39

JAERI-Data/Code
99-017

FERMILAB
MAY 17 1999
LIBRARY

JAERI-DATA-CODE-99-017

ALPHA VISUAL DATA COLLECTION STX005-025: MELT DROP STEAM EXPLOSION EXPERIMENTS

Fermilab Library
0 1160 0062398 7

March 1999

NAME | ID No. | M.S.
RETURN TO FERMILAB LIBRARY

Kiyofumi MORIYAMA, Norihiro YAMANO,
Yu MARUYAMA, Tamotsu KUDO and Jun SUGIMOTO

日本原子力研究所
Japan Atomic Energy Research Institute

本レポートは，日本原子力研究所が不定期に公刊している研究報告書です。
入手の問合わせは，日本原子力研究所研究情報部研究情報課（〒319-1195　茨城県那珂郡東海村）あて，お申し越しください。なお，このほかに財団法人原子力弘済会資料センター（〒319-1195　茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

This report is issued irregularly.
Inquiries about availability of the reports should be addressed to Research Information Division, Department of Intellectual Resources, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan.

© Japan Atomic Energy Research Institute, 1999

編集兼発行　　日本原子力研究所

JAERI-Data/Code 99-017

ALPHA Visual Data Collection
STX005-025: Melt Drop Steam Explosion Experiments

Kiyofumi MORIYAMA, Norihiro YAMANO*, Yu MARUYAMA,
Tamotsu KUDO and Jun SUGIMOTO

Department of Reactor Safety Research
Nuclear Safety Research Center
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken

(Received February 15, 1999)

Steam explosion is a phenomenon in which a high temperature liquid gives its internal energy to a low temperature volatile liquid extremely quickly causing rapid evaporation and shock wave generation. In the field of nuclear reactor safety research regarding severe accidents in LWRs, steam explosions involving molten fuel and coolant has been recognized as a potential threat to the integrity of the reactor containment vessel.

In the ALPHA (Assessment of Loads and Performance of Containment in Hypothetical Accident) program, experiments were performed to investigate the phenomenology of vapor explosions using iron-alumina thermite melt as a simulant of molten core.

This report collects the experimental results especially emphasizing the visual observations by high speed photography.

Keywords: Steam Explosion, FCI, Experiment, Visual Observation, ALPHA

* This work is dedicated to Mr. Norihiro Yamano (1955-1997) ; *Requiescat in pace*

JAERI-Data/Code 99-017

ＡＬＰＨＡ画像データ集
ＳＴＸ００５-０２５：溶融物落下水蒸気爆発事故

日本原子力研究所東海研究所安全性試験研究センター原子炉安全工学部
森山　清史・山野　憲洋※・丸山　　結・工藤　　保・杉本　　純

（1999年２月15日受理）

水蒸気爆発は、高温の液体から低温揮発性の液体への急速な伝熱、高温液体の細粒化等の一連の過程が、低温液体の急速な蒸発による衝撃波の発生、伝播とともに進行し、結果的に高温液体の保有する熱エネルギーが機械的エネルギーへと変換される現象である。原子力安全、とくに軽水炉のシビアアクシデントの分野では、溶融炉心と冷却材の接触による水蒸気爆発が格納容器の健全性に対する潜在的脅威として認識され、研究されてきた。原研では事故時格納容器挙動試験（ＡＬＰＨＡ）計画の中で、鉄－アルミナテルミット混合溶融物を溶融炉心模擬材として用いた水蒸気爆発実験を行った。本報告は、とくに高速度カメラによる画像情報に重点をおいて実験データを提供するものである。

東海研究所　〒319－1195　茨城県那珂郡東海村白方白根２－４
※　本報告を1997年10月に逝去された山野憲洋氏に捧げる。

Contents

1. Introduction 1
2. Experimental Procedures 2
3. Experimental Conditions 4
3.1 Parametric Aspects 4
3.2 Melt Material 4
3.3 Configuration and Kinetics of the Melt Drop 4
4. Results and Comments 6
4.1 Visual Observations 6
4.2 Energetics and Effect of Premixing Conditions 31
4.3 Debris Size Distribution 31
5. Recommendations and Suggestions for Modelers 33
Acknowledgments 34
References 34

目　　次

1．はじめに …… 1
2．実験方法 …… 2
3．実験条件 …… 4
3．1　実験におけるパラメータ …… 4
3．2　溶融物の物性 …… 4
3．3　溶融物落下時の形状および速度 …… 4
4.　実験結果および説明 …… 6
4．1　高速度写真による観測 …… 6
4．2　エネルギー変換率および粗混合条件の影響 …… 31
4．3　デブリの直径分布 …… 31
5.　本データを利用するモデル開発者への推奨事項 …… 33
謝　辞 …… 34
参考文献 …… 34

1 Introduction

Steam explosion is a phenomenon in which a high temperature liquid gives its internal energy to a low temperature volatile liquid extremely quickly causing rapid evaporation and shock wave generation. In the field of nuclear reactor safety research regarding severe accidents in LWRs, steam explosions involving molten fuel and coolant has been recognized as a potential threat to the integrity of the reactor containment vessel.

In the ALPHA (Assessment of Loads and Performance of Containment in Hypothetical Accident) program conducted at Japan Atomic Energy Research Institute (JAERI) since 1991, more than 20 cases of experiments were performed to investigate the phenomenology of vapor explosions using iron-alumina thermite melt as a simulant of molten core, varying the melt/water mass and temperature as well as the ambient pressure as parameters. (ALPHA-STX0xx series)

This report briefly describes the experimental procedures and conditions, and presents the results especially emphasizing the visual observations.

A general description of the important part of the results on the phenomenology and the thermal-fluid-dynamic behavior was published in the previous article [1].

This report was prepared to provide a database collecting especially the visual information useful for code and model verification works and also for researchers getting started in this field to get a concrete physical idea on the phenomena. Other important data, i.e. the debris characteristics and the energetics, were also included to give a perspective to modelers.

Unfortunately the photographs given in this report is monochrome and not in high quality. However, the original digital data are in JPEG format having 1280×960 resolution and 24bit (16M) colors, and those files can be offered to readers who wish to use them for their research works.

Contact person:
MORIYAMA, Kiyofumi
Severe Accident Research Laboratory
Department of Reactor Safety Research
Japan Atomic Energy Research Institute
phone: +81-29-282-5871, fax: +81-29-282-5570
email: mori@sarl.tokai.jaeri.go.jp

2 Experimental Procedures

A schematic illustration of the ALPHA melt-drop steam explosion experiments (STX series) is given in Fig. 1. The facility consists of two parts, the model containment vessel and the melt generator. The inner dimensions of the model containment are 3.9m in diameter and 5.7m in height, corresponding to a volume of $50m^3$. The model containment was designed to contain the pressure and temperature of up to 20bars and 250°C. The melt generator has a capacity of 100kg.

The detail of the experimental procedures was described elsewhere [1]. While, in brief, it was as follows. The melt is generated by thermite reaction of iron oxide and aluminum in the melt generator and delivered gravitationally into a water pool located at the center of the containment.

Several kinds of water vessels were used. A cylindrical steel vessel of 1m in inner diameter and 1.2m in height was used for some early experiments and for the case where water temperature was set high (near the saturation point). Rectangular vessels made of transparent acrylic panels in three kinds of size, L, M and S, were used for the cases where optical observation was aimed at. The cross section of the vessels were 0.88 by 0.88m for "L", 0.63 by 0.63m for "M" and 0.45 by 0.45m for "S". Grid lines with spacing of 10cm was drawn on the side panel for the reference of dimensions in the photographs.

High speed cameras (E-10, Kodak) were used to observe the phenomena through view windows. Frame rates were set in the range from 2000 to 5000f/s. The view windows were protected from debris flying out of the explosion center by multiple layers of Pyrex glass plates with thickness of 20mm each and steel bars. Two cameras were set in the azimuthal angles 90° different from each other, thus the directions are denoted as 0° and 90° in the captions of Figure 2a~w.

Note that determination of the dimensions of objects in the middle of the vessel containing water directly referring the grid on the vessel panel involves an error ranging from 5 ("S" vessels) to 10% ("L" ones) due to the difference of the distance from the camera.

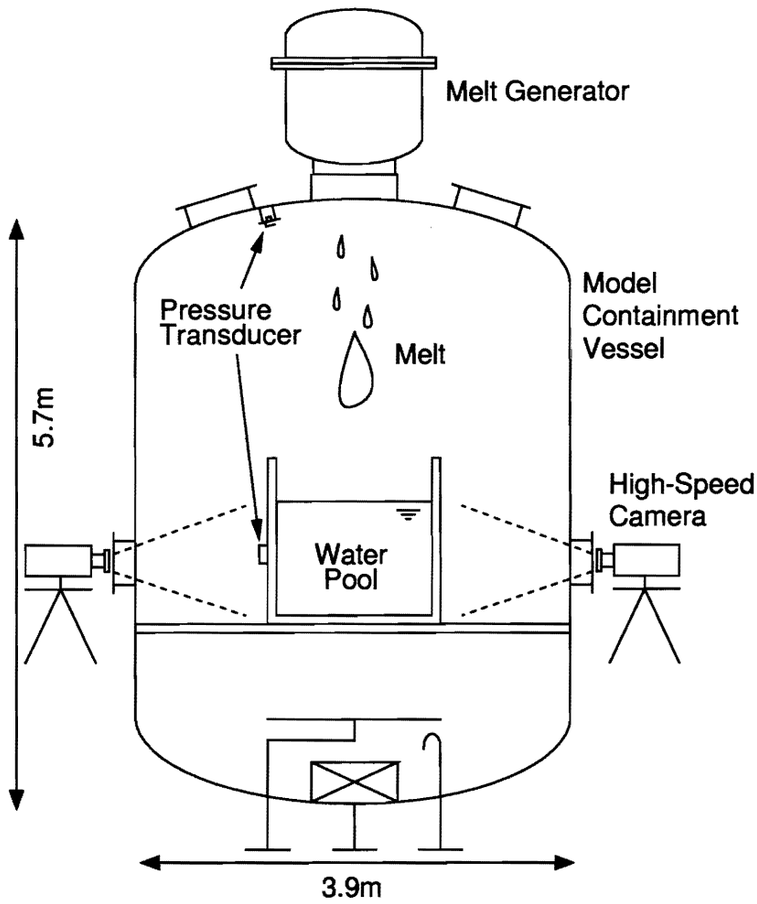

Figure 1: Schematic illustration of the ALPHA melt-drop steam explosion experiments

3 Experimental Conditions

3.1 Parametric aspects

The experimental conditions and the results in terms of the occurrence of steam explosions are summarized in Table 1. Cases are ordered in terms of their objectives in the table.

The first 7 lines of the table are base case experiments performed with the melt mass of 20kg, ambient pressure of 1bar and water at room temperatures (high subcooling), where explosive interactions were observed in every case.

Melt mass was reduced to 10kg in the next 3 cases. Steam explosion was not observed in 2 cases among them.

The next line, STX014 was a saturation water case, where steam explosion did not occur.

Next 4 lines were high pressure cases. Steam explosion was suppressed in 3 cases.

STX023 was a shallow pool case.

The effect of dissolved non-condensible gas in the coolant was tested in STX024.

The last 6 lines were tests on artificial dispersion of the melt, where a steel mesh, made by wires of thickness 2mm with spacing of 25mm, was placed above or below the water surface to forcedly disperse the melt.

3.2 Melt material

The melt material was a mixture of iron and alumina produced by thermite reaction (exothermic oxidation and reduction). Physical properties of this material are unfortunately not precisely known, but some of them were measured or evaluated previously by Maruyama et al. [2]. The data obtained there are summarized in Table 2.

3.3 Configuration and kinetics of the melt drop

The bottom of the melt generator was placed about 3.5m above the water surface. which gives the velocity of the melt up on the contact with water surface about 8.3m/s considering the gravitational fall.

The release hole of the melt crucible has an opening of 20cm in diameter, which is initially covered by Pyrex glass plate and broken by the temperature rise by thermite reaction occurring above it. Because of this method, the shape of the melt drop during the free fall was not very well conditioned due to some uncontrollable features. However, it is not a bad assumption that typically the main body of the melt drop is a single lump of 10~20cm in diameter and 20~50cm in length.

As a reference, if 20kg of thermite melt is filled in a cylindrical configuration, diameters of 12 and 20cm leads heights of 48.9 and 17.6cm, respectively, according to the density in Table 2.

Table 1: Summary of ALPHA-STX0xx experiments

Run No.	Melt mass	Pressure	Cover gas	Water temp.	Water pool	Explosion	Water depth	Water mass	Comment
	(kg)	(MPa)		(K)		(Yes/No)	(cm)	(kg)	
STX002	20	0.1	Air	289	Steel	Yes	100	785	
STX003	20	0.1	Air	292	Steel	Yes	100	785	
STX005	20	0.1	Air	300	Acryl(L)	Yes	100	774	
STX009	20	0.1	N_2	289	Acryl(L)	Yes	100	774	
STX016	20	0.1	Air	295	Acryl(S)	Yes	90	174	
STX017	20	0.1	Air	286	Acryl(S)	Yes	90	174	
STX018	20	0.1	Air	283	Acryl(S)	Yes	90	174	
STX001	10	0.1	Air	293	Steel	No	100	785	
STX010	10	0.1	Air	297	Acryl(L)	Yes	100	774	
STX013	10	0.1	Air	284	Acryl(L)	No	100	774	
STX014	20	0.1	Air	372	Steel	No	100	816	Saturated water
STX008	20	1.6	N_2	288	Acryl(L)	No	100	774	Elevated pressure
STX012	20	1.6	N_2	290	Acryl(L)	No	100	774	Elevated pressure
STX015	20	1.0	N_2	282	Acryl(L)	No	100	774	Elevated pressure
STX025	20	0.5	Air	280	Acryl(M)	Yes	90	416	Elevated pressure
STX023	20	0.1	Air	285	Acryl(L')	Yes	30	358	Shallow pool
STX024	20	0.1	Air	280	Acryl(M)	Yes	80	318	CO_2 is dissolved
STX006	20	0.1	Air	298	Acryl(L)	No	100	774	Dispersion device
STX011	20	0.1	Air	290	Acryl(L)	Yes (Mild)	100	774	Dispersion device (locally broken)
STX019	20	0.1	Air	281	Acryl(M)	Yes	90	392	Dispersion device (broken?)
STX020	20	0.1	Air	281	Acryl(L)	No	100	774	Dispersion device
STX021	20	0.1	Air	281	Acryl(L)	Yes	90	697	Dispersion device (under water)
STX022	20	0.1	Air	286	Acryl(L)	No	80	620	Dispersion device

Table 2: Material data of iron-alumina thermite mixture

Composition [w%]	Iron 58 , Alumina 42 (after reaction) Iron oxide 78 ($FeO + Fe_2O_3$), Aluminum 22 (before reaction)
Density [kg/m^3]	3.62×10^3
Specific heat [J/kg K]	1.0×10^3 (measurement including latent heat) 0.96×10^3 (average of components)
Temperature after reaction [K]	2700 (surface, measurement)
Reaction heat [J/kg]	3.35×10^6
Latent heat [J/kg]	1.0×10^6 (estimation from measured temperature, reaction heat and component-average specific heat)

4 Results and Comments

4.1 Visual observations

Figures 2a~w shows the selected frames from the high speed photographs. A general observation can be described as follows.

