A HYDROGEN-AIR EXPLOSION IN A PROCESS PLANT: A CASE HISTORY

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ABSTRACT

In the summer of 1985 a severe hydrogen-air explosion occurred in an ammonia plant in Norway. The accident resulted in two fatalities and the destruction of the building where the explosion took place. This paper presents the main findings from an investigation in 1985 and 1986 of the gas explosion and its consequences. The event started when a gasket in a water pump was blown out. The water pump was situated inside a 100 m long, 10 m wide, and 7 m high building. The pump was feeding water to a vessel containing hydrogen gas at pressure of 30 bars. This pressure caused a back flow of water flow through the pump and out through the failed gasket. The hydrogen reached the leakage point after about 3 minutes. The discharge of gas lasted some 20 to 30 seconds before the explosion occurred. The total mass of the hydrogen discharge was estimated at 10 to 20 kg hydrogen. The main explosion was very violent and it is likely that the gas cloud detonated. The ignition source was almost certainly a hot bearing. Several damage indicators were used to estimate the amount of hydrogen that exploded. The indicators include deflection of pipes and panels, distances traveled by fragments, and the distribution of glass breakage. We found that 3.5 to 7 kg of hydrogen must have been burning violently in the explosion. Window glass was broken up to 700 m from the centre of the explosion. Concrete blocks, originally part of the north wall of the building and weighing 1.2 metric tons were thrown up to 16 meters. The roof of the building was lifted by an estimated 1.5 meters before resettling. The displacement of the roof caused a guillotine break of a 350 mm diameter pipe connected to the vessel that was the source of the original gas discharge. The gas composition in the vessel was 65 - 95 % hydrogen. This resulted in a large horizontal jet fire lasting about 30 seconds. Minor explosions occurred in the plant culvert system.

To our knowledge this gas explosion is one of the largest industrial hydrogen explosions reported. We believe this case history is a valuable reference for those who are investigating the nature of accidental hydrogen explosions.

1.0 INTRODUCTION

In 1985 a hydrogen leakage inside a building caused a severe explosion in an ammonia plant. A large jet fire followed the explosion. Three men were seriously injured in the accident. Two of them later died from the injuries. The building was irreparably damaged. To our knowledge this gas explosion is one of the largest industrial hydrogen explosions reported. The objectives of this paper are to present our findings from the accident investigation and to describe the nature of such large hydrogen explosions.

2.0 ENVIRONMENT AND INCIDENTS LEADING TO THE EXPLOSION

In the ammonia plant hydrogen was produced by partial oxidation of a heavy hydrocarbon fuel. The main explosion took place in the purification section of the hydrogen plant. This section contained a wash tower where CO_2 was being removed from the H_2 by absorption in water. A simplified process diagram is shown in Fig. 1. The hydrogen concentration in the gas feed to the absorption tower was typically 65% (vol). The remainder of the feed was mainly CO_2 and CO. At the outlet of the tower, the hydrogen concentration was approximately 95% hydrogen and 5% CO. The wash tower and the hydrogen pipelines were located outdoors. The two water pumps A and B were located inside a 100 m long, 10 m wide, and 7 m high building. The capacity of the pumps was 2600 m^3/hr and water pipeline diameter was 600 mm.

The accident occurred when operators were trying to change over from pump B to pump A. Unfortunately they did not observe that the inlet valve on the low-pressure side of pump A was closed. Only the small bypass valve was open. When pump B was stopped, the water supply from pump A was too low to maintain the water level in the absorption tower, resulting in an automatic shut down. A second attempt to start pump A resulted in a higher vibration level then normal for the pump. The operators discovered that the inlet valve was closed. They tried to open the valve, but failed because of the large pressure difference over the valve. Then bluish smoke was observed coming from the pump bearing, which had turned red-hot. At the same moment, water started to leak from a flange between the pump and the closed inlet valve. Pump A was then stopped. Normally the interlock system should then have closed valve block valve A1. However, this valve failed in 40% open position. Since the back flow was relatively low the check valve did not close. The water leak lasted for about 3 minutes before hydrogen gas from the tower reached the leaking gasket. Hydrogen was discharged into the building for 20 to 30 seconds before the explosion occurred.

