1. INTRODUCTION*

This introductory chapter looks at the phenomena of flame acceleration (FA) and deflagration-to-detonation transition (DDT) from four different perspectives:

- relevance of these processes for core-melt accidents,
- basic physical phenomena that define the detonation limits involved in these processes,
- options for control of FA and DDT, and
- hydrogen mitigation.

1.1 Relevance of FA and DDT in Severe Accidents.

The relevance of FA and DDT processes in postulated severe accidents arises from theoretical estimates and large-scale experiments. The assumption is that 100% of the fuel-cladding Zircaloy oxidizes (but not the other in-vessel Zr or steel structures) and that the generated hydrogen is homogeneously distributed in the available containment volume, thereby leading to dry hydrogen concentrations of between 12% and 21% in American plant designs [1.1]. For operating and future European pressurized-water reactor (PWR) designs with a large dry containment, the same assumptions lead to dry H_2 concentrations of between 17% and 20% [1.2]. Typical steam concentrations are from 20% to 70%, depending on the accident scenario. These conditions define the “global distribution” area shown in Figure 1.1-1.

Since nuclear power plant (NPP) containments are highly complex multi-compartment structures, H_2 gradients can generally develop in certain space and time intervals. The inhomogeneity of the hydrogen distribution mainly depends on details of the H_2 source (location, release rate), the containment design, and the efficiency of natural-convection processes. Three-dimensional distribution calculations for German 1300 MWe PWRs have often shown gas compositions in the “local distribution” area of Figure 1.1-1.

Hydrogen distribution under severe accident conditions was extensively investigated on full reactor scale in the HDR-E11 test series, using Helium gas as H_2 simulant [1.3]. Typical measured H_2 (He)-steam concentrations are included in Figure 1.1-1 for HDR tests simulating different accident sequences. A detailed state-of-the-art report (SOAR) on containment thermalhydraulics and hydrogen distribution has been published [1.4].

Figure 1.1-1 also depicts estimates for limits of flammability, FA, and DDT on a large scale. Comparison of these limits with the above described fields of possible gas compositions clearly shows that FA and DDT are relevant for severe accident studies. These fast combustion modes appear possible on local and even global scales, depending on details of the hydrogen source. It is also important to note that the steam concentration in the containment has a large effect on the combustion mode. The steam concentration is mainly governed by the balance between the steam release rate and the steam condensation rate, which, in turn, depends on the size and surface temperature of the internal containment structures.

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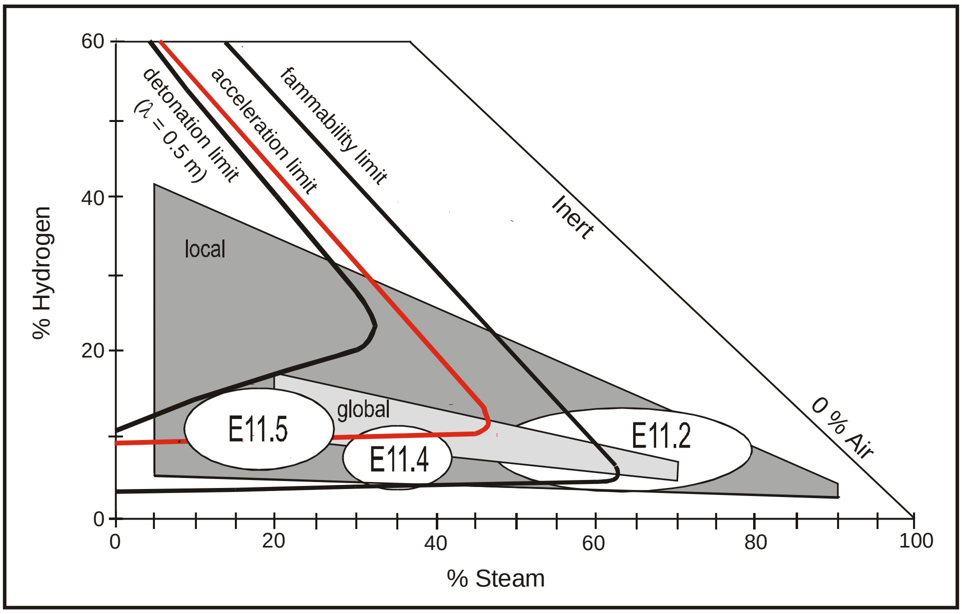

Fig.1.1-1.Theoretical estimates and large-scale HDR E-11 distribution tests demonstrate the possibility of FA and DDT processes in severe accidents

Relatively dry or wet containment atmospheres can develop in different accident sequences, as, for example,. demonstrated by the HDR distribution tests E11.5 and E11.2, respectively (Figure 1.1-1). Flame acceleration and DDT become a major concern in dry or medium-dry scenarios (tests E11.5, E11.4, Figure 1.1-1).

