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The uranium silicide plate-type fuel having initial enrichment <20 w/o ^{235}U is scheduled to be used in many research and material testing reactors. Fresh silicide mini-plates having density of 4.8 gU/c.c. fabricated by CERCA and B&W were pulse-irradiated in the Nuclear Safety Research Reactor (NSRR) at the Japan Atomic Energy Research Institute (JAERI) over the melting point of aluminum (Al) cladding.

As in-core instrumentation, Pt/Pt-13%Rh bare wire thermocouples spot welded directly to the Al cladding surface were used. Two irradiation tests were conducted in stagnant water at room temperature (about 20°C) and 1 atmospheric pressure inside the sealed irradiation capsule. In the course of pulse-irradiation changes of cladding temperatue rise were observed indicating departure from nucleate boiling (DNB) and Al cladding melt occurred in the tested fuel plates. The former was 174°C and the latter was 579°C in average. The latter is lower than that of phase diagram (640°C) due to the fin effect of thermocouples.

The peak cladding surface temperature recorded was 971°C in maximum. Temperature rise rate in average was 3.3×10^3 °C/s.

Post-pulse-irradiation examination (PIE) revealed tha the tested mini-plate was damaged at the energy deposition of 164 cal/g fuel by the melting of Al cladding and that of aluminum matrix. Molten aluminum reacted with U_3Si_2 particles dispered in Al matrix. This reaction resulted in forming multi-reaction phases at the surroundings of the original U_3Si_2 particles with different thickness of reaction phases where concentration of uranium, silicon and aluminum elements across reaction phase changed greatly. This redistribution has a potential to reduce the melting point (m.p.) of original fuel core (m.p. 1665°C) by formation of U_3Si (m.p. 985°C) and UAl_x (m.p. 1350°C). Additionally, as a result of eutectic reaction, many small particles were precipitated inside the original U_3Si_2 particles.

When the fuel was heated up over the melting point, molten Al cladding agglomerated significantly. At the plate center, many aluminum holes with various diameters were formed. At the plate edge, separation of fuel core occurred.

In spite of these damages, within this experimental scope, there occurred neither fuel plate fragmentation nor mechanical energy release.

Keywords: Interaction, Molten Al Cladding, Silicide, U_3Si_2, Transient, NSRR, Pulse-irradiation

過渡条件下におけるU_3Si_2芯材粒子と溶融アルミニウム被覆材との相互作用

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柳澤　和章

（1993年6月2日受理）

ウランーシリサイド板状燃料（初期濃縮度＜20 w／o ^{235}U）が数多くの試験研究炉にて使用されることが計画されている。燃料密度4.8 gU／c.c. なる未照射小型燃料板を仏・セルカ社及び米国B＆W社にて製作したのち，原研の安全性試験研究炉（NSRR）を用いてパルス照射を行い，アルミニウム被覆材の融点を超えた状態に至らしめた。

炉内計装として，Pt／Pt－13％Rh細線を直接アルミニウム被覆材にスポット溶接し熱電対として使用した。パルス照射は1回毎に燃料板を交換して合計2回実施したが，そのいずれもが大気圧下であり静止冷却軽水温度は約20℃であった。両パルス試験では，供試燃料板いずれにおいても核沸騰離脱（DNB）とアルミニウム被覆材の溶融が発生した。被覆材表面温度平均読み値によれば，前者は174℃でまた後者は579℃での発生である。アルミ被覆材の溶融が相図上の融点である640℃よりも低いのは，熱電対のフィン（冷却加速）効果によるものである。

実験を通じて記録された燃料板の表面最高温度は971℃であり，燃料被覆温度の上昇速度は平均で3.3×10^3℃／sであった。パルス照射後に実施した照射後試験によれば，供試小型燃料板は発熱量164 cal／g・fuelで損傷しており，そこではアルミニウム被覆材のみならず芯材のアルミニウムマトリクスの溶融も生じていた。溶融アルミニウムはアルミニウムマトリクス中に分散していたU_3Si_2芯材と反応もおこしていた。この反応の結果，初期U_3Si_2粒子のまわりに三重の厚みの異なる反応層が形成され，各々の層毎にウラン（U），ケイ素（Si）及びアルミニウム（Al）元素の濃度が著しく変化していた。この元素再分布はU_3Si（融点985℃）やUAl_x（融点1350℃）の形成を促進し，もともとの芯材の融点（1665℃）を低下させる可能性がある。さらに，U_3Si_2濃度変化に応じて共析反応が生じ芯材粒子中に反応生成物ができたことが分かった。

アルミニウム被覆材の融点を超える過渡加熱がおこると，燃料板のアルミニウム被覆材が溶融するとともに溶融アルミニウム孔が形成され，これらによって著しい塊状集積作用のおこることも判明した。すなわち，供試小型燃料板の中央部では，様々の直径をもつ溶融Al孔が燃料板の形状に著しい寸法変化をもたらし，芯材端においては，燃料芯材の局所的な分離が発生した。

これらの損傷にも拘らず，本実験の範囲内においては，供試小型燃料板からの破壊エネルギの発生は生じなかった。

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Contents

目　　次

1. Introduction

In many research and material testing reactors, the uranium silicide plate-type fuel having initial enrichment <20 w/o ^{235}U is scheduled to be used as an alternative of aluminide plate-type fuel having a high enriched uranium such as 93%. The development of this high density fuel was investigated widely, especially by the Reducing Enrichment in Research and Test Reactors (RERTR) Program of the US Department of Energy (DOE)[1][2]. In-core experiments with respect to plate-fuel behavior during steady-state operation have been in progress[3][4], however, those with respect to plate-fuel behavior during severe accident conditions are none, to date. The experiments were only addressed to aluminide related fuels[5-10].

To collect necessary data base for severe accident study, the experiment was conducted in the Nuclear Safety Research Reactor (NSRR) at the Japan Atomic Energy Research Institute (JAERI). Emphasis was made on understanding the interaction mechanism of aluminum cladding with U_3Si_2 particles over the melting point of aluminum. For this purpose, a scanning electron microscope (SEM) combined with X-ray microalalyzer (XMA) was utilized.

2. Experiment

2.1 Test Fuel Plate

The test fuel plates used in this study, shown in **Fig. 1**, were designed by JAERI and fabricated by CERCA in Romans, France. Untilization of the similar fuel plates is planned for the cores of JMTR and JRR-3. The fabrication processes for these test fuel plates are described elsewhere[3][11].

A test fuel plate consists of the fuel core (25 × 70 × 0.51 mm) sandwiched by Al-3 w/o Mg based alloy cladding (35 × 135 × 0.38 mm), hereafter abbreviated as "Al cladding". As the fuel core was sandwiched tightly by Al cladding with a volume ratio of fuel core to fuel plate of 38%, the thermal expansion of the fuel core would seem to be limited significantly.

Characteristics of the test fuel plate are summarized in **Table 1**. According to the U-Si binary phase diagram[10], the melting point of a fuel core consisting of U_3Si_2 + USi (U-8 w/o Si) is about 1,570℃. While the melting point of Al cladding (Al-3 w/o Mg) is 640℃.

