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In-core Behavior of Silicide Fuel

-Power Transient by Abnormal Control Rod Withdrawal and Cold Coolant Induction-

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Japan Atomic Energy Agency

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The safety study of the silicide fuel for the use in the Japan Materials Testing Reactor (JMTR) under the power transient was carried out. (1) It was revealed from the experimental tests that the peak cladding surface temperature (PCST) for the “abnormal control rod withdrawal (ACRW) during the reactor start-up” was 137 ℃ and that for the “cold coolant induction (CCI) at the secondary loop” was 111 ℃. The values were higher than those of the EUREKA-2 code calculation used for the JMTR licensing. (2) The PCST of the two tests did not exceed the minimum DNBR and the fuel integrity of them was kept without causing any fuel damage. Consequently, experimental results cleared the judging criteria for safety of ACRW and CCI. These experimental facts lead that the predictions made by the code for ACRW and CCI is safe enough.

Keywords; Uranium Silicide Plate-Type Fuel, Research Reactor, NSRR, JMTR, Abnormal Control Rod Withdrawal, Cold Coolant Induction, Low Enrichment Uranium, Fuel Damage

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シリサイド燃料の炉内ふるまい

-制御棒の異常引抜と冷水導入による出力過渡-

日本原子力研究開発機構経営企画部
柳澤　和章

（2010 年 11 月 26 日　受理）

材料試験炉（JMTR）で出力過渡を受けた場合のシリサイド燃料の安全性を研究した。（１）“JMTR 初期起動時に発生した制御棒の異常引き抜き（ACRW）”に関する想定実験で究明された燃料板最高温度（PCST）は１３７℃であった。“二次系ループにおける冷水導入（CCI）”に関する想定実験で究明された燃料板最高温度は１１１℃であった。これら想定実験値は JMTR 安全審査で使った EUREKA-2 コード計算値よりも高く、保守的であった。（２）両想定実験では最小 DNBR は生じなかった。また、両想定実験で用いた燃料板は破損する事無く健全性が維持した。すなわち、実験結果は ACRW と CCI に関する安全性判断基準をクリアしていた。この実験事実から、ACRW と CCI に関する EUREKA-2 計算コード予測は十分安全余裕を有している事が裏付けられた。

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1. INTRODUCTION

Uranium silicide plate-type fuel having an initial density of 20 wt% ^{235}U is widely used in many research and materials testing reactors in the world. As of 1994, the JMTR in Japan was completed the full loading of the silicide fuel in the core. The silicide fuel had a density by 4.8g/cm^3 (hereinafter abbreviated as 4.8 g/c.c.). During the licensing of the JMTR, two power transients, that is, (1) an abnormal control rod withdrawal (ACRW) during the start-up and (2) a cold coolant injection (CCI) at the secondary loop, were considered as the matter of safety concern. For this purpose, JMTR used the computer code EUREKA-2 to calculate the peak cladding surface temperature (PCST) of the silicide fuel plate and showed that there was no possibility to bring the plate into the minimum ratio for the departure from the nucleate boiling (DNBR).

The present paper will describe the result of experiment performed to simulate the aforementioned two transients. It was aimed at showing the safety margin of the EUREKA-2 calculation through the experimental data. The obtained results are new, not reported before.

2. EXPLANATION OF THE TRANSIENT

2.1 ACRW during the reactor start-up

The main cause of this phenomenon was addressed to the malfunction of the control rod driving devices or to mishandling of the devices by the operators. In both cases, a continuous withdrawal of the control rod occurred to give the excess reactivity into the reactor core [1]. For the safety analysis, the computer code EUREKA-2 was run with significant conservative inputs [2]. As shown in **Fig. 1**, the PCST and the maximum fuel core temperature [1] were 110 ℃ and 119 ℃, respectively. A coolant temperature was increased from the inlet (49 ℃) to the outlet (68 ℃). As mentioned above, the safety criterion was the minimum DNBR. The fuel plate should not be damaged by any temperatures calculated [3].

