
Insights and Lessons Learned from the Brunsbüttel Piping Failure Event

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Abstract:

1. INTRODUCTION

The severe damage in a pipe section of the reactor pressure vessel head spray line gave reason to investigate again safety implication caused by the accumulation of radiolysis gas in light water reactors. The pipe failure event at Brunsbüttel has been published in different articles (ATW ...) and is summarised in the first part of this paper followed by a review of past incidents in German PWRs and elsewhere. It is the intention of this review to revisit this past experience to evaluate the availability of related knowledge to identify additional lessons learned and to address the issue how our knowledge base has to be maintained to evaluate rare events adequately.

2. PIPING FAILURE EVENT AT BRUNSBÜTTEL

On December 14, 2001, several control room signals in the Brunsbüttel nuclear power plant – which was in power operation mode at the time – indicated a leak of the pressure boundary inside the containment. The leak located to be in the area of the reactor pressure vessel head spray line was isolated manually after approx. 4 minutes. Following a first analysis, full-load operation was resumed the same day. Further detailed analysis of various signals as well as numerical estimations did not yield conclusive results to explain the main measured signals. During a walk-down on February 18, 2002, extensive damage was detected on the head spray line in the area isolated from the reactor pressure vessel between the check valve and the internal containment isolation valve (Figure.....). An approx. 2.7 m long horizontally and vertically arranged piping section had burst and was completely destroyed. The torn-off flanged piping section originally installed in the affected piping area was found still in one piece, with parts of the connecting piping still attached. The unsevered end in the vertical head spray line area close to the reactor showed several gapings with the split ends bent backwards (Figure...). The remaining unsevered end in the horizontal part was located in direct vicinity to a pipe suspension and showed large-scale deformation.

The head spray line (NB 100, wall thickness: 5.6 mm, that of the pipe bends and the flange areas 8.0 mm) is used for cooling the inner surface of the reactor pressure vessel head and the flange area upon plant shutdown and only has operational functions. The head spray line leads from the reactor water clean-up system (TC) through the containment to the reactor pressure vessel head (Figure...). Inside and outside the containment, one motorised containment isolation valve each is installed; during power operation, both are closed. Immediately behind the internal containment isolation valve there is a branch for draining (operational draining), which is open during power operation. Among other things, main-steam valves are also connected to this drain system. The drain pipe (NB 25) can be isolated by a motorised valve installed upstream of the head spray line. It is assumed that the event was caused by a

failure of the spray line due to high internal pressure as a result of a radiolysis gas reaction. Such reactions can occur as combustion, deflagration or detonation, depending on how fast the chemical conversion of the involved gases hydrogen and oxygen takes place. This also determines the rate of the pressure build-up and the extent of the effects of such a reaction, which may differ considerably from case to case.

The following explanation can be assumed for the gas accumulation and reaction (Figure...): due to internal leakages from the two building isolation valves, cooler water from the reactor water clean-up system was able to reach into the lower area of the head spray system line. The leakage was favoured by a drain valve between the two building isolation valves which during the 2001 refuelling outage was fitted with a new seal. During the operating period prior to this replacement, part of the leakage water had been removed via this leaky drain valve. The steam flowing from the drain system into the head spray line condensed to an increased degree on the cooler water. In the course, an amount of the radiolysis gas entrained with the steam that was several times higher than assumed for the normal sequence was released into the head spray line. Furthermore, the condensate and leakage water could not drain off easily due to the fact that the drain valve was only about one third open. What is assumed to have caused the ignition of the radiolysis gas is either an energy input resulting from the movement of the check valve or a spontaneous flange leak on a removable piping section.