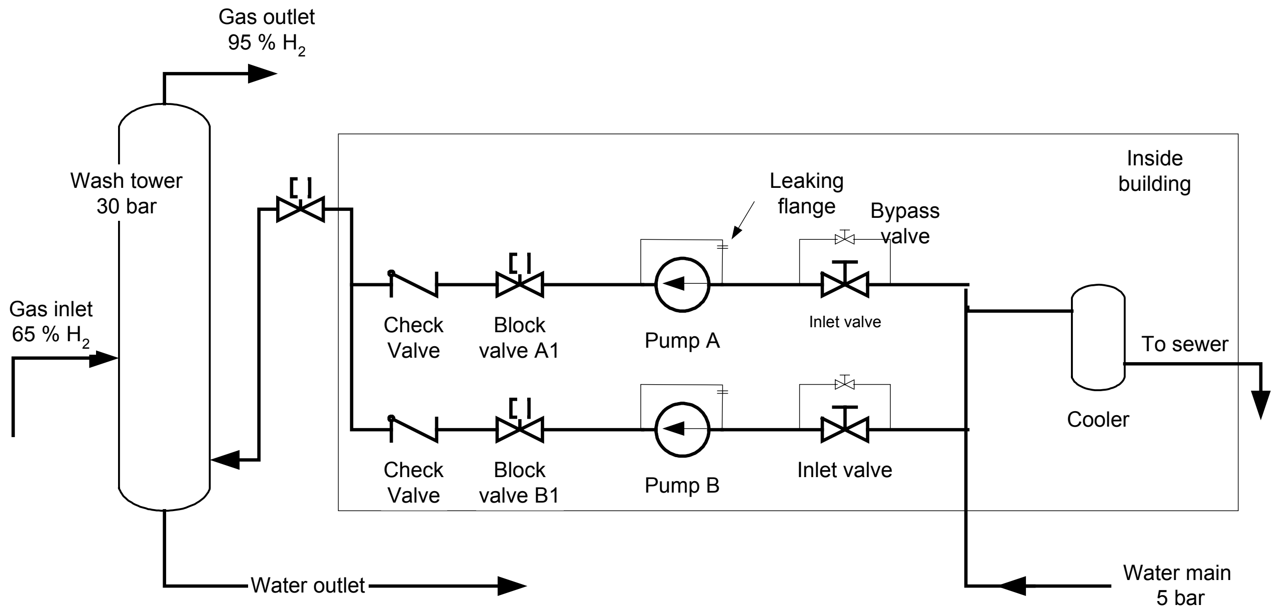

Figure 1. Simplified process diagram

An investigation of the causes of the accident concluded that it was due to a combination of operational error, technical failures and weakness in the design. A more detailed description of the initial events and the process can found in [1].

3.0 THE EXPLOSION

When hydrogen leaked out in building it mixed with air and formed a combustible gas cloud. Most likely the hot bearing ignited the cloud. The explosion that followed was very violent. We believe a large part of the cloud detonated (i.e. the flame was a supersonic combustion wave). From the damage it is clear that explosion pressures inside the building must have reached at least the order of 10 bars. 60 meters of the sidewalls were blown out and the roof was lifted up more than one meter. As the roof lifted, it tore off a 350 mm diameter pipe coming from the wash tower. This new release resulted in a jet fire with an initial flame length of 50 meters lasting for approximately 30 sec. Hydrogen also leaked also through the small bypass valve into the sewer system. Explosions in the sewer system then followed. Fig. 3 shows the coarse of events.