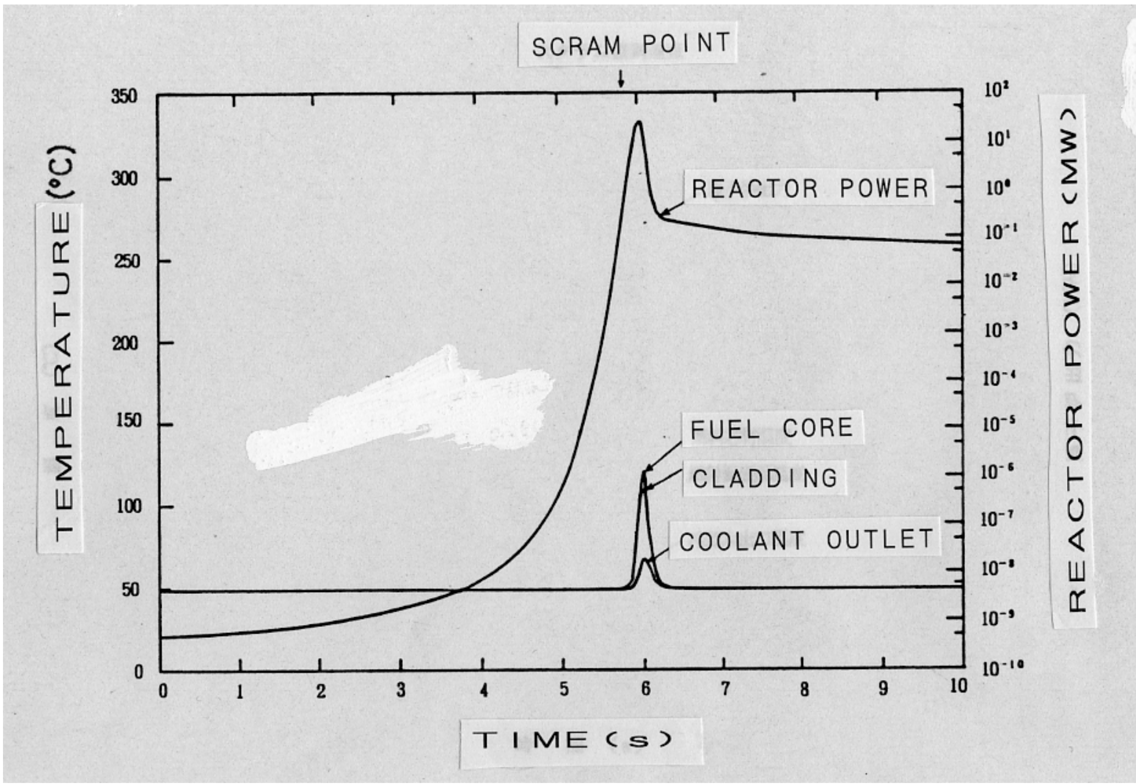

Fig.1 Reactor power, maximum fuel core temperature, PCST and coolant outlet temperature run by the computer code EUREKA-2 for the abnormal withdrawal of the control rod.

2.2 CCI at the secondary loop

During the licensing, a sudden drop of the coolant temperature in the primary loop due to the cold coolant induction at the secondary loop was considered as the main cause. This inserts the positive reactivity into the core and gives the transient power increase to the fuel. For the safety analysis, the computer code EUREKA-2 was run with significant conservative inputs. As shown in **Fig. 2**, the PCST and the maximum fuel core temperature were 53 ℃ and 54 ℃, respectively. A coolant temperature was increased from the inlet (49 ℃) to the outlet (50 ℃). The same safety criterion as mentioned above was used.

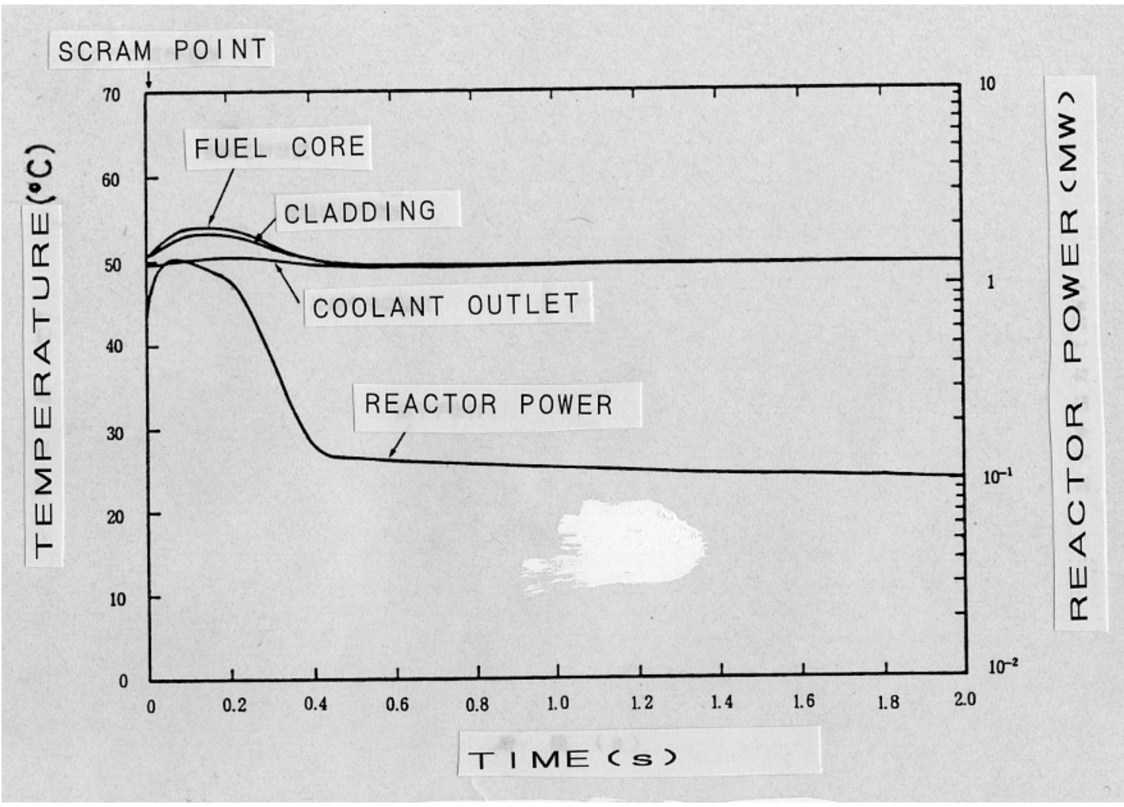

Fig.2 Reactor power, maximum fuel core temperature, PCST and coolant outlet temperature run by the computer code EUREKA-2 for the cold coolant induction.