Premixing

The melt entered the water, broke up coarsely into droplets, and a region of multi-phase mixture involving water, steam and melt droplets were formed. This state lasted typically for 0.2-0.5 seconds. Melt droplets had downward velocity of about 5m/s below water. Thus, it took about 0.2 second for the melt leading edge to reach the bottom of the water pool of about 1m deep. The melt had a bright radiance because of its high initial temperature (about 2700K).

Triggering

At a certain moment, a dark spot appeared in the premixing region. It was probably due to the fact that a steam explosion began locally and the fragmented debris generated there were extremely rapidly cooled down.

Propagation

The dark spot grew larger and larger, and finally covered the entire premixing region. The velocity of the developing front of the dark region (propagation velocity) was typically 300~500m/s, which corresponds to the sonic velocity in a multiphase mixture.

Expansion

The darkened mixture expands, broke the vessel, and fly apart. The velocity of the expansion front was typically 40~70m/s.

When an explosion was not triggered, the state 1, premixing, ended with gradual cooling and darkening of the melt droplets. Such no-explosion cases are shown in Figs. 2e, f, q and r.

Values of the time put to the frames in the figures were calculated from the frame rates, setting the origin on a frame in which "triggering" was identified. And following frames were selected to adequately illustrate the propagation process. For no-explosion cases, the moment of melt-water contact was set as time 0, and frames were picked up more coarsely to illustrate the premixing process.

Note that no synchronization was devised between two films on a same experiment from different directions (0 and 90°), thus the time 0 in two figures for a same experiment does not necessarily mean the same instance.