3. FORMATION AND TREATMENT OF RADIOLYSIS GAS IN LIGHT WATER REACTORS

The interaction of the radioactive radiation in the reactor and the water used for cooling and moderation causes the separation of a certain part of the water into its constituents hydrogen and oxygen. Hydrogen and oxygen are referred to as radiolysis gases. Radiolysis thus occurs in the area of the reactor where radiation levels are highest. In a **boiling water reactor**, the radiolysis gas is entrained with the main-steam flowing to the condenser. Here, it is exhausted and recombined to become water again. However, the radiolysis gas entrained with the steam flow also reaches into systems and plant components bordering on the reactor coolant system and connecting to it. Here it is possible that – under favourable conditions – it may accumulate in isolated areas through which there is no flow of coolant. The accumulation of radiolysis gas is strongly favoured e. g. by condensation of the steam or by evaporation due to a pressure drop. As the accumulated radiolysis gas is present at an ideal stoichiometric ratio, an accumulation of radiolysis gas always bears the risk that it may come to a reaction (detonating gas). This presupposes that there is an ignition mechanism available. This may be e. g. a pressure surge or heat-up process upon valve operation. Depending on the severity of the reaction, components such as piping may be destroyed, or the function of active components may be impaired. Since the problem of radiolysis gas accumulation has been long known, comprehensive countermeasures have in the meantime been taken in risk locations, e. g. the installation of recombiners or the purging of previously isolated room areas.

As in boiling water reactors, radiolysis gas also forms in the area of the reactor core of **pressurised water reactors**. In such a reactor, hydrogen is added to the coolant to optimise the water chemistry of the primary system. This also results in the increased bonding of the oxygen, with the effect that there is practically no radiolysis gas present at an ideal stoichiometric ratio in the primary system of a pressurised water reactor. The hydrogen is then released again together with other gases into various tanks and vessels, e. g. coolant storage tanks. In order to avoid the formation of explosive hydrogen-oxygen mixtures in these vessels, the vessel atmosphere is continuously purged with nitrogen.

In the past of some cases hydrogen reactions have been reported in foreign PWR nuclear plants. All of them occurred when the plants were in shutdown state, which is when additional oxygen enters an area where hydrogen has accumulated and an explosive gas mixtures may be formed and react in the primary system or connecting components.

4. EVENTS IN GERMAN NUCLEAR POWER PLANTS

Based on abnormal occurrence reports a selection of previous events are described, characterizing the variation of damage observed related to radiolysis gas reactions.

4.1 Hydrogen reaction in a drain system line in a BWR

During an inspection of the overflow line on the precoat tank of the reactor water clean-up system a hydrogen reaction occurred when the line was about to be decoupled. There were no personal injuries nor any damage to plant components. The drain and ventilation lines of the reactor water clean-up system connect to the piping section concerned. In the event of slight leakages in these lines and during drain processes it is possible that hydrogen may accumulate at the highest position in this line.

4.2 Break of a control line in a BWR

On November 1999, a test of the turbine protection system low-pressure (LP) bypass valves was carried out as part of the in-service inspections of the turbine protection systems. Upon operation of one of the control valves it was found that it did not function as specified. An on-site inspection revealed that the supply line (NB 40, material: 15 Mo 3) upstream of the control valve SA18 S525 between the control valve and the upstream connected hand-operated isolation valve SA18 S522 had burst and ruptured completely. The steam leak could be stopped by manual closing of the hand-operated isolation valve. Until isolation, about 6 Mg of steam had flown into the turbine building. In the event of a load rejection on the turbine or generator, the function of the LP bypass valves is to direct part of the steam flow from the high-pressure part of the turbine directly to the turbine condenser – bypassing the low-pressure section – by opening automatically for a limited period of time (Figure...). Together with other measures, this measure has the effect that increase in revolutions of the turboset is minimised and overspeed is prevented.

The break location is made up of one longitudinal crack and two circumferential cracks. It was concluded from the damage symptoms that there had been overloading due to increased internal pressure (Figure...). The internal pressure that was generated lay above the burst pressure of the pipe concerned and was put down to a radiolysis gas reaction. In the case presented here there was a direct connection to the main-steam line. One can assume that the pipe had filled up with radiolysis gas upstream of the gas-tight control valve and at the highest closed location of the system. The energy released upon the operation of the control valve was sufficient at the prevailing pressure to start off the radiolysis gas reaction.