3. EXPERIMENTAL METHOD

3.1 Test fuel plate

Two test fuel plates, that is, CS514837 and JRRJ4851 were prepared. For ACRW, the former was used in the experiment (Ex.) 508-12 and for CCI; the latter was used in Ex. 508-14. Two fuels were designed by the Japan Atomic Energy Research Institute (JAERI, now the Japan Atomic Energy Agency), and fabricated by the CERCA in Romans, France. The different fuel number was addressed to the different uranium batch in the fuel fabricator. As-fabricated characteristics of the fuel were summarized in the **Table 1**.

Table 1 As-fabricated characteristic of the test fuel plate

Experiment no.	508-12	508-14
Objective	Abnormal Control Rod Withdrawal	Cold Coolant Induction
Plate no.	CS514837	JRRJ4851
Density （g/cc）]	4.8	4.8
Enrichment （wt %）	19.86	19.77
Core material	A5NE（Al-0.14%Fe-0.06%Si）	A5NE
Core weight （g）	5.76（1.12g A5NE+4.64gU_3Si_2）	5.80（1.07g A5NE+4.73gU_3Si_2）
U total （g）	4.28 including 0.85gU-235	4.35 including 0.86gU-235
Plate weight （g）	19.41	19.43
Void （%）	4.8	6.1
Cladding	AG3NE（Al-2.8%Mg-0.29%Fe）	AG3NE
Tensile stress（MPa）	193	203
0.2% Yeild （MPa）	126±4	142
Elongation （%）	26±1	22
Fabrication	CERCA, France	CERCA, France

The content of the ^{235}U in the uranium metal in the fuel core was 0.85 grams, which corresponded to the initial nominal enrichment of about 19.9wt%. Fuel core was A5NE composed of U_3Si_2 (>87wt%)+USi dispersed into the aluminum alloy matrix, where U_3Si_2 particles were made of 7.7wt%Si and 92wt%U. The fuel core made of 25mm wide x 70mm length x 0.51mm thickness was sandwiched by the Al-3wt%Mg based alloy cladding; AG3NE having the size by 35mm wide x 130mm length x 0.38mm thickness. The latter is abbreviated as the Al cladding. A volume ratio of the fuel core to the fuel plate was about 38%, leading to the limited thermal expansion of the fuel core. A void fraction in the core matrix was about 5-6%, measured by the water immersion method.

The similar fuel plate in the form of the assembly was used as the JMTR, of which size was about 25 times the test specimen except the thickness. The one of fuel fabricator for the JMTR was the CERCA. The fabrication process for the test specimen, that is, the author called it as the test mini-plate was described elsewhere [4].

3.2 Instrumentation and irradiation capsule

To measure the PCST, Pt/Pt-13%Rh thermocouple (T/C) was directly spot welded onto the Al cladding surface, where a maximum number of the T/C was nine. Each test specimen had the engraved identification number at an onside of a fuel bottom end, so that the author denoted the side as the front side. All T/C's were only arranged to the front side as shown in **Fig. 3**.

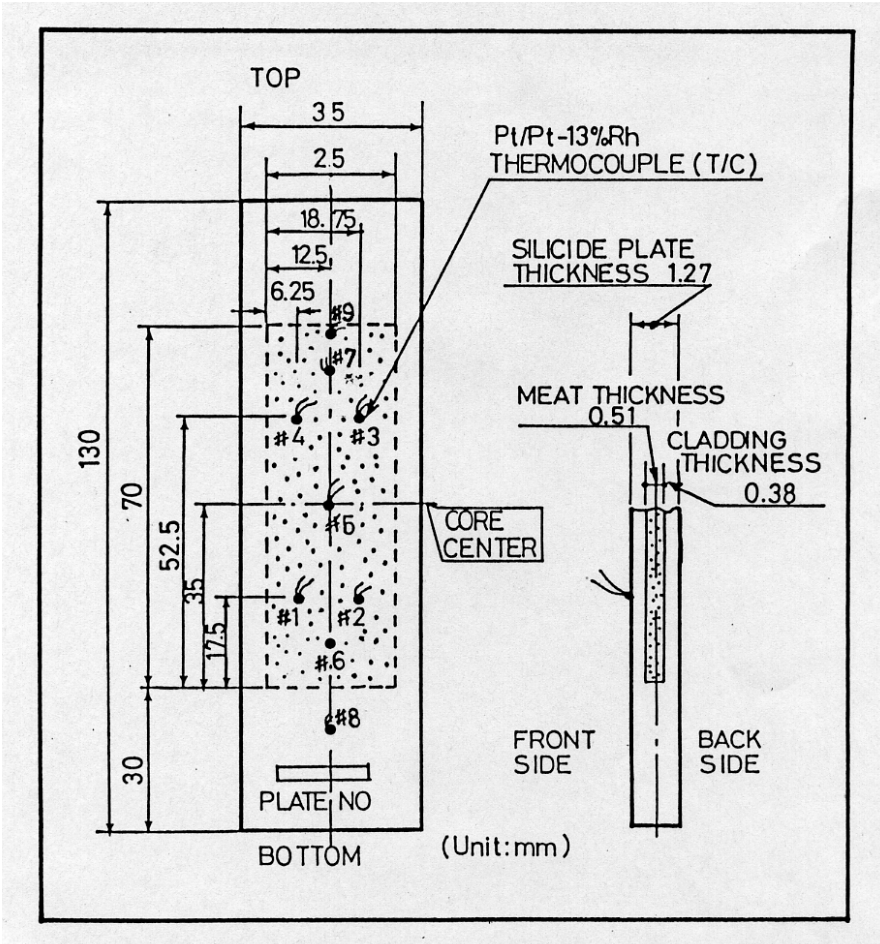

Fig.3 Schematic representation of the test fuel plate and spot welded thermocouples onto the fuel front side, where fuel plate number was engraved at the plate bottom end.

