MASSIVE H2 PRODUCTION WITH NUCLEAR HEATING, SAFETY APPROACH FOR COUPLING A VHTR WITH AN IODINE SULFUR PROCESS CYCLE

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ABSTRACT

In the frame of a sustainable development, investigations dealing with massive Hydrogen production by means of nuclear heating are carried out at CEA. For nuclear safety, thermodynamic efficiency and waste minimization purposes, the technological solution privileged is the coupling of a gas cooled Very High Temperature Reactor (VHTR) with a plant producing Hydrogen from an Iodine/Sulfur (I/S) thermochemical cycle. Each of the aforementioned facilities presents different risks resulting from the operation of a nuclear reactor (VHTR) and from a chemical plant, including Hydrogen, other flammable and/or explosible substances as well as toxic ones. Due to these various risks, the safety approach is an important concern. Therefore, this paper deals with the preliminary CEA investigations on the safety issues devoted to the whole plant, focusing on the safety questions related to the coupling between the nuclear reactor and the Hydrogen production facility. Actually, the H2 production process and the energy distribution network between the plants are currently at a preliminary design stage. A general safety approach is proposed, based on a Defence In Depth (DID) principle, permitting to analyze all the system configurations successively in normal, incidental and accidental expected operating conditions. More precisely, the dynamic answer of an installation to a perturbation affecting the other one during the previous conditions, as well as, the potential aggressions of the chemical plant towards the nuclear reactor have to be considered. The methodology presented in this paper is intended to help the designer to take into account the coupling safety constraints and to provide some recommendations on the global architecture of both plants, especially on their coupling system. As a result, the design of a VHTR combined to a H2 production process will require an iterative process between design and safety requirements.

1. INTRODUCTION

The ability of VHTR to heat the gas coolant at a very high temperature, namely around 1000°C, is a favorable feature for the efficiency of electricity generation, as well as, for reaching a high efficiency in industrial processes requiring high temperature energy. Among these processes, those permitting hydrogen production are currently of concern due to the decrease of fossil energy stores and the necessity to limit the release of carbon dioxide regarding the green house effect. CEA contributes in research programs on VHTR and is involved in research on massive hydrogen production. The nuclear plant investigations are based on the Generation IV Forum specifications for VHTR concept. Its main specified features imply a fluid temperature at the core outlet larger than 950°C, an inherent passive safety and an improved valorization of natural resources, including a substantial reduction of the amount and radioactivity of waste. Regarding the massive hydrogen production from nuclear heating, several processes are investigated :

- high temperature electrolysis of water (HTE) ;
- steam reforming of the natural gas ;
- sulfur-iodine water splitting cycle (IS process).

Other processes are investigated, as for instance that one developed by Westinghouse [1] ; they correspond to hybrid cycles. These cycles combined a thermochemical cycle and electrolysis in order to take benefit of the two technological solutions. As an illustration, the Westinghouse cycle permits to reduce the electric tension, even at a low temperature because it includes the electrolysis of not only water but also sulfur dioxide. Moreover, it involves only three chemical species (H, O, S), thus eliminating technical challenges resulting from the utilization of iodine in the IS process. The HTE process mentioned above is penalized by a low thermodynamical efficiency and requires an electric supply (Fig. 1). The steam reforming is the most efficient way to produce hydrogen and it is a robust process. However, two major drawbacks result from this process, that is, the need of fossil fuel and the release of carbon dioxide as a secondary product of the steam reforming. Finally, for economical (energy cost) and environmental (sustainable development) reasons, the IS process is the most promising way to produce hydrogen. More precisely, the thermodynamical efficiency of the whole process is expected to be close to 50 %. Considering the previous statements, CEA is currently involved in research on IS thermochemical cycle as well as in its development at industrial scale. However, other options, like HTE are also under investigation in order to prospect in various directions.

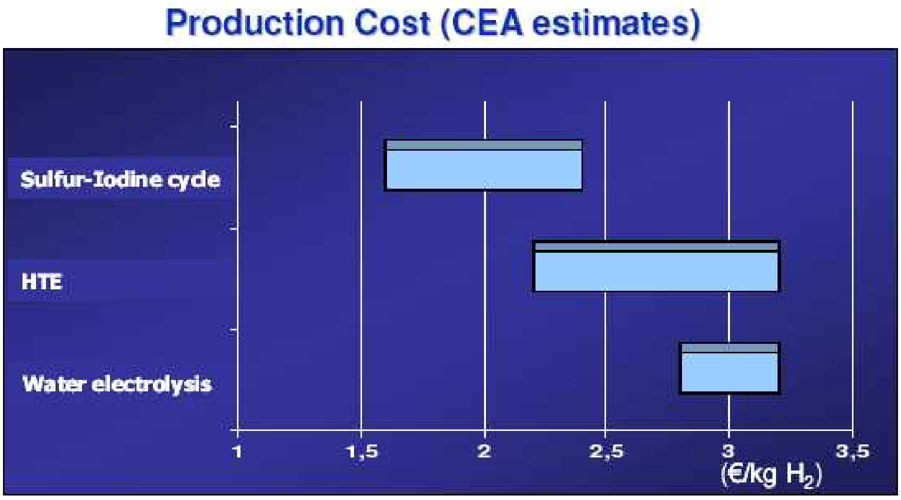


Figure 1 [2]. Hydrogen production cost assessment

Regarding the experiences of nuclear heating for chemical processes, investigations on the coupling of an experimental reactor (called HTTR, 30 MW) with a hydrogen production plant using steam reforming of methane are under way in Japan [3]. Moreover, in Germany, another project was initiated in 1977. The aim of this project was to provide heat to gasification processes of coal, by means of a HTR (high temperature reactor) concept called PNP500 [4]. Beyond the technological challenges to cope with, the coupling of a VHTR with a Hydrogen production plant (called HYPP later on) requires a safety strategy taking into account, in the same time, the specificities of the two facilities and the potential increase of risks resulting from the vicinity of the facilities and from the exchange of fluid and signals from one facility to the other.