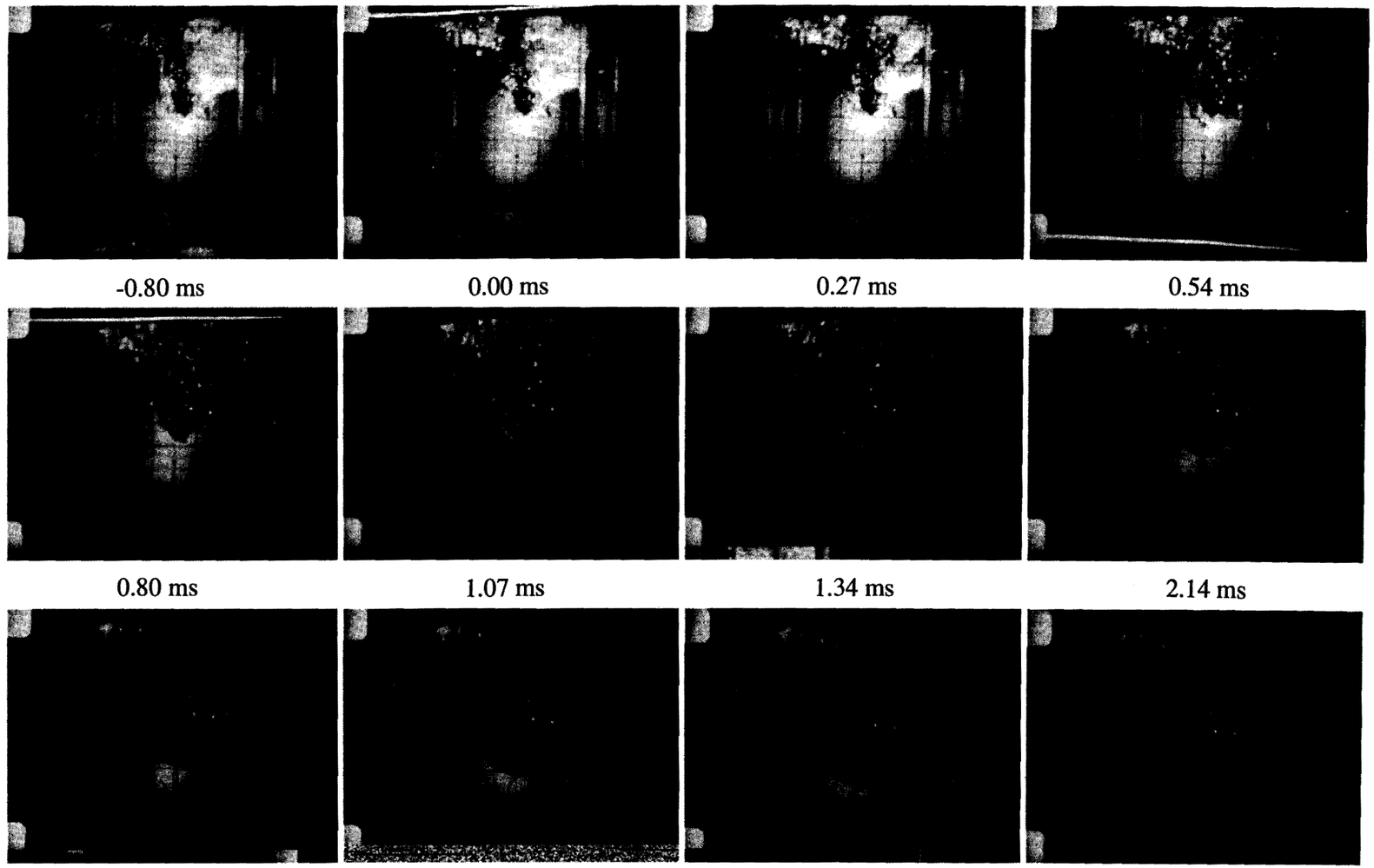

Figure 2a: STX005 High speed photograph at 3730 frames/s

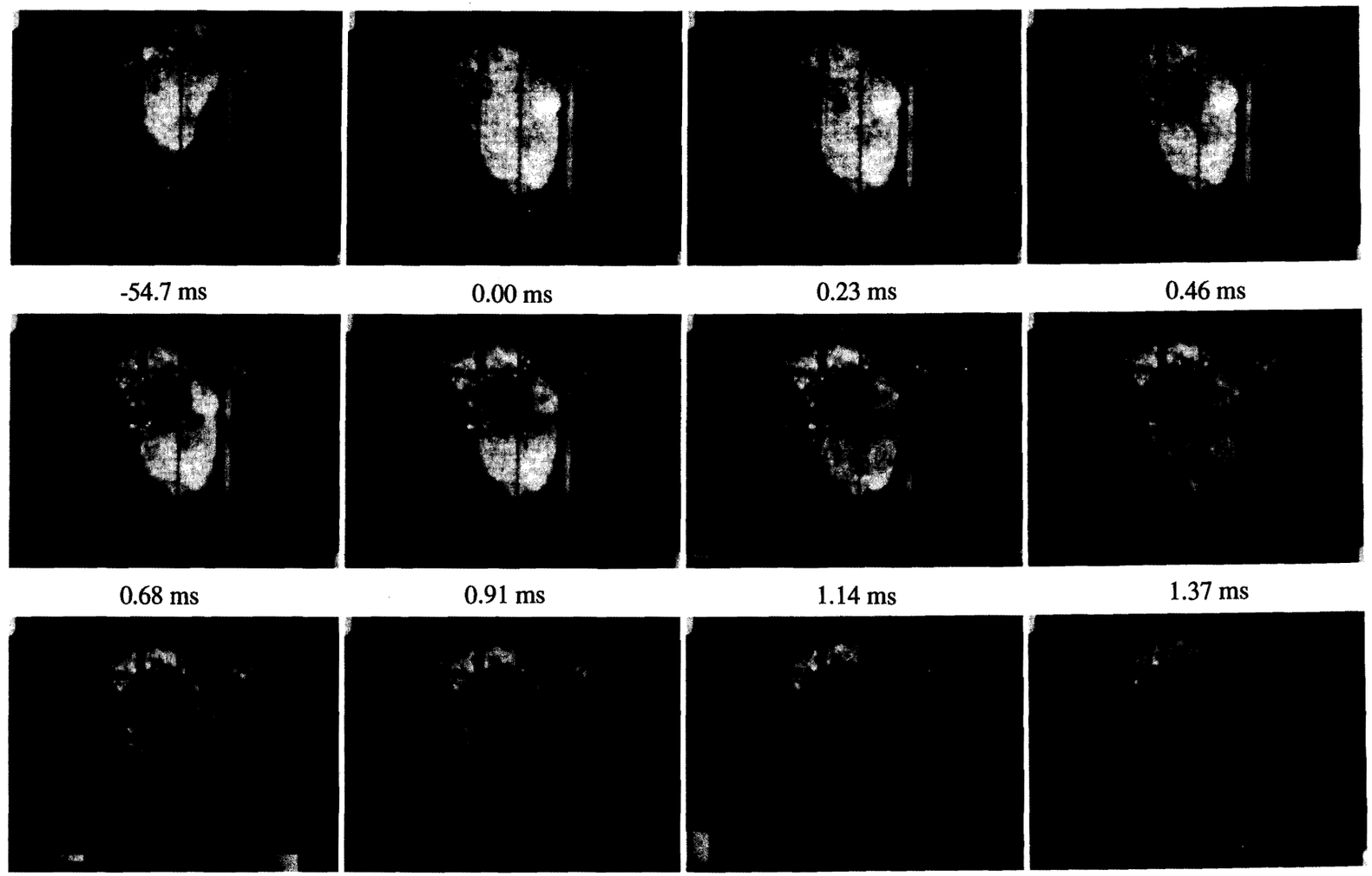

Figure 2b: STX009 High speed photograph at 4380 frames/s

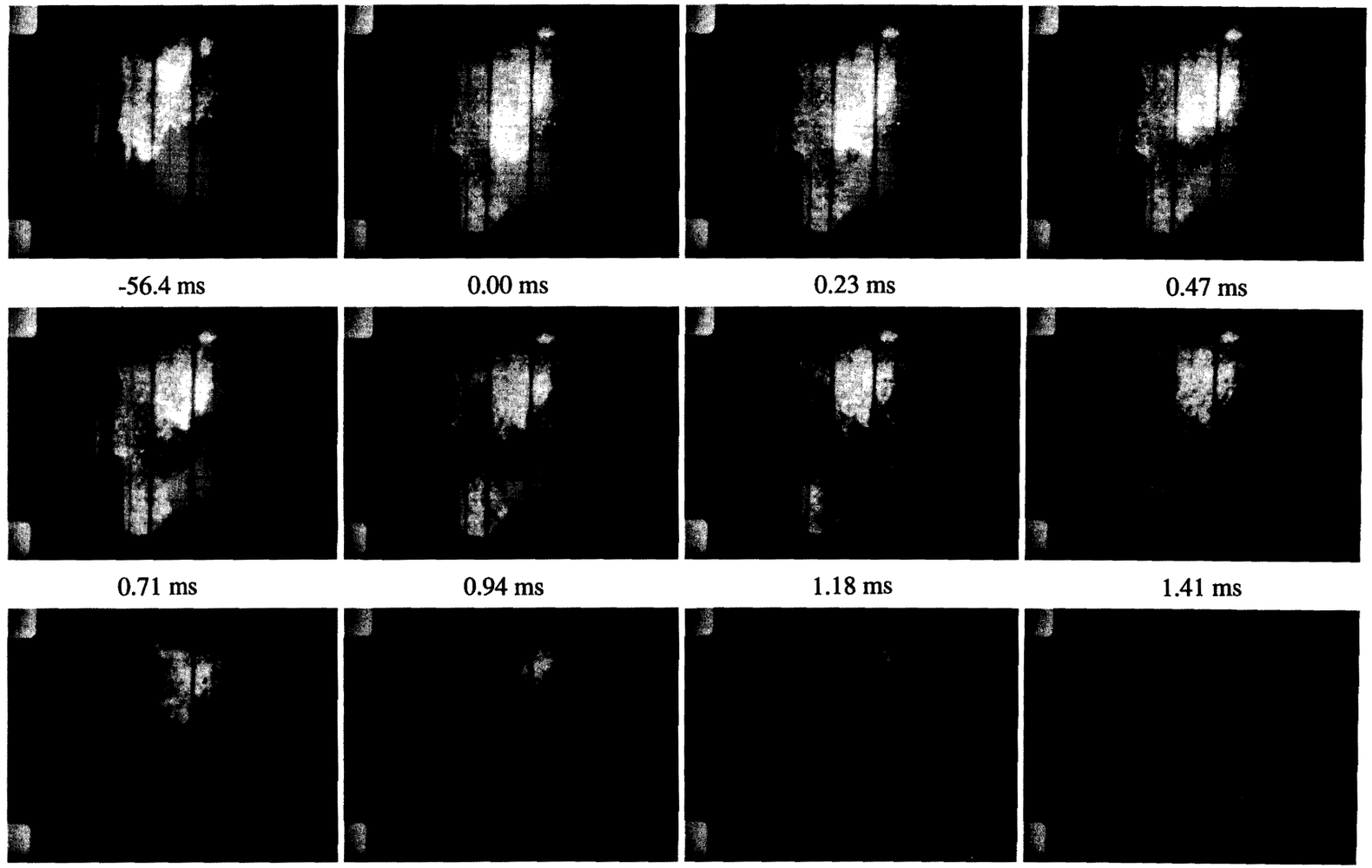

Figure 2c: STX010 High speed photograph at 4260 frames/s

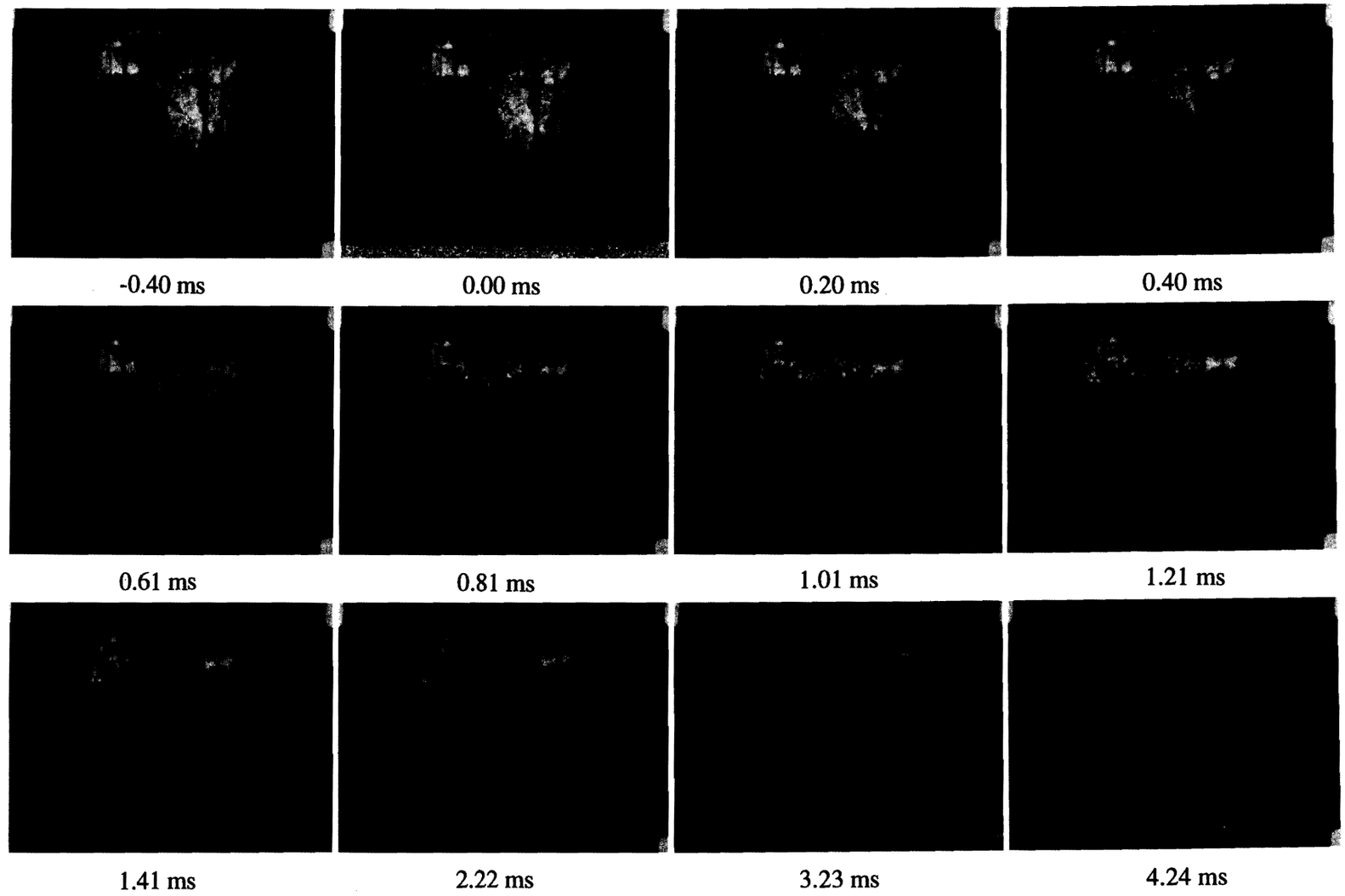

Figure 2d: STX011 High speed photograph at 4960 frames/s

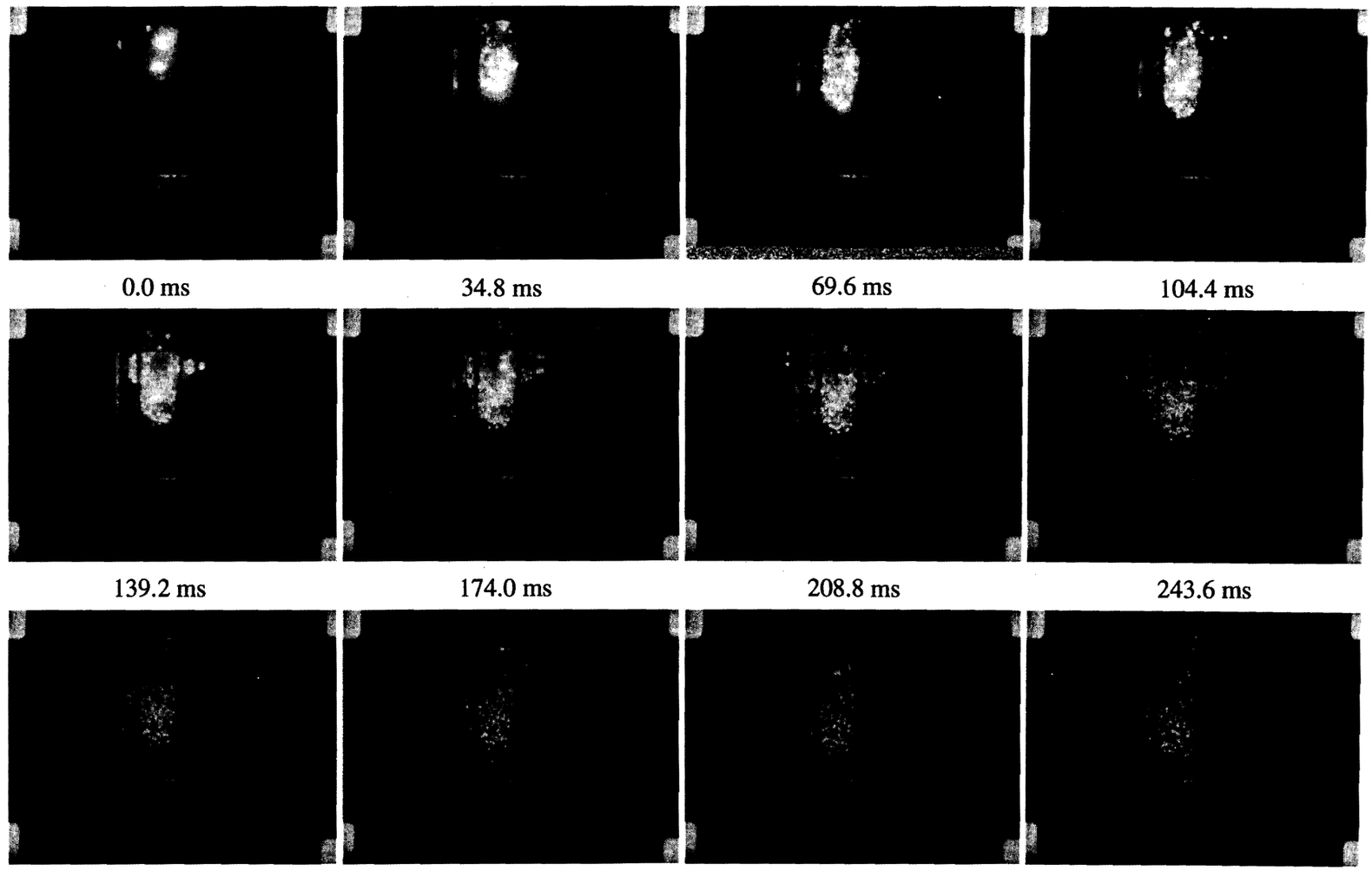

Figure 2e: STX012 (no explosion) High speed photograph at 4310 frames/s

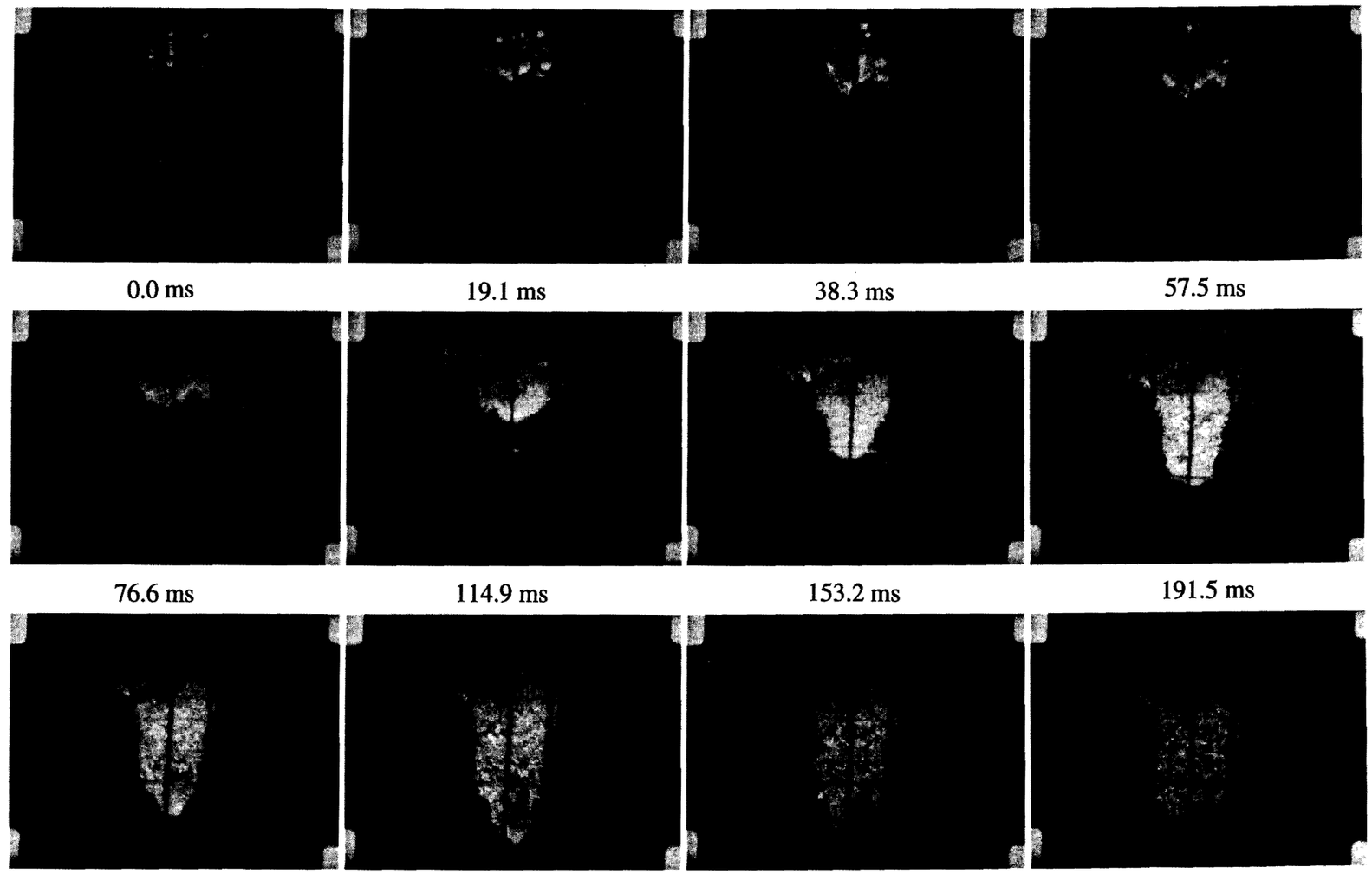

Figure 2f: STX013 (no explosion) High speed photograph at 2610 frames/s

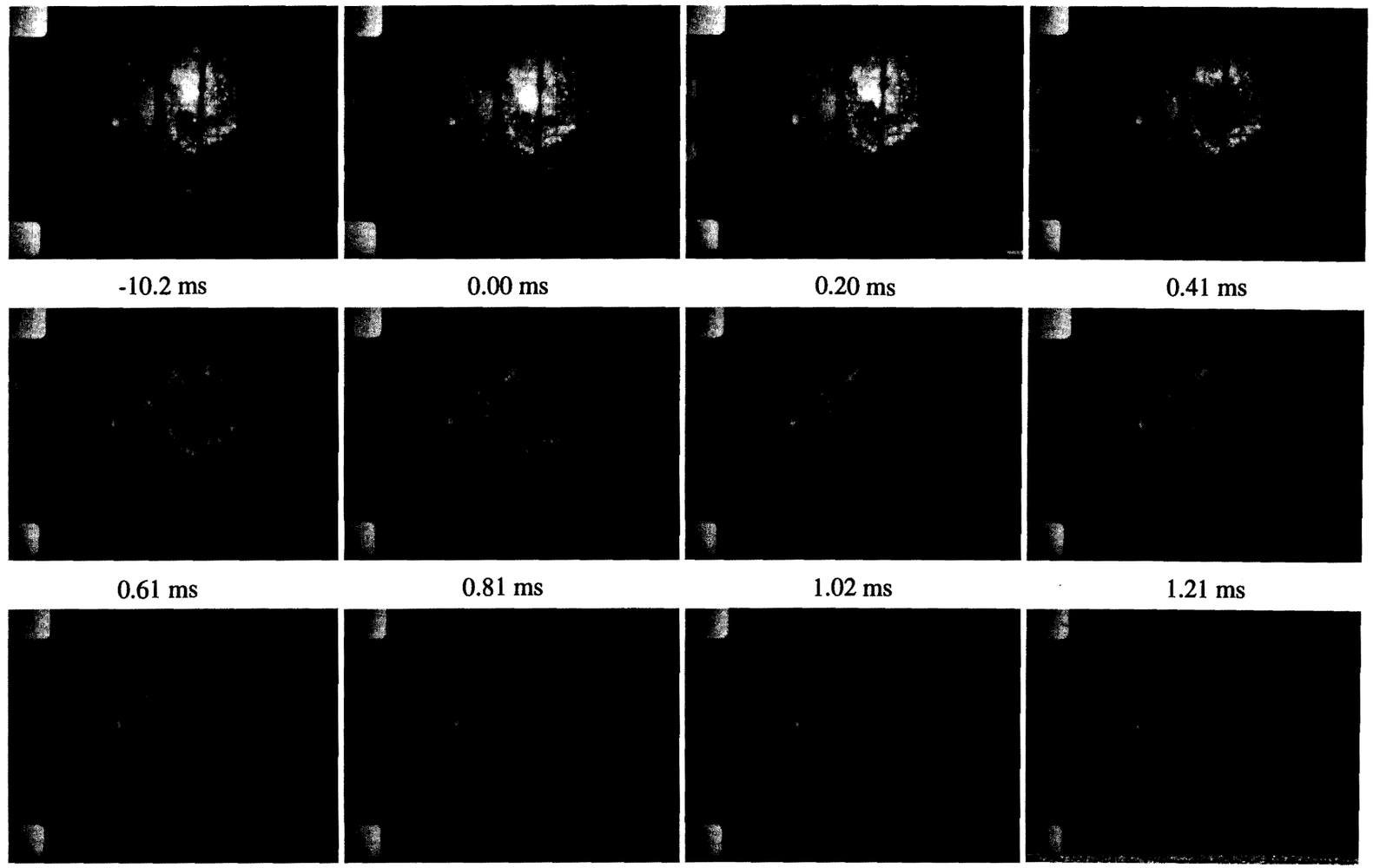

Figure 2g: STX016 High speed photograph at 4930 frames/s (direction 0°)

