injections require various operator actions and that liquid injection may have a negative effect from a safety-related point of view on components, instrumentation, etc. However, the additional pressure increase during partial post-inerting, especially in the case of CO_2, does not differ considerably from the increase at complete inerting; deflagrations are yet still possible at partial inerting.

The results of these studies can be summarised as follows:

From a technical point of view, effective post-inerting of a large dry containment with known conventional methods is quite possible. However, as post-inerting also brings safety-related disadvantages with it, the majority of the experts (whose work has been evaluated for the present report) believe that there must be clear, accident-specific injection criteria available before post-inerting is initiated. There are no clear indications for the time span required in practice from "injection criteria fulfilled" over "prepare injection" until "start of injection"; this is neither the case even when requirements for the start and the finish of the injection are given. The problem of a "correct" decision on injecting at an early stage on the basis of possibly insufficient decision criteria is obvious. Further details from the various studies are shown in Table 2.1 (cf. also chapters 3 and 4 on this issue).

2.3 Pre-inerting of the Pressure-Suppression System of BWR Reactors

Studies of beyond-design-basis accident processes with core meltdown in BWR plants have shown that in this case rather large quantities of hydrogen will be formed (2 to 3 times the mass of zirconium in the core structure compared with a PWR) that may be released into the containment. In order to avoid hydrogen deflagration at high concentrations in the relatively small containments with pressure-suppression system, the German Reactor Safety Commission (RSK) recommended in December 1986 the pre-inerting of BWR plants /21/. Inerting was carried out with nitrogen gas.

The inerting system has the following tasks:

- to replace after the start-up of the plant the air in the containment with nitrogen, leaving only a specified residual O_2-concentration (in general < 5 % by volume);
- to keep up the inerted state during power operation after inerting has been carried out (here ***also*** called "post-inerting", cf. Table 2.2).

The following tasks must also be considered:

- monitoring of the O_2-content in the containment;
- de-inerting (purging) to re-establish access to the containment for the operating personnel.

For most BWR plants of the 69-line, separate inerting/de-inerting of the control-rod-drive room (SAR) is provided. In the Würgassen nuclear power plant, however, the ventilation of the control-rod-drive room cannot be isolated from the drywell; thus, both are inerted and purged together.

Inerting of the drywell and the wetwell can take place independent of each other. It is more convenient to start with inerting the wetwell and then proceed with the drywell. Inerting of the drywell does not begin until all recurring tests and inspections (on foot) during the start-up of the plant have been completed and the plant has entered the planned state for continuous operation.

Inerting is carried out according to the mixing principle, i.e. the gaseous nitrogen that has been pre-heated to 15-20 °C is injected into the containment air. The air-recirculation system mixes the nitrogen with the containment air; a part of the mixture corresponding to the injected quantity of N_2 is at the same time exhausted.

De-inerting is carried out with the help of the air-recirculation sytem and the purge-air system. De-inerting of the containment is started no earlier than 24 h before the planned shutdown procedure. If only the drywell has to be inspected (on foot) by plant personnel, then it will be purged exclusively; in such a case, the wetwell remains inerted.

The main components of the inerting system are:

- N_2-supply station with N_2-evaporator plant and pre-heater;
- N_2-injection line in SAR, wetwell, drywell + SAR with control and isolation valves as well as the corresponding measuring devices for mass flow, pressure and temperature.

The N_2-inerting system operates together with

- the air-recirculation system within the pressure-suppression system
- the purge-air/ventilation system
- the H_2-reduction system
- the H_2-sampling system
- the instrumentation of the containment.

N_2-injection is linked into existing systems located before the twin isolations of the containment-isolation valves. For purge-gas removal, the existing systems are also used.

The gas-mixture/air quantities to be replaced and removed during inerting and purging respectively are released via the filter systems of the purging system, consisting of aerosol and activated-charcoal filters, and via the stack into the environment. There are no additional releases of radioactive substances by purging.

Inerting usually takes between 3 and 20 h (cf. Table 2.2); de-inerting, on the other hand, may take place more quickly.

For O_2-monitoring, gas samples are taken from the drywell, the wetwell and the control-rod-drive room via the existing pipes of the H_2-sampling system.

For the determination of the O_2-concentration, the H_2-sampling system is switched to two O_2-analysors. During the inerting process, the readings of all measuring devices of the sampling system are taken one after the other until the desired final O_2-concentration in the containment is reached.

An inspection (on foot) of the containment by plant personnel is in principle only admissible after it has been ensured that a certain O_2-concentration (generally > 17-19 % by volume of O_2) has been reached.

The O_2-concentration in the containment is indicated and registered in the control room. If operational O_2-monitoring of the inerted plant shows an increase of $O_2 \geq 5$ %, post-inerting has to be carried out.

Table 2.2 shows the technical data of the pre-inerting of BWR reactors.

3 Technical Application of the (Post-) Inerting Principle (Experience; Basic Requirements)

3.1 Use of Halon

In /6/, the inerting with Halon 1301 is suggested. Halon 1301 is a hydrocarbide halogenated with fluorine and bromine, carrying the chemical name of monobromine-trifluorinemethane ($BRCF_3$). The excellent fire-extinguishing characteristics of this gas are based on the dissociation of Halon 1301 under temperatures above 510 °C. This dissociation results in the formation of bromine (Br_2), hydrogen bromide (H Br), hydrogen fluoride (HF) as well as COF_2 and CO Br_2. The dissociation products of Halon 1301 prevent the activation of the oxygen in the air through capturing free electrons on the flame's reaction front. However, as the released halogen combinations have recently been suspected of damaging the ozone layer of the earth's atmosphere, the otherwise technically favourable characteristics of this gas, especially the very limited ignition range of the hydrogen in the ternary diagramme, can no longer be used: since 1992, Halon has been withdrawn from circulation for environmental reasons.

3.2 Practices in BWR plants

The practices of pre-inerting BWR nuclear power plants will now be illustrated on the example of the boiling water reactor plant Philippsburg (KKP-1) /22/.

The complete nitrogen(N_2)-inerting plant for KKP-1 generally comprises the following five areas:

1. N_2-supply
2. N_2-evaporation (cold)
3. Pressure set-up for N_2-system
4. Heating up the N_2 to room temperature
5. Control and injection into the containment

ad 1: N_2-supply

N_2 is stored in a double-walled, cylindrical horizontally situated container which is about 10 m long and has a diameter of 2.6 m (outer container). The inner container, holding about 31.5 m^3, containes liquid nitrogen and is protected from the outer container by a vacuum and perlite isolation. The vacuum is checked every three months by the supplier firm Messer-Griesheim. A specific check-up of the vacuum through KKP-1 is not provided. The N_2-facility is rented from Messer-Griesheim (cf. also chapter 3.3). The N_2-storage tank is situated in a protective N_2-building (burst-protection bunker) which is open on the long side that is not facing the stack. In case the N_2-storage tank explodes, the pressure load acting on the front wall of the bunker is calculated to be approx. 4.8 bar! The N_2-storage tank is designed for a maximum filling level of 21270 m^3 of N_2 (at 1 bar, 15 °C, with 95 % filled). As the loss of N_2 due to heat transfer is relatively high when the tank is filled with such a quantity, the operational filling level usually is approx. 15500 m^3. The respective conditions of the liquid N_2 lie between -169 °C and 8 bar (shortly after filling) and -150 °C and 15 bar (relief pressure). The quantity given above is sufficient for one complete inerting process and 4 partial inertings (control-rod-drive room). Statistics have been kept in KKP-1 about the loss of N_2. They reveal that approx. 86 m^3 per day (January-April 1989) are lost through evaporation, the equivalent of 0.55 %/d of a filling volume of 15500 m^3. The horizontal position of the N_2-storage tank favours these losses (approx. 31400 m^3/a) - there is an unfavourable surface/volume ratio when the tank is filled to the top. New supplies of N_2 can be delivered within one day by an articulated 15000-m^3 tank truck.

ad 2: N_2- evaporation

On the roof of the protective N_2-building there are 3 parallel air vaporisers (cf. also chapter 3.3) which take the energy required for vaporising the liquid N_2 from the surrounding air. The N_2-gas, which is still relatively cold (10 °C below the surrounding temperature) and under too high pressure, is led to the pressure-reduction station, which is briefly described in the following.

ad 3: pressure-reduction station

After vaporisation, the gaseous nitrogen is transported at fixed pressure reduction (5 bar) via the main path to containment inerting (pipeline DN 80); the volume flow is approx. 1500 m^3/h. For partial and post-inerting there is a parallel path (pressure reduction to 1.5 bar) with a volume flow of 150 m^3/h (pipeline DN 40). Pipeline DN 40 ends in the main pipeline DN 80.

ad 4: Heating up the N_2 to room temperature (RT)

As the nitrogen flows out of the pressure-reduction station at a relatively low temperature, it is necessary to heat up the N_2 to room temperature (approx. 20 °C). The 1500 m^3/h volume flow is thus heated up in the temperature-regulation area of 10-55 °C to room temperature (max. 45 °C). This facility has a capacity of approx. 30 KW. For post-inerting (150 m^3/h) the heat taken up from the heat capacity of the long piping is usually sufficient so that no additional electrical heating of the N_2 is necessary.

ad 5: control and injection area

The N_2 that has been heated up to RT is injected into the drywell (3700 m^3) and the control-rod-drive room (SAR 200 m^3) and separately into the wetwell (2172 m^3). In the drywell the N_2 is injected on various levels; the inerting is carried out in a purging process, i.e. a mixture-volume flow equivalent to the injected N_2-volume flow is removed via the vent-air pipe. For an improved N_2-distribution the air-recirculation system is also operated (75000 m^3/h, air-exchange ratio: 10/h). The times for inerting are for drywell and SAR approx. 4.1 h and for the wetwell approx. 2.4 h (cf. also Table 2.2); de-inerting of the drywell and the SAR is completed after approx. 3 h, and of the wetwell after approx. 1.5 h. The SAR can also be purged separately. Monitoring of the residual volume of O_2 is carried out with the installed H_2-monitoring system, which in this case is switched to an O_2-sensor.

3.3 Properties of Gases, Transport and Technical Availability

3.3.1 Characteristics, Properties of Gases

The two gases nitrogen and carbon dioxide that are interesting from the point of view of inerting exist in nature as molecular elements of air. The quantity of nitrogen in the air is approx. 78 % by volume, that of carbon dioxide around 0.03 % by volume. As regards their suitability as inert-gases, their behaviour is very similar. Nitrogen is favoured for long-term inerting (e.g. pre-inerting of BWR plants) because carbon dioxide can bring corrosion problems with it in the long term. This, however, will only play a subordinate role when it comes to post-inerting during accident scenarios.

If during partial inerting the possibility of hydrogen deflagrations in the containment arises, the temperature resistance of the used inert-gases, especially of CO_2, becomes important. However, CO_2 will only dissociate from approx. 1900 K (approx. 1600 °C). The gas is then separated into CO and O_2. At higher temperatures (> 2100 K) there will also form atomic oxygen. The dissociation rates of CO_2 in the temperature range mentioned above are relatively small; there will remain CO_2-percentages of > 95 % (1-6 bar). When the pressure increases, the dissociation rate is reduced again. There are no considerably higher temperatures than the ones mentioned above to be expected in connection with hydrogen deflagrations in the containment.

The main properties of the inert-gases CO_2 and N_2 are summarised in Table 3.1.

As regards the minimum quantities of inert-gas - already mentioned in chapter 2.1 - for complete inerting (no flammability of the gases), Table 3.2 shows the specific data for the storage of CO_2 and N_2 in pressurised gas cylinders. In comparison, Table 3.3 shows the corresponding data for storing the inert-gases CO_2 and N_2 in storage tanks. Table 3.4 contains the specific data for the gaseous or liquid injection of CO_2 or N_2 into the containment.

For the liquid injection of inert-gases, the injection of the low-temperature liquid inert-gas by a jet pump, mixing the liquid gases with the containment atmosphere, is a possibility. As a presupposition for such an application there must be larger compartment volumes (retention of energy) where in addition there must not be any safety-relevant systems that could be affected by the jet stream. The exit temperature of the mixture could thus be kept at e.g. above 0 °C. If there were, for example, a ratio of 5 (containment atmosphere to inert-gas), an atmosphere temperature of approx. 69 °C would be sufficient to get a gas-mixture temperature of about 0°C. The temperature required for CO_2 is similar. Consequently, if there are higher mixture ratios, lower atmosphere temperatures are also useful. Tabels 3.2 to 3.4 show that special materials (-162 °C) are required for pipes, valves, etc. when liquid N_2 is used for injection into the containment.

For tank storage of the inert-gases, the supply of heat into the tank (vaporiser) may also be a possibility, in the case of CO_2. With regard to nitrogen it is only possible to heat the tank electrically because no freezing mixtures are available due to the low temperature of N_2.

3.3.2 Storage, Transport and Technical Availability

Nitrogen N_2

For the storage and transport of liquid nitrogen, high-quality vacuum-insulated containers are normally used /23, 24/. The smaller the size of the container, the higher are the requirements for the quality of the insulation because the surface/volume ratio becomes ever more unfavourable.

The low-temperature liquid nitrogen is transported in tank trucks. According to /24/, small retailing vehicles (with a volume of 6000 to 15 000 l) or large articulated tank trucks for long-distance travel (up to 300 000 l) are used for whichever need arises.

The storage tanks for low-temperature liquid gases are designed according to the requirements of the respective individual demand cases /24/.

