SOURCES AND EFFECT OF NON-CONDENSABLE GASES IN REACTOR COOLANT SYSTEM OF LWR

P. Kral
UJV Rez, a. s.
Hlavni 130, Husinec-Rez, Czech Republic
pavel.kral@ujv.cz

J. Hyvärinen
LUT School of Energy Systems / Nuclear Engineering
PO BOX 20, FI-53851 Lappeenranta, Finland
juhani.hyvarinen@lut.fi

A. Prošek
Jožef Stefan Institute
Jamova cesta 39, SI-1000 Ljubljana, Slovenia
andrej.prosek@ijs.si

A. Guba
Hungarian Academy of Sciences Centre for Energy Research (MTA EK)
P.O. Box 49, H-1525 Budapest, Hungary
guba.attila@energia.mta.hu

ABSTRACT

The issue of presence and effects of non-condensable gases (NCG) in primary circuit of light water reactors (LWR) is discussed in the paper. The first objective of the work is to identify all main sources of NCG for reactor coolant system (RCS) of light water reactors. Both release and ingress of gases are assumed. Further, possible effects of NCG on RCS behavior are evaluated – with help of general discussion, analyzing experimental measurements and results of calculations. Beside the effects of NCG on RCS, also the passive safety systems are briefly discussed. Also, an illustrative quantification of individual gas sources is done for LOCA conditions and middle size PWR (VVER-440). The research presented in the paper was initiated in frame of the NUGENIA association.

KEYWORDS
Non-condensable gas, safety analysis, thermal hydraulics, reactor coolant system

1. INTRODUCTION

The presence of non-condensable (NC) gases in pressurized water reactor (PWR) or boiling water reactor (BWR) coolant system could lead to more adverse course and consequences of number of accidents and transients, e.g. by interfering with heat transfer and/or blocking flow paths, particularly during natural circulation conditions and “boiler-condenser” heat transfer mode, both typical to long-term post-accident reactor cooling.

The primary circuit of PWR/VVER reactor contains both in steady state and in transient/accident conditions not only water, but also other chemical substances, like boron and non-condensable gases. The NCG are normally dissolved in liquid water or separated from RCS, e.g. nitrogen in accumulators (ACC), but in accident conditions they can be released or otherwise supplied into RCS and consequently affect the system behavior.

Presence of NCG in primary system of PWR/VVER can have substantial effects on local thermal hydraulic (TH) phenomena and also on whole system behavior (decreased heat transfer in steam generator (SG), higher primary pressure, blocking of upper U-tubes, onset of subcooled boiling etc.).

Although, the sources of NC gases are not so numerous in case in BWR and the RCS is not so affected by gas presence, the NCG should be also here assumed in relevant initiating events and scenarios.

The development of system TH computer codes has brought some capabilities enabling modeling presence and transport of non-condensable gases in reactor coolant system [1].
All major system TH codes (RELAP5, TRACE, CATHARE etc.) can besides the basic coolant – water in liquid or vapor phase – model presence of non-condensable gases in gas field. Lastly, some TH codes have got also the capability to model gases dissolved in liquid water (APROS, ATHLET). However, further development of models (field equations, source terms, delay constants under various flow conditions, closure equations) and their validation is necessary.

Nowadays, there is clear need for a change in the approach to TH safety analyses of nuclear power plant (NPP) – to move in safety analyses of relevant scenarios from modeling of two-phase water to two-phase multi-component coolant in RCS. The research presented here was initiated in frame of the NUGENIA association – during work on a project idea dealing also with non-condensables.

2. SOURCES OF NON-CONDENSABLE GASES FOR REACTOR COOLANT SYSTEM

The release and ingress of NC gas in reactor coolant system can have number of reasons. Generally the gas release from solute state is connected with decrease of pressure or with change of temperature that leads to lower gas solubility. Opposite process is the gas dissolution in liquid water. The delay time constants depend on specific gas and liquid, flow regime (interfacial area) and flow duct geometry.

Considering typical PWR/VVER and whole range of transients/accidents (including loss-of-coolant accident, LOCA) there is number of potential sources of NC gases for the reactor coolant system:

a) Hydrogen or other gases released and accumulated in pressurizer (PRZ) top due to continuous PRZ spraying and electrical heater operation
b) NCG's dissolved normally in primary coolant and their release after RCS pressure decrease
c) Nitrogen dissolved in ACC water and its release after injection into depressurized RCS
d) Inadvertent direct inflow of gaseous nitrogen into RCS due to failure in ACC isolation
e) Release of NCG gases dissolved in non-deaerated water in tanks of Emergency Core Cooling System (ECCS) and injected into RCS during LOCA (supply of water to compensate water boil-off in core, deaeration in core)
f) Radiolysis of water (gamma rays) continuing after reactor scram and stop of Chemical and Volume Control System (CVCS)
g) Reverse flow at break in LBLOCA if primary pressure drops under containment pressure
h) Production of hydrogen in LOCA due to core uncovery, overheating and clad-water reaction
i) Inflow of all gaseous nitrogen from ACC's to RCS in later phase of station blackout (after operator depressurization of RCS; isolation valves not operating due to station blackout, SBO)

Special attention should be pain to shutdown (SD) conditions with number of additional sources of NC gases for RCS:

j) Continuous spraying of PRZ with nitrogen above the level
k) Free reactor level in contact with containment atmosphere
l) Inflow of nitrogen from PRZ to primary loop after inadvertent decrease of PRZ level
m) Penetration of gas to RCS over not tight lines of deaeration system
n) Inadvertent operator connection of nitrogen system to RCS
o) Inadvertent operator under-drainage of RCS connected with reactor level drop to outlet nozzles elevation and inflow of air into hot legs

Sources of NC gases for BWR:

a) Steady-state content of hydrogen and oxygen due to radiolytic decomposition of reactor water
b) Hydraulic scram system driven by nitrogen pressure
c) Continuing radiolysis of water after reactor scram and stop of water cleaning
d) Release of NC gases dissolved in non-deaerated water in suppression chamber and in condensate storage tank and injected into reactor by high pressure and low pressure pumps during accident
e) Release of gas from water returning from isolation condenser (IC).
f) Production of hydrogen due to core overheating and clad-water reaction

