THE SNR-300 STEAM GENERATOR SMALL LEAK DETECTION SYSTEM

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ABSTRACT

Small leak detection in the SNR-300 steam generator moduls is achieved by hydrogen meters. Development and design of the Nickel membrane - ion getter pump combination are described and sensitivity requests derived. Results of calibration tests by water/steam injections in a sodium loop are presented. The arrangement and interconnection of signals in SNR-300 are given and possibilities for inservice calibrations are discussed, supported by long time operation tests in the KNK-reactor plant.

1 INTRODUCTION

When starting the design of SNR-300 it was decided to develop hydrogen detectors for the leak tightness control of the steam generators. In 1971 those systems were requested by the German licensing authorities. At that time there was nearly no knowledge available about self wastage, plugging of micro-leaks, sudden enlargement of such leaks, etc.; it was assumed internationally, that a small leak of still uncritical size, with respect to wastage, appears and remains constant for sufficient long times. This describes the design basis for the hydrogen detector development.

2 DETECTOR ARRANGEMENT AND SIGNAL PROCESSING

Arrangement and design of the SNR-300 secondary heat transfer systems are shown in fig. 1. The steam generating part is subdivided in 3 evaporators followed by 3 superheaters each operating in parallel. Two of the secondary circuits are equipped with straight tube modules; the third loop operates with helically coiled ones. While large leak protection is achieved by rupture discs, hydrogen meters are provided for the detection of small leaks. These hydrogen meters are installed at the sodium outlet of each module and two in the main cold leg additionally.

Signal processing of the hydrogen detectors is given in fig. 2. The two detectors in the main pipe have to serve for two functions:

- measurement of the absolute hydrogen content to control the hydrogen diffusion from the water side and the effectivity of cold trap operation
- direct signalisation of the concentration gradient which is used to adjust different alarm levels.

The signals of the 6 detectors at the module outlets serve for the identification of a failed module. This is achieved by the measurement of concentration differences between each module outlet and the main pipe detectors.

3 REQUIREMENTS FROM STEAM GENERATOR OPERATION

It is a well known fact, that the size of a wastage producing flame depends mainly on leak size and water/steam conditions /1,2/. According to the leak detection philosophy, a leak the size of which does not yet produce wastage on an adjacent tube should already be detectable /3/. For SNR-300 tube bundle geometries this leak was determined to 0,09 mm diameter; resulting under superheated steam conditions in a minimum leak rate of 500 gr/h. This leak rate corresponds with an increase of hydrogen concentration in the affected loop of 0,43 ppm/h.

Derived from reactor - and test plant operations the hydrogen diffusion from the water side - due to magnetite formation - is calculated to some $2,5 \cdot 10^{-3}$ ppm/h for normal operation. Hydrogen diffusion during commissioning of the plant is assumed to be up to $2,5 \cdot 10^{-2}$ ppm/h.

Furtheron reactor - and test plant operation show that a minimum hydrogen concentration - due to cold trapping - of < 0,1 ppm is attainable.

The sensitivity of leak detection is strongly influenced by cold trap efficiency which increases with increasing hydrogen concentrations. In order to limit the leak signal reduction to 10 % by cold trap operation the maximum allowable hydrogen concentration had to be limited to 1 ppm.

In conclusion, a leak signal is always superimposed on a fluctuating background, the level of which is controlled by hydrogen diffusion and cold trap operation. Therefore it was decided to use concentration gradients rather than absolute values as alarm levels. Two levels are under discussion:

- 0,1 ppm/h as a prealarm to draw the operators attention to the affected loop

- 0,3 ppm/h as wastage alarm which should be followed by a water side isolation and depressurisation.

4 THE HYDROGEN DETECTOR

Basic principle of the detector design is the world-wide wellknown combination of nickel membrane and ion getter pump, where the electrical current of the continuous operating ion getter pump serves as a measure of the hydrogen diffusing through the nickel membrane. A sketch of the detector is given in fig. 3. The nickel membrane, consisting of 4 cylindrical fingers, is fed with sodium by a small electro-magnetic pump with a flow rate up to 1 m^3/h. Membrane material is Ni 201 ≙ LCNi 99. The thickness of the fingers is 1 mm and the surface 65,6 cm^2. A controlled membrane temperature of 500°C is maintained, independently from the loop temperature, by an electrical heater system combined with a tube in tube heat exchanger. Sodium flow is controlled by a permanent magnetic flow meter.

The ion getter pump has a pumping speed of appr. 3,5 l/s for hydrogen and operates normally in a pressure range from $1 \cdot 10^{-8}$ to $5 \cdot 10^{-6}$ mbar. This corresponds to a lower sensitivity level of $< 2 \cdot 10^{-2}$ ppm. The operation range is defined from 0,03 to 1 ppm. The static mode response time from 0 - 63 % is in the order of appr. 100 s, the dynamic mode response time which is the normal mode is negligible. For the ion getter pumps a life time of 2 - 4 years is expected.

5 PERFORMANCE TESTS

Performance tests with complete detector units have been subdivided into two main groups:

- dynamic steam injection tests in the 50 MW_{th} steam generator test facility at Hengelo, NL,

- normal operation tests in the KNK II reactor at Karlsruhe /4/.

In addition long time tests with more than 40.000 hours per detector are under performance in different test loops as well as pumping speed measurements of ion getter pumps and temperature stability tests.

