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BIBLIOGRAPHIC REVIEW OF THE COMPUTER CODES AND EXPERIMENTS DEALING WITH STEAM EXPLOSION IN EUROPE

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Abstract.

Since the Three Mile Island accident in 1979, steam explosion has been considered as a potential risk for PWR nuclear power plants because it might lead to potentially catastrophic environmental consequences caused by an early and massive containment failure. Assuming that a loss of coolant caused a degradation of the core and its melting, a large-scale steam explosion progresses through four distinct phases: the relocation of the molten fuel in the lower plenum (premixing), the triggering of the explosion, the escalation of the initial pressure pulse and the expansion phase liable to damage the structures.

In Europe, the research program concerning steam explosion is based on the understanding of the local phenomena governing the explosion by means of several complementary test-facilities such as KROTOS, ECO, MICRONIS and TREPAM. It is also based on the development of numerical computer codes able to predict globally the pressure pulse propagation like IDEMO, CULDESAC and CASTEM-PLEXUS or codes specialized in the local description of the steam explosion as MC3D and COMETA.

1 INTRODUCTION

If a hot liquid melt contacts a cooler volatile liquid, in some circumstances the energy transfer rate can be so rapid and coherent that an explosion results. Such vapour explosions are a well-known hazard in the metal-casting industry, in the transportation of liquefied natural gas over water, in the paper industry where a molten salt may contact water and it is postulated that steam explosions may occur in submarine volcanisms. They have also been studied in the nuclear industry for the past 30 years as a possible cause of radioactive release in the unlikely event of extensive core melting during a severe accident.

Since the Three Mile Island accident¹ on 28 march 1979 and the publication of the Rasmussen report known as WASH 1400, steam explosion has been considered as a potential risk for PWR nuclear power plants. Among the hypothetical severe accidents induced by a core melting, steam explosion has been intensely studied^{2,3} and is still studied for future reactors^{4,5,6} because it might lead to potentially catastrophic environmental consequences caused by an early and massive containment failure.

Assuming that the loss of coolant caused a degradation of the core and its melting, a large-scale steam explosion progresses through four distinct phases and may be followed by a slug impact^{7,8,9,10,11,12}.

Premixing¹³ The corium relocates from the core area into the lower plenum. Corium and water, which are initially separated, inter-penetrate and premix on a relatively coarse geometric scale. The jet of corium fragments under the action of hydrodynamic forces in large drops whose characteristic size is 1 cm. The thermal exchanges are limited by the presence of a stable vapor film boiling, surrounding the corium drops and by the water depletion.

Triggering^{14,15} If the vapour layer collapses in some small region of the mixture, direct liquid-liquid contact generates high heat transfer rates and a localised sharp pressure increase.

Escalation The pressure pulse can escalate and propagate through the entire mixture leading to coherent energy release. The propagating pulse collapses the vapour blanket and causes a fine scale fragmentation of the drops and intermixing of the two liquids, either by differential acceleration of the fluids or by thermal mechanisms. Both processes strongly increase the corium thermal exchange surface and allow the explosive vaporization of the water due to high energy transfers between the corium and the water.

Expansion Energy transferred from the hot melt to the cold water forms high pressure vapour which expands through the lower head. The resulting dynamic forces may reach a magnitude sufficient enough to damage the surrounding structures or fail the lower head vessel.

Slug acceleration¹⁶ At the same time, the interaction zone expands against the core support plate, accelerating upwards all the materials above the explosion zone. During this process, the mechanical energy of the explosion is transformed into kinetic energy for the slug.

The slug may be energetic enough to crush and fail the upper structures. The mixture of slug and upper structure pieces may hit the upper head vessel.

The impact may fail the upper head or part of it and thus create missiles, flung upwards thanks to the remaining energy.

Impact on the containment If the missile are not resisted by shields or massive obstacles, they might be hurled against the containment roof and penetrate or seriously damage it. This scenario would lead to an α -mode failure.

The potential risks due to an α -mode accident are globally quantified through Probabilistic Safety Assessment studies^{7,17,18}. These studies are based on the understanding and the evaluation of each key event thanks to the realisation of small and medium scale experiments and the development of numerical models and codes.

In Europe, several research centers have been working on steam explosion for several years. The whole work has been organized so as to share out the study set necessary to fully understand the matter between the different research centers and countries and to pool the final knowledge.

The European research program is divided into three main themes: the premixing phase, the steam explosion and the slug impact. For each issue, test-facilities and numerical computations have been realised. This paper comprises a review of the test-facilities and codes available in the last years and at the present time in Europe for steam explosion.

2 GENERAL DESCRIPTION OF THE EUROPEAN RESEARCH PROGRAM

The steam explosion concerns the step of large vaporization of the water heated by the hot corium what leads to the escalation and propagation of a pressure wave through the PWR lower head. In turn this pressure wave can damage seriously the internal structures and the vessel itself.

This subject has been studied in the European nuclear research centers for many years because the potential rupture of the lower head vessel, owing to the overpressures involved in the accident, would probably cause a release of radioactive primary water in the containment. That contamination of the building would impose a definite stop of the plant and drastic safety rules to avoid a contamination of the environment.

The numerical studies concerning steam explosion can be divided into two approaches. In the first approach, because of the lack of experimental precise data to validate sophisticated tools, steam explosion has been considered from the point of view of a pressure wave propagation. The old codes could only predict steady-state propagation like the 1D steady-state code developed at IKE in Germany.

Then the codes were able to compute the escalation, propagation and decay of a pressure wave; this generation of codes has concerned the 1D transient code IDEMO developed at IKE in Germany and the 1D code CULDESAC developed by the Culham Laboratory in England.