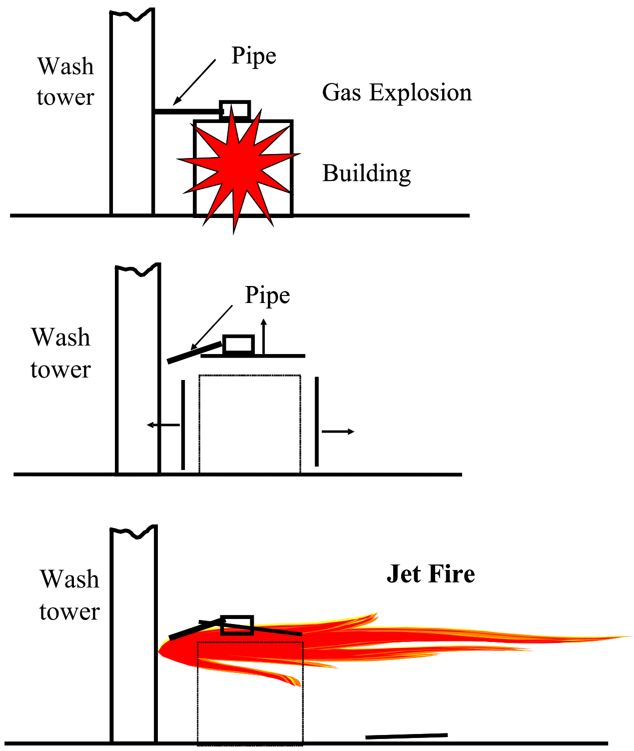

Figure 2. The explosion inside the building lifted the roof and a 350 mm diameter pipe was sheared off and large quantities of hydrogen leaked out and burned as jet flame

4.0 DAMAGE TO THE WALLS AND THE ROOF

The north wall consisted of prefabricated concrete wall elements. These elements were 1.45 m wide and 7 m high. The lower part of the element was a solid concrete block acting as a "foot". We estimated the weight of the wall and the foot to 1.2 and 2.0 metric tons, respectively. The total weight of a wall element was thus 3.2 tons. As shown in Figs. 2 and 4 these wall elements were thrown out and heavily damaged over a distance of nearly 30 m. Four of the elements were thrown 12 to 16 m out from its original position. We used the RCM code [2] to calculate the impulsive load the wall elements were subjected to. We used both constant volume combustion and detonation pressure profiles as input for these calculations. The calculations show that the impulse is proportional to the mass of hydrogen taking part in the explosion and that for rapid combustion the impulse is almost independent of the combustion time. The results are shown in Table 1. Taking account of the displacement of the wall in the calculations had no significant effect on the calculated impulse.