4.3 Heating pipe bulging in the moisture separator/preheater in a BWR

On August 1984, during the refuelling outage, a pressure increase on the auxiliary condensate side of the moisture separator/preheater was noted upon flushing operation of the feedwater system. Investigations revealed through-wall damage on a total of four heat exchanger tubes. One of them had ruptured; a 420 mm long piping section was missing. In this area, erosion damage was found on the surrounding heat exchanger tubes and support structures. The cause of the damage was put down to flow-assisted corrosion in connection with vibrations. The defective heating pipes were plugged. The plant was operated without reheat for one cycle. During the course of the 1984/85 operating period, the pipe bundle was removed for damage analysis. This also revealed bulging on two of the pipes, which had been caused by high internal pressure. The cause was put down to a radiolysis gas reaction. It could not be established whether there was also a connection between the radiolysis gas reaction and the ruptured heat exchanger tube.

4.4 Deformation of safety and relief valve internals in several BWR

In the years 1987/1988, three German boiling water reactors reported disturbances in connection with the operation of safety and relief valves. These safety and relief valves are multiply redundant self-medium-operated valves that have two functions, namely to limit pressure and to decrease pressure in the event of a transient until residual-heat removal can start. The safety and relief valves open upon main-steam admission. For this purpose, each valve has three solenoid pilot valves (Figure 1). Some valves are equipped with diverse electromotive pilot valves.

On May 1987, an inspection at Unit C of the first plant revealed that one safety and relief valve opened extraordinarily fast and that unusually high pressures had occurred in the valve control unit. One pilot valve had suffered such extreme deformation that it failed to reclose after opening. A subsequent investigation showed that the central guide bolt for the valve cone had been compressed and expanded in the valve concerned as well as in two other valves (Figure 2).

On November 1987, the safety and relief valves in the second plant were challenged during a transient. The subsequent analysis of the control pressures and opening times revealed that the latter had been unexpectedly short and that the control pressures had reached very high levels. Moreover, the opening travel of the valves had been reduced by 10 to 20 %.

In March 1988, the safety and relief valves in Unit 1 of the third plant were examined in the wake of the events that had occurred in the other German boiling water reactor plants. The results showed that here, too, the central guide pins had been compressed and expanded.

The cause of the damage in the three plants was in each case a radiolysis gas reaction in the valve control lines. The excess pressures that had occurred had resulted in the compression of the central guide pins and the damage to the pilot valves.

The significance of the event lies in the fact that the deformation of the valve internals may cause an impairment in their opening function and that the damage to the pilot valves may lead to the failure to close of individual safety and relief valves. At the time, the main recommendation of the Information Notice issued by GRS was to carry out further investigations concerning radiolysis gas formation and to implement precautionary measures, such as the use of recombiners and purging in the areas of the safety

4.5 Spindle deformation in the pilot valves of main-steam isolating valves in a BWR

An inspection of the solenoid pilot valves of the main-steam isolating valves showed that the spindles of three of these pilot valves were bent. The spindles are 249 mm long and have a diameter of 6 mm. The valves were slightly leaky in the area of the valve seat, but the function of the main valves was unimpaired. Investigations revealed that there had been radiolysis gas accumulations in the pilot valves, although only when the main valves had remained closed for a longer period of time. The pilot valves were subsequently fitted with recombiners to prevent a repeat of the event. Their effectiveness was demonstrated.