1.2 Basic Physical Processes

If severe accidents should lead to mixtures inside the detonation limits shown in Figure 1.1-1, two classes of detonation initiation can, in principle, be distinguished:

- direct strong initiation by an external energy source; and

- indirect initiation with a weak ignition, followed by a self-induced FA and DDT.

In the first case, the energy necessary to establish a self-sustaining stable detonation front wave system is provided by the external source, e.g., a spark or high explosive. In the second case, the initiation energy is provided by the combustible mixture itself. Different modes have been observed for the indirect detonation initiation; it can be induced, for example, by FA along tubes or channels, turbulent jets, and turbulence-generating fans.

In severe accident environments, the direct initiation by an external energy source seems less likely than the indirect mode because the necessary initiation energies are much greater than those for a weak ignition. The measured orders of magnitude for direct initiation in free clouds are 10 to 1000 kJ for H_2-air mixtures with equivalence ratios from 0.75 to 0.5 [1.5], whereas only millijoules are required to trigger a weak ignition in H_2-air mixtures. The only potential ignition source for a direct initiation may be a high-voltage spark or arc in a well-confined geometry. Many more possibilities exist for weak ignitions. It has been suspected that the spontaneous burn in the Three Mile Island (TMI) Unit 2 accident that led to the only significant containment load (3 bar), was initiated by a ringing telephone. The processes following a weak ignition in a sensible combustible mixture, which is enclosed by a complicated 3D structure with internal flow obstacles, involve extremely complex interactions between turbulent flow and chemistry. From a global point of view, chemical energy is converted and concentrated to high mechanical energy densities, which, in turn, trigger large chemical reaction rates through high temperatures. The simulation of these processes generally requires computation of unsteady, turbulent, and compressible reactive flow problems in multi-dimensional geometries with high spatial resolution.

The significance of FA and DDT processes for reactor safety is due to the fact that these fast combustion modes can be extremely destructive. They have the highest damage potential for internal containment structures; for safety systems that are required for safe termination of the accident (sprays, recombiners); and for the outer containment shell that is the last barrier against the release of radioactivity into the environment.

The concern about the outer containment shell is not only connected to its function as the ultimate barrier, but the concern is also due to its complicated structural behaviour. All modern containment buildings are a complex composite of different structural elements, including an undisturbed shell, personal and material locks, and hatches of different sizes and design, as well as penetrations for electrical cables and pipes. This system has been qualified for a certain global and static design pressure, which is generally related to the maximum blowdown pressure from a break of the primary coolant line.

However, in a severe accident, which is not part of the licensing process, in existing plants FA and DDT may become possible. In this case, new containment load classes would arise, namely high local or even global dynamic loads. The structural behaviour of containment components under such dynamic pressure and impulse loads is complicated and difficult to evaluate. An effective way to protect the containment integrity even for the case of beyond-design accidents is therefore to control the hydrogen behaviour in such a way that the possibility of FA and DDT occurring is decreased or even excluded. It is clear that this improvement of public and environmental protection against the consequences of severe accidents requires a detailed understanding of FA and DDT.

1.3 Options for Control of FA and DDT

The strengthening of the containment barrier function for severe accident scenarios is realized in various countries by introducing hydrogen management systems. For existing plants, the goal is to significantly reduce the probability of containment failure in cases of degraded core accidents, whereas for future plants the goal is generally a hydrogen control system that prevents the occurrence of FA and DDT by design for a spectrum of representative accident scenarios.