The aim of this paper is to present the safety approach proposed by CEA in order to integrate safety constraints to the pre-conceptual studies on Hydrogen production by means of nuclear heating at high temperature. In the first part of the paper, few elements regarding the VHTR and the preliminary design of the HYPP are presented. In the following part, beginning by recalls of the safety rules to apply in the nuclear industry on one hand and in the conventional industry, on the other hand, the safety approaches are compared in order to bring out a consistent safety approach for the whole facility, combining the reactor and the H_2 production plant. Afterwards, this approach is described, then it is applied to the safety of the coupling of the VHTR and the HYPP. Finally, in the last part of the paper, few envisaged safety provisions are presented considering the very preliminary design of the HYPP.

2. PRESENTATION OF THE FACILITY

In this chapter, the main features of the VHTR and of the HYPP are presented first separately. Then the way they should be coupled is also briefly described. More details regarding the design of the coupling system will naturally be deduced from the safety approach declined later on.

2.1. Main reference case assumptions regarding the whole facility

In the frame of the feasibility studies carried out at CEA, a reference case configuration has been adopted and the main assumptions resulting from this concept are listed below :

- the nuclear reactor is fully devoted to the hydrogen production ;
- the thermal power of the reactor is equal to 600 MW ;
- due to design constraints, the HYPP has to be divided in several units whose power should range from 50 to 100 MW.

The principle scheme of such a facility is presented on the figure 2 below (IHX : intermediate heat exchanger). The number and the capacity of the H_2 production units has not yet been determined but in the frame of the safety methodology, it will be considered several units, this approximate being sufficient to present the principles of the methodology.

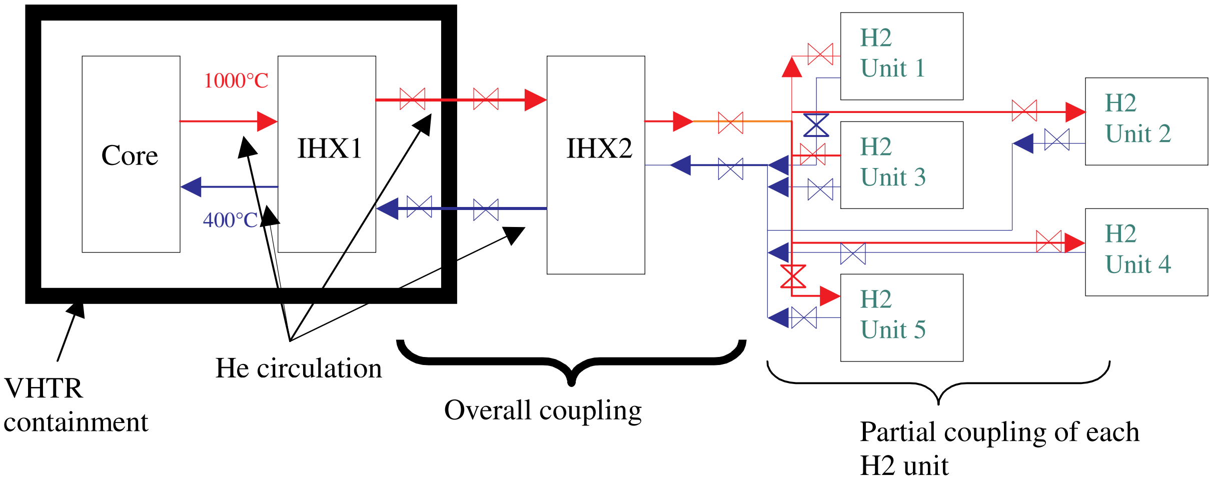


Figure 2. Conceptual scheme of VHTR/HYPP coupling

2.2. Brief presentation of the VHTR

The reactor applies the block type (prismatic) core design, in which, the coated particle fuel, a common feature of all HTRs, is contained within prismatic graphite blocks that are arranged to form an annular core geometry [5]. The core is sized to produce 600 MW of thermal power, with a targeted outlet temperature of 1000°C. Helium is used a the primary heat coolant. The thermal power produced by the core is transferred to a secondary circuit by means of an intermediate heat exchanger IHX (Fig. 3). The reactor and the IHX1 are enclosed within separate steel pressure vessels. For electricity production purposes, the secondary coolant is a mixture of Nitrogen and Helium permitting to use a classical air-breathing gas turbine. In the case of interest (reactor fully devoted to H_2 production), the secondary fluid is assumed to be Helium due to its good thermal properties. Furthermore, the advantages of the VHTR come from its ceramic fuel system, graphite moderator and Helium coolant. These features provide a high temperature capability associated to the elimination of the possibility of fuel damage [5] thanks to the ability of the core to store the heat and then, to release the residual power through radiative and conductive exchanges.