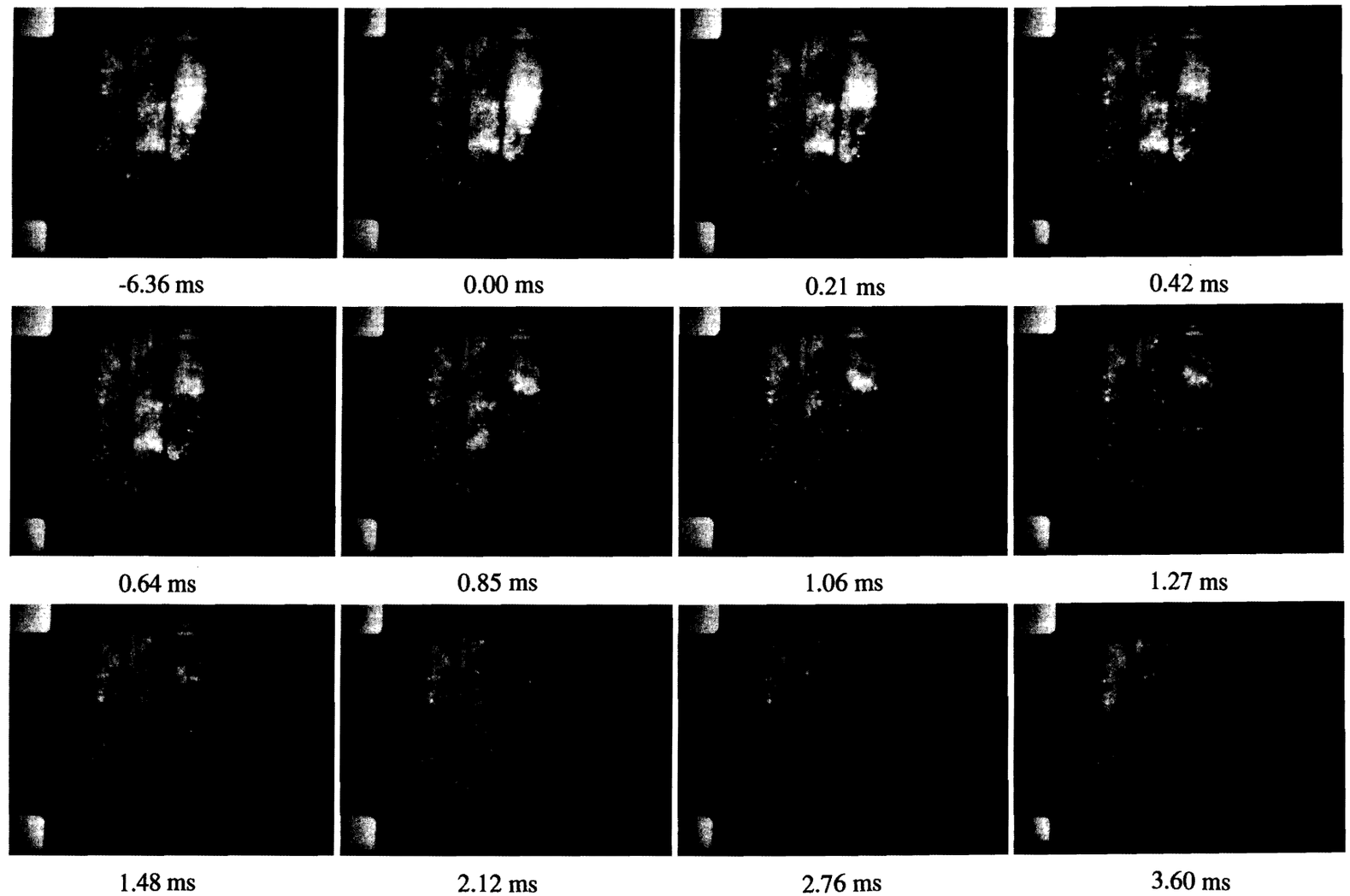

Figure 2h: STX016 High speed photograph at 4720 frames/s (direction 90°)

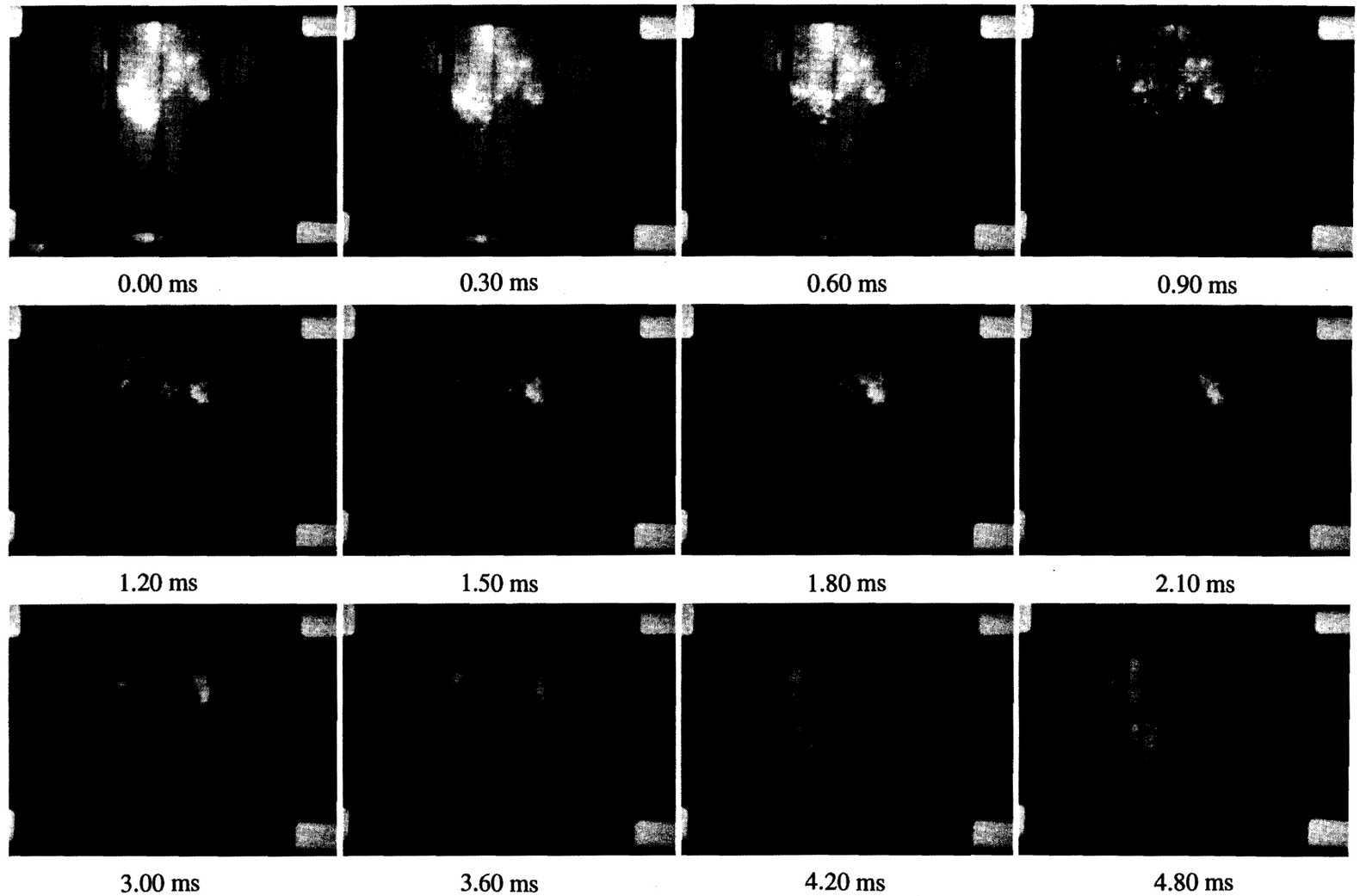

Figure 2i: STX017 High speed photograph at 3330 frames/s (direction 0°)

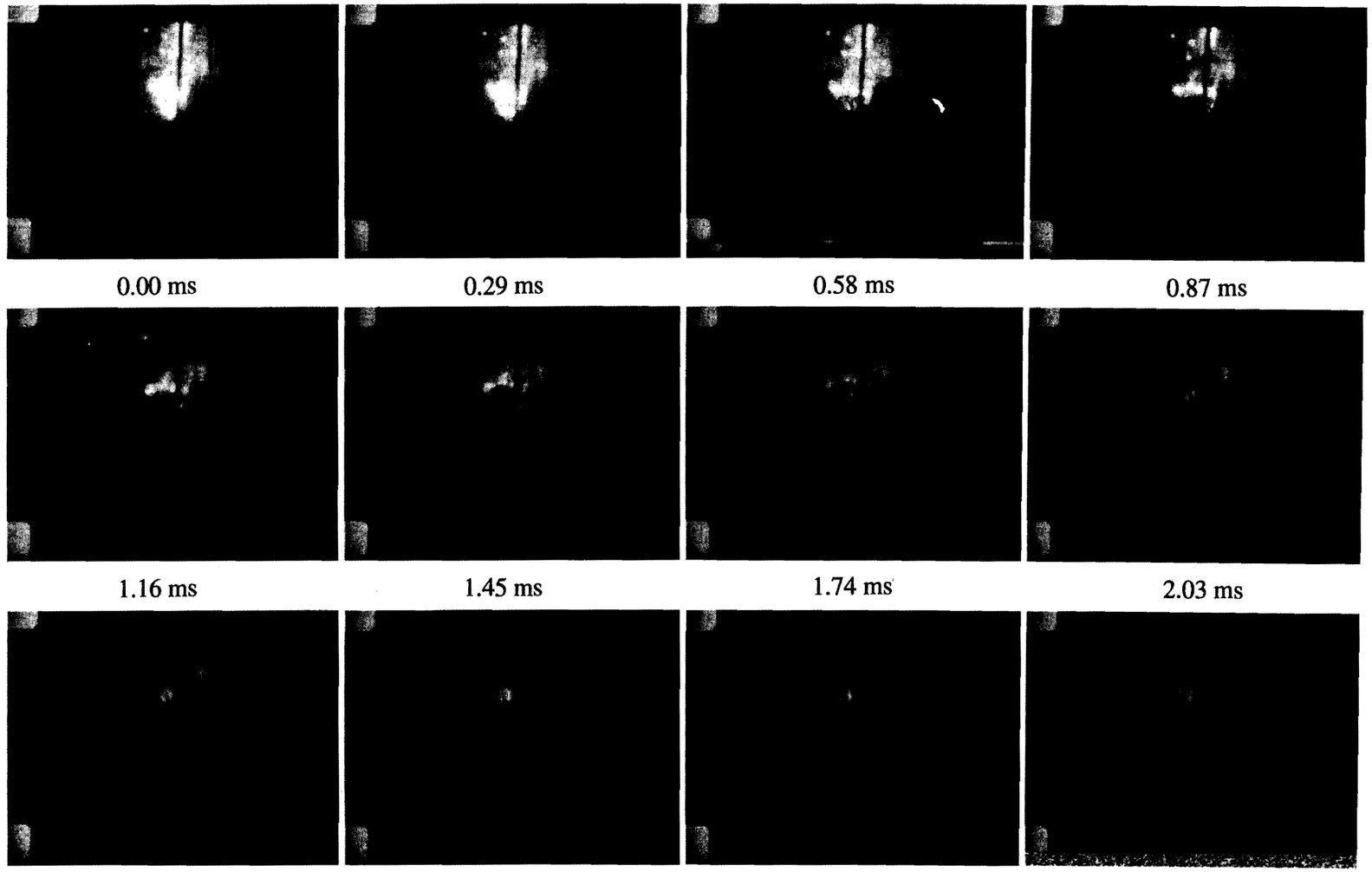

Figure 2j: STX017 High speed photograph at 3420 frames/s (direction 90°)

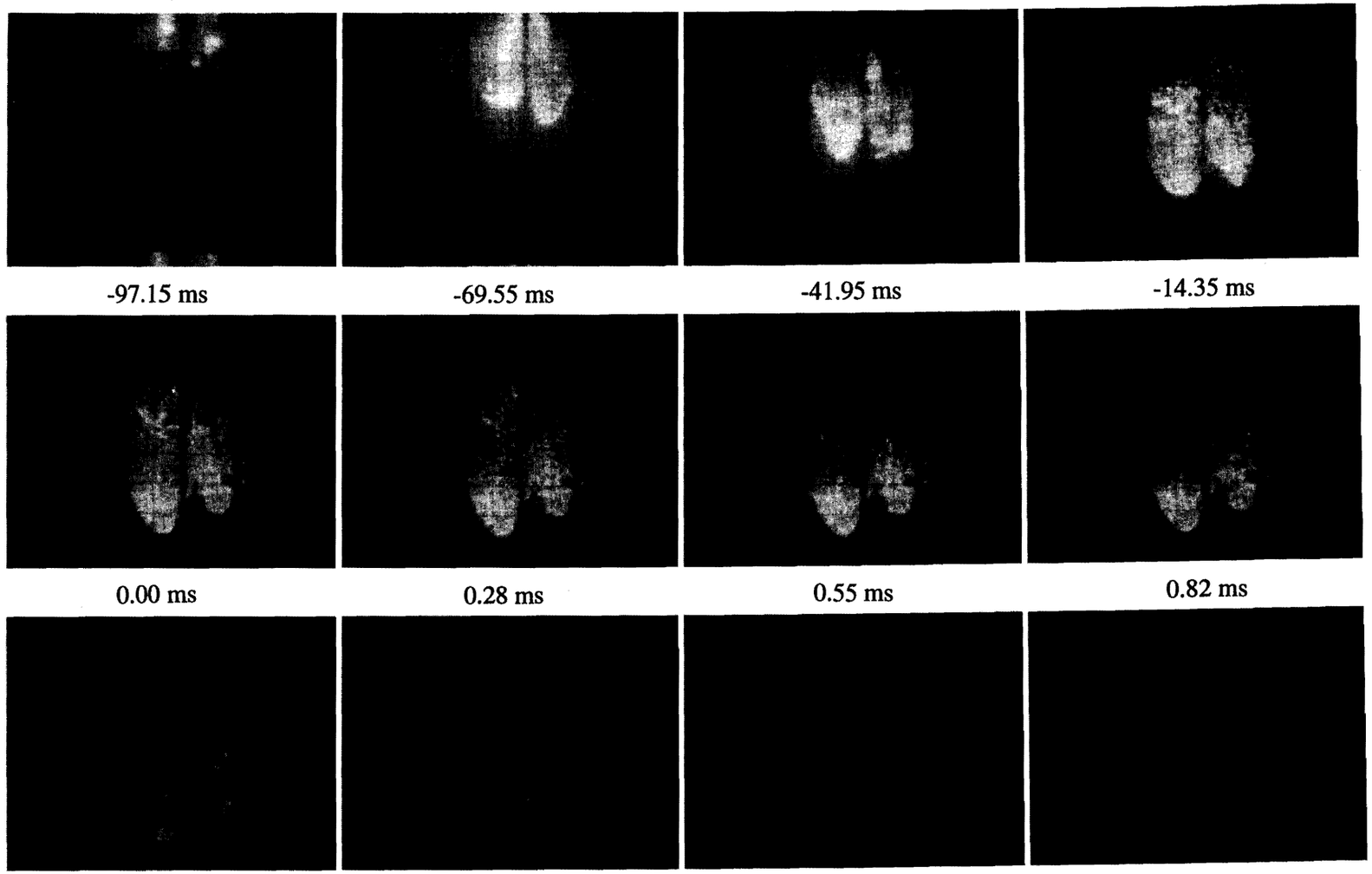

Figure 2k: STX018 High speed photograph at 3620 frames/s (direction 0°)

