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REVIEWS OF EXPERIMENTAL STUDIES ON VARIOUS GEOMETRICAL CONTACT MODES IN VAPOR EXPLOSIONS

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Reviews of Experimental Studies on Various Geometrical Contact Modes of Vapor Explosions

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Vapor explosion or so-called energetic Fuel-Coolant Interaction (FCI) is the phenomenon in which a hot liquid rapidly releases its internal energy into a surrounding colder and more volatile liquid when these liquids come into contact with each other. Such a rapid energy release leads to excessive amounts of vapor production, within a time scale short compared to vapor expansion, causes local pressurization similar to an explosion and eventually threatens the surroundings by the subsequent expansion. Since this phenomenon has a potential to generate destructive mechanical energy release and high pressure load to the surrounding system, it has been a safety concern in nuclear power reactors as one of hypothetical severe accident scenarios as well as many industrial processes which deal with hot and cold liquids.

Vapor explosions can be classified in terms of modes of contact between the hot and cold liquids, since different contact mode may provide different characteristics of vapor explosions; the mixing conditions of the hot and cold liquids in particular. It is generally accepted that most vapor explosion phenomena fall into three different modes of contact; i.e., pouring, stratified and injection (coolant injection and melt injection) modes.

The review aims to collect the available experimental information mainly on the stratified and injection modes of vapor explosions and identify areas requiring additional research. A substantial number of works have been performed on the pouring mode of vapor explosions since the pouring mode of vapor explosions is considered to be the most predominant geometric conditions

in hypothetical severe accidents in nuclear power plants. However, other types of mode of vapor explosions are relatively less focused. Because of their different sequential progresses and mechanisms of vapor explosions especially at the initial stage of the event, it is essential to identify their mechanisms to make more clear understanding and eventually to provide a methodology for prevention in these types of vapor explosions. It has been recognized that the development of scaling methodologies in the experimental view points to bridge the experiment to prototypic conditions is of great importance under the circumstances of no relevant theoretical models in vapor explosion phenomena. In the sense, it will be useful to perform vapor explosion experiments in an experimental facility which can not only well control the initial and boundary experimental conditions, but also directly measure the energetics of vapor explosions. In particular, it is recommended to study the vapor explosion phenomena in such a facility which has additional capability of providing various contact modes to identify their mechanisms and to scale the energetics of vapor explosions in various contact modes in terms of a precisely measured conversion ratio.

Keywords: Vapor Explosions, Severe Accident, Review, Experiment, Pouring Mode,Stratified Mode, Coolant Injection Mode, Melt Injection Mode

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種々の接触モードにおける水蒸気爆発に関する実験的研究のレビュー

日本原子力研究所東海研究所原子炉安全工学部
パク　ヒョンソン・山野　憲洋・丸山　結
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（1996年10月25日受理）

水蒸気爆発、あるいは強い燃料－冷却材相互作用（ＦＣＩ）は、高温の液体が低温の揮発性の液体と接触し、急速な伝熱を生じる現象である。そのような急速な伝熱が生じると、蒸気が膨張する時間スケールより短い時間スケールの間に大量の蒸気が発生し、爆発に似た局所的な加圧が起こり、それに続く膨張により周囲に脅威をおよぼす。この現象は破壊的な機械的エネルギー放出と周囲への大きな圧力負荷を生じる可能性があるため、高温と低温の液体を扱う種々の工業において、および原子炉のシビアアクシデントシナリオのひとつとして安全性に関する問題となっている。

水蒸気爆発は高温液と低温液の接触モードによって分類できる。異なる接触モードは異なる性質の水蒸気爆発、特に高温液と低温液の混合条件において異なる現象を生じさせると考えられるからである。一般的に、ほとんどの水蒸気爆発現象は３つの接触モード、すなわち溶融物落下、層状および注入（溶融物注入及び冷却材注入）モードに分類できると認められている。

このレビューの目的は、おもに層状と注入モードの水蒸気爆発についての実験的な知見を収集し、さらに研究を必要とする分野を見つけることである。落下モードの水蒸気爆発については、原子炉のシビアアクシデントで最も重要なモードと考えられていることから、多くの研究が行われてきた。しかし他のモードの水蒸気爆発についてはあまり注目されていない。それらは現象の進展や、特に初期段階の機構が異なるため、それらの機構を明らかにすることは現象の理解を深め、やがてこれらのタイプの水蒸気爆発の防止法を提案するためにも必要である。水蒸気爆発現象については理論的なモデルが確立されていない状況においては、実験から実機条件へのスケールリングを行うために実験的な視点からスケーリング法を開発することが非常に重要と認められている。この意味で、初期及び境界条件をよく制御することができるのみならず直接機械的エネルギー放出を測定できる実験装置で水蒸気爆発実験を行うことは有効である。特に、いろいろな接触モードにおいて実験を行い、その機構を調べられる装置で水蒸気爆発研究を行い、また、いろいろな接触モードでの水蒸気爆発のエネルギー発生を正確に測定されたエネルギー変換率に基づいてスケーリングすることが望ましい。

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1.1 General

The vapor explosion is the phenomenon in which a hot liquid rapidly releases its internal energy into a surrounding colder and more volatile liquid when these liquids come into contact with each other. Such a rapid energy release leads to excessive amounts of vapor production, within a time scale short compared to vapor expansion, causes local pressurization similar to an explosion and eventually threatens the surroundings by the subsequent expansion.

For almost three decades, vapor explosion phenomenon has been intensively studied as one of hypothetical accident scenarios in the nuclear power plant. In the hypothetical case of a complete failure of normal and emergency safety systems in a nuclear reactor, the reactor core could melt due to the fission product decay heat. If the molten fuel and structural materials, so called corium, come into contact with residual water either inside or outside the reactor vessel, such a contact could result in an vapor explosion. The destructive mechanical energy release from the vapor explosion may eventually threaten the integrity of the containment and then release radioactive materials to the environment.

Since this phenomenon deals with a direct contact of hot and cold liquids, it is not only of particular interests in nuclear industry, but also in non-nuclear industries [1]; *e.g.*, molten metal-water contact in the metal-casting industry [2], LNG (Liquefied Natural Gas) spilling over water during its transportation [3], leakage of cooling water onto molten salts, "smelt", in the paper industry [4], and lava flow into sea water [5] and some experimental research facilities which may have a potential to generate hot liquid near a cold liquid reservoir.

1.2 Mechanisms of Vapor explosions

The vapor explosion is a phenomenon combining several different physical processes or phases which occur in sequence. It is commonly accepted that these phases are conceptually identified as four different phases [6]: (1) Mixing, (2) Triggering, (3) Propagation/escalation and (4) Expansion phases.

In the mixing phase, a hot liquid (melt, hereinafter) is broken down into smaller sizes due to fragmentation process as it interpenetrates a cold liquid (coolant, hereinafter) in a time scale of the order of a second. The fragmented melt drops mostly with a size of the order of 10 mm or less, are subsequently mixed with the coolant and separated from the coolant by a meta-stable vapor film which prevents significant heat transfer between the melt and coolant. It is noted that the composition of the melt, vapor and coolant in the mixing phase is considered as an initial condition of the propagation and expansion phases of vapor explosions.

In the triggering phase, if this meta-stable vapor film collapses locally due to a disturbance, very rapid heat transfer occurs due to the direct contact between the melt and coolant, and produces local high pressures due to the rapid vaporization process. This local explosion provides a trigger source to generate more melt surface area and vapor generation in the adjacent mixture. These reactions produce a spatial propagation of the explosive interaction as a shock wave passes through the melt-coolant mixture with a velocity of the order of several hundreds meter per seconds. With this shock passage in the mixture, additional fuel fragmentation and heat release occur behind the shock and reinforce the shock wave strength.

During the expansion phase, high heat transfer rates from melt to coolant produce rapid vapor volume increases and converted to a mechanical energy. Both mechanical energy and the high pressures generated eventually cause mechanical damage against the surrounding system constraint.

1.3 Modes of Contact in Vapor explosions

Vapor explosions may also be classified in terms of modes of contact between the melt and coolant, since those may directly affect each phase of vapor explosions, the mixing phase in particular. It is generally accepted that most vapor explosion phenomena fall into three different modes of contact as shown in Figure 1; *i.e.*, pouring, stratified and injection modes.

In the pouring mode, a stream of melt with relatively low velocity (mostly driven by a gravitational force) is poured into a coolant. Interpenetrating into a coolant, the stream of melt breaks into small fragments and both melt stream and its fragments are mixed with the coolant. In this mode, comparing to other modes of contact, relatively longer mixing time, mostly equivalent to the pouring time, can be provided. It allows more time for the melt to be fragmented. A relative velocity between the melt and coolant which directly affects the fragmentation process is relatively low in general compared to the injection mode of contact.

In the stratified mode, the melt and coolant exist as stratified layers since one is separated from the other due to density differences, by the vapor layer generated at the interface. Once the stratified layers are formed and a local disturbance as a trigger source is provided, the explosion propagates and escalates along the stratified interface.

The injection mode is accompanied with a relatively high speed injection and/or an orientation of the injection, such as top or bottom injections. This mode can be divided by two different types in terms of the injected liquid; the melt injection and

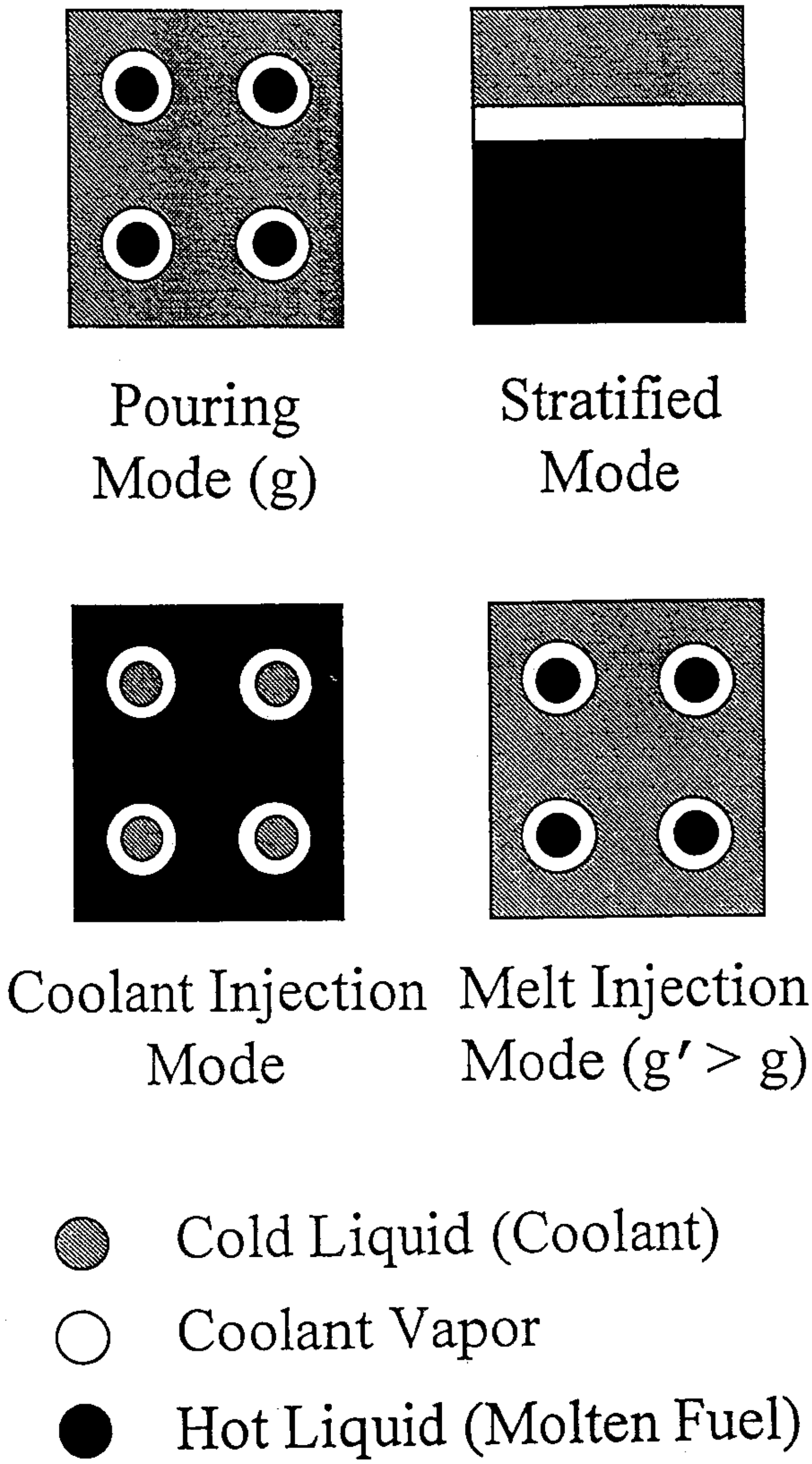

Figure 1: Conceptual Diagram for Various Contact Modes of Vapor Explosions

coolant injection modes. In the coolant injection mode, the coolant is injected into or onto the melt and can be explosively vaporized inside the melt. For the melt injection mode, however, a jet of melt is injected into a coolant with a relatively high velocity. Because of a higher velocity of injecting liquid comparing to one in a pouring mode, more fragmentation during the injection (or the mixing phase) is anticipated. In this mode, the mixing phase is often denoted as a "forced mixing phase" because of a high relative velocity between the melt and coolant.

These three modes of contact mentioned above may be anticipated in a hypothetical accident in nuclear power plants as a typical example. For the pouring mode, the molten corium drops into the residual water coolant either inside or outside the Reactor Pressure Vessel (RPV), and can result in vapor explosions. In the case of the molten fuel relocation to the cavity due to the failure of the RPV, water injection to the accumulated molten fuel has been considered as one of severe accident management methodologies for preventing a containment basement failure. Still, it is an issue whether the introduction of water causes vapor explosions or not [7]. Such a water injection may result in the coolant injection and/or stratified modes of vapor explosions at certain conditions. If the RPV is ruptured by the molten corium accumulated in the lower head region as reactor core pressure is still high, high speed molten corium will be ejected to a pool of water coolant located at the cavity. It may eventually cause the melt injection mode of vapor explosions. Recently, there is a growing safety concern related to vapor explosions in a heavy water nuclear power plant [8]. If the fuel in the pressurized tube is melted and forcibly ejected into a heavy water coolant in a CANDU type reactor, there is a possibility of melt injection mode of vapor explosions.