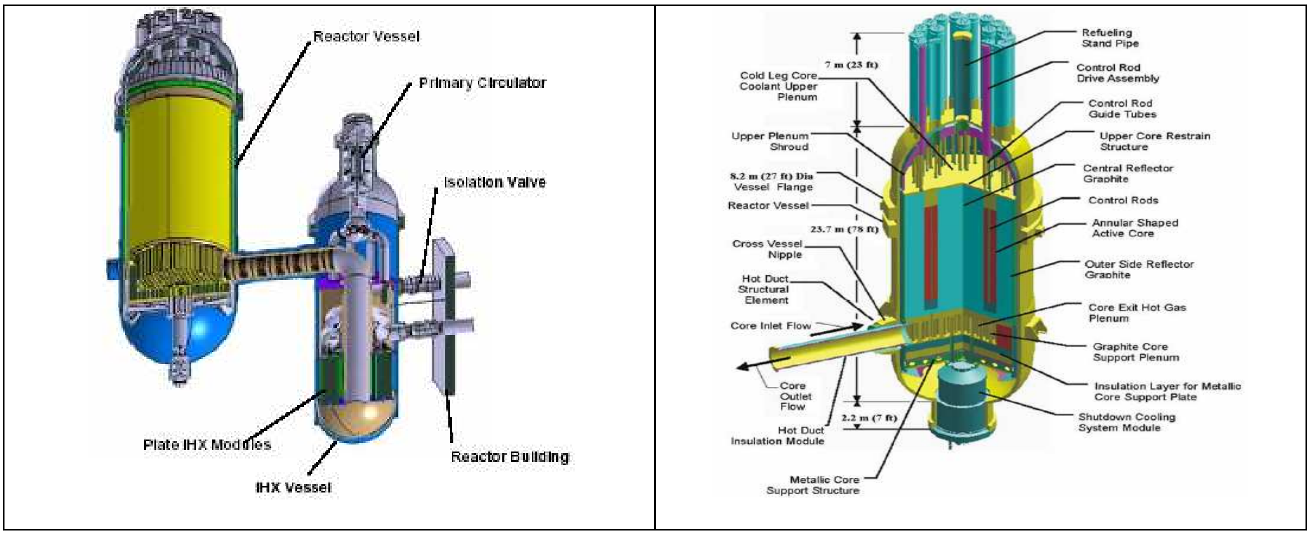
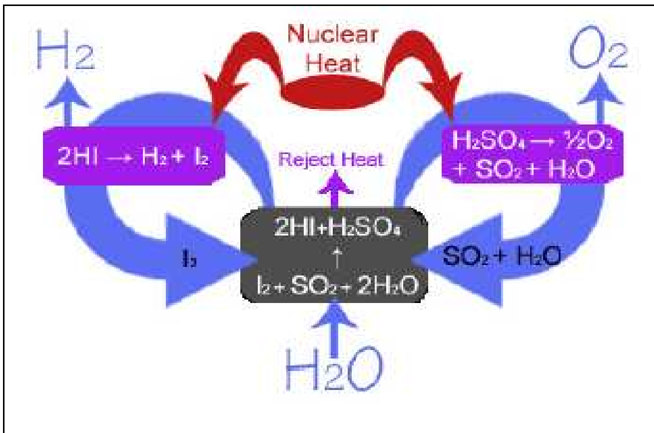


Figure 3 [5]. VHTR core and vessel system arrangement

2.3. Brief presentation of the IS process and of the coupling of the H_2 production plant

As usual, the aim of this kind of cycles is to split the water molecule at a lower temperature than the direct decomposition. As shown on Figure 4, for IS cycle and for an optimal efficiency, the required temperature is approximately 900°C (endothermic decomposition of sulfuric acid) instead of 2850°C for an efficient direct decomposition. Basically, the principle of the IS thermochemical cycle is represented on Figure 4. From an ideal point of view, considering an ideal two stages cycle, the endothermic high temperature reaction is combined with a low temperature exothermic reaction releasing the hydrogen and/or the oxygen not produced by the high temperature reaction and also restituting the chemical substances in their initial thermodynamical state. Practically, the IS cycle includes three stages and the presence of substances in different physical phases. Theoretically, the only reactant that will need to be added to the cycle is water. The efficiency of the whole cycle can be increased by the optimization of the heat recuperation at low temperature and its transfer towards higher temperature stages. CEA is currently involved in such an optimization. Studies dedicated to the pre-sizing of main equipments of HYPP are also under way. These studies led to a technological issue including several units because of sizing constraints, as surface over volume ratio of the components and maximum admissible pressure, considering the diameter of the components. On the basis of multiple hydrogen production units, a conceptual coupling scheme can be drawn (Fig. 2). The important point to notice is that production units can be connected or disconnected, separately (partial coupling). It is also possible to connect or disconnect the whole hydrogen plant by means of another gates system (overall coupling). It is only a simplified scheme for coupling the reactor with the HYPP ; the final coupling system will also include redundancies, emergency gates and so on.



$H_2O \rightarrow H_2 + ½\, O_2$

Obtained by the sum of :

$H_2SO_4 \rightarrow H_2O + SO_2 + ½\, O_2$ (T > 850°C)

$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$ (T ~ 100°C)

$2HI \rightarrow H_2 + I_2$ (T ~ 400°C)

Figure 4 [6]. Conceptual scheme and main chemical reactions of IS cycle

3. SAFETY APPROACH

The safety approach, guided by the regulation and based on safety analysis methodology is presented for the nuclear power plant as well as for the conventional plants. The synthesis of these two regulations permitted to propose a methodology for the safety approach of the VHTR coupled with the HYPP, consistent with both regulations.

3.1. Safety approach for nuclear reactors

3.1.1. Regulation and safety reports

Being a nuclear facility, the VHTR design and operating is submitted to safety rules emanating from the nuclear safety authorities (Direction Générale de la Sûreté Nucléaire et de la Radioprotection (DGSNR) in France). Moreover, safety objectives have to be defined for each nuclear facility ; the strategy and the foreseen provisions are described in a safety report showing the compliance with these safety objectives.

3.1.2. Deterministic safety approach

Nuclear reactors present very specific risks due to the accumulation of radioactive materials and to energy release occurring even after the shutdown of the facility. Considering this specificity, physical barriers are interposed between the radioactive materials (fission product) and the environment, in order to prevent their release. In the VHTR, the three barriers are respectively, the silicon carbide layer of the fuel coated particle, the primary circuit and the containment building. Safety functions defined to preserve the integrity of these barriers are : the control of the nuclear reactivity and the cooling of the fuel (necessary to the protection of the first barrier) and the confinement of fission products (necessary to the confinement in itself). Moreover, conception rules are adopted with respect to the principle of defence in depth (DID) including generally five levels (cf. 3.3.2).