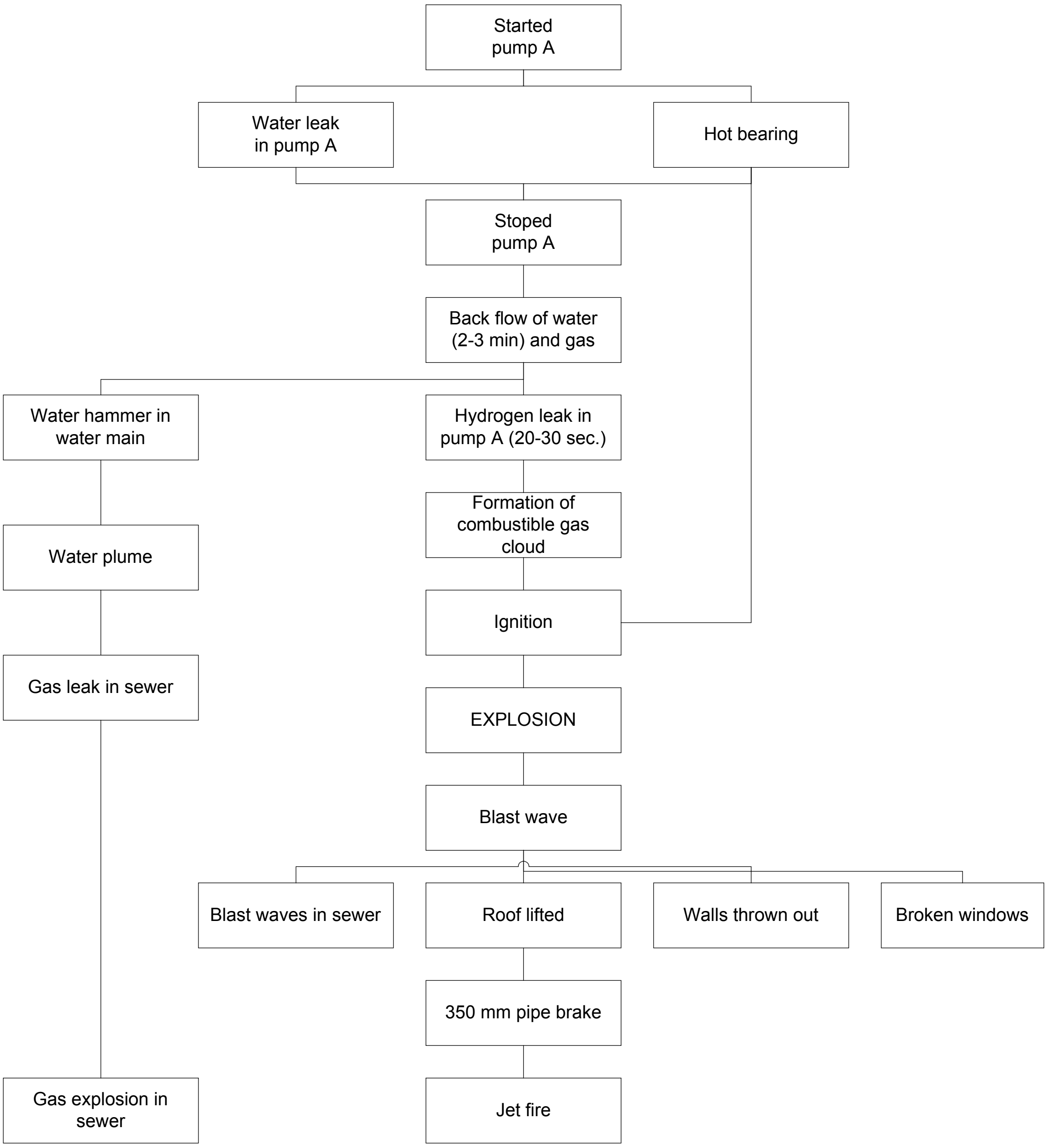

Figure 3. Course of events

We used a highly simplified model to study the trajectory of the wall elements: We assumed that the impulse from the pressure loading was transferred to the wall without significantly deforming it, and that the "foot" mass had an initial velocity of zero. If we disregard all forces on the wall except gravity, it is straightforward to calculate the angular velocity of the wall and the trajectory of the centre of mass. The resulting motion is indicated in Fig. 5. The figure neatly explains the somewhat confusing fact that the wall fragments were found with their inside down. As shown in Table 1 both the 7 kg and the 14 kg cases yield results that are consistent with observations, whereas it is more difficult to reconcile the 3.5 kg case with the observed position of the wall fragments.

a)

b)

Figure 4 a and b. The wall element of the north wall thrown out

Table 1. Impulse and estimated distance an element was thrown (m) vs. mass of hydrogen

Mass of hydrogen (i.e. kg H_2)	3.5	7.0	14.0
Impulse (Pa · s)	2100	4200	8400
Distance an element was thrown (m)	5.7	12.0	13.5