Corresponding to their tasks, the storage tanks are differentiated as follows:

- cold gasifier (liquid-gas storage tank)
- cold-storage tank.

Cold gasifier

The needed quantity of liquified gas is taken from the cold gasifier with the required pressure which is kept up by the low-temperature vaporisation; then it is converted into gaseous form in the following gasifier from where it is injected into the consumer network.

Cold-storage tank

For direct use as a cooling agent, low-temperature liquid nitrogen is stored and then taken from the tank in liquid form. The storage tanks (standard sizes from 2230 to 238 000 l of geometric volume) are manufactured according to the German pressure-vessel regulations and are periodically checked by the German technical inspectorates (TÜV). Cold gasifiers and cold-storage tanks are double-walled vessels, mainly designed in upright position. The inner cylindrical pressure vessel is made of low-temperature-resistant steel; the outer vessel is made of carbon-steel with long-term corrosion protection ensured by a high-quality two-component coating.

Insulation is normally carried out by application of the powder-vacuum technique. Super-vacuum insulations are also available for special requirements. The inner vessel can be isolated by two safety valves. Each individual safety valve ensures the integrity of the vessel. The minimum pressure of response can be checked without pressure changes in the vessel and without demounting of the safety valves. An overpressure protection at the outer vessel prevents an overpressure within the insulation area. The air-vaporisers needed for the cold gasifiers mostly operate independent of energy supply and are environmentally friendly. The cryogenous liquid taken from the cold gasifier (storage tank) is transformed into gaseous state in the following gasifier and then transported through a pipe to the consumer point. The air-vaporisers manufactured by the Messer-Griesheim company /24/, for example, have a large heat-exchange surface due to their finned-aluminium-pipe design, which ensures a reliable supply even during peak-consumption periods.

The vaporiser capacities are influenced by

- the type of gas that is to be vaporised,
- the surrounding site conditions,
- the temperature of the gas at the outlet of the air-vaporiser and

- the time of operation of the vaporiser.

If larger quantities are taken from the cold gasifier it is also common practice to use vaporiser units which are heated by steam, electricity or hot water. Which of these supply methods is the most appropriate one depends on the procedure and the surrounding conditions (distance to the supplying factory) as well as on the required quantity.

To cover any smaller demand for gaseous nitrogen, pressurised-gas cylinders are the most economical way of supply. The standard sizes (50 l, 40 l and 10 l) allow volume contents of 10 m^3 and 6 m^3 of nitrogen at an operational pressure of 200 bar and of 2 m^3 at 150 bar. If medium quantities are needed and the corresponding operating conditions allow, it is most convenient to use bundles of gas cylinders. Here, several individual cylinders are bundled in a rack, interconnected with high-pressure pipes and equipped with an inlet and outlet valve. The most widely used type holds 12 cylinders, containing 120 m^3 of nitrogen at an operational pressure of 200 bar.

For larger quantities of gas, the transport through pipelines is the most economical way of supply. It ensures a continuous supply even if the demanded quantities vary considerably. Pressure accumulators and the volume of the piping itself will compensate any periodically re-curring peaks in demand. Liquid nitrogen is in addition stored in large tanks and - if necessary - gasified and injected into the pipe network. The Messer-Griesheim company for this reason operates networks of nitrogen pipelines for the supply of industrial consumers, e.g. in the Ruhr- and Cologne areas as well as in the Saarland.

Carbon dioxide CO_2

In a similar way as described above for nitrogen, storage tanks are also supplied for carbon dioxide according to /24/, e.g. by the Buse Gase GmbH company in Bochum.

The CO_2 can be taken from the tank continuously or sporadically, in liquid or gaseous form. The CO_2-tank is used with preference where liquid CO_2 is needed or where economical storage of large quantities of CO_2 is required. For large-scale supplies of gaseous carbon dioxide, the installation of electric heaters or outer vaporisers is provided.

According to /24/, the CO_2-storage tank consists of a cylinder vessel of low-temperature-resistant steel, designed and tested according to the existing safety codes and the technical rules and regulations; it is equipped with

- CO_2-inlet, outlet and safety valves,
- a weighing facility to control the refill, consumption and reserve CO_2-quantities,
- a refrigerating machine for compensating the small losses of gas due to heat transfer,
- tank insulation to reduce the loss of heat, and
- additional extra devices for special demand cases.

After the initial filling of the CO_2-storage tank by the CO_2-tank truck a leaktightness test is carried out, and the weight of the CO_2-reserve is determined and fixed. At the start of its operation and at regular prescribed intervals, the storage tank is checked by the responsible regulatory authority in accordance with the relevant regulations. The CO_2 is stored in the tank at between 243 and 253 K (-30 and -20 °C) with a corresponding pressure of 15 to 20 bar. Any small quantities of heat that may possibly be caused by the 150 mm PU-foam insulation is compensated by a refrigerating machine which has a heat exchanger situated inside the tank. The refrigeration machine is controlled depending on the pressure; it can, for example, operate within a range of 15 - 17 bar. If the pressure in the tank exceeds 18 bar, a contact for an alarm signal is triggered. If the pressure increases to above 20 bar, the safety valves open and prevent a further pressure increase.

The CO_2-storage tank rests on a gauged tank-weighing lever with movable jockey. The highest admissible filling level is printed on the gauge. The exact scaling allows the exact registration of the volume weight and of the current flow of CO_2 out of the tank. When a reserve quantity that has been previously fixed on the weighing lever is reached, a visual or acoustic signal can be triggered by a contact switch and thus indicate that new CO_2-supplies must be ordered. The weighing facility is protected from third-party intervention by being situated in a locked casing.

When the reserve quantity is reached, the CO_2-tank truck is ordered from the supply factory.

/24/ presents the following additional information:

- The use of low-temperature liquid gases (spraying) on an industrial scale (in an area of around 200 t) is very rare.
- For extinguishing fires in coal pits (e.g. in the mining area of the Ruhr) there is an emergency-standby plan which guarantees a permanent supply of N_2 within 20 to 24 h.
- A fully equipped 50-t-storage tank for CO_2 at present costs approx. DM 150 000 (non-committal).
- The largest presently available standard N_2-storage tank (approx. 180 t of N_2) costs approx. DM 250 000 (non-committal), with N_2-storage tanks being slightly more expensive due to the more complicated insulation (-196 °C) than CO_2-storage tanks (-79 °C).
- With the use of a CO_2-distribution system without pre-heating (liquid) it must be ensured that the pre-pressure before the jet nozzle always is > 5 bar; otherwise, there is a danger that the liquid might freeze (plugging).
- According to the experts from the Buse company, the solubility of CO_2, e.g. in warm containment-sump water, does not present a relevant problem.
- Static charging caused by inert-gas injection (e.g. of CO_2) has not been encountered by the gas experts /24/.
- A containment penetration for supplying low-temperature liquid gas (e.g. N_2) requires the same big technical insulation effort like the storage in tanks at low temperature.
- The gas experts in /24/ do not see any clear technical advantages of either N_2 or CO_2. The prices per Nm^3 are similar for N_2 and CO_2. The gas experts do not consider the use of CO_2 to be an environmental problem since CO_2 is won from smoke/exhaust fumes which otherwise would be released (with their CO_2 percentage by volume) into the environment anyway.

4 Requirements for Inerting Derived from Accident Analyses

4.1 Basic Issues

There are requirements for the post-inerting of a containment which are derived from operational aspects, controlled incidents as well as from incidents and accidents beyond the design basis up to core meltdown. The studies that are outlined below focus on post-inerting under the framework conditions of severe accidents leading to core meltdown.

Specific requirements and characteristics for a post-inerting concept are derived from such scenarios, like e.g.:

- time of the start of post-inerting
- injection rates and duration
- required total quantity
- pressure increase in the containment
- basic issues on the selection of places of injection
- local and temporal accident loads
- local gas concentration and temperature distribution.

While for the estimation of the first four points relatively simple codes, e.g. one-zone calculation programmes, can be employed, the last three points require detailed multi-zone programmes for the simulation of the local thermodynamic conditions.

It must be noted that the state of knowledge about such accident sequences still involves larger uncertainties that cannot be quantified in detail. It furthermore has to be noted that risk-orientated analyses for PWR plants have only been carried out on a plant-specific (Biblis-B) level.

4.2 BWR Scenarios

A risk-orientated safety analysis (level 2) for the boling water reactors operated in the Federal Republic of Germany is not yet available. The plant operators therefore contracted the plant vendor Siemens to carry out an initial analysis on the topic of beyond-design-basis accidents. In a parallel effort, GRS performed studies on the same subject on behalf of the Federal Minister for the Environment, Nature Conservation and Nuclear Safety (BMU). The Krümmel nuclear power plant served as reference plant for the 69-line. Considerations are also going on concerning the possibility of transferring the results onto smaller BWR plants of the same line.

Three event sequences were selected for the analyses (cf. also /25/) which are meant to be "covering" other possible accident sequences as well. As regards the issue of hydrogen in the containment, the relevant event sequence is the one dealing with the "leak accident" scenario. Here, a loss of coolant is assumed with consequent failure of the emergency-injection into the containment when switching to suppression-pool cooling. In the course of such a severe accident, the release of steam into the pressure-suppression system and the relatively high rate of hydrogen formation lead to a considerable pressure increase which clearly exceeds the containment's design pressure of 4.5 bar. Hydrogen deflagration combined with an increase in pressure and temperature could already lead to containment failure at an early stage. Therefore the pre-inerting of German BWR plants with nitrogen was introduced as a safety-related measure; in its process, the oxygen content in the containment is lowered to such a degree that the flammability of gases like hydrogen can be excluded.

During the time span of the examined possible event sequences (< 20 h) an ignition of the hydrogen is thus impossible due to the pre-inerting. Any long-term formation of additional quantities of oxygen and hydrogen through radiolysis in the wetwell and/or the drywell sump in BWR plants must be prevented by supplementary inerting (which is known as post-inerting, too) (cf. also chapter 3.2).

The necessity of supplementary inerting of BWR plants is derived from the hydrogen/oxygen-monitoring system (cf. chapter 2.3).

At the onset of the accident the containment is already completely inerted due to pre-inerting; there are no particular necessary requirements derived from various accident scenarios on the condition that there is no influx of air into the containment during the accident process.

4.3 PWR Scenarios

4.3.1 One-zone CONDRU Calculations on N_2- or CO_2-Post-Inerting

In the framework of this study, scoping calculations on the issue of post-inerting have been carried out with the one-zone code CONDRU /26/ with respect to the core-melt accident sequences analysed in the German Risk Study, Phase B, as well as to the LP- (loss-of-coolant accident with failure of emergency core cooling) and LP*- (high-pressure scenario with the measure "depressurisation of the primary system") cases. The LP-case stands for a core-melt accident where counter-measures for controlling the hydrogen situation in the containment have to be initiated at a relatively early ($\leq$ 1 h) stage. The LP*-case, on the other hand, stands for a core-melt accident where counter-measures become necessary at a relatively late (> 3 h) stage.

The objective of these calculations was to obtain first indication values concerning required injection rates and total quantities of inert-gas in order to ensure that either an ignition of the hydrogen will only lead to mild deflagration (limitation of flame acceleration by partial inerting) or that the gas mixture containing the hydrogen is not flammable. A further framework condition was that through the injection of inert-gas the criteria for containment venting should not already be reached at an early stage of the accident sequence, in the present case at about 6 bar. Additionally, the filters in the containment-venting paths are not designed for early venting (higher exposure to radioactivity).

The right moment for starting the inerting process is a vital issue. For the calculations, the moment of the first massive hydrogen release into the containment was selected. Figure 4.1 from /27/ gives a survey of the quantities of hydrogen that are produced dependent on time during core-melt accidents. Such a hydrogen release may possibly be registered - with some time delay - by the existing hydrogen-measuring system. The calculations for the LP-path showed that the first massive hydrogen release takes place after 2100 s (approx. 0.6 h); for the LP*-path, the time is 18 720 s (5.2 h) (cf. Table 4.2). In the calculations, these times were applied as the starting point of the simulation of inert-gas injection. The calculations for the LP*-path were carried out for both N_2 and CO_2-inert-gases in order to obtain results for comparison. Calculations were also made for CO_2-injection in the LP-path. A survey of selected calculations is shown in Table 4.2.

The investigations described in the following were mainly carried out under the assumption of a ***dry*** melt-concrete interaction (without sump-water contact). According to /27/, a contact with sump water is no sooner to be expected than after about 9 h for the LP-path and after approx. 14 h for the LP*-path. In both cases an inerting measure will only be effective if applied much earlier. A contact of sump water with the melt which involves considerable vaporisation of an already inerted atmosphere quickly leads to the vent criterion.

The resulting pressure runs for the LP*-path during N_2-injection are shown in Figure 4.2 for calculations No. 1 and 2 (cf. Table 4.2) in comparison to the reference case (without N_2-injection and without sump-water contact). Figure 4.3 shows the corresponding concentrations in a ternary diagramme, where the percentages by volume of CO_2 (from the melt-concrete interaction) and N_2 are included in the steam as injected inert-gas and the CO from the melt-concrete interaction is attributed to the hydrogen. Here it must be noted that the flammability limit is only valid for pure steam (cf. also Figure 2.3). The flammability limits for an inert-gas mixture consisting of H_2O-steam, N_2 and CO_2 are presently not available. It has to be considered that the calculations are based on the assumption of gaseous N_2-injection at an injection temperature of 1 °C.