5. EVENTS IN FOREIGN NUCLEAR POWER PLANTS

BOILING WATER REACTORS

5.1 Steam line rupture in a BWR (Japan)

On September 2001, a steam line rupture occurred in a plant in Japan. The steam line concerned is located in the reactor building outside the containment. It branches off from the supply steam line of the high-pressure turbine (HP) of the feed system and leads to the turbine condenser via an afterheat cooler. The supply steam line of the HP turbine ties in to the main-steam line. The line affected is needed for the operating mode "steam condensation via the afterheat cooler". Upstream of the afterheat cooler, an isolating valve is installed which is closed during operation. The nominal bore of the line concerned is 150 mm and the wall-thickness 10 mm. The line is made of ferritic carbon steel. The single-train feed system can be isolated by two valves located upstream of the reactor pressure vessel inside and outside the containment.

The double-ended break of the line with the subsequent steam discharge occurred during a function test of the feed system. This involved steam from a main-steam line being guided to the HP turbine of the feed system, which meant that it could also reach the steam line affected. The break location lies in the area of a pipe elbow arranged in front of the isolating valve upstream of the afterheat cooler.

The break zone is locally limited and shows considerable deformation, which indicates a catastrophic failure of the steam line. There are typical signs that the pipe burst as a result of a forced rupture. The break pattern is ramified both in longitudinal and in circumferential direction. Five fragments were found that had been detached from the break zone. Also, a pipe section that had been torn off from its original position showed strong deformation (deflection: approx. 2 m).

The damage characteristics of the break and the deformation of the pipe section show that there must have been a high energy input leading to the bursting and deformation of the steam line. There was no incipient damage such as e. g. corrosion. The cause of the damage was put down to a radiolysis gas reaction. The radiolysis gas may have accumulated in a longer horizontally laid out area upstream of the isolating valve, which also forms the highest point of the steam line affected. The ignition might have

been triggered by the energy input as a result of the activation of the feed system. In all, another fourteen plants in Japan have the same system layout, with piping arrangements similar to the plant affected.

5.2 Hydrogen deflagration in an auxiliary steam generator during maintenance work preparation in a BWR (Switzerland)

On August 1995, Hydrogen during the refuelling outage, an in-service inspection of the auxiliary steam generator was planned. In the course of the plant shutdown, auxiliary steam production was changed over to the electrical steam generator, and the auxiliary steam generator was isolated for cooldown. After pressure release and cooldown, work permission was given to open the upper manhole. After the flange has been opened, a special membrane with a weldable seal has to be removed. For this purpose, special equipment, similar to a small lathe, was used. During the work a hydrogen deflagration occurred inside the auxiliary steam generator, injuring the two workers who were standing outside. The fire extinguished itself. The source of ignition was probably a spark. As permission was only given to open the vessel and not to enter it, the work procedure did not include any flushing of the vessel prior to opening. It had been intended to carry out gas control measurements before entering the vessel for the in-service inspection.

Normally no hydrogen can be present on the secondary side of the steam generator, which uses main-steam for heating. An investigation revealed that the hydrogen was produced during the three-day duration of the "wet conservation" process. This means that the venting line of the steam generator was connected to the outlet header of the degasifier. During refuelling, the auxiliary steam is produced by an electrical steam generator, and this steam contains small quantities of hydrogen and oxygen. At the outlet of the degasifier a higher hydrogen concentration was measured. During cooldown, the hydrogen was transported to the steam generator, and the concentration increased by steam condensation.

5.3 Generic problems concerning pilot valves in the automatic depressurisation system of several BWR (Sweden)

Recurring problems with solenoid pilot valves in the automatic depressurisation system (ADS) had occurred in the past in two plants. Similar problems then also occurred in two Finnish plants. The problems, mainly observed during periodic testing, were either a failure to open on demand, a long opening time, or a failure to reclose properly.

Following cleaning, repair or replacement of the internal parts of the pilot valves concerned, the malfunctions recurred. A renewed investigation concluded that the damage observed was the result of local radiolysis gas reaction triggered by atoms of pure nickel from the nickel plating of the pilot valve solenoid plunger. In some cases, combustion was followed by an explosion inside the valve. The energy of this reaction was enough to deform the valve body or result in other mechanical damage.