In Ex. 508-12, T/C number 8 (T/C#8) was spot welded to the enriched region but T/C #9 was done to the non-fueled region to know the temperature difference between the two. In Ex-508-14, T/C#8 was spot welded to the non-fueled region but the T/C#9 was done to the boundary between the fueled region and non-fueled one. Due to this specialty, the two data were omitted from the average temperature. To monitor the temperature of the coolant (water), an alumel-chromel T/C was prepared at about 10mm distance far from the plate backside. In **Photo.1**, (a) part shows the test fuel plate for Ex 508-14, the supporting jig and electric cables and (b) part shows the alumel-chromel T/C at the mid point of the test specimen.

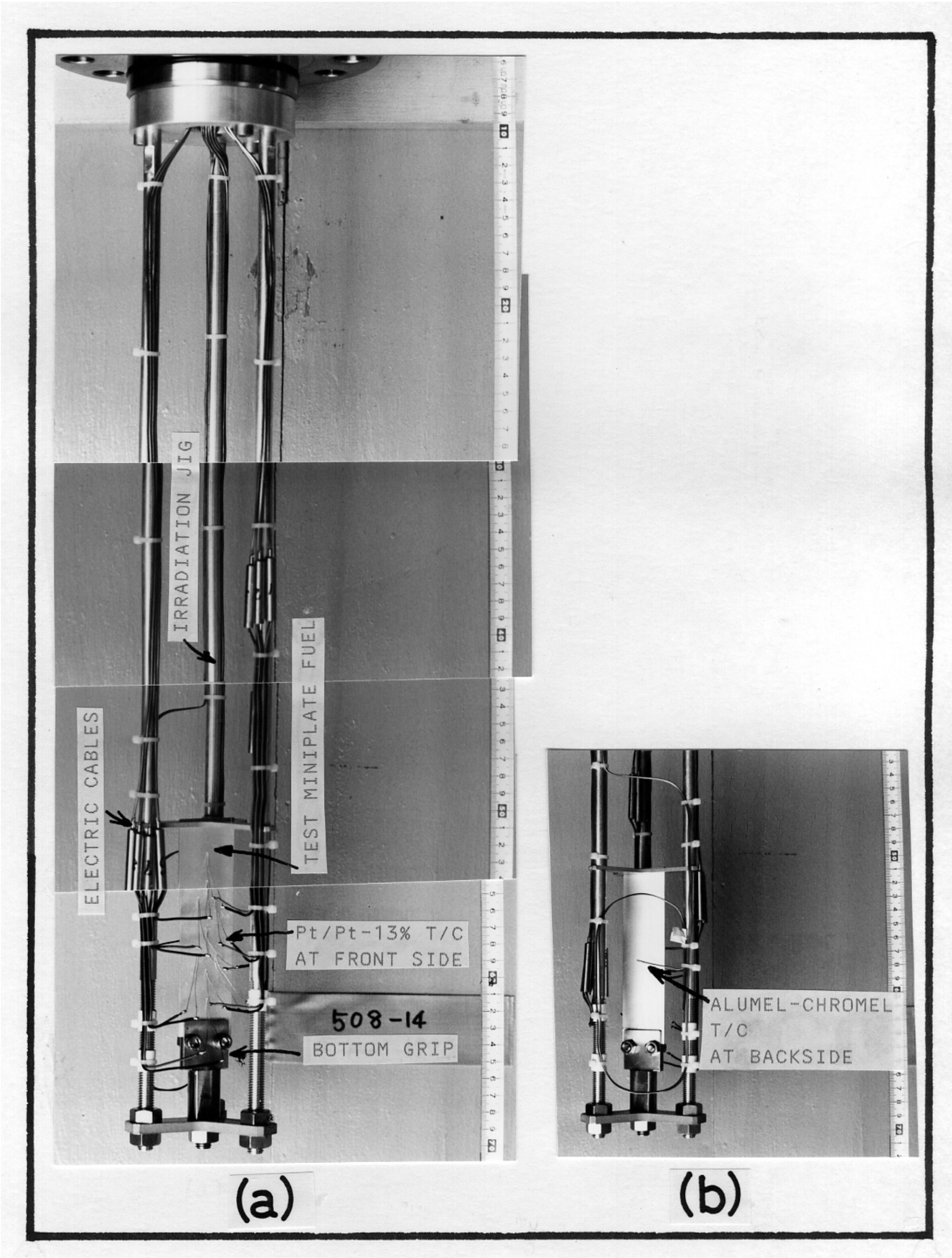

Photo.1 (a) the test fuel plate for Ex 508-14, the supporting jig and electric cables; (b) the alumel-chromel T/C at the mid point of the test specimen.

An irradiation test was conducted with the test fuel assembly loaded into the sealed irradiation capsule. It contained stagnant water at the atmospheric pressure and room temperature about 20 ℃. Details of the irradiation capsule and attached instrument were described elsewhere [5, 6].