A photomicrograph of an as-fabricated cross section of the fuel core (or meat) is shown in **Fig. 2**, where the average U_3Si_2 particle size measured by two dimensional intercept method is about 20 μm. As seen from this figure, U_3Si_2 fuel particles are almost uniformity dispersed in the aluminum

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2.2 Instrumentations and Irradiation Capsule

In-core instrumentation attached to the silicide fuel plate was five Pt/Pt-13%Rh thermocouples (hereinafter abbreviated T/C's), of which melting point was 1780° C. These were, as shown in Fig. 1, spot welded directly to the front surface of the plate fuel at five different locations. After assembling the fuel plate in the supporting jig with electric cables, it was loaded into the irradiation capsule as shown schematically in **Fig. 3**. The T/C No.5 (abbreviated #5) of the plate fuel in the capsule was positioned at the NSRR core midplane. An alumel-chromel T/C is set to monitor the coolant (water) temperature at about 10mm from the fuel surface on the reverse side of T/C #5.

In addition, the pressure sensors were provided at top plenum end and at bottom end of the capsule to measure the pressure pulse generated upon fuel plate fragmentation. A water level sensor was also installed to measure the movement of the top front of the water slug ejected upwards by the steam explosion.

All the irradiation tests with these instruments were conducted in stagnant water at room temperature (about 20° C) and 1 atmospheric pressure inside the sealed irradiation capsule[12].

2.3 Pulse History

The half-width of power of NSRR pulse irradiation is a minimum of about 4.4ms at a maximum integral power of 110 MWs. The value of this width varies from 4.4 to 20ms depending on the magnitude of inserted reactively. The effect of pulse width variation in this experiment is, however, negligible since the pulse-width is below the thermal time constant of the fuel plate (approximately 0.1s). A typical history of power pulse in NSRR was described in detail elsewhere[12].

The integral value of the reactor power P (MW·s) measured by micro fission chambers was used to estimate deposited energy Eg (cal/g·fuel) in each test fuel plate. Hence, $Eg = kg \times P$, where the power conversion ratio kg (cal/g fuel per MWs) is the ratio of fuel plate power to reactor power. This power conversion ratio was determined through fuel burn-up analysis[13] taking the radial and axial power skew into consideration.

Figure 4 shows the longitudinal (left) and transversal (right) power profile of the fuel plate shown by nuclides of ^{95}Nb[14]. These profiles were relatively flat, although locally sharp peaks with about 15%～28% higher than the average were revealed at both ends of the fuel plate. It is worthy of mentioning that power profiles at T/C's were almost unity.

3 . Results and Discussion

3.1 Transient Temperature

In **Table 2**, a summary of fuel behavior derived from in-core measurements and postpulse-irradiation examination (PIE) is shown. In **Fig. 5**, a typical transient temperature measured by T/C #4 at energy deposition of 97 cal/g·fuel is shown with the pulse power, indicated by the dotted line. It can be seen from the figure that the cladding surface temperature (hereinafter abbreviated CST) exceeded the boiling temperature, Ti (154℃), beyond the saturation temperature, Tsat (100 ℃), due to the pulse irradiation. Commencement of coolant boiling at temperature Ti was confirmed by the movement of water column which was detectable by the installed water level sensor. Details of the water level sensor were described elsewhere[15]. The CST continued to increase to an overshoot temperature, Tov (203℃). It then decreased to 194℃ where it remained for about 10 ms. This CST was thought to be the commencement of the film boiling. We signify it as T_{DNB} and denote here as the departure from nucleate boiling (DNB) temperature. The DNB value was found to be 174 ± 6℃ from the average of thirty-one data points. The temperature rise rate from room temperature, T_c, to T_{ov} was found to be approximately 3.34 × 10^3℃/s.

The increase in CST beyond T_{DNB} terminated at temperature T_{max} (244 ℃). The temperature rise rate between T_{DNB} and T_{max} was found to be 2.80 × 10^3℃/s. The quench occurred at temperature T_P (116℃) during an interval of 0.135 s. The magnitude of the temperature difference is given by $\Delta T = T_{max} - T_P$. Note that peak CSTs measured are all above T_{DNB}.

In experiments 508-4 and 508-5, all peak CSTs exceeded the melting point (m. p.) of Al cladding. **Figure 6** shows transient temperature of experiment 508-4 at interval of 0.05s around melting point. It can be revealed from this that measured solidus-liquidus temperatures ranged from 531° C to 612° C. Measured melting point of the Al cladding was found to be 579 ± 36℃, an average obtained from ten T/C's. On the other hand, physical solidus-liquidus temperatures according to the phase diagram are between 573℃ and 640℃. Consequently, the measured melting point was lower than that given by the binary phase diagram. This difference might be attributed to the fin effect of welded T/C's[16]. Since measured temperature is always lower (61° C in maximum) than realistic plate temperature, meaning that evaluations on fuel behavior according to the unmodified temperature are addressed more safety side.

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As shown in **Fig. 7**, the liquidus-solidus phase transformation during quench occurred repeatedly. It occurred similarly to that of temperature rise. In the experiments, this phase transformation only lasted to 0.02s.

Figure 8 summarizes the relation between the measured peak CST and the given deposited energy. Peak CST increases with increasing energy deposition. The maximum was 971℃ at 154 cal/g·fuel recorded in experiment 508-4. At temperatures beyond the Al cladding melt (579℃), the test fuel plates used in experiment 508-4 and 508-5 were damaged with accompanying significant molten aluminum holes and agglomeration, fuel core separation, and through-plate cracking(14). The locations of these damages are identified from PIE as shown schematically in **Fig. 9**. It is worthy of mentioning that not only Al cladding but also matrix aluminum was melt completely except the fuel core edge.

In-core data are shown in **Fig. 10**, where (a) is the data from experiment 508-6 (96 cal/g·fuel) performed without cladding melt and (b) is the data from experiment 508-5 (164 cal/g·fuel) performed with cladding melt. In both cases, neither increase of capsule pressure nor movement of water column was detected. Hence, in spite of the occurrence of Al cladding melt, there was no evidence to show the release of mechanical energy from interaction between molten aluminum and coolant.

The overview and X-ray of the specimen with Al cladding melt at 164 cal/g·fuel is shown in **Fig. 11**. The fuel plate was deformed significantly without fragmentation. Elapsed time above melting temperature ranged from 0.08 to 0.73s. Average was 0.40s.

3.2 Reaction of molten aluminum with U_3Si_2

In spite of a very short temperature excursion over melting point of Al cladding (<0.7s), Al cladding and matrix aluminum were reacted with silicide particles consisted of U_3Si_2 and USi compounds.

To confirm this clearly, a study by SEM/XMA was made. In this study, longitudinal and transverse section were made near T/Cs. The specimens cut from Ex. 508-4 (154 cal/g·fuel), Ex. 508-5 (164 cal/g·fuel) and Ex. 508-6 (96 cal/g·fuel) were polished and etched by 70%HCl + 25%HNO_3 + 5%HF.

SEM/XMA photograph of T/C #3 (peak CST >746℃) obtained from Ex. 508-5 and that of T/C #1 (peak CST <270℃) obtained from Ex. 508-6 are shown in **Photo. 1** for comparison. An original particle diameter measured by two dimensional intercept method is 82 μm for the former and 47 μm for the latter.

A relative magnitude of Al (aluminum), Si (silicon) and U (uranium) elements along the detection line ℓ was studied. For the case (a) of no melt, no trace of reaction between aluminum matrix and silicide particle is observed. Namely more than 97 w/o U_3Si_2 remained as it was.