The next generation of computations is represented by the code CASTEM-PLEXUS developed by the CEA-Saclay in France: the code can predict all the steps of the pressure propagation as well as the mechanical effects of the explosion on the structures thanks to fluid-structure coupling. Moreover, a linkage with the premixing module of the french thermalhydraulic code MC3D allows precise evaluation of the steam explosion propagation and of the mechanical response of the structures

The second approach is based on the understanding of the local phenomena governing the vapour explosion. The studies started many years ago with experiments and code developments relative to the premixing phase preceding the steam explosion.

More recently, several experimental devices have been settled to provide reliable data on the explosion itself and its consequences: the explosion escalation has been studied with the test-facilities KROTOS of the european research centre JRC-Ispra, the mechanical effects of the explosion are investigated by the german mock-ups ECO at FZK, the thermal transfers between corium debris and water and the thermal and hydrodynamical fragmentation processes are going to be investigated by the french experiments TREPAM and MICRONIS of the CEA-Grenoble.

In parallel, numerical tools are being developed in order to be able to compute the fuel-coolant interaction from the beginning (premixing) to the end (explosion): MC3D at the CEA-Grenoble in France and COMETA at JRC-Ispra. These codes have been essentially validated on results issued from KROTOS.

The next chapters describe the specificities of each experiment and code, the evolution of its development and capacities up to now and the main applications.

3 Test-facility KROTOS

The KROTOS experiment aims at providing benchmark data to examine the effect of fuel/coolant initial conditions in well-controlled geometries on premixing and explosion energetics¹⁹.

The experimental set-up²⁰ consists of a radiation furnace, a release tube and a test section below (Figure 1).

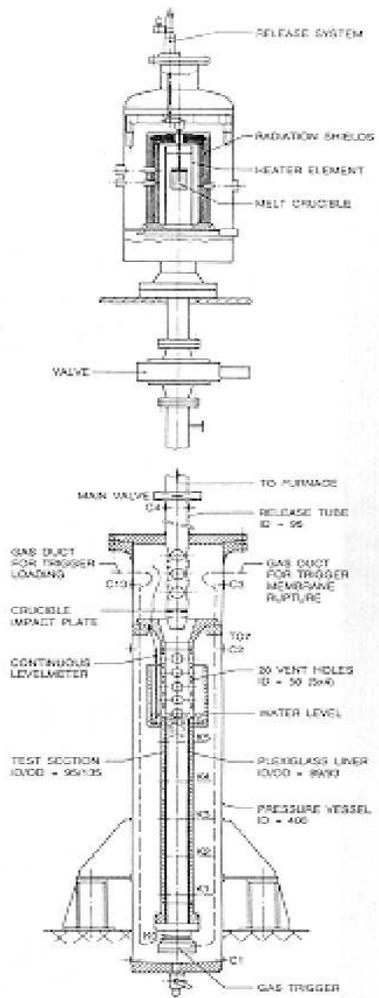


Figure 1: Test-facility KROTOS

The furnace comprises a cylindrical heater element, surrounded by radiation shields to reduce heat losses and covered by a bell-shaped lid designed to withstand a little over-pressure. The furnace encloses a crucible containing the melt material. Melt masses in the range of about 1 to 10 kg can be used at a maximum achievable temperature of the order of 3273 K.

Having reached the desired melt temperature, the crucible is released from the furnace and drops by gravity through a long tube until it impacts onto a retainer ring, at the end of the tube, where a conical-shaped puncher breaks the crucible bottom thus allowing the melt to pour out. During its fall, the crucible has cut a copper wire generating the zero time signal for the data acquisition.

The exit of the melt can be delayed by some hundreds of milliseconds by a sacrificial disk which has to be molten by the melt itself. Then the melt is released by gravity through a funnel defining the melt jet diameter.

The lower part of the KROTOS facility consists of a cylindrical pressure vessel and test section, both made of stainless steel. A test tube, containing water at variable heights, is fixed inside the pressure vessel. Two test sections of different diameter were tested²¹. To minimise the risk of an early steam explosion, the test tube can be provided with a thick plexiglass tube, thus avoiding direct contact between the melt and the wall of the test section.

At the upper part of the test tube, holes allow the steam produced to be released into the pressure vessel volume. The bottom of the test sections can be closed by either a flat plate or a gas trigger device²². When the melt penetrates down into the lower region of the test tube, the membrane closing the gas chamber is destroyed, generating a pressure pulse which propagates vertically upwards.

Pressures, temperatures and water level swell are the main experimental parameters measured during the melt coolant interaction. The test-facility is instrumented with pressure transducers in the test tube, in the gas trigger and in the cover gas atmosphere. Thermocouples are placed in the test tube, in the cover gas and just below the funnel releasing the melt in order to detect the position of the melt jet leading edge during its penetration into water. Level meters measure the level swell during the premixing phase.

Extra sensors are added in the upper part of the test section to detect the beginning and the duration of the melt release from the crucible. The data acquisition system consists of several transient data recorders. At the end of the experiment, the particle size and shape of the debris are observed.

Several tests were realised with alumina and corium melts from different initial conditions²³. The main differences between the tests consisted in the water conditions (water height and initial temperature), fuel released mass, presence or not of a trigger device, presence or not of the sacrificial disk above the funnel, diameter of the test tube, thickness and presence of the plexiglass liner, initial pressure...

The results can be summarized as follows: when alumina melt is poured into subcooled water at ambient pressure generated spontaneous supercritical explosions. With near-saturated water pools, the spontaneous explosions were suppressed but still produced by adding an initial trigger pulse.

