Int. J. Heat Mass Transfer. Vol. 21, pp. 325–333. Pergamon Press 1978. Printed in Great Britain

THERMAL INTERACTION FOR MOLTEN TIN DROPPED INTO WATER

V. H. ARAKERI, I. CATTON, W. E. KASTENBERG and M. S. PLESSET
Energy and Kinetics Department, University of California, Los Angeles, CA 90024, U.S.A.

(*Received* 18 *March* 1976 *and in revised form* 11 *April* 1977)

Abstract—Multiflash photography with extremely short duration exposure times per flash have been used to observe the interaction of molten tin dropped into a water bath. Detailed photographic evidence is presented which demonstrates that transition, or nucleate boiling, is a possible triggering mechanism for vapour explosions. It was also found that the thermal constraints required to produce vapour explosions could be relaxed by introducing a stable thermal stratification within the coolant. In the present work, the threshold value of the initial tin temperature required for vapour explosion was reduced from about 500 to 343°C.

1. INTRODUCTION

IN RECENT years [1, 2] considerable attention has been given in understanding the consequences of molten fuel coming into contact with a coolant in the event of a hypothetical reactor core accident. In the past, accidents have been recorded [3] in non-nuclear industries where the mixing of two liquids at considerably different temperatures has produced "explosive" vapour formation resulting in shock waves in the cold liquid causing mechanical damage and with added possibility of health hazards. The phenomenon of explosive vapour formation causing shock waves is commonly termed a "vapour explosion" or a "thermal explosion" simply because the initial source of energy is of thermal origin rather than of chemical origin or of nuclear origin. The underwater explosions resulting in shock waves caused by energy sources which are of chemical origin are well documented [4]. In the case of chemical explosions the mechanism for efficient energy release to cause shock waves is fairly well understood. However, efficient energy release mechanism in the cases of thermal energy sources is not all adequately understood. It is now known that the efficient release of energy within explosive time scales (order of milliseconds) is not possible through usual heat-transfer processes including nucleate boiling. In addition, it is known that explosive energy release is also not possible if the hot material is in solid form at the instant of contact with a coolant. In view of these observations and experimental evidence [5] of area enhancement of the hot material accompanying vapour explosions, one of the postulated mechanisms for efficient energy release is through rapid interfacial area enhancement by the rapid dispersal of the hot material into the coolant. The observed area enhancement of the hot material after completion of the interaction is commonly termed as "fragmentation".

Several mechanisms [6] have been proposed to explain fragmentation observed in numerous experimental studies [7]. Most of these consider dispersal of the hot material as a single-stage process. However, from a recent experimental study Board *et al.* [8] note the possibility that the several mechanisms considered by Cronenberg *et al.* [6] may be a single-stage initiating process for mechanical mixing but the subsequent dispersion is through spatial propagation via a feedback mechanism. Based on several experimental observations the feedback mechanism is postulated to be successive growth and collapse of vapour regions. It is also pointed out that the physical process in spatial propagation is formation of a liquid jet [9] during collapse of a vapour region and which upon penetrating the hot molten material causes dispersal releasing thermal energy in time scales required for explosive vapour generation.

A mechanism for explosive energy release without requiring dispersal of the hot meterial has been proposed by Katz *et al.* [10]. The explanation is based on the hypothesis that the transition boiling regime in the classical boiling curve with solids [11] is not applicable due to lack of nucleation sites at liquid–liquid interfaces. Thus, without nucleation sites the more volatile liquid is heated to superheat limits associated with "homogeneous nucleation" upon which explosive vapour formation takes place. A similar hypothesis has been utilized by Fauske [12] to explain the explosive interactions observed by Armstrong [13] when liquid sodium was injected into molten uranium dioxide. In a later study, Fauske [14] has indicated that vapour explosions when a hot liquid is mostly surrounded by a cold liquid are only possible if the calculated interface temperature is greater than the spontaneous nucleation temperature* of the cold liquid. From this condition one may expect a sharp lower threshold value for the initial temperature of the hot liquid for the occurrence of vapour explosions. This has been noted, for example, by Henry *et al.* [15] for mineral oil and freon system. Similar threshold observations have also been observed by Board *et al.* [8] for molten tin and water system.

However, it is not at all convincing that the threshold observations for the occurrence of vapour explosions in all liquid–liquid systems are associated with either

* For perfectly wetting systems the spontaneous nucleation temperature is equal to the homogenous nucleation temperature.

homogeneous or spontaneous nucleation characteristics of the more volatile liquid. In particular this is so, since detailed photographic observations suitable for resolving transient events characteristic of vapour explosions are not available. For this reason, it was decided to study molten tin and water interaction by the multi-flash photographic technique made possible by readily available light sources* with exposure times per flash of the order of 1 μs. It was believed that photographs obtained with such duration flashes should be able to show considerably more details of the interaction than possible with conventional high speed photographic techniques [8].

During the course of the photographic study it was found that temperature stratification within the coolant had a significant effect on the occurrence of vapour explosions. In particular, it was discovered that explosive interactions could take place for lower initial tin temperatures in a thermally stratified water bath than was possible in a uniform temperature water bath. Thus, the investigation was extended to see if vapour explosions would be possible when the initial tin temperature is low enough such that the calculated interface temperature is lower than the homogeneous nucleation temperature of water.

2. EXPERIMENT

A test chamber fabricated with four aluminium panels and divided into two sections was utilized for the present experimental work. Each panel was 0.635 cm in thickness and about 65 cm in height. The upper section of the test chamber contained a graphite crucible in which the metal was heated by two half circular electrical heaters (each rated at 250 W). The lower section of the test chamber contained about 35.0 l of water which acted as the coolant medium for the present tests. In addition, each panel in the lower section was equipped with a 7.62 cm × 10.16 cm glass window for photographic purposes. Further details of the test chamber may be found in reference [16].