For the case (b) of melt, there is a trace of reaction between aluminum matrix and silicide particles. This resulted in the formation of two additional phases (① and ②) at outermost of the silicide particles. The point analysis at selected places made by characterized X-ray revealed that the outermost region (①) roughly consists of 77 w/o U + 5 w/o Si + 18 w/o Al, that is, Al rich (U, Si)Al compounds. The thickness was about 10 μ m at maximum. The subseqequent phase (②) roughly consists of 86 w/o U + 11 w/o Si + 3 w/o Al, that is, Si rich (U, Si) Al compounds. Magnitude of aluminum element content decreased gradually. The thickness was about 5 μ m at maximum. The last largest phase consists of original compounds, that is, 92 w/o U + 8 w/o Si.

Reaction of molten aluminum with small-sized particle (<20 μ m) at temperature 918 ℃ is shown in **Photo. 2**. The outermost phase roughly consists of 78 w/o U + 6 w/o Si + 16 w/o Al, while the subsequent phase consists of 78 w/o U + 14 w/o Si + 8 w/o Al. This shows that at higher temperature molten aluminum reacted with U_3Si_2 significantly. Reaction products such as UAl_3 (m.p. 1350℃) at outermost region from Al rich (U, Si) Al compounds may reduce the melting point of original (U, Si) particles.

From macroscopic observation on Ex. 508-5 (164 cal/g·fuel) as shown in **Photo. 3**, it was revealed that many island type precipitates existed within the original particles. The precipitates such as U_3Si (m. p. 985℃) might have been formed from the eutectic reaction between U and Si element.

3.3 Dimensional Stability

Dimensional stability was studied using data obtained from PIE. Taking data obtained from prepulse-irradiation stage into consideration, changes of thickness in fuel meat and cladding as well as magnitude of bowing were determined by the specimens cut either longitudinally or transversally from pulsed fuel plate. Data summary is shown in **Table 2**. In the PIE, either longitudinal or transversal cutting of the tested silicide plate was performed along the T/C's in order that, a dimensional stability of the plate could directly be related to the measured local temperatures.

In **Fig. 12**, a maximum bowing of the fuel plate as a function of peak CST is shown, where data from reference[14] are included. As the fuel plate temperature was below 400°C, the bowing was negligible. When the temperature exceeded 400°C, however, the bowing became greater. The bowing was enhanced significantly by necking, that is, a significant thinning of plate wall thickness at end peak locations where melting of Al cladding and fuel separation occurred simultaneously.

Photograph 4 shows the conditions of the fuel plate after transient used in Ex. 508-4 (154 cal/g·fuel). As seen from (a), the fuel meat was

deformed greatly. Fuel meat separation at end peak location and plate wavy deformation are apparent in (b). In cross section of (A)-(A) in the macrophoto. (c), the bowing, the fuel separation, the necking, the denudation of meat and the molten aluminum are shown. With respect to the bowing, it is worthy of mentioning that the maximum channel flow width in existing research reactors is to be designed between 2.7 and 3mm. So, care must be taken not increasing the fuel plate temperature above 400° C so as not to cause the channel closure.

4. Conclusions

The conclusions reached in the present experiments are summarized as follows:

(1) Melting point of Al-3 w/o Mg cladding measured was 579 ± 36℃. The value was lower (61℃ in maximum) than that of Al-Mg binary phase diagram due to the fin effect of welded T/C's. The cladding melt occurred at energy deposition of 154 cal/g·fuel.

(2) Above energy deposition of 154 cal/g·fuel, the tested silicide plate was severely damaged resulting in causing molten aluminum holes and agglomeration, fuel core separation, and through-plate cracking. Neither fuel plate fragmentation nor mechanical energy release occurred in the present experiments.

(3) Reaction between molten aluminum and U_3Si_2 fuel particles occurred resulting in producing two different metallurgical phases at the outermost of the original U_3Si_2 particles. The concentration of U, Si and Al elements among the phases changed. The observed eutectic reaction have a potential to lower the melting point of the original U_3Si_2 particles due to the new phases such as U_3Si (m. p. 985℃) precipitated in the original matrix. The smaller the U_3Si_2 particle size, the greater the magnitude of eutectic reaction.

(4) Dimensional stability of silicide plate was degraded much as a result of interaction between molten aluminum and fuel core.

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(2) Above energy deposition of 154 cal/g·fuel, the tested silicide plate was severely damaged resulting in causing molten aluminum holes and agglomeration, fuel core separation, and through-plate cracking. Neither fuel plate fragmentation nor mechanical energy release occurred in the present experiments.

(3) Reaction between molten aluminum and U_3Si_2 fuel particles occurred resulting in producing two different metallurgical phases at the outermost of the original U_3Si_2 particles. The concentration of U, Si and Al elements among the phases changed. The observed eutectic reaction have a potential to lower the melting point of the original U_3Si_2 particles due to the new phases such as U_3Si (m. p. 985℃) precipitated in the original matrix. The smaller the U_3Si_2 particle size, the greater the magnitude of eutectic reaction.

(4) Dimensional stability of silicide plate was degraded much as a result of interaction between molten aluminum and fuel core.

Acknowledgments

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Table 1 Physical and mechanical parameters of the silicide plate-type miniature fuel

1. Silicide core : (U-21w/o Al-7.5w/o Si)	
(1) Dimension (mm)	70(L)x 25(W)x 0.51(t)[+]
(2) Enrichment (w/o)	19.89 (0.84～0.86g U-235 per plate)
(3) Element : Si (w/o)	7.5
U (w/o)	92.3, U density=4.8g/cm³ Void fraction=5.0±0.9
(4) Composition : Fuel	U_3Si_2+USi, U_3Si_2 density=12g/cm³, U_3Si_2 > 97w/o
: Matrix	A5NE[++]
2. Aluminum alloy cladding	
(1) Dimension (mm)	130(L)x 35(W)x 0.38(t) in both sides
(2) Composition	Al-2.8w/oMg-0.04w/oMn-0.01w/oCr(AG3NE)
(3) Density (g/cm³)	2.67
(4) Mechanical properties at room temperature	
Tensile stress (MPa)	240
0.2% proof stress (MPa)	130
Elongation (%)	25
(5) No blister at annealing temperature of 475℃, >1hr	

Note : (+) L=Length, W=Width and t=thickness
(++) Industrial standard od France

Table 2 Summary of the results of in-core measurements and PIEs for the tested silicide plate-type miniature fuel

Experiment		508-6	508-8	508-3	508-4	508-5
Fuel plate no.		CS514831	CS514832	CS514819	CS514829	CS514830
Deposited energy (cal/g·fuel)		96	97	116	154	164
Peak cladding surface temperature (℃) #1		270	309	350	971	779
#2		229	261	372→387 (2)	893	689
#3		202	211	414	652	×
#4		× (1)	244	393	881	918
#5		205	330	424→544	930→957	578→656
Average ± standard deviation (℃)		227±31	271±48	418±74	871±128	761±117
Coolant temperature (℃) : prepulse		21	25	18	17	22
: peak		43	46	47	35	34
Cladding wall (mm)	min	0.347±0.015	0.330±0.021	0.154±0.180	0.000 (3)	0.010±0.033
	max	0.416±0.026	0.412±0.033	0.540±0.096	0.671±0.254	0.652±0.357
Core thickness (mm)	min	0.423±0.021	0.442±0.033	0.447±0.034	0.565±0.085	0.578±0.119
	max	0.558±0.031	0.560±0.019	0.620±0.080	1.078±0.744	1.125±0.354
Plate thickness (mm)	min	1.233±0.019	1.224±0.016	1.058±0.338	0.560±0.180	0.795±0.137
	max	1.258±0.012	1.261±0.019	1.440±0.122	1.515±0.360	1.549±0.399
Max bowing (mm)		0.53±0.16	0.14±0.07	1.2±0.85	6.4±1.8	2.7±1.2
Observation in PIE (4)		IC(1) PT(1)	IC(1) PT(1) HS(1)	IC(3)	PT(2) CS, CM	IC(1) PT(1) CS, CM