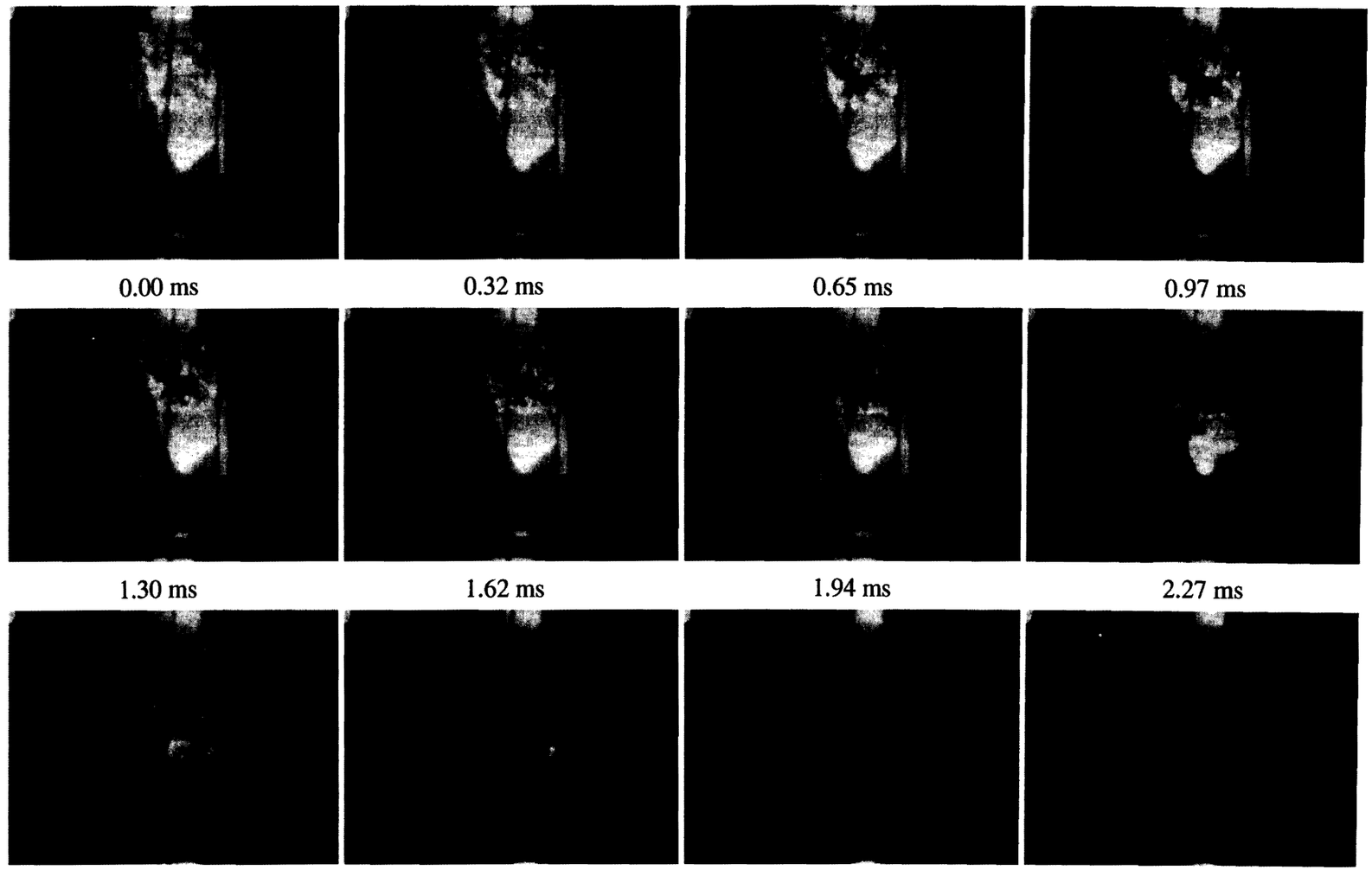

Figure 2l: STX018 High speed photograph at 3090 frames/s (direction 90°)

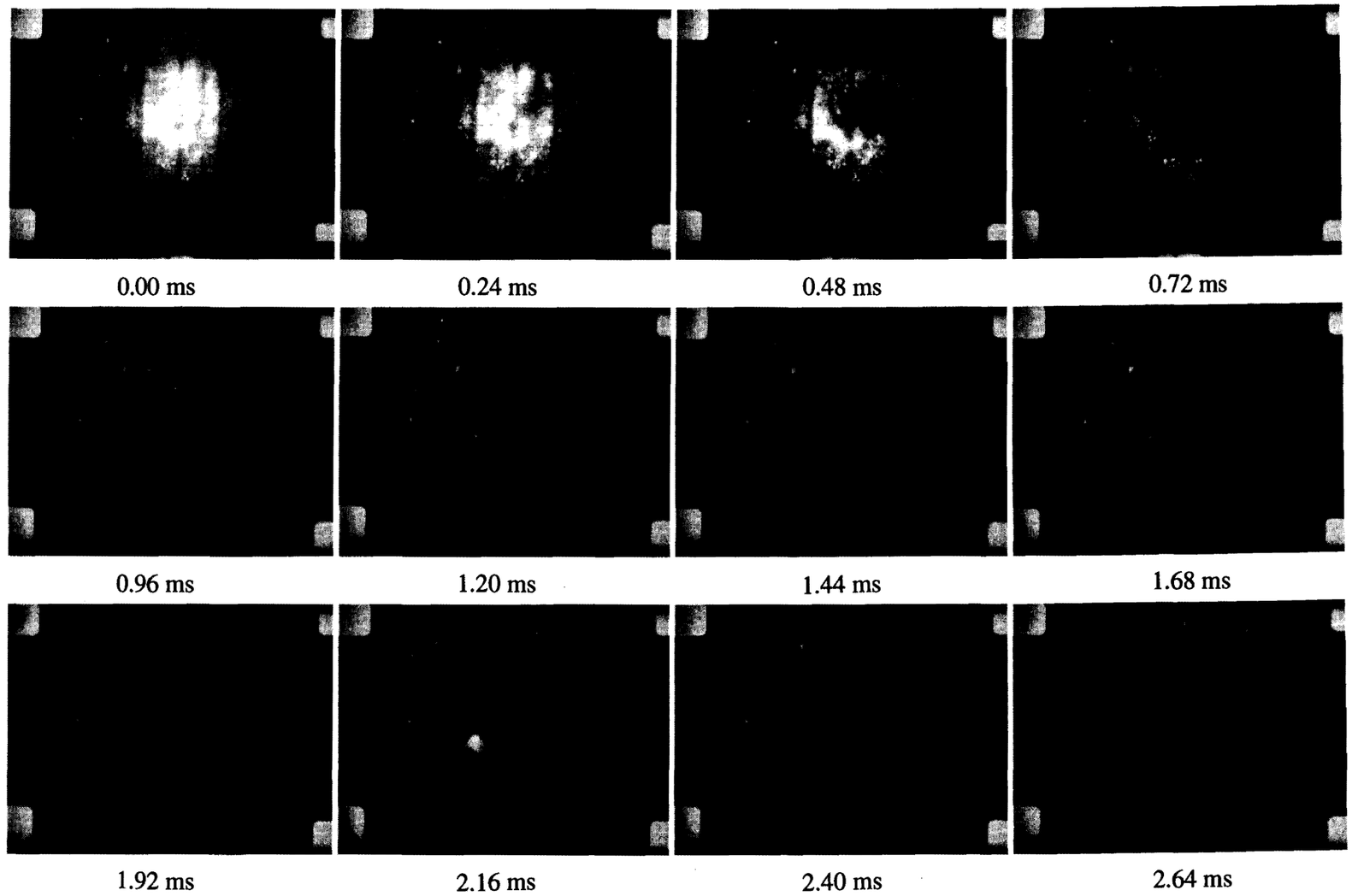

Figure 2m: STX019 High speed photograph at 4100 frames/s (direction 0°)

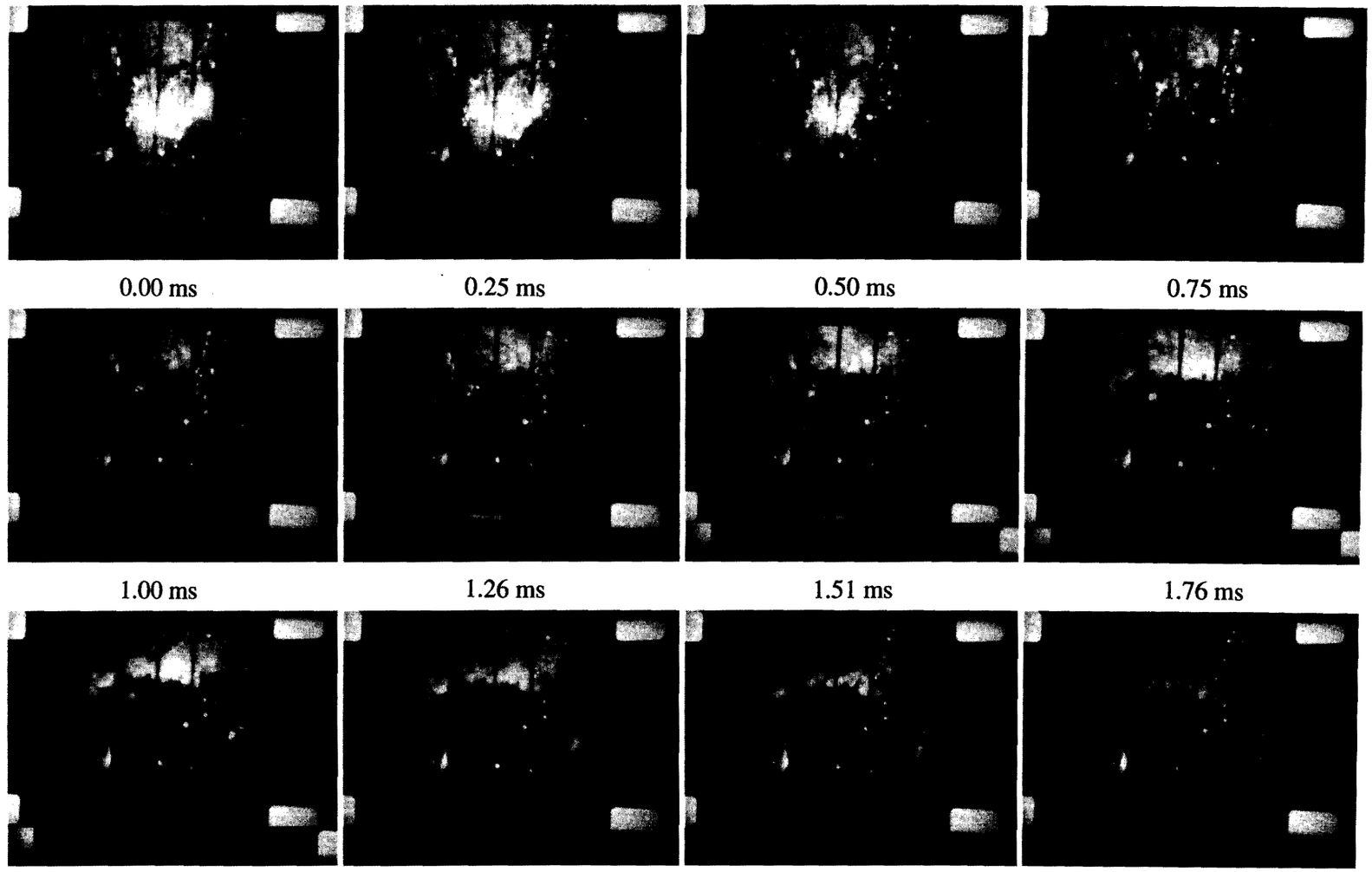

Figure 2n: STX019 High speed photograph at 3980 frames/s (direction 90°)

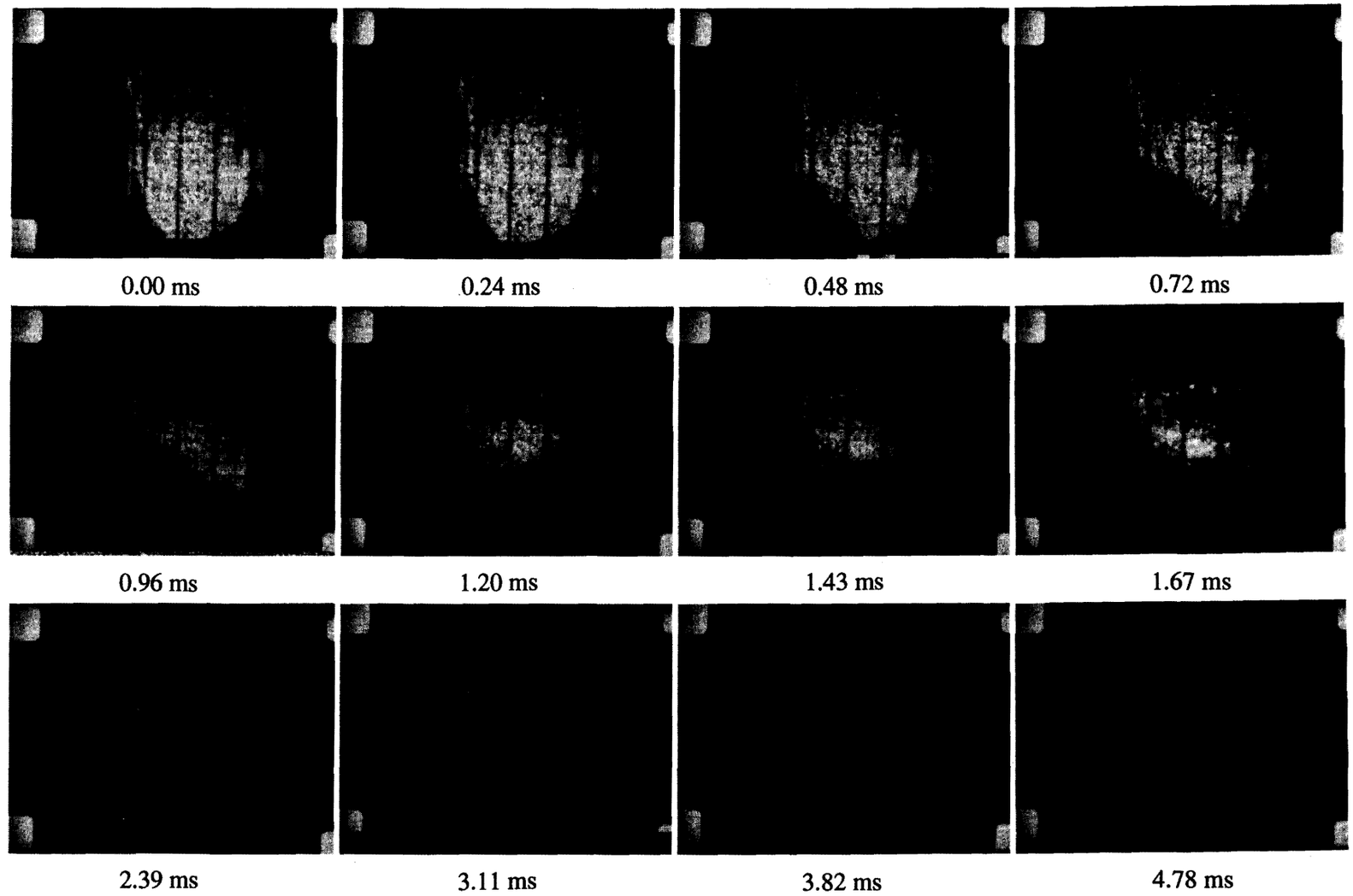

Figure 2o: STX021 High speed photograph at 4180 frames/s (direction 0°)