1.4 Scopes and Objectives

A substantial number of works have been performed on the pouring mode of vapor explosions since the pouring mode of vapor explosions is considered to be the most predominant geometric conditions in hypothetical severe accidents in nuclear power plants. However, other types of mode of vapor explosions are relatively less focused. Because of their different sequential progresses and mechanisms of vapor explosions especially at the initial stage of the event, it is essential to identify their phenomena to make more clear understanding and eventually to provide a methodology for prevention in these types of vapor explosions.

In so doing, this review aims to collect the available information mostly on the stratified and injection modes of vapor explosions and identify areas requiring additional investigation. The remainder of this paper contains reviews of (1) some selected studies for pouring mode of vapor explosions; (2) the stratified mode of vapor explosions; (3)

the injection modes of vapor explosions and ends up with (4) some conclusions and recommendations for the future work.

2 Pouring Mode of Vapor explosions

In this section, some selected experimental works related to the pouring mode of vapor explosions are briefly reviewed to provide reference information for the following reviews on other modes of vapor explosions. A substantial number of works have been conducted in this area since it is the most likely geometric conditions in accidents of nuclear as well as non-nuclear industries. Detailed reviews on this area are shown in many literatures [9, 10, 11, 12].

Three experiments, KROTOS [13, 14, 15], WFCI [16], and ALPHA [17] are selected in this review with several reasons: (1) all those experiments are well instrumented to measure the detailed characteristics of the vapor explosions and (2) they are all in a complementary relation in terms of a geometric and material scales and scopes of the experiments. For examples, they are all use different material as a melt simulant from metal to oxide and test geometry from one dimensional shock tube to three dimensional tank types.

2.1 The KROTOS Experiments at JRC-Ispra, Italy

At the European Joint Research Center (JRC) at Ispra, two different sets of experiments (KROTOS and FARO) related to severe accidents in light water reactors are being conducted. The FARO facility was designed to provide an experimental data base on the molten fuel jet and water quenching and mixing phenomena. This series of test was performed with 150 kg mass scale of corium in prototypical conditions. This test simulates the corium penetration into the water in the lower plenum of a reactor pressure vessel (RPV), the corium settlement on the bottom head of the RPV and its quenching sequence. This series of experiments, however, will not be reviewed in this report since the scopes of this test mainly concentrated on the mixing phase, providing unlikely initial conditions for vapor explosions.

The KROTOS facility shown in Figure 2 was built to obtain experimental information on vapor explosions. Several different types of simulant materials for fuel were tested, *e.g.*, tin, aluminum oxide and recently corium. In the KROTOS facility, the test section consists of the pressure vessel with an inner diameter of 0.4 m and a height of 2.2 m, to compensate the vaporization of water, and the test tube with an inner diameter of 95 mm and a height of 1.25 m placed inside the pressure vessel to measure pressures and temperatures during the explosion. Recent experiments, such as the injection modes of vapor explosions and ends up with (4) some conclusions and recommendations for the future work.

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KROTOS-37, however, used the test tube of an inner diameter of 200 mm. The melt jet with about 30 mm pouring diameter pours into the test section and triggered by a highly pressurized gas release (up to 15 MPa) at the bottom of the test tube.

The KROTOS tests can be divided by two sets in terms of fuel materials; (1) corium tests (KROTOS-32 to 37) and (2) aluminum tests (KROTOS-26 to 30 and 38 to 42). The corium test was performed five times with varying initial conditions, such as coolant subcooling, external trigger and an inner diameter of the test section. None of tests, however, produced vapor explosions. Huhtiniemi *et al.* [15] observed that without any energetic interactions the melt was fragmented into relatively fine debris (1 to 3 mm) and substantial amount of vapor (about 50) was generated. Because of strong upward steaming due to vigorous vapor generation during the pouring period, the mixing of the corium melt with the coolant was limited in the narrow test section (of 95 mm inner diameter). However, the melt was successfully introduced into the test section (of 200 mm inner diameter).

In the alumina tests, however, energetic interactions between the alumina melt and water at wide ranges of initial conditions were observed. First set of the alumina tests [13], KROTOS-26 to 30, were focused on the effects of the subcooling and external trigger on the vapor explosions in the test section with an inner diameter of 95 mm. For nearly saturated water (KROTOS-27 and KROTOS-28), the effect of an external trigger was demonstrated. The KROTOS-28 test with an external trigger of 8.5 MPa triggered explosions with a peak pressure of more than 50 MPa in contrast with the KROTOS-27 test which had no explosion but a significant amount of steam was produced. For subcooled water (40 to 80 K of subcooling), however, all tests (KROTOS-26, KROTOS-29 and KROTOS-30) with and without an external trigger, produced spontaneous explosions. The KROTOS-30 test, for example, spontaneous explosion with a peak pressure of greater than 100 MPa occurred and extremely fine debris were collected after the experiment.

Recently, the second set of alumina tests (KROTOS 38 to 42) accompanied with larger test section with an inner diameter of 200 mm was aimed at not only collecting data in the extension of the previous set of experiments (KROTOS 26 to 30) under similar conditions, but also observing differences in mixing behavior between corium and alumina. These test results showed that the alumina melt produced a highly energetic vapor explosions with a peak pressure of more than 100 MPa and propagation speeds of the order of 1000 m/s. One experiment (KROTOS-41) with low subcooling (of 5 K) produced no explosion and a small cake with some coarse debris were found. It is significantly different from the corium test (KROTOS-37) under the similar condition, in which the debris was much finer. It illustrated that two melts, corium and alumina, behaved differently in their fragmentation and mixing processes.

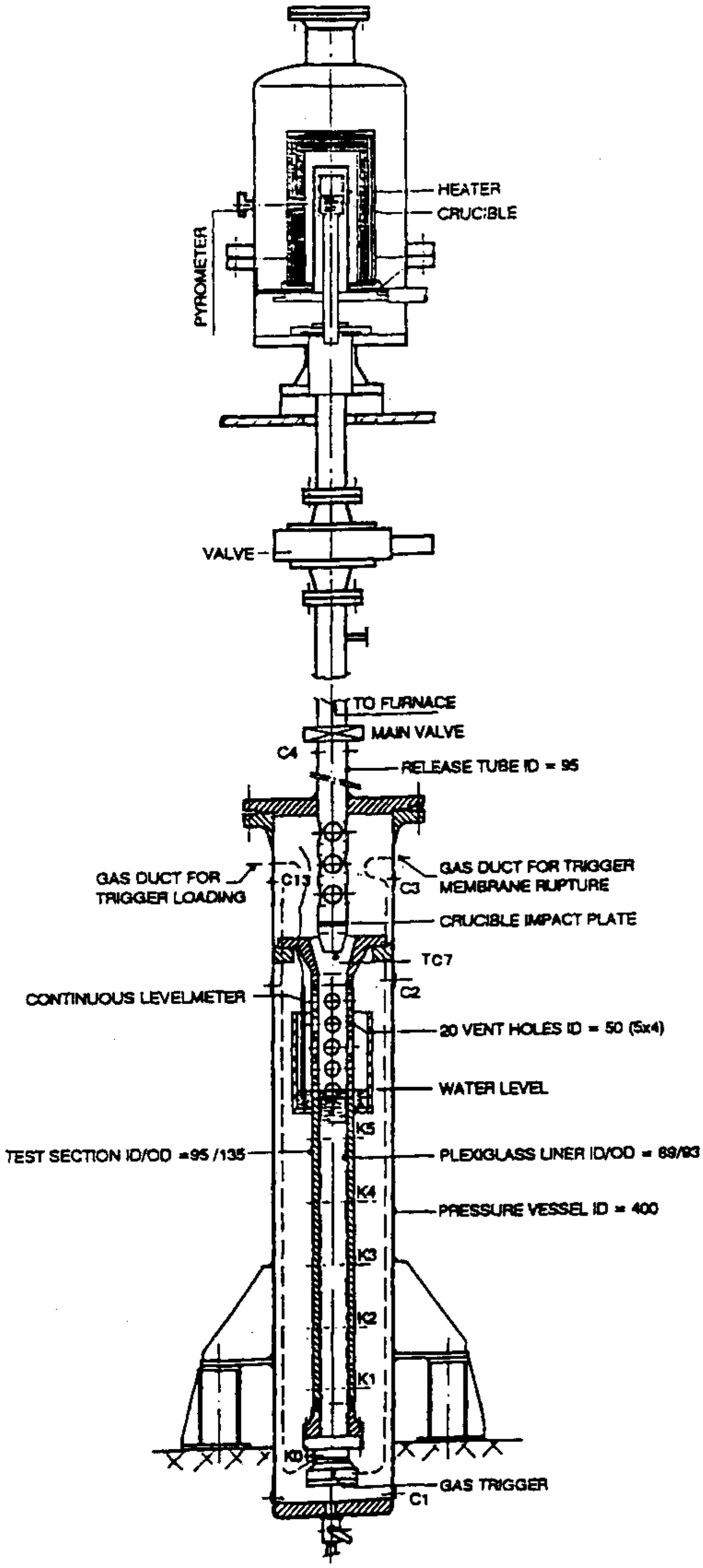


Figure 2: Schematic Illustration of the KROTOS Facility in JRC-Ispra, Italy

2.2 The WFCI Experiments at University of Wisconsin, USA

The WFCI (Wisconsin Fuel-Coolant Interaction) tests [16] have been performed at the University of Wisconsin in the Unite States to obtain the detailed experimental data for the propagation/escalation and expansion phases of vapor explosions. The facility as shown in Figure 3 was specially designed as a controlled one-dimensional geometry to reduce complexity of geometric dependency and equipped with a direct measurement of energy releases from the vapor explosions and variable external trigger system. The series of experiments in the WFCI facility were performed with several kilograms of tin as a molten fuel simulant and a column of water as a coolant filled in the test section. Most experiments were conducted with pouring a jet of melt with a jet diameter of mostly 38 mm by a gravitational head into a water column with an inner diameter of 87 mm and a length of 1.7 m. After the melt pouring, it penetrated into and mixed with water for about 2 seconds. About 2 to 4 MPa peak pressure of the external trigger was provided at the bottom of the test section and initiated the interactions between the fuel and coolant, causing vapor explosions. The shock pressure wave generated by the vapor explosion propagated upward. Resulted vapor volume expansion was eventually released through the expansion tubes as shown in Figure 3. During the experiments, an axial shock wave propagation and horizontal expansion speeds were measured and compared in terms of different initial mixing conditions set before the experiments.

Most results pertaining to the explosion characteristics showed that the average shock pressures were in the range of several hundreds of atmospheric pressure and shock speeds of 200 to 600 m/s in the melt-water mixture. The conversion ratios defined by the ratio of the explosion kinetic energy to initial melt internal energy were measured less than 1 %. It is substantially lower than about 30 %, estimated by the thermodynamic models. Park *et al.* [18, 19] explained by using the thermodynamic models in accompanying with thermal detonation model and post debris analysis results from the experiments that these differences resulted from the limited participation of the melt during the explosion. Park*et al.* [20, 21] also showed the dependency of the energetic of vapor explosions on the degree of system constraints and volume ratio of the melt to coolant. Such a dependency was explained that the conversion ratio reached a certain optimal value as the system constraint increased because two count-effecting factors, melt-coolant energy transfer and melt quenching effects, played dominant roles each other as the system constraint was varied. Other parameters such as thermal conditions of fuel and coolant, external trigger strength were examined. Also the suppression effects due to a change of coolant properties by adding polymer additives were investigated, showing that a small quantity of polymer additives (1.5 times higher in viscosity) was sufficient to suppress the vapor explosions in highly subcooled coolant.

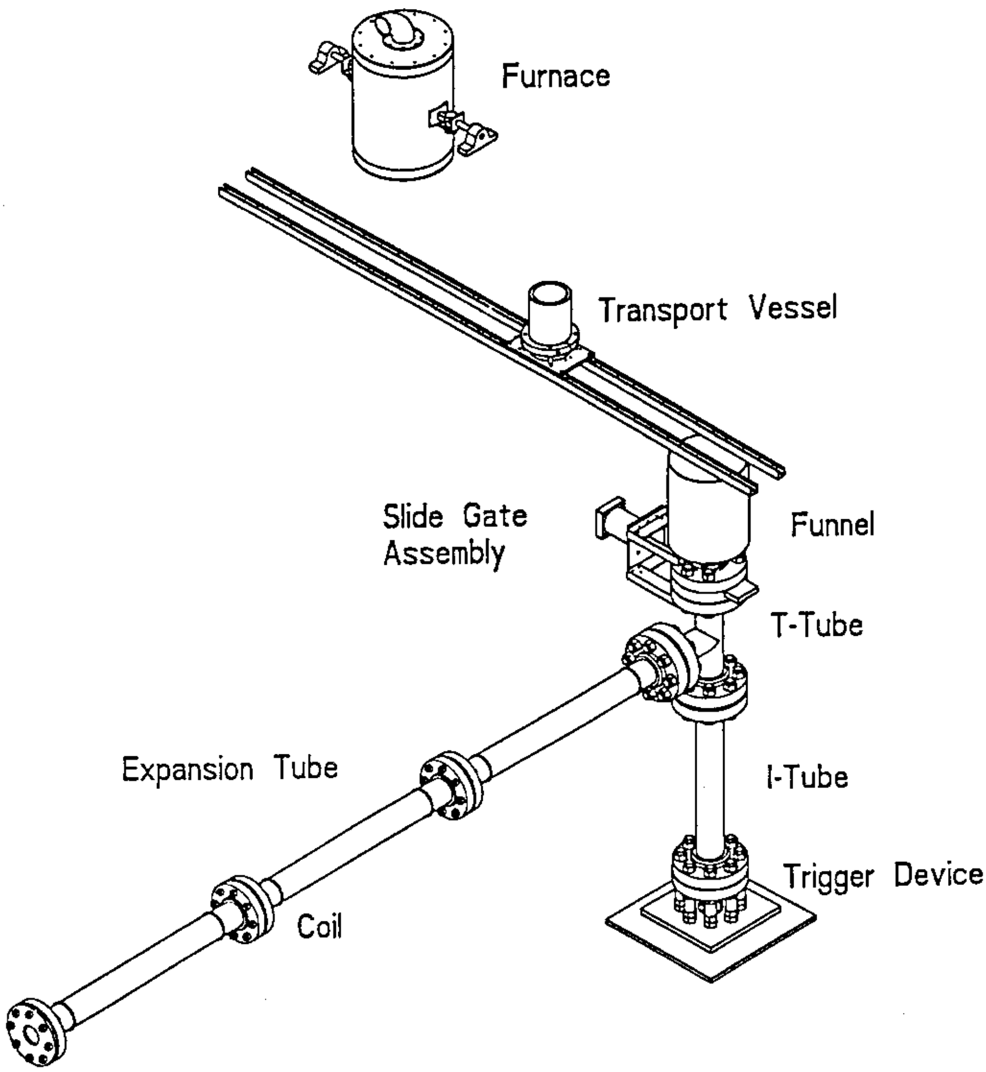


Figure 3: Overall Three Dimensional View of the WFCI Facility in University of Wisconsin-Madison, USA

2.3 The ALPHA Experiments at JAERI, Japan

The ALPHA (Assessment of Loads and Performance of a containment in a Hypothetical Accident) program was initiated at JAERI (Japan Atomic Energy Research Institute) in Japan to investigate the phenomena which would threaten the nuclear reactor containment integrity during postulated severe accidents. As one of the sub-programs, a vapor explosion phenomenon has been investigated using a chamber type facility, named ALPHA as shown in Figure 4. The ALPHA facility [17] simulates the containment with a diameter of 3.9 m, a height of 5.7 m and an inner volume of 50 m^3. The melt was generated in the melt generator located at the top of the vessel by a thermite reaction with iron oxide and aluminum.