(1) × Thermocouple malfunctioned
(2) Two peaks
(3) No cladding wall due to significant Al agglomeration and denudation
(4) IC : Incipient crack (number of observations), PT : Through-plate crack, CS : Core separation, CM : Cladding melt

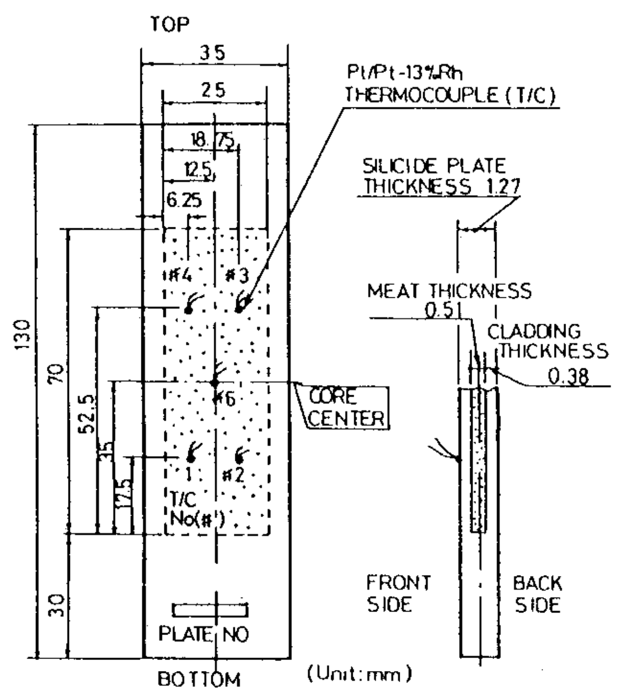


Fig. 1 Schematic representation of tested silicide plate-type miniature fuel, having enrichment by 19.89% ^{235}U and density by 4.8 gU/ml

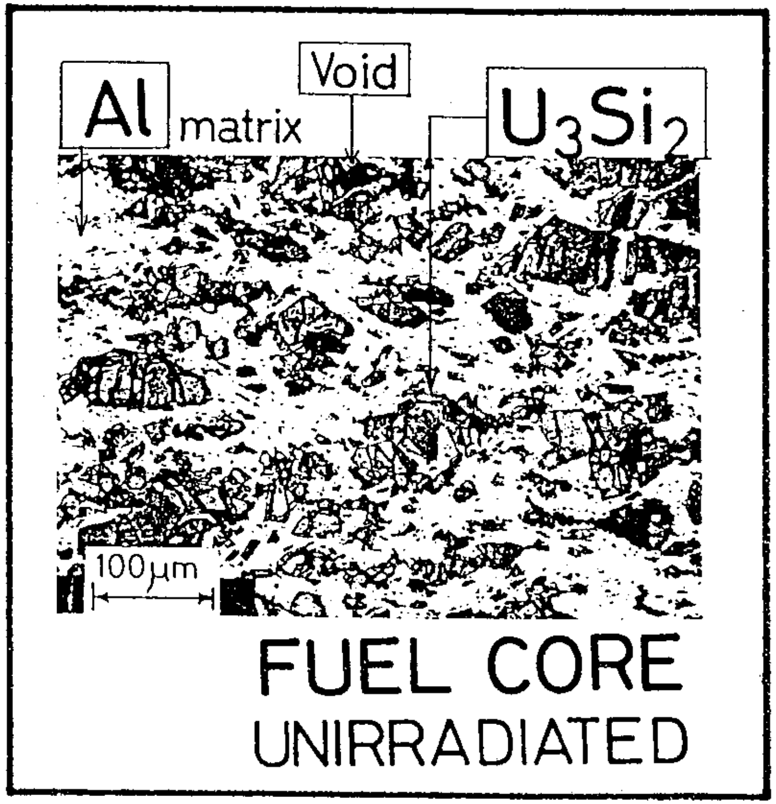


Fig. 2 Photomicrograph of an as-polished cross section of the unirradiated silicide plate-type miniature fuel fabricated by CERCA, showing U_3Si_2 particles with an average size of 20μm dispersed in the aluminum matrix with a 5% void fraction

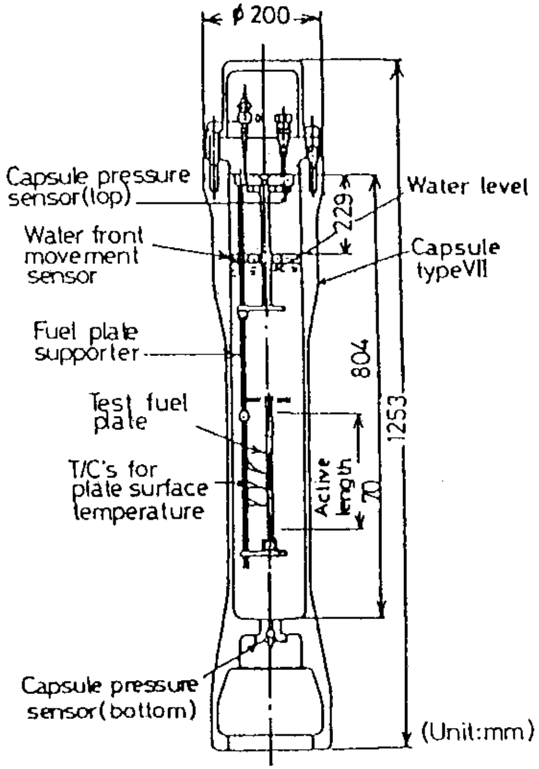


Fig. 3 Schematic drawing of NSRR irradiation capsule type Ⅶ

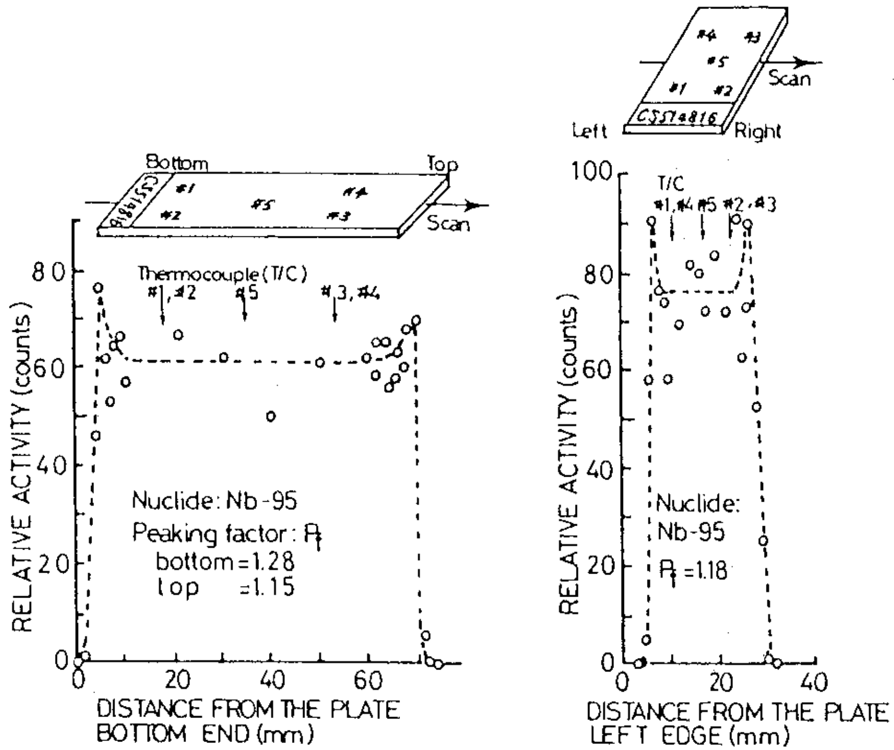


Fig. 4 Longitudinal and transversal power distribution of tested silicide plate-type miniature fuel at 77cal/g・fuel, where γ-radioactivity from ^{95}Nb was measured by γ-scanning device