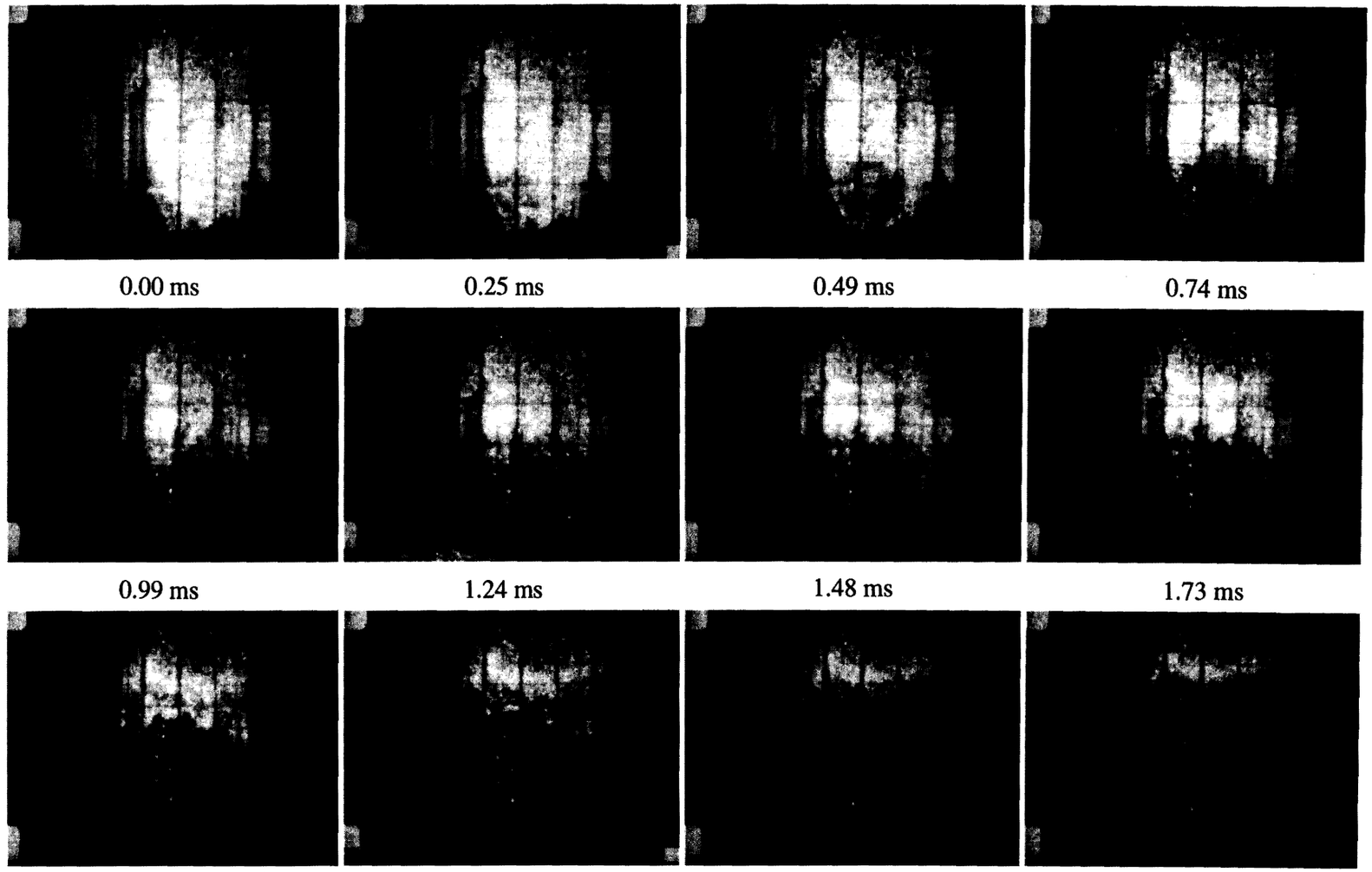

Figure 2p: STX021 High speed photograph at 4050 frames/s (direction 90°)

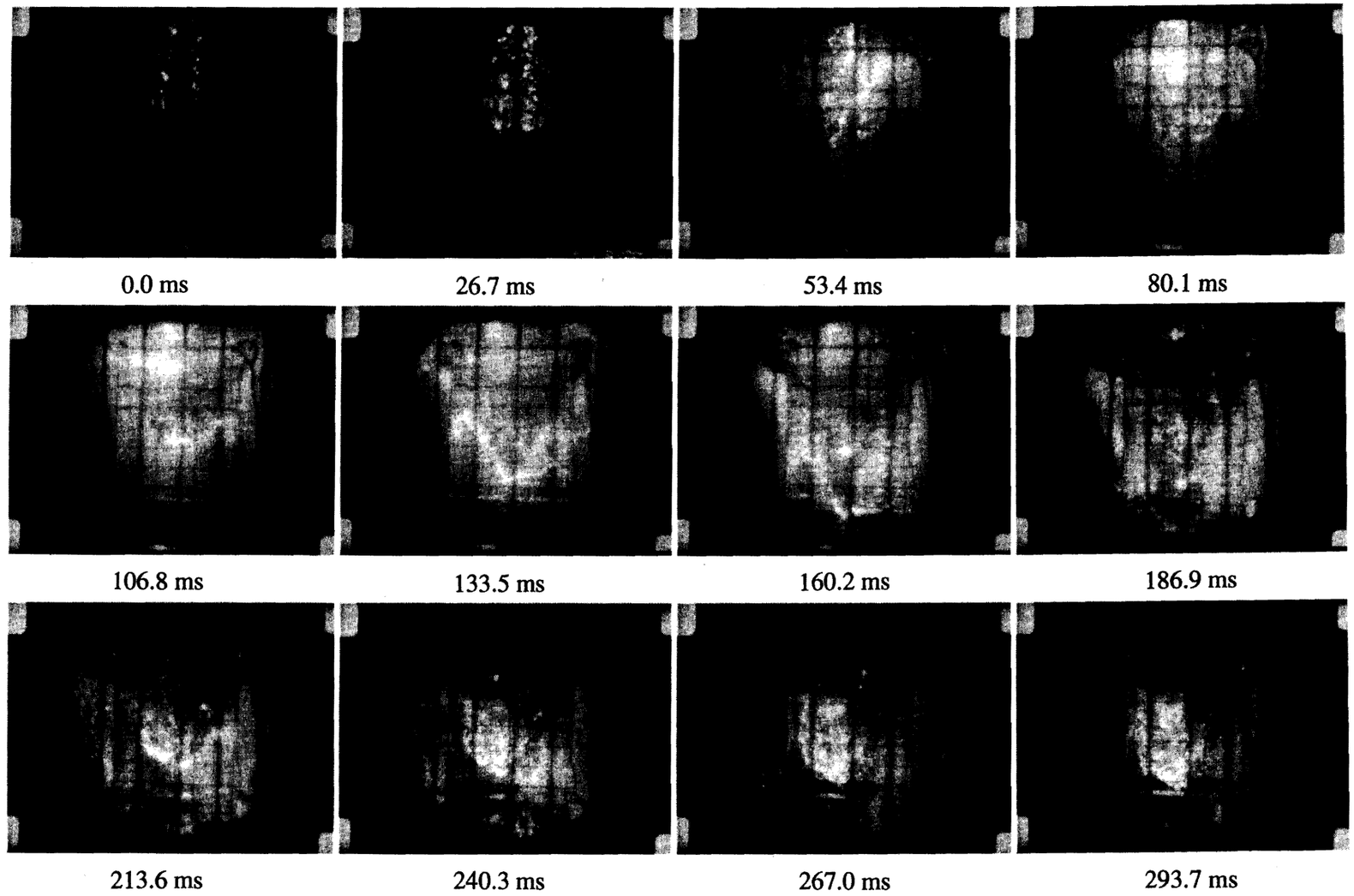

Figure 2q: STX022 (no explosion) High speed photograph at 3750 frames/s (direction 0°)

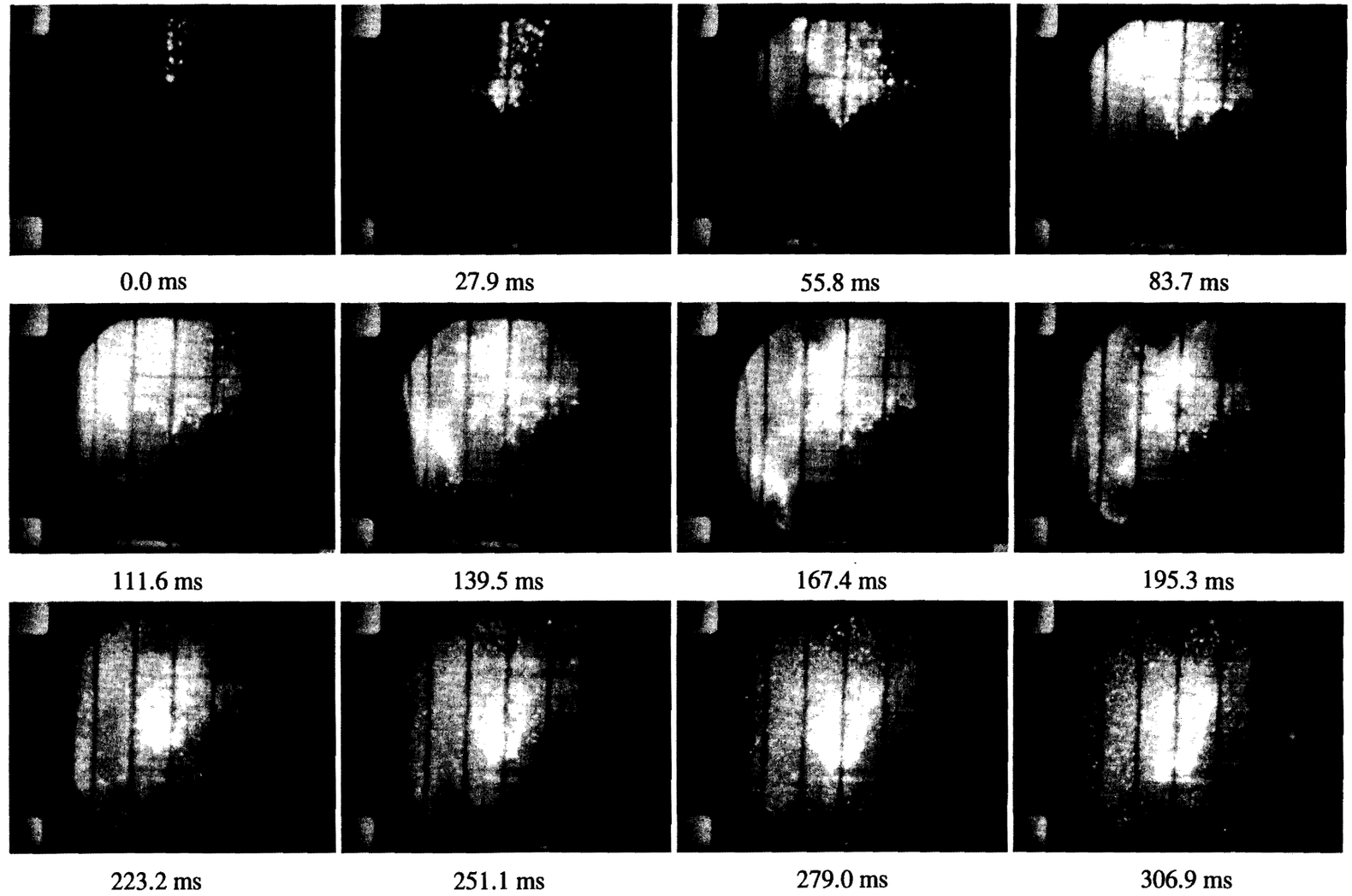

Figure 2r: STX022 (no explosion) High speed photograph at 3590 frames/s (direction 90°)