The illustrations show that a clear improvement of the critical hydrogen situation in the containment is already achieved by the relatively low N_2-injection rate of 4 kg/s (middle graph in the ternary diagramme, Figure 4.3). However, N_2-injection causes a considerably stronger pressure increase in the containment (Figure 4.2), which will quickly lead to the vent criterion. In calculation No. 2 (Table 4.2), N_2-injection is stopped after 200 t of N_2 have been injected, and the vent criterion is reached relatively early, after 2.4 d.

Calculation No. 1 (shown in Table 4.2) is an example of an LP*-path calculation ***with*** sump-water contact; here, the vent criterion is already reached after 19.4 h when N_2 is injected at a rate of 4 kg/s.

A better result is achieved if a N_2-quantity of 40 kg/s is injected, as shown in the ternary diagramme (lower graph in Figure 4.3), which far removes the flammability limit already at an early stage. Figure 4.2 shows, however, that the high N_2-injection rate leads to a sharp increase in containment pressure. The maximum pressure after N_2-injection is completed (1 h of N_2-injection = a total of 114 t of injected N_2, cf. Table 4.2) remains only just below the vent criterion of 6 bar. The smaller quantity of 144 t of N_2, compared with the 230 t of N_2 mentioned in chapter 2.1, results from the additional steam inerting. The fact that the vent criterion is reached later during the accident progress, after approx. 4.3 d, is a fulfilment of the framework condition for controlled containment venting with regard to a long enough period for fission-product depositing. Other studies whose results are not described here have shown that the vent criterion is reached earlier if higher N_2-injection rates than the above-mentioned 40 kg/s are applied; they were therefore not evaluated any further.

In summary, the investigations - carried out under simplified conditions - have shown that an injection of N_2, initiated when a quantity of H_2 first enters the containment, appears to be appropriate for mitigating a critical hydrogen situation or generally to prevent the H_2 from reaching its flammability limit. Quantities of inert-gas that are injected in the short term at relatively high injection rates seem to have a more favourable effect on the pressure build-up and the concentration course in the containment than quantities injected over a long period at low injection rates. However, high injection rates are limited by the fact that the vent criterion is reached at an early stage. This also particularly applies to the case of an additional evaporation of sump water, which begins at a later stage.

In principle these general results also apply to the pressure runs shown in Figures 4.4 and 4.5 as well as to the concentrations in the LP*-path during additional CO_2-inert-gas injection. In the case of the concentrations, the additional CO_2 from the injected inert-gas as well as the CO_2 from the melt-concrete interaction are included in the steam while on the other hand the CO from the melt-concrete interaction is attributed to the hydrogen.

Compared with N_2 as inert-gas, CO_2 as inert-gas has clear advantages with regard to reaching the vent criteria later (cf. Figure 4.4 and Table 4.2).The ternary diagramme also shows its more favourable concentration behaviour (Figure 4.5).

Figures 4.6 and 4.7 show in supplement examples of CO_2-inert-gas injection during low-pressure core-melt accidents (LP-path) where inert-gas injection must start relatively early (in this case after 2100 s). The pressure in Figure 4.6 shows that the vent criterion is reached relatively late, after about 5.5 d. The (minimum) injection rate of 17 kg/s of CO_2-inert-gas selected here shows in the ternary diagramme (Figure 4.7) that the average concentration in the containment does only just not reach the flammability limit for hydrogen. In order to be on the safe side a higher injection quantity with corresponding short injection time would be required (vent criterion).

In conclusion it can be derived from the scoping calculations that, when post-inerting is performed, a large quantity of inert-gas should be injected into the containment as early as possible for a short period of time. By such a practice the production of any dangerous hydrogen concentrations during the development of the accident can a priori be prevented. The pressure increase caused by the injection of inert-gas should, however, be limited to certain values to ensure that the design criteria for the containment are not already reached or exceeded during the early phase at the coincidence of the accident-related pressure increase and the gas injection. Any injection of inert-gas into an "isolated" containment therefore represents the duality between the wish for quickest possible inerting and the requirement for venting the containment at the latest possible moment.

In the context of the results and conclusions mentioned above it must be noted that these scoping calculations were performed with the one-zone code CONDRU. For the verification of these results and conclusions it is necessary to perform comparative calculations with multi-zone codes like e.g. RALOC. However, multi-zone codes mainly serve for obtaining indications about the distribution of gas and temperatures in the individual containment rooms during the injection of inert-gas.

4.3.2 Multi-Zone RALOC Calculations on N_2-Post-Inerting

4.3.2.1 Description of the Main Assumptions for the Calculations

In an initial scoping multi-zone calculation /28/ with the RALOC code /29/ the distributions of the gases in a PWR containment during post-inerting were examined. For this purpose, the 28-zone model developed in /27/ for the reference plant Biblis-B was used and the LP*-core-melt accident was selected as basic scenario. Parallel to the accident progress, 20 kg/s of N_2-gas were injected for 5560 s when the fuel elements reached high temperatures (after approx. 19 000 s). It must be taken into account that during the examined period the so-called "residual-water evaporation" takes place when the molten core collapses into the lower RPV-plenum. In the context of this calculation, the gaseous nitrogen was injected into one of the lower steam-generator zones at a temperature of 1 °C. The energy required for gasifying and heating up the liquid N_2 was simulated in the same zone with an energy subtraction of about 12 MW. During the LP*-accident scenario steam and H_2 are first released into one of the middle steam-generator compartments (pressuriser relief tank) during the in-vessel phase, which was of main interest.

4.3.2.2 Main Calculation Results

During the N_2-injection described above, a total quantity of 111.2 t of N_2 was injected into the containment, which led to a pressure increase of about 1.7 bar (compared with the accident without N_2-injection) to 4.7 bar (cf. Figure 4.8). The energy release from the fission products during the considered period is about 7.5 MW; the containment is heated up to an average temperature of 120 °C, and the sump is filled with > 200 t of water with a temperature of 80 °C. This means that the energy that exists during that particular time in the containment is sufficient to provide the energy for N_2-gasification.

However, the method chosen in this calculation to use the energy of the lower-zone atmosphere to heat up the N_2 leads to specific consequences for the calculations of local H_2-concentrations. There is, for example, a maximum temperature drop in the lower steam-generator zone from 125 °C to about 25 °C (cf. Figure 4.9). The neighbouring zones also cool down, but not to the same extent. The condensing steam is replaced with N_2, and thus no critical H_2-situation arises. All main results underline the plausibility of this calculation. Figures 4.9 and 4.10 show that there is a temperature stratification of about 80 °C in the containment at the end of the in-vessel phase. Initially, the H_2-concentrations are very inhomogeneous; however, during the course of the residual-water evaporation in the RPV they become more homogeneous, but at the end of the calculation there is again a stratification.

4.3.2.3 Assessment of these Calculation Results and Further Aspects

Apart from the unfavourable effect of a pressure increase, the local temperature calculations principally do not show any disadvantages that might arise when low-temperature inert-gas is injected. However, it must be noted that only medium temperatures were calculated for the individual rooms. The H_2-concentrations are clearly influenced by the residual-water evaporation. During the process of inerting there are no flammable gas mixtures being produced at any time in any location of the 21 calculated containment zones. To illustrate the positive effects of inerting, the ternary diagrammes for four different zones are depicted as examples in Figures 4.11 to 4.14. In these diagrammes, the gas concentrations are shown with and without nitrogen injection. The inerting nitrogen was interpreted like inerting steam. However, it is obvious that further multi-zone calculations covering different accident scenarios need to be performed to be able to evaluate the usefulness of local post-inerting, especially because of the inhomogeneous gas distribution during the injection of inert-gas.

This initial multi-zone calculation mainly revealed that an injection of inert-gas can drastically reduce the flammability of hydrogen-gas mixtures in all simulated individual rooms. These results are to be seen as supplementary to the statements made in the context of the global one-zone calculations (cf. chapter 4.3.1) of the flammability of hydrogen during the injection of inert-gases.

4.3.3 PWR Scenarios Bypassing the Containment

/27/ deals with the "break of a residual-heat-removal pipe in the annulus" accident scenario as an example of a release of primary coolant outside the containment. In this case, the containment remains under relatively low pressure with low atmosphere temperatures until the melting of the reactor pressure vessel (RPV) because the content of the primary circuit as well as the quantities of water from the emergency-cooling systems are released directly into the annulus, bypassing the containment. The quantities of hydrogen being produced in the RPV during the core-destruction phase (in-vessel phase) are at first not released into the containment. Only after the RPV-bottom has melted through and the melt-concrete interaction has started in the reactor cavern (ex-vessel phase) is the main part of the gases CO_2, CO, H_2 and steam released into the containment which at that time is nearly without pressure. Since the released quantities of gas are relatively low, the pressure and temperature in the containment increase slowly to state of equilibrium (open system). The containment does not experience any substantial pressure increase. When such an accident sequence is recognised early, a clear and early inerting measure can be initiated before the RPV melts through. In order to avoid a release of more fission products than necessary during the melt-through of the RPV via the break location into the annulus due to an overpressure in the containment, an effective measure would be ***purging*** the containment with inert-gas at neutral pressure ***before*** melt-through (no fission-product effects from the accident yet). Due to the low energy content in the containment atmosphere (also, there is only little sump water), the inert-gases could only be injected in gaseous form ($t > 0$ °C). In this context it is also important to note that a containment which is opened to such an extent may require "permanent inerting".

5 Requirements for a Technical Realisation of the Inerting Concept

5.1 Operator Actions

Figure 4.1 shows that in the most unfavourable case - the LP-path - large quantities of hydrogen are released into the containment after only 1 hour. It must therefore be possible to inject inert-gas no later than at this point in time. For this purpose, due to the time required for the preparation of the injection (opening of the feed valves, pressure regulation, if necessary pre-heating and operation of the pre-heating path, opening of the distribution path), a decision must be made about 15 - 20 min before the hour has passed about the performance of the necessary operator actions. As there may occur maloperations under stress, approx. 1/2 h should be allowed for preparing the injection. At the time of the decision, the automated accident sequence in the LP-path is just coming to an end. At that moment it is not necessarily forseeable whether the accident will develop into a core-melt accident. However, since an accident normally can be controlled, inerting at first should not be performed because of the possible negative effects (pressure increase, leaks, local temperature problems during low-temperature injection, and corrosion problems with CO_2).

A final decision at an early stage for or against post-inerting is therefore always problematic.

Preparations for inerting can, however, be already made at an early stage; the final decision on injecting inert-gas into the containment is then only taken when clear criteria are available, like e.g. RPV-level low, temperatures at core outlet high, emergency RPV-feeding interrupted, etc. This procedure is particularly appropriate for scenarios like the LP*-case where there is enough time available for a decision on inert-gas injection.

Along with manual post-inerting there is the possibility of fully automatic injection and monitoring. It relieves the operators from having to take a questionable decision in a stressful early phase of the accident. The actuation can come from the general accident signals or from the available criteria. In the former case, inerting takes place in all cases, also in those that are controlled. However, this procedure requires a detailed examination as to whether it conforms with the existing safety concept. It has to be ensured that fully automatic injection does not take place during normal operation, re-curring tests and (minor) accidents. In the case of the existing criteria, the operator actions, e.g. pre-heating of the vaporiser, have to be performed in the short period between the clear indication that a criterion is fulfilled and the first release of hydrogen. Experience has shown that this period is very limited so that hydrogen release and non-inerted surroundings may for a short time overlap.

Between ***fully automatic injection*** and injection carried out only by ***manual actions*** lies the ***automatic preparation for injection*** at the start of every accident. The start of the injection can consequently be manually initiated as required by the accident progress and the indication of clear criteria. The decision on injecting can therefore be made immediately before the moment when injection is necessary.

The required injection period (about 1 hour), the injection quantity or the results from test samples can be used as criteria for ending the post-inerting process. However, since there may be an inadmissable pressure increase it has to be ensured that the maximum quantity is not exceeded or that the quantity of injected inert-gas can be limited. In this context, the possibility of valves failing to close (e.g. through freezing) must also be taken into account. The option of limiting the quantity by using separate tanks from which certain individual quantities can be taken (e.g. 3 x 50 %, 5 x 25 %) should also be included in the considerations on this issue.

In all, the system should be as easy and clear to operate as possible. In the case of CO_2-inerting, the number of required operator actions is reduced compared with the use of N_2.

5.2 Inert-Gas Injection

If existing systems are used for inert-gas injection into the containment, the inert-gas must be pre-heated to the temperature of the containment's normal operating conditions (15-20 °C, approx. 1 bar) so that their design limits are not exceeded during the injection. This method was selected in the Federal Republic of Germany for the N_2-pre-inerting of BWR plants.

When liquid CO_2 is injected (-79 °C) there must always be a pre-pressure of > 5 bar in a CO_2-distribution system located in the containment so that freezing of the distribution system is prevented. The quantity of injected CO_2 may be affected by this. It must furthermore be guaranteed that e.g. a distribution system in the containment is itself not damaged or affected in its functioning by a preceeding accident.

The equipment and operating rooms are mainly considered as places for injection. Injection into the equipment rooms is carried out in the direct vicinity of the possible place where H_2 is released and there leads to fast inerting. When the inert gases enter at low temperature, there may be a stratification of gases in which the inert-gases are found in the lower area (equipment rooms) and the hydrogen and the air in the upper area (operating rooms). Mixing devices (energy required!) may possibly be needed. This requires detailed examinations, also concerning among others the issue of gas distribution with a multi-zone model (RALOC type). The injection of inert-gases must be carried out in such a way that no valves, motors, pipelines, etc. that are necessary for controlling the accident lie in the direct path of the jet stream.