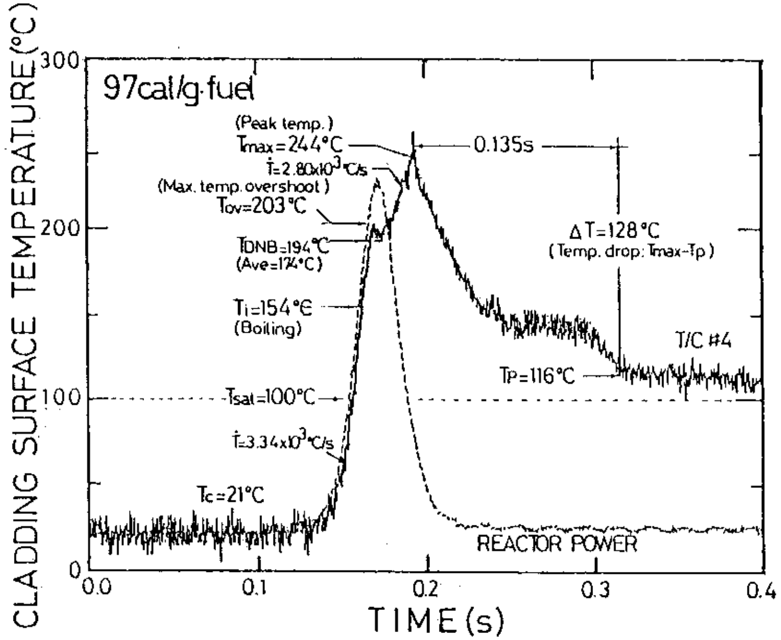


Fig. 5 Typical example of cladding surface temperature (solid line) and reactor power (dotted line), showing boiling temperature (Ti), DNB temperature (T_{DNB}), maximum overshoot temperature (T_{OV}), peak CST (T_{max}), quench temperature (T_p), and temperature drop (ΔT). This is from T/C #4 of the miniplate used in ex.508-8 (97cal/g·fuel, failure)

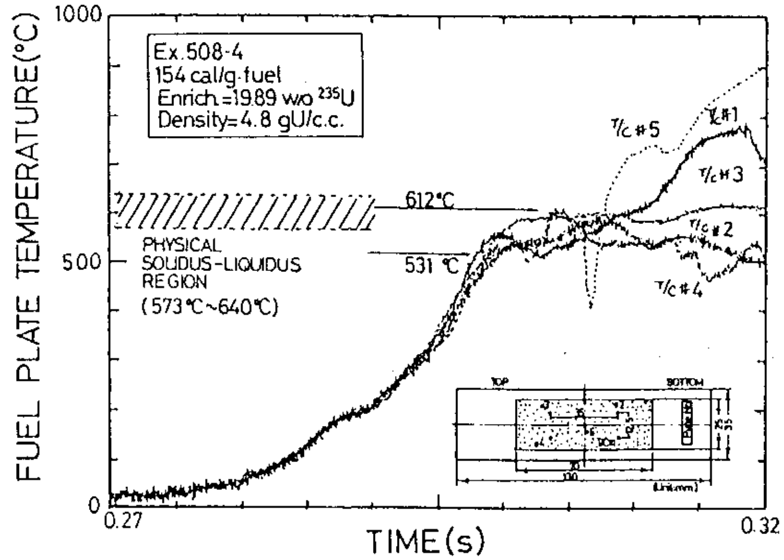


Fig. 6 Experimentally observed solidus-liquidus transformation temperature of Al-3% Mg alloy (AG3NE) by T/C's welded to fuel plate surface and metallurgically observed solidus-liquidus transformation temperature of the alloy shown by hatched area