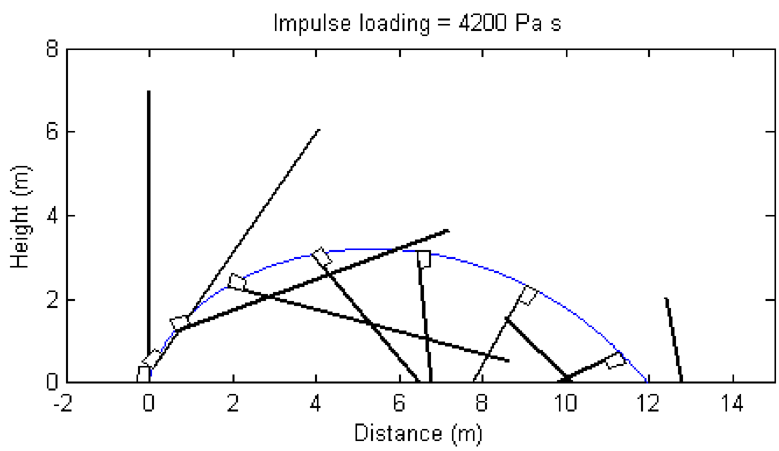

Figure 5. Trajectory of a wall element from the north wall

Three of the four wall elements that were thrown out were located next to each other. The fourth was 3 m from the three others. Damage inside the building indicated that strong local explosions (i.e. high pressure zone) had occurred in four distinct areas.

The south wall was a brick wall with steel beams. About 60 m of this wall was destroyed. According to Harris [3] the natural frequency and failure pressure for such brick walls are 20 to 40 ms and 0.07 to 0.15 bar. If we take dynamic loading into account and assume a spherical expanding blast wave we found that 3.5 to 7 kg of H_2 was required to cause this damage.

Figure 6. A fragment from the south wall landed 50 m away

We estimated the mass of the roof to be 750 kg/m^2. For an impulse caused by strong 7 kg hydrogen explosion the roof would have lifted 1.5 m up before falling back to its original position after 1 sec.

5.0 DAMAGE TO WINDOWS

In explosion accidents flying fragments from broken windows represent a severe hazard to humans [4]. In the present accident glass fragments hurt no one. The accident occurred on a Saturday and very few people were in the area at the time of the explosion. If the explosion had occurred during normal working hours the number of casualties could have been much higher. Broken windows were found out to a distance of 700 m. Within 400 m of the explosion more than 10 % of the windows were broken. No ordinary window glass remained intact inside a 100 m radius.

The neighbouring building on the north side had a large window section facing the explosion area. The glass thickness was 6 mm. This window section shattered and glass fragments had hit the wall on the opposite side. This wall consisted of building plates made out of wood shaving and concrete. As shown in Fig. 7 the glass fragments penetrated into this rather strong wall material. From the impact pattern we estimated the initial velocity of the fragments to 25 m/s, consistent with a reflected pressure of 0.9 bar.

Figure 7. Glass fragments penetrated into a wall

The control room building containing offices was located about 50 m to the south of the explosion centre. One of the office windows had a blast resistant glass and a solid frame. This window was not damaged. An adhesive plastic film protected the window glass in another office. This window was blown in as shown in Fig 8. Although the plastic film did not save the window it kept most fragments together, potentially reducing the severity of injuries somewhat.