3. POSSIBLE EFFECTS OF NC GASES ON RCS BEHAVIOR

Presence of non-condensable gases in PWR or VVER reactor coolant system can affect in numerous ways both local TH phenomena or whole system behavior:

- Degradation of heat transfer at SG, especially in condensation mode [2,3]
- Full blocking of heat transfer surfaces (SG's or other heat exchangers)
- Higher primary pressure in some transients and accidents
- Blocking of flow paths due to cumulation of NCG's in upper parts of RCS (or, in extreme case, pushing out of liquid coolant from whole RCS above break elevation)
- Reduced efficiency of operating pumps
- Effect of dissolved gases on the onset of subcooled boiling and critical heat flux
- Lower spraying efficiency
- Dissolved gases affects pressure waves
- Effect of dissolved gas on onset of subcooled boiling
- Reduction of performance on passive safety systems connected to RCS
- Creation of explosive mixture of gases in upper parts of RCS or in containment

More detailed analyses of sources and effects of NCG on thermal hydraulics of PWR/VVER will be done in chapters 5, 6 and 7 below.

In case of BWR, the sources of NC gases are not so numerous and the BWR reactor coolant system is not so sensitive to NCG presence. The nitrogen (from scram system drivers) dissolved in the hydraulic system water and brought to the RPV is likely to be released in any large quantity only if the reactor system is depressurized rapidly soon after the reactor scram; under such conditions, reactor flooding by the low-pressure core flooding system is imminent, and the presence of non-condensable gas is not likely to interfere with core cooling.

Some old boiling water reactors had isolation condensers, passive heat removal loops which condense reactor steam and return the condensate to the RPV. Such devices have been reintroduced on many recent BWR designs (the SWR-1000 by Areva, Toshiba ABWR, and GE Hitachi ESBWR). Isolation Condensers would be sensitive to a large amount of non-condensable gas; they work best close to nominal reactor operating conditions, where the volume of non-condensables brought to the RPV would be at its smallest.

In addition, modern BWR designs have passive cooling loops to remove decay heat from the containment – these containment cooling devices have been designed to function in the presence of non-condensables and are provided with noncondesable gas venting lines that allow flushing of the heat transfer surfaces.

4. SPECIAL NOTES TO NC GASES AND PASSIVE SAFETY SYSTEMS

This paper is primary focused on non-condensable gases and their effect on RCS, but one should at least briefly mention also the passive safety systems. Passive safety systems have been proposed in order to enhance the safety at LWR [4]. Among them, a passive containment cooling system (PCCS) is one of the most promising candidates as a safety system to be installed at actual NPPs, in order to prevent excessive releases of radioactive materials in LOCA. In fact, the PCCS is part of design of e.g. SBWR, AP-600, AP-1000, VVER-1200 etc.

In the paper [5] a computer program called HVTNC (heat transfer in vertical tubes with non-condensables) has been built up as response to the need to assess PCCS in SBWR. Available Vierow experimental trends have been reproduced. Heat transfer has been found to be severely degraded by the presence of non-condensables.

In the paper [6] steam condensation onto the internal surfaces of the AP600 containment walls has been investigated in two scaled vessels with similar aspect ratios to the actual AP600. The heat transfer degradation in the presence of non-condensable gas has been analyzed for different non-condensable mixtures of air and helium (hydrogen simulant). Results show that the effect of a light gas (helium) in the non-condensable mixture were found to be negligible for concentrations less than approximately 35 molar percent but could result in stratification at higher concentrations.

The correlation based on experimental condensation heat transfer results [4] measured for anticipated LOCA conditions has been derived due to lack of relevant empirical correlations. It is applicable in a wider range of subcooling than existing correlations and it is judged to be applicable to the design of the PCCS to be installed in actual NPPs, insuring seismic integrity as well [7].

The separate effect tests carried out on a Passive Containment Condenser unit in the PANDA large-scale thermal-hydraulic facility considered also the effect on the condensation heat transfer of non-condensable gases heavier than steam (air) and lighter than steam (helium). The recent study [8] shows that both the GOTHIC and TRACE codes are able to reasonably predict the heat transfer capability of the passive containment condenser as well as the influence of non-condensable gas on the system. A slight underestimation of the condenser performance is obtained with both codes. Both codes deviate more from the experiments for the tests with helium, which is explained by the emerging of a complex circulatory flow pattern in the experiments that the models fail to predict.

Other passive safety systems have also been studied. For example, non-condensable gas effect test was performed to study the characteristics of the condensation heat transfer in the heat exchanger of passive auxiliary feedwater system (PAFS) when the nitrogen gas was injected [9].

5. OVERVIEW OF TESTS WITH NC GASES IN COOLANT SYSTEM

In last decade, the experimental projects put more attention on tests with NC gases in the reactor coolant system. Results of measurements from several integral test facilities (ITF) and separate effect test (SET) are discussed below.

5.1. Tests with Non-condensable Gas Performed at PKL Integral Test Facility

The PKL facility [10] models the entire primary side and significant parts of the secondary side of a PWR at a height scale of 1:1. Volumes, power ratings and mass flows are scaled with a ratio of 1:145. The experimental facility consists of 4 primary loops with circulation pumps and steam generators arranged symmetrically around the reactor pressure vessel (RPV).

Table I. Overview of PKL tests with NC gas in primary circuit

Test identification	Date	Description
PKL2 G1.1	2009	Parametric study on heat transfer mechanisms in the SG in presence of nitrogen, steam and water (single loop operation)
PKL2 G1.2	2009	Parametric study on heat transfer mechanisms in the SG in presence of nitrogen, steam and water (double loop operation)
PKL3 H2.1	2014	Station blackout (SBO) with secondary side depressurization and primary side depressurization and 4/8 ACC injection (including inadvertent outflow of all nitrogen from ACCs to RCS)

The PKL2 tests G1.1 and G1.2 [10] were focused on investigation of the heat transfer in the SGs in the presence of nitrogen (with complementary tests in the Hungarian PMK test facility for horizontal SGs). Strong effect of NCG at SG heat transfer was detected both in PKL and PMK tests.

The PKL3 test H2.1 [11] modeled SBO with operator depressurization of both secondary and primary side. The resulting ACC injection and non-availability of electricity for ACC isolation valves led to inflow of nitrogen from ACC into RCS. Nitrogen cumulated in the SG on the primary side and substantially decreased heat transfer from primary to secondary side.