Pressure measurements were made with a Celesco† model LC-10 hydrophone. The hydrophone was located in the lower section of the test chamber about 25 cm away from the center of the water bath. The hydrophone used in the present experiments had essentially a flat response up to about 200 kHz and the sensitivity with the cable was 2.78 V bar^{-1}.

The light sources for multiflash photography were two General Radio stroboscopes (model 1538). These were capable of flashing at a maximum rate of 2500 flashes per second (fps) with quoted exposure time per flash of about 0.3 μs. At lower flashing rates of the order of 200 fps the exposure time per flash increases to about 1 μS. Twenty-five to thirty multiflash photographs of the event were recorded on a 10 cm × 12.7 cm sheet film rotating at the image plane. Typical rotation speed required at a framing rate of one thousand photographs per second was about 1725 rev/min.

In order to record only one set of multiflash photographs per film, the flashing of the stroboscopes to a limited number of flashes was achieved externally. First, the motion of the shuttle to drop the molten metal from the crucible was sensed with a photo electric pick-up and the signal was amplified and delayed through a delay circuit. Then, the output from the delay circuit was used to trigger a scope which produced a negative gate. This gate was fed into an on–off or a coincidence circuit which also had a signal from a signal generator as a second input. The output of the on–off circuit contained the signal from the signal generator only for the limited time period when the gate from one scope had negative going voltage. This output signal from the on–off circuit was used to drive the stroboscopes. The circuitry associated with this method of sychronizing the multiflash photography with the event is shown in the form of a schematic diagram in Fig. 1. It may be noted here that the stroboscopes provided considerably more light at lower flashing rates of the order of 200 fps than at the highest possible flashing rate of 2500 fps. This additional light at lower flashing rates enabled one to photograph some details of the boiling mode existing on the molten metal surface as it traversed through the coolant. For this reason a majority of the photographs were recorded at a rate of 200 fps.

Present tests were conducted with 25 g of molten tin initially at temperatures of 787, 676, 537, 426 and 343°C dropped into a tank of uniform temperature water bath of various temperatures within a range of 8–52°C. The nominal drop height for these tests was 11.25 cm. Additional tests were conducted with the same initial tin temperatures mentioned above but with a temperature stratified water bath. One method of obtaining temperature stratification within the coolant was by filling the lower section of the test chamber with water and turning on the crucible heater. Some typical temperature stratifications obtained by this technique after a time lapse of about 2 h and a crucible temperature of 760°C are shown in Figs. 2(a) and (b). Another method used to obtain temperature stratification was the insertion of a 100 W calrod heater through the crucible into the water to a depth of about 15 cm. With this technique it was possible to obtain sharper temperature gradients at the top as may be seen by comparing the temperature profile shown in Fig. 2(c) with that shown in Fig. 2(a). In the present experiments tin was melted in the crucible with the presence of air and also in the presence of a constant supply of argon gas fed through the top of the test chamber. No noticeable able differences in the experimental results were noted due to the above mentioned difference in the environment of tin melting.

3. RESULTS AND DISCUSSION

3.1. *Presence of multiple interactions within a vapour explosion*

With the present photographic technique, it was possible to observe some new details of the interaction between molten tin and water. From the photographs,

* General Radio stroboscopes.

† Celesco Industries, Canoga Park, CA.

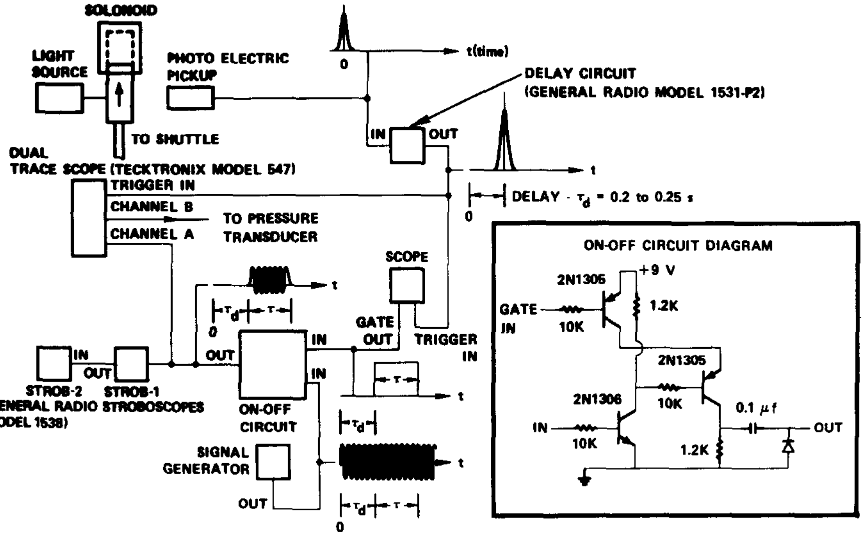

FIG. 1. Schematic diagram illustrating the technique of synchronizing the multiflash photography with the event.