5.1 Steam injection tests

To proove the dynamic behaviour of the detector under water/ steam leak conditions it was felt to be necessary to perform real steam injection tests instead of the normally used hydrogen injections. Tests in smaller sodium loops with capacities up to some tons of sodium showed the difficulties to adjust continuous steam flows which should produce hydrogen concentration gradients of about 0,3 ppm/h as mentioned in chapter 3. Therefore it was decided to perform these calibration tests in the 50 MW_{th} test facility at Hengelo, the Netherlands which is operated by TNO. This loop system (fig. 4) contains appr. 60 tons of sodium. In order to protect the steam generator against the effects from a small leak simulation, steam injection was made in a special bypass connected to the steam generator head. The hydrogen detector was located at the steam generator outlet. Superheated steam for injection purposes was produced by a small electrically heated steam generator unit. The leaks were simulated by small, calibrated austenitic tubes of 0,2 mm inner diameter.

Test program and main results are given in table I. The loop was operated under isothermal conditions as well as under real steam producing conditions. Sodium temperatures and flow rates were varied. Injections were performed up to appr. 1 hour duration. 12 out of 15 experiments gave evaluable results. Three tests failed due to plugging of the leak tubes.

Before starting an injection experiment the absolute hydrogen concentration was measured by a so called "Baratron" a device which allows the measurement of the hydrogen partial pressure in an high vacuum system operating in an equilibrium (static) mode. The hydrogen partial pressure is than applied to the sodium system by Sievert's law

$$c_{H_2} = K \cdot \sqrt{p_{H_2}} \quad ; \quad \text{where } K = 4,25 \text{ ppm} \cdot \text{mb}^{-1/2}$$

A typical plot of an experiment is given in fig. 5. It shows the slope of water flow rate which is well reflected by the development of the ion getter pump signal. Quantitative comparisons between ion getter pump signals and the increases of hydrogen concentrations are shown for isothermal operation in fig. 6 and for steam producing conditions in fig. 7. (The background level is calculated from the corresponding ion getter pump current). As expected there are no differences between isothermal and non isothermal conditions. The comparison of these curves was made by the assumption (which has been prooven by additional absolute concentration measurements) that all the hydrogen of the injected water is available for detection; with other words the wellknown reaction scheme /5/ given in fig. 8 is completed. This assumption is valid as far as the concentrations are kept below the saturation limit. The tests with sodium temperatures below 300°C showed another situation. Due to the unfavourable arrangement of the injection point in a by-pass (see fig. 4) an oversaturation of sodium hydride took place at lower sodium temperatures. This is shown for two examples in fig. 9. The average sodium flow rate in the injection by-pass was adjusted to appr. 3 m³/h.

For the tests in question No. 5 and 10 (see table 1) the following table contains some interesting informations:

test No.	water leak gr/h	theor.hydr.[x)] concentr. $C_o + \Delta$ ppm =	sodium temp. °C	sat.hydr.[xx)] concentr. ppm
5	252	0,255+11 = 11,255	282	10,47
10	177	0,205+ 7,72 = 7,925	245	4,28

x) theor. hydr. concentr. $= \dot{m}_{H_2O} \cdot \frac{2}{18} \cdot \frac{1}{\dot{m}_{Na}} \cdot 10^6$ /ppm/

xx) acc. to Whittinghams formula in fig. 8.

The input of hydrogen is higher than the capability given by the saturation curve.
This results in a deposition of reaction products in the by-pass system and thus in a reduced signal. This assumption is confirmed by fig. 10 which shows clearly the slow dissolution of these reaction products after having already stopped the injections.

The measured and calculated hydrogen concentrations and the recorded signals of the ion getter pump current were used to establish a calibration curve for the detector. With an overall accuracy of better than ± 10 % the relation

$$c_{H_2} = 0{,}036 \cdot I_{IG}^{0{,}85} \quad = \text{ppm, when } I_{IG} = \mu A$$

was found. This curve is given in fig. 11 in comparison with a calculated one which is written:

$$c_{H_2} = 0{,}011 \cdot I_{IG}^{0{,}873} \quad .$$

The signal efficiency of the theoretical curve for a given concentration is 3 - 4 times higher than that of the experimental one.

A number of possibilities have been discussed in order to explain these differences. The two most probable sources are:

- Definition of the diffusion constant. This value is normally derived from diffusion processes from only a gaseous phase through a nickel membrane. It is very likely that in the existing case where hydrogen is dissolved in liquid sodium the real value is lower than expected.

- Pumping speed of the ion getter pump. Pumping speed measurements in the necessary pressure range < $1 \cdot 10^{-7}$ mb are still difficult and incorrect measurements of factor 2 quite possible.

5.2 Normal operation tests in the KNK reactor plant

In order to collect experiences from normal reactor operation the two secondary sodium systems of the KNK reactor at Karlsruhe FRG, were equipped with two hydrogen detectors. Compared with the SNR-300 systems the KNK prototyps operate with nickel membranes of 0,5 mm thickness and a surface of 55 cm². Up to the end of July 1982 the overall operation time for each of the detectors was 26.000 hours. When operation started a calibration curve (see fig. 12) was established by variation of the cold trap temperature and measurement of the hydrogen partial pressure with the "Baratron".