For the corium, no energetic explosions were observed, even using trigger. But the pressurisation remained high in the long term maybe due to the generation of non-condensable gas (hydrogen) during the corium-water interaction²⁴. High local void fractions seemed to suppress the propagation of steam explosions and of the trigger pulse, by depleting the water from the mixing zone.

Further tests are planned to understand the process that lead to a suppression of steam explosions with corium melts. Corium tests with quantitative hydrogen measurement and tests with alumina with non-condensable gas injection will be performed.

4 Test-facility ECO

The experiment ECO has been conceived to measure energy conversion rates of triggered steam explosions under controlled conditions in a closed apparatus. The ECO facility (Figure 2) is similar in size to the PREMIX facility used for the visualisation of melt-jet penetration and steam generation in the premixing study.

Up to 20 kg of thermite can be used as melt simulant to be injected into saturated or sub-cooled water. A trigger is used to initiate the explosion.

The central body of the experiment is composed of two cylinders. The inner cylinder is fixed on the top part of a rigid frame placed above the experimental device. The outer cylinder is put on layers of crushing material, placed themselves on the bottom part of the frame. Both cylinders can slide vertically the one relatively to the other.

When the thermite is released into the cold water, water vaporizes around the thermite fragments. The trigger composed of a high-pressure gas capsule, destroys the steam film, thus initiating the explosion. The interaction zone expands downwards by crushing the crushing material.

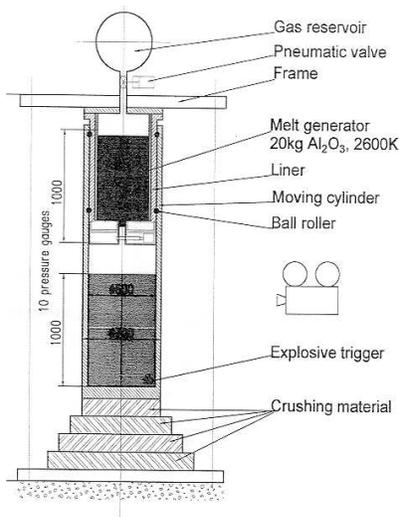


Figure 2: Test-facility ECO

The main instrumentation of the facility is composed of strain gauges to measure the vertical force exerted on the rigid frame, pressure and deflection gauges and void probes inside water. The deformation of the crushing material will be measured. A high-speed camera will record the explosion progress.

The main quantity to be determined by ECO experiments is the mechanical work W performed via kinetic energy due to the explosion. It will be calculated from the measurements by three independent methods. Compared to the total heat content Q of the melt, the energy conversion efficiency is defined as $\eta = W/Q$. The facility²⁵ is designed to measure η values from 1 % to 20 %. As the ECO experiments are just starting, there are not yet available results.

5 Test-facility TREPAM

TREPAM is a new test-facility devoted to the study of thermal transfer between corium debris and water²⁶. It consists in cooling a hot filament into cold water and to observe the thermal transfer from the filament to water. The filament is planned to have a diameter comprised between 1 and 100 μm and its temperature will be in the range 300 - 3000°C. The water conditions will be a temperature in the range 20°C to saturation and a pressure in the range 1 to 250 bar. No information is available at the present time as the experiment is just starting.

6 Test-facility MICRONIS

MICRONIS is a new test-facility dedicated to the study of thermal and hydrodynamical fragmentation²⁶. Its aim is to visualize the fragmentation and the explosion of a drop due to the passing through of a pressure wave in a water pool. The drop will be made of tin or UO_2 and its size will go from 3 to 10 mm. The measurements will concern the fragmentation duration and the size of the fragments. Three kinds of fragmentation are planned to be observed: diphasic fragmentation during the premixing stage, thermal and hydrodynamical fragmentation during the propagation of the pressure wave. No data are available as the experiment is still in project.

7 Experiments of melt fragmentation and computations of detonations with the code IDEMO

In order to understand the mechanisms of melt jet fragmentation, experiments²⁷ were performed with jets of low-melting Wood's metal in water. The jets are released, by a piston driven by compressed air, from a crucible with a siphon shaped outlet into a transparent tube filled with water. The piston velocity is recorded by a transducer and appearance of the jet is filmed by a high speed camera (Figure 3). After the tests, an analysis of the jet leading edge advance, from the high speed film, and of the debris by sieving is performed.

A large theoretical work was undertaken to model fragmentation behavior. The models are based either on deformation breakup and Taylor instability, or stripping by capillary waves induced by shear flow instabilities²⁸. The theoretical results were compared with experimental ones.

A steady-state detonation code was first developed²⁹. This one-dimensional code describes a stationary wave running through a uniform premixture. The main points considered concern the fragmentation process, the exchange terms in the multiphase description and the processes determining the formation of detonation waves. The melt fragments are assumed to be fine enough to come instantaneously into thermal equilibrium with the surrounding water which is assumed to be heated homogeneously. The steady-state code is adapted to the propagation of self sustained wave. However, trigger pulses which lead to decreasing or escalating events cannot be analysed with this modelling. The test KROTOS 21 was analysed with the steady-state code (Figure 4). The code predicted correctly the vapour production and the fragmented fraction of melt but not the pressure.