3.2. Safety approach applicable to a conventional facility

3.2.1. Regulation and report for operating authorization delivery

This regulation consists in laws applicable to the facility “classified for environment” and eventually in the SEVESO II European directive, depending on the quantities of dangerous substances included in the facility. Of course, the conception rules (for equipments under pressure for example) of the art have to be applied.

3.2.2. Danger studies (French safety report for conventional facilities)

Before receiving the authorization to build and to operate a facility, its owner has to provide among other, an impact study quantifying the impact of the substances released by the facility in normal operation conditions. A danger study has also to be provided in order to analyze the safety of the facility and to describe the foreseen provisions to prevent and to limit the accident consequences. Finally, several representative major accidents (as an envelope) are chosen in order to assess security distances devoted to the urbanization mastery, resulting from the consequences (toxicity, pressure wave, thermal radiation) assessment of these major accidents. These distances determine two zones within irreversible effects and lethal effects on human beings are respectively to fear (Tab. 1).

Threshold/Type of effect	Toxic	Thermal	Overpressure
Irreversible effects	Corresponding threshold concentration	3 kW/m^2	50 mbar
Lethal effects	LC 1 % (1 % of lethality)	5 kW/m^2	140 mbar

Table 1 [7]. Thresholds of accidental effects defining safety distances according to French regulation

3.3. Synthesis of the nuclear and conventional safety approaches, approach for the coupling of VHTR and HYPP

As explained before, the regulations applicable to nuclear and conventional facilities are different. Nevertheless, they take a part of the safety referential to cope with, even though, in case of very conservative rules, technical demonstrations are sometimes accepted for exemption purpose (for example, French basic safety rule regarding gas explosion risks in the vicinity of a reactor is based on the pessimistic TNT equivalent method associated to conservative assumptions for the location of the ignition and the amount of gas exploding, but, more realistic methods have already been used to assess explosion effects). Moreover, the deterministic approach is declined in a less rigorous way in the conventional industry, but, as in the nuclear facilities, it is more or less based on the defence in depth principle and on studies of postulated major accidents. However, the concept of barriers is less strictly applied in the conventional industry, the first barrier being most of time, a pipe wall or a capacity wall, and the last (virtual) barrier being a security distance.

3.3.1. Safety functions of the coupled facilities (VHTR/HYPP)

According to the previous statements, three overall safety functions can be defined for the whole facility (VHTR/HYPP) in order to prevent and to limit the consequences of dangerous releases in case of accidents :

- the control of the nuclear reactivity and of the chemical reactivity ;
- the extraction of the nuclear power, of the thermal power (heat release by chemical reactions, phase changes) and of the mechanical power (compressors, pumps, pressure wave associated to phase changes or very rapid gas expansion due to heat release) ;
- the confinement of hazardous substances : fission product and chemical substances.

Obviously, the two first safety functions are required to avoid excessive solicitations of components constituting a barrier. The last safety function states the protection of the barriers in itself.

Levels of defence in depth	Objective	Essential means for achieving the objective
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

Table 2 [8]. Defence in depth levels (for a nuclear facility)

3.3.2. The concept of defence in depth

Defence in depth (DID) consists in a hierarchical deployment of different levels of equipment and procedures in order to maintain the effectiveness of physical barriers placed between hazardous materials and workers, the public or the environment, in normal operation, anticipated operational occurrences and, for some barriers, in accident at the plant (Tab. 2). Generally, several successive physical barriers for the confinement of radioactive materials are in place in a nuclear plant. According to the principle of DID, if the provisions of a given level fail to control the evolution of a sequence, the subsequent level will come into play. Therefore, the strategy of the defence in depth (DID) is based on the principle of reduction and limitation of consequences of incidents and accidents. The different levels are intended to be independent to the extent practicable, the general objective of DID being to ensure that a single failure at one level of defence, and even combinations of failures at more than one level of defence, do not propagate to jeopardize DID at subsequent levels. In the following chapters of this paper, the application of DID to the coupling of the VHTR and HYPP is proposed on a theoretical point of view.

4. PREVENTION OF ABNORMAL OPERATION AND FAILURES (LEVEL 1 OF DID)

The set of provisions regarding this level of DID are aimed to reduce the possibility of departure from the normal operating domain of the facility. To reach this target, design rules and limits of normal operating domain must be defined considering the specificities of the VHTR/HYPP facility and are detailed below.

4.1. Selection of design rules adapted to chemical substances specificity and to different operating conditions

Obviously, the various components of the coupling system, VHTR and HYPP have to be designed to match the thermodynamic conditions of the facility (pressure and temperature) including safety margins. Moreover, sulfuric acid and iodhydric acid are very corrosive substances and, when mixed with each other, they even present a synergetic behaviour regarding corrosion. As a result, choosing the right material is a very challenging task because they are only few acceptable candidates, only considering technological aspects, no matter the cost is : Tantale, glass coated steels, ceramics, steel alloys. Another concern is the hydrogen embrittlement of the walls of cryogenic storages due to the combination of low temperature and hydrogen diffusion in metals. Finally, design options limiting the diffusion of tritium from the reactor primary circuit towards the HYPP, as well as, options limiting the hydrogen diffusion from the HYPP towards the VHTR core must be adopted. The concentration of tritium in the plant must respect the radiological limit imposed by regulation and must be compatible with commercial specifications of hydrogen. Conversely, a too high hydrogen concentration in the primary circuit represents a threat for the graphite of the VHTR core, which could react with hydrogen [3].

4.2. Provisions regarding parameter variations transmitted from one facility to the other on through the coupling system

Among other goals, the coupling system is devoted to energy exchange between the VHTR and the HYPP by means of Helium flows and heat exchangers (IHX1 and IHX2 on Fig. 2). Considering the nominal operating regime and also the normal starting and normal stopping transients, provisions are retained to keep the facility in normal operating domain. As a consequence, the features of the energy fluxes exchanged between both facilities must be controlled in terms of temperature, flow rate and pressure. Therefore, the possible solicitations of a facility by the other, via the coupling system, must be analyzed in order to implement design solutions respecting HYPP normal operating regarding the hot Helium and, conversely, respecting VHTR normal operating regarding cold helium coming back from the HYPP. JAERI [3] proposed and is currently validating a steam generator whose liquid phase is crossed by the cold Helium. Thus, this latter is cooled to the saturation temperature of the water, controlled by the pressure of the steam phase of the generator. By the way, this regulation is mainly passive.