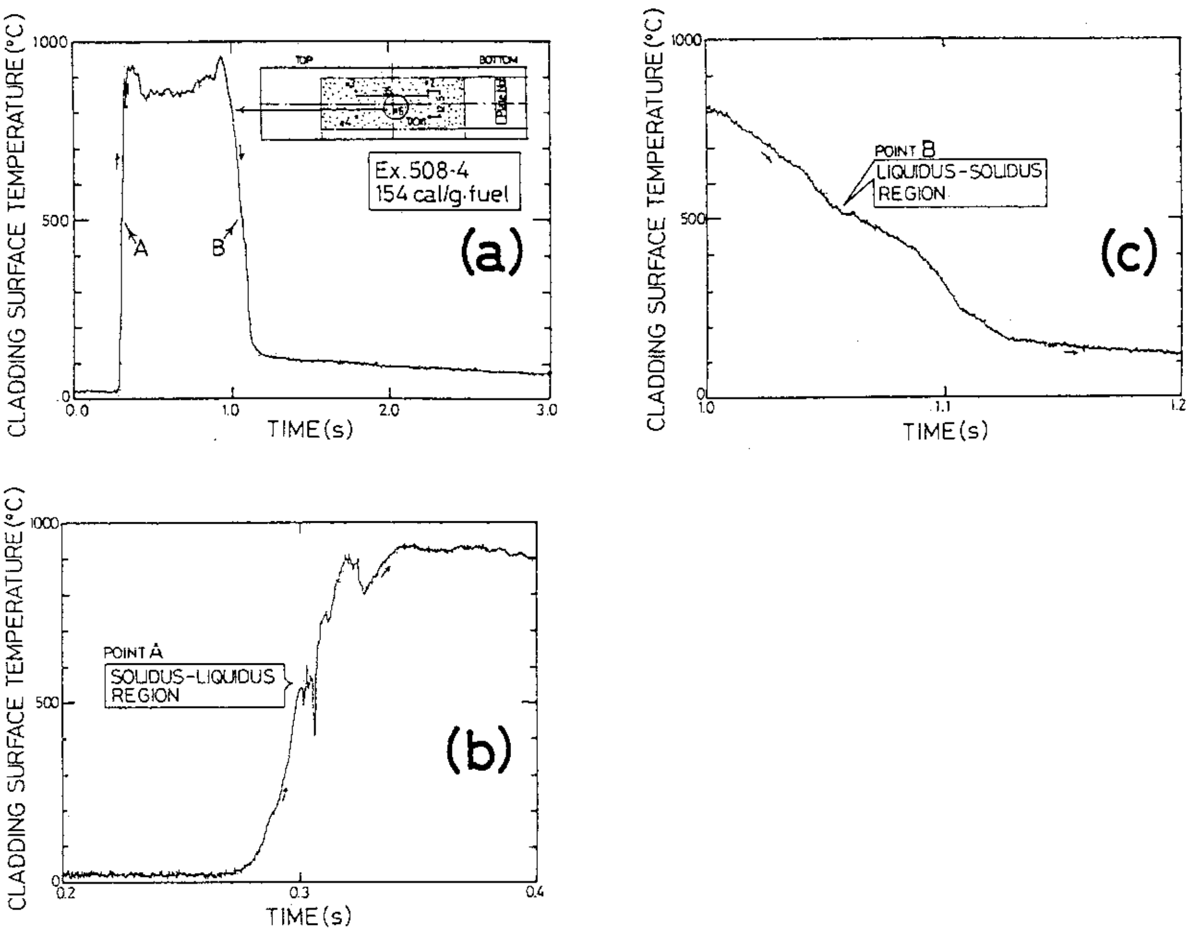


Fig. 7 Solidus-liquidus phase transformation of silicide plate fuel observed about 500°C in ex. 508-4 (154cal/g·fuel)
(a) Transient temperature profile measured by T/C #5 of which location is shown in inset
(b) "Point A" correponded to solidus-liquidus transformation occurred during temperature rise
(c) "Point B" correponded to liquidus-solidus transformation occurred during quench

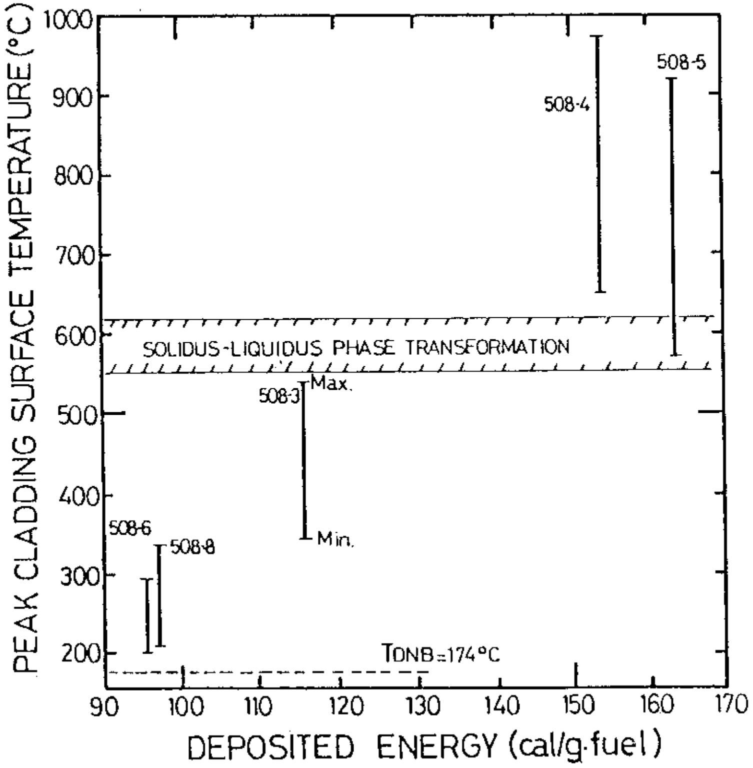


Fig. 8　Cladding surface temperature read directly from the welded thermocouples (bare 0.2mmϕ wire Pt/Pt-13%Rh) as a function of deposited energy. The dotted line at the bottom of the figure indicates the DNB temperature of 174°C

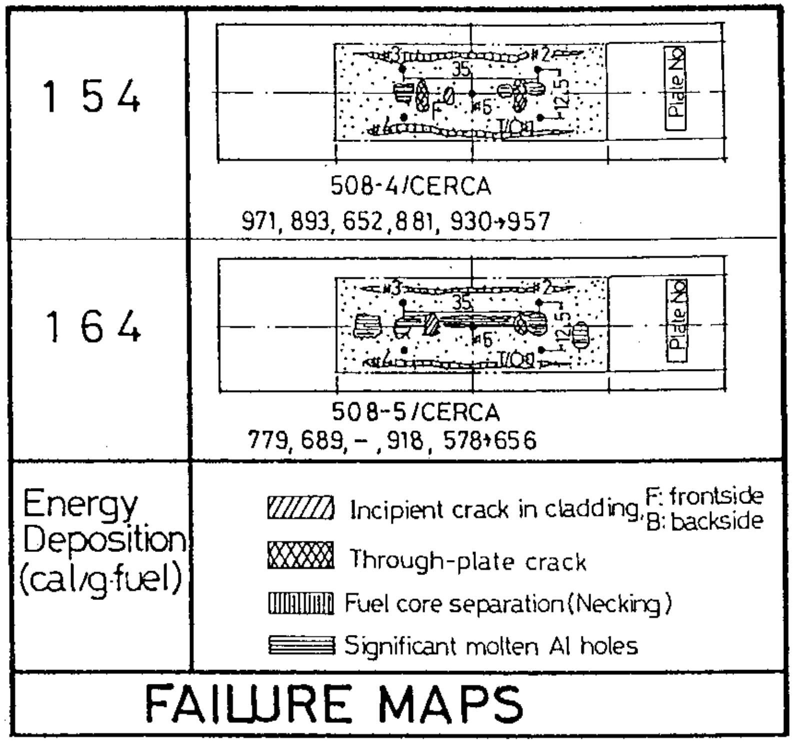
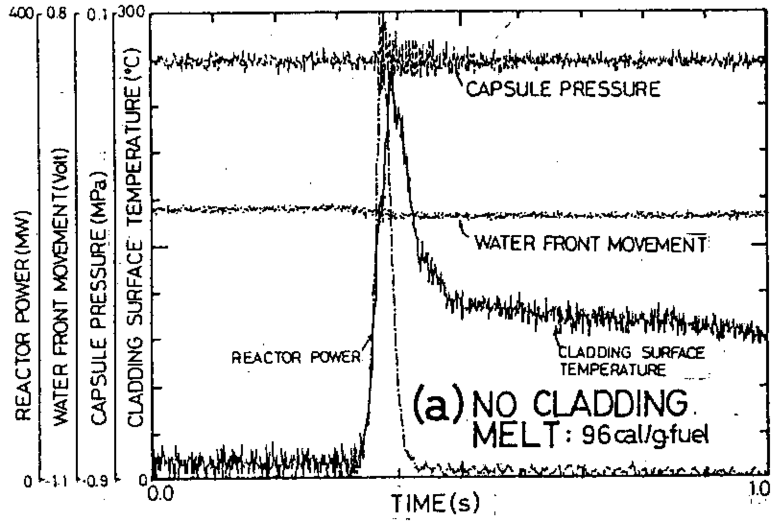


Fig. 9　Failure maps of the miniplates sustaining damage in the experiments as a function of energy deposition