5.2. Tests with Non-condensable Gas Performed at PACTEL Integral Test Facility

The PACTEL integral test facility ([14] was at first designed and constructed as model of VVER-440, later reconfigured to model PWR (EPR, European Pressurized Reactor) plant. PACTEL in its original configuration modeled the entire primary side and significant parts of the secondary side of VVER-440. The 6 loops of NPP were modeled by 3 loops of PACTEL. The height scale was 1:1 with exception of SG tube bundle. The volumetric scale of whole primary circuit was 1:305. The maximum operating pressures on the primary and secondary sides were 8 MPa and 4.6 MPa, respectively. The core power was 1 MW (20 % of scaled full power).

Table II. Overview of PACTEL tests with NC gas in primary circuit

Test identification	Date	Description
NCG (RUN-1)	1997	Release of dissolved non-condensable gas from water (55 bar)
NCG (RUN-2)	1997	Release of dissolved non-condensable gas from water (4,8 bar)
NCG (RUN-3)	1997	Release of dissolved non-condensable gas from water (66 bar)
NCG-1	1999	Behavior of non-condensable gases (one loop, air, inventory ~50 %)
NCG-2	1999	Behavior of non-condensable gases (one loop, air, inventory 100 %)
NCG-3	1999	Behavior of non-condensable gases (one loop, helium, inventory ~50 %)

Test identification	Date	Description
NCG2-03	2002	Behavior of non-condensable gases (one loop, air, inventory ~50 %)
NCG2-04	2002	Behavior of non-condensable gases (one loop, helium, inventory ~50 %)
NCG2-05	2002	Behavior of non-condensable gases (one loop, helium, inventory ~50 %)

System-wide effects of non-condensables on decay heat removal at natural circulation have been studied in PACTEL in the VVER configuration. During small break LOCAs, accumulators discharge into the primary a large quantity of coolant that has been saturated with dissolved nitrogen. In the reference plant of PACTEL, at the time of these studies, the accumulator pressure exceeded 5 MPa, and thus the dissolved quantity was considered large enough to warrant attention. The main concern was that nitrogen, coming out of solution at low system pressure, could create in the main coolant pumps gas pockets large enough to completely block loop flow. Another concern was blocking of the heat transfer tubes in the horizontal steam generators, but the volume of gas required for this was significantly larger than that required to block the main coolant pumps.

In order to analyze small break LOCAs, taking into account the effect of released non-condensable, the non-condensable gas transport model in CATHARE, the French system code, was extended. System codes at the time transported non-condensables as a simple passive scalar convected with gas; Sarrette and Bestion [12] modified this by adding a mass balance for gas dissolved in liquid and an interphase mass flux (representing dissolution or release). The interfacial mass flux was modeled simply as $\sim \frac{X - X_{eq}}{\tau}$, or the difference of current and equilibrium non-condensable concentrations divided by a release/dissolution time constant τ (to be determined experimentally). The gas energy equation was also updated to account for the energy transfer with the non-condensable gas.

The first series of PACTEL experiments on non-condensable behavior reported by Sarrette et al ([12], [13]; NCG RUN-1,2,3) focused on determining the release time constant. PACTEL pressurizer was used as a test vessel, filled with water, pressurized with nitrogen, and after the liquid had saturated, stepwise depressurization was performed to force some of the gas out of the solution. Vessel voiding was estimated from pressure drop measurements and the time constant fitted based on CATHARE simulations of the experiments.

The second series of PACTEL experiments has been reported in Purhonen ([14] summarizing NCG-1,2,3 and adding repeat tests NCG2-03,04,05). In these tests, non-condensable gas, air or helium, was injected into the hot leg in front of one of the steam generators, with the system at boiler-condenser natural circulation in two tests and at full liquid inventory at one test. The purpose of the experiments was to see how the non-condensable impacts primary to secondary heat transfer in the horizontal steam generator. In the air experiments, air accumulated in the topmost tubes; if the volume was large enough to fill the whole tube bundle, system heat removal was reduced, the system pressurized, the gas bubble was reduced in size, and adequate primary-to secondary heat transfer resumed. In the helium experiments, helium accumulated in the middle elevation of the tube. This behavior remained unexplained, despite several repeats, as discussed in Puustinen [15]; the primary-to-secondary heat transfer remained adequate nevertheless.

5.3. Tests with Non-condensable Gas Performed at PMK Integral Test Facility

The PMK-2 facility [16] is a scaled down model of the VVER-440/213 and it was primarily designed for investigating small-break loss of coolant accidents (SBLOCA) and transient processes of this type of NPP. The volume and power scaling of PMK facility are 1:2070, the elevation scale is 1:1. Transients can be started from nominal operating conditions. The six loops of the plant are modeled by a single active loop. In the secondary side of the steam generator the steam/water volume ratio is maintained.

Table III. Overview of PMK tests with NC gas in primary circuit

Test identification	Date	Description
OMFB 00307/91	1992	7,4% LOCA with 3/4 ACC and 0/3 high-pressure injection system (HPIS), accident management (AM), NCG, secondary bleed and feed
OMFB 00307/91	1992	7,4% cold leg break, ECCS configuration: 3/4 ACC, 0/3 HPIS, 1/3 LPIS, AM, non-condensables, secondary bleed and feed
PA Rt,. GFK1	1993	Study of disturbances: shut-down conditions, N_2 in the upper plenum
OMFB, GFK2	1998	Effect of gas injection to the upper plenum
IMP31 (T3.1)	2004	Large-break LOCA 30% from hot state, nitrogen in PRZ.
T1 (OECD-PKL2)	2009	Under-drainage of reactor in shutdown state. Operator intervention after loss of natural circulation and beginning of boiling in core. 3 variants.
T2 (OECD-PKL2)	2010	Small break LOCA 1% during system cooldown (2.5 MPa, 180 °C, steam or nitrogen in PRZ, no ECCS, various availability of secondary relief valves). 3 variants T2.1, T2.2, T2.3 - see below.