5. CONTROL OF ABNORMAL OPERATION (LEVEL 2 OF DID)

The objective of this level is to prevent the propagation of a perturbation (incidental excursion out of normal operating conditions) affecting a facility to the other one and to avoid that the situation degenerate into an accident. The provisions adopted for this purpose deals mainly with surveillance, control and regulation systems. It should be noticed that possible abnormal operations could be induced during nominal regime (full power) or during operating transients. As a consequence, the behaviour of the whole facility must be simulated or at least investigated in both cases, in order to obtain the kinetics of the possible transients and to design an efficient regulating system. The security and limiting systems acting automatically in case of abnormal operation are designed to operate before the triggering of systems of third level of DID, especially, the automatic emergency shutdown of the facilities (VHTR and HYPP). The steam generator mentioned in 4.2 belongs to this set of systems. The scram of a nuclear reactor is a very sudden transient that is not expected to happen too frequently, because it induces large solicitations of the components of the core and of the primary circuit, followed by eventually time-consuming processes before starting again the reactor.

5.1. Control of abnormal operation occurring in the HYPP

In order to maintain the VHTR in normal operating conditions, the magnitude and the kinetics of possible thermal instabilities in the cold Helium flow coming back from the HYPP must be limited in case of abnormal operation in one or more (possible common cause failure) hydrogen production units in the plant. If a thermal perturbation cannot be controlled without inducing abnormal operation in the VHTR, when it is coupled to all hydrogen units, the following strategy is proposed (Fig. 5) and consists in a set of provisions gathered in the so-called *sublevel 1* :

- uncoupling and shutdown of the H_2 unit(s) being out of normal operation domain (partial uncoupling on Fig. 2) ;
- the VHTR is kept in operation when possible by means of an alternative way for extracting power :
    - a fraction of the helium flow is switched towards heat sink (cold source) of variable power ;
    - switch of the extra power towards other H_2 units if conceivable ;
    - a fraction of the helium flow could be driven in a dedicated gas turbine.

- other H_2 units are kept in operation until the coupling of the unit(s) affected by abnormal operation after restoration of normal functioning.

In case of failure of *sublevel 1* or in case of initiating events not allowing to keep the facilities coupled (bypass of sub-level 1) without triggering the safety systems of level 3 (does not reach the objectives of level 2 of DID), *sublevel 2* is proposed :

- uncoupling of the whole IS plant (overall coupling on Fig. 2) ;
- normal shutdown of the H_2 units of HYPP ;
- alternative energy sink for the VHTR (cold source and/or dedicated turbine).

In case of failure of *sub-level 1 and 2* and/or in case of more severe initiating events leading to bypass upstream sub-levels, the control of the abnormal operation of the coupled facilities fails and the consequences of this failure must be mitigated. Consequently, the VHTR has to be shutdown in order to prevent degradation of the incidental situation into an accident. Then, the so-called *sublevel 3* comes into play :

- normal shut down of the VHTR ;
- if possible, normal stopping of the HYPP to avoid emergency shutdown inducing sudden transient, subsequent cleaning of the facility and loss of a part or totality of reactants.

5.2. Control of abnormal operation occurring in the HTR

Taken into account the robustness of the VHTR, particularly regarding the stability of the core outlet temperature, at least in stationary full power operation, if a thermal disturbance occurs in the VHTR cooling system, its magnitude and its kinetics should be compatible with the inlet temperature range of the HYPP which will be certainly less demanding that of the VHTR. However, provisions have to be foreseen to control a temperature instability on the reactor side, in order to not exceed the threshold of the emergency shut down of the HYPP and nor induce an accident. Such provisions could, among others, consist in Helium temperature regulation loop derived from the ternary Helium circuit.