3.3 Transient power history

The deposited energy Eg (cal/g・fuel plate) can be expressed by the equation

Eg = kg x P・・・・・・・・・・・・・・・・・・・・・・・・・・・・・・/1/

where, P(MW・ s) is the integral value of the reactor power and kg(cal/g・fuel plate per MW・s) the power conversion ratio. The former is directly obtainable from the micro-fission chambers set at the NSRR core. The latter is obtainable from the burn-up analysis [7]. Namely, after the pulse irradiation, the test specimen was cooled about one month in the irradiation pit of the NSRR. Subsequently, the irradiated test specimen was unloaded from the irradiation capsule and provided to the burn-up analysis. A gross amount of radioactivity from ^{137}Cs was counted for the determination of the kg, taking into consideration of axial and radial peaking factors. In this case, peaking factors at the fuel core edge were ranged from 1.15 to 1.28. It should be mentioned that the power profiles at all T/C locations were almost unity.

3.3.1 ACRW (Ex.508-12)

Integral reactor power P of 5.2 MW・s was given to the test specimen; this corresponded to the energy deposition of 32 cal/g・fuel plate. In **Fig. 4**, the reactor power (MW), the cladding surface temperature (CST) at T/C#5, and T/C#8 from the no-fueled region and coolant temperature are represented. The reader can notice that the in-core data included significant noises because the reactor power given was as much as the lowest level in the magnitude of the NSRR pulse. The PCST observed in T/C#5 was a rather high than EUREKA-2 calculation cited in the previous Fig.1, that is, the experimental data was more conservative than that of the calculation.

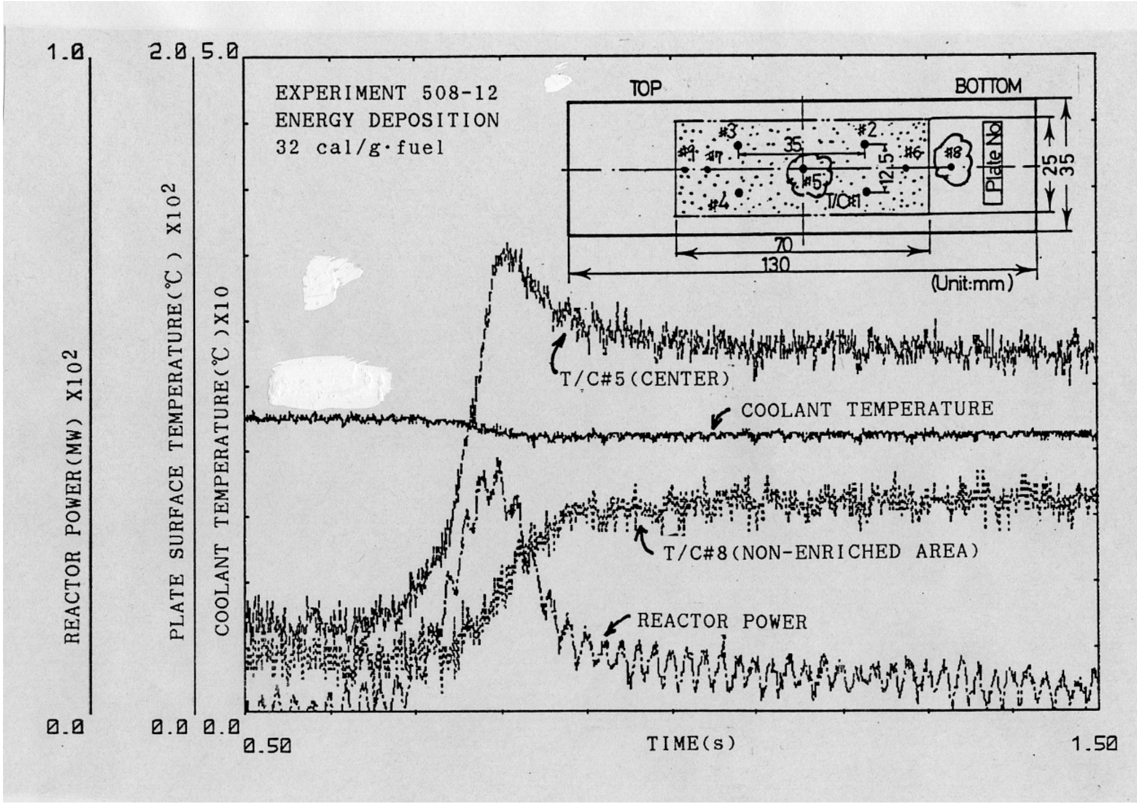

Fig.4 Reactor power (MW), the cladding surface temperature (CST) at T/C#5, and T/C#8 from the no-fueled region and coolant temperature obtained from Ex. 508-12 for ACRW.

3.3.2 CCI (Ex.508-14)

A trapezoidal pulse was prepared to this case. The integral reactor power P of 47.6MW・s was given to the test specimen; this corresponded to the energy deposition of 191 cal/g・fuel plate[1]. The unique shape of the pulse was intended to give the similar temperature profile as the same as shown in Fig. 2. In **Fig. 5**, the reactor power (MW), the cladding surface temperature (CST) at T/C#5 and coolant temperature are represented. Note that the trapezoidal pulse composed of the two steps, where the first step was not requested by the author but the request from the operational security. The increase of the CST, however, occurred mostly at that time. A temperature increase was little during the second step due to no adiabatic heating. Resultantly, PCST at T/C#5 was rather high than that of EUREKA-2 prediction, namely the experiment was more conservative than that of the calculation.

[1] Due to the rather isothermal (no adiabatic) heating mode, the value had almost no physical meaning. It should be used as the reference only.