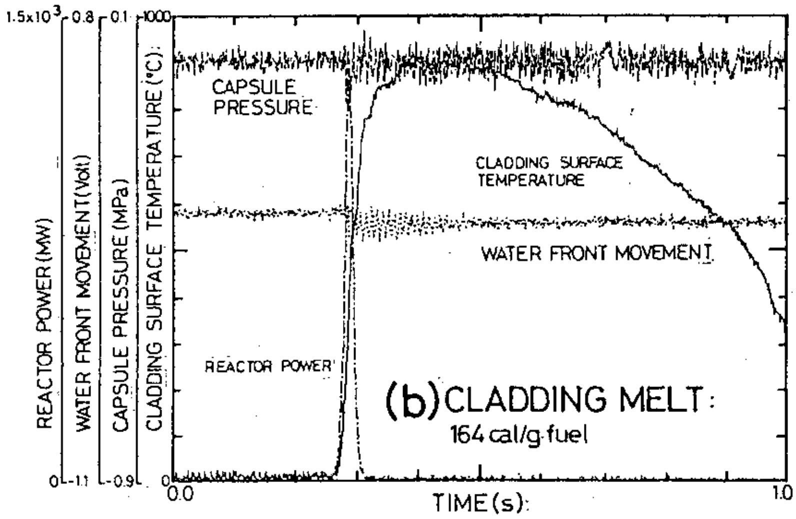
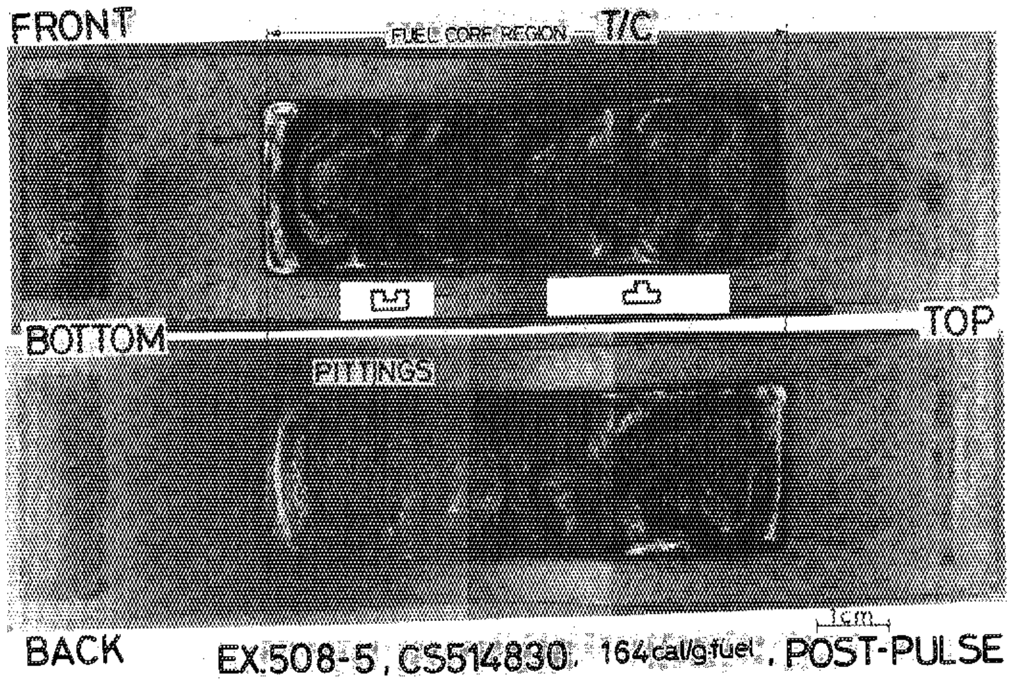


Fig. 10 In-core measurement of capsule pressure, water front movement, cladding surface temperature, and reactor power obtained from
(a) Ex. 508-6 (96cal/g•fuel): no cladding melt
(b) Ex. 508-5 (164cal/g•fuel): cladding melt where a slight variation of data in capsule and water front was observed due to occurrence of DNB but not due to occurrence of fuel fragmentation



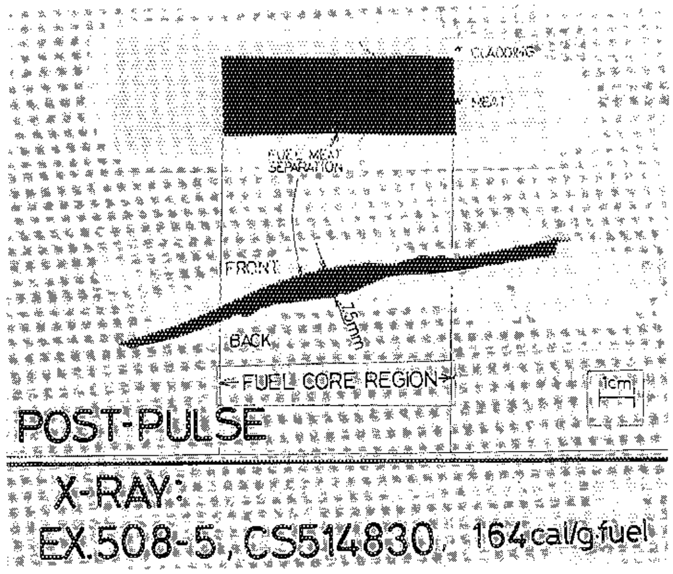


Fig. 11 (TOP) overview of tested fuel plate pulsed at 116cal/g·fuel, peak CST of 918°C in ex. 508-5, (bottom) X-ray of the fuel plate after pulse

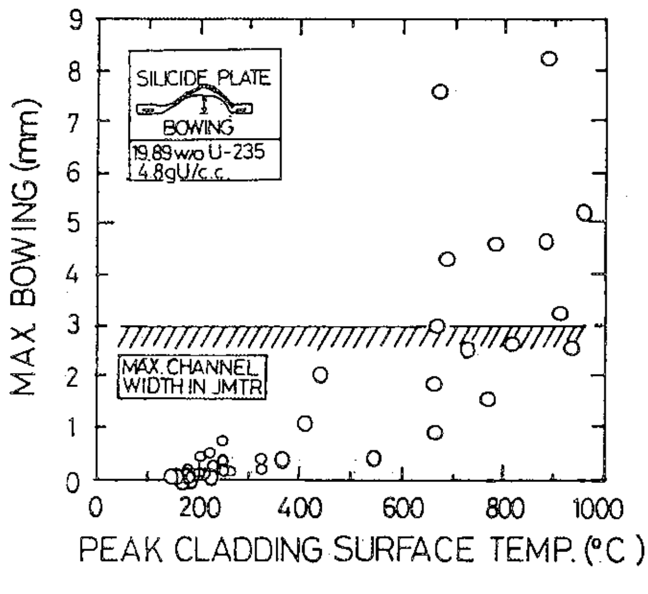


Fig. 12 Observed maximum bowing of silicide plate-type fuel from PIE, where five cuttings a plate fuel were made either of longitudinal (T/C #5) or of transversal sections (T/C #1-4) resulting in at least one T/C in a specimen

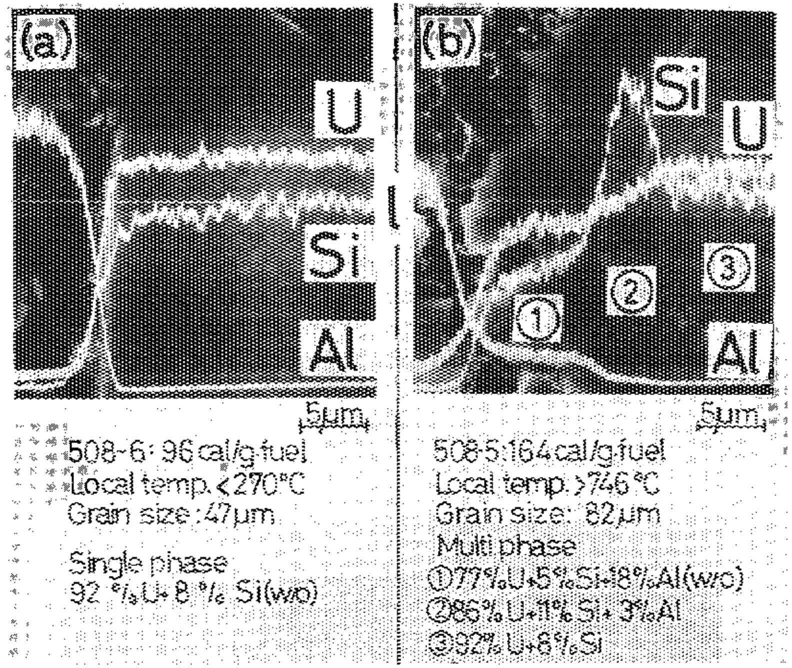


Photo. 1 SEM/XMA along line ℓ obtained (a) from Ex. 508-6 (96cal/g·fuel, peak CST 270°C) and (b) from Ex. 508-5 (164 cal/g·fuel, peak CST>746°C), where magnitude of each elements from the baseline of photo. was relative such as Al:Si:U= 1:1:5 for (a) and Al:Si:U=1:2.5:5 for (b), respectively