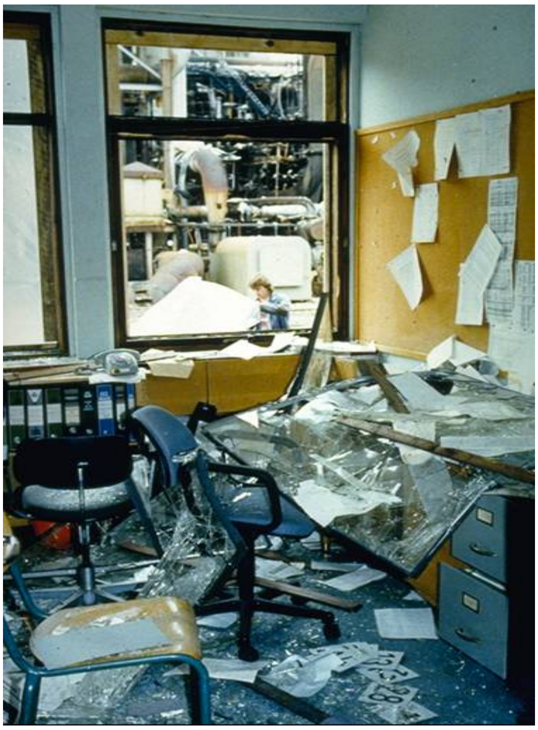

Figure 8. Glass window with plastic film

We estimated breakage pressures for seven different glass windows. These windows were located 250 to 670 m from the explosion. The breakage pressure was calculated from static breakage pressure and dynamic load factor. An explosion of 3.5 to 7 kg hydrogen could explain most of the window breakage.

6.0 DEFORMATION OF STRUCTURES

The load from the blast wave caused plastic deformation of some structures such as pipes and beams. To analyse these damage indicators we used pressure-impulse diagrams and isodamage curves as described in Baker et al. [5]. The p-i diagrams for spherical hydrogen detonations were provided by Strehlow [6]. To select structures that only had been deformed by the blast waves was a challenge. Some the deformed structures had also been hit by flying fragments and could therefore not be used in this analysis. The result from the analysis is given in Table 2. Most results indicate that more than 7 kg hydrogen had contributed to the explosion. Since the analysis assumed a spherical detonation and blast wave it may overestimate the amount of hydrogen, especially in the near field of the explosion.

Table 2. Estimated detonating H_2 from plastic deformation structures

Case	Distance (m)	Cloud diameter (m)	Mass H_2 (kg)	p (bar)
A	9	13	15.2	4.0
B	25	10	7.0	0.4
C	25	10	7.5	0.42
D	32	13	15.3	0.45
E	42	14	19.1	0.36

7.0 IGNITION

Hydrogen-air clouds are known to ignite easily due to the low ignition energy. This is confirmed by Ordin [7] who has reviewed NASA's experience with accidental release of hydrogen. He found that 64 out of 83 releases ignited. It is also claimed that a release of hydrogen from a high-pressure reservoir may self ignite.

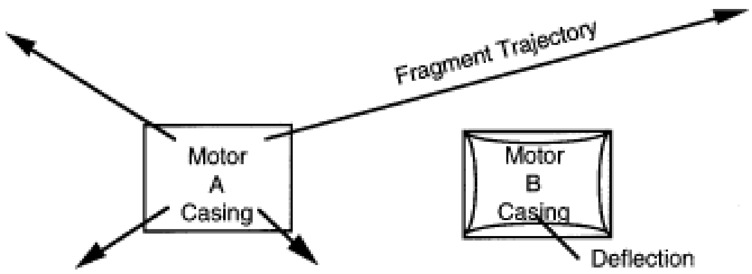

Figure 9. Casing of motor A and B

In the present accident the ignition source was almost certainly the hot bearing. From the damage to the motor A casing we know that the cloud was ignited in the area of the hot bearing. As shown in Fig 9 the four sections of the casing was found up to 15 m from their original position. It is evident that hydrogen must have intruded into motor A and that the flame in an early phase of the explosion propagated under the casing and blew away the four sections.

8.0 RELEASE, YIELD AND COMBUSTION MODE

The release of gas from the blown gasket lasted for 20 to 30 sec. The hydrogen content of the gas was about 95 % (rest mostly CO). The reservoir pressure and temperature were 30 bar and 10^0C. The leak area was approximately 6 cm^2. We estimated the total release of hydrogen to be 10 to 20 kg.

We found from the damage indicators, such as broken windows, deformation of structures and damage walls, that 3.5 to 7 kg of hydrogen must have been burning violently in the explosion. That gives a yield factor of 35 %.