The amount and rate of hydrogen generated in an accident varies for different reactor designs and accident scenarios. Large reactors have a proportionally greater mass of available zirconium, and, hence, a potentially large hydrogen source term. The CANDU design is exceptional in having a comparatively small initial hydrogen release term. The relatively small hydrogen release for the CANDU design is due to the distributed channel-type core surrounded by an additional heat sink provided by the moderator water, which effectively arrests severe-accident progression at the point of fuel-cladding oxidation, preventing the continued hydrogen releases associated with complete core-melt. Moreover, CANDU fuel cladding is relatively thin, for neutron economy purposes, resulting in a correspondingly small mass of hydrogen released in the short term from fuel-cladding oxidation. The net result is a total short-term hydrogen mass release of less than 100 kg for the CANDU 600 MW reactors, and up to 300 kg for the new CANDU 900 MW design. As a result, the initiating sequence for hydrogen production (loss of cooling + loss of emergency core-cooling) in the CANDU reactor is included in the design basis of the plant.

For CANDU reactors, the strategy of hydrogen management is either to dilute or to remove the hydrogen in the containment atmosphere. Because of a limited hydrogen source term and a relatively large containment building, dilution of hydrogen with containment air is the most readily available means of dealing with a broad range of hydrogen releases. Besides relying on natural convection to mix the hydrogen with containment air, CANDU reactors also employ local air coolers, for steam removal, that promote forced convection circulation, provided electrical energy is available. A "well-mixed" containment atmosphere is not flammable. In situations when a flammable mixture is created in isolated regions inside the containment, a deliberate ignition system is employed as a second line of defence. For removal of hydrogen, CANDU reactors employ both igniters and catalytic recombiners for short- and long-term hydrogen control, respectively.

Hydrogen management in existing German 1300 MWe nuclear power plants is designed to cope with the potential in-vessel hydrogen production, which is typically about 500 kg. The first licensing applications for a system of catalytic recombiners were submitted in 1998; implementation of the recombiners is expected to start in 1999. Detailed distribution analyses of the recombiner concept with lumped-parameter codes and with a 3D computational fluid dynamics (CFD) code have shown the exclusion of significant containment loads from FA and DDT for the investigated accident scenarios. A large risk reduction will be obtained for beyond-design accidents with the proposed hydrogen control by a catalytic recombiner.

For the future EPR, which is a joint development of the German and French industry for a next-generation European plant design, the new safety goal is that even in case of a severe accident the radiological consequences must be essentially restricted to the plant itself and may not lead to large permanent relocation areas. This goal implies that containment integrity must be demonstrated for all possible hydrogen combustion loads. The joint recommendations of the French and German Advisory Committees (Groupe Permanent des Reacteurs and Reaktorsicherheitskommission) require that the plant has to be designed to cope with the maximum amount of hydrogen that could accumulate in the containment building during a low-pressure core-melt accident. More specifically, the Committees requested that the possibility of global detonations must be practically eliminated. Catalytic recombiners and igniters were recommended as possible components of a hydrogen control system. In order to exclude large-scale detonations and to demonstrate that the maximum possible combustion loads during representative severe accident sequences remain within the containment design capabilities, extensive 3D distribution and combustion calculations will be performed with different recombiner-igniter options. An important aspect of these analyses is to show that FA and DDT can be controlled. For future plant designs that try to shift the design-basis loads into the extremely unlikely region of severe accidents, the understanding of FA and DDT is of the utmost significance.

1.4 Hydrogen Mitigation

In the context of FA and DDT, the current SOAR appropriately addresses issue of <u>controlling</u> these fast combustion modes under severe accident conditions. We first summarize the general requirements for hydrogen mitigation systems and then give a brief discussion of the most important current technical options for hydrogen control in NPPs. An extended summary of this topic can be found in Reference [1.6].

1.4.1 General Requirements

As required for any other industrial installation, the requirements for a combustion and fire protection system in a nuclear containment must be carefully evaluated to provide the necessary basis for the technical specification.

The system must first of all fulfil the following acceptance criteria:

- There should be no adverse effects on normal operation, plant personnel, and plant response to severe accidents.

- The containment will be protected, and no new load mechanisms should appear (thermal loads, missiles).

- The safety systems for accident termination should remain unaffected.

With respect to the design of the mitigation system, the following requirements must be met:

- The mitigation system must perform the intended function with high reliability in all anticipated severe accident environments.

- The design of the mitigation system must be effective for a wide spectrum of accidents.

- The design of the mitigation system must be qualified for seismic design event.