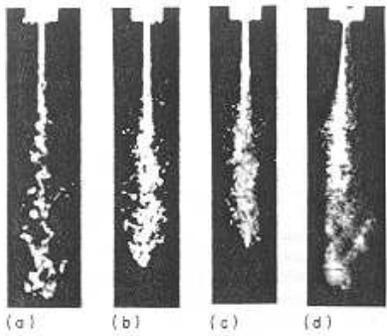


Figure 3: Fragmentation of jets at IKE

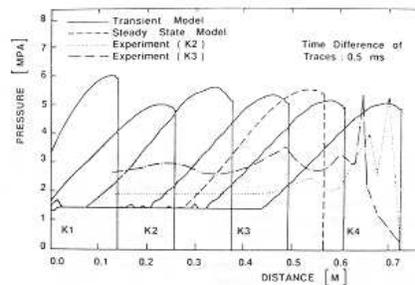


Figure 4: Computation of the test KROTOS 21 with the steady-state code of IKE

For the description of the escalation or decay of an arbitrary trigger pulse in a fuel-coolant mixture, a transient model is needed. The transient one-dimensional Eulerian thermal detonation code IDEMO describes four flow phases: melt droplets, melt fragments, steam and water³⁰. It uses the MacCormack's two-step non-centered finite difference method. The code IDEMO considers several fragmentation mechanisms: drop deformation, Taylor's instabilities or stripping of crests of shear-flow produced waves.

Assumptions of mechanical equilibrium between steam, water and melt fragments, kinematic equilibrium between debris and coolant as well as thermal equilibrium between steam and water are done. Melt and fragments are considered as incompressible. A non instantaneously heat transfer from the fragments to the coolant is uniformly attributed to the coolant phase while the drag work is divided up between coolant and fragments, thus heating both.

The usual multiphase flow equations have been applied with all species at a common pressure. Two separate momentum conservation for the heavy phase (melt drops) and the light phase (surrounding fluid) enables the calculation of different velocities. A shock fitting enables the description of the escalation and propagation of a shock wave in an explosive mixture, causing vapor collapse and establishing a flow field with three phases and two velocities behind the front. No vapor exists behind the front until the coolant reaches the saturation conditions.

The experiment KROTOS 21 was analyzed with the code IDEMO³¹. First, the simulation of the trigger itself was checked against experimental results from tests in which the KROTOS gas trigger was applied to a column of pure water. A rather good agreement was obtained for the pressure development. Then complete test was modelled (Figure 5). The results were better than with the steady-state code but some discrepancies were still observed.

Further work will include more detailed modeling of leading edge effects, the fragmentation process, non-homogeneous water heating, steam production and instability analysis. Comparisons with a larger data base are planned.

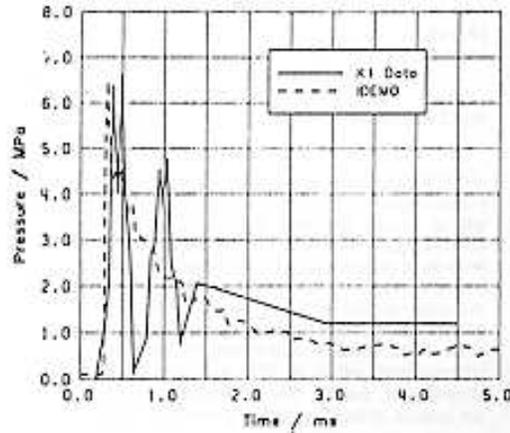


Figure 5: Computation of the test KROTOS 21 with IDEMO

8 Parametric studies about detonations with the code CULDESAC

The code CULDESAC was specially developed to examine escalation and decay of detonations as well as steady-state propagation. The model was transient and one dimensional. The code used a finite difference method employing a staggered grid arrangement. It was mainly used to carry out parametric studies to understand the influence of various parameters on the propagation of the detonations.

The first numerical model concerned a mixture of two gases, namely a burnt and an unburnt gas. It used a multi-gas formulation of the mass, momentum and energy conservation equations³². This theory is deduced from kinetic theory and is appropriate when the species can be regarded as nearly perfect gases. The model was restricted to a one-dimensional duct with constant cross-sectional area.

The following model³³ was based on the multiphase theory. A common pressure was introduced and the presence of either gaseous species was represented by volume fractions. One species could be converted into another one when a critical temperature or pressure was exceeded. The method was based on 'shock capturing', that means the equations were solved throughout the solution domain and the location of shocks was predicted by the scheme.

The governing equations described the conservation of mass, momentum, total energy, a constraint on the occupancy rates and an equation of state for each species. Viscous forces were neglected. No internal mass sources or sinks were considered. The domain was closed at both ends, so that the boundary conditions were a velocity equal to zero. An option allowed to compute a variable duct area. The model was validated on analytical results³⁴: steady shock calculation involving one gas, shock tubes containing two different gases separated by a diaphragm (weak shock or strong shock), detonations.

The next model³⁵ could treat a mixture of melt particles, water and steam. Behind the detonation front, the particles were fragmented by boundary layer stripping (Figure 6) and the water was heated by energy transfer from the fragments. The model used three components: melt droplets, melt fragments and water. Steam and water were supposed to be in thermal and mechanical equilibrium when both phases existed. The melt fragments and water were in mechanical equilibrium and had the same velocity.

The mathematical model was still based on multiphase flow equations. The effects of pressure gradient force, drag between the melt particles and an effective fluid consisting of water plus the fragments, heat transfer were described by additional terms in the conservation equations. The model also contained an additional equation for the length-scale of the melt droplets. As the melt droplets and fragments were supposed incompressible, the melt equation of state was a simple caloric one. The water was described by an approximate EOS.

To simulate triggering, some of the melt was fragmented in a small region, causing a high heat transfer rate in those cells; the pressure raised locally and the detonation wave could develop. All convective terms were modelled using upwind differencing for stability. Except the source terms treated implicitly, the code used explicit methods. The model was validated on analytical results of detonations³⁶ (steady-state weak detonations, strong ones, Chapman-Jouguet condition ones, spherical geometry, no thermal equilibrium between melt and water) and on dusty and droplet laden gases with and without droplet fragmentation³⁷. The effect of void fraction, of cross-section geometry (planar, cylindrical or spherical), of heat transfer rate were tested³⁵.