A set of experiments (denoted as STX series) [17] were focused on the mixing phase and explosion behaviors by measuring shock pressures and visualizing the events, studying the effects of ambient pressure, fuel mass and melt dispersion on the vapor explosions. Those experimental results showed that the tests with the dispersion device generated larger steam production. However, the relationship between the void fraction and likelihood of the spontaneous explosion was not clearly observed.

For the tests with the elevated ambient pressures up to 1.6 MPa, spontaneous explosions were ceased as the ambient pressure reached to 1.0 MPa. However, at the pressure of 0.5 MPa, no spontaneous explosion was observed at the surface of water pool as shown in other tests with an ambient pressure of 1.0 MPa but energetic explosion was triggered as the leading edge of the melt stream hit the bottom of the test tank. It clearly showed the effect of the ambient pressure on the vapor explosions. Explosion suppression at the high ambient pressure was generally understood by the fact that the ambient pressure strongly affected the mixing behavior with changing film boiling characteristics. However, note that at the intermediate system pressure with a highly subcooled water condition, the explosion can be more energetic than one at the low system pressure since more melt can penetrate into water and participate to fuel-coolant interactions without surface spontaneous explosions. Therefore, it is necessary to take caution on system pressure effect on the vapor explosions.

Most test results with spontaneous explosions showed that a propagation velocity ranged from 300 to 500 m/s, estimated void fractions from 20 to 80 % and conversion ratios from 0.6 to 5.7 % estimated based on the pressure. Even with a large uncertainty with estimating the conversion ratio, it also showed the order of magnitude lower than the thermodynamic upper limit. In comparison to previous two experiments, the KROTOS and WFCI, this series of experiments showed the visualized information and multidimensional effects on mixing and propagation phases.

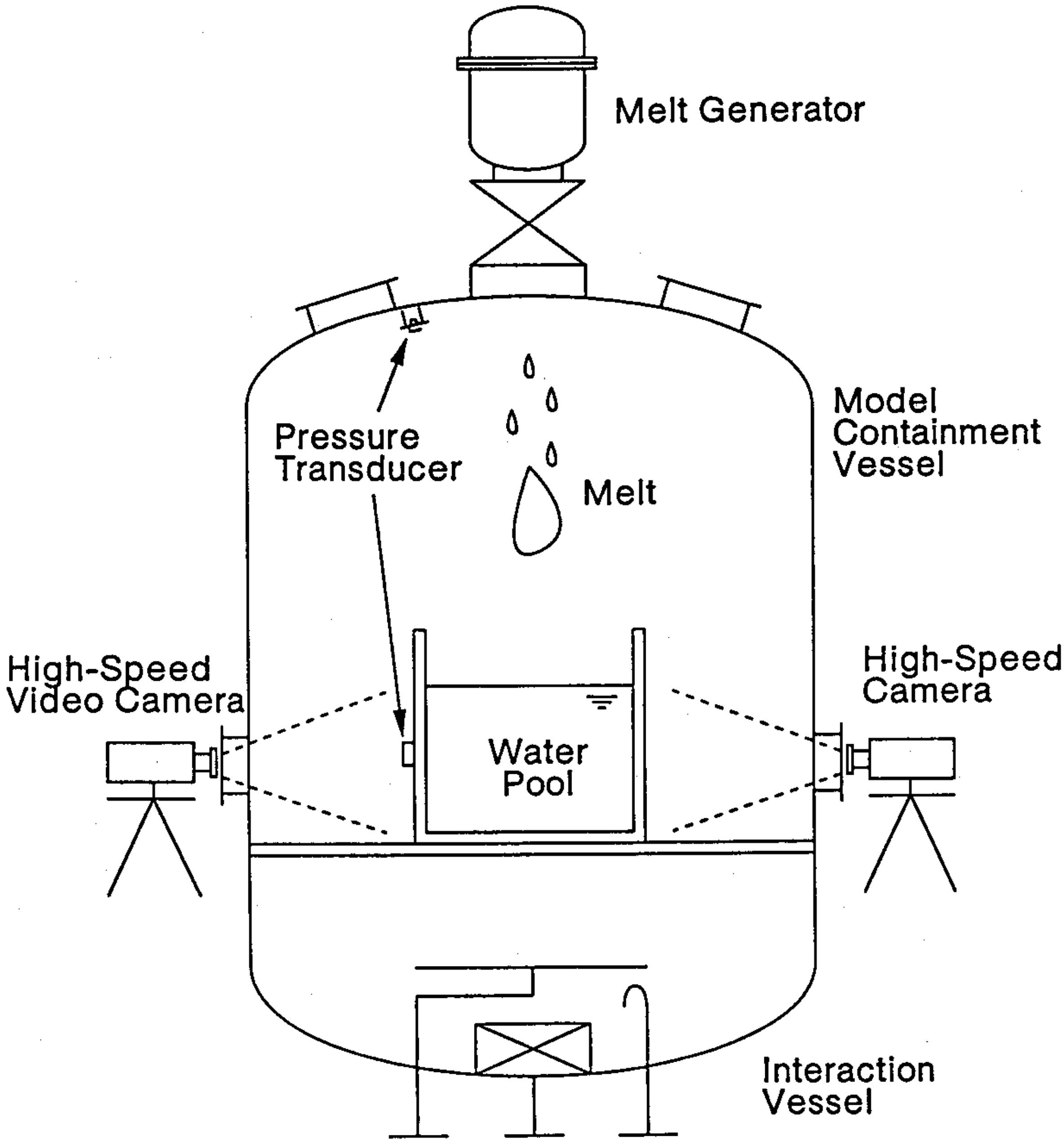


Figure 4: Schematic Illustration of the ALPHA Facility in JAERI, Japan

3 Stratified Mode of Vapor Explosions

3.1 Board and Hall's Experiments

Board *et al.* [22] performed small scale experiments in the facility with different molten metal catchers to examine the propagation characteristics of the vapor explosion. About 200 g of molten tin at temperatures of 700 to 750 °C were poured into two different types of melt catchers, a trough type and a narrow channel type immersed in the water tank with a water temperature of 80 °C. In this conditions, no spontaneous explosion was expected. The trough catcher had a shallow 'V' shaped cross section and was 300 mm long. An explosion was triggered at one end of the catcher by a steel rod impulse. Localized explosions occurred discontinuously from one end to the other. To produce a more continuous spatial propagation of the explosion, a narrow channel type of catcher was introduced. The chamber was a 150 mm wide, 30 mm deep and 200 mm long with one transparent wall. In this experiments, the depth of tin layer was about 7 mm. The interaction was initiated by tapping the base near one end and an explosion propagated through the tin-water interface with a velocity of approximately 50 m/s. It was believed that the propagation of the violent explosion resulted from the radially constrained long propagation length. These tests, including some other experiments [6], provided the insight to develop their well-known thermal detonation model [23].

3.2 Experiments at ANL, USA

Anderson *et al.* [24] performed the four series of experiments with different techniques to produce the well defined and reproducible geometry for the stratified vapor explosions. In their first series of tests, a tin with temperatures ranged from 600 to 700 °C was prepared in a long and narrow chamber (1 m long, 50 mm wide and 90 mm deep), forming about 30 mm molten tin layer. A low subcooled water with a temperatures ranged from 85 to 95°C was gently poured on to the molten tin. Experimental results showed that the spontaneous explosions occurred in wide time ranges. One of tests resulted in energetic explosions producing a propagation velocity of about 75 m/s and about 35 mm interaction zone at the interface was visually observed.

In the second and third series of experiments with a chamber of a 0.3 m long and 50 mm square cross section, elevating initial pressure of the chamber and with a vertical chamber, dropping two liquid columns respectively, all failed to produce the reproducible stratified geometry due to the premature interactions. In the fourth series experiments with a vertical chamber, a R-22 as a coolant and water as a fuel were prepared and separated from a 0.25 mm thick mylar diaphragm as shown in

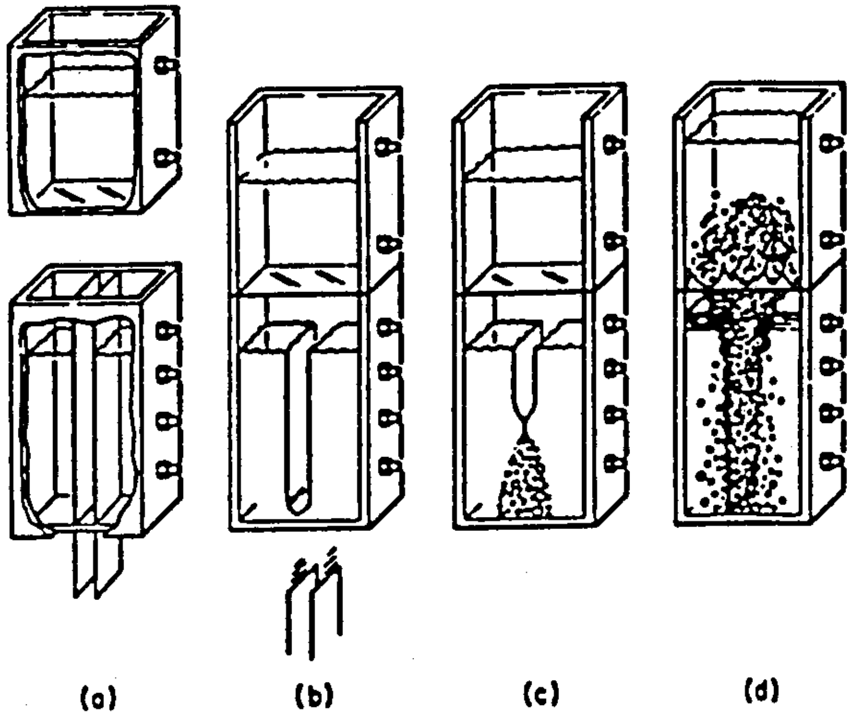


Figure 5: Schematic of Experimental Apparatus for Stratified Geometry in Argonne National Laboratories, USA

Figure 5. The stratified geometry was produced by rapidly moving the diaphragm downward. The interaction started from the bottom of the chamber due to the trigger and propagated vertically upward. Most tests produced the vapor explosions with a peak pressure and shock propagation speed of up to 1 MPa and 150 m/s respectively.

3.3 The ACM Tests at SNL, USA

Berman [25] reported two tests in a series of experiments, so-called ACM (Alternative Contact Mode), for the stratified vapor explosion. In these two tests, the melt (iron/alumina mixture) generated by the thermite reaction was prepared in a graphite crucible and water was gently poured by a gravitational head into the crucible. To reduce the effects of forced mixing resulted from direct pouring onto the melt surface, the nozzle was positioned to cause the coolant to impact the inside wall of the crucible. Table 1 shows the initial experimental conditions of two experiments.

In the ACM-1 test, ten kilograms of melt were contacted with water at 1 second after the thermite reaction was completed. The energetic vapor explosions occurred at about 3 s after water contacted with melt. Water with a 0.6 kg had been delivered to the melt pool at the time the explosion had occurred. Several eruptions before explosion indicated surface agitation (2.4 and 2.8 s). These eruptions ejected molten material more than 1 m above the melt/water pool. In the ACM-2 test, water holding time, defined as time between the completion of the thermite burning and the introduction of water, was increased from 1 to 4.5 s to investigate the effect of melt solidification on vapor explosions. The high-speed film records showed that all activities at the surface of the melt pool had ceased 1 to 2 s before the coolant was introduced and no explosions were observed. It may tell that the surface of the melt have solidified before the water contact. Post test examination of the crucible showed the presence of an alumina crust, about 6 mm thick, that had formed about 20 mm above the molten pool.

Table 1: Experimental Conditions for the ACM Tests at SNL, USA

Run	ACM-1	ACM-2
M_f (kg)	10	18.5
M_c (kg)	0.6	3.8
R_m	0.06	0.35
T_c (K)	298	298
ΔT_{sub} (°C)	69	69
$\dot{V}_c$ (m/s)	1.0	1.8
P_{amb} (MPa)	0.083	0.083
τ_{hold} (s)	1	4.5

Test results seem to show that the agitation of the melt surface may be responsible to the energetic vapor explosions observed in the ACM-1 test. The mechanism of agitation on the melt surface which allows the ejection of a sufficient quantity of melt particles from the melt surface into the overlying water pool may be of importance in this stratified geometry. Therefore, the energetic of the explosion in this mode may depend on the water penetration depth due to water agitation, leading to different mixing conditions.

Rough estimate on the minimum quantity of melt, called mass threshold, that may have mixed during ACM-1 test, was estimated by authors. Below a certain melt mass spontaneous explosions did not occur (actually volume threshold not simply a mass threshold) For the thermite melt, it is about 2 kg and for the purely oxidic melt, about 1 kg. In the ACM-1 test, the explosion occurred spontaneously and involved the oxidic phase of the melt; melt masses between 1 and 5 kg were responsible for the explosion. The alumina phase of the melt rises very quickly to the top of the melt pool due to a factor of 1/2 in the densities of it and iron phase. The alumina phase is usually about 2 as deep as the iron phase, unless the water penetration more than 2/3 the total melt depth, it probably did not encounter the iron phase.

3.4 The ACM Tests at ALPHA, Japan

Yamano *et al.* [17] also performed a series of experiments, called ACM, similar to SNL tests mentioned in a previous section to investigate the coolability of the melt as it was covered by the poured water. Figure 6 shows the schematic diagram of this series of experiments. The series of experiments were performed in the ALPHA facility (Figure 4). Thermite as a melt was prepared in the various sizes of the MgO crucibles with inner diameters ranged from 0.2 to 0.36 m and a height of 0.5 m. Several K and B types of thermocouples were installed to measure the temperatures of the bottom and side walls of the crucible as well as overlying water. After the ignition of thermite reaction in the crucible, water was poured onto the thermite melt surface at a injection velocity of approximately 0.4 m/s through the pipe or spray nozzle. The nozzle exit was located at about 0.3 m above the center of the melt surface.