Under certain circumstances, injection into the upper equipment rooms may be more advantageous because the inert-gases cause strong convection with the corresponding mixing effect when the place of injection is high. A precondition for this is the existence of large enough openings between the operating and equipment rooms. It may be that due to the preceeding accident the existing pressure-relief openings have not completely opended (small leak, V-sequence, valve flaps falling close again) with the consequence that an active-opening measure becomes necessary.

5.3 Storage

With regard to the storage of large quantities of inert-gas (in the range of 200 t) it may for several reasons be better to distribute these quantities over several smaller tanks. By separately activating these tanks it is e.g. possible to gain better control (overfeeding, pressure increase in the containment). If there is a correspondingly large number of individual tanks (storage of reserve quantities) it is still possible, in case one of the tanks fails (e.g. valve fails to open), to inject a sufficient quantity of inert-gas during the necessary period from the remaining tanks. The larger the tanks are, the greater is the loss through evaporation; several smaller tanks, on the other hand, cause greater losses than one large tank holding the same quantity. Short-term refills are therefore necessary. Depending on the geographical location of the nuclear power plant, a connection to an existing N_2-pipeline network, like the one available for the Ruhr- and Cologne areas, might also be considered. The large capacity of the pipeline (cf. also chapter 3.2, 3.3) would ensure the short-term delivery of any required quantities of N_2 (in gaseous form). Compared with N_2, the storage of CO_2 has more advantages because any evaporation losses can be compensated by the use of relatively small refrigeration machines (cf. also in this context chapter 3.3, Tables 3.2 and 3.3).

6 Evaluation of Advantages and Disadvantages of Post-Inerting

This chapter introduces the tables (cf. chapter 9 further below) that summarise the investigations and examinations described in detail in the previous chapters by listing the obvious advantages and disadvantages of post-inerting. The respective table headings indicate the topic area they are dealing with.

At the comparison of the individual advantages and disadvantages it may occur that the arguments on both the positive and negative sides overlap. This is, for example, the case with the disadvantage of an early reaching of the vent criterion caused by sump-water evaporation, which in turn would again have the advantage of additional steam inerting.

The individual tables deal with the following issues:

Table 6.1:	Post-inerting, general points
Table 6.2:	Selection of CO_2 or N_2
Table 6.3:	Liquid or gaseous injection into the containment
Table 6.4:	Inert-gas storage inside/outside the containment
Table 6.5:	Operator actions
Table 6.6:	Place of injection

It should be noted that these tables make no claim to be complete. They mean to give a survey of the various partial aspects of post-inerting. Any influences by particular plant characteristic, by the accident sequence or even by normal operation could only be touched upon or not be considered at all.

The particular specifications for an inerting system require a much more detailed study on the advantages and disadvantages.

7 Summary

This report has tried to give a systematic survey of the better and less well known facts regarding the issue of "post-inerting of large dry containments". Starting from basic issues and the description of the possible concepts as they are introduced in the various publications, this report has presented the current status of research up to the requirements for such a concept that are derived from the findings concerning possible accident sequences and also including a comparison of different advantages and disadvantages of individual strategies, inert-gases, etc.

In addition, scoping calculations with the thermohydraulic RALOC and CONDRU codes were performed in order to obtain data for orientation, e.g. about required quantities of inert-gas, injection rates, the pressure history and gas distribution in the containment, for an assessment of the effectiveness and the feasibility of such measures.

In the course of the research performed for this report a number of different unresolved questions turned up which require a more detailed examination, like e.g.:

- Which are the criteria for the preparation and for carrying out an inerting measure, depending on the type of accident?
- What happens if the post-inerting system fails or - within a limited, short period (LP-path) - cannot be activated?
- How can it be ensured that the inerting system is not inadvertently activated?
- What local effects of low-temperature injection are possible on safety-relevant components within the containment?
- What are the flammability limits for gas mixtures of various temperatures and pressures (e.g. H_2-CO_2-steam-air)?

The transferability of the available experimental results concerning the local flame-acceleration rate onto real conditions in a large dry containment has not yet been verified, especially not for the strategy of partial inerting, which is to prevent highly turbulent deflagrations and detonations. In this context as well as for further related issues there still exists a considerable need for research if such a strategy should be chosen for technical implementation.

As an initial conclusion, the following statements can be made:

1. Technical realisation of the post-inerting concept is possible. If implemented, it can safely prevent H_2-deflagration.

2. Of the available inert-gases, CO_2 has considerable advantages over N_2.

3. A post-inerting measure cannot be performed independent of the accident progress. Clear criteria for activating an inerting system must still be comprehensively investigated.

4. After complete inerting of the atmosphere, the design pressure of the containment is reached or exceeded far earlier. This results in more stringent requirements for filtered venting (e.g. design of filters).

5. The problem of long-term leakages becomes even more important when inerting has been carried out (increased pressure).

6. Partial post-inerting can mitigate the consequences of possible H_2-deflagrations; however, deflagrations are in principle still possible.

7. A single complete inerting process does not give full long-term protection (weeks, months) against H_2-deflagration. The production of O_2 due to sump-water radiolysis requires O_2-monitoring and, if necessary, repeated inert-gas injection.

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9 Tables

Table 2.1: Considerations for post-inerting of large dry containments

	Battelle 1982 / BMI-contract SR 212 /1, 4, 5, 6, 8/			Bechtel 1982 /3/	Karwat 1988 *) /9, 12/	Jahn 1991 /17, 18/		Siemens 1991 /32, 33/		
Inert- gas	CO_2	N_2	N_2	CO_2	N_2 (CO_2)	N_2(CO_2)	N_2 (CO_2)	N_2	CO_2	CO_2
Kind of inerting	Injection			Injection	Injection	Injection	Purging	Injection	Injection	Injection Partial inerting
Start of injection	30 min			Water level	15 - 20 min	> 30 min		1.5 h		
Duration of injection		1 h	1 h	0.5 h		0.5 - 1.5 h		1 h		
Injection rate							30 kg/s	202 500 m^3/h	105 600 m^3/h	22 500 m^3/h
Injection quantity	105 000 m^3 210 000 kg	210 000 m^3 265 000 kg	210 000 m^3 265 000 kg	up to 50 Vol.-% of CO_2 in containment						
Additional pressure	2.0 bar	4.8 bar		1.9 bar			no add. pres.		1.7 bar	0.7 bar
Injection pipe		DN 300	DN 300				DN 600	DN 400	DN 300	DN 200
Distribution	Pipe system with sprays			Spray nozzles pool	Dome comp. or equipment rooms	Pipeline into the containment sump		Spray nozzles in equipment rooms and dome compartment		
Operation	manually			manually		manually				
Vent pipe					as existing		DN 600	as existing		
Storage	Outside containment				in dome compartment	outside containment		outside containment		
State of the inert-gas	liquid 20 bar -20° C	gaseous 40 bar	liquid	liquid	liquid 6, 18, 22 bar	liquid		liquid, 430 m^3 30 bar, -155° C	liquid, 200 m^3 50 bar, 15° C	liquid, 50 m^3 50 bar, 15° C
Auxiliary devices	no	no	Evaporator	no		He-pressure storage		Evaporator		
Evaporation heat	35 MWh from the accident	no	15 MWh	Energy release of the accident				1 300 l of oil	800 l of oil	200 l of oil
Evaporation power								18 MW	11.3 MW	2.8 MW

*) for a test-recommendation in HDR-containment

Table 2.2: Technical details of the pre-inerting of boiling water reactors (BWR)

Nuclear power plant	Free volume		N_2-demand		N_2-storage		N_2-injection	Time needed for N_2-inerting		Time needed for de-inerting		Remarks
	KK m^3	DK+SAR m^3	KK m^3	DK+SAR m^3	max. m^3	min. m^3	20° C, 1 bar m^3/h	KK h	DK+SAR h	KK h	DK+SAR h	
KWW, Würgassen	2700	3700	6400	9100	21000	11000	1200	6	8	6	2	Stationary liquid N_2-storage
KKB, Brunsbüttel	2284	3816	3800	6400	8300		800	6.5	8	1.5	2	Stationary liquid storage only for post-inerting *)
KKI, Isar	2252	3816	3734	6328	17300		1200	19	6	1.5	3	Stationary liquid N_2-storage
KKP I, Philippsburg	2172	3700	3600	6136	21270	15500	1500	2.4	4.1	1.5	3	Stationary liquid N_2-storage
KKK, Krümmel	2714	4970	4000	7000	8300		1500	3	4	6	3	Stationary liquid storage only for post-inerting *)
KRB II, Gundremmingen	6000	only KK is inerted	18000	-	18000		1000	< 24	only KK is inerted	5	only KK is inerted	Stationary liquid N_2-storage

* For new inerting, the stationary storage tank is refilled by mobile tank trucks

KK = wetwell, DK = drywell, SAR = control-rod-drive room

Table 3.1: Properties of carbon dioxide and nitrogen

Characteristics	Dimension	CO_2	N_2
Molecular weight	kg/kmol	44.01	28.02
Gas constant	kJ/kg K	0.189	0.297
Normalised density (at 0° C and 1013 bar)	kg/m^3	1.977	1.25
Melting temperature	°C	-56.6	-210.5
Melting enthalpy	kJ/kg	184	25.75
Saturation temperature (at 1013 mbar)	°C	-78.2	-195.7
Critical temperature	°C	31.1	147.16
Critical pressure	bar	73.92	33.93
Real specific heat (at 25° C, 1 bar)	kJ/kg K	0.846	1.038
Thermal conductivity (at 25° C, 1 bar)	W/m K	0.016	0.026
Dynamic viscosity (at 25° C, 1 bar)	10^{-5} Ns/m^2	1.48	1.78

Table 3.2: Storage of Iinert-gases in pressurised gas cylinders (50-l standard cylinder)

Specifications	Dimension	CO_2	N_2
50-l cylinder (standard), t_{max} = 57 °C, p = 200 bar	kg per cylinder	37.23	9.51
Required number of cylinders at a minimum inert-gas quantity of 191 t for CO_2 and 227 t for N_2	-	5700	26 500
Mass flow for an injection time of 1 h	kg/s	53	63
Final temperature after discharge of the cylinder (without additional heating of the cylinder)	°C	-36	-156
Final pressure after discharge of the cylinder	bar	11.6	6
Pipe diameter, approx. (related to the final pressure)	mm	160	300
Average flow velocity	m/s	48	53
Dimensions of the storage building, approx. W x H x L	m	9 x 12 x 60	9 x 12 x 270

Table 3.3: Storage of inert-gases in storage tanks

Specifications	Dimension	CO_2	N_2
Storage pressure	bar	15	15
Storage temperature	°C	-28	-162
Maximum content of standard tank width x height	m^3 m		238 5 x 18.1
Required tank volume at a discharge rate of 80 % (CO_2: without ice formation within the tank) related to the required quantities of 191 t CO_2 and 227 t N_2	m^3	235	483
Loss of evaporation (large tanks)	kg/d %/d	0 Refrigerating machine	500 - 1260 0.5 - 1 (0.2 - 0.5)
Required refrigerator power (only for CO_2), approx.	KW	6	-

Table 3.4: Data for gaseous or liquid inert-gas injection from storage tanks (see Table 3.3)

Specifications	Dimension	CO_2	N_2
Gaseous injection			
Mass flow related to the required quantities of inert-gas: CO_2 = 191 t, N_2: 227 t and a discharge within 1 h	kg/s	53	63
Evaporation power (heating-up of the inert-gas up to + 0° C)	MW	18.2	21
Required pipe diameter, approx.	mm	300	500
Average flow velocity	m/s	58	53
Liquid injection			
Final temperature in the storage tank	°C	-44	-177
Final pressure in the storage tank	bar	8.5	6.1
Required pipe diameter, approx.	mm	160	160
Average flow velocity	m/s	14	30

Table 4.1: Timings of accident sequences with core-melt

Core-melt accident	Time in minutes at start of accident		
	Core uncovery	**Start of core melt**	**Pressure-vessel failure**
LOCA with ECCS-failure (low-pressure case LP)	< 1	55	120
Station blackout (high-pressure case HP)	84	110	140
Failure of the feedwater supply with the measure: Primary-system-pressure release (LP*-case)	285	330	410
Rupture of a ECCS-line within the annulus (outside containment)	< 8	80	140

Table 4.2: Scoping calculations with the one-zone code CONDRU regarding core-melt accidents with inert-gas injection

No.	Calculation	Inert-gas	Start of inert-gas injection h	Injection-rate of inert-gas kg/s	Total amount of injected inert-gas kg	6 bar reached in containment (venting criterion) h	flammability[1] 0 = not possible 1 = interfacial area 2 = possible	Remarks
1	LP*-case with sump contact	N_2	5.2	4	205 000	19.4	1	Venting criterion is reached earlier due to N_2-injection
2	LP*-case without sump contact	N_2	5.2	4	200 000	58.4	1	Venting criterion is reached due to accident (+ N_2- inj.) End of injection: 68720 s
3	LP*-case without sump contact	N_2	5.2	40 (during 1 h)	144 000	104.2	0	Venting criterion is reached due to accident (+ N_2-inj.) End of injection: 22320 s
4	LP*-case without sump contact	CO_2	5.2	7	115 000	166.7	1	Venting criterion is reached due to accident (+ N_2- inj.) End of injection: 35187 s
5	LP*-case without sump contact	CO_2	5.2	50 (during 1 h)	180 000	123.6	0	Venting criterion is reached due to accident (+ N_2- inj.) End of injection: 22320 s
6	LP-case without sump contact	CO_2	0.6	17	142 000	133.3	1	Venting criterion is reached due to accident (+ N_2- inj.) End of injection: 10482 s

[1] Homogeneous mixing within the containment

Table 6.1: Post-inerting, general points

Advantages	Disadvantages
- Sufficient inert-gas injection minimises the percentage by volume of the oxygen in the containment atmosphere. Thus the gas mixture is not flammable.	- Flammable gases are not eliminated. - Start of injection and injection rate are depending on the accident. - Additional pressure build-up in the containment caused by later inert-gas supply. - Therefore the conditions for containment venting are reached earlier. - Thereby a higher loading of fission products in the venting filters is given due to the earlier containment venting. - An intensive inert-gas injection may influence the deposition of fission products (resuspension of deposited aerosols).