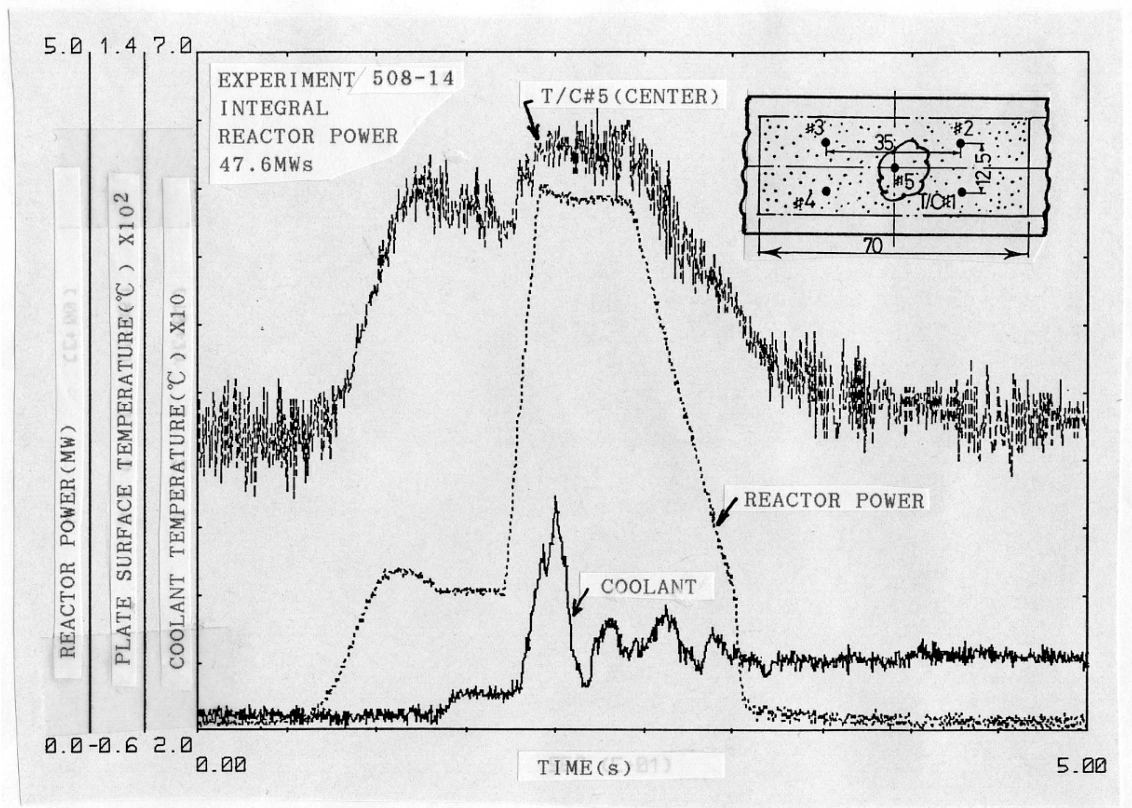

Fig.5 The reactor power (MW), the cladding surface temperature (CST) at T/C#5 and coolant temperature obtained from Ex. 508-14 for CCI.

4. RESULTS AND DISCUSSION

4.1 Transient temperature

T/C data obtained from the two experiments were summed up in **Table 2**. It should be mentioned that there occurred no DNB in any T/C measurement. Namely, the first safety criterion not causing the minimum DNBR was cleared at this stage. The author made detail comparison between EUREKA-2 calculation and experimental results for the JMTR silicide fuel. It is summarized in **Table 3**. By using the two tables, the following discussions were made. For EUREKA-2, one expected to have the overestimated output because the inputs were rather conservative. Because the result obtained from the experiment was rather conservative than those of the code prediction, therefore, if the experimental results could clear the licensing criterion, the EUREKA-2 could clear the matter apparently.

Table 2 Summary of T/C data obtained from Ex.508-12 and Ex.508-14

Experiment	508-12	508-14
Miniplate fuel number	CS514837	JRRJ4851
Fuel type	Silicide	Silicide
Numbers of fuel plate	1	1
Deposited energy (cal/g・fuel plate)	32	Set as equivalent as 191
Fuel density (g/cc)	4.8	4.8
Fuel enrichment (wt %)	19.89	19.89
Pulse mode	N (normal)	Trapezoidal
Inserted reactivity ($)	1.16	(47.6MW・s)
Peak cladding surface temperature (℃)		Temp. at two power steps
#1	133	82→107
#2	136	84→113
#3	136	95→106
#4	134	92→108
#5	139	101→１１５
#6	139	77→１１６
#7	140	98→１０９
#8	60	25→36
#9	135	70→74
Average±sn-1(℃)	137±3	90±9→111±4
DNB(Departure from nucleate boiling)	No	No
Coolant temperature; prepulse (℃)	21	21
; peak (℃)	26	37
Heat up rate(℃ms) to Tmax	1.20±0.09	T1=14.1±1.8, T2=12.1±8.9℃/s
Time to quench, tq（ｓ）	0.11±0.01	14.4±1.4
Temp.drop ΔT(Tmax-Tp);(℃)	28±2	83±2
Cladding wall; min (mm)	0.256	0.341±0.012
Cladding wall; max (mm)	0.412	0.395±0.023
Fuel meat thickness; min (mm)	0.433	0.489±0.030
Fuel meat thickness; max (mm)	0.556	0.560±0.000
Fuel plate thickness; min (mm)	1.235	1.306±0.011
Fuel plate thickness; max (mm)	1.253	1.302±0.075
Maximum bowing (mm)	0.22±0.14	None
Failure (F) / No Failure (NF)	NF	NF
Failure mode		
Findings in PIE{g}		No damage and clean surface except dirty surface at T/Cs