The following model³⁸ was an extension of the previous one allowing for the presence of a permanent gas in the mixture and an improved water equation of state using computerized CEGB steam tables. The model represented four components: melt droplets, melt fragments, gas and water. Besides the previous hypotheses, gas species was in mechanical equilibrium with melt fragments and water. Water, fragments and gas were assumed to have the same velocity. The effect of the gas presence was tested on the sound speed and the pressure rise.

A parameter survey^{39,40} investigates the effect of increasing the melt size particle, changing the vapour film collapse pressure or the initial ambient pressure, reducing the trigger, suppressing the heat transfer of the large melt drops, changing the grid size, the initial mixture conditions (melt volume fraction, void fraction, initial melt droplet size) and heat transfer coefficient, on the peak pressure and the detonation velocity. CULDESAC predicted that detonations could develop, albeit at different rates, for a wide range of initial conditions and parameters (Figure 7).

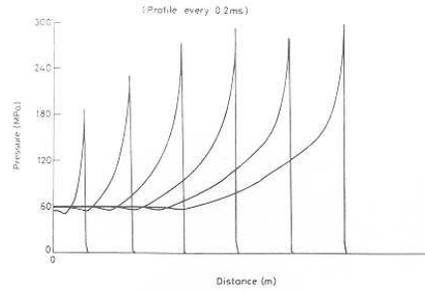
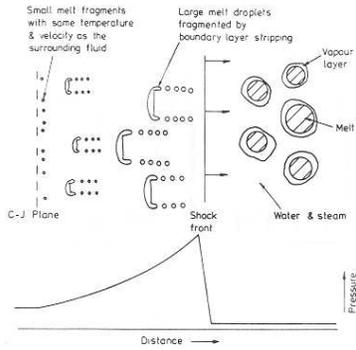


Figure 7: Example of detonation computed with

Figure 6: Modeling of the melt fragmentation with CULDESAC

The propagation of detonations in 1D inhomogeneous mixtures was investigated by introducing melt free regions into a uniform mixture (Figure 8): the detonation decayed rapidly when it left the mixture zone but was sufficiently strong to restart a new detonation when it crossed a mixture zone (Figure 9).

Later, an empirical model of fuel fragmentation was developed to simulate better the thermal fragmentation by introducing a delay between the vapour film collapse and the beginning of the fragmentation⁴¹. A study about grid refinement showed that the propagation speed was controlled by the grid size rather than the physical processes for large grids. Adding an artificial viscosity suppressed the apparition of high frequency pressure spikes leading to numerical instabilities.

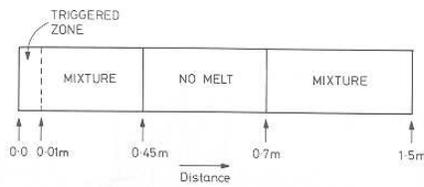


Figure 8: Model of inhomogeneous mixture

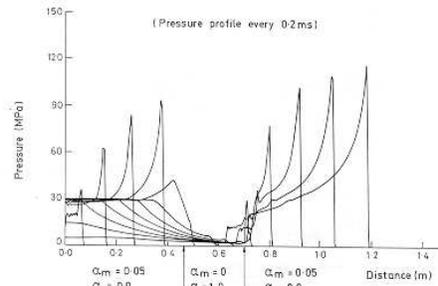


Figure 9: Computation of a detonation in an inhomogeneous mixture

The development of the code CULDESAC was stopped because the 1D models are not sufficient to represent a 3D phenomenon. The future work will concern the development of an explosion module in the code CHYMES dealing with the premixing.

9 Evaluation of the mechanical consequences of a steam explosion on the lower head vessel with the code CASTEM-PLEXUS

The computations described here aim at evaluating the resistance of the reactor pressure vessel in case of an in-vessel steam explosion. CASTEM-PLEXUS^{42,43,44} is not a code devoted to the analysis of the premixing study followed by a steam explosion. It is a general finite element software devoted to the analysis of fast transients. It can provide mechanical calculations of structures in one, two or three dimensions. Structures may be either solids or fluids, with a possibility of coupling. The main fields dealt with are impacts⁴⁵, explosions, circuits, hydrodynamics.

The formulation can be Lagrangian, Eulerian or A.L.E. (Arbitrary Lagrangian Eulerian Method) according to the kind of problem to be solved. The time integration is done with an explicit Newmark algorithm. CASTEM-PLEXUS uses the mass and energy conservation laws to calculate mass and energy flows between contiguous elements and it solves the momentum equation.

The liquid water and steam are described by a single water constitutive law including vaporization but supposing a homogeneous mixture. That means that the two phases are assumed to have the same pressure and no phase sliding.

As the corium is finely splitted up at the beginning of the explosion, it is closely mixed with water and cannot be meshed. To take into account the corium interacting with water during the explosion without modelling it, the corium is represented by a zone containing only water and where energy is injected. It is described through its thermal exchanges with water.

The code was used to predict the mechanical response of the PWR lower head in case of a large-scale steam explosion. In a first time, the initial parameters needed to describe the explosion were not precisely known. So they were estimated roughly and parametric studies were carried out to assess the influence of these parameters on the lower head response^{46,47,48}.

The parameters considered were: two locations and shapes of the corium zone, three energy injection kinetics to model the thermal transfer from corium to water, several amounts of transferred energy and two water constitutive laws. A large set of computations was performed with CASTEM-PLEXUS and the vapour explosion was analyzed throughout its progression.