A typical picture of the normal operation behaviour is shown in fig. 13. Due to the hydrogen diffusion from the water/steam side the hydrogen concentration increases with a rate of $1{,}5 \cdot 10^{-3}$ ppm/h. This corresponds to an overall hydrogen diffusion rate of 0,27 mg/m².h, a value which agrees quite well with those given in /3/. The cold trap was found to be very effective with respect to hydrogen. Concentrations below 0,08 ppm hydrogen were attained. These values are in good agreement with the requirements for SNR-300 operation as stated in chapter 3.

5.3 Some remarks on hydrogen concentrations versus plugging temperatures

For the control of soluble impurities such as Na_2O, NaOH or NaH in sodium normally plugging meters are used. With respect to steam generator leaks a comparison of hydrogen concentrations and plugging temperatures seems to be meaningfull. This has been done for both, the steam injection tests (see 5.1) and the KNK operational tests. The results are depicted in fig. 14. In addition the saturation curves for hydrogen and oxygen are given.

$$\lg c_{O_2} = 6{,}239 - \frac{2447}{T} \qquad \text{(Eichelberger's equation)}$$

$$\lg c_{H_2} = 6{,}467 - \frac{3023}{T} \qquad \text{(Whittingham's equation)}$$

In the figure saturation temperature and plugging temperature are set equal. (Depending on the cooling transient and the sedimentation time of the plugging meter, plugging temperatures are normally some degrees lower than the corresponding saturation temperatures). But the hydrogen concentration sloops are completely framed by the two solubility curves. At least qualitatively it can be concluded, that the solubility of hydrogen increases remarkably due to already small amounts of oxygen.

6 CALIBRATIONS IN SNR-300

Already at an early stage of development it was decided to search for possibilities for in situ calibrations and recalibrations. In situ was felt to be necessary because of a number of reasons, such as:

- The complex design of the detectors with special attention to the needed sensitivity and accuracy of the signals
- manufacturing tolerances including tolerances of pumping speeds of the ion getter pumps which are no special design but bought from stock
- aging effects of the pumps and possibly the nickel membranes by which a shift of the calibration curves might occur.
- The expected life time of the ion getter pumps is 2 - 4 years; in situ replacement was requested.

To save capital costs for additional installations such as hydrogen- or even steam-injection devices, to minimize charging of the cold traps by additional impurities and to enable the operator to check the calibration at any time, the method under test at KNK in a modified way has been choosen for SNR-300. The basic idea is to use the impurities which are in any case available in the sodium for the calibrations and to measure the hydrogen content by the "absolute partial pressure" method as already demonstrated in the 50 MW test plant and still in KNK. For this purpose one of the two hydrogen detectors in the main cold leg pipe of each SNR-300 secondary loop (fig. 1) will be equipped with a "Baratron" parallel to the ion getter pump. The "Baratron" operates in an equilibrium mode. The time necessary to equalize partial pressure and hydrogen content, in order to apply Sievert's law, is < 2 hours. For that time the ion getter pump of this special detector of course has to be valved off.

The first in situ calibration will be performed during the nonnuclear, high temperature clean up operation phase. According to the operation range of the detectors (0,03 - 1,0 ppm) the calibration should not exceed the 1 ppm limit. It is assumed that during this clean up operation a hydrogen concentration of that level is easily available in the sodium. By a step wise cold trap operation the calibration curves are established.

Recalibrations during normal plant operation are proposed to be performed by the use of the hydrogen which diffuses through the steam generator tube walls into the sodium. Due to the low expected diffusion rates of appr. $2,5 \cdot 10^{-3}$ ppm/h the equilibrium error of the "Baratron" is negligible.

The normal operation tests in KNK where also this recalibration work is under test, support strongly this progress in calibration method.

7 FINAL REMARKS

Supported by reactor- and test plant experiences the occurance of a sudden tube rupture in a steam generator is unlikely. Experiences show that leak incidents in a steam generator always start with small leak sizes. The sensitivity and stability of the SNR-300 hydrogen meter is sufficient to detect leaks of still uncritical sizes as far as wastage on adjacent tubes is concerned. This statement does not include the additional aspects of microleak plugging and leak propagation. To a certain extend leak propagation has to be accepted as a reality /5/.

Based on the work, reported on in /6/ and supported by the experiences gained from intensive performance tests of prototype steam generators the probability of small leak occurance in

SNR-300 is expected to be less than 0,25 - 0,3 per year of operation. In the case of occurance of a leak the hydrogen detectors will be suitable instruments to save capital costs due to outage time of the reactor.