Table 3 Comparison between EUREKA-2 calculation and experiment for the JMTR silicide fuel

Phenomenon studied	Unit	(1) Abnormal withdrawal of control rod during start-up		(2) Reactivity insertion due to cold coolant induction	
1. Pre-set condition		EUREKA-2	Ex. 508-12	EUREKA-2	Ex. 508-14
Coolant flow rate	m^3/h	6000	0	6000	0
Coolant pressure	MPa	0.15	0.1	0.15	0.1
Coolant temperature	℃	49	21	49	21
Reactor output	W	$0.5x10^{-3}$	0	$500x10^3$(critcal)	$1x10^6$
Reactivity insertion	%Δk/k/s	0.15	0.35	0.5%Δk/k/step(1)	1MW to 5MW by 2.3s
Energy deposition	cal/g・fuel plate	-	32	-	191(2)
2. Results					
Pulse mode		Single	Single	Trapezoidal	Trapezoidal
Coolant max. temp	℃	68	26	50	37
PCST	℃	111	137±3	53	90 at 1MW, 111at 5MW
Fuel core temp.	℃	119	Not measured	54	Not measured
DNB		No	No	No	No
Failure(F)/No failure(NF)			NF		NF

Note:(1) Each step led the the reduction of coolant by 15℃, (2) Nominal value only

4.1.1 ACRW

Average PCST from the eight T/C data showed that ACRW heated the test specimen up to 137 ℃; that was greater than that of EUREKA-2 (111 ℃). PCST in this experiment was conservative as much as 27 ℃ in magnitude. The author compared the present data with those obtained from the previous experiments [5, 8], where the fuel damaged by the through-plate cracking or the cladding melt. The resultant plotting is shown in **Fig. 6,** where the initiation of the DNB (T_{DNB}; 174 ℃) was drawn as the dotted horizontal line. It is clear that the ACRW did not damage the fuel plate because their PCST was lower than that of T_{DNB}. The author understood that the licensing criterion for not causing the minimum DNBR is really adequate to prevent the fuel plate from the failure.

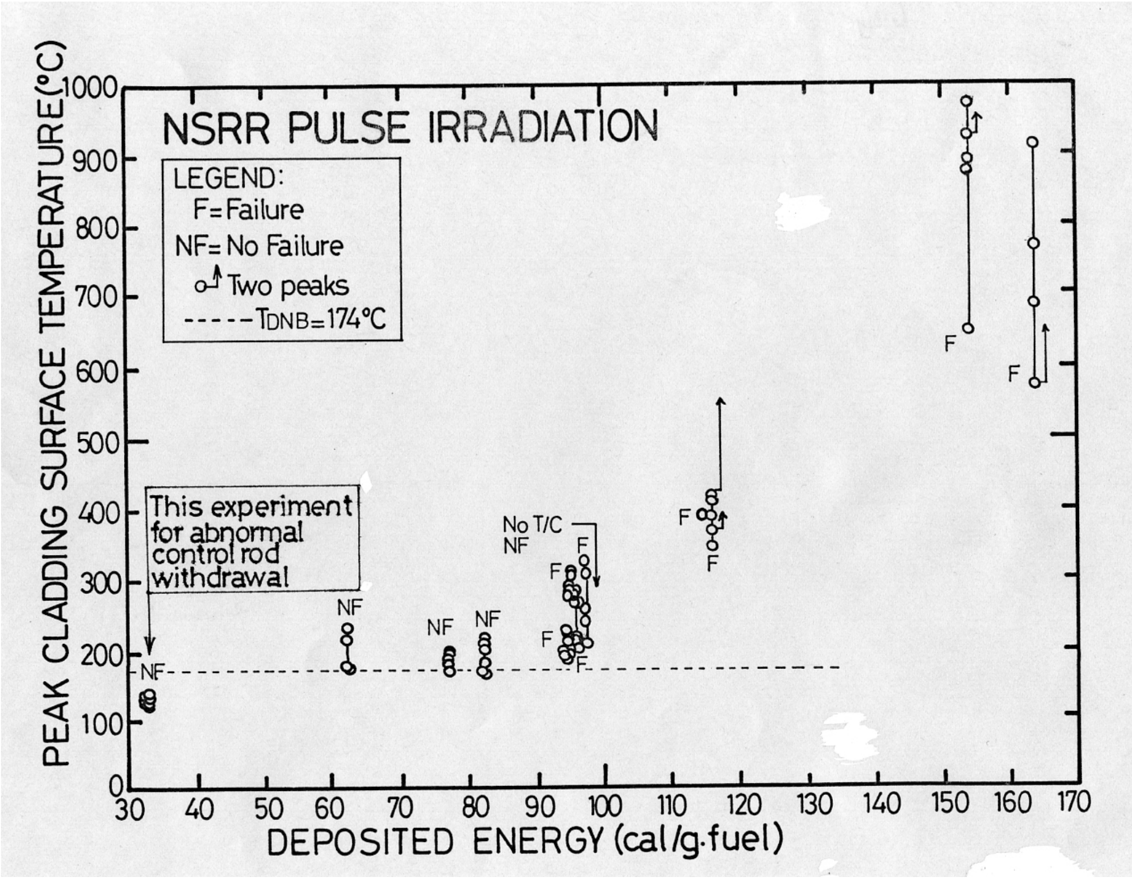

Fig.6 PCST as a function of deposited energy obtained from the present study and the previous experiments [5, 8], where the fuel damaged by the through-plate cracking or the cladding melt occurred. The initiation of the DNB (T_{DNB}; 174 ℃) was drawn as the dotted horizontal line.