The parametric study showed that the vessel response was strongly influenced by the corium location - which determind the possibility for the pressure wave to expand ot the confinement in a small area of an overpressure - and by the amount of energy transferred by the corium to the water - what governs the explosion power. The figures 10 and 11 represent the propagation of the pressure wave through water and the vessel displacements.

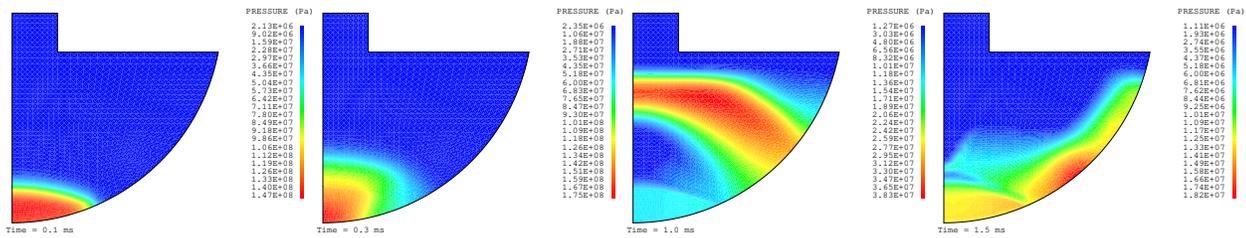


Figure 10: Computation of the pressure with CASTEM-PLEXUS

In a second step, the french thermalhydraulic code MC3D, developed by the CEA Grenoble, was used to compute the premixing phase preceding the explosion and initialize the steam explosion computations with the code CASTEM-PLEXUS. MC3D could predict accurately the location and the thermodynamic characteristics of the corium and the water from the falling down of the corium jet into the water pool until the end of the premixing. At the instant corresponding to the most probable configuration for the beginning of the explosion, the results of MC3D were transferred into CASTEM-PLEXUS (Figure 12). The main difference with previous approaches is that the mechanical effects of the explosion are dealt with local data⁴⁹.

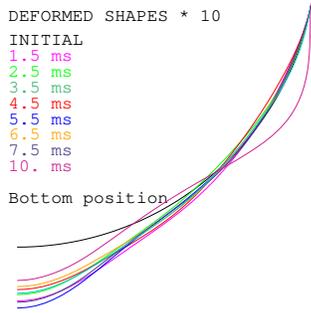


Figure 11: Computation of the deformed shape of the vessel with CASTEM-PLEXUS

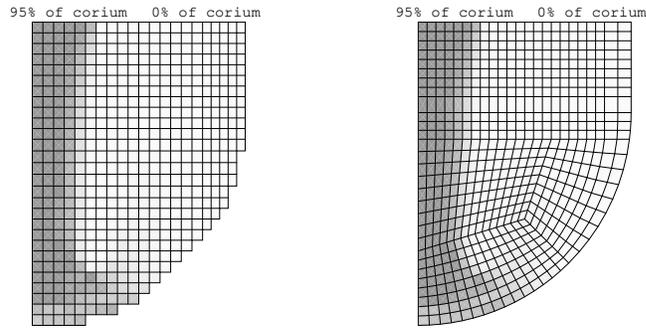


Figure 12: Linkage of the codes MC3D and CASTEM-PLEXUS

Because of the progresses in the development of the code MC3D which is now able to deal at once with the premixing and the steam explosion, these linked computations at the end of the premixing are going to be abandoned. They will probably be replaced by a new linkage at the end of the steam explosion computations: the thermohydraulic phenomena will be computed by MC3D and the mechanical response of the vessel by CASTEM-PLEXUS.

10 Escalation and propagation of steam explosions with the explosion module of the code MC3D

MC3D is a three-dimensional, multi-component, semi-implicit, Eulerian computer code⁵⁰. Its purpose is to model fuel-coolant interaction from the beginning (the premixing of fuel drops with water) to the end (the fragmentation into small fuel droplets and the escalation and propagation of the steam explosion). MC3D possesses a common kernel (including solvers, input, output...) and several modules written to model particular problems.

The explosion module of MC3D⁵¹ is dedicated to model the fine fragmentation phase and the explosion. The code models four fields: liquid coolant, vapor, fuel drops and fuel fragments. The code distinguishes the small fuel fragments from the large fuel drops because the heat transfer process with water is different for both kinds of fuel.

For each field, the code solves a mass equation, a momentum equation for each of the three directions and an energy equation. An additional volume conservation completes the equation set. Pressures can be either subcritical or supercritical.

The mass equations account for two fuel fragmentation mechanisms:

- The thermal fragmentation is caused by the destabilization of the vapor film surrounding the fuel drops, which is induced by the pressure wave. This fragmentation process can only occur when the liquid is continuous and when the pressure is subcritical. It has a great influence at the beginning of the explosion when the velocities are weak and when the pressure increases rapidly.
- The hydrodynamic fragmentation is induced by the velocity difference between the fuel drops and the coolant. This mechanism occurs when the fluids are accelerated by the pressure wave. This is the only fragmentation mechanism for the super-critical pressures.

The momentum equations contain interfacial friction terms. Four models of friction forces are used according to the flow regime: Stokes, viscous, distorted particle or churn turbulent regime.

In the energy equations, heat transfer is assumed to be effective from one fluid to another, except between the liquid coolant and the vapor, where the interface is supposed to be at saturation. The code models convective, conductive and radiative heat transfers. The heat transfer coefficients are different when the pressure is subcritical or super-critical.