Table 2 shows initial experimental conditions and brief results of seven experiments which were denoted as ACM02[†] through ACM08. In this table, ΔT_{TR} is a duration time of thermite reaction evaluated from measured temperature in the bottom wall of the MgO crucible. T_{cp} and T_{erup} are a time for a water coolant pouring and a time difference between water pouring and eruptions, respectively. D_n is the nozzle diameter. The depth of melt was set at approximately 80 mm. At the initiation of

[†]Authors intentionally changed the name of each test, for example from ACM002 in original to ACM02 by omitting one "0" because of the arrangement of Table 2

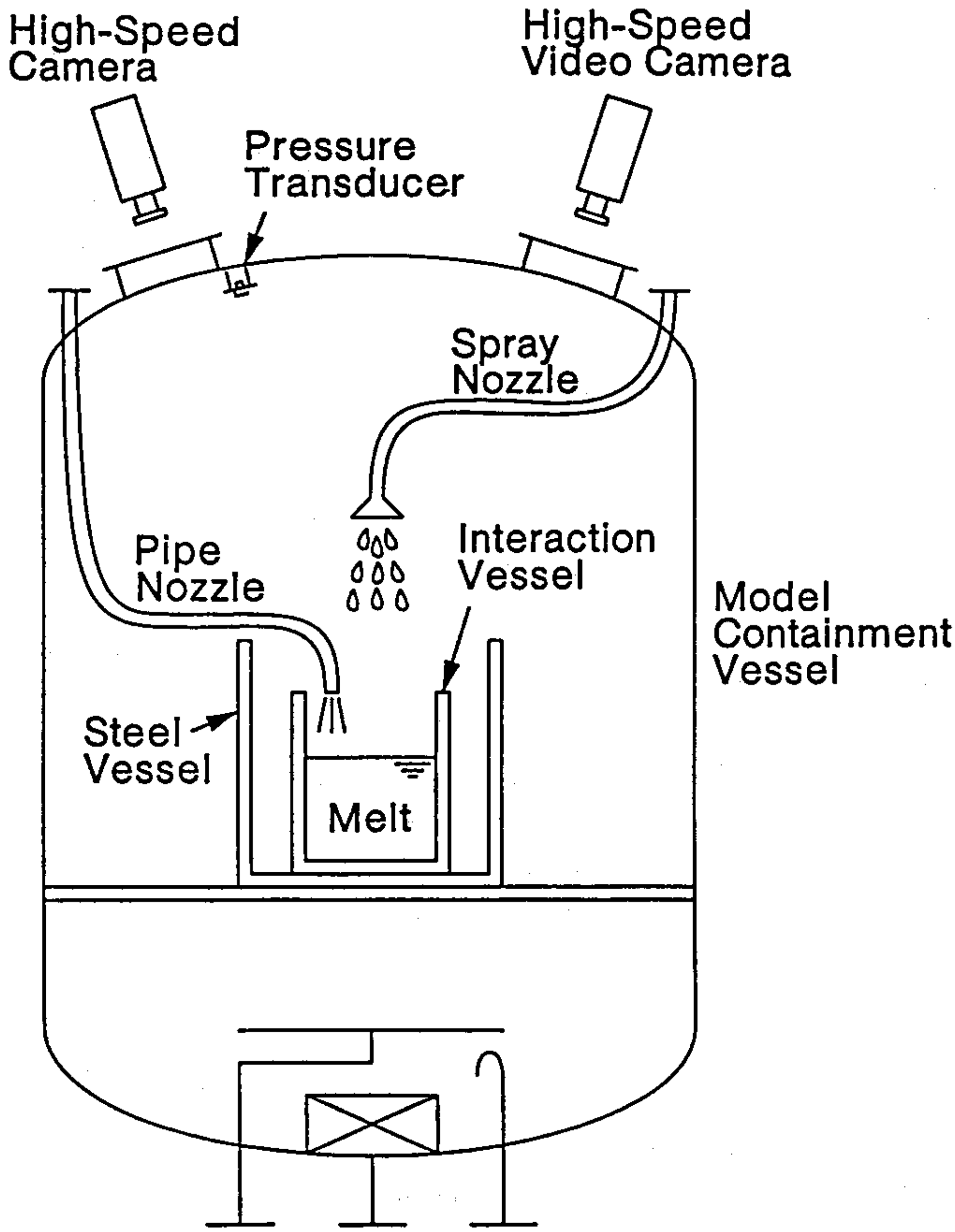


Figure 6: Schematic of Experimental Apparatus for ACM Series of Tests in JAERI, Japan

Table 2: Experimental Conditions and Results for the ACM Tests at JAERI, Japan

Run	ACM02	ACM03	ACM04	ACM05	ACM06	ACM07	ACM08
M_f (kg)	10	10	2.5	10	31.5	10	30
D_f (m)	0.2	0.2	0.1	0.2	0.355	0.196	0.333
Poured by	Pipe	Spray	Pipe	Pipe	Pipe	Pipe	Pipe
D_n (mm)	16.7	-	8.0	16.7	32.9	16.7	16.7
$\Delta T_{sub}(^oC)$	85	90	80	0	76	77	74
ΔT_{TR} (s)	17	19	10-15	19	23	14	17
T_{cp} (s)	36	26	34	28	31	32	35
T_{erup} (s)	9	-	2,8	-	N/A	31,33,35	14,17,20
Results	Ex	NE	ME	NE	-	ME	ME

N/A : Unsuccessful visual observation

Ex : Explosion

NE : No Eruption

ME : Multiple Eruptions

water addition, temperature of the melt surface of approximately 2500 K was measured from two separate tests.

Experimental results show that multiple eruptions occurred during the experiments as the subcooled water was injected with a relatively low speed through a pipe nozzle. However, when the water was injected through a spray nozzle (ACM03) or the water temperature was saturated (ACM05), no indication of eruption was detected as expected.

One out of eight experiments (ACM02) shows energetic interaction, but it was weaker than pouring mode tests performed previously. It was evidenced by the fact that a cumulative mass fraction for fine debris in the ACM02 test was smaller than one in the STX005 test as one of typical pouring mode tests in the ALPHA program. In this ACM02 test, immediately before the explosion, consecutive eruptions of the melt took place. Such a similar pre-eruption was also observed in the SNL experiments. Authors noted that such pre-eruptions are of an importance for explosive interactions since it enhanced the coarse mixing configuration and provided a trigger source in the stratified geometry. Multiple eruptions were observed in other tests (ACM04, ACM07 and ACM08). However, these eruptions were smaller in scale than those observed in the ACM02 test. Although the effects of melt mass, melt surface area and nozzle diameter were also investigated, no significant remarks were drwan by authors.

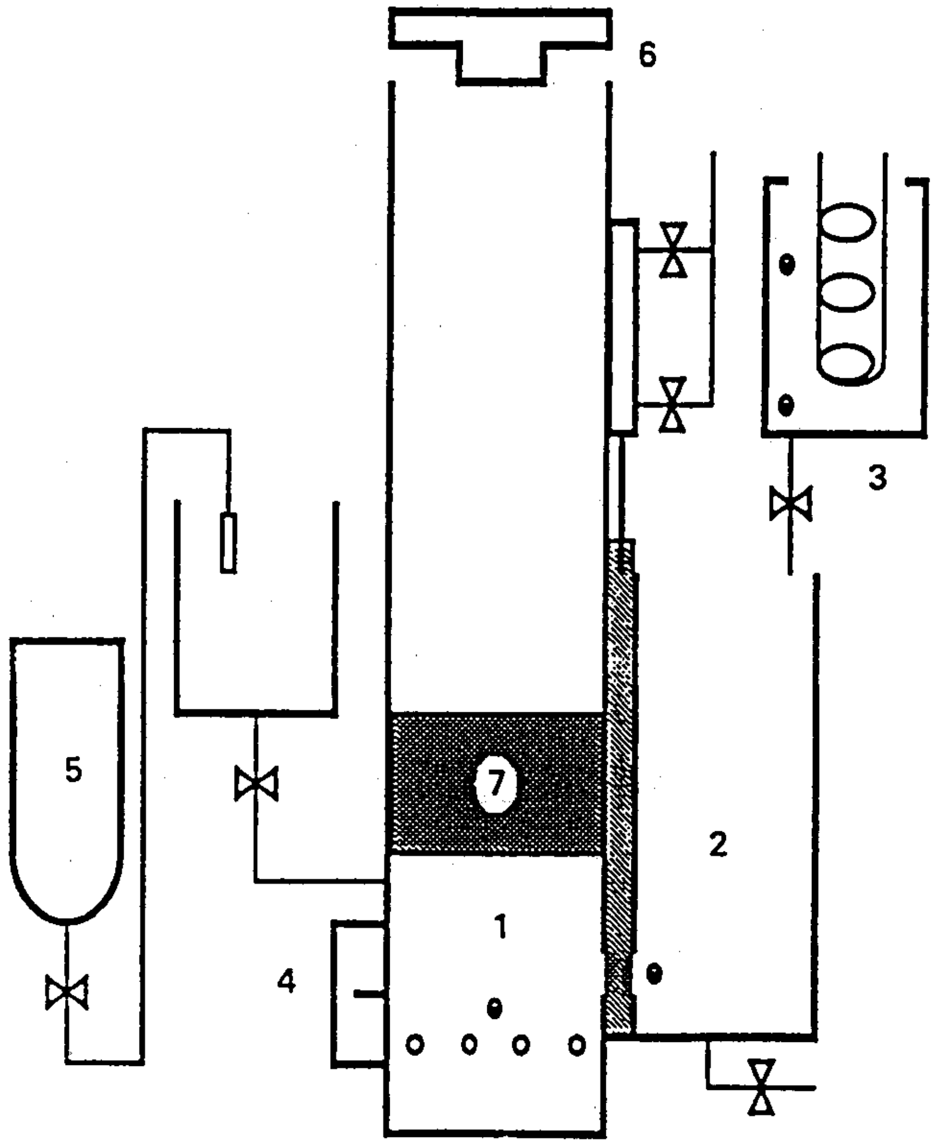
3.5 Experiments at University of Wisconsin, USA

Bang *et al.* [26] conducted a series of experiments with water/liquid nitrogen and water/Freon-12 systems in test sections of two different sizes (geometric scale ratio of 2 to 5). A schematic of the experimental apparatus shown in Figure 7 is the small-scale test section with an interaction vessel of a 25 mm wide, 0.2 m long and 0.65 m high for the water/LN_2 tests and 1.26 m high for the water/R12 tests. However, the large-scale test section is geometrically identical but longer horizontal length of the vessel (0.5 m). The interaction vessel consisted of a front transparent window, the slug placed above to measure the mechanical work output from the explosion and external trigger system. Four quartz pressure transducers were mounted on the vessel wall to measure the pressure traces propagating along the vessel during the interactions.

Table 3 shows the ranges of experimental parameters. In addition to these parameters, the effect of the external trigger strength was also investigated. Table 4 shows that energetic interactions with an average propagation speed of 40-250 m/s were observed and the water/R-12 pair produced more violent explosions than the water/LN_2 in this geometry. For the water/R-12 pair tests, up to 1.5 kJ of work done by the explosion was measured. However, no significant effect of trigger pressure with up to 4 bar was also observed. The reason for more violent explosions in the water/R-12 system was suggested that the interfacial contact temperature, T_i, plays an important role as the shock front arrives. In the case of the water/R-12 system, since T_i is less than a critical temperature, T_{crit} of the liquid, vapor film collapse readily. However for the water/LN_2 which has much higher T_i compared to T_{crit}, vapor films behave as a supercritical fluid making collapse more difficult. The result showed that the depth of the mixing in this geometry appears to be small less than 10 mm in a single propagation. However, pre-mature explosions or erruptions can enhance the mixing if the system is well constrained.

Table 3: Experimental Conditions the Stratified Mode of Vapor Explosions at University of Wisconsin, USA

	Scale I		Scale II	
Size (mm)	25Wx200Lx650H		64Wx500Lx1500H	
Top liquid	Water	R-12	Water	R-12
Bottom liquid	LN_2	Water	LN_2	Water
T_w (°C)	10-85	50-91	30-70	83-94
D_w (mm)	5-100	30-100	100	30-80
T_c (°C)	-196	-30	-196	-30
D_c (mm)	50-75	10-100	50-100	6-100
M_{slug} (kg)	1-4	1-4	25.4	25.4



1. Interaction Vessel
2. Water Reservoir
3. Water Heater
4. Electro-Magnet
5. Freon Tank
6. Impact Absorber
7. Slug

• Thermocouples
o Pressure Transducers

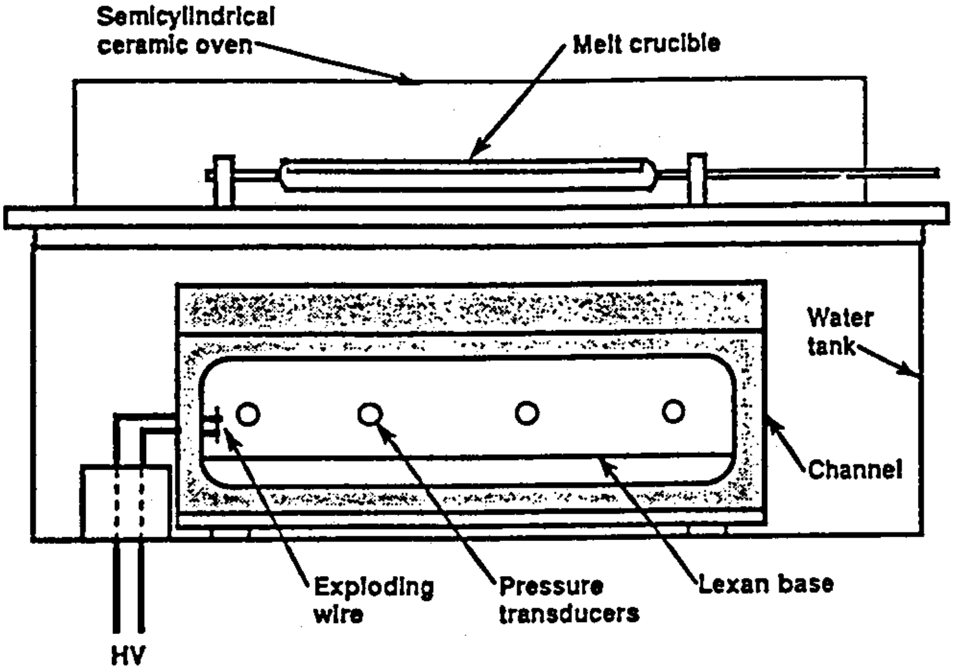
Figure 7: Schematic Diagram of Experimental Apparatus for the Stratified Mode of Vapor Explosions at University of Wisconsin, USA