- The mitigation system must have redundancy of components.

- The mitigation system must be fail-safe.

- The mitigation system must have clear activation criteria if it is an active system.

- The mitigation system of an existing plant must have the potential to be retrofitted.

- The mitigation system should be cost-effective to install, maintain, and test.

When technical components have been qualified with respect to these design requirements, the next step is to predict the outcome of a system of components for severe accident conditions and for full containment scale. The following analysis requirements exist:

- The system efficiency must be predicted for different bounding accident scenarios, e.g., the integral hydrogen removal rates of the system.

- A sensitivity analysis of the number and location of the components is needed to ensure adequate design and safety margins.

- The consequences of a random ignition for the mitigation system and for containment pressure loads must be understood.

- The verification of the theoretical tools and codes used for the scale-up and the prediction of component efficiency for the reactor case must be performed.

A large amount of work has been devoted in a number of countries to identify mitigation solutions that satisfy these stringent requirements. It turned out that conventional non-nuclear combustion and fire protection methods are not directly adaptable to severe accidents in NPPs. The problems are mainly related to the large scale of the containment, high-potential flame speeds (little time for system activation), high hydrogen release rates (kilograms per second of H_2), and incompatibility with other nuclear safety rules (fire prevention).

1.4.2 Hydrogen Mitigation Techniques

The following three load-reducing mitigation techniques have shown sufficient potential for application in existing and future PWR power plants:

- catalytic recombiners,
- spark igniters, and
- pre- and post-accident dilution.

1.4.2.1 Catalytic recombiners

Figure 1.4.2.1-1 shows as an example the catalytic recombiner developed by Siemens. Other designs were developed by Atomic Energy of Canada Limited (AECL) in Canada and Nuklear Ingenieur Service (NIS) in Germany. Hydrogen recombines with oxygen from air on Pt-containing catalytic surfaces. The heat of reaction produces a natural draft in the convection duct and establishes a stable self-feeding process of the gas at the lower entrance. The advantage of such a module is that it works passively and also in steam-inerted mixtures as long as the H_2 and O_2 concentrations are above approximately 1%. The disadvantage is the relatively low removal capacity per module (several grams per second of H_2), compared with typical release rates, which can reach 1 kg/s H_2 in large plants. This typical release rate clearly creates the possibility of local H_2 enrichments occurring during transient accident phases with high H_2 release rates.

Another currently unresolved issue is ignition of the hydrogen-air-steam mixture under certain overload conditions, which depend on the recombiner design and steam concentration. It is anticipated that new improved recombiner designs for H_2 concentrations above 10% will become available in the near future. Recombiner ignition should either be suppressed or become predictable, so that this effect could be taken into account in future containment analyses.