The equations of state⁵² of the water are either the equations used in the code CATHARE until the critical pressure or equations built on the steam tables⁵³ which are still valid in the super-critical region. The equations of state of the fuel take into account the latent heat of solidification, the liquid and solid heat capacities and the liquid and solid densities.

The ability of MC3D to perform calculations of the propagation of a shock wave was first tested. The test consisted of a shock tube closed at both ends and divided in the middle by a diaphragm. One section was filled with a high-pressure mixture of argon and water and the other with a low pressure mixture. The computations were isothermal and homogeneous. The liquid was assumed non compressible and the gas perfect. The propagation of the shock wave into the low pressure section and of the rarefaction wave into the high pressure one was compared with the analytic solution in 1D and 2D.

Then, 1D calculations were carried out on a closed tube containing a mixture of water, steam and fuel drops (Figure 13). The initial conditions and the geometry were those described for the code CULDESAC⁵⁴. Besides, these computations tested the influence of the fragmentation mechanisms. The explosion was triggered at one end by a small over-pressure. The results showed that the pressure increased more with both thermal and hydrodynamic fragmentation processes than with the thermal one alone, that the pressurization was more rapid at the beginning and the pressure increase lower than Fletcher's simulation.

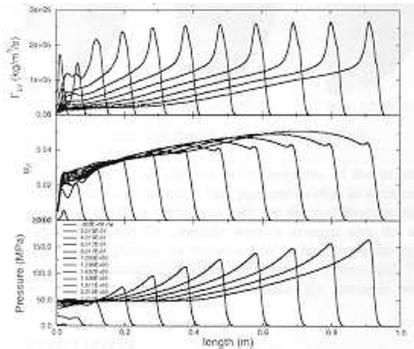


Figure 13: Computation of steam explosion in a shock tube with MC3D

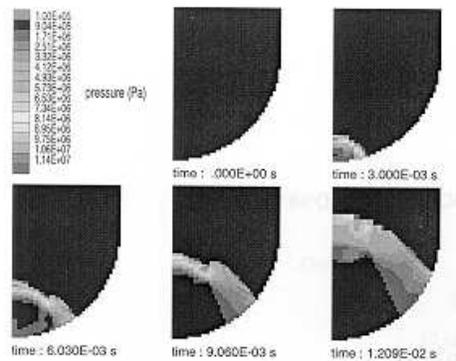


Figure 14: Computation of steam explosion in a lower plenum with MC3D

A propagation calculation of a steam explosion was performed in the lower plenum of a PWR with a 2D axisymmetric geometry (Figure 14). The initial conditions roughly corresponded to a jet corium falling from the core through the lower plenum and touching the bottom of the vessel, triggering the explosion. The computations were realised with the thermal fragmentation mechanism only.

In order to qualify the explosion module on experimental results, computations of the KROTOS test 21 with tin and water were performed in 1D and 2D. In 1D, the calculations involved two initial uniform steam volume fractions and initial fuel drops of 1 cm diameter. The first cell represented the gas chamber and the two last ones the gas blanket above the free surface. The numerical results were compared to the experimental ones for the pressure wave increase and the celerity of the propagation. The 2D computations with an axisymmetric geometry matched better the experimental pressure (Figure 15).

The current work concerns the improvement of the numerical model: especially the thermal fragmentation model. The transient heat transfer coefficients from fragments to liquid are presently parametric and will be replaced by deterministic physical laws. Then the explosion module of MC3D will have to be validated.

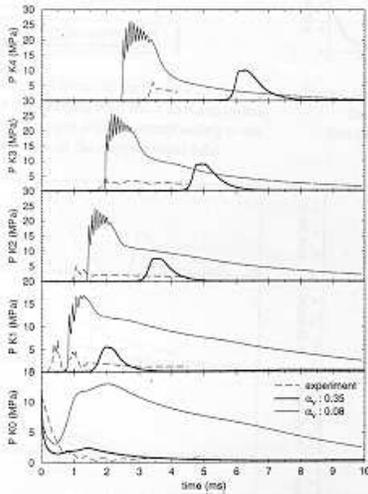


Figure 15: Computation of the test KROTOS 21 with MC3D

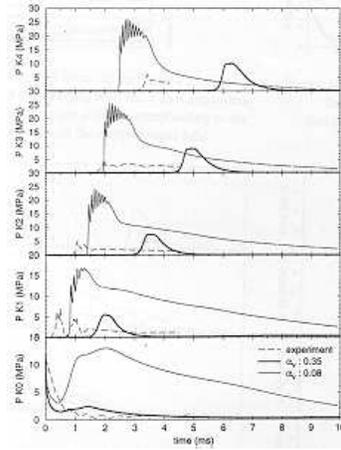


Figure 16: Computations of the test KROTOS 45 with COMETA

11 Computations of the KROTOS tests with the code COMETA

The code COMETA (COre MELt Thermalhydraulic Analysis) is a coupled thermalhydraulic and fuel fragmentation code conceived for the simulation of fuel coolant interaction and quenching as represented in the FARO test facility. Although COMETA was not developed to model energetic fuel coolant interactions as configured in KROTOS, some scoping calculations were performed.

The code is composed of a two-phase flow field which is described by $6 + n$ equations (mass, momentum and energy for each phase and n mass conservation equations for n non condensable gases) and a corium field with three phases: the jet, the droplets and the debris. The two-phase field^{55,56} is described in Eulerian while the corium field in Lagrangian coordinates.

The fuel is released in the form of a coherent jet which is conical shaped with a wavy and rough surface. Three models⁵⁷ for jet fragmentation and fragment creation are included in the original COMETA model based on the jet break-up length concept, the Corradini-Tang model similar to the model present in the TEXAS code and the IKEJET model developed by Bürger.