Table 6.2: Selection of CO_2 or N_2

Advantages	Disadvantages
CO_2	
- Smaller amounts of gas are needed for complete inerting - Smaller pressure build-up in the containment in comparison with N_2 - Reduction of the flammability limits in the ternary diagramme in comparison with steam (Fig. 2.3)	- Intensively branched pipe system is required for liquid injection of CO_2 - A pre-pressure > 5 bars is required before the CO_2-spray nozzles in the case of liquid injection (formation of dry ice, plugging) - The above requirement may not be met in case of a severe accident (partial destruction of the pipe system)
N_2	
- No danger of freezing by low-temperature gas injection	- Greater quantities of gas for complete inerting are required. - Significantly greater pressure build-up in the containment in comparison with CO_2 - Increasing of the flammability limits in the ternary diagramme compared to steam (Fig. 2.3) - Relatively high storage losses.

Table 6.3: Liquid or gaseous injection into the containment

Advantages	Disadvantages
Gaseous injection	
- No technical problems - Negligable influence on normal operation - Utilisation of existing systems possible for injection	- Energy demand for heating and evaporation of the inert-gases (different for CO_2 and N_2, cf. chapter 3.3)
Liquid injection	
- Energy consumption for heating and evaporation, thus pressure and temperature reduction in the containment - For CO_2 simple manually operated measures for injection	- New technical design for the penetrations of liquid-gas pipes (insulation) through the steel shell of the containment - Material problems possible due to freezing shocks for safety related components and instrumentations (also freezing)

Table 6.4: Inert-gas storage inside/outside the containment

Advantages	Disadvantages
Storage outside containment	
- No technical problem with standard sizes (approx. 50 t) - Technical solutions for storage of inert-gas in large containers seem to be possible - CO_2-storage has advantages compared with N_2 because evaporation losses can be avoided by using relatively small refrigerators	- New technical design for containers larger than standard size is required, because up to now not available - Evaporation losses rise proportional to the container size - Pressure-resistant storage building (bunker) is required as protection of the environment against rupture of the gas container
Storage inside containment	
- No cold-insulated penetrations through the containment shell are necessary	- Protected storage areas within containment are required for standard and large containers - Later installation leads to problems at existing plants - High numbers for storage in cylinders (> 20 000 for N_2), complicated distribution system, large floor space required - No accessibility during an accident - Restrictions during normal operation caused by the storage of high-pressure gas cylinders (protection bunker)

Table 6.5: Operator actions

Advantages	Disadvantages
Manual injection	
- Injection time and injection quantity can be decided depending on accident type - Failures (components, operator actions) will be immediately noticed	- The decision for the earliest injection time must be made under stress within the first hour minus the time for the various operator actions, although no clear decision criteria are available - Inadvertent injection possible
Fully automatic injection	
- No incorrect decisions or actions due to stress situations or unclear decision criteria are possible	- At a controlled incident not exceeding the design basis an inadvertentinjection leads to negative consequences concerning high pressure, leakages, temperature and corrosion problems - Loss of the entire system is possible
Automatic injection preparation	
- Injection preparation can take place immediately, decision for injection is made depending on accident type, manual operator actions possible	- Loss of the system is noticed too late or not at all

Table 6.6: Place of injection

Advantages	Disadvantages
Injection into the equipment rooms	
- Injection near the H_2-release, at this place direct inerting	- Stable gas stratification between equipment and operating rooms may influence the inerting of the upper operating rooms - Active mixing devices (energy consumption) are necessary
Injection into the operating rooms	
- Convection by cold inert-gas injection leads to well-mixed conditions - Endangering of safety-related components due to the low-temperature gas injection is low	- Opening cross-sections between equipment and operating rooms must provide the possibility of being actively opened

10 Figures

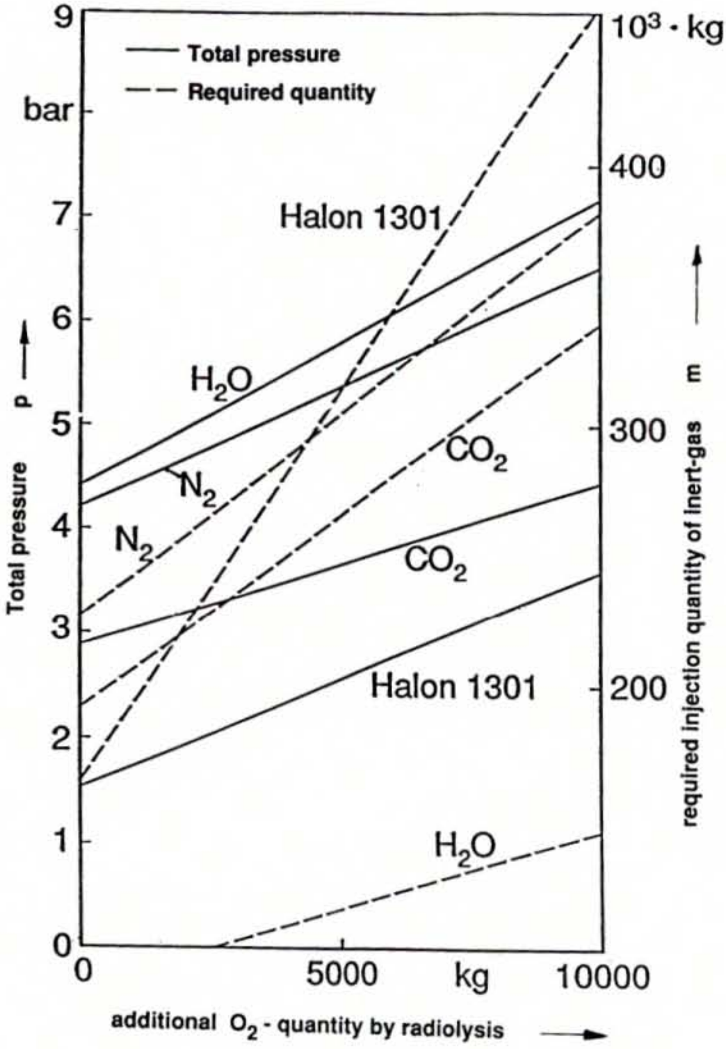

Figure 2.1 Long-term inert-gas injection in a 70 000-m³ containment (cold state)

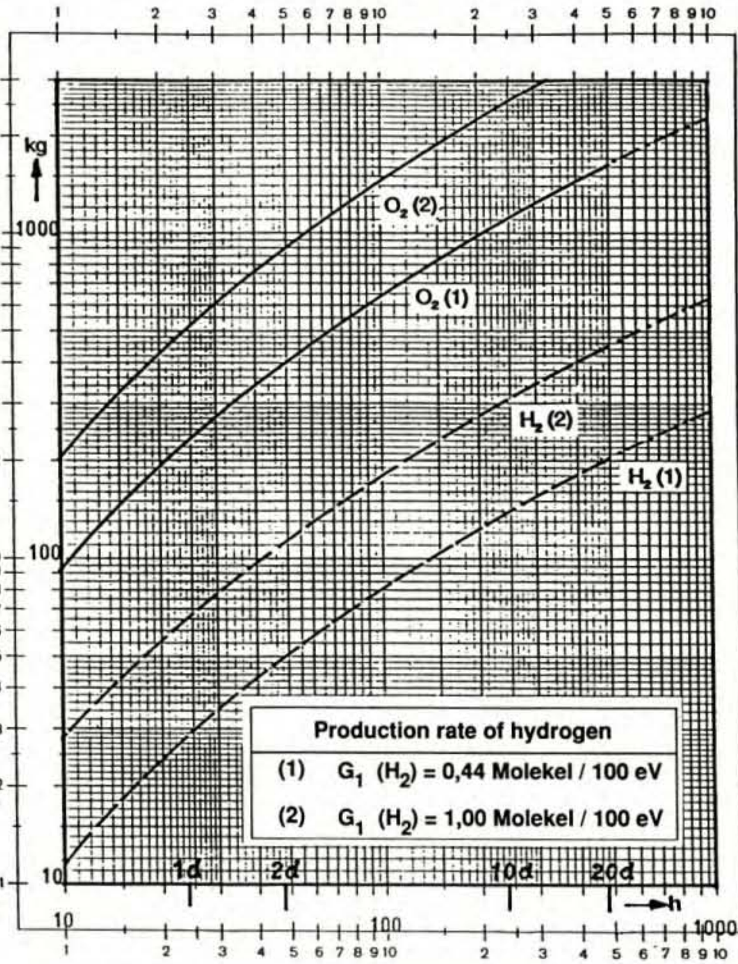

Figure 2.2 Long-term gas production due to sump-water radiolysis after a core-melt accident