For the 6 cm^2 leak we calculated the amount of flammable hydrogen in a free jet to only 0.6 kg. However, it is not surprising that the amount of hydrogen with flammable concentration was significantly higher. To dilute a 20 kg release of H_2 to the lower flammability limit of 4% will require a volume of about 5500 m^3, which is nearly the total volume of the 100 m long building. A flammable hydrogen/air mixture must have filled a significant part of the building cross-section near the release point. The damage pattern showed that strong localized explosions had occurred at floor level. The explosion centres correspond to positions of high-velocity combustion inside the flammable cloud.

We believe that the explosion started as a slow deflagration (i.e. subsonic combustion wave) at the ignition point. When the flame propagated under the casing of motor A the explosion became confined and the pressure increased. The casing disintegrated because of the pressure build-up and jets of hot combustion products ignited the cloud on the outside of the casting. Such hot jets are known to cause strong localized explosions and even DDT (deflagration to detonation transition). From the damage indicators we have not been able to positively conclude that the cloud detonated, since the damages were determined by the total impulse rather that the maximum pressure. R.A. Strehlow visited the plant a short time after the accident and took part in the accident investigation. He was in no doubt that the cloud had detonated [6]. According to Strehlow the present case was very similar to an accident in Sarnia [8] in 1984. In the Sarina accident an unconfined hydrogen cloud had detonated. The high yield factor and the local strong explosion indicate also that the cloud detonated.

9.0 JET FLAME

When the roof lifted and the 350 mm diameter tube broke off, we got a violent jet flame. Assuming the gas contained 65 % hydrogen (rest mostly CO_2) we estimated the maximum release rate of hydrogen to 20 to 30 kg/s. The leak lasted for 30 sec before the reservoir was emptied. For a free jet flame we estimated the flame length to be about 150 m. However the building construction acted as a flame holder and reduced the flame length. From burn marks we believe the actual flame length was 50 m.

In accidents it is common that fires follow strong explosions as a domino effect.

10.0 EXPERIENCE FROM THE INVESTIGATION

Our experience from investigating this accident on site can be summarized as follows: Documentation of the damage has to start immediately, and should be done by an explosion expert and a structural response expert(s). Take many photographs, both of the area view and the specific damages. Use a professional photographer and make systematic records of locations and directions of all the photos taken. Organise a fragment map, showing the original position of the fragments and where they landed. Fragments can be a good indicator of where the explosion occurred and of the magnitude of the explosion [5,10].

11.0 END STATEMENT AND CONCLUSIONS

The paper describes a hydrogen explosion in a process plant. The accident took place in the summer of 1985 and the accident investigation was carried out during 1985 and 1986. The results we present here are those of the original work with only minor modifications. We are currently reinvestigating the accident with modern CFD-tools and new experiments. This new work is part of an IEA-project on hydrogen safety and the results will be published in the future.

The main conclusion from the original investigation can be summarized as follows:

- The accident occurred due to a combination of operational error, technical failures and weakness in the design
- 10 to 20 kg of H_2 leaked out inside the building
- Most likely a hot bearing ignited the gas cloud
- 3.5 to 7 kg of hydrogen must have been burning violently in the explosion
- We have no quantitative evidence that the cloud detonated, but from the damage observed, experience from other accidents and experiments detonation seems most likely.
- The explosion caused large number of fragments representing a severe hazard
- Glass windows were broken up to 700 m from the centre of the explosion. Within a radius of 100 m all ordinary windows were broken. The window fragments represent a severe hazard to humans
- The explosion was followed by jet fire. Domino events such as fires are common after gas explosion.
- Damage indicators can be of great help in investigating accidental explosion

To our knowledge this gas explosion is one of the largest industrial hydrogen explosions reported. We believe this case history is a valuable reference for those who are investigating the nature of accidental hydrogen explosions.

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