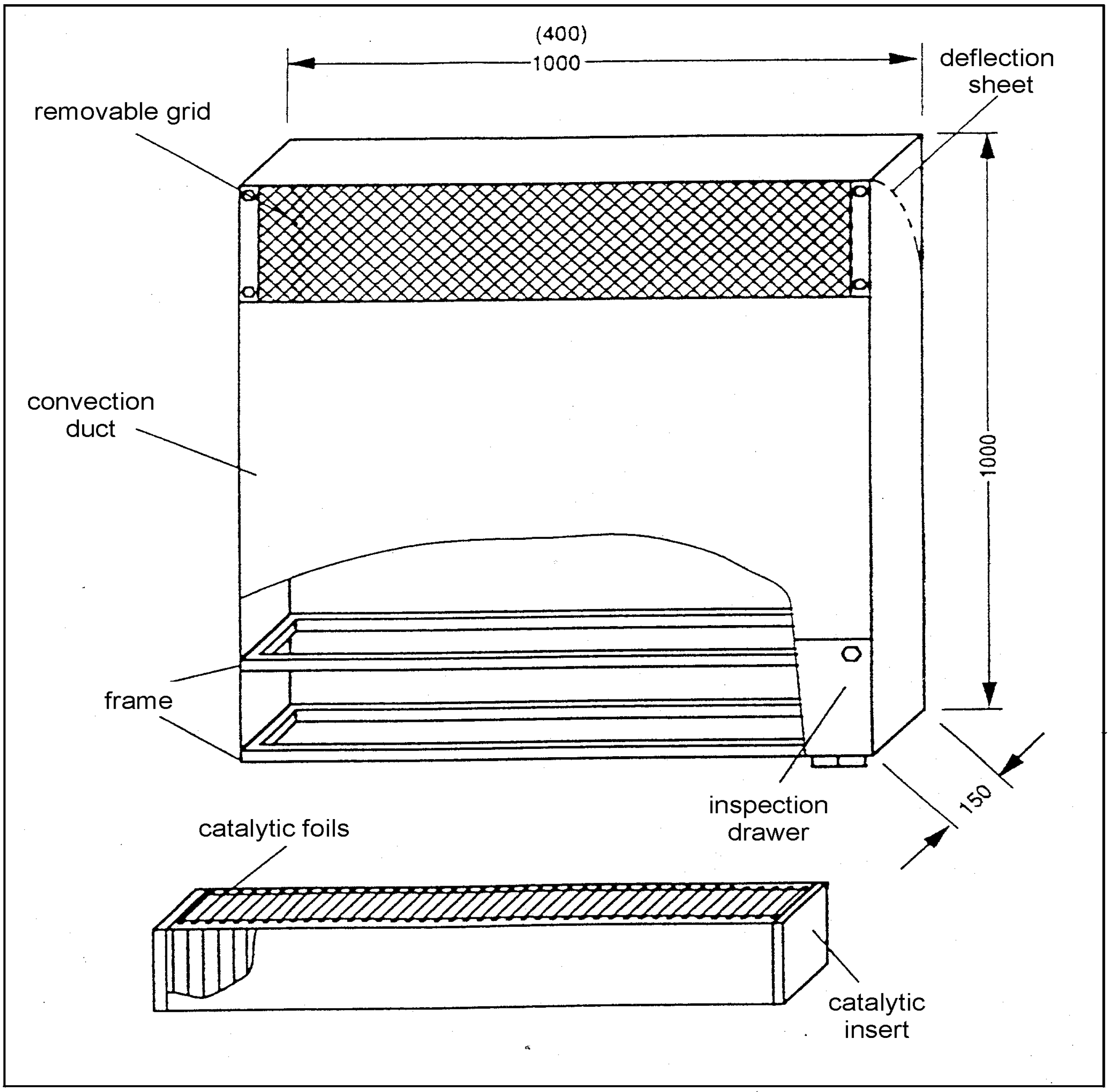

Figure.1. 4.2.1-1 Catalytic recombiner design of Siemens KWU

Recent investigations for German PWR plants using the 3D CFD program GASFLOW [1.7] have revealed a number of new results for recombiner efficiency on full plant scale:

- The removal rate of a recombiner depends only on the local H_2 concentration at the recombiner position, which, in turn, is largely determined by the global flow field in the containment. The natural draft of the recombiner itself can be neglected in most cases because the effected space region is limited to a distance of a few metres. A good resolution of the local H_2 concentration is necessary for a realistic calculation of the individual recombiner efficiency.

- In the investigated small-break (SB) and large-break loss-of coolant accidents (LBLOCA) scenarios, the recombiners did not provide a noticeable additional mixing effect because the small momentum of the recombiner exhaust gases is dissipated in the near environment, and the succeeding exhaust gas motion is buoyancy-dominated.

- In accident sequences leading to well-mixed conditions, a system of catalytic recombiners can be an effective safety-oriented mitigation approach, which acts within the first few hours after hydrogen release. (For example, in one of the investigated cases with about 50 recombiners and 530 kg H_2 total release, the integral H_2 removal rate was initially 180 kg/h H_2 and then decreased proportionally to the residual H_2 or O_2 concentration in the containment.)

Corresponding lumped-parameter analyses covering also the long-term evaluation of the containment atmosphere composition, pressure and temperature were performed with the RALOC code [1.8].

In summary, present recombiner designs fulfil the above-listed acceptance, design and analysis requirements almost completely. The principal drawback of current designs is the low recombination rate, related to the hydrogen sources expected during core degradation. An open point concerns the potential of mixture ignition under transient overloads during accident phases with high H_2 release rates.

Future recombiner designs should find the best compromise between the two apparently opposing requirements of high recombination rate and low ignition potential.