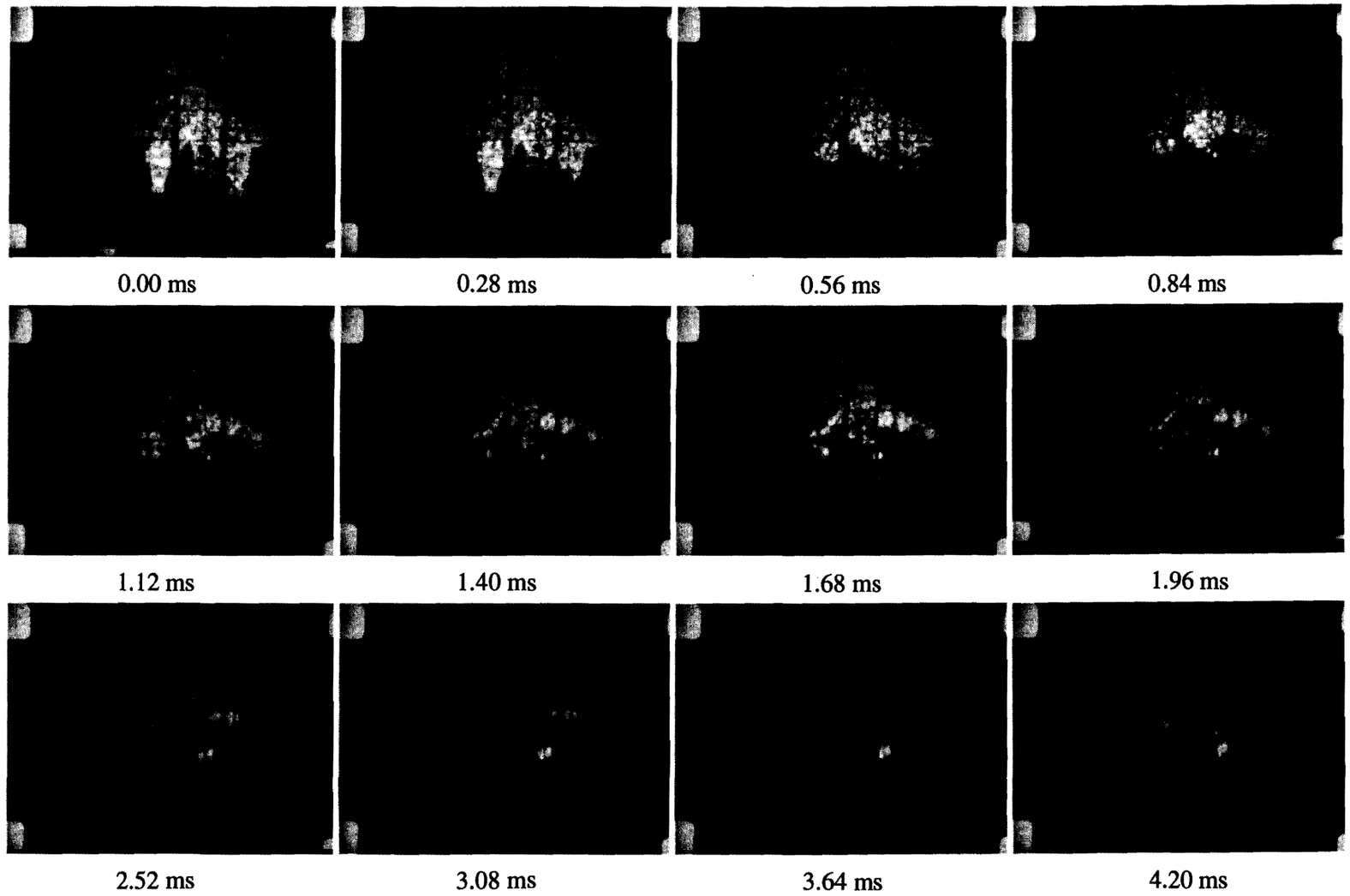

Figure 2s: STX023 High speed photograph at 3560 frames/s (direction 0°)

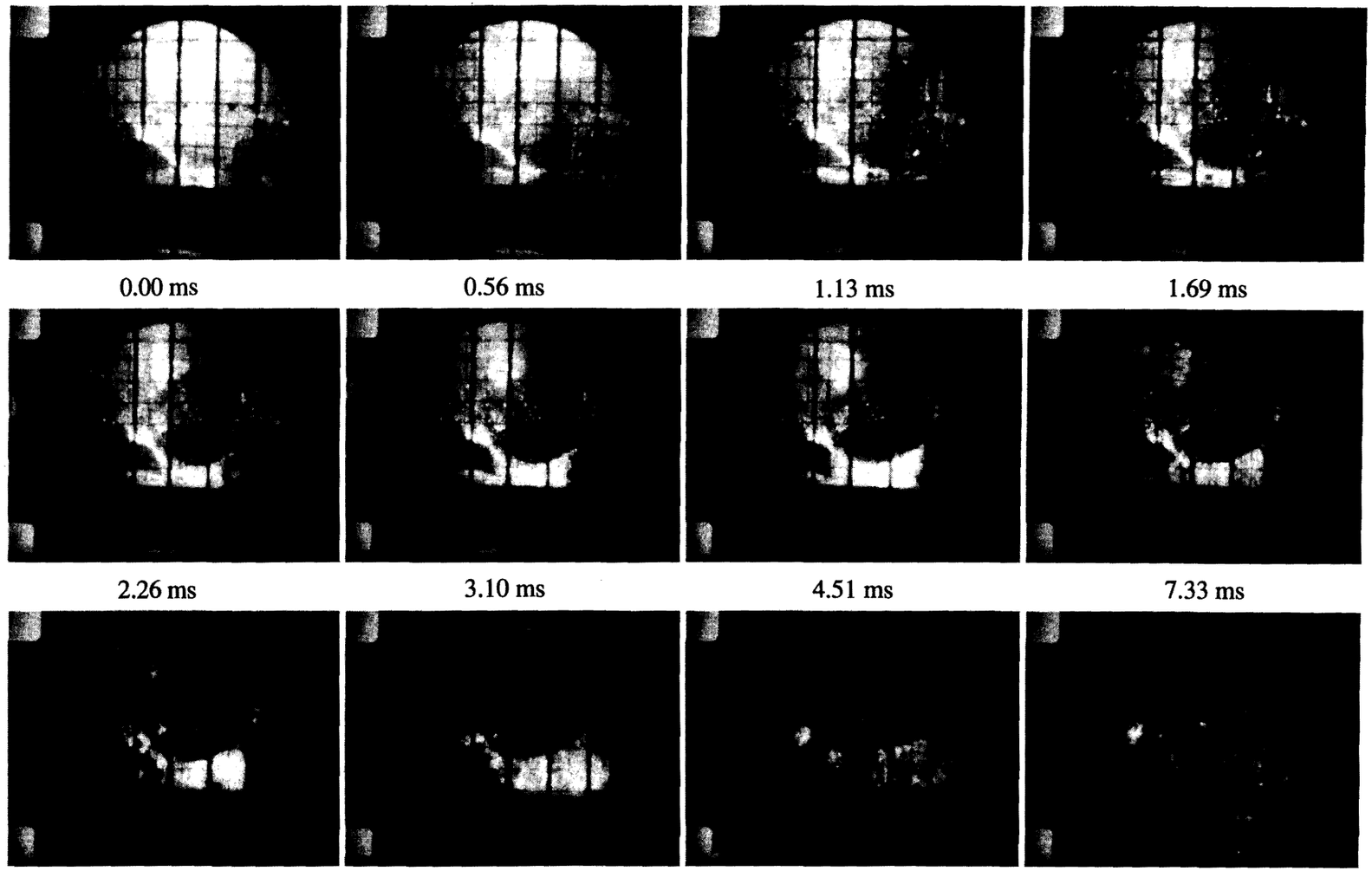

Figure 2t: STX023 High speed photograph at 3550 frames/s (direction 90°)

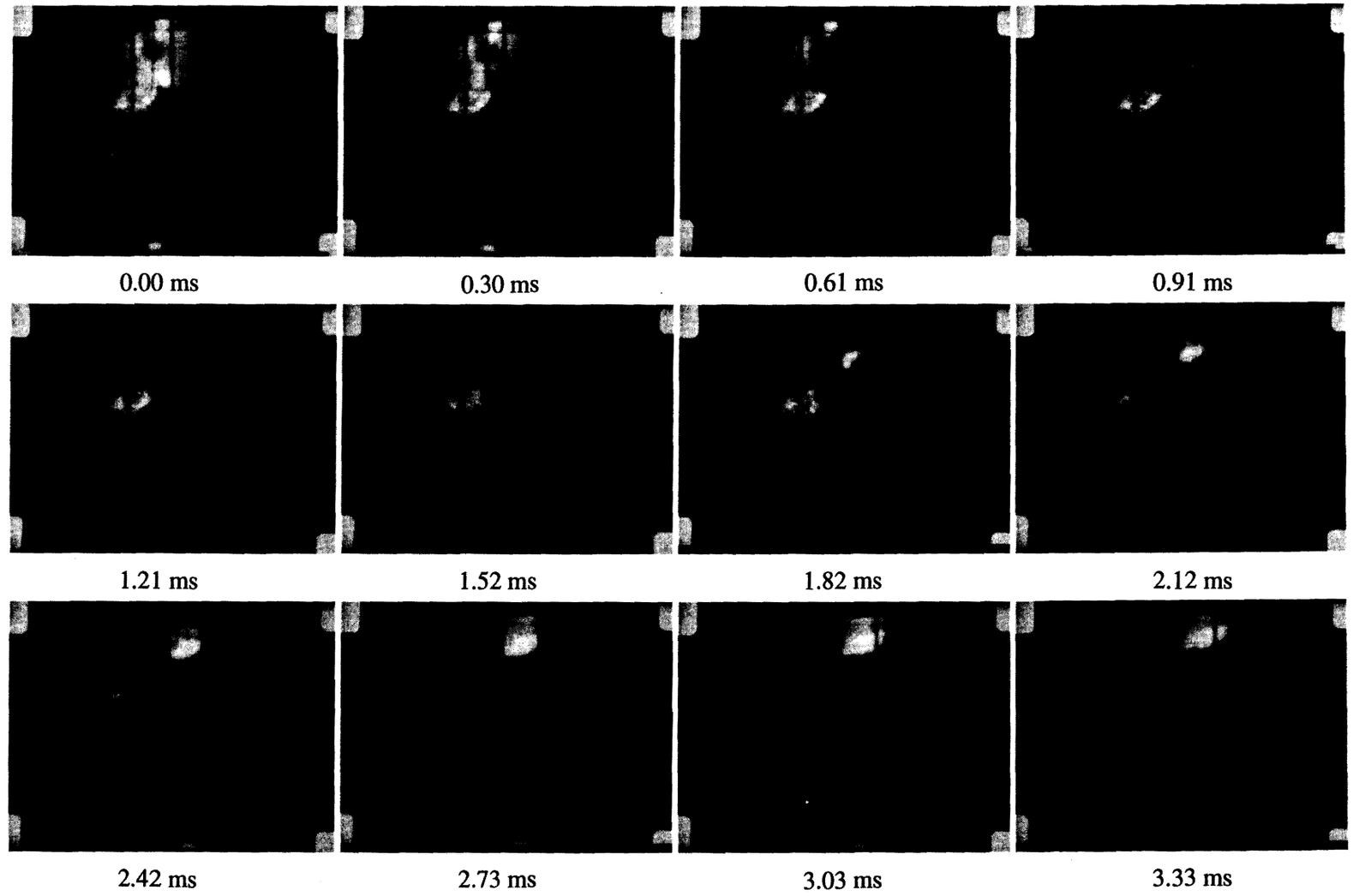

Figure 2u: STX024 High speed photograph at 3300 frames/s (direction 0°)

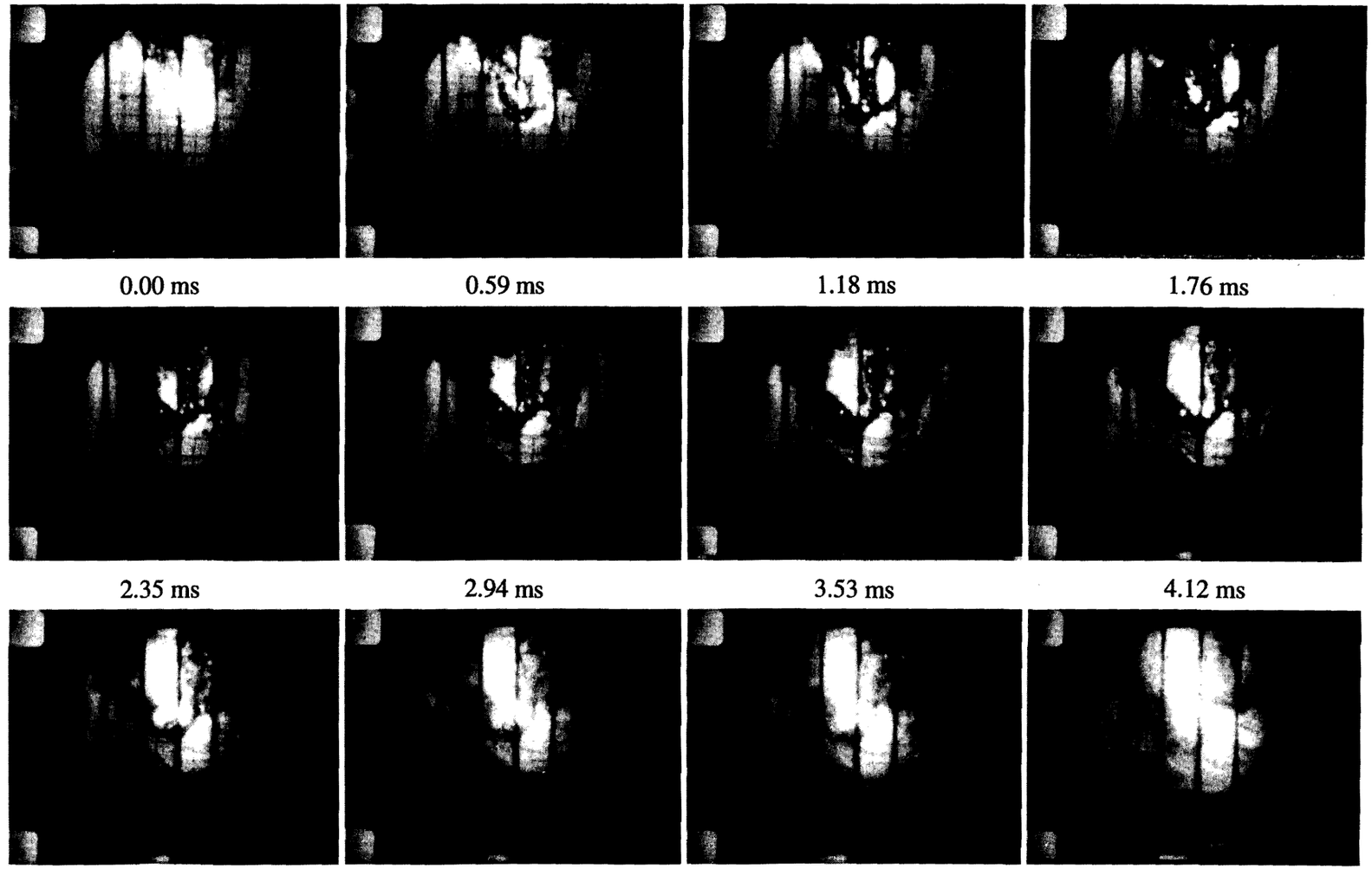

Figure 2v: STX024 High speed photograph at 3400 frames/s (direction 90°)