Table 4: Experimental Results for the Stratified Mode of Vapor Explosions at University of Wisconsin, USA

	Liquids	Results	
I	H_2O/LN_2	General	- Stable FB due to much higher T_i than T_{MFB} - Low P_{peak} (1-2 bar) due to low P_{vapor} - V_{prop} = 100-250 m/s
		T_w D_w	- Work tends to increase as T_w increases - 2 MPa P_{peak} at 70 °C water - Scattered data but work decreases as D_w<10mm
		M_{slug}	- Work reduction of ~25% as M_{slug} decreases 4 to 1 kg
		P_{tr}	- Scattered data but work increases with P_{tr} increase
	H_2O/R-12	General	- More energetic interaction than H_2O/LN_2 - V_{prop} = 100-250 m/s
		T_w	- Cut-off temperature of 58 °C - Work up to 300J at high temperature
		D_{mix}	- Intermixing depth of less than 10 mm
		Vol_w	- Work up to 300J with water volume increase
II	H_2O/LN_2	General	- No self-sustained propagation, Work of 10~88 J
	H_2O/R-12	General	- Self-sustained propagation - Typical work of 1.5 kJ, V_{prop} = 70-100 m/s
		P_{tr}	- No effect on overall process with P_{tr} of 1 to 4 bars
		Vol_w	- Work increases with water volume increase

3.6 Experiments at McGill University, Canada

Ciccarelli *et al.* [27, 28] performed laboratory scale experiments to investigate the propagation and the role of confinement on vapor explosions in a stratified molten tin-water system. In so doing, two different experimental apparatus were used; one was for the narrow channel experiments and another for the cylindrical tank experiments as shown in Figure 8. First, the narrow channel experiments were performed in a narrow interaction channel (12.7 mm wide, 130 mm high and 400 mm long) with either Lexan or glass windows submerged in a main water tank. Tin was melted and discharged from a 50 mm diameter graphite cylinder with a 12.7 mm wide slot mounted inside the semi cylindrical ceramic oven located above the water tank. Approximately 400 g of tin at 700±50 °C was discharged into the narrow channel submerged in the water at 67-71 °C and placed along the base of the channel forming an about 11 mm thick meta-stable molten tin (approximately 1 s after the tin is dropped). The melt-water interaction is then triggered by an exploring wire (discharged by a capacitor of 4 μF at 4 kV) mounted 30 mm above the channel base. Explosion was initiated and propagated along the channel with an average velocity of about 40 m/s, producing a wedge-shaped (wedge angle of 10^o) interaction zone.



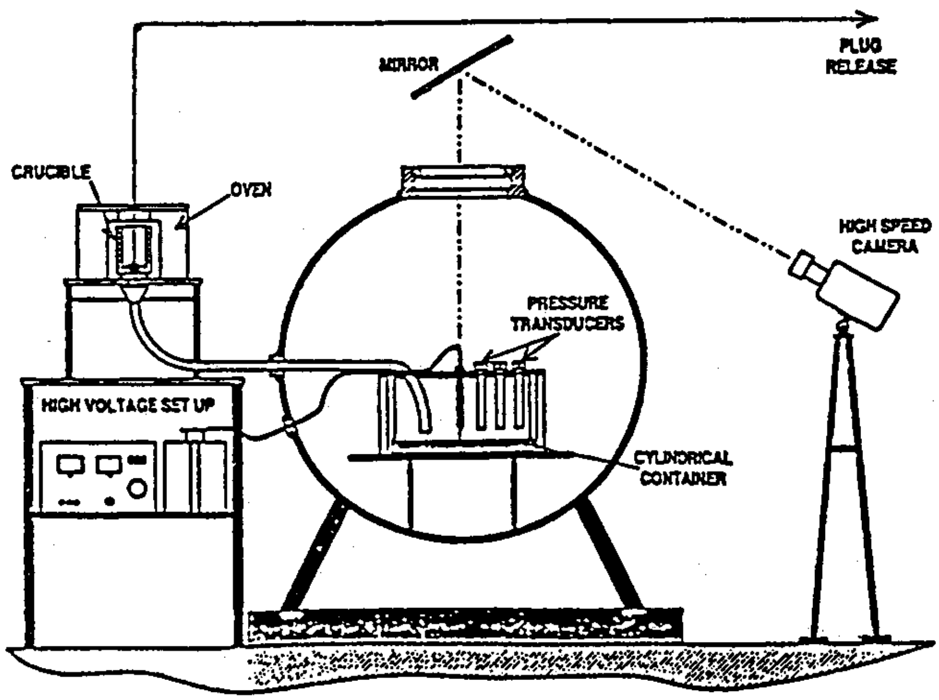


Figure 8: Schematic Diagrams of Experimental Apparatus (Top: Narrow Channel Experiment and Bottom: Cylindrical Tank Experiment) at McGill University, Canada

They reported a critical water layer height of about 50 mm in their geometry. Below this, the propagation of explosions was always failed and pressure generated decayed rapidly. In another test section similar to previous one in size but with a slide gate between the oven and narrow channel to preventing any vertical expansion in the channel, it resulted in an increase of the impulse by a factor of 3 to 4 but slight increase of propagation velocity by about 25 %.

In the cylindrical tank experiments as shown in Figure 8, the test apparatus consisted of a Lexan cylinder (0.273 m diameter) with a Teflon base, filled with water at a temperature of about 74 °C and a depth of about 0.1 m. About 4 kg of molten tin at 400 °C was prepared in an oven and discharged into the cylinder to form a molten tin layer of about 11 mm deep. The same exploding wire was mounted 33 mm above the tin surface at the center of the cylinder and exploded by a discharge of high voltage capacitor (0.2 μF at 17.5 kV). Interaction propagated radially from the center of the cylinder in this geometry as the most loosely confined system. About 30 % less energetic interactions and considerably small quantity of finely fragmented tin than those in the narrow channel experiments were observed.

From these two sets of experiments, the system confinement played important role on the energetic of vapor explosions in the stratified geometry. It is explained that at highly confined system, the probability of the occurrence of a second interaction was increased and this second interaction is more energetic due to well-mixed mixture produced by the first interaction.

4 Injection Mode of Vapor Explosions

As briefly mentioned in previous section, this mode of vapor explosions can be divided by two parts in terms of an injection liquid; (1) coolant and (2) melt injection modes. In this section, the review will be performed separately in the following subsections.

4.1 Coolant Injection Mode

4.1.1 Experiments at ANL, USA

Armstrong *et al.* [29, 30] carried out three sets of laboratory scale experiments with UO_2-Na, NaCl-H_2O and Al-H_2O pairs of fuel-coolant system injecting cold liquids into a crucible of molten fuels, both above and below the melt surface. In the UO_2-Na tests, the UO_2 was prepared in a tungsten crucible with an 16 mm diameter and a 25.4 mm depth located inside the stainless steel chamber accompanying with a sodium injection

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Table 5: Experimental Conditions and Results for Sodium Injection into UO_2 at ANL, USA

Run	3	6	8	9	12
T_{Na} (^oC)	392	395	400	400	405
M_{Na} (kg)	5.7	5.0	5.2	5.1	6.3
T_{UO_2} (^oC)	2950	3000	3090	3180	2920
M_{UO_2} (kg)	29.27	51.06	49.02	49.59	62.08
H_{inj} (mm)	+1.0	+2.3	+2.3	+2.2	-1.9
V_{inj} (m/s)	5.0	7.5	7.5	9.5	3.0
M_{Na-Inj} (g)	2.5	-	0.56/0.62	0.14/1.37	0.85
M_{UO_2-Ej} (g)	13.9	-	22.5	42.25	36.72
F_{peak} (N)	1780	-	203/98.8	1775/2122	947
P_{peak} (kPa)	41	-	-	34/-	-
Impulse (N-s)	0.423	-	0.0609/0.030	0.489/0.476	0.36
V_{front} (m/s)	160	-	44.2/15	157/-	94.5

system. The test facility was roughly similar to the one as shown in Figure 9 used in the NaCl-H_2O tests, which will be described in the next paragraph.

Five out of twelve tests produced vapor explosions as indicated by data recorded from pressure and force transducers on the base of the crucible and by 20,000 fps high-speed camera pictures. Four explosions resulted from the sodium injection above the melt surface and one from the sodium injection below the melt surface. Table 5 shows the summary of experimental conditions and results for tests with vapor explosions. As shown in this table, the effect of an injection velocity on an energetic of interactions is not certain. They observed a time delay ranged from a few millisecond to a few hundred milliseconds prior to the explosion event in all tests produced energetic interactions. High speed pictures for the subsurface injection test showed that the relatively long delay time resulted from a preliminary small explosion and more violent explosion was followed. In other seven tests, mechanical failure of apparatus prior to injection, frozen crust of UO_2 and low sodium injection velocity may be attributed to lack of explosions [31].

They performed NaCl-H_2O tests by injecting water from above and below the surface of molten salt [32] in the test facility shown in Figure 9. In the series of tests, three types of water injection techniques were tested. First, water was injected from a hypodermic needle with a 0.9 mm diameter located 40 mm above about 80 g of molten salt with a temperature of 1122 °C in a 38 mm wide, 25.4 mm deep and 51 mm high quartz crucible.

A small interaction occurred initially as the water penetrated the salt and produced a small sphere of water entrapped which subsequently exploded violently. Injection

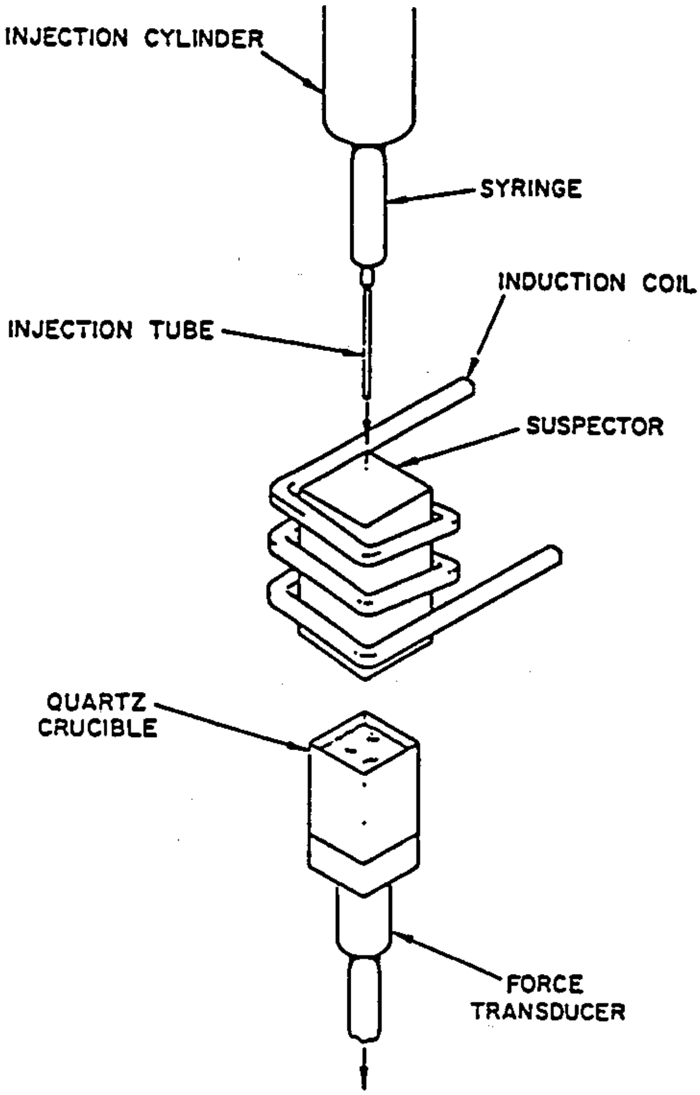


Figure 9: Schematic of Experimental Apparatus for Coolant Injection Mode of Contact in Argonne National Laboratories, USA

velocities of 3.0 to 9.1 m/s produced initially small explosions followed by a delay period and larger secondary explosion. As the injection velocities increased more up to 24.4 m/s, the interaction tended to be more violent than lower injection velocity cases.

Second, glass of spheres filled with water were dropped into the salt and allowed to break either from internal pressure buildup or crash against the bottom of the crucible. The technique to deliver water into the salt, however, always failed to produce an explosion.

Lastly, the same injection syringe needle with insulation was lowered to the subsurface of the molten salt. This method produced explosions and provided a better picture of the detailed interaction between the water and the salt. High speed pictures (13,000 fps) showed that vapor was generated around the jet as the water jet injected into the molten salt. The water jet insulated by this vapor blanket reached the bottom of the crucible and explosion occurred simultaneously at 3.2 ms after the initiation of injection. From these pictures, the estimated maximum transferred heat during the injection period was only a small fraction of the measure explosion energy. It indicates that most energy released after the initiation of the explosion.

Anderson *et al.* [33] performed this mode of experiment with aluminum and water to investigate the effect of injection speed on the vapor explosions. They performed four sets of experiments; for (1) low velocity of a water jet (2) ultra-high velocity of a water jet (3) water entrapment without a exploding wire and (4) water entrapment with a exploding wire. For the first set of experiments, a water jet was injected across a 0.1 m air gap through 30 mm diameter tube driven by injection pressures of 0.9~3.1 MPa. Mild splashing of molten aluminum with no explosive interactions was observed.

For the second set of experiments, a 0.5 mm diameter of water jet with about a velocity of 400 m/s was injected to a 130 g of molten aluminum at temperatures of 800~1000 °C in a 28 mm diameter and 76 mm depth crucible. About 60 % of molten aluminum was ejected from the crucible and relatively mild interactions were observed. The authors suggested that the reason for no or mild explosive interactions be due to the non condensable gas entrapment during the traveling of water jet across the air gap. To verify their hypothesis, the third set of experiments was performed with a small glass sphere filled with water. In this series, about 0.7 g of water in the glass sphere was introduced into a 1 kg of molten aluminum at 900 °C. However, no explosive interactions were observed.

Lastly, to enhance the water dispersion into the molten aluminum, an exploding wire was placed inside the glass sphere. In this system, violent interactions were observed if the energy of the exploding wire was greater than a threshold, about 380 J in these experiments. However, the relationship between the energy of exploding wire and energy output of explosive interactions was not clearly observed.