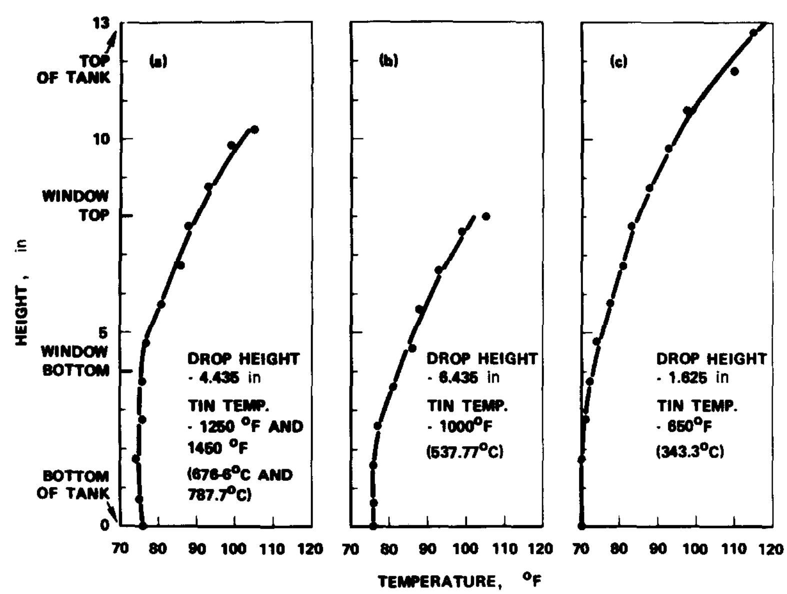

FIG. 2. Measured temperature variation in the water bath for stratified coolant bath tests for different initial tin temperatures.

it was noted that the molten tin initially in the shape of a cylinder distorts to an irregular shape as it traverses through the coolant. In addition, in most cases the interaction leading to vapour explosion was observed to begin locally at the distortions. An example of this is illustrated in the sequence of photographs obtained at 2500 fps and shown in Fig. 3. Four distinct interactions are observed to lead to a vapour explosion within a time period of about 10 ms. It may, however, be noted that the growth of the fourth interaction which presumably resulted in the peak pressure pulse (pressure record from the transducer is also shown in Fig. 3) is complete within a time period of approximately 2 ms. These findings are in excellent agreement with the observations of Board *et al.* [8] from similar experiments. However, present photographic studies could not support their proposed model of successive growth and collapse of vapour regions leading to a thermal explosion. In addition, the sequence of photographs recorded at 2500 fps did not reveal the triggering mechanism leading to the first interaction and subsequently the vapour explosion. The primary difficulty at this framing rate was the limited amount of light available for front illumination of the molten metal surface. However, a sequence of photographs obtained at 200 fps did indicate additional details regarding the triggering mechanism of an explosive interaction, as described below.

3.2. *Transition or nucleate boiling as a triggering mechanism*

In the first frame of Fig. 4, a smooth and glossy surface at the molten metal front is apparent which strongly suggests the presence of film boiling. In about

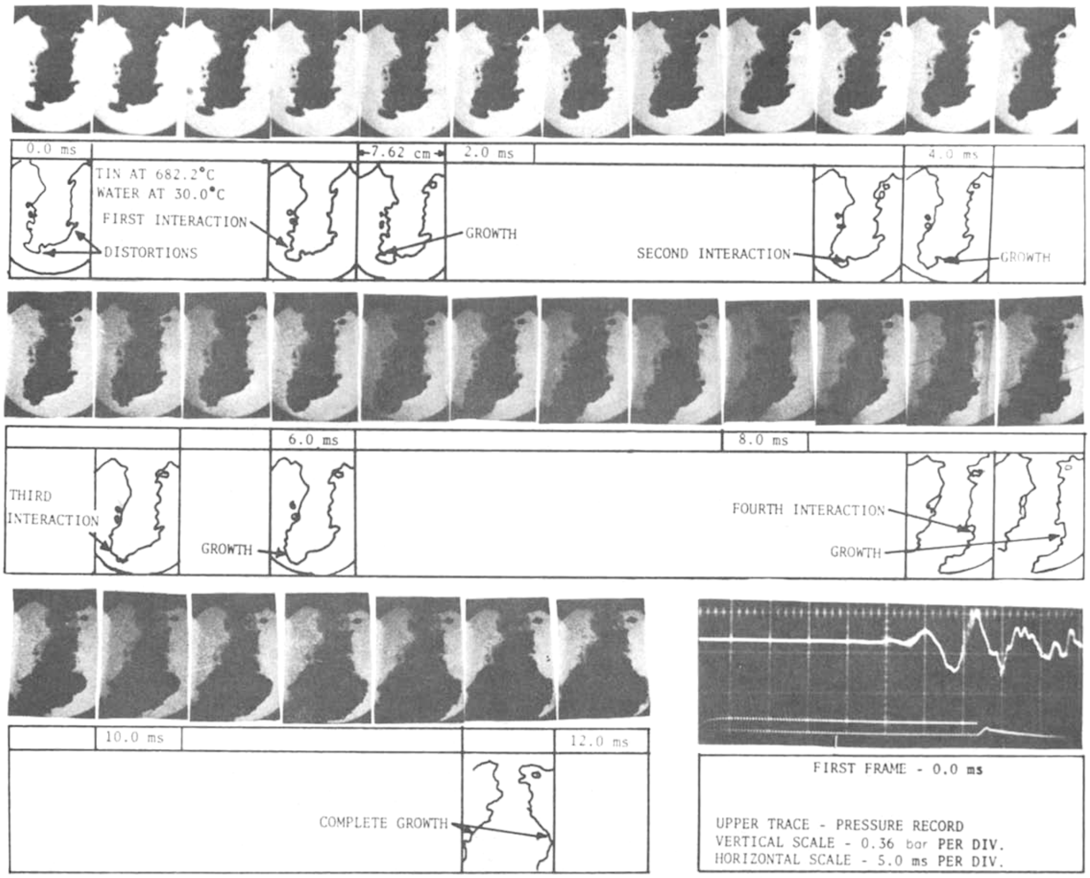

FIG. 3. Multiflash photographs obtained at 2500 frames per second show the presence of four separate interactions.