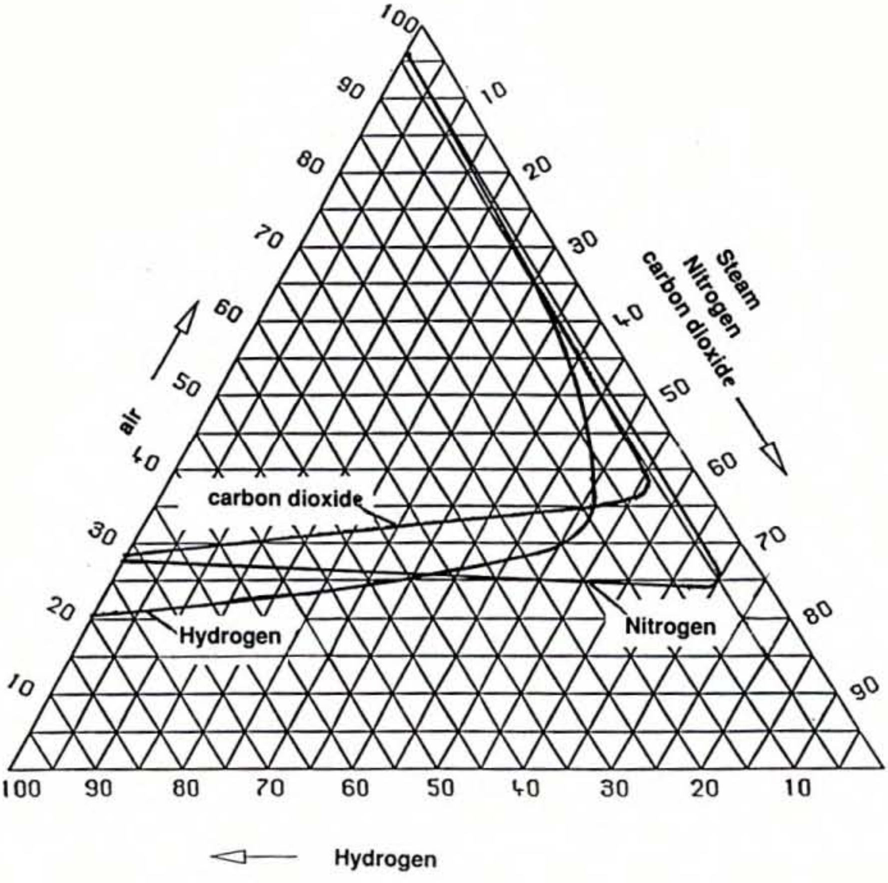

Figure 2.3 Flammability limits of hydrogen, air and inert-gas mixtures

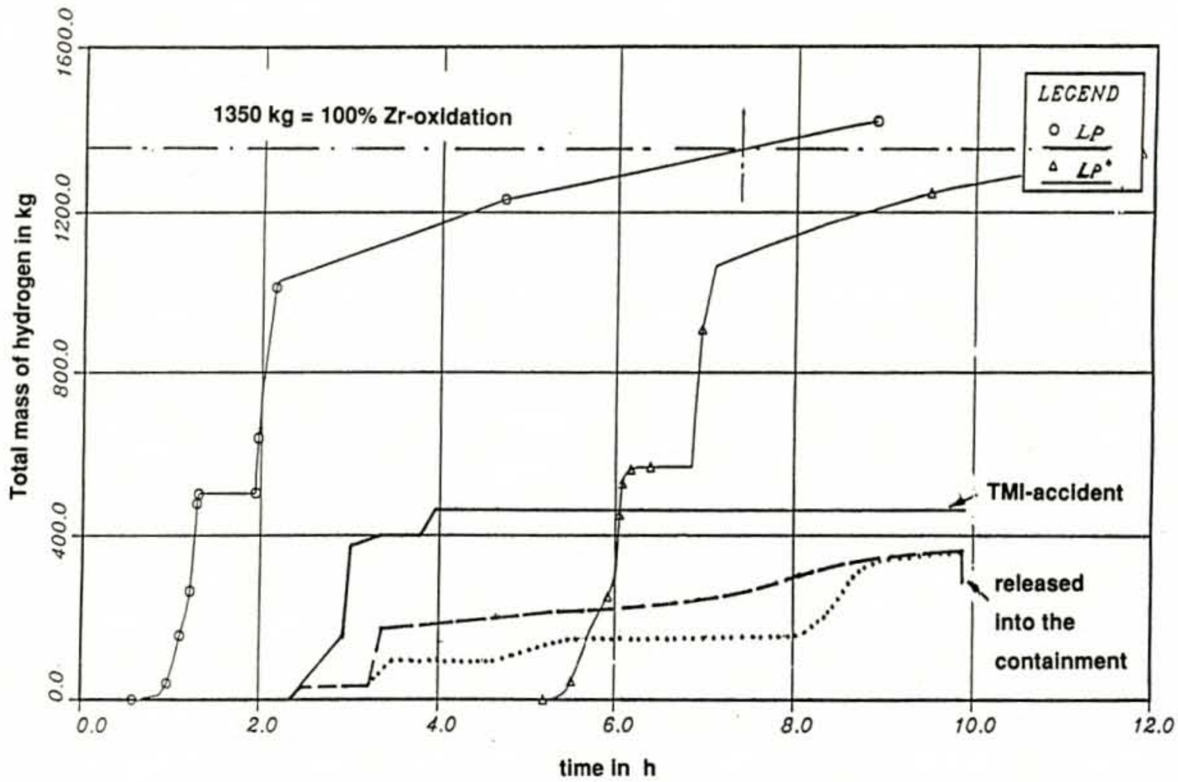

Figure 4.1 Total amounts of hydrogen for various accident sequences

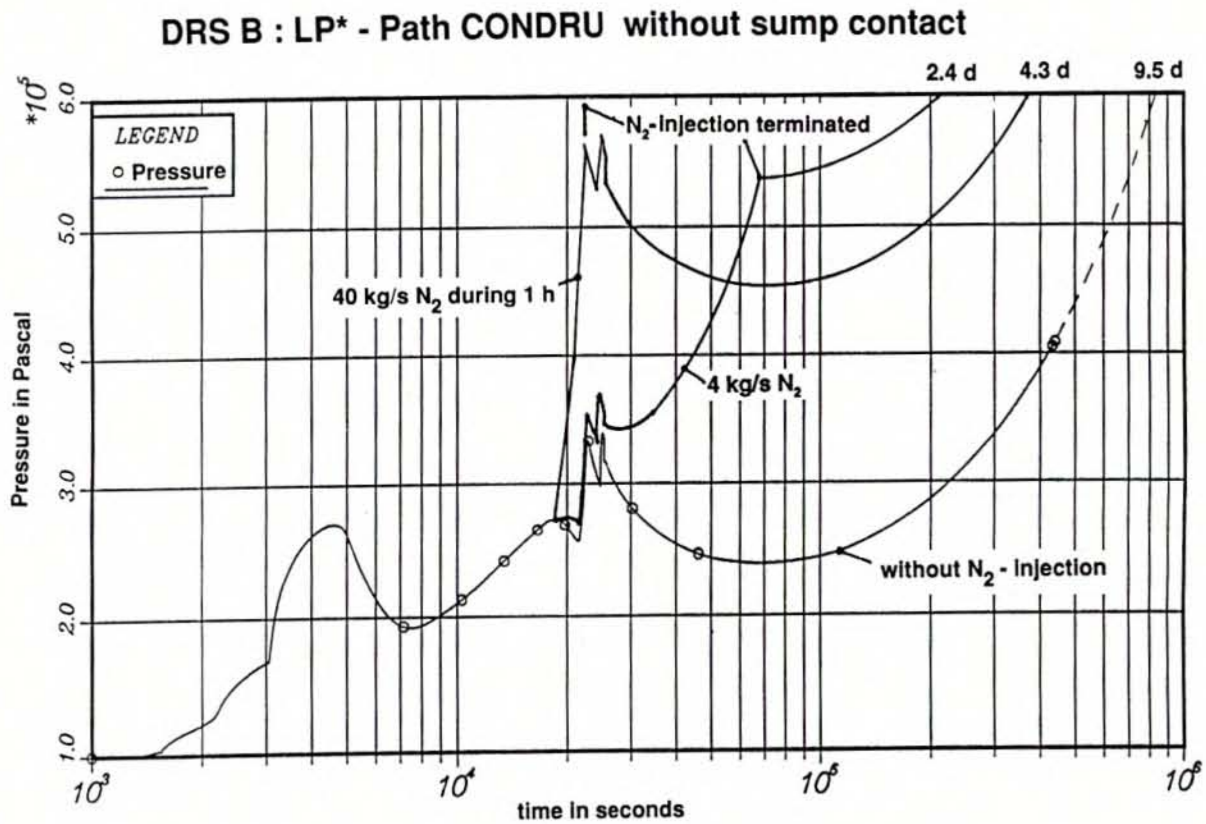

Figure 4.2 Pressure distribution in the containment during nitrogen injection

Flammability limits for

hydrogen - air - inert-gas mixtures

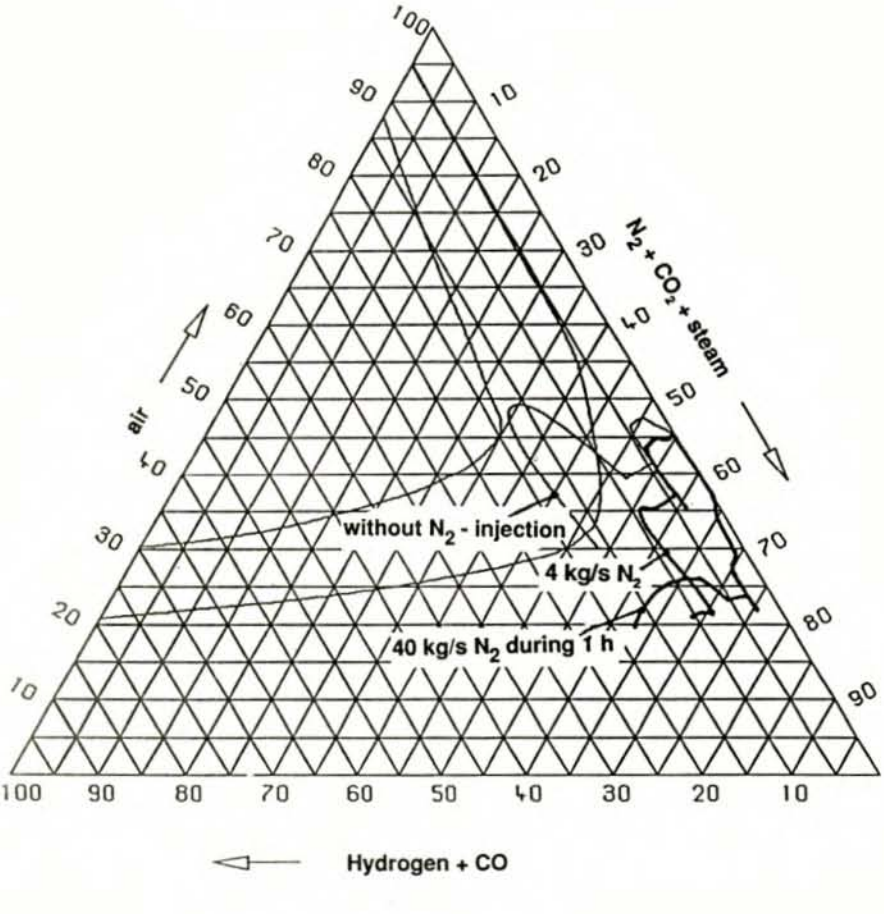

Figure 4.3 H_2-concentration in the containment during N_2-injection
LP*-path without sump contact