4.1.2 Experiments at Grenoble, France

Amblard *et al.* [34] performed the experiments, called CORECT-I, for the coolant injection mode which involved much smaller quantity of molten UO_2 (~3 g) than the ANL experiments (~50 g) mentioned in a previous section. The schematic diagram of the test facility is shown in Figure 10. Under an atmosphere of 120 liters of hydrogen at an absolute pressure of 0.5 MPa, the 3.2 kg of UO_2 melt was prepared in a crucible. The sodium container consisted of a sodium chamber pressurized by an argon at 1 MPa and stainless steel tube with a copper membrane underneath the sodium chamber. The 300 g of sodium was injected into the molten UO_2 pool as the sodium container dropped and the steel tube broke the UO_2 solid layer. Subsequently, the copper membrane was melted and the sodium and UO_2 interface were formed. Experimental results showed that an outer chamber pressure reached up to 0.98 MPa in 0.5 from its initial pressure of 0.5 MPa. Only 300 g of UO_2 was scattered. Among them, 30 g of which was between 1 and 100 μm in diameter. The crucible deformed by the sudden generation of steam as shown in Armstrong's experiments.

4.1.3 Experiments at Howell, UK

Asher *et al.* [35] studied possible explosive interactions between the sodium and stainless steel fuel cladding as a first step to investigate the sodium-uranium dioxide interactions in fast reactors. About 2 g of liquid sodium at about 380 °C was injected from a pressurized stainless steel bellows unit at 0.5 MPa into inside molten steel of about 54 g at 1530 °C. Violent vapor explosion caused the rupture of the crucible. The maximum force measured by the force transducer located below the melt chamber reached approximately 600 N, corresponding to a pressure of 2 MPa. Due to the explosion, the steel was finely fragmented producing predominant particle size of approximately 500 μm or less which is contributing about 50 % of the total particle surface area. Another experiment [36] with 1.5 g of sodium at 400-450 °C and 80 g of molten stainless steel at 1750-1800 °C was conducted in the same facility. However, Peak forces were an order of magnitude below that of the previous test but steel was much finely fragmented.

Asher *et al.* [37] also conducted water injection test into molten metal, tin. In this experiments, approximately 1 g of water were injected below the surface of the molten tin by a 2 mm diameter hypodermic needle at an injection velocity of 0.24 m/s. Table 6 shows their experimental results in terms of the degree of interaction severity defined as a scale of 0 to 4 by measuring the amount of metal expelled from the crucible and noise generated by the interaction. All experiments shown in this table were performed at a water temperature of 22 °C and an injection depth of 18 mm. As shown in the table,

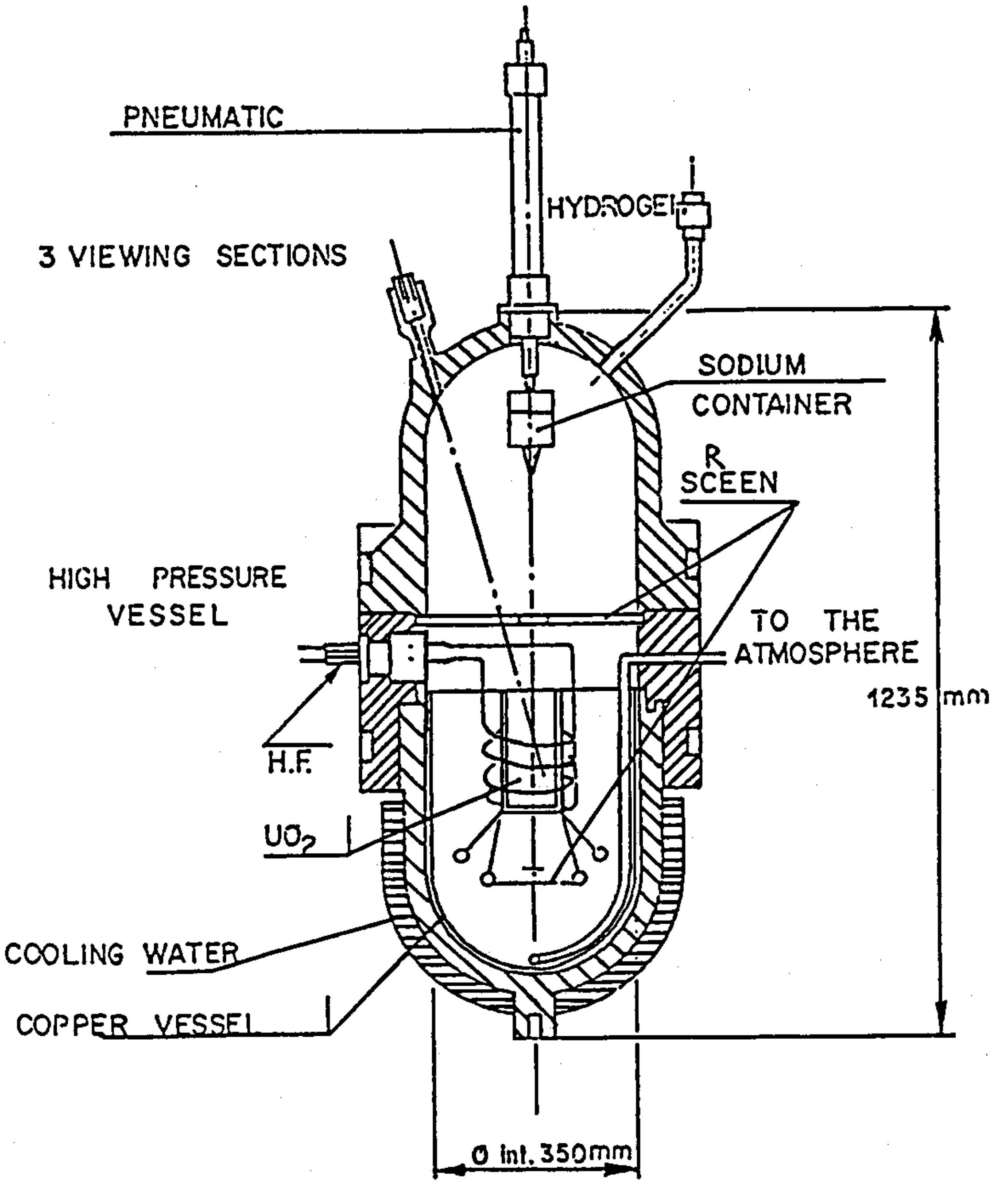


Figure 10: Schematic of CORECT-I Experimental Apparatus at Grenoble, France

the explosion was not occurred up to a molten tin temperature of 290 °C because of a low super heat of the molten tin. Violent explosions were observed in melt temperature ranged from 300 to 440 °C and again ceased above 450 °C.

Table 6: Summary of Asher's Experimental Results at Howell, UK

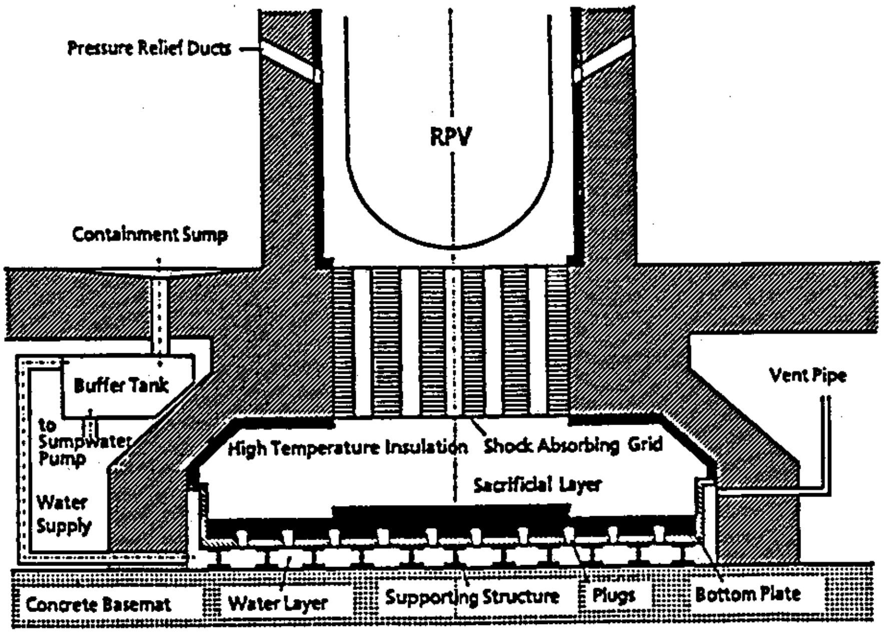
T_f (°C)	No. of Runs	Tin Expelled (% Total)	Severity of Interaction	Remarks
250~290	3	<1.7	0	
300~440	20	53-98	1-4	At T_f=380, <1.7 % of tin was expelled and severity was 0
450~900	8	<1.5-10	0	

4.1.4 Experiments at University of Wisconsin, USA

Recently, Baker *et al.* [38] started this mode of vapor explosion injecting water and gas into the pool of a molten tin to verify the likelihood of vapor explosions in the Catalytic Extraction Processing (CEP) [39]. The CEP has been developed for the treatment and recycle of both hazardous and radioactive wastes, injecting wasted stream and reactants into a pool of molten iron. The facility consists of the stainless steel test section (40 mm x 100 mm x 850 mm) and two injectors located at the bottom. During the injection and explosion phases, images in near-real time can be produced by a 9 MeV X-ray source. The images are utilized for producing a two-dimensional void fraction map. In an initial set of test, streams of nitrogen gas and water were injected with gas and water flow rates of 1.4 liters/s and 0.062 liters/s respectively, into a pool of 15 kg molten tin at the temperature of 400 to 500 °C and explosive interaction was observed. They are planning to identify the cutoff temperature in this mode of vapor explosions and eventually to examine the effect of void fraction and its distribution on the initiation of vapor explosions.

4.1.5 The COMET Experiments at FZK, Germany

Forshungszentrum Karlsruhe (FZK) has studied a core catcher design as shown in Figure 11 to be integrated into a new PWR design, which prevents the core debris from penetrating the basement and damaging important structures in the lower part of the containment. One of key features in the design is that the coolability of the core catcher is achieved by spreading and fragmenting the ex-vessel core-melt due to cooling water injection from the bottom through the melt [40]. To assure the safe operation of the design, it is essential to verify any possibility of vapor explosions during the



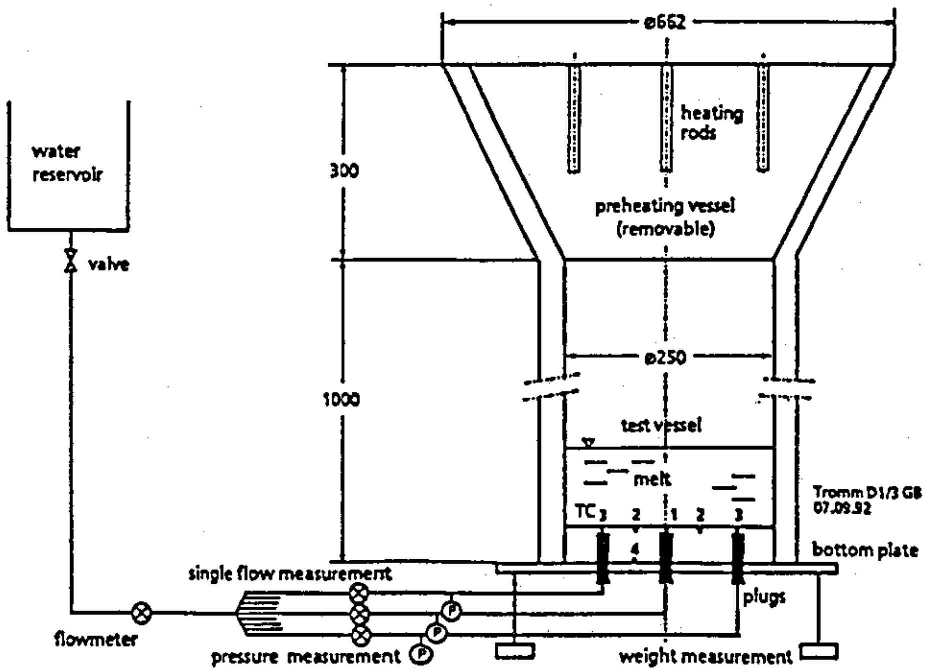


Figure 11: Conceptual Diagram for the Core Capture (Top) and Schematic of COMET-T Experimental Apparatus (Bottom) at FZK, Germany

direct contact of melt and water provided on purpose. In so doing, Tromm *et al.* [41] performed medium scale experiments in which multiple jets of coolant were injected from the bottom through the melt as shown in Figure 11.

This series of experiments, denoted as COMET-T, used thermite melt of 50 kg as a core melt simulant and water was injected at the bottom of the test-vessel with a total flow rate of about 200 ml/s at a water supply pressure of 0.2 bar. The test vessel consists of a cylinder of 0.1 m height and 250 mm inner diameter with radial MgO insulation. Nine easily melting plugs were installed and covered by concrete layer with a overall thickness of 450-500 mm, 5-10 mm of which covers the tip of the plugs in the bottom steel plate. The experiment is initiated by the ignition of the thermite power and thermite melt generated erodes the concrete layer on the top of the plugs. As the melt melts the tip of the plug at 120 s after the ignition, the water ingression starts through the openings of the plugs. The surface of the melt solidified at 160 s and water droplets were visible at 180 s. Only mild interactions of melt and water were observed and the melt was completely solidified and flooded by water at 240 s. One thing to note is that the composition of the melt will be significantly altered from initial thermite by the dissolved concrete layer located between the thermite melt layer and water injection plugs. Other series of experiments, called COMET-H, is planning to perform in the modified BETA facility, providing sustained heating into the melt. At present, even if no further information is available to authors, these tests will provide valuable information on the coolant injection mode of vapor explosions.

4.2 Melt Injection Mode

4.2.1 Experiments at University of Tokyo, Japan

Kondo *et al.* [42] injected a 2 mm diameter of molten tin jet from the bottom of the test section filled with a water to investigate the effect of spatial incoherence of fuel injection on vapor explosions. The test section consisted mainly of the water channel and melt injection system as shown in Figure 12. Maximum about 4 grams of molten tin can be prepared in the melt reservoir and injected into the water channel. Table 7 shows the ranges of test conditions and brief results. It tells that explosions occurred at a molten tin temperature of above 350 °C and water temperature of below 70 °C. At some given conditions, multiple explosions were observed. In their report, however, there is no explicit information on the effect of jet speeds on vapor explosions, even if they used two different injection pressures. Several tests were visualized by a high speed camera with frame speed of 3,000∼4,000 frames per seconds, observing molten jet behavior during the injection period and explosion process.

The interaction was initiated at the nozzle exit and propagated vertically upward.