the third frame, a small portion of the molten metal is observed to form a finger-like protrusion at the front. Initially, both the finger and the bulk of the molten metal is observed to be in the film boiling regime. This state of affairs is seen to persist up to the tenth frame. However, in the eleventh frame, transition boiling is indicated at the tip of the finger-like protrusion. In the twelfth frame, nucleate boiling is clearly visible at the tip and in the fourteenth frame, the finger-like protrusion is observed to expand suddenly indicating the beginning of an explosive interaction. In the same frame, the bulk of the molten metal is still intact with some nucleate boiling apparent at the base. In the fifteenth frame, the bulk is also observed to expand suddenly and the maximum expansion is reached by the sixteenth frame. Thus, the sequence of photographs just described show that explosive interaction began on the finger-like protrusion after transition or nucleate boiling had been reached and either this local interaction propagated through the rest of the molten metal or was responsible in triggering further interactions on the rest of the molten metal surface to result in a vapour explosion.

Another sequence of photographs presented in Fig. 5 shows the presence of nucleate boiling on the bulk of the molten metal prior to the occurence of explosive interaction resulting in a pressure pulse within the coolant medium. In this case, nucleate boiling is observed to persist for more than 50 ms on most of the molten metal surface prior to the eventual occurence of a vapour explosion. Again, this sequence of photographs shows that transition or nucleate boiling appears to be a triggering mechanism for an explosive interaction.

In addition, the persistence of nucleate boiling for about 50 ms prior to the occurence of explosive interaction indicates that apparently the explosion noted was not as a consequence of superheating of the coolant to a limiting threshold value associated with homogenous nucleation [10–12]. A more likely explanation for the observed explosion in Fig. 5 is the dispersal of hot material into the coolant since the final debris did indicate significant porous type of fragmentation. The above observation based on photographic evidence is supported further from the noted effect of stratification in the coolant on the occurrence of vapour explosions as described below.

3.3. *Effect of thermal stratification in the coolant*

The measured peak pressure magnitudes with and without thermally stratified water bath at various initial tin temperatures are shown in Fig. 6. The measured temperature profiles within the coolant for most of the thermally stratified water bath tests are shown in Fig. 2. The required temperatures distribution within the water bath to produce vapour explosions at the lower tin

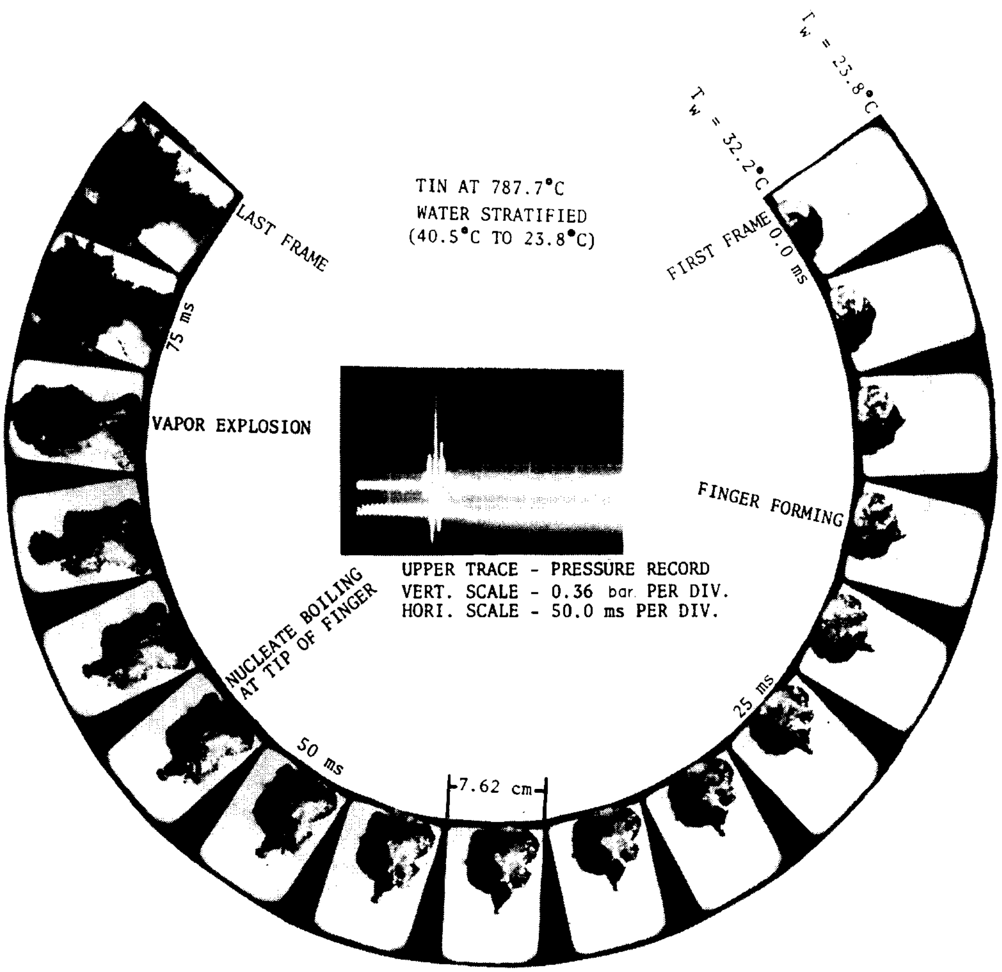

FIG. 4. Sequence of photographs illustrating the development of nucleate boiling prior to explosive interaction on portion of the molten metal surface.