1.4.2.2 Igniters

The second important mitigation approach is deliberate ignition of flammable accident mixtures with igniters. The intention is to start a deflagration as early as possible before dangerous amounts of hydrogen have accumulated. Two types of devices have been developed, namely glow-plug and spark igniters. Glow-plug igniters require a continuous power supply, which may not be available in severe accident sequences. Siemens developed an autark battery-powered spark igniter, which is activated by temperature or pressure set points (Figure 1.4.2.2-1). This module operates passively and does not require operator action. The reliable function was shown for a wide range of severe accident conditions [1.9].

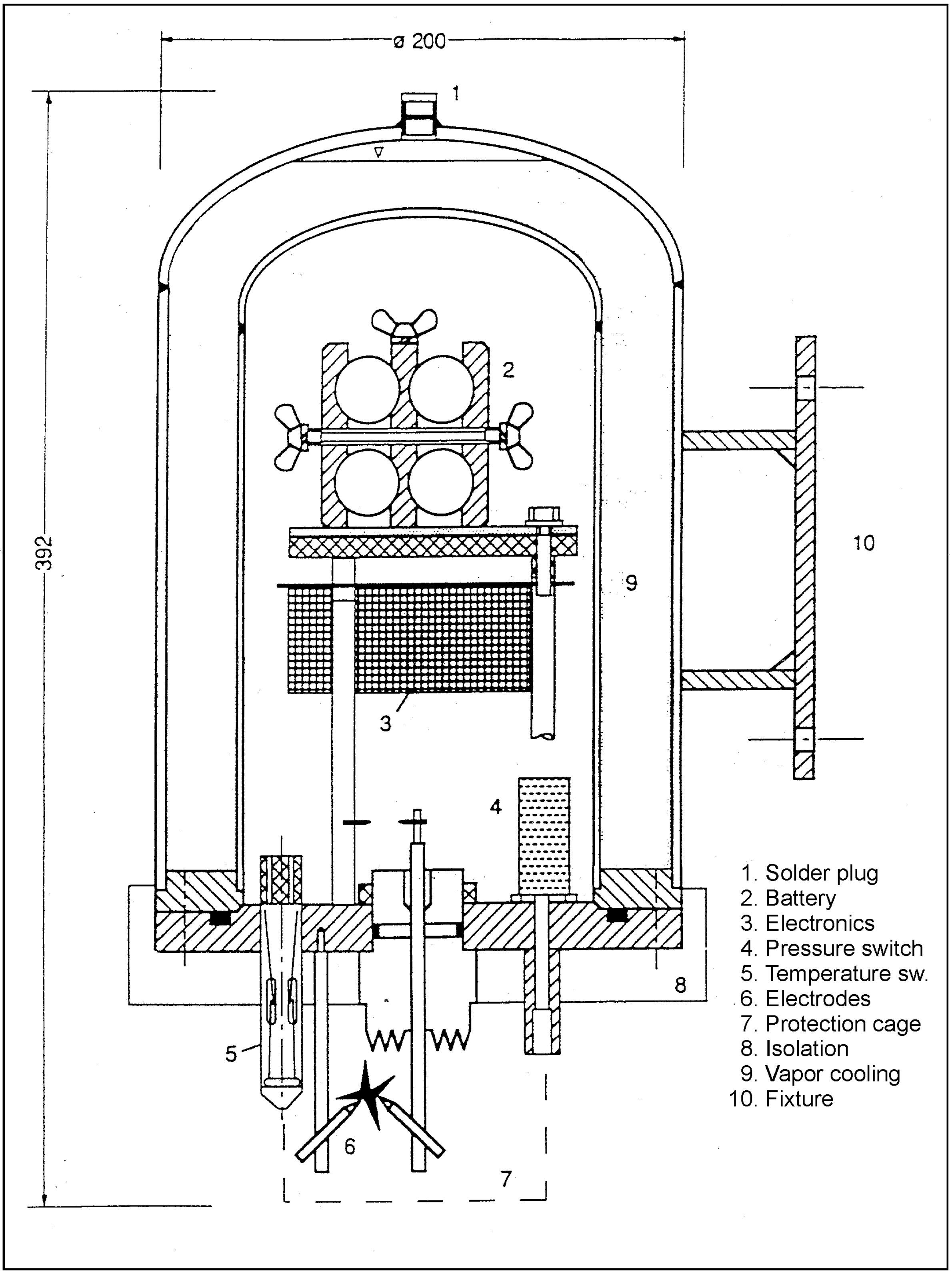

Figure 1.4.2.2-1 Autark spark igniter developed by Siemens WZB 89

The initial design used a spark interval of 10 s. Large-scale experiments with dynamic H_2 injection and spark ignition [1.10] have shown however, that a shorter spark interval would bring an additional safety margin. Ignition occurs only after the edge of the combustible gas cloud has arrived at the nearest igniter position, and the next spark is activated. The flame then travels back to the source location. A short spark interval would minimize the H_2 content of the cloud at first ignition.

The main question in the application of the igniter concept is its safety orientation. The use of igniters should reduce the overall risk to the containment and should not create new additional hazards such as a local detonation. A new methodology for safe igniter implementation in a 3D containment was recently developed and implemented into the GASFLOW code [1.11]. The method was applied to a bounding dry release scenario in a future PWR in which the steam from the core is condensed in a water pool. In the unmitigated case, significant DDT potential developed in the whole containment, including the possibility of global detonations. The analysis with igniters in different positions predicted deflagration or detonation in the break compartment, depending on the location of the igniter. Igniter positions were found that lead to early ignition, effective H_2 removal, and negligible pressure loads. This approach can be used to determine the number and position of igniters necessary to control different hydrogen-release scenarios in different plant designs.

In summary, the installation of an igniter system for H_2 mitigation requires careful analysis regarding the number and location of igniters to exclude local detonations. The theoretical understanding and the numerical tools are sufficiently developed and verified to allow conclusive predictions with sufficient safety margins. The principal drawback of igniters is that they are not effective under inert conditions, which can arise from high steam concentrations or local oxygen burnout.

1.4.2.3 *Pre- and post-accident dilution*