8 LITERATURE

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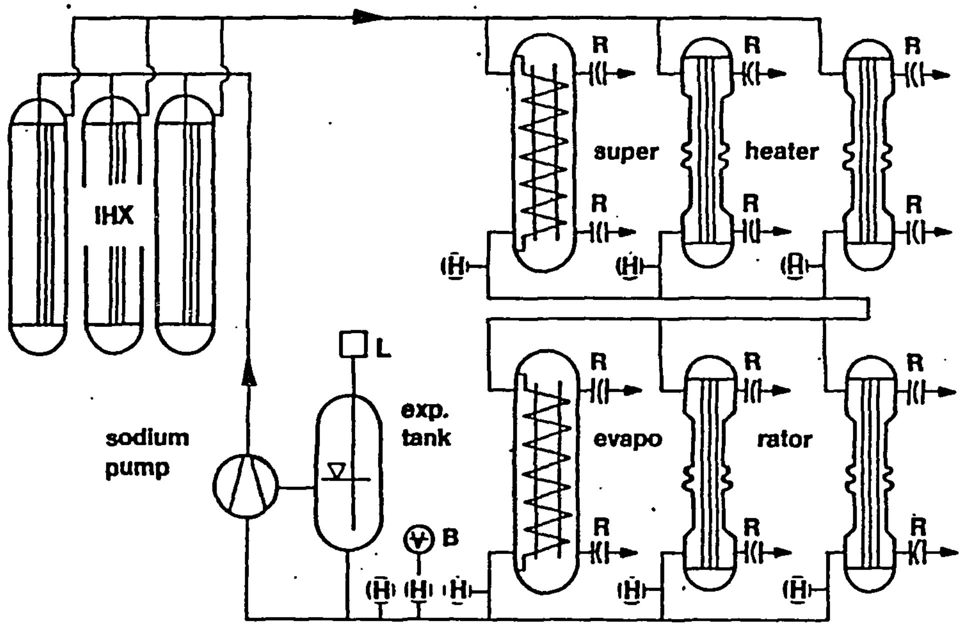
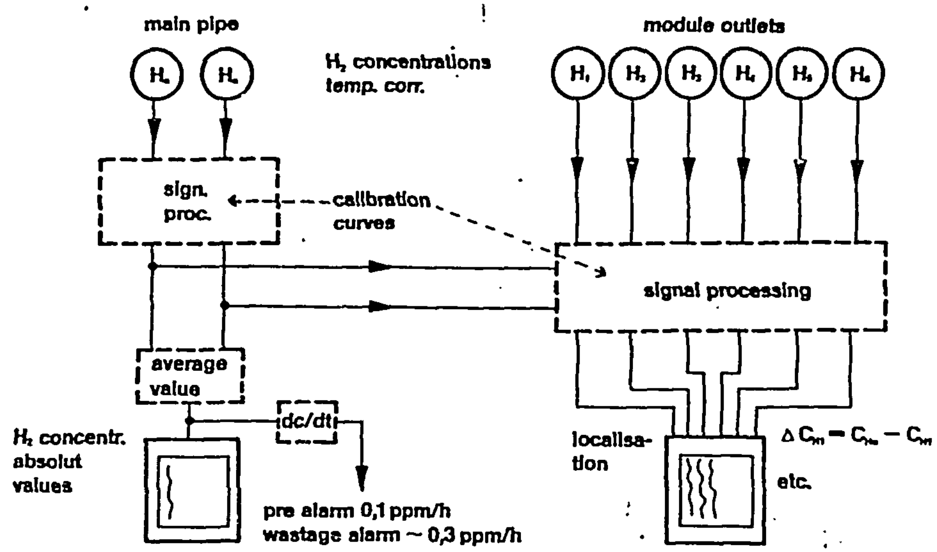
Table 1

Test No.	main loop conditions T_{Na} °C	Q_{Na} kg/s	m_{Na} to	steam injections m_{H_2O} gr	inject. time s	plugging temp. bef. °C	after °C	hydrogen concentr. bef. ppm	after ppm	concentr. gradient ppm/h	pump current bef. µA	after µA
1	445	386	63,7	90	1480	119	130	0,20	0,357	0,382	12,7	23,7
2	442	137	62	76	1223	117	135	0,24	0,376	0,40	13,2	22,9
3	335	465	66,2	84	1497	102	127	0,072	0,213	0,34	2,3	9,0
4	340	> 465	66,2	115	1505	131	-	0,22	0,413	0,462	8,4	18,5
5	282	457	67	84	1200	126	136	0,255	0,394	0,417	10,2	15,5
6	283	162	66	97	1250	125	139	0,23	0,393	0,47	8,3	15,65
7	225	480	66	~ 13		122	122	0,2			6,2	
8	225	481	66	~ 4		122	122	0,2			6,3	
9	245	470	67,6	106	1775	< 105	120	0,08	0,254	0,353	2,0	7,4
10	245	162	67,6	88	1785	121	-	0,205	0,398	0,292	7,4	11,2
11	413/317	139	64	106	1727	110	135	0,13	0,314	0,384	4,93	13,65
12	410/329	296	64	~ 4		114	114	0,183			7,53	
13	410/329	296	64	57	1440	113	132	0,183	0,282	0,248	7,8	12,9
14	416/338	439	64,5	62	1040	113	130	0,195	0,302	0,37	8,25	13,25
15	420/315	205	58	208	3377	112	146	0,195	0,593	0,425	7,55	27,10