The T2 (OECD-PKL2) test series performed in 2010 [10] addressed directly the comparison of a transient with having steam (T2.1) or air in the primary system (T2.2, T2.3). The objective of test series T2 was the investigation of SG heat transfer effectiveness in case of a SBLOCA during the cool-down of the plant to cold shut-down conditions. According to the cool-down procedures below 2.5 MPa the PRZ steam atmosphere is replaced by nitrogen, ACC's and HPIS are disconnected from the primary system and the automatic start-up of low-pressure ECCS is disabled. A LOCA in this situation results in N_2 injection to the primary system from the PRZ, most of it being collected in the SG. Since emergency injection is not available, there is a competing process between cladding temperature rise and pressure reduction to the set-point of low-pressure injection system (LPIS) that strongly depends on the heat transfer effectiveness in the SG, this latter being impacted by the presence of N_2. Obviously, secondary bleed is an important action for reaching LPIS injection in time.

In order to investigate the processes described above three test runs were defined with the same break size of 1% on the top of the downcomer:

- T2.1: Steam atmosphere in the PRZ, secondary bleed by one relief valve (RV). The test constitutes the base case for SG heat transfer, without non-condensables in the primary circuit.
- T2.2: Air atmosphere in the pressurizer, secondary bleed by one RV. This test addresses the effectiveness of the bleed action in the presence of non-condensables.
- T2.3: Air atmosphere in the pressurizer, secondary bleed by two RVs. The test investigates the effect of stronger bleed rate in presence of non-condensables.

The comparison of the tests gives indication of the presence of the non-condensable gas in the primary circuit. Due to the loss of the primary coolant via the break the pressurizer level decreases. After it is emptied, in T2.1 steam is arriving to the hot leg loop seal, some passing bubbles towards the SG can be seen from the void measurements. The steam from the pressurizer is condensing; there is no level decrease in the SG collectors. Steam starts to enter the collectors just after hot leg loop seal clearing.

In T2.2 and T2.3 the non-condensable gas enters the hot leg from the pressurizer, then passes to the SG hot collector and accumulates in the upper parts. None of the five void probes detected any bubbles in the reactor side of the hot leg loop seal up to its clearing. The gas fills the top of the SG collectors and the heat transfer tubes. The collector levels decrease significantly. After hot leg loop seal clearing the steam produced in the core model reaches the steam generator causing further level drop. In the case of air-filled pressurizer – the primary pressure stays about 1.5 bars higher than the secondary one after depressurization due to degraded heat transfer in presence of air in the steam generator.

The cold leg loop seal behavior is also different in the presence of non-condensables. In T2.1 the loop seal level begins to show frequent passage of steam bubbles, but all the steam condenses before reaching the break at the top of the downcomer for about 600 s. In T2.2 and T2.3 there are some void detected by LV52 (void probe in the end part of cold leg) and the time delay up to the void reaching the break is much less due to the non-condensables. Void measurements indicate that the non-condensable gas accumulated at the steam generator outlet is evacuated in about 500 s via the cold leg loop seal towards the break.

In the tests with air, the secondary bleed is much less effective to recover the core level due to degraded heat transfer in the steam generator and quenching of the heater rods takes longer after initiation of the secondary bleed. As a consequence, cladding temperatures reach higher values. As indicated by the third test, faster depressurization of the SG secondary side reduces the maximum temperature.

In both tests with and without non-condensables continued primary inventory decrease after secondary bleed provokes renewed overheating of the heater rods, however, the low-pressure injection set-point is reached in both cases in time to limit the maximum temperature to about 400 ^{o}C (with somewhat higher values in the presence of air). The faster secondary depressurization in the last test ensures low-pressure injection before renewed core heat-up would occur. After low-pressure injection initiation the rising vessel level guarantees stable core cooling in all the three tests. The tests supplied important data for system behavior and for code validation, especially for SG heat transfer with and without NCG and propagation of NC gas in the RCS following a small break.

5.4. Condensation of Steam in Presence of NC Gas Measured in Separate Effect Tests

Degradation of steam condensation in presence of non-condensables is one of the major effects of NCG in RCS. Therefore results from several representative condensation separate effect tests (SET) with various geometries (vertical pipe, horizontal plate, horizontal pipe, sloped pipe) are summarized here.

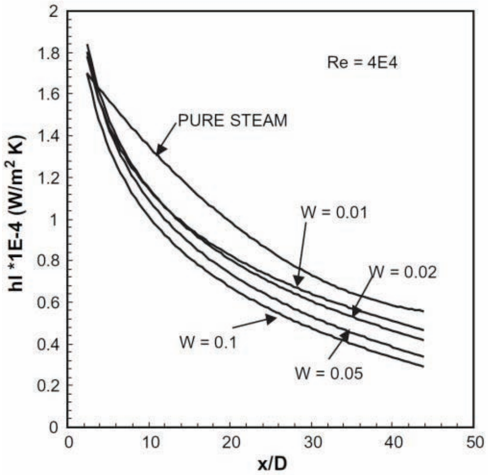


Figure 1. The axial profile of the average heat transfer coefficient in vertical pipe [2]

Revankar and Pollock [2] studied laminar film condensation in a vertical tube in the presence of NCG. In Figure 1 above, the axial profile of the heat transfer coefficient is shown for a 16 mm diameter condenser at inlet Reynolds number of 4×10^4 for 1–10% non-condensable concentration. The pure steam heat transfer coefficient is also shown for comparison. The average heat transfer coefficient decreases with the length of the pipe. Lower heat transfer coefficients are observed with higher non-condensable gas concentration. From entrance region to $x/D \leq 20$, the heat transfer coefficient for vapor with non-condensable gas decreases rapidly than that for pure vapor. The decreases of heat transfer coefficient between pure vapor and 1% non-condensable vapor mixture is large compared to that between 1% and 10% non-condensable vapor mixtures. This indicates that slight presence of the NCG gas drastically reduces condensation rate.

Huhtiniemi and Corradini [17] performed experimental measurements of steam-air condensation on inclined surfaces. The test section was developed with a mechanism to allow condensation surface inclination (0° to 90°). Tests were performed for 0 to 87 % inlet air mass fractions and for 1 to 3 m/s of steam-air mixture velocities. In vertical position (90°), there was a decrease of 15 to 25 % in condensation heat transfer coefficients, depending on the inlet air mass fractions. Experimental data were compared with some previously published results and showed good agreement.