As a first step, the stability of the code to fast transients was checked against specific characterization tests⁵⁸. The threshold for the initiation of an explosive interaction in COMETA is based on a cell pressurization rate: when the defined value is attained, the melt present in the concerned cell is fragmented into fine particles with a consequent increase of heat transfer and steam generation rate, increase of pressurization which eventually propagates to adjacent cells and the interaction escalates similar to chain reactions.

This was basically an hydraulic test (no melt was used) with a test section filled with water. Upon rupture of the trigger membrane, the trigger pulse propagated through the test section. The agreement between test results and calculation was good.

Some KROTOS test cases were analysed with the aim to characterize void condition as influenced by hydrogen generation (Figure 16). Calculations with saturated and subcooled conditions were performed with the COMETA jet fragmentation model and with and without the hydrogen generation model. The KROTOS tests 45 and 37 were simulated. With the hydrogen generation model, the experimental results were considerably better reproduced. The conclusions of these computations were that hydrogen generation in case of the intercation of UO_2/ZrO_2 melts could be a significant contributor to void formation and could thus inhibit pressure wave propagation and an eventual energetic escalation.

In order to ascertain KROTOS test conditions which would be favorable to UO_2/ZrO_2 explosive interactions, a parametric analysis was carried out with COMETA. The analysis spanned over a range of variations with respect to injected mass, discharge orifice, initial pressure and trigger time.

The code COMETA is being upgraded according to the FCI test requirements and extended to 3D for calculating reactor cases. Improvements are in progress concerning the chemical reaction kinetics during FCI and concerning the numerical schemes⁵⁸.

The american code TEXAS was used to simulate the fuel-coolant interaction during its mixing, triggering and explosion phases. To simulate the KROTOS tests 38, 42 and 44, the coarse mixing calculation was stopped when the leading edge of the melt arrived at a particular penetration depth. After saving the output data, the computation was continued as an explosion calculation. The mechanical trigger was modeled by adding a small Eulerian cell, filled with highly pressurized steam, below the discretized mesh layout used for the coarse mixing calculation. The comparison of the TEXAS pressure predictions with experimental ones was generally good^{57,59}. Those computations also showed that fragmentation time was an important parameter of the fragmentation model.

The base-plate deformation observed in the violent explosion KROTOS test 43 was calculated with the code SEURBNUK/EURDYN⁶⁰ developed at JRC Ispra. The experimental plate was represented by a simplified axisymmetric uniformly thick plate and the six bolts by a complete annulus. The computed pressure at the center of the base plate was in good agreement with the measured one.

12 Conclusion

The investigation about steam explosion started about 20 years ago in Europe. In a first time, the research was focused on the development of 1D codes involving simple models: the steady-state code of IKE could only predict the propagation of pressure waves and the first model of the code CULDESAC concerned only perfect gases.

In a second time, the work aimed at assessing the sensitivity of the explosion escalation and propagation to different parameters. In the KROTOS test-facility, a large set of tests was realised with various environmental conditions to determine in what conditions a spontaneous or triggered steam explosion is liable to occur. Parametric computations were also carried out in 1D with the progressively improved versions of the code CULDESAC to understand the conditions necessary for the escalation or the decay of an explosion.

The third step could be characterized by the first attempts to validate the numerical tools on experimental data. The experimental results were provided by KROTOS and concerned global measurements at different levels of the test section. These experimental results were compared to the ones computed by the code IDEMO.

In parallel with this step relative to the progress in the thermohydraulic codes, mechanical aspects were dealt with the code CASTEM-PLEXUS and particularly the possibility of a reactor vessel failure in case of a high energy steam explosion. Parametric studies regarding the explosion characteristics were first performed with global initial data and then with local initial data issued from the premixing module of the code MC3D.

The current step is largely based on the acquirement of local precise data and the qualification of the codes on the experimental results. The macroscopic scale results in the thermohydraulic field provided by the KROTOS test-facility are going to be completed by the microscopic scale ones of the test-facilities TREPAM and MICRONIS. The mechanical and energetic aspects of the explosion are to be studied by the ECO test-facility.

The new generation of thermohydraulic codes specialized into steam explosion comes from the extension of the codes devoted to the premixing. The codes MC3D and COMETA were first developed for the premixing phase preceding the explosion and they were validated for many years on premixing test facility results. The models of both codes are now being extended to the explosion phase. As the development of these vapour explosion modules is very recent, the models will probably need improvements to fit better the experimental results.

Globally, the experimental program is relatively complet because the test-facilities were carefully chosen in order to get complementary information about the thermalhydraulic phenomenon. The influence of the non-condensable gases should be estimated more precisely with the acquirement of measured local data in the KROTOS experiment.

From the mechanical point of view, the measurement of the energy conversion efficiency in the ECO test-facility provides only a global information about the impact of the pressure wave due to the explosion on the structures. The experimental tools enable small-scale tests but the transposition to the reactor scale has not been investigated.

The numerical program is mainly focused on the understanding and the modelling of the physical laws governing the vaporisation process. As the current thermalhydraulic codes used for computing the steam explosion are also competent for the premixing, the link between the premixing phase and the explosion phase is optimum.

But the thermalhydraulic codes are not able to handle the mechanical aspects. Consequently the structure behaviour, under the impact of the overpressure wave caused by the explosion, has to be dealt by general codes of mechanics. The method consists in initializing the mechanical computation with data resulting from a thermalhydraulic computation. This process does not take into account the possible fluid-structure couplings, what means the influence of the structure movement on the physics of the explosion.

The link between the steam explosion and the possible acceleration of a slug is not considered even with the mechanical codes.

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