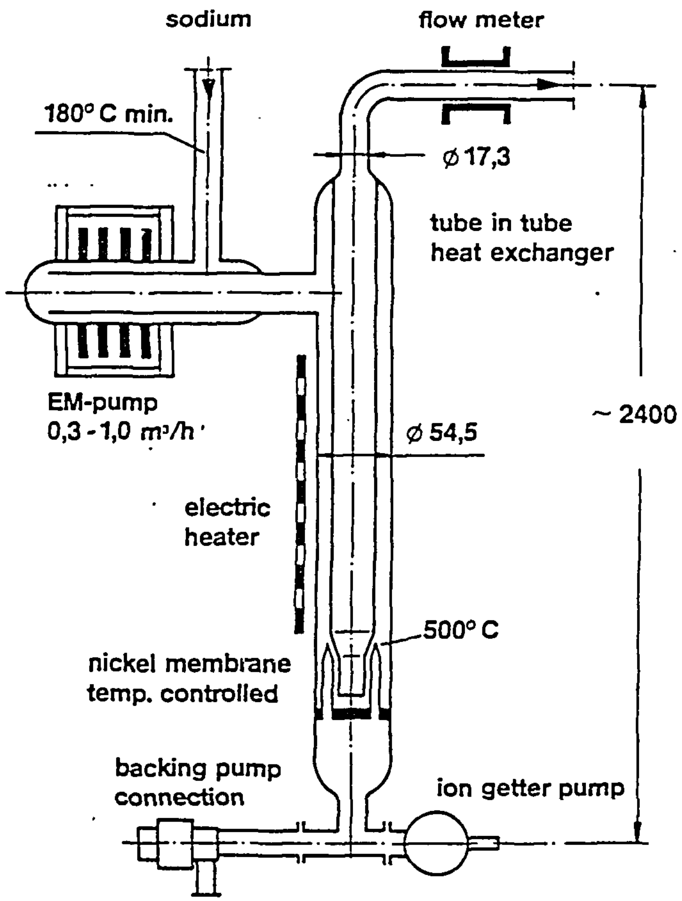
secondary system SNR-300

fig.1



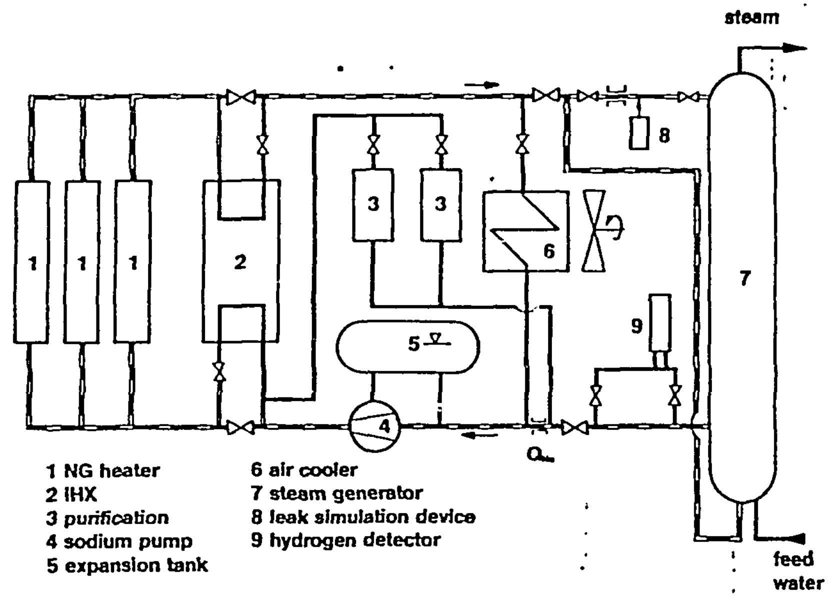
H_2 detection SNR-300

fig.2



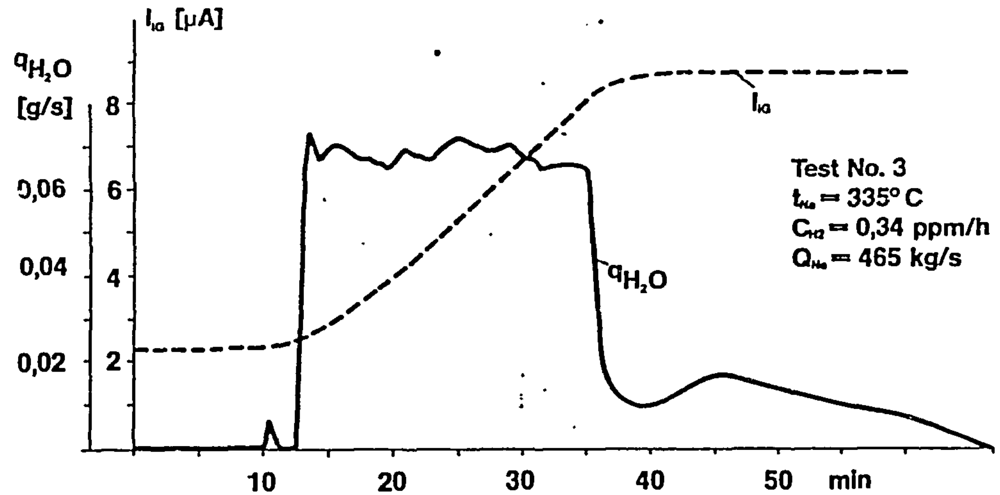
hydrogen detector SNR-300

fig.3