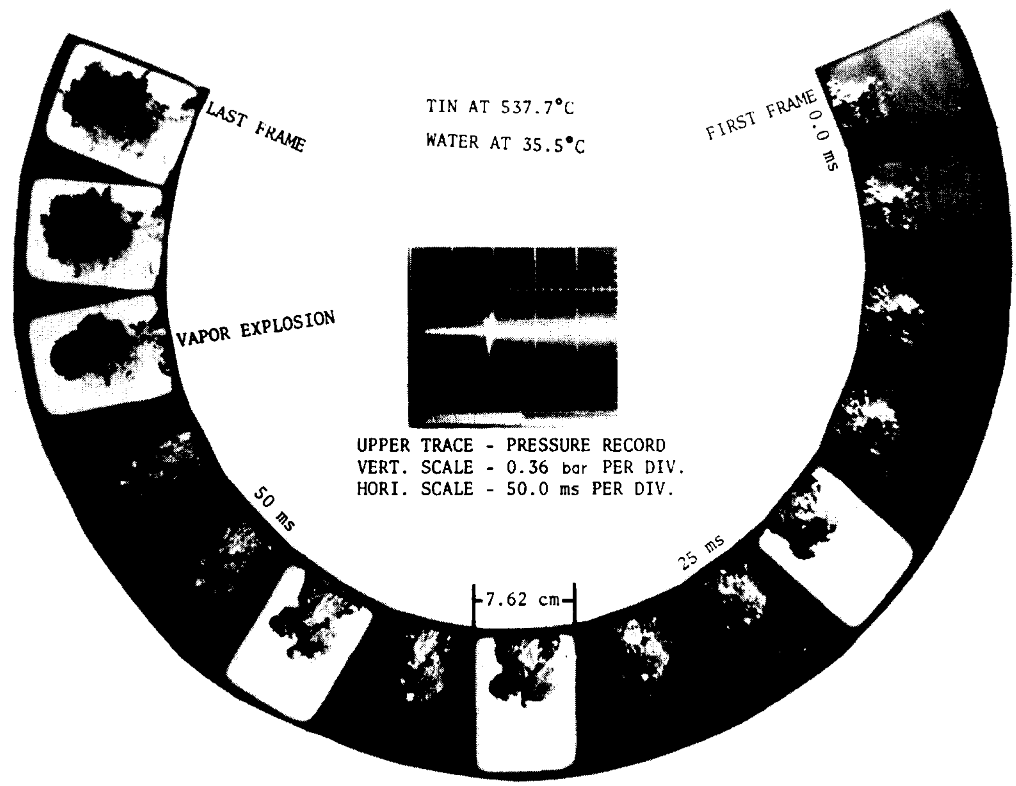

FIG. 5. Sequence of photographs illustrate the presence of nucleate boiling on the molten metal surface for up to 50 ms prior to the occurrence of vapor explosion.

temperatures of 537, 426 and 343°C, were determined by trial and error. It was found that vapour explosions at these initial tin temperatures were possible only if the temperatures at the top and bottom of the water bath were within 5°C of those shown in Fig. 2. Generally, if on the plus side the molten metal would solidify with little fragmentation and if on the minus side, fragmentation would be observed with no detectable interaction taking place.

It is clear from the comparison afforded in Fig. 6 that the threshold initial tin temperature required to produce pressure pulse within the coolant is considerably reduced by introducing a stable thermal stratification in the water bath. With uniform temperature water bath, no vapour explosions were detected and initial tin temperatures of 426°C or lower. However, photographic evidence of persistent nucleate boiling on the molten tin surface prior to the occurrence of explosive interaction as noted earlier (Fig. 5).

The effect of thermal stratification in the development of vapour explosions may be likend to the collapse of cavitation bubbles as they pass from low pressure regions to high pressure regions. Thus, the thermal stratification may facilitate destabilization of an existing vapour film to promote transition or nucleate boiling. Some evidence for such a happening is presented in the sequence of photographs in Fig. 4. In the first frame of Fig. 4, a smooth and glossy surface at the front is indicated strongly suggesting the presence of film boiling. In about the third frame a small portion of the molten metal is observed to form a finger-like protrusion at the front. Initially, both the finger and

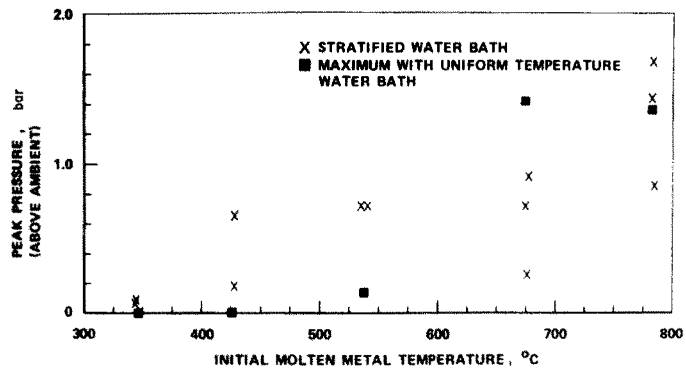

FIG. 6. Peak pressure vs initial tin temperature with and without thermal stratification in the water bath. For uniform temperature water bath tests maximum value of the peak pressure measured for a coolant temperature range of 8–52°C are shown.