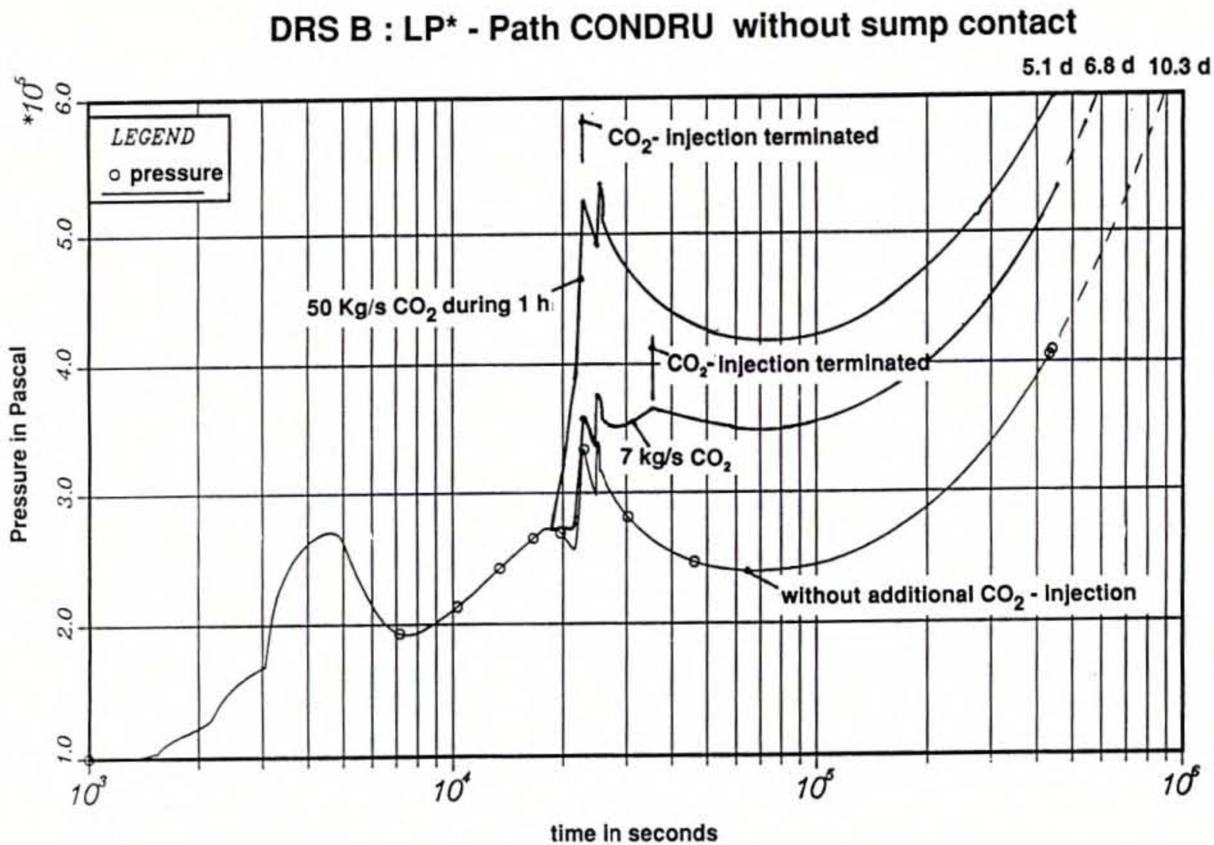

Figure 4.4 Pressure distributions in the containment during CO_2-injection

Flammability limits for

hydrogen - air - inert-gas mixtures

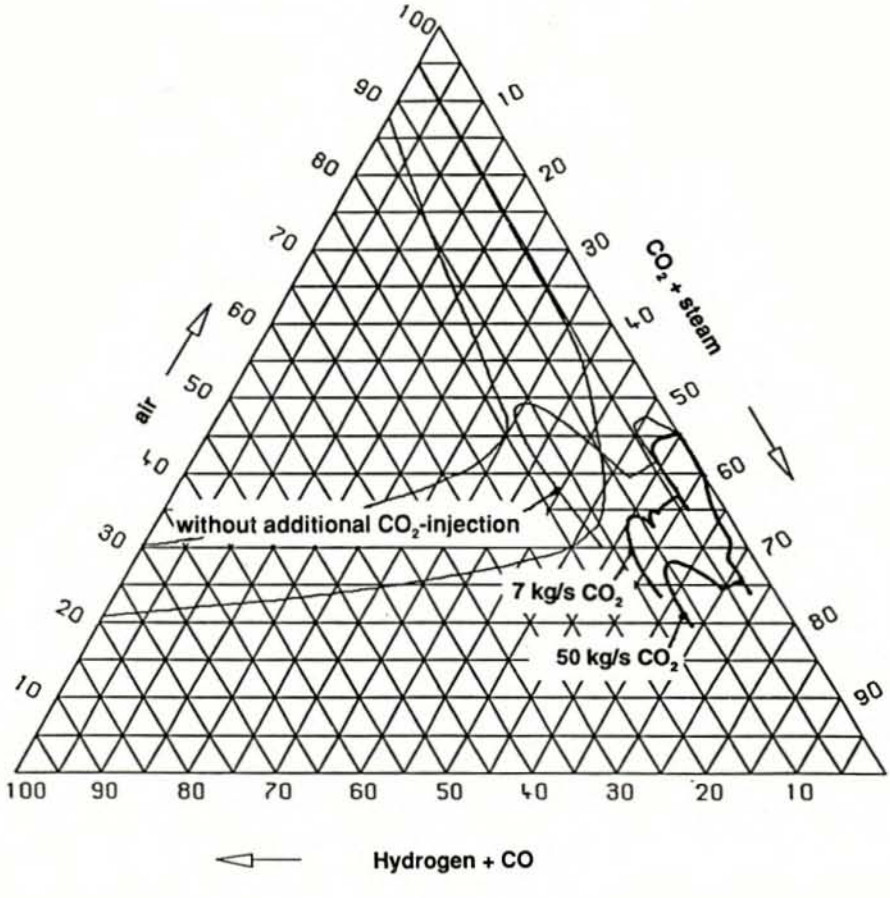

Figure 4.5 H_2-concentration in the containment during CO_2-injection

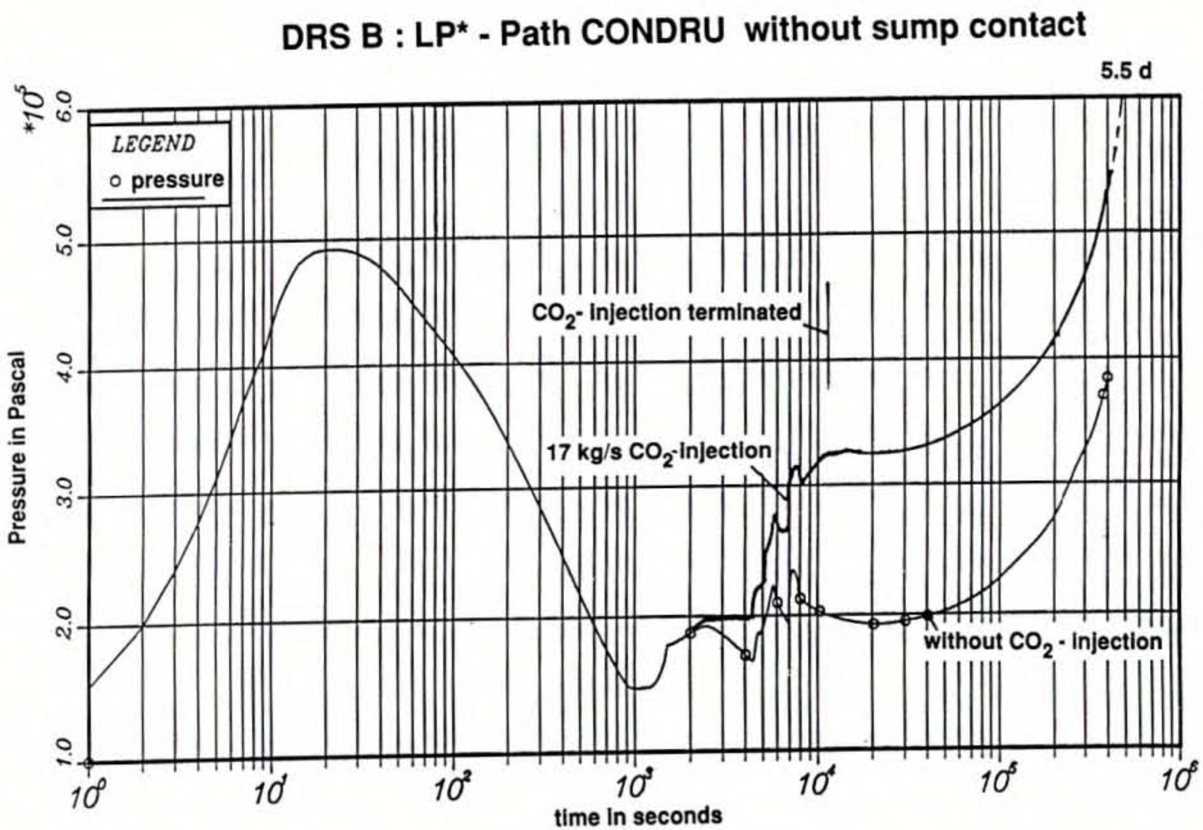

Figure 4.6 Pressure distribution in the containment during CO_2-injection

Flammability limits for

hydrogen - air - inert-gas mixtures

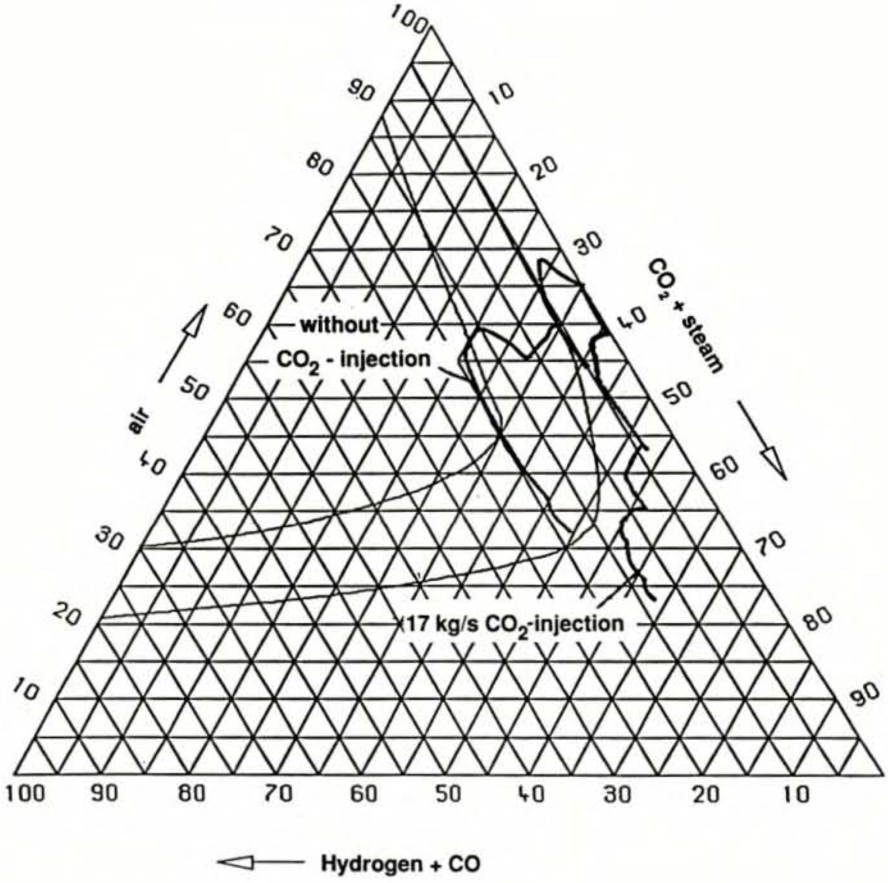

Figure 4.7 H_2-concentration in the containment during CO_2-injection LP-path without sump contact

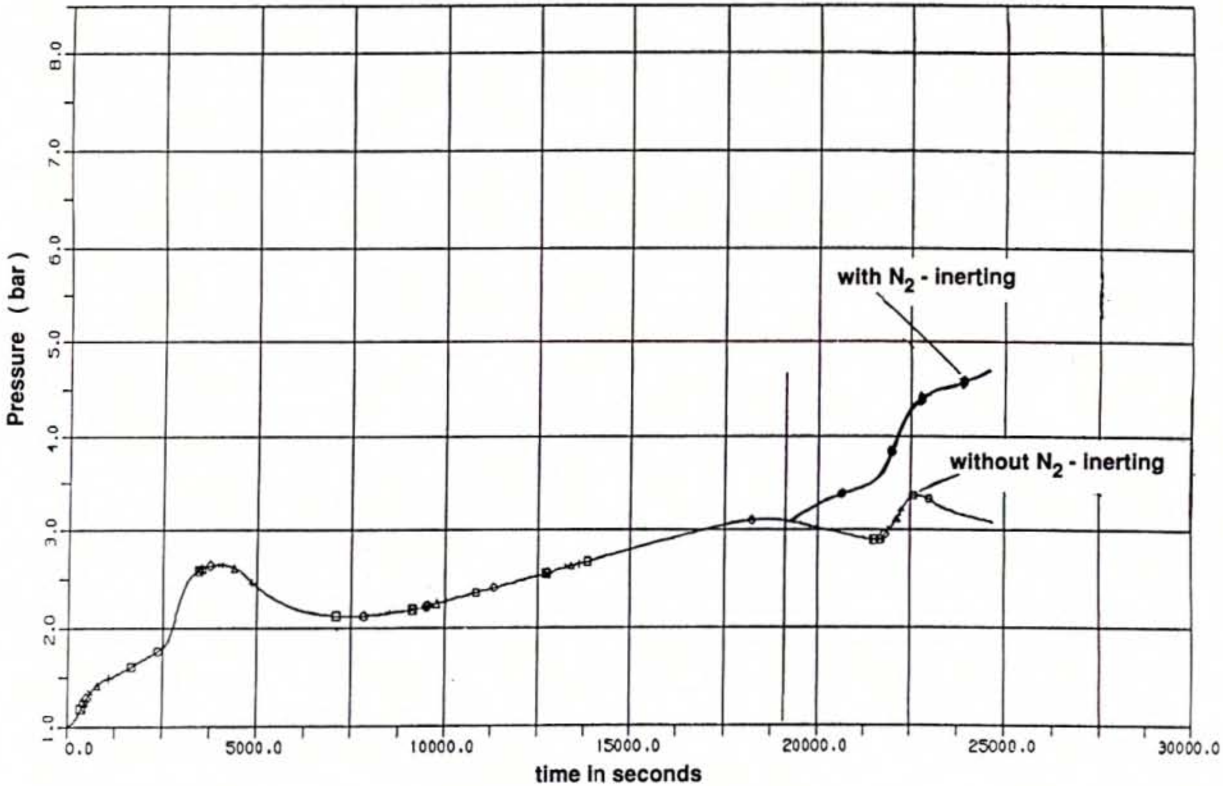

Figure 4.8 Zone-pressure distribution with and without N_2-inerting in the LP*-path

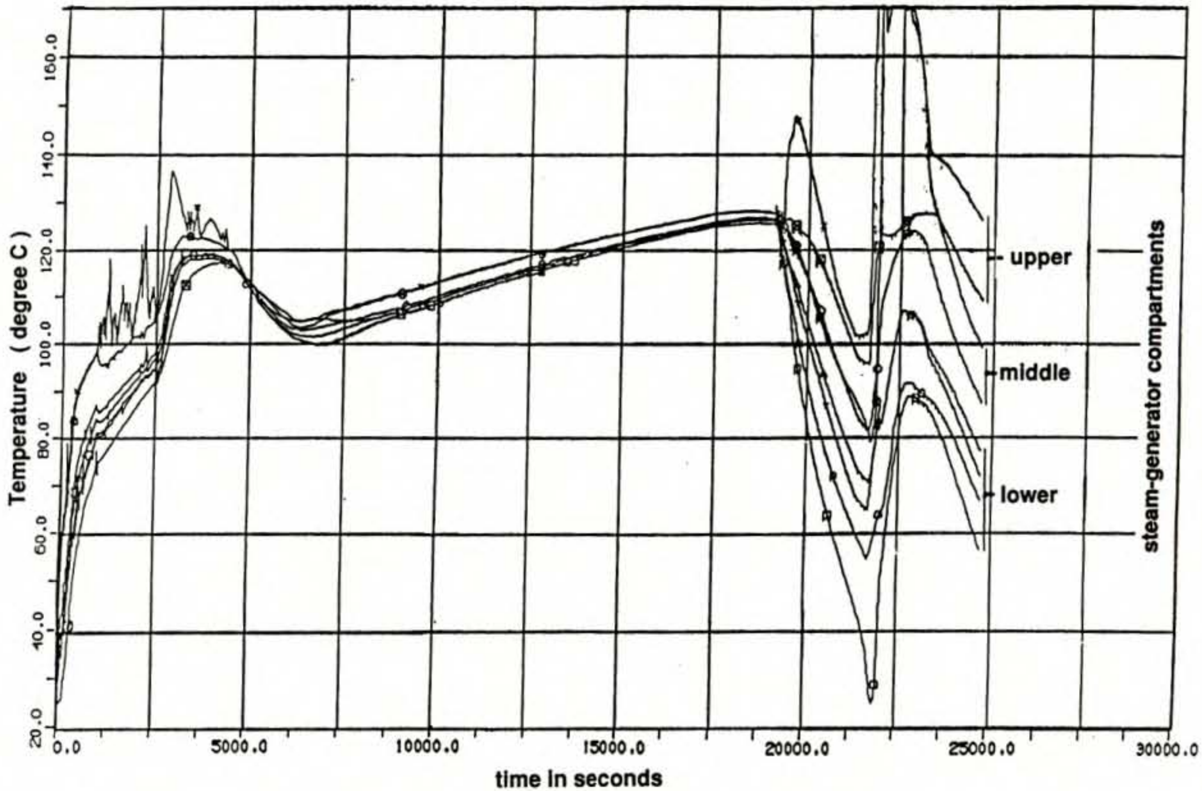

Figure 4.9 Temperature distributions in the steam-generator compartments during N_2-inerting