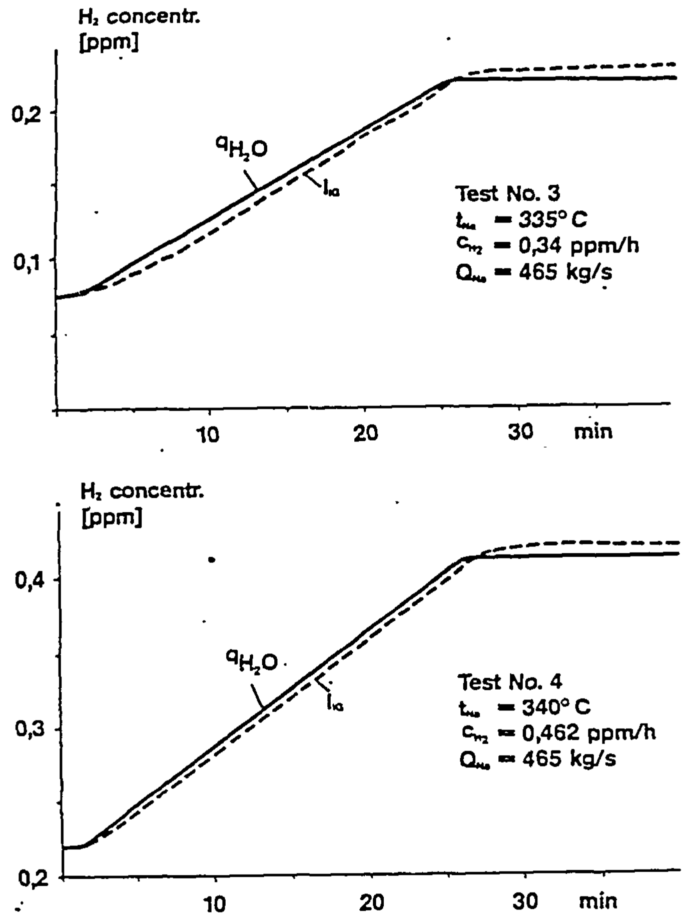
50 MW_{th} test plant, Hengelo

fig.4



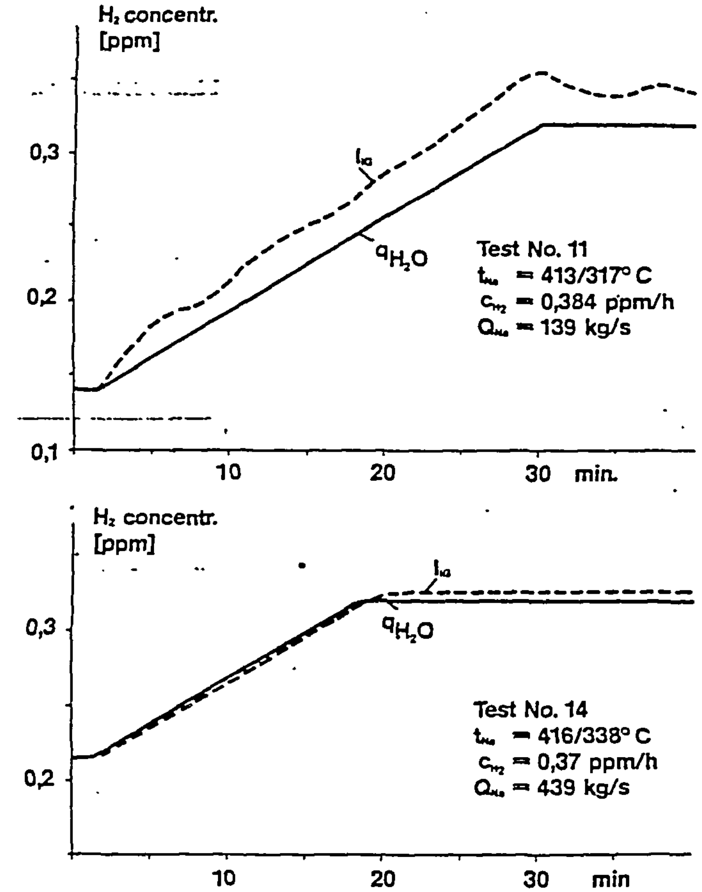
leak flow rate and hydrogen signal

fig.5



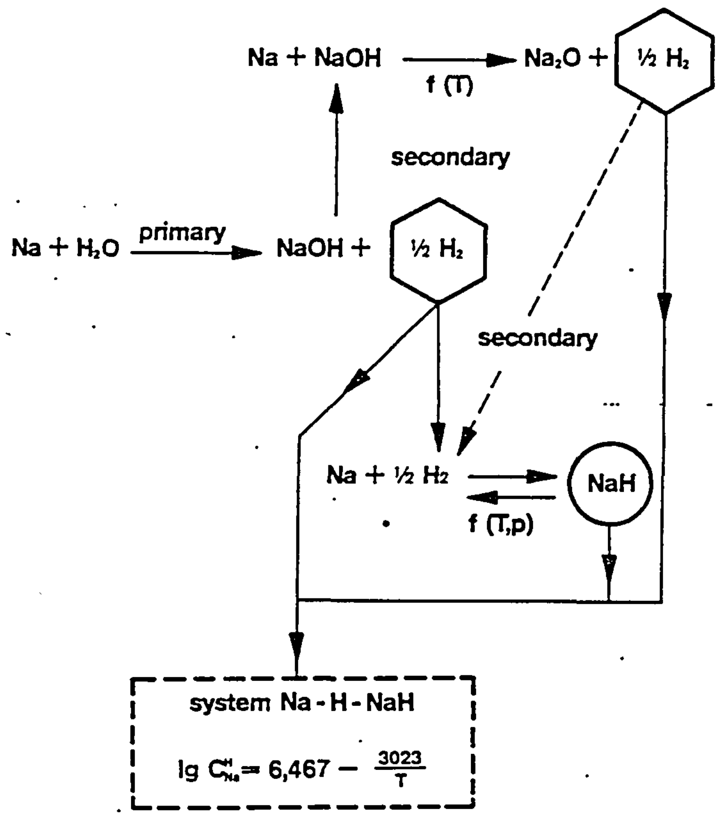
injected and detected leakages
isothermal operation