4.1.2 CCI

Average PCST of the test specimen was increased in stepwise manner from 90 ℃ to 111 ℃. Simultaneously, the coolant temperature increased from 21 to 37 ℃. As shown in **Fig. 7**, the PCST for CCI obtained from the experiment was larger than that of the code prediction. For the time to peak, the predicted value by the code was fairly short and small in magnitude (53 ℃ compared with those of the experiment (90 ℃). Namely, the experiment was significantly conservative to that of the code prediction.

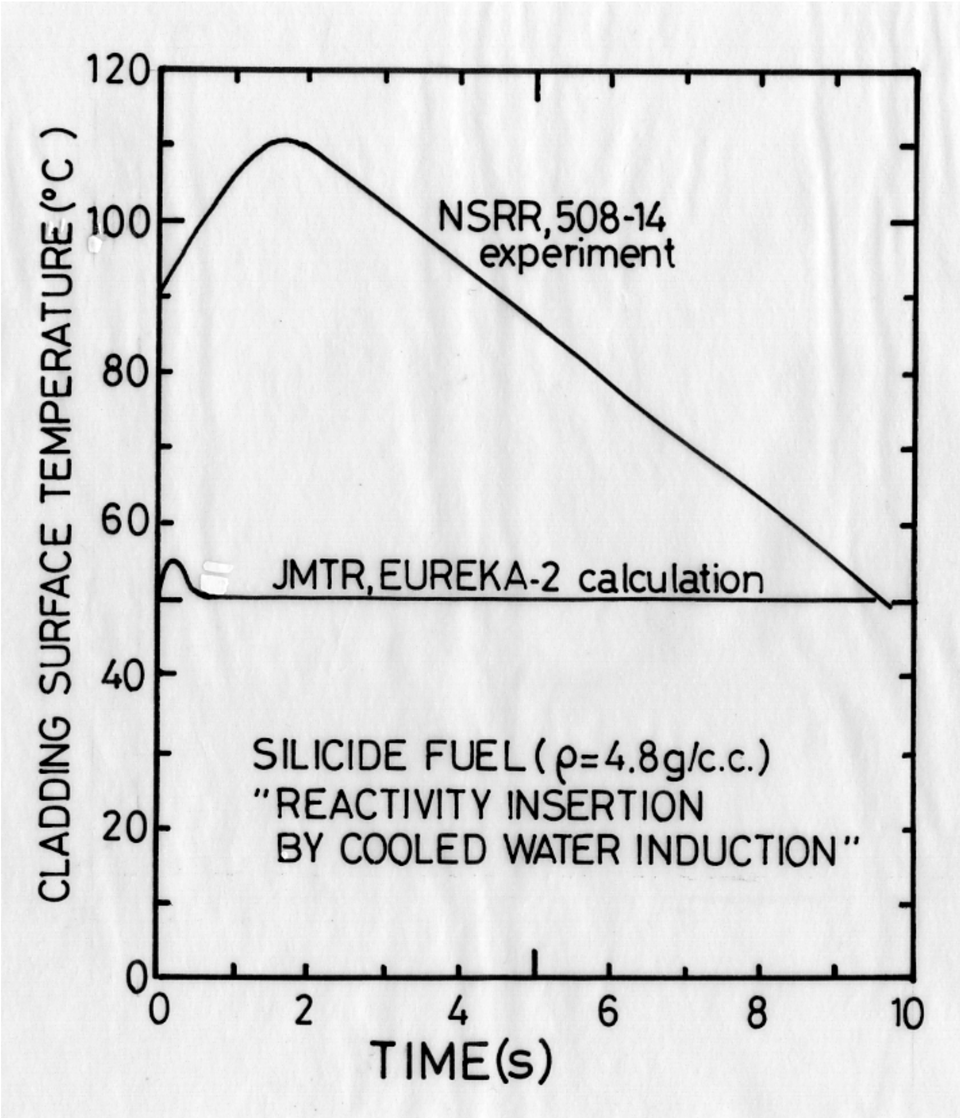

Fig.7 Cladding surface temperature as a function of time, where EUREKA-2 calculation result was compared directly with the data obtained from the Ex.508-14 for CCI.

4.2 Post irradiation examination (PIE)

After disassembling of the test specimen from the irradiation capsule, the PIE was carried out.

4.2.1 ACRW

In **Photo.2**, the overview of the test specimen (CS514837) observed from the PIE is shown. At the location (a) of the plate top area the scratch and the discoloration occurred due to the mechanical interaction between the fuel plate and the supporting jig made of a stainless steel (SUS). All T/C were found to be intact. At the location (b) of the plate bottom area the fuel identification number corroded slightly due the reaction between the plate and the cladding grip made of SUS. At the location (c) in the backside of the fuel plate several small pits cause by the electric spark during the spot welding are seen. Neither the bending nor the marked changes in dimension were revealed. The author judged that the test specimen was intact.