As remedial action, all nickel inside the valve body of the ADS's solenoid pilot valves in Forsmark were removed. Also, following theoretical studies and experiments, the pilot valve internals were fitted with an adequate recombiner in order to recombine the oxygen and hydrogen gases before the concentration limit is reached at which combustion (explosion) can occur.

PRESSURIZED WATER REACTORS

5.4 Hydrogen reaction in a steam generator during maintenance in a WWER (Ukraine)

When the event occurred on January 1990, the plant was shut down for repairs of the SG-2 cold header. Following reactor shutdown and afterheat removal, the level of residual hydrogen concentration in the coolant reached 1.5 nmL/kg as a result of degassing the primary system. This level is permissible in connection with the depressurisation of the primary system. The upper block of the reactor was not removed, and the vent valves of the reactor, the pressuriser and the steam generators were open. On December 1989, four control rod position transmitters were unsealed. The next day, five days after shutdown, the special gas purification system was disconnected. Cooling was carried out via steam generator No. 4. Pre-maintenance work was in progress on steam generators Nos. 1, 2 and 3. On January 1990, the repair team in the area of the SG-4 cold header heard a "bang", and one half of the servicing platform (weighing 16 kg) was blown off from the SG-4 hot header side, striking the thermal

insulation of the SG steam header. Subsequent inspections revealed that the plastic sheet covering the SG-1 cold header had also been blown off and that the fabric flooring had been partially forced into the crack between the halves of the servicing platform on the SG-1 cold header side. The repair men at SG-2 did not see anything but heard a noise similar to the movement of coolant in the cold header. The lightweight caps covering the openings of the four control rod position transmitters were in place. A subsequent analysis showed that the hydrogen concentration in the coolant was 1.7 nmL/kg and more than 2 % in the SG-4 cold header.

In WWER-1000 reactors remaining in the "cold" state with undischarged spent fuel for a long time, hydrogen may accumulate in explosive concentrations in the free inner spaces under the reactor pressure vessel head and in primary system equipment. The event had been caused by an increase in the hydrogen concentration in stagnant, unventilated parts of the primary system, resulting in a hydrogen detonation.

5.5 Damage to reactor internals due to a radiolysis gas reaction in a WWER (Russia)

On September 1990, the unit was shut down for intermediate scheduled maintenance. On September 1990, while uncovering the reactor pressure vessel head structure, maintenance personnel found damage on 54 nuclear instrumentation tubes of the upper internals structure (UIS) in the form of "ballooning" swelling. 21 tubes of the 54 had through-wall vertical ruptures that were 5 cm long. The majority of defects were located at the same distance of 55-60 cm from the UIS top plate. In addition, 45 of the guide tubes of the control rod drive mechanisms (CRDMs) had swellings and dents concentrated at the same distance of 0.8 cm from the CRDM bottom and fixture. The results of subsequent CRDM tests showed that all 45 guide tubes were operable. Therefore the revealed damage to the reactor internals had no significant impact on reactor operation.

In WWER-1000 reactors remaining in the "cold" state with undischarged spent fuel for a long time, hydrogen may accumulate in explosive concentrations in the free inner spaces under the reactor pressure vessel head and in primary system equipment. According to the results of an operational documentation analysis and of tests performed, the damage was caused by a radiolysis gas reaction under the reactor cover during restart operations while in cold shutdown on August 31, 1989.

5.6 Hydrogen reaction in PWR (USA)

On January 1989, a hydrogen reaction occurred in a safety injection accumulator while the plant was in a refuelling outage. Prior to the event, the "2a" accumulator had been drained to allow repair of a leaking manway. After draindown of the accumulator was completed, the drain valve to the reactor coolant drains collection tank (RCDT) was left open per procedure. At the time the containment was open to the auxiliary building. Prior to the event the licensee observed an increase of airborne activity inside containment. This activity consisted primarily of xenon, but at the time the activity's source had not been identified as being the open vent path between the RCDT and the open accumulator manway.