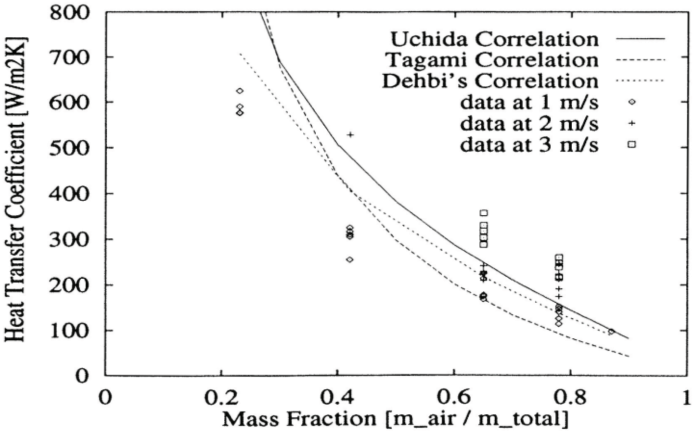
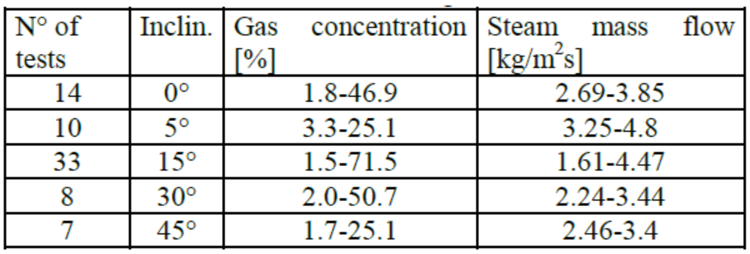


Figure 2. Average heat transfer coefficient as function of air mass fraction [17]

Caruso et al [3] performed series of tests at COTINCO (1999-2001) and ITACSO (2003) separate effect test facilities in the University of Roma "La Sapienza", where steam and air-steam condensation inside horizontal and inclined tubes was studied. Results obtained from COTINCO and ITASCO condensation tests show that NCG have a strong influence on the condensation heat transfer coefficient (HTC). With the same conditions (test section inclination, power level and cooling flow rate), the higher air percentage is, the lower the condensation heat transfer coefficient becomes.

Table IV. COTINCO tests with non-condensable gas



N° of tests	Inclin.	Gas concentration [%]	Steam mass flow [kg/m^{2}s]
14	0°	1.8-46.9	2.69-3.85
10	5°	3.3-25.1	3.25-4.8
33	15°	1.5-71.5	1.61-4.47
8	30°	2.0-50.7	2.24-3.44
7	45°	1.7-25.1	2.46-3.4

The influence of NCG in the mixture on condensation heat transfer coefficient is always very effective at low NCG concentration in the mixture, while as NCG percentage increases further, the effect on condensation heat transfer coefficient becomes less important in all experimental conditions. The condensation HTC decreases to 50% of its original values when the air percentage in the mixture changes from 0% to 2%, while with an air percentage of 10% the condensation heat transfer coefficient is reduced to 10% of the condensation heat coefficient with pure steam.

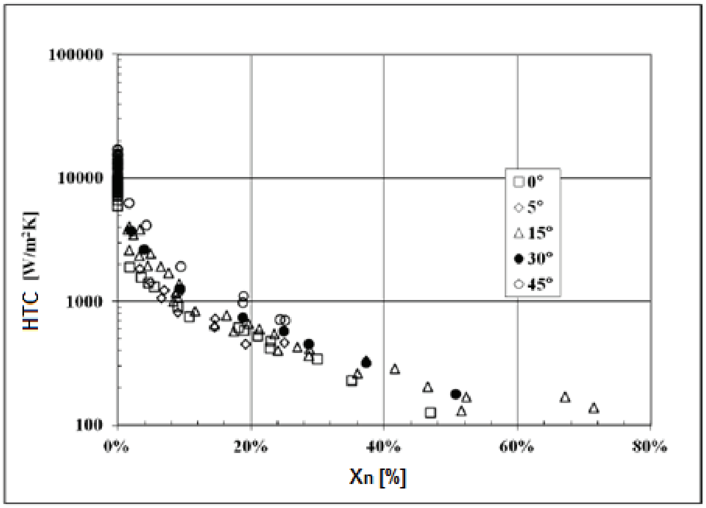


Figure 3. Condensation HTC versus mass fraction of air (COTINCO tests, [3])

6. QUANTIFICATION OF NCG SOURCES IN CASE OF MIDDLE SIZE PWR AND LOCA CONDITIONS

In this chapter, the individual gas sources relevant for PWR and LOCA conditions listed above in chapter 2 will be quantified. As the reference middle size PWR, the VVER-440 will be used.

6.1. Continuous Release of NCG Gases from Primary Coolant in PRZ in Steady-state

Pressurizer (PRZ) with steam production at electric heaters and continuous spraying acts partially as the deaerator. Especially the light gases like hydrogen can cumulate in upper part of PRZ, what can be detected by decrease of measured temperature at PRZ top (connection of PRZ SV line).

For example, at VVER-440 the hydrogen must be vented off from PRZ top approximately 2 times per week. Otherwise, up to 57 kg of hydrogen (634 normal cubic meters, Nm^3) would cumulate here during 11 months of operation). Assuming just half a week (4 days) accumulation of hydrogen in PRZ, the amount of it would be 0.69 kg (7.7 Nm^3).

Normal allowed content of gases in primary coolant (VVER-440):

Hydrogen:	25 ÷ 40 Nml/kg (limit = 50 Nml/kg)
Oxygen:	1 ÷ 8 µg/kg (limit = 10 µg/kg)
Ammonia:	8 ÷ 13 mg/kg (limit = 20 mg/kg)
Nitrogen:	not limited (usual content of N in water is about 15 Nml/kg)

6.2. Release of NCG Gases Normally Dissolved in Primary Coolant

Generally, the gases dissolved normally in primary coolant can be released either by decrease of pressure or by change of temperature leading to lower gas solubility. Relation between partial pressure and solubility of gas in a liquid can be expressed by Henry-Dalton Law:

$$p_i = K_H(T) \cdot N_i \tag{1}$$

Where p_i is the partial pressure of the gaseous solute above the solution, N_i is the molar fraction of gas in the liquid and K_H is the Henry's law constant, which depends on the solute, solvent and temperature.