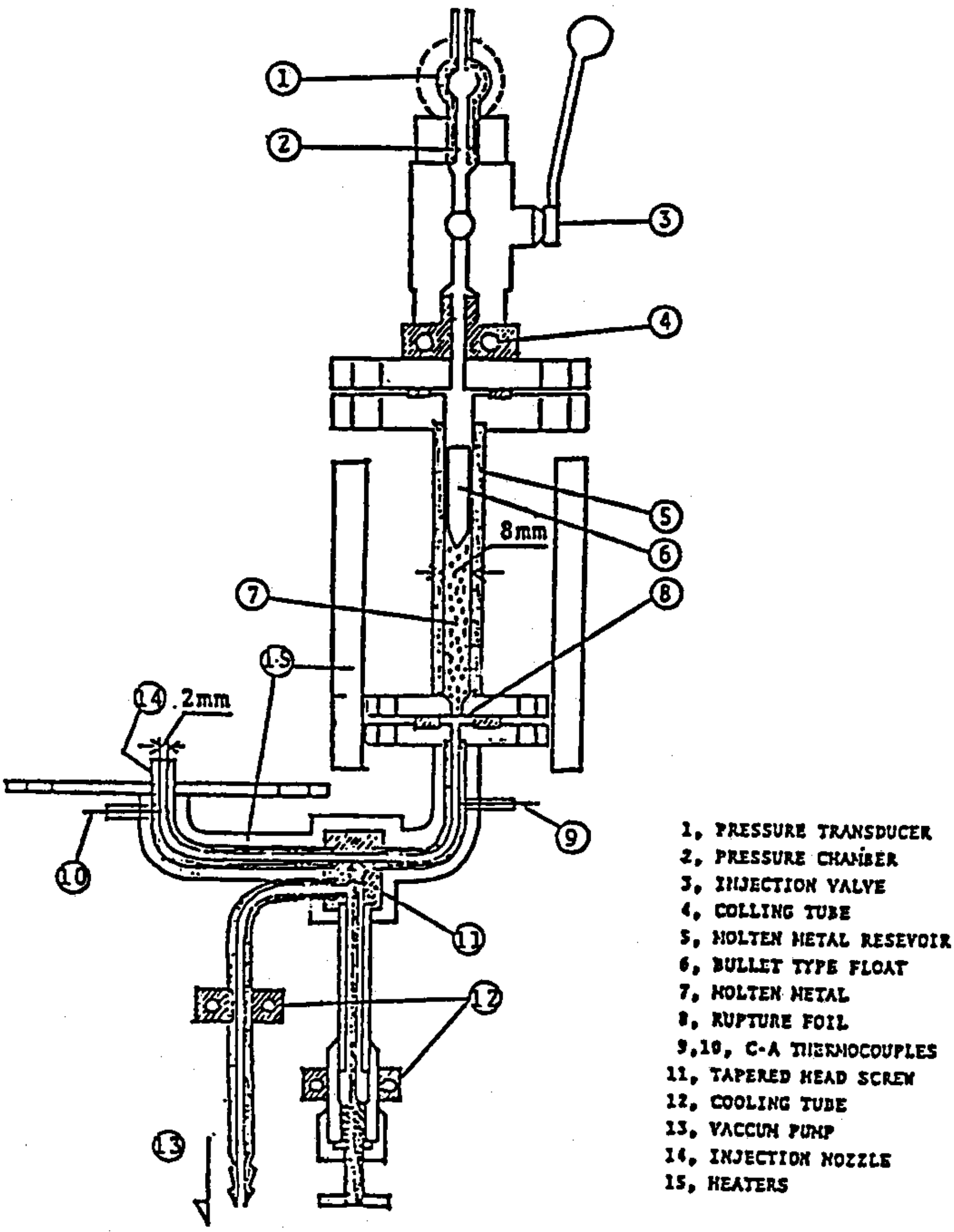


Figure 12: Schematic of Kondo's Experimental Apparatus at University of Tokyo, Japan

Interaction region expanded radially with a velocity of approximately 10 m/s and collapsed after a few milliseconds. They also estimated the conversion ratio from pressure data, defined as the ratio of the total mechanical work done by multiple pressure pulse to the thermal energy of the molten tin injected. For one of typical tests, Run 18, the overall conversion ratio was about 0.03%.

Table 7: Ranges of Experimental Parameters and Results at University of Tokyo, Japan

Parameter	Ranges (Fixed Parameters)	Results
T_f (°C)	308~580 (P_{inj}=1.14, T_w=50) - Multiple explosions	- P_{max} tends to increase linearly (0.5-1.5 MPa)
T_w (°C)	33~98 (T_f=455±12)	- TIZ exists at 63~69 °C
P_{inj} (MPa)	1.14, 0.7	
Condition of Injection Region	Intact (T_f=468, T_w=44)	- Multiple explosions
	Mechanical disturbance (T_f=470,580, T_w=33)	- A 2 mm dia. copper wire located 5 mm above the jet nozzle - No multiple explosions - Extensive fragmentation
	Existence of air bubble (T_f=373, T_w=40)	- No multiple explosions

4.2.2 Bradley's Experiments

Bradley *et al.* [43] performed experiments for a melt injection mode of vapor explosions injecting a small diameter (1.6 mm) jet of molten metal horizontally into subcooled (24 °C) distilled water. They used four types of metal, *e.g.*, mercury, a low melt temperature fusible alloy (Asarolo-158), a lead-tin alloy and tin. The test apparatus consisted of a quenching-fluid tank, molten-metal injection system and the measurement equipment. The molten metal was prepared in the metal sample heating chamber located side of the tank. The metal sample was pressurized with argon gas and injected into distilled water tank by opening a quick-acting solenoid valve through the gate-nozzle. Most case the melt was injected at 0.68 bar through the nozzle of 1.6 mm diameter. For the tin melt injection tests, violent explosion occurred and massive backflow caused jet solidification in nozzle. At 1.36 bar, however, no backflow was caused even with a violent interaction.

4.2.3 Experiments at SNL, USA

Tarbell *et al.* [44] performed two sets experiments to investigate the Direct Containment Heating (DCH) phenomenon in which the molten fuel assumed to be discharged at high velocity through the failed lower vessel into the cavity. Since their main objectives are to study the jet ejection phenomena and debris dispersal behavior when the water is filled in the cavity, these series of experiments are still interested in the melt injection mode of vapor explosions. Total five experiments were performed: two were a part of System Pressure Injection Test (SPIT) series and the other three were a part of High Pressure Melt Streaming (HIPS) series at Sandia National Laboratories in USA.

Table 8 shows the initial experimental conditions. The main differences in two series of tests are the size and integrity of the cavity and the fuel mass; a 1:20 scaled weak cavity and 10 kg thermite for SPIT series (Figure 13) and a 1:10 scaled rigid concrete cavity and 80 kg thermite for HIPS series (Figure 14). In general, the melt at about 2700 K was generated by the thermite reaction in the melt generator which is located top of the cavity. In all tests except the HIPS-6W, the melt was directly injected into a water.

Table 8: Initial test conditions of SPIT and HIPS series tests at SNL, USA

	SPIT-15	SPIT-17	HIPS-4W	HIPS-6W	HIPS-9W
Test section	Acrylic Box	Aluminum Cavity	Concrete Cavity	Concrete Cavity	Concrete Cavity
Scale	–	1:20	1:10	1:10	1:10
Melt	Thermite	Thermite	Thermite	Thermite	Thermite
Melt Mass (kg)	10	10	80	80	80
Gas	N_2	N_2	N_2	CO_2	N_2
Gas Vol. (m^3)	0.03	0.03	0.11	0.11	0.22
Pressure (MPa)	6.8	8.7	7.0	2.5	4.3
Water Temp. (°C)	21.4	20.5	13.1	15.3	18.0
Water Depth (m)	0.51	0.29	0.47	0.47	0.13

In the SPIT-15 test, the melt with a penetration speed of about 42 m/s injected directly into a transparent acrylic box filled with a water. The violent interaction occurred when the leading edge of the melt reached the bottom of the water chamber. There was no evidence of coherent propagation of shock waves as one of typical characteristics of vapor explosions. It may be explained by the fact that the water chamber was not rigid enough to maintain the interaction zone leading subsequent interactions during the first violent interaction. In the SPIT-17 test, however, the 1:20 scaled Zion cavity was constructed of aluminum. It resulted in violent interaction with pressures

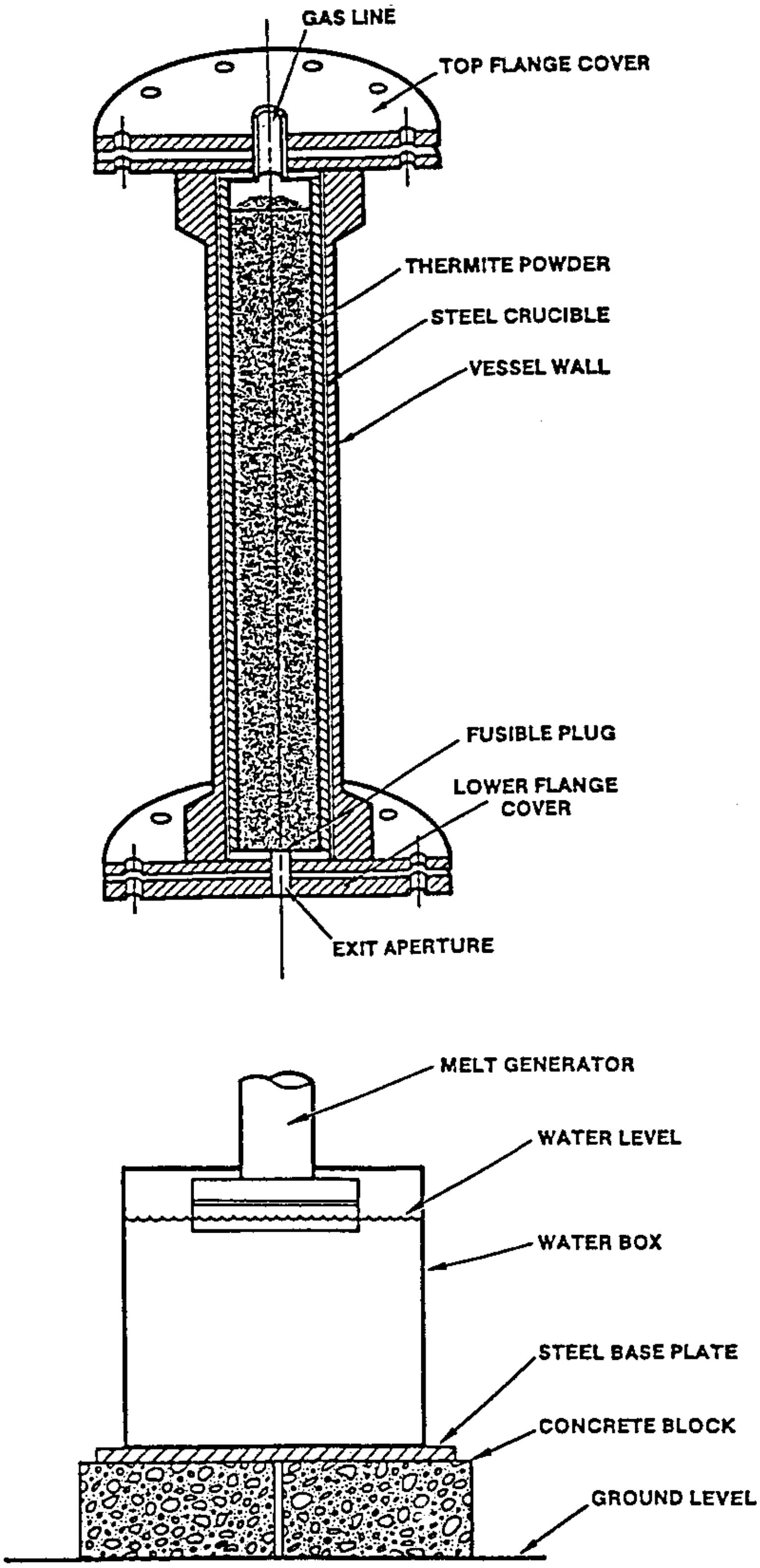
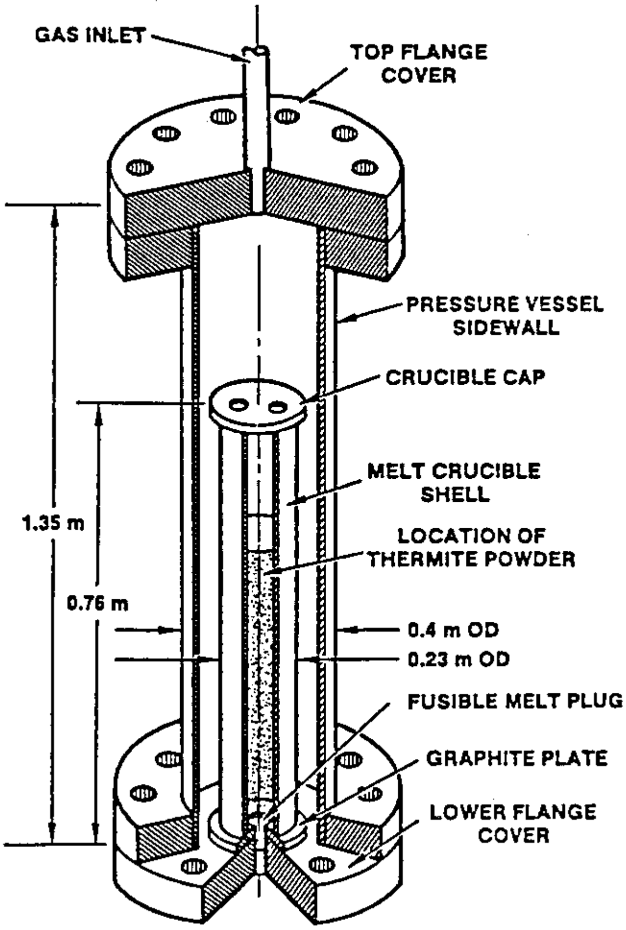


Figure 13: Schematic Diagram of the Melt Generator and Cavity for the STIP Series of Tests in Sandia National Laboratories, USA



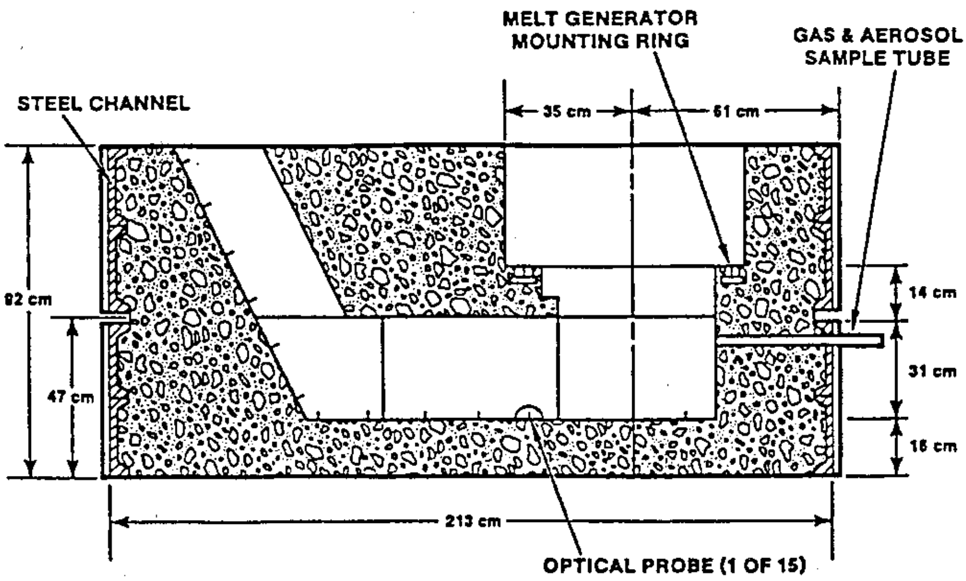


Figure 14: Schematic Diagram of the Melt Generator and Cavity for the HIPS Series of Tests in Sandia National Laboratories, USA

in excess of 207 MPa and comparable duration and rise time of the pressure to some of reported vapor explosion experiment.