with thermal stratification vapour explosions were detected at initial tin temperature* of as low as 343°C. It is important to point out here that the calculated interface temperature based on the observed threshold temperature for uniform temperature water bath (>426°C) is at least 40°C above the estimated temperature for homogenous nucleation (~314°C) in water; whereas, the calculated interface temperature based on the threshold temperature with thermally stratified water bath tests (~343°C)† is about 20°C below the temperature for homogenous nucleation in water. Thus, the uniform temperature water bath tests (which are also in fairly close agreement with the observations of Board *et al.* [8]) may tend to support the hypothesis that vapour explosion is a phenomenon associated with homogenous nucleation in the more volatile liquid supporting other similar experimental observations [11, 15]. However, present findings with thermally stratified water bath tests certainly show that vapour explosions are possible without heating the coolant to superheat limit associated with homogenous nucleation. This observation is also consistent with the present the bulk of the metal are observed to be in the film boiling regime. This state of affairs is seen to persist up to the tenth frame. However, in the eleventh frame, transition boiling is indicated at the tip of the finger-like protrusion. In the next (twelfth) frame nucleate boiling is clearly visible at the tip and to a lesser extent boiling is also visible in the thirteenth frame again the same area. In the fourteenth frame, the tip and finger are observed to expand suddenly indicating the beginning of an explosive interaction. It may be noted that, in the same frame, the bulk of the molten metal is still intact but, with some nucleate boiling now apparent at the base. In the fifteenth frame, the bulk is also observed to expand suddenly and the maximum expansion is reached by the sixteenth frame. Thus, the sequence of photographs just described clearly show that interaction began on the tip after transition or nucleate boiling had been reached and either this local interaction propagated through the rest of the molten metal or was responsible in triggering further interactions in the rest of the molten metal to result in a vapour explosion.

*Melting temperature of tin is about 230°C.

†The tin temperature will be below the instantaneous interface temperature due to cooling during the film boiling regime.

3.4. *Nature of fragmentation*

It is apparent from the illustrated pressure pulse recordings that considerable variation in the observed magnitude of the peak pressure exists. Examination of the final product indicated that the extent of fragmentation was directly related to the measured peak pressure pulse for tests with or without stratified water bath. Basically three types of fragmentation were observed as follows: (i) fine porous fragmentation, (ii) coarse porous fragmentation and (iii) non-porous solidified distorted fragmentation. It was not possible to ascribe any quantitative information with respect to the area enhancement due to various types of fragmentation. However, qualitatively the area enhancement decreased gradually by going from type (i) to type (iii).

In most cases the final product with dominant fragmentation of the types (ii) and (iii) stayed intact. With fragmentation of type (i), in some cases the final product was intact but in other cases the final product was split further. In extreme cases, the final product was scattered at the bottom in fine powder form. This type of final debris was generally observed for tests with initial tin temperature of 787 and 676°C and stratified water bath. In addition, these tests were accompanied by the presence of a strong pressure pulse (greater than 1 bar) as detected by the pressure transducer. Typically, fine porous type of fragmentation was observed for tests with initial tin temperatures of 787 and 676°C and uniform temperature water bath. These tests were accompanied with pressure pulses on the order of 1 bar. Even lower magnitude pressure pulses were detected for the cases when the dominant fragmentation was of a coarse porous nature. It may be pointed out here that for fixed initial tin temperature the extent of fragmentation was always greater for tests with stratified temperature water bath than for tests with uniform temperature water bath. At the lowest initial tin temperatures of 426 and 343°C very little or no fragmentation was observed for tests with uniform temperature water bath whereas significant fragmentation was observed for tests with stratified temperature water bath with the same initial tin temperatures. In any case, it was clear that for tests with or without stratified water bath, the magnitude of pressure pulse detected was directly related to the extent of fragmentation observed from the final product. In particular, it was found that tests with dominant fine porous type of fragmentation were always accompanied by a detactable pressure pulse. However, tests with local fine porous fragmentation or dominant coarse porous fragmentation were not always accompanied by a detectable pressure pulse. A summary of the general qualitative relationship observed in present experiments between the type and extent of fragmentation with the detected pressure pulse is presented in Table 1.

Table 1. Qualitative relationship between nature of fragmentation and magnitude of peak pressure pulse

Type of fragmentation	Range of peak pressure pulse
(a) Fine porous fragmentation with final product split up	>1
(b) Dominant fine porous fragmentation with final product intact	1.0–0.75
(c) Coarse porous fragmentation with some fine porous fragmentation	0.75–0.4
(d) Dominant coarse porous fragmentation	0.4–0.2
(e) Dominant non-porous solidified distorted fragmentation with local fine porous fragmentation	0.2–0.0
(f) Dominant non-porous solidified distorted fragmentation with or without local coarse porous fragmentation	0.0

4. REMARKS ON THE OCCURRENCE OF VAPOUR EXPLOSIONS

There is strong evidence from the photographs (Fig. 4) that the effect of stratification in the coolant is to induce transition or nucleate boiling locally which initiates an explosive interaction. Similar local initiation of an explosive interaction without thermal stratification in the coolant is possible if the molten metal distorts significantly to produce finger-like protrusions at the surface (Fig. 3). In either case, the local interaction then propagates spatially within the rest of the molten metal to result in a coherent vapour explosion. A possible mechanism for spatial propagation of a local explosive interaction has been proposed by Board *et al.* [8]. On the other hand, if transition or nucleate boiling sets in on most of the molten metal surface prior to development of significant distortions at the surface, then the possibilities for multiple incoherent explosive interactions are increased without resulting in a vapour explosion. The chances of this occurring are great if the coolant at uniform temperature is highly subcooled or if the initial tin temperature is low. Thus, present experimental findings suggests that the threshold temperature is associated with whether transition or nucleate boiling can set-in locally or on the bulk of the surface rather than with the interface criterion required for homogenous nucleation in the coolant. It is perhaps this mechanism which is responsible for the observed threshold initial tin temperature for the occurrence of vapour explosions in uniform temperature water bath (Fig. 6). A possible chain of physical processes required for the development of a vapour explosion based on present photographic observations is shown in Fig. 7.