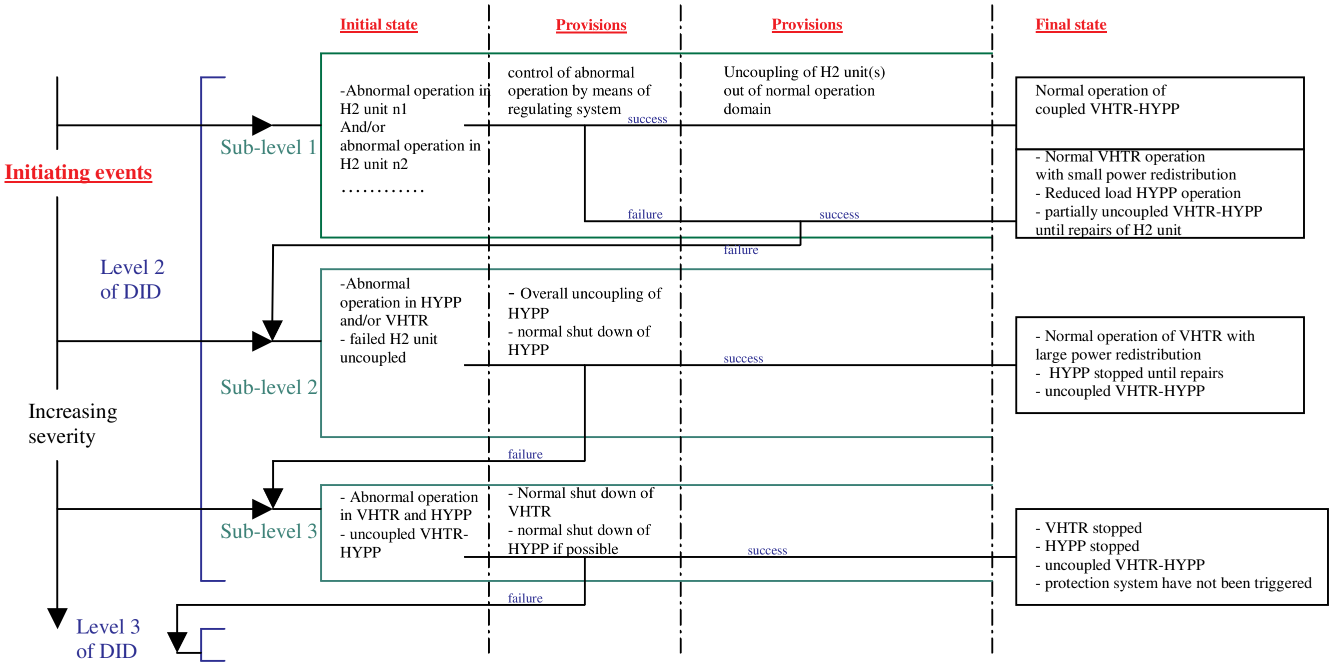


Figure 5. Illustration of provisions of level 2 of DID to control abnormal operations initiated by HYPP

6. CONTROL OF THE PROGRESSION OF ACCIDENTS AND LIMITATION OF THEIR CONSEQUENCES (LEVEL 3 OF DID)

Despite the provisions resulting from the two upstream levels of the DID, at this level, it is supposed that accidents can occur (in nuclear safety, they could be defined as triggers of safety systems). Basically, the kind of accidents considered here should be controlled within the design basis conditions and, therefore, should not induce large leakages through the last physical barriers nor explosions/fires being likely to aggress significantly the HYPP or the VHTR. The latter accidents will be treated at the level 4. The third level is aimed to control the accidents and to reach a safe state of the facility, that is, a state permitting to fulfill durably the safety functions defined at paragraph 3.3.1. By the way, the safe states of the facilities correspond to an uncoupled state that permit to insure independently the safety functions of each facility. The definition and the means for reaching this safe withdrawal state will have to be specified at a more advanced stage of the design.

6.1. Provisions and systems devoted to the fulfillment of safety functions

The control of the nuclear and chemical reactivity in case of accidents is insured by the emergency shutdown systems. For the VHTR, it mainly consists in the control rods insertion whereas in the HYPP, it consists in the cutoff of the chemical reactors feeding and of the heating and where necessary, in the inerting of parts of the H_2 units. The safety function devoted to the thermal power extraction from the HYPP is directly linked to the control of the chemical reactivity because the kinetics of chemical reactions increases with the temperature. As a result, there is a feed back between these two safety functions showing the importance of their simultaneous fulfillment by independent provisions. As far as the power extraction is concerned, the VHTR is equipped with radiative screens capable to passively evacuate the residual power [5] and the HYPP can be cooled by emergency systems, water streaming on equipments, spraying systems, in case of chemical reaction runaway, internal or external fire and hazardous leakage resulting from a small breach in an equipment. The extraction of the mechanical power has an influence on the chemical reactivity as well, by controlling the pressure (and thus the chemical equilibrium and the temperature) in the HYPP components. Provisions like safety valves, expansion tanks, flarestacks, can be foreseen in order to release the pressure, thus avoiding the failure of equipments due to excessive mechanical solicitations. Finally, the confining safety function is expected to be fulfilled by means of successive barriers that are protected by the two other safety functions. However, the confinement can also be obtained by dynamic ways (overpressure outside from a barrier or leakage rate compensating) or by systems permitting to insulate leaking pipes in the HYPP. Furthermore, the last containment has to be protected from internal solicitations and possible environmental aggressions (air crash, extreme meteorogical conditions, earthquakes) thanks to provisions regarding their design.

A particular attention has to be paid to the coupling system in itself because it consists in an extension of barriers, confining hazardous materials. It avoids their transfer towards the atmosphere and from one facility to the other one. The heat exchanger (IHXs) walls and the uncoupling gates (overall and partial coupling) are among these physical barriers. Beyond the confinement function, the coupling system also permits to indirectly insure the two other safety functions (VHTR/HYPP interfacial control, regulation of parameters and corrective actions permitting to control reactivity and to extract power). Consequently, the coupling system plays a role in the whole safety architecture of the VHTR/HYPP facility by contributing to the safety functions and also by intervening at least in levels from 1 to 3 of DID. Therefore, the design of this system has to include redundancies and high reliability equipments (nuclear materials classification could be used) because it is the central point of the safety of the facility and it must not induce a breach in the DID.

6.2. Accidents relating to level 3 of DID, prevention and protection measures

The main accidents considered at this level are listed below (this list is not yet exhaustive) :

- the loss of electric supply or other support systems (secondary products evacuation, pneumatic systems) ;
- coupling system failure or rupture as an accident initiator ;
- design basis accident in the VHTR ;
- equipment failure in the HYPP without external leakage ;
- limited leakages without ignition in the HYPP ;
- simultaneous rupture of IHX1 and IHX2 eventually initiated by a breach (detailed in paragraph 6.3).

The prevention measures to control the accident consists in the triggering of emergency shutdown systems in VHTR and in HYPP associated to the overall decoupling of the facilities. These actions constitute the first steps required to reach a safe state for both facilities. Theoretically, if an accident occurs in the HYPP, without significant leakage nor ignition, the emergency shutdown of the units not affected by the accident is not mandatory. Regarding, the loss of station or other support systems, redundancies and emergency systems have to be foreseen. Regarding the prevention of ignition of flammable/explosible gases in case of limited leakage, a lot of efforts are required in terms of early detection and classification of materials for explosive atmospheres.