In the HIPS series of tests, the 1:10 scaled Zion cavity was made of concrete and 80 kg of thermite was injected. For the HIPS-4W and 6W tests, two different driving gases, nitrogen and carbon dioxide, and initial gas pressures, 7.0 and 2.5 MPa for HPIS-4W and HPIS-6W respectively, were used. Cavities were severely damaged and pressures of almost 10 MPa were recorded as indicators of violent interactions. The authors also noted that the driving gases might effect to the interaction because of their different solubility at different pressures. For the HIPS-9W, the cavity was filled a half of water to investigate the effect of air volume on the melt injection. The damage of the concrete cavity in this test showed that more energetic interactions than either HIPS-4W and 6W tests occurred. Frid [45] reported some of previous SPIT and JETA tests which focused on the expansion and breakup of melt jet during high velocity ejection driven by the gases, *i.e.*, nitrogen, carbon dioxide and hydrogen. The visual observation for nitrogen gas driven melt ejection showed that highly luminous and divergent cone shaped melt jet (about 40 degree at half angle) ejected from the melt generator. The X-ray photograph also shows that the portion of melt was about 10 degree at half angle. It may tell that large amount of melt was fragmented during the ejection but before contacting with water in the case of the HIPS-9W test, providing more efficient mixing condition. It may result in more energetic FCIs.

4.2.4 Fuketa's Experiments at JAERI, Japan

Fuketa *et al.* [46] conducted the in-pile experiments to demonstrate the destructive force generation due to the fuel-coolant interactions during a severe reactivity initiated accident. The experiment was performed in the NSRR facility at JAERI in Japan. The NSRR facility has a capability to provide a large pulsing power to enriched fuel to reach its temperature above the melting point of the uranium dioxide. The test section shown in Figure 15 is composed of the test fuel rode with a length of 279 mm and internal vessel with an inner diameter of 72 mm and total length of 468 mm. In the test rod, four of PWR type fresh UO_2 pellets with a enrichment of 5, 10 and 20 % were stacked. The initial internal pressure of the test rod was varied from 0.1 to 8.5 MPa. The energy deposition was also varied from 1.11 to 1.65 kJ/g. The internal vessel was filled with a water at atmospheric pressure and ambient temperature. The strain gauge type transducer was installed in the internal vessel to measure the pressure pulse generated at the fuel failure.

They correlated the intensities of the destructive force generation with the initial internal pressure of the test fuel rods and fuel debris distributions. The test results shows that the energetics of FCI seemed to increase an order of magnitude as the

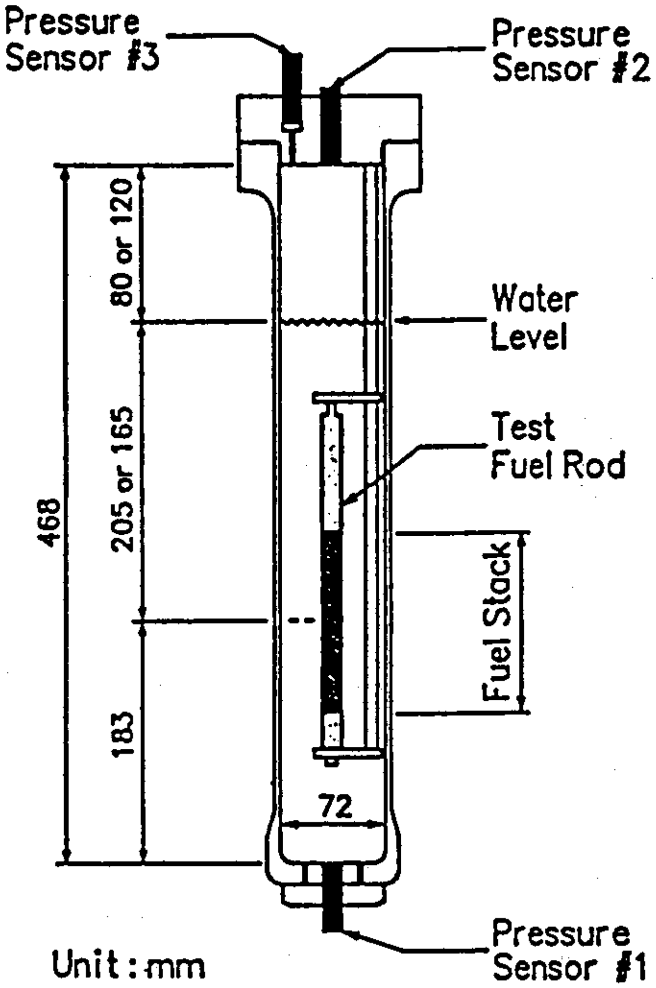


Figure 15: Schematic Diagram of the Test Capsule of Fuketa's Experiments at JAERI, Japan

initial internal fuel rod pressure increased in the case of 10% fuel enrichment. They hypothesized that the high pressure in the fuel rod cause the strong molten fuel jet expel during the rod failure and subsequently provide the enhanced mixing conditions to the fuel and coolant mixture, resulting in more energetic FCIs. The fuel enrichments used in this experiment are much higher than one used in a commercial reactor. In the case of pre-irradiated and low enrichment fuel, they noted that the internal fuel rod pressure increased but also the fuel melt became soft and spongy due to the accumulation of gaseous fission products. They also demonstrated that the specific surface area for the debris, defined as the total surface area of the debris per unit mass, is a good measure of the intensity of FCIs.

5 Summary

In the previous sections we have reviewed an experimental works of vapor explosions in various contact modes, *i.e.*, pouring, stratified, coolant injection and melt injection modes performed to date. In this review, a number of observations which may assist in directing the future research activities to understand and consequently prevent vapor explosions in many industrial processes have been revealed. We will summarize and discussed our finding through this review work in the following subsections.

5.1 The Pouring Mode of Contact

The pouring mode of vapor explosions has been intensively studied by many researchers since it is most likely to occur in molten metal-coolant related accidents in several industrial processes including nuclear power plant. Current experimental efforts provide some insight of the effects of fuel material, geometry and initial thermal conditions on vapor explosions and realistic vapor explosion energetics, directly measuring the work done by the explosions. The experimental data have been collected from precise measurements on mixing, triggering, explosion and expansion phases of vapor explosions in well-controlled experimental facilities. Most large scale experiments mainly focused on studying the propagation and expansion phases of vapor explosion and some 'separate effect' tests [47, 48, 49] for the mixing phase have provided valuable data and contribute to the assessment of mechanistic computer modes. However, more detailed investigations are still required to identify the mechanisms, energetics of vapor explosions and scale available experiment data up to the prototypic conditions.

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5.2 The Stratified Mode of Contact

Most precise experimental works in this contact mode were conducted in relatively small scale facility with fuel simulants, *i.e.*, cryogenic liquids and low melting temperature metals and result in relatively less energetic fuel-coolant interactions. Therefore, it may suggest that some experiments with oxidic fuel simulants with detailed measurement be desired to compare their energetics and behavior of vapor explosions to those from other contact modes. Although a few experiments with oxidic fuel simulant, such as molten thermite, were previously performed, observations from those experiments are mostly lack of detailed measurements.

It is also worthwhile to note that following four factors may affect the energetics of vapor explosions in this contact mode comparing to others; (1) limited mixing phase, (2) limited propagation phase, (3) limited melt participation and (4) system constraint. First, for the mixing phase, relatively no or less breakup of molten fuel than in the pouring mode is anticipated. Comparing to the pouring mode, the molten fuel in this mode experiences less drag forces during the coolant introduction on to the surface of the fuel melt since most tests performed in this mode, the coolant was gently supplied on to the water and immediately separated by the stable vapor film. Some of experiments showed that energetic explosions were observed when there was violent water agitation which may enhanced the mixing conditions. Second, for the propagation, once a local explosion is triggered, the explosion can propagate along the fuel-coolant interface. In this mode, much more energy generated by the explosion should be used for stripping the melt from the bulk of melt at the interface instead of breaking pre-fragmented smaller fuel particles in the case of the pouring mode. Therefore, in a loosely bounded system, a self-sustained interaction can not be maintained. Third, the melt participation during the explosions seems to be quite limited because most experimental results show that only a small part of the melt layer estimated by the coolant penetration depth interacted with coolant. Therefore, directly comparison energetics of vapor explosions in the stratified geometry with others in terms of a initial fuel mass loaded in the system will not be appropriate. Lastly, in the loosely confined stratified geometry, during the propagation and expansion phase, a large amount of the explosion energy is released to the environment, consequently resulting incoherent propagation. However, if the system is well confined; *e.g.*, narrow channel or deep water pool on the melt, mostly energetic explosion was observed. Those factors mostly lessen the energetics of vapor explosions in the stratified geometry. However, if the stratified geometry is established in wider area with relatively strong confinement, the energetic of vapor explosions in this mode may increase.

5.3 The Injection Mode of Contact

5.3.1 The Coolant Injection Mode of Contact

Early studies on the coolant injection mode of vapor explosions were performed for a viewpoint of safety concerns in the fast breeder reactors. A prototypic pair of melt-coolant, uranium dioxide and liquid sodium, was mostly used but the mass of fuel was quite small as order of few grams. Other simulants, for example, NaCl, Al, Sn *etc.*, were also used only for supporting their observations in uranium dioxide and liquid sodium pair. Their experimental measurements were rather limited to phenomenological observation, for example, to verify the spontaneous nucleation theory proposed by Henry*et al.* [50]. The energetics of explosions were also examined by the explosion pressures and visual observations.

Recently, metallic and oxidic fuel simulants with order of tens of kilograms in mass were started to use for this mode of vapor explosions to aim at assessing any possibilities of vapor explosions in systems of which they are concerning and investigating the effects of coolant dynamics on this mode of vapor explosions. It is promising to collect data for the effects of coolant dynamics from these experiments, because they are not clearly reported in early experiments, although the systems they are examining not directly related to a current nuclear power plant. Comparing to the stratified mode of vapor explosions, if the high speed of coolant jet is introduced into the pool of molten liquid and coolant slug is formed rapidly, it is anticipated that more energetic vapor explosion may occur since high speed of coolant jet will penetrate into the melt and relatively large amount of melt will be fragmented due to the dynamic of coolant vaporization inside melt. However, there are counting effects; the degree of penetration and quenching effects in the melt surface due to the high speed of coolant. High speed coolant injection on to the surface of melt may result in rapid quenching of the surface and consequently be solidified due to higher heat transfer, which was commonly observed in jet impingingment phenomena. Therefore, these effects are still quite uncertain. One thing to note is that none of experiments measured or plan to measure the energetics of vapor explosions in this mode as like in a pouring mode.

5.3.2 The Melt Injection Mode of Contact

Authors recognized through this review efforts that experimental researches in the melt injection mode of vapor explosions for a light water reactor application are rarely performed. Only a few experiments, in small scales and for other applications (DCH and RIA), were found and reviewed in thanks of McCahan at Toronto University in Canada [51]. One of main factors in this mode of vapor explosions is the effect of melt jet velocity. If the melt speed increases when it penetrated into coolant, the melt experiences a higher relative velocity against the coolant and much finer melt fragmentation is expected than one in the pouring mode mainly driven by a gravitational head. Such an enhanced fragmentation during the mixing phase may result in two cases: one is to generate more energetic vapor explosion and another to lead rapid quenching of fine fragments consequently resulting less energetic interactions. Most previous experiments were not sufficient to answer for such a question at present.

6 Conclusions and Recommendations

As discussed in previous subsections, relatively a few experimental data are available for stratified and injection modes of vapor explosions in comparison with the pouring mode. Since most previous works for stratified and injection modes provided rather phenomenological results, more detailed and precise measurements of mixing conditions and energetics and dynamics of vapor explosions to build a database for assessing currently available mechanistic models are necessary. In specific, experimental studies on injection mode of vapor explosions can assist the development of breakup and fragmentation models which are one of mostly uncertain areas to model the vapor explosion phenomena. It will be also useful to investigate the coolability of molten fuel and likelihood of vapor explosions if the water injects to a pool of molten fuel and to build the database for the high-pressure ex-vessel vapor explosion in a light water reactor and fuel melt ejection in a heavy water reactor.

Most experimental investigations in vapor explosions, have been performed with various simulants used for the actual fuel material in smaller geometry than the prototypic system. Therefore, it is of importance to establish an appropriate scaling law for the vapor explosion to bridge the experimental results to the prototypic situations. In the theoretical approach, however, a direct usage of governing equations to scale the phenomenon is not practical because the details of vapor explosion dynamics, involving mixing, fuel fragmentation and explosion propagation, are still quite uncertain. Rather, it will be more practical to consider which initial and boundary conditions are of great importance and how to scale them in the experiments. In the sense, it will be useful to perform vapor explosion experiments in an experimental facility which has abilities not only well to control the initial and boundary experimental conditions, but also directly to measure the energetics of vapor explosions. It will be also beneficial to identify the mechanisms and to scale the energetics of vapor explosions in various contact modes in terms of a precisely measured conversion ratio if the various contact modes of vapor explosions can be simultaneously examined at the facility.

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