The spatial propagation of a local interaction which is required to produce extensive fragmentation and vapour explosion may itself be characterized in two different categories; namely, (i) surface spatial propagation, and (ii) internal spatial propagation. In (i), the propagation takes place by a local interaction inducing further interactions on the surface of the molten metal. In (ii), the propagation takes place internally as an interaction or fragmentation front much like a detonation wave in the case of chemical explosives. Of course, in large mass systems, the combined propagation due to both types cannot be ruled out.

The surface propagation may actually take place by local interaction promoting further transition or nucleate boiling if the rest of the molten metal is under film boiling regime. Some evidence for this mechanism

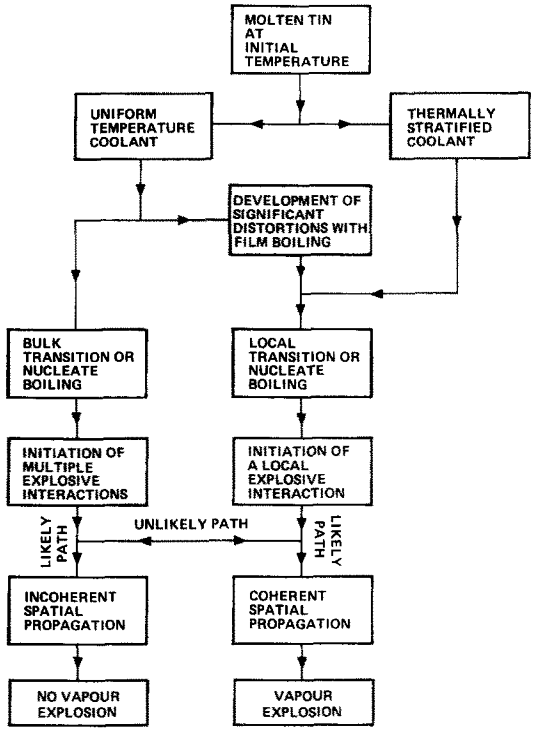

FIG. 7. Chain of physical processes involved in the development of a vapor explosion. The possible role of thermal stratification in the coolant is also illustrated.

of propagation is apparent in the sequence of photographs shown in Fig. 4 and discussed earlier. However, if the bulk is already under nucleate or transition boiling regime, then the propagation may take place by promoting collapse of vapour bubbles in additional areas. The surface propagation will probably be very effective in the presence of a vapor film which can act as an excellent communicating medium resulting in extensive fragmentation and a vapor explosion. In the absence of a vapor film, inefficient propagation may take place which produces incoherent multiple interactions resulting in fragmentation but not necessarily a vapor explosion.

One of the conditions for efficient internal propagation will be that the molten metal remain intact without predispersing at the instant of the initiation of a local interaction. A mechanism for such propagation through dispersal of hot material into coolant to produce extensive fragmentation and vapor explosion has been proposed by Board *et al.* [8] as discussed previously. However, neither the work of Board *et al.* nor the present work suggests exact conditions required for rapid dispersal of hot material to produce vapor explosions. Most of the present observations do, however, bring out the point that vapor explosions are apparently due to rapid area enhancement of the hot material rather than achievement of limiting superheats in the coolant. This contention is supported from the following two important observations.

(i) In Fig. 5 the persistence of nucleate boiling for about 50 ms prior to the occurrence of an explosive interaction indicates that apparently the explosion was not as a consequence of superheating of the coolant due to lack of nucleation sites at the liquid-liquid interface.

(ii) In Fig. 6 the effect of thermal stratification in the coolant is to reduce the threshold temperature required to cause explosive interaction between molten tin and water.

It is not certain as to how nucleate boiling may trigger the initial interaction. However, it may be suspected that the vapor bubble at the molten metal surface under transient heat conditions may behave similarly to a cavitation bubble including the collapse stages. Thus, a coolant jet [9] penetrating the molten metal may trigger an interaction. This local interaction will be expected to propagate efficiently if film boiling regime exists on bulk of the molten metal surface, since the vapor film can act as an excellent communicating medium for spatial propagation. This will not be the case if most of the molten metal surface is under nucleate boiling regime, due to the repeated acoustic impedance mismatching at vapor–liquid interfaces. In addition, the molten metal will cool rapidly if most of the surface is under nucleate boiling regime losing its initial available thermal energy. Thus, for the above two reasons it is contended that if nucleate boiling occurs on most of the surface then the likelihood of a vapor explosion is considerably reduced even though interfacial area enhancement may still take place.

5. CONCLUSIONS

Thermal interaction of molten tin dropped into a water bath has been observed by the use of multiflash photographic techniques developed for this purpose. In one sequence of photographs, a portion of the bulk molten metal is observed to go into transition or nucleate boiling after which an explosive interaction is initiated. In another sequence of photographs, nucleate boiling on bulk of the molten metal surface is observed to persist up to 50 ms after which a vapor explosion is developed. These observations show that the presence of transition or nucleate boiling is a possible triggering mechanism for the occurrence of vapor explosions in present experiments. In addition, these same observations show that vapor explosions are not just caused by superheating of the coolant upon contact with hot liquid as a result of a lack of nucleation sites.

The threshold value of the initial molten tin temperature required for the occurrence of a vapor explosion was found to be considerably reduced by introducing a stable thermal stratification in the water bath. In present tests, the reduction was sufficient to show that vapor explosions are possible even if the calculated interface temperature is below the homogenous nucleation temperature of water; thus, indicating that vapor explosions are possible without achieving the limiting superheats in the coolant associated with homogeneous nucleation.