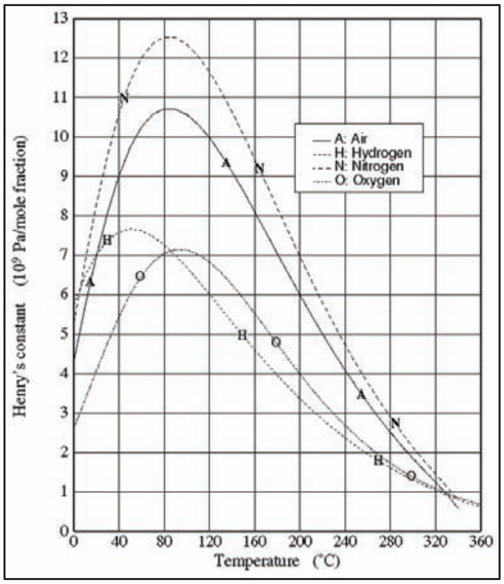


Figure 4. Dependence of Henry constant on temperature

Opposite process to gas release is the gas dissolution. The time delay constants of gas release and dissolution depend on the solute and solvent, flow regime (interfacial area) and flow channel/tank geometry and are of great importance in correct calculation of dynamic gas release or dissolution.

In LOCA, the dominating mechanism for NCG release would be strong decrease of pressure, supported by boiling (in core, in SG with reversed heat transfer, at hot walls of RCS). If one assumes 220 tons of water inventory of VVER-440 RCS and the content of gases at the upper end of operational range (see above), the hypothetical release of all normally dissolved gases would lead to following quantities:

Hydrogen (H_2):	220000kg·40 Nml/kg = 8.8 Nm^3 = 0.792 kg
Oxygen (O_2):	220000kg·8 μg/kg = 1.76 kg = 1.23 Nm^3
Ammonia (NH_3):	220000kg·13 mg/kg = 2860 kg = 3813 Nm^3
Nitrogen (N_2):	220000kg·15 Nml/kg = 3.3 Nm^3 = 0.264 kg

6.3. Release of Nitrogen from Accumulators Water

Applying Henry's constant for nitrogen in water in ACC of VVER-440 (at pressure 3.5 MPa), one can derive that the amount of dissolved nitrogen in 1 ACC is approximately 105 kg. During LOCA, the primary pressure change between ACC injection start and final pressure stabilization due to LPIS injection equals to pressure decrease from 3.5 MPa to 0.9 MPa. When accounting also for the decreasing solubility of the gas with increasing temperature (the temperature in RCS is substantially higher than ACC temperature 50 °C), one can make an approximate quantification of amount of nitrogen, that would be released from ACC water after its injection to RCS, as 80 kg. An exact quantification of nitrogen released from ACC water injection must be calculated case-by-case in system TH calculation with a computer code containing equations for dissolved gases.

6.4. False Inflow of Gaseous Nitrogen from Accumulators

False inflow of gaseous nitrogen from accumulators due to failure of ACC isolation valve(s) is the major potential gas source for RCS. The approximately 30 m3 of gaseous nitrogen at 3,5 MPa in one ACC equals to 1040 kg of N2 (1300 Nm3). So the 4 ACC's contain 4160 kg of nitrogen in gaseous phase (5200 Nm3). Isolation of ACC at the end of its injection (by level drop to 0.5 m) is at first performed by float valve. Consequently, operator should close the isolation valves at the ACC injection line. In case of failure of the float valve, one can expect either full or partial leak of ACC nitrogen into the RCS.

A special case of inadvertent ACC nitrogen inflow into RCS could be the injection of ACC in later phase of station blackout (SBO). If operator succeeds to decrease RCS pressure enough to initiate ACC injection, it could help to postpone core overheating. But the stop of ACC injection from low level could be problematic – there would be no electricity for closing of ACC isolation valves. This situation could lead to outflow of part or all nitrogen from ACC's to RCS.

The issue of inadvertent flow of nitrogen from ACC's to RCS in SBO has been lastly studied also in PKL3 project, in the H2.1 test [3]. Measurements at PKL3 experimental facility showed deterioration of heat transfer at SG due to blocking of tube bundle with nitrogen. Less condensation in SG led to higher steam outflow and coolant loss through PRZ relief valve.

Technical note to ACC gas sources(both dissolved and gaseous nitrogen) quantification above: Original design nitrogen pressure in VVER-440 accumulators was 6.0 MPa. The ACC pressure reduction /optimization to 3.5 MPa was done firstly at NPP Dukovany [2] and later at some other NPPs. At VVER's with original pressure 6.0 MPa, the amount of dissolved and gaseous nitrogen in ACC's is nearly double.

6.5. Release of Gases from Non-deaerated Water Injected by ECCS into RCS during LOCA

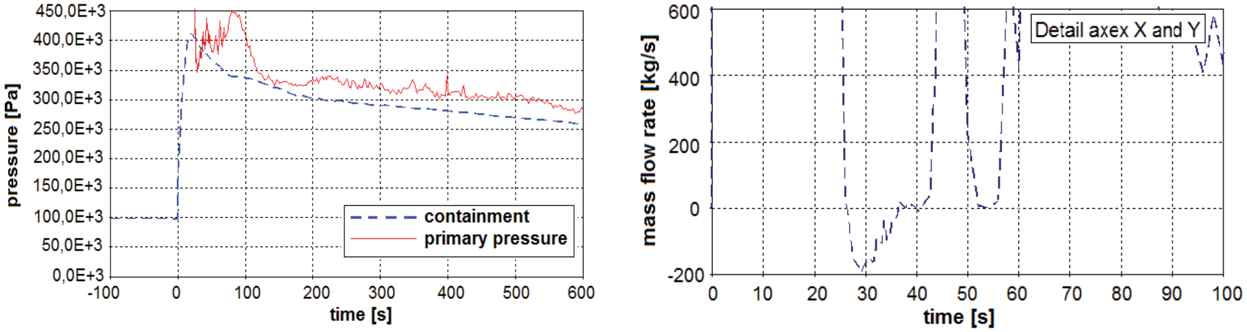
The water in HPIS and LPIS tanks is in contact with atmosphere and so there is equilibrium of partial pressure of major atmospheric gases above the level and amount of dissolved gases in the tank water. Typical content of the main air gases - nitrogen (78%) and oxygen (21%) - in water tanks with open level at temperature 50 °C is approximately 9 mg of O_2 and 17 mg of N_2 per one liter of water.