fig.6



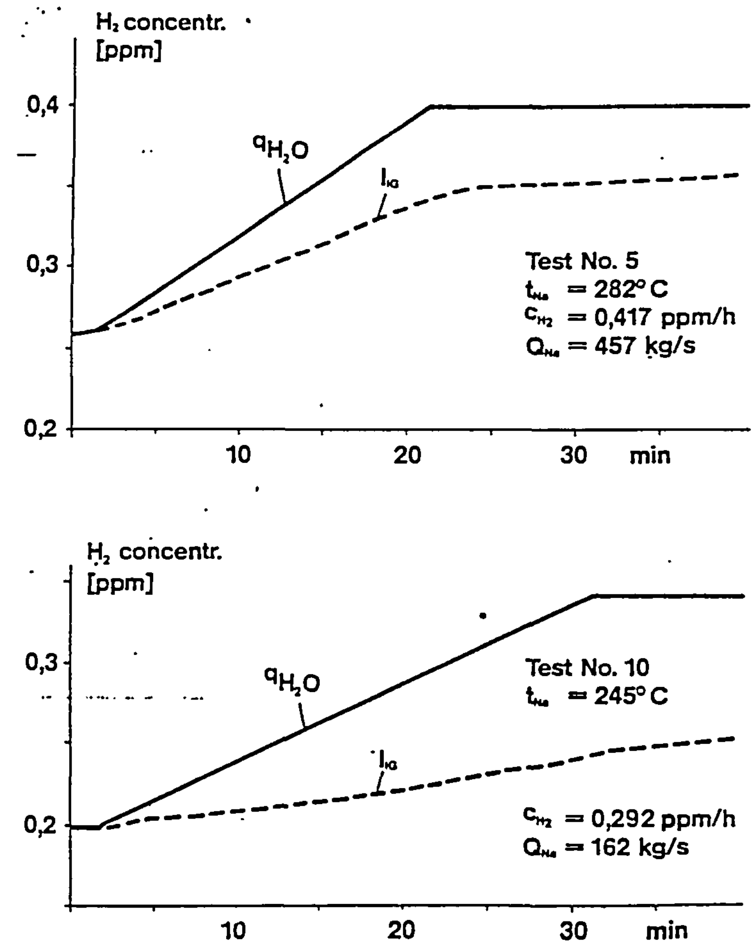
injected and detected leakages
steam generator operation

fig.7



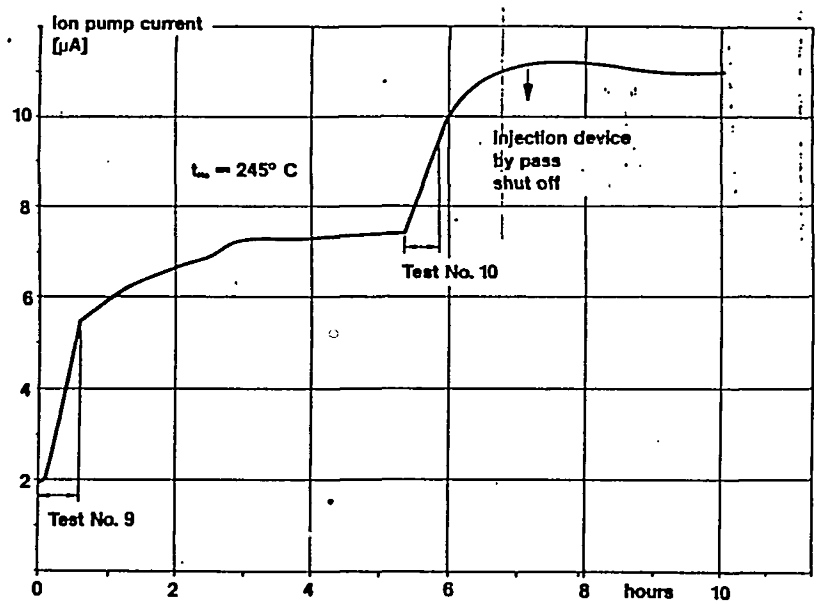
scheme of chemical reactions

fig.8



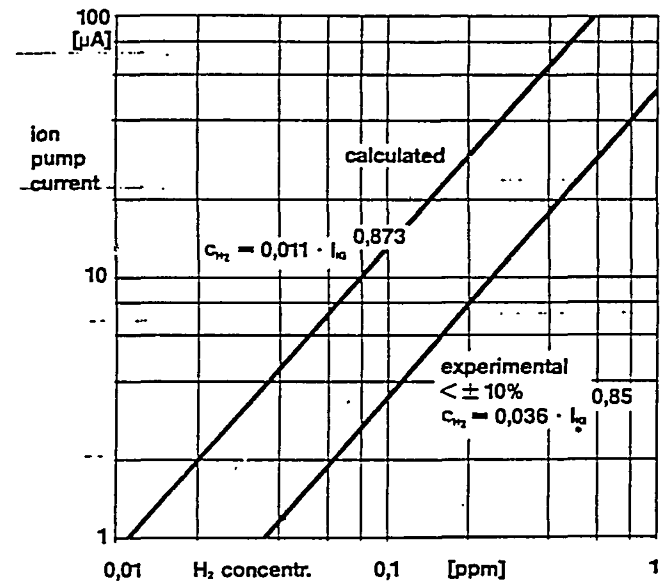
injected and detected leakage
isothermal, low temp. operation