6.3. Particular case of cumulated rupture of IHX1 and IHX2

A depressurizing wave in He circuits could induce a rupture of IHXs because a pressure difference exceeding several bars between the two fluids of IHXs, would not be tolerated at their operating temperature. Thus, rupture of IHXs could be initiated by a breach in the primary or secondary circuits of VHTR in the containment (breaches A or A' on Fig. 6). In this case, hazardous substances (corrosive and flammable/explosible) could enter the containment if the emergency insulation gates of the coupling system do not operate correctly. Similarly, in case of IHXs rupture without a breach (depressurization wave in

HYPP following an equipment failure for example), radioactive materials could enter the HYPP. If this depressurization results from a breach in a pipe downstream of IHX2 (B or B' on Fig. 6) hazardous releases (radiological and chemical) could occur. Depending on the amount released by B or B', on the VHTR containment and on coupling system states, these accidents can degenerate in severe accidents.

IHXs rupture accidents can be controlled thanks to the emergency insulation gates of the coupling system (preferentially independent from normal operating gates). However, the probability and the consequences of these accidents will have to be assessed, because they will certainly be dimensioning accidents of the VHTR/HYPP facilities. In particular, if plausible, the possibility of a combustion in the containment has to be investigated. At the end, such studies will contribute to reliability and performance requirements for IHXs (number of plates allowed to be broken), for uncoupling system, for systems devoted to balance the pressure across the IHXs walls and for containment. In order to prevent the formation of a flammable atmosphere (if conceivable) in accidents considering at the level 3 of DID, inerting system can be implanted in the containment. Attention must also be paid to possible ignition sources in order to reduce combustion probability if a flammable mixture is formed despite the inerting provisions.

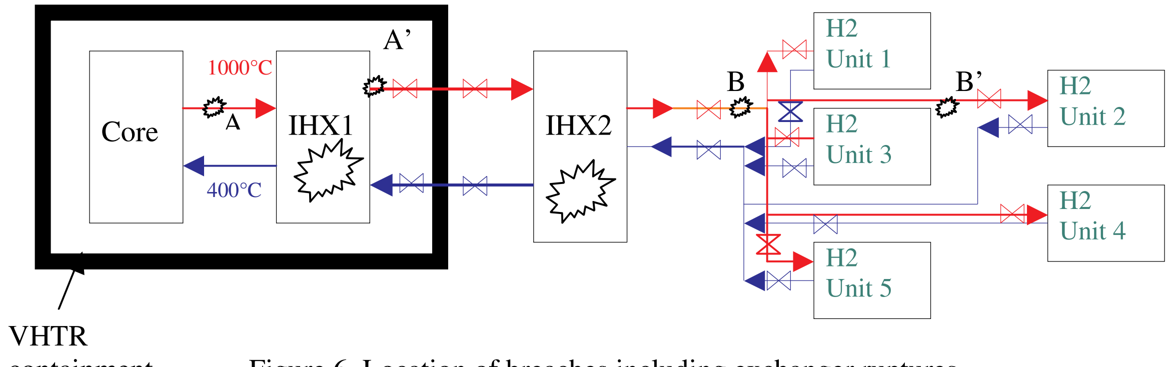


Figure 6. Location of breaches including exchanger ruptures

7. CONTROL OF SEVERE PLANT CONDITIONS, MITIGATION OF SEVERE ACCIDENTS CONSEQUENCES (LEVEL 4 OF DID)

In spite of upstream levels, severe accidents are considered at level 4 ; it results from low probability sequences including multiple failures. Complementary provisions aiming to limit the consequences of such accidents are provided, especially regarding the integrity of the last confinement barrier (containment for VHTR, last wall and safety distances for HYPP). At this level, provisions are also proposed in order to prevent and to mitigate possible "dominoes effects" due to the proximity of the two facilities and of the different units of HYPP (Fig. 7). It should be noticed that the beyond design accidents of VHTR are not investigated here, except when they play a role in the safety of the coupling of VHTR and HYPP. Basically, at this preliminary stage of the safety approach, only the aggressions from the HYPP towards the VHTR are considered, as well as, the scenarios including the by-pass or the leak of the VHTR containment.

7.1. Hypothetical severe accident scenarios

In order to assess the potential aggressions of the VHTR resulting from an accident in the HYPP, the consequences of major accident scenarios postulated in the HYPP have to be assessed (in danger study). The relevance of these scenarios regarding VHTR aggression has to be checked, because the "envelope" accidents are not necessarily the same for out-site consequences as for VHTR aggressions. As an illustration, the toxic consequences of a sulfur dioxide release could impose the larger safety distance regarding the environment, whereas a conservative scenario could be a hydrogen deflagration regarding the VHTR aggressions. Conversely, it does not mean that a toxic or corrosive release is not to consider as an aggression towards the VHTR, because it could induce intoxication of the personal of the control room of the reactor or a degradation of the confinement properties of the containment. The pressure wave generated by the combustion of an explosible gas cloud in the HYPP, as well as, the thermal flux emitted by a large fire in the

HYPP (Breach A on Fig. 7) or by a BLEVE (Boiling Liquid Expanding Vapor Explosion) of the larger hydrogen capacity (if stored on-site) consists a priori in the main causes of VHTR aggressions by HYPP. Despite their expected low probabilities, accidents cumulated to a failure and/or a rupture of the coupling system are also considered here. Basically, this kind of accident would lead to a containment bypass (radioactive releases) in case of breach outside of the containment (Breach B on Fig. 7) combined to a rupture of IHX1. IHXs rupture without breach B, would induce transfer of fission product in the HYPP. IHXs rupture combined with a breach of the reactor cooling system in the containment (breach C on Fig. 7) would lead to a transfer of combustible gases and/or corrosive vapors in the containment (sulfuric acid). If this acid reacts with metals within the containment, it will form hydrogen. This type of accident can threat the containment integrity if combustible/explosible atmosphere is ignited.