In LOCA with boiling in the core and no circulation in RCS, the water from ECCS injection compensates evaporation in the core. And on the other hand, the steam production in the core enables release of NCG gases from water (deaerator effect like in PRZ with boiling at electrical heaters – see above).

<u>Simplified computation of NCG release in core during LOCA:</u>
If reactor decay heat 15 MW is assumed (average decay heat of VVER-440 in time interval 5000-25000 s after scram), then the relevant steam production in core is 7.3 kg/s (valid for phase enthalpies at 1.0 MPa). Then the necessary supply of ECCS water to core region is also 7.3 kg/s and relevant gases release in core region is 66 mg/s (0.24 kg/hr) of oxygen and 124 mg/s (0.44 kg/hr) of nitrogen. Some additional evaporation of water (and relevant release of gas) can happen at hot wall and structures of RCS and especially in hot steam generators.

6.6. Temporary Reverse Flow at Break in LBLOCA

Temporary reverse flow can occur at break in course of large break loss-of-coolant accident (LBLOCA) if primary pressure (e.g. due to intensive condensation of steam at cold water from ACC) drops under the containment pressure. As a result, the steam-gas mixture from containment flows temporary into RCS.



(a) (b)

Figure 5. Pressure in RCS and containment / Break flow (LBLOCA, VVER-1000)

This phenomenon was not detected in VVER-440 with confinement and pressure suppression system (bubble-condenser), but in VVER-1000 with PWR-like full-pressure dry containment. In case of typical analysis of LBLOCA in VVER-1000 (including containment model), the reverse flow at break occurs in time interval 25-40 s with maximal negative flow rate -200 kg/s. It results in entering NCG from containment into primary circuit, what could have influence on behavior of the system. The maximal content of NCG in RCS in this interval is about 10 kg of NC gases.

6.7. Radiolysis of Water Continuing after Reactor Scram and Stop of CVCS

Radiolytical decomposition of water in reactor (due to continuing gamma radiation) is the source of hydrogen and oxygen. For the VVER-440, the cumulative production of H_2 from radiolysis of water is approximately 3.2 kg during 1 day, 5.3 kg during 2 days and 70 kg during 100 days after scram.

6.8. Production of Hydrogen due to Core Overheating and Clad-water Reaction

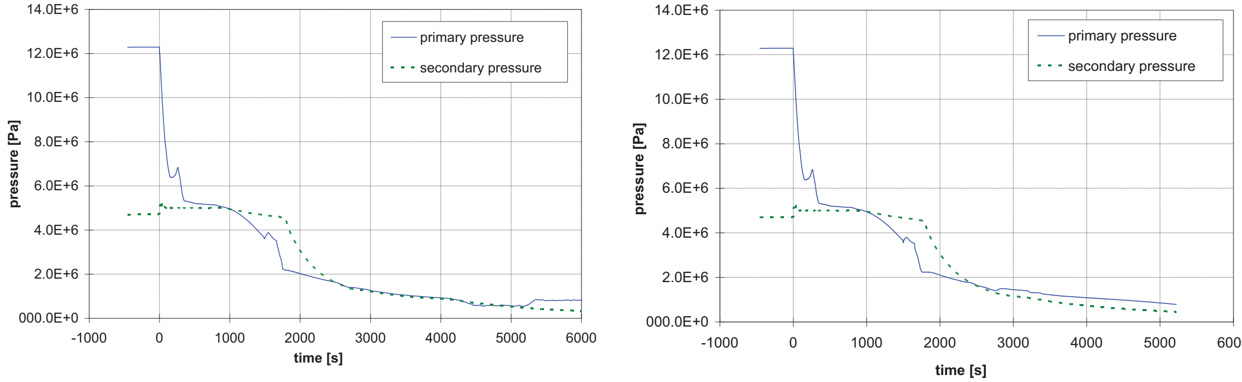
The typical amount of hydrogen from clad-water reaction in LBLOCA safety analysis (VVER-440) is 0.05÷0.1 kg, what is negligible amount comparing to other sources of NCG. This source could become more important in cases of beyond design basis accidents (BDBA) or severe accidents.

7. EXAMPLES OF SYSTEM TH ANALYSES OF LOCA WITHOUT/WITH NCG IN RCS

Effect of presence of NC gas on results of SBLOCA analysis can be demonstrated by comparative calculation of a SBLOCA scenario with and without NCG in RCS. The model of VVER-440/213 and system TH code RELAP5 were used for the calculations. The SBLOCA scenario was as follows:

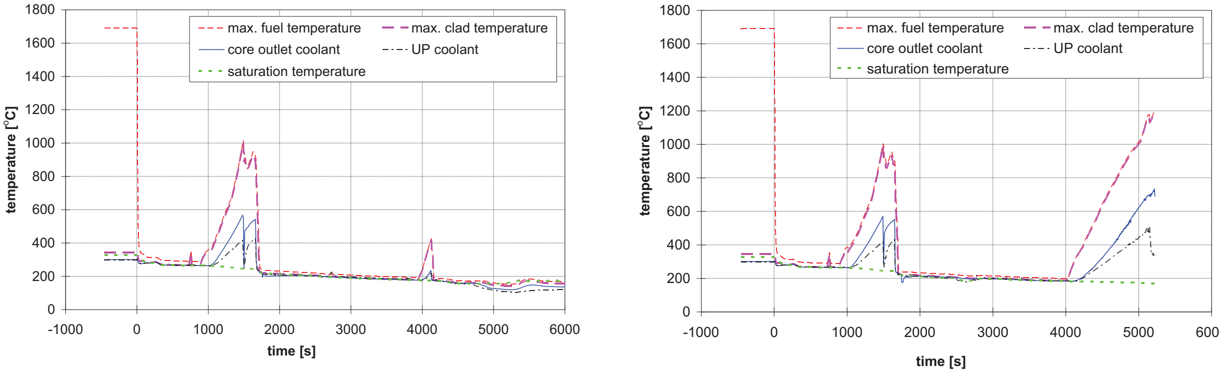
- SBLOCA with break D60 mm in cold leg without HPIS, operator cool down of system by steam dump to atmosphere (SDA) after 1800 s.
    - Variant No.1: non-condensable gases not assumed in RCS
    - Variant No.2 release of 184 kg nitrogen from ACC injection (80 kg N_2 dissolved in ACC water + 104 kg of gaseous N_2 due to false isolation of one ACC (10% N_2 leakage assumed).