fig.9



low temp. operation, dissolution
of oversaturated reaction products

fig.10



calibration curves
calculated and experimental
SNR-300 prototyp

fig.11

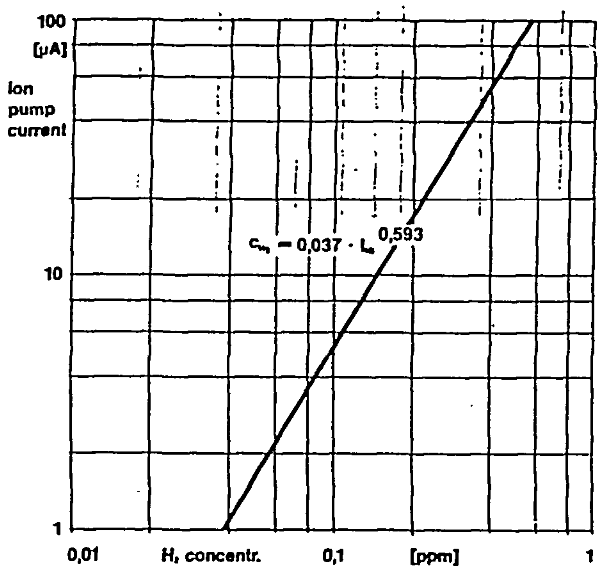
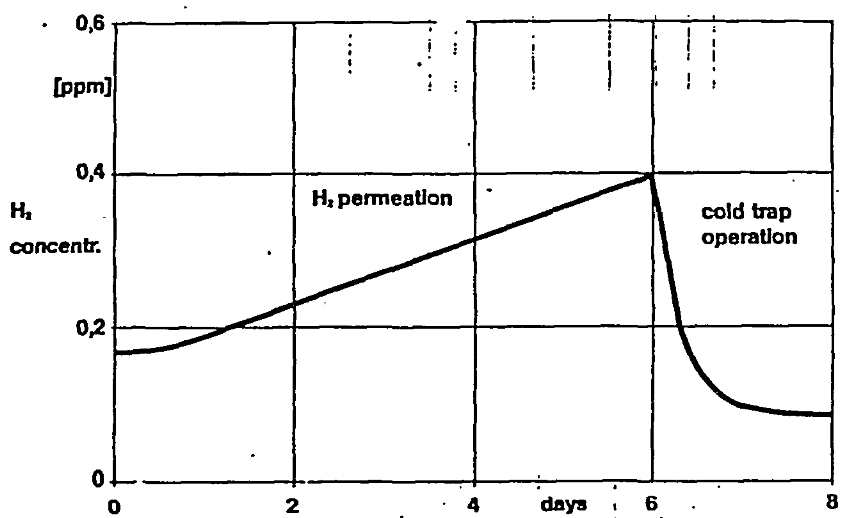


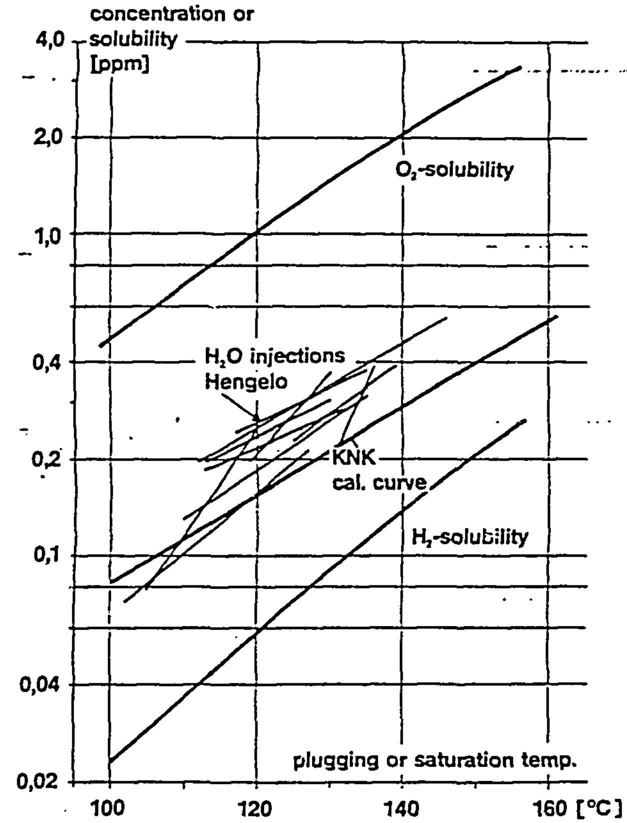
fig.12

KNK H_2 detector
experimental calibration curve



KNK, hydrogen background during
normal operation

fig.13



solubility curves compared with
plugging temperatures and H_2 concentrations

fig.14