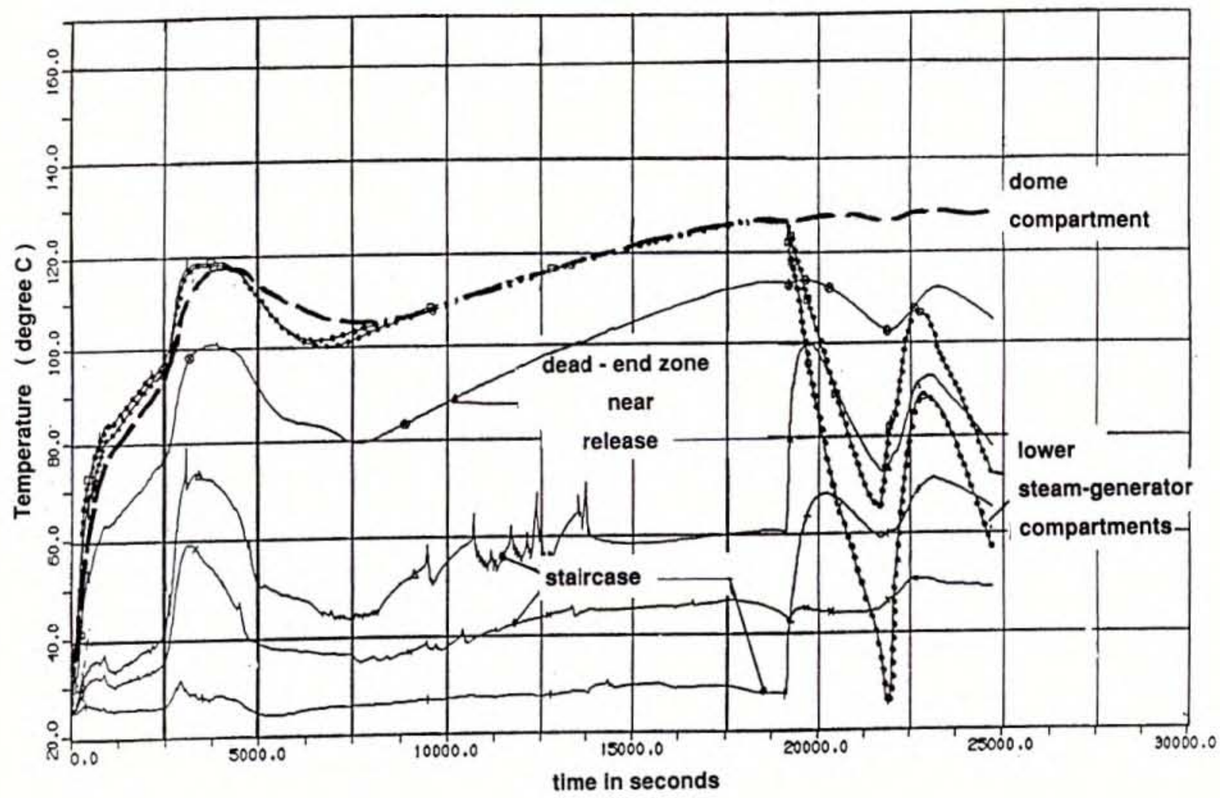

Figure 4.10 Temperature distributions in various zones during N_2-inerting

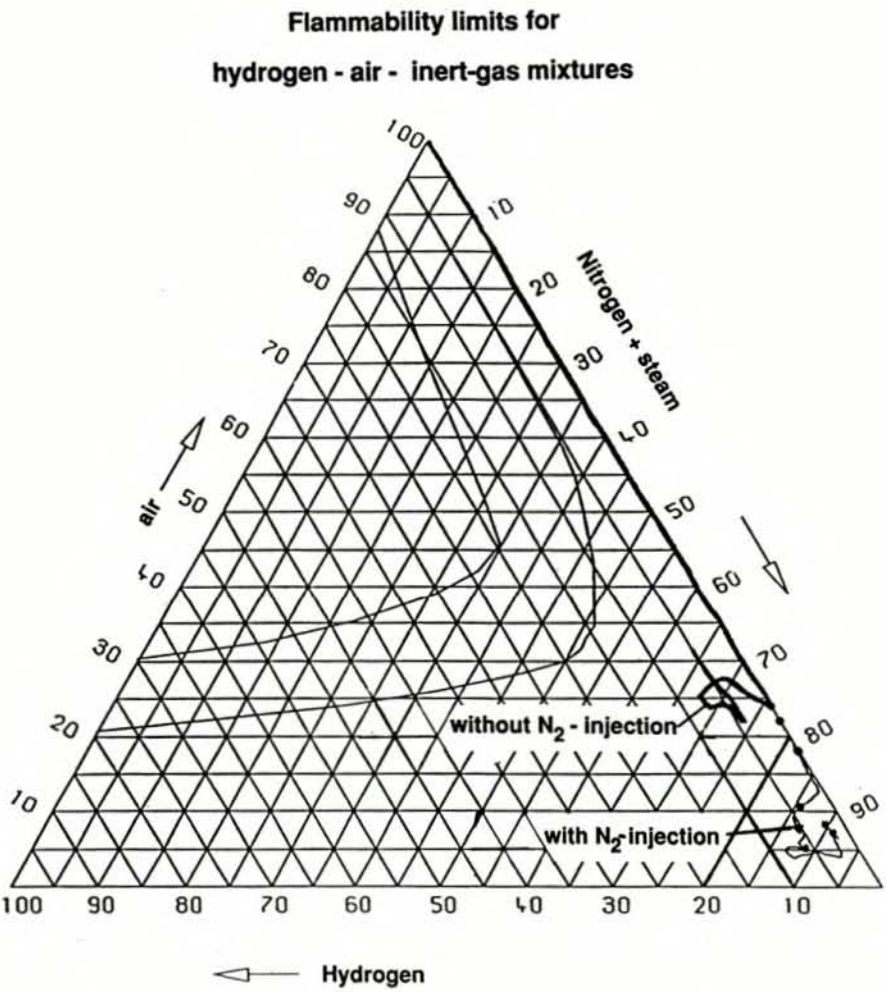

Figure 4.11 H_2-concentration in the lower SG-compartment with and without N_2-inerting

Flammability limits for

hydrogen - air - inert-gas mixtures

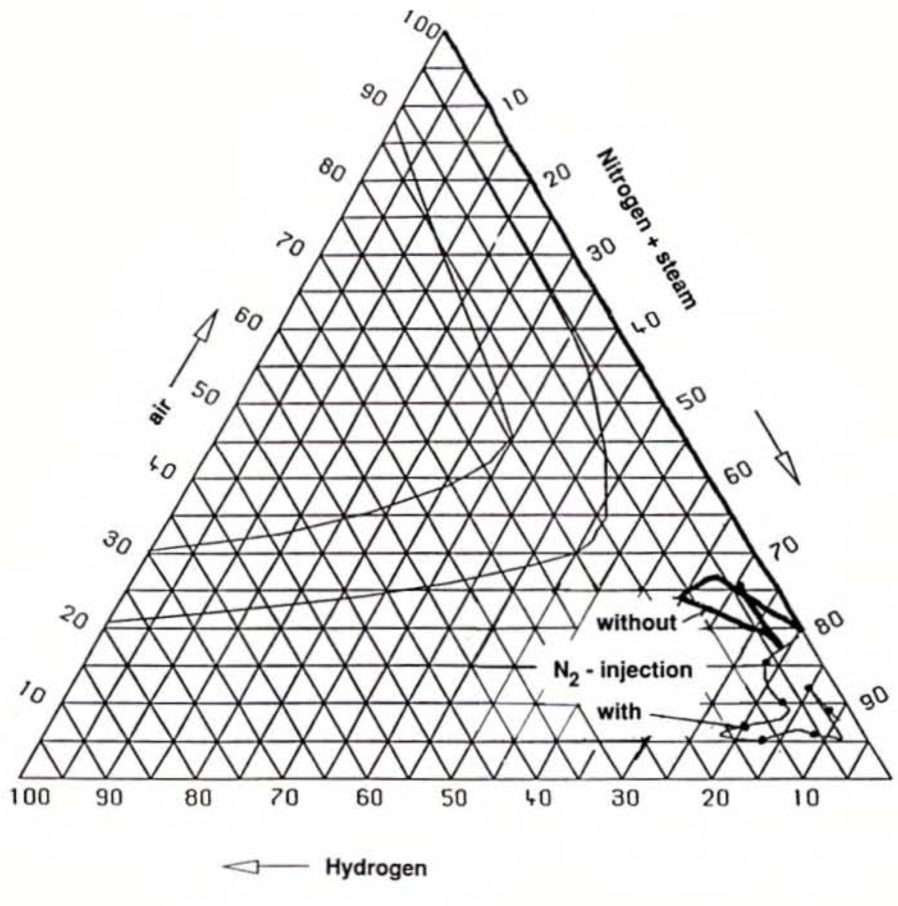

Figure 4.12 H_2-concentration in the middle SG-compartment with and without N_2-inerting

Flammability limits for

hydrogen - air - inert-gas mixtures

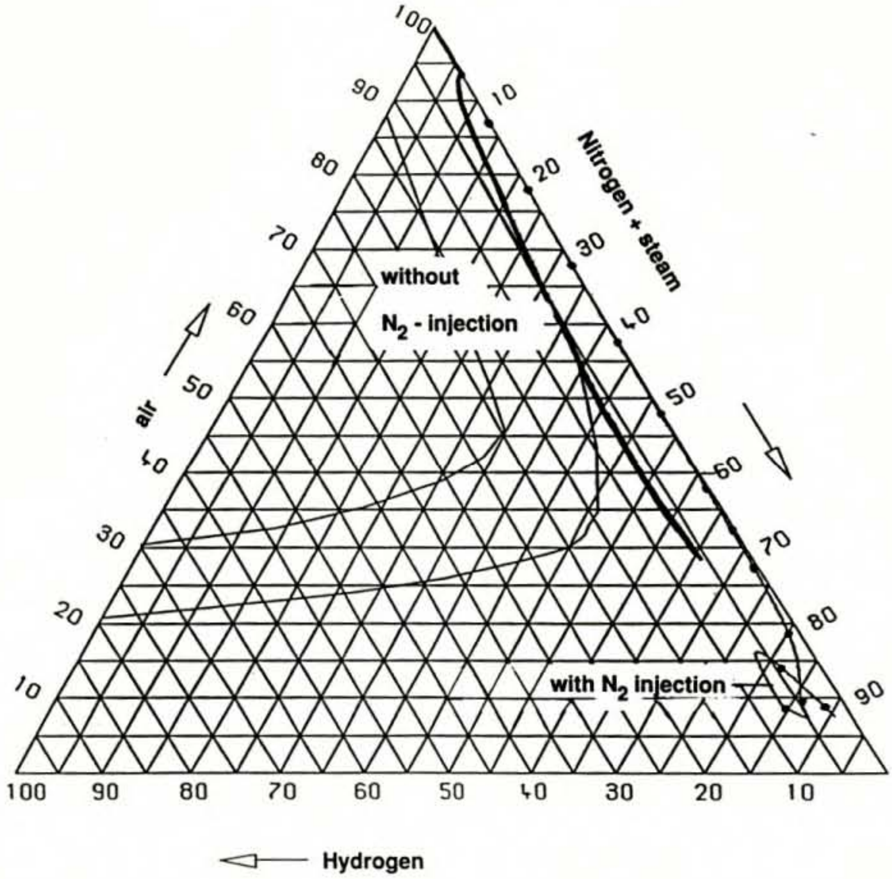

Figure 4.13 H_2-concentration in staircase 1 with and without N_2-inerting

Flammability limits for

hydrogen - air - inert-gas mixtures

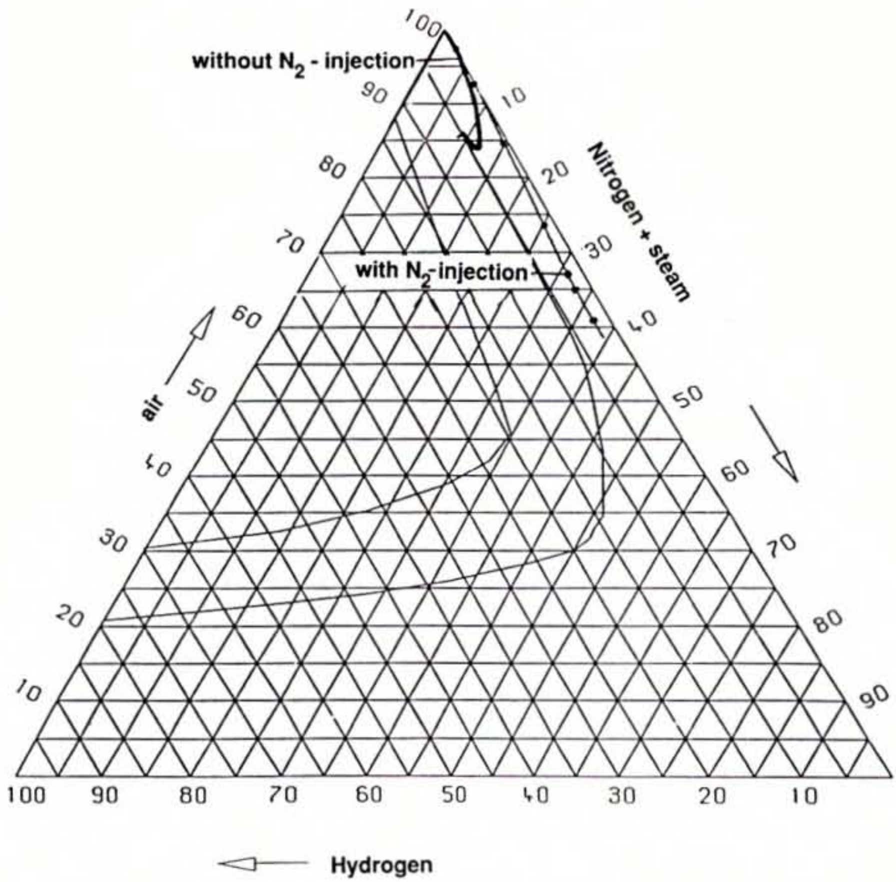

Figure 4.14 H_2-concentration in staircase 2 with and without N_2-inerting

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