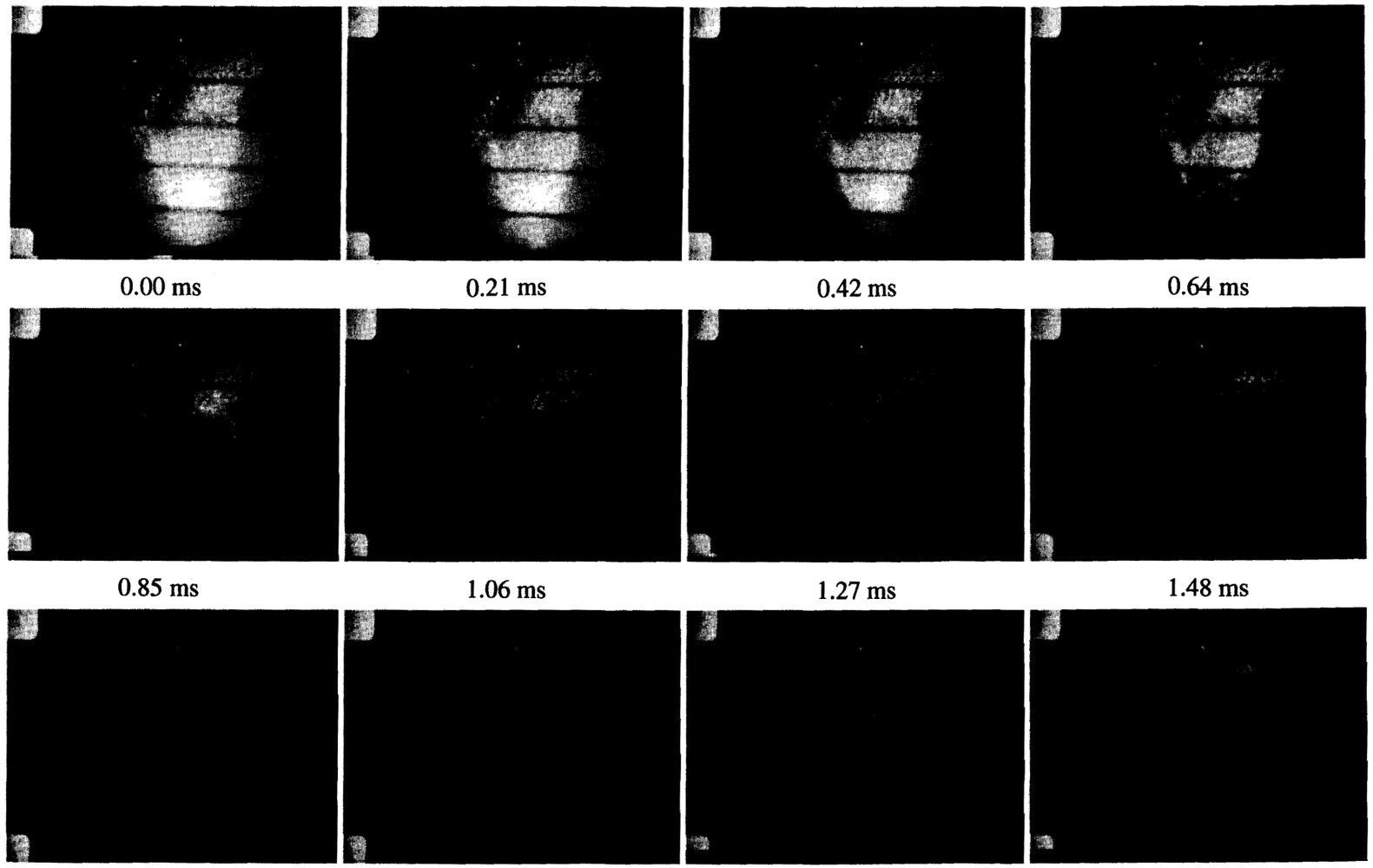

Figure 2w: STX025 High speed photograph at 4700 frames/s

Table 3: Steam explosion energetics and effect of premixing conditions

Run No.	Explosion	Settling velocity	Propagation velocity	Expansion velocity	Void fraction	Conversion ratio	Conversion ratio
	(Yes/No)	(m/s)	(m/s)	(m/s)	(-)	(press. base)	(temp. base)
STX017	Yes	5.17	395	43	NA	0.66	3.52
STX018	Yes	5.5	320	66	0.203-0.252	3.33	4.76
STX019	Yes	4.88	523	99	0.419-0.497	5.67	19.45(?)
STX020	No	2.09	NA	NA	0.578-0.681	NA	NA
STX021	Yes	3.19	380	56	0.630-0.793	4.05	4.95
NA: Not Available							

STX017, STX018: Base case

STX019: Dispersion device broken (?), Very strong explosion (high settling velocity, low void increase)

STX020: Dispersion device

STX021: Dispersion device under water

4.2 Energetics and effect of premixing conditions

The thermal to mechanical energy conversion ratio was evaluated from the measurement of temperature and pressure in the model containment vessel. Also, the void fraction in the premixing region, descending velocity of the melt in water, propagation and expansion velocity were evaluated from the film. Table 3 summarizes those numbers for selected cases. The detailed method was described in the previous publication [1].

The effect of artificial dispersion of the melt was examined with 6 cases of experiments as described in Section 3.1. This aspect is considered to affect the characteristics of premixing. In Table 3, the first two cases are base cases and the others are those in which the artificial dispersion of the melt was intended.

On the energy conversion ratio, it can be stated that the value was in the range of 1~5%, eliminating the extremely large value evaluated from the temperature data of STX019. The artificial dispersion of the melt suppressed steam explosion in one case but enhanced the energetics in other cases.

For code verification works, it is encouraged to refer the energy conversion ratio more than the pressure. The conversion ratio shown here is more reliable than either of the pressure or temperature data, because it has an integral feature and cross checked for both. Regarding to the void fraction in the premixing region, the numbers shown here is deduced assuming a uniform material distribution in the premixing region. It may be not in the reality, although it may work as a starting point in examining propagation calculations.

4.3 Debris size distribution

To show the typical sizes of melt particles before and after the explosive interaction (propagation phase of steam explosion), debris size distribution for the experiments with and without explosion are plotted in Figs. 3 and 4.

Fig. 3 shows the result of base case experiments STX017 and 018 where steam explosions were observed. A part of the melt was found not fragmented but lumped in a continuous body. This lumped mass was not characterised in terms of the size. Thus the curves end at the fraction

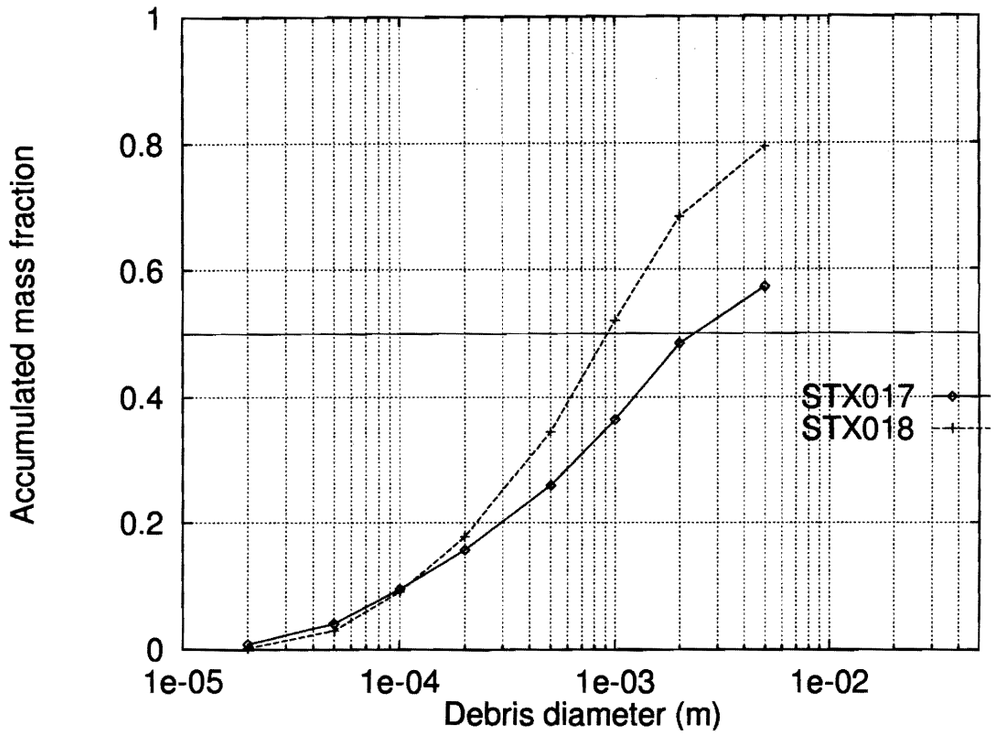

Figure 3: Debris size distribution with steam explosion (Base case experiments)

less than 100%. (e.g. In STX018, 4.4kg (out of total 21.4kg) was remained as a lump.)

Fig. 4 shows the results of the cases where the influence of artificial dispersion was examined. It is considered that the melt was divided into droplets whose sizes were less than 25mm by the steel mesh placed near the water surface. In this figure, a comparison is made between the cases steam explosion occurred (STX019 and 021) and not occurred (STX021). In the cases with steam explosions, the melt was fragmented more finely than the base case experiments in Fig. 3 due to the pre-breakup by the mesh. There was no large lumps remained after the explosion.

The difference between the cases with and without explosion is clear. The figure shows that the steam explosion fragmented most of the melt into particles smaller than 1mm, and about half of it smaller than 0.2mm. Particles smaller than 0.2mm was scarcely found in the no-explosion case.

From the view point on the modeling, many simulation codes for propagation phase (e.g. JASMINE-pro [3]) has separate fields for the melt droplets (before the explosion) and fragments (resulted from the explosion). For those models, a characteristic size specific for the fragments, separated from the original droplets, is required. Seeing the result in Fig. 4, the curve is shifted to left by the explosion, and it can be stated that debris smaller than 1mm is mostly not found in the result of premixing but produced by the explosion. Considering that smaller range of the size has more importance in the heat transfer surface area, a typical fragment size of 0.05~0.1mm will be a good assumption in the modeling.

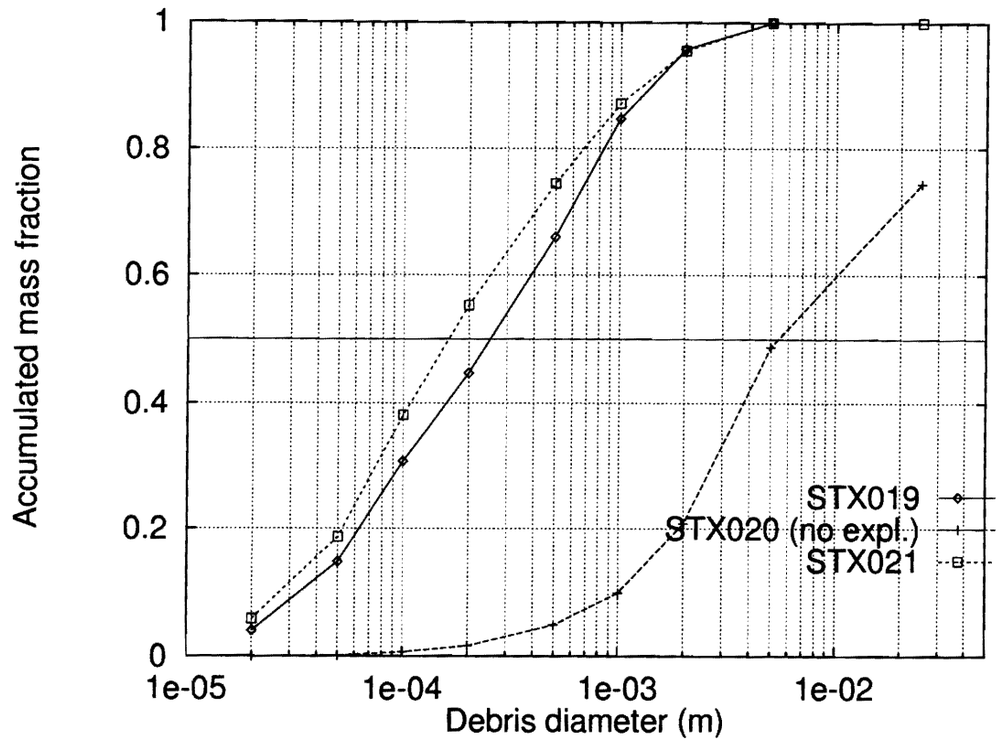

Figure 4: Debris size distribution with and without steam explosion (Experiments with artificial dispersion of melt)

5 Recommendations and suggestions for modelers

In this report, the steam explosion experiments performed at the ALPHA facility were described and the data were collected emphasizing especially the visual information. Some recommendations and suggestions are given below for researchers who will use those data for code development and assessment.

It is recommended to refer the cases STX018, 019 or 021 for the examination of steam explosion simulation code.

The void fraction in the premixing region and energetics, various velocities observed are given in Table 3. An attention should be taken on STX018 where a part of the melt (4.4 out of 21.4kg) was not fragmented but remained as a lump. The geometry of the premixing region can be obtained from the photographs.

The void fraction in Table 3 was evaluated assuming a uniform material distribution in the premixing region. It may be not in the reality. If the distribution has a strong influence on the results of propagation simulations, that aspect is remained to be solved by premixing simulation works.

A typical debris size in the range of 0.05~0.1mm specifically for the fragments will be a good assumption in the modeling.

On the energetics of steam explosions, it is more encouraged to compare code calculations and experiments in terms of energy conversion ratio given in Table 3 than do that on the pressure data only. It is easy to track the total kinematic energy in the system in simulations, and it has a more integral feature than the pressure as well as its importance.

Acknowledgments

Authors would like to gratefully acknowledge the cooperation of Mr. P. Hakan, a student of Kyoto University and Mr. D. Tochio, a student of Yamagata University , who worked at Severe Accident Research Laboratory of Japan Atomic Energy Research Institute in July and August, 1998, especially on the digitization of the high speed films.

References

[1] N. Yamano, Y. Maruyama, T. Kudo, A. Hidaka, and J. Sugimoto. Phenomenological studies on melt-coolant interactions in the ALPHA program. *Nuclear Engineering and Design*, 155:369–389, 1995.

[2] Y. Maruyama, N. Yamano, H. Ito, K. Komori, H. Sonobe, R. Yagioka, and J. Sugimoto. Evaluation of specific heat and temperature of thermite used in melt coolant interaction test in ALPHA program. Technical Report JAERI-M 93-096, Japan Atomic Energy Research Institute, 1993. in Japanese.

[3] Y. Yang, K. Moriyama, H. S. Park, Y. Maruyama, and J. Sugimoto. JASMINE-pro a code for the propagation phase of steam explosions. In *Proc. NTHAS98: First Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, Pusan*, pages 511–518, 1998.