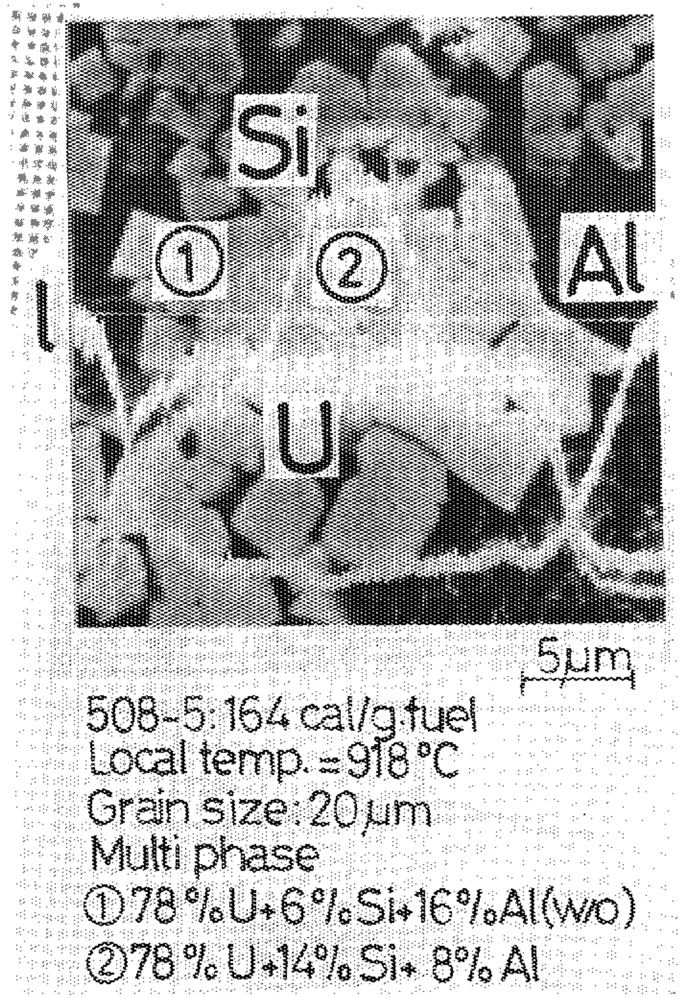


Photo. 2 SEM/XMA along line ℓ obtained from Ex. 508-5 (164cal/g·fuel, peak CST= 918°C) showing reaction of molten Al with small-sized particle (<20μm), where magnitude of each elements from the baseline of photo. was relative such as Al:Si:U=1:2.5:5

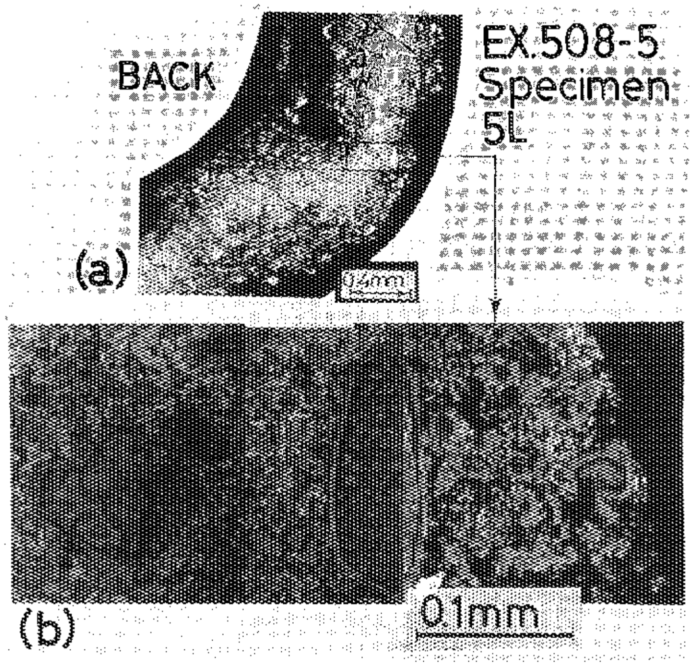


Photo. 3 (a) Microstructure obtained from Ex.508-5 (164cal/g·fuel, close to T/C #5 of which peak CST=656°C) and (b) magnified structure showing island type precipitates of U_3Si_2 formed by eutectic reaction

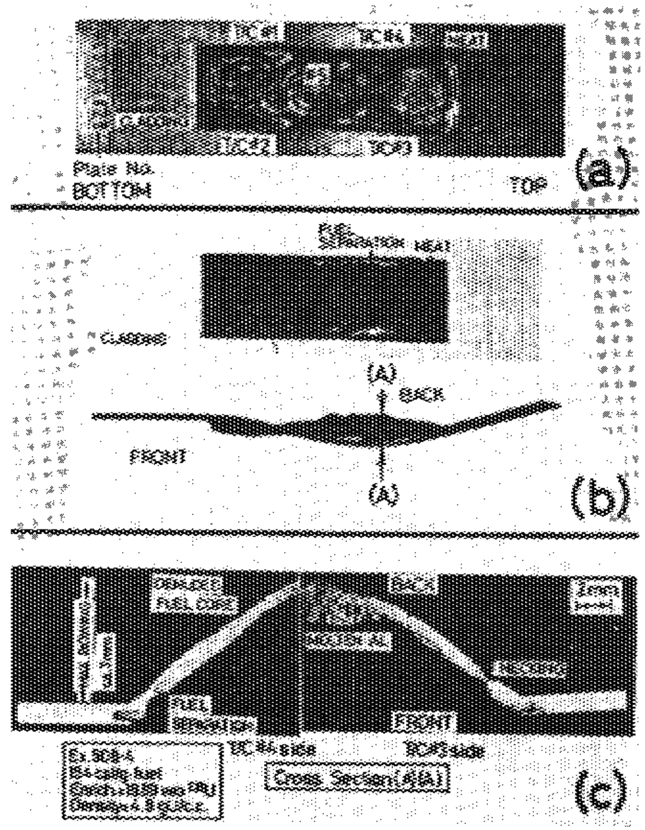


Photo. 4 (a) Overview of front surface of tested plate-type miniature fuel at 154cal/g·fuel in Ex.508-4, where peak CST measured by attached T/C's #1-#5 were 971,893,652,881 and 957°C respectively, (b) results of X-ray inspection taken by two directions and (c) cross section of (A)-(A) in picture (b)