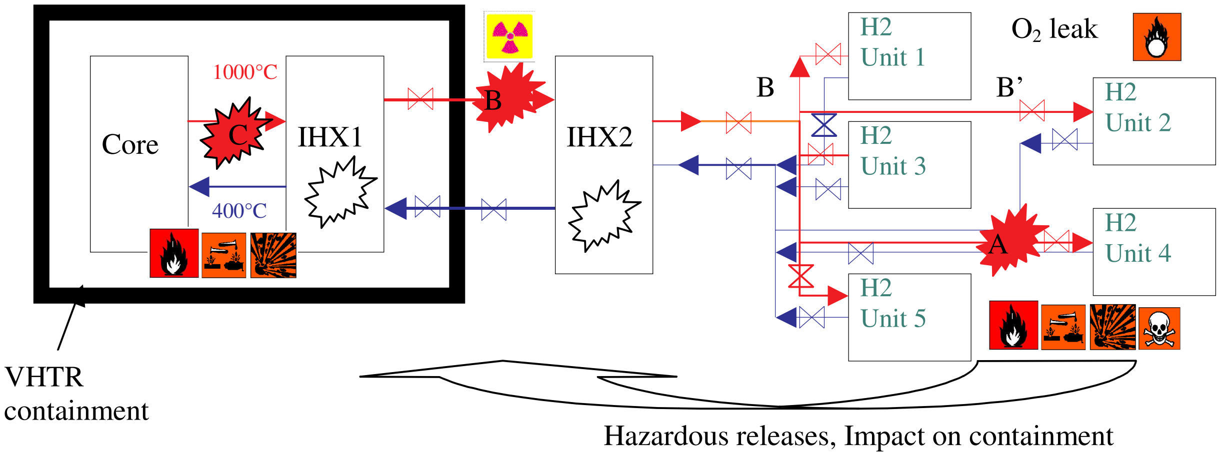


Figure 7. Schematic of hypothetic severe accidents consequences

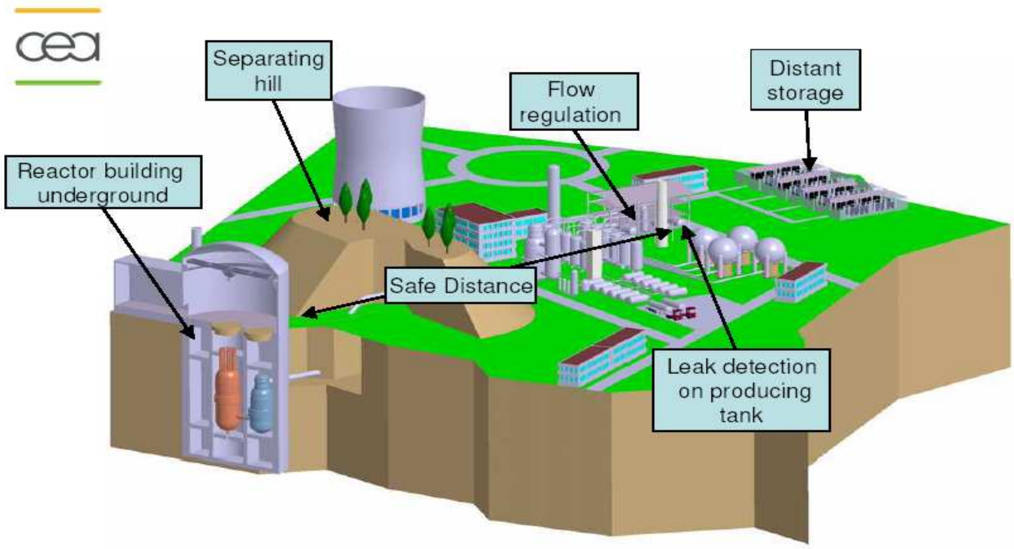


Figure 8. Possible provisions to mitigate pressure wave aggression on VHTR

7.2. Provisions for severe accidents prevention and mitigation of their consequences

Studies of hypothetical severe accidents will permit to verify (considering their calculated consequences) if their estimated occurrence frequencies are low enough to fulfill safety objectives of the VHTR/HYPP facilities. Especially, the containment resistance to an explosion wave must be evaluated in order to size it appropriately (best-estimate CFD approach less pessimistic than TNT equivalent approach could be use if necessary). These studies should contribute to prevent this kind of accidents by complementary measures (added to those of level 3) and should also permit to limit their consequences by relevant provisions like (Fig. 8) :

- reduction of energetic ignition sources (risk of fast combustion regime) ;
- absence of confinement and of obstacles (pipe agglomerate) to avoid flame acceleration and DDT ;
- inerting or igniting systems in confinement ;
- events systems, physical barriers between the VHTR and the HYPP, deflectors, reasonable safety distance ;
- possible grounding of the coupling system and/or the VHTR ;
- training of rescue teams and emergency means optimization ;

8. MITIGATION OF RADIOLOGICAL AND CHEMICAL CONSEQUENCES OF MAJOR ACCIDENTS, OFF-SITE EMERGENCY RESPONSE (LEVEL 5 OF DID)

This last level deals with emergency plans foreseen to insure the ultimate protection of population. Considering the stage of the project, these aspects will not be treated in this paper but subsequently.

9. CONCLUSION

A methodology based on the defence in depth (DID) concept has been proposed in order to reach a safety level compatible with the operating of a nuclear reactor (VHTR) coupled with a Hydrogen production plant (HYPP) by thermochemical split of water. By implementing different levels of DID, safety constraints related to the design of the HYPP and to its coupling it with a VHTR have been analyzed. Preliminary provisions resulting from this analyze have been presented in this paper. These provisions are aimed to fulfill the safety functions (proposed here for the whole coupled facility) and to protect the various barriers permitting to confine hazardous materials, especially the reactor containment. Finally, the analysis performed has shown the importance of the coupling system of the facilities, which would permit to prevent and to mitigate a large part of conceivable accidents. By the way, this system plays a role in different levels of DID, thus underlining the effort to be done (reliability, performance, redundancies, system protection) to insure that this system would correctly accomplish its expected mission, in case of incident or accident in the HYPP/VHTR facilities.

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