Results of both variants are briefly compared in Figures 6 and 7. The standard analysis without assumption of NCG in RCS results in effective cool down and depressurization of the system (figures on the left). On the contrary, assumption of presence of NCG in RCS leads to slower depressurization of primary circuit and consequently to core uncovery and overheating (see the figures on the right).



(a) (b)

Figure 6. Primary and secondary pressure in SBLOCA with break D60 mm in cold leg without NCG in RCS (left) and with NCG (right)



(a) (b)

Figure 7. Reactor core temperatures in SBLOCA D60 mm in cold leg without NCG in RCS (left) and with NCG (right)

8. CONCLUSIONS

The work presented in the paper is focused on issue of presence and effects of non-condensable gases in primary circuit of light water reactors. The NC gases are usually neglected in safety analyses, which could for certain scenarios lead to non-conservative results. With help of complex identification of all potential sources of NCG for reactor coolant system, quantification of individual sources for a middle size PWR and general, experimental and calculation evaluation of their effects on the RCS behavior, the authors try to demonstrate importance of assuming NCG in relevant safety analyses. The objective of the effort is a transition in safety analyses practice - from modeling two-phase water only to modeling of two-phase multi-component coolant in RCS. The research presented here was initiated in frame of the NUGENIA association – during work on a project idea dealing also with non-condensables.

REFERENCES

1. P. Král, “*RELAP5/MOD3.3 Assessment against PMK Test T3.1 - LBLOCA with Nitrogen in PRZ*,” USNRC NUREG/IA-0246 (2010).
2. S. T. Revankar, D. Pollock, *“Laminar film condensation in a vertical tube in the presence of non-condensable gas”,* Applied Mathematical Modelling, Volume 29, Issue 4, April 2005, Pages 341–359 (2005).
3. G. Caruso, F. Giannetti, A. Naviglio, “Experimental investigation on pure steam and steam–air mixture condensation inside tubes,” *Intn'l Journal of Heat and Technology* 30, pp. 77-84 (2012).
4. M. Kawakubo, M. Aritomi, H. Kikura, T. Komeno, An Experimental Study on the Cooling Characteristics of Passive Containment Cooling Systems. *J Nucl Sci Technol* 46, 339-345 (2009).
5. L.E. Herranz, J.L. Munoz-Cobo, G. Verdu, G., Heat transfer modeling in the vertical tubes of the PCCS of the simplified boiling water reactor. *Nucl Eng Des* 178, 29-44, (1997).
6. M.H. Anderson, L.E. Herranz, M.L. Corradini, Experimental analysis of heat transfer within the AP600 containment under postulated accident conditions. *Nucl Eng Des* 185, 153-172 (1998).
7. M. Kawakubo, N. Inaba, H. Kikura, M. Aritomi, T. Yamauchi, ‘‘Fundamental research on the cooling characteristic of a passive containment cooling system,’’ *Proceedings of 12th Int. Conf. on Nuclear Engineering*, Arlington, VA, Apr. 25–29, 2004, ICONE12-49330, 1–6 (2004).
8. D. Papini, C. Adamsson, M. Andreani, H. Prasser, Assessment of GOTHIC and TRACE codes against selected PANDA experiments on a PCC. *Nucl. Engineering and Design* 278, 542-557 (2014).
9. B.-U. Bae, S. Kim, Y.-S. Park, K. H. Kang, Simulation of Transient Scenarios for Passive Auxiliary Feedwater System in APR+, *Transactions of the KNS Spring Meeting*, Gwangju, Korea, (2013).
10. C. Agnoux, E. Coscarelli, S. Kliem, A. Konvtonyuk, S. Marshall, M. Sanchez-Perea, I. Toth, S. P. Schollenberger, L. Dennhardt, B. Schoen, K. Umminger, “*OECD-PKL2 Project Final Report*, AREVA PTCTP-G/2012/en/0004, Erlangen (2012).
11. K. Umminger et al, *“PKL III H2.1 Station Blackout*,” OECD/PKL3 project, AREVA PTCTP-G/2014/en/0007, Erlangen (2014).
12. C. Sarrette, D. Bestion, Analysis of non-condensable gas effect during small break transient in VVER-440 geometry with CATHARE2 V1.3L, *Eight International Topical Meeting on Nuclear Reactor Themal-Hydraulics (NURETH-8),* Kyoto, Japan, September 3 - October 4, (1997).
13. C. Sarrette, V. Kouhia, H. Purhonen, D. Bestion, Non-condensable Gas Release and Dissolution: Analytical Experiment and Calculation with CATHARE2 V1.3L. *Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9),* San Francisco, Ca., (1999).
14. H. Purhonen, “*Experimental thermal hydraulic studies on the enhancement of safety of LWR,”* Acta Universitatis Lappeenrantaensis 293, D.Sc. Diss. Lappeenranta University of Technology (2007).
15. M. Puustinen, Natural Circulation Flow Behavior at Reduced Inventory in a VVER Geometry. *Nuclear Engineering and Design 215*, pp. 99-110, (2002).
16. L. Szabados, G. Ezsol, L. Perneczky, I. Toth, *Results of the Experiments Performed in the PMK-2 Facility for VVER Safety Studies*, Akademiai Kiado, Budapest, Hungary (2007).
17. I. K. Huhtiniemi, M. L. Corradini, “*Condensation in Presence of Non-condensable Gases*.” Condensation and Condenser Design, ASME (1993).
18. P. Král, J. Macek, R. Meca, E. Hofmann, M. Trnka, “Thermal Hydraulic Analyses for Optimization Hydroaccumulator Parameters in VVER-440,” *Proceedings of 14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14),* Toronto, Canada (2011).