The observed effect of thermal stratification on the phenomenon of vapor explosions is of particular significance in predicting the possible occurrence of vapor explosions in a reactor environment based on laboratory studies. Thermal stratification within a reactor core does exist and most similutude laboratory tests, to date, have been conducted in uniform temperature coolant mediums.

Acknowledgements—This work was supported by the Reactor Safety Division of the Nuclear Regulatory Commission, under Agreement No. AT(04-3)-34, P.A. 223, Mod. 1. This assistance is gratefully acknowledged.

REFERENCES

1. L. C. Witte and J. E. Cox, Thermal explosion hazards, *Adv. Nucl. Sci. Technol.* 7, 329 (1973).
2. *Proceedings of the Fast Reactor Safety Meeting*, USAEC-CONF-740401, Part 1, held at Beverly Hills, CA, pp. 883–1005 (1974).
3. L. C. Witte *et al.*, The vapor explosion, *J. Metals* **22**, 39–44 (1970).
4. R. Cole, *Underwater Explosions.* Princeton University Press, Princeton (1948).
5. R. W. Wright, Kinetic studies of heterogeneous water reactors, Annual Summary Rep. STR-372-30, TRW Systems, Los Angeles (1973).
6. A. W. Conenberg and M. H. Gromles, A review of fragmentation on models relative to molten UO_2 break-up when quenced in sodium coolant, ASME paper No. 74-WA/HT-42, Presented at the ASME Winter Annual Meeting, New York (1974).
7. M. S. Kazimi, Theoretical studies of some aspects of molten fuel coolant thermal interactions, Sc.D. thesis, Nucl. Engng Dept. Rep. No. MIT NE-155, MIT, Cambridge (1973).
8. S. J. Board, C. L. Farmer and D. H. Poole, Fragmentation in thermal explosions, *Int. J. Heat Mass Transfer* **17**, 331–339 (1974).
9. M. S. Plesset and R. E. Chapman, Collapse of an initially spherical vapor cavity in the neighbourhood of the solid boundary, *J. Fluid Mech.* **47**, 283 (1971).
10. D. L. Katz and C. M. Sliepcevich, LNG/water explosions: cause and effect, *Hydrocarb. Process.* **50**, 240 (1971).
11. R. Cole, Boiling Nucleation, in *Advances in Heat Transfer*, Vol. 10, p. 85. Academic Press, New York (1974).
12. H. K. Fauske, On the mechanism of uranium dioxide–sodium explosive interactions, *Nucl. Sci. Engng* **51**, 95–101 (1973).
13. D. R. Armstrong, Reactor Development Program Progress Report, ANL-RD-2, Argonne National Laboratory, IL (1972).
14. H. K. Fauske, Some aspects of liquid–liquid heat transfer and explosive boiling, in *Proceedings of ANS Conf. on Fast Reactor Safety*, Beverly Hills, CA, p. 992 (1974).
15. R. E. Henry *et al.*, Large scale vapor explosion, in *Proceedings of ANS Conf. on Fast Reactor Safety*, Beverly Hills, CA, p. 922 (1974).
16. V. H. Arakeri, I. Catton, W. E. Kastenberg and M. S. Plesset, An experimental study of the thermal interaction for molten tin dropped into water, UCLA-ENG-7592, University of California, Los Angeles (1975).

INTERACTION THERMIQUE POUR L'ETAIN FONDU PLONGE DANS L'EAU

Résumé—On a utilisé la photographie à plusieurs flashes, avec des temps d'exposition à très courte durée par flash, pour observer l'étain fondu tombant dans un bain d'eau. Une observation détaillée des photographies montre que la transition, ou l'ébullition nucléée, est un mécanisme de déclanchement des explosions de vapeur. On trouve aussi que les contraintes thermiques nécessaires pour la production des explosions de vapeur peuvent être supprimées en introduisant une stratification thermique stable dans le réfrigérant. La valeur de seuil de la température initiale de l'étain nécessaire à l'explosion de vapeur a été abaissée de 500°C à 343°C.

UNTERSUCHUNG DER THERMISCHEN REAKTION ZWISCHEN ZINN UND WASSER, WENN FLÜSSIGES ZINN IN WASSER TROPFT

Zusammenfassung—Zur Sichtbarmachung der thermischen Reaktion, welche durch in Wasser tropfendes flüssiges Zinn hervorgerufen wird, bediente man sich der Mehrfachblitz-Fotografie mit extrem kurzen Belichtungszeiten pro Blitz. Die Fotografien zeigen, daß Blasen- oder instabiles Filmsieden mögliche Auslösemechanismen für die Dampfexplosionen sind. Durch Erzeugung einer stabilen thermischen Schichtung im Wasser konnten die thermischen Bedingungen zur Erzeugung von Dampfexplosionen gemildert werden. Der Grenzwert der Zinn-Anfangstemperatur, die für die Dampfexplosion erforderlich ist, konnte von ungefähr 500°C auf 343°C gesenkt werden.

ТЕПЛОВОЕ ДЕЙСТВИЕ РАСПЛАВЛЕННОГО ОЛОВА, БРОШЕННОГО В ВОДУ

Аннотация — Для наблюдения за поведением расплавленного олова, брошенного в ванну с водой, применялось импульсное фотографирование с чрезвычайно коротким временем экспозиции. Полученные снимки показывают, что фазовый переход или пузырьковое кипение является потенциальным механизмом возникновения паровых взрывов. Найдено также, что тепловые ограничения, необходимые для возникновения паровых взрывов, можно ослабить путем создания стабильной тепловой стратификации в теплоносителе. В настоящей работе пороговое значение начальной температуры олова, необходимое для паровых взрывов, снижалось примерно от 500°C до 343°C.