The licensee believes that hydrogen entered the accumulator from the RCDT either from coolant outgassing or from the waste gas collection system which exhausts into the gas space in the RCDT. A grab sample (taken before the event but analysed after it) indicated that initially there was a hydrogen concentration of 7.6 % and an oxygen concentration of 9.6 %. On January 1989, a radiation protection technician (RPT) lowered a motor-driven air sampler into the open "2A" accumulator. Sparking from the motor ignited the gaseous contents of the accumulator. A small cloud of smoke and a rush of warm gas were expelled from the accumulator manway, accompanied by considerable noise and vibration. The RTP's outer layer of clothing (a rain suit) was shredded; however, he was not contaminated. There was no damage to plant equipment.

The root cause of the event was attributed to procedural inadequacies because personnel had not been informed of hazardous conditions involving hydrogen and oxygen concentrations within the reactor coolant and associated systems. Procedures regarding the draining of the safety injection accumulator, and regarding sampling (by portable air sampling units) of enclosed spaces connected to the reactor coolant system, were reviewed and appropriate cautionary notes and steps were included to preclude similar events.

6. LESSONS LEARNED

It is not the intention here to identify lessons learned in respect to the system design, the precautionary measures and monitoring for the individual plant. This is dealt with in detailed investigations regarding all plant specific aspects.

Here the discussion is restricted to two areas:

- Are the basic requirements to avoid safety relevant events by the accumulation of radiolysis gas sufficient?
- Have previous recommendations triggered by incidents been sufficiently clear and comprehensive?

In the view of the author both questions have to be answered with no in light of the experience gained with the latest two events.

Looking back to the design of the light water reactors we see that in the design specifications attention is given to avoid accumulation of radiolysis gas, to provide adequate draining and purging of systems, and to install systems to recombine hydrogen and oxygen. As it is the case with other issues which interface different systems and disciplines the related safety requirements are very general. If we analyse to what extent the available knowledge has been codified in the represent KTA safety standards we have to admit that the user of the safety standard find little guidance regarding precautions to avoid or to control accumulation of gases adequately. Looking through periodic safety review reports safety implications caused by reaction of radiolysis gas is hardly mentioned. The extent of damage related to the two events in the year 2001 is unique compared to previous events. Nevertheless, the number of events happened in the past indicate that our present very general requirements should be supplemented to add some more prescriptive guidance in our safety standards. The first attempt in this direction is done in the draft of new generic KTA 2000 basic safety standards.

Regarding the second question we learn from both incidents that there is not a single root cause leading to a situation which differs from previous ones. It seems to be the case for both events that the accumulation of gas was affected in such a way that several influencing parameters were acting in an unfavourable direction. For infrequent events this is quite normal otherwise we would have seen such events much more frequently in the past. In conclusion of this more attention has to be given in the analysis of incidents with respect to potential degradations or system malfunctions which could lead to an aggravation of the scenario being investigated. On the other hand it has to be remembered that the robustness in the system design may be a better way to solve problems.

7. CONCLUDING REMARK

In the analysis of rare events it is a reoccurring experience that the retrieval of relevant information is a time-consuming and difficult process. The time interval between similar events in most cases may be larger than the duration of individual technical experts staying at certain departments as part of their professional career. This means that most of the technical experts involved can not drawn from own experience in the evaluation of such cases but have to rely on knowledge hidden in documents or gained in training courses. This issue becomes even more important in situation where a considerable percentage of experienced personnel is replaced by less experienced personnel.

A practical way for a quick information access is in an advanced development stage at GRS. Based on the operating experience specifically of the German nuclear plants as well as important experience internationally a database is being developed which allows a well structured access to relevant information for all important damage mechanism. As a starting point relevant national and international events are related to the time scale over the last thirty years. Figure ... gives an example how this looks like for the case of incident with radiolysis gas. To each event the event description, root cause analysis and recommendations are available as electronic documents. Further on relevant background information is identified. By this systems the most relevant information of similar events could be screened on a PC within hours or a day depending on the amount of information available.