A third option for H_2 mitigation is dilution of the accident atmosphere with an incondensable gas to suppress energetic combustion regimes or even full inertization to suppress combustion completely. The inert gas (CO_2 or N_2) can, in principle, be added before or after initiation of a severe accident.

The most rigorous solution of course is complete permanent inertization of the containment atmosphere. General consensus is that this approach is acceptable for boiling-water reactor (BWR) plants; however, it violates the first acceptance criterion given above in the case of PWR plants, namely no adverse effect on normal operation. There are three main reasons for this difference:

- Meltdown of a BWR core would create much larger hydrogen masses because of the additional Zr shrouds; the resulting mixtures could be very reactive.
- BWR containments are much smaller, and hence easier to inert and de-inert for refuelling.
- All important safety and technical support systems are located outside of the BWR containment and can be easily checked during normal operation.

For many BWRs worldwide, permanent inertization has been chosen as the optimum hydrogen mitigation method. This approach appears very convincing for accidents that occur while the reactor is on-power, but accidents that occur during a shutdown state are not protected because of containment de-inertization during refuelling and maintenance.

For PWRs with large dry containments the options of partial or full inertization after initiation of a severe accident remain. Both approaches have been investigated experimentally and theoretically, e.g., [1.12, 1.13], using gaseous or liquid carbon dioxide.

With respect to the general acceptance, design, and analysis requirements for mitigation methods, the following aspects of post-accident dilution are important:

- It is an active method, which requires decision, actuation, and completion within a restricted time window to be effective (0.5 to 1 h),

- A complex system is required for technical realization (permanent storage of ≈100 tonnes of liquid or gaseous CO_2).

- The distribution and mixing of a CO_2 jet in a complex multi-room structure filled with lighter gases (air, steam) is a non-trivial process, requiring detailed CFD analysis; the result can strongly depend on time and location of the CO_2 injection [1.14].

- Addition of CO_2 may increase the pressure significantly, for example, for full inertization roughly 60 vol % of (steam + CO_2) are required.

- The addition of CO_2 leads to an overpressurized containment, even long after termination of the accident.

A good compromise with respect to the various requirements and safety aspects could be a fast truly homogeneous post-accident dilution technique with proven suppression of the fast combustion regimes, only marginal pressure increase, and reduced maintenance costs. However, the design of post-accident dilution (or inertization) methods is not a simple straightforward task because complex natural-convection processes between fluids of different densities in a multi-room structure determine the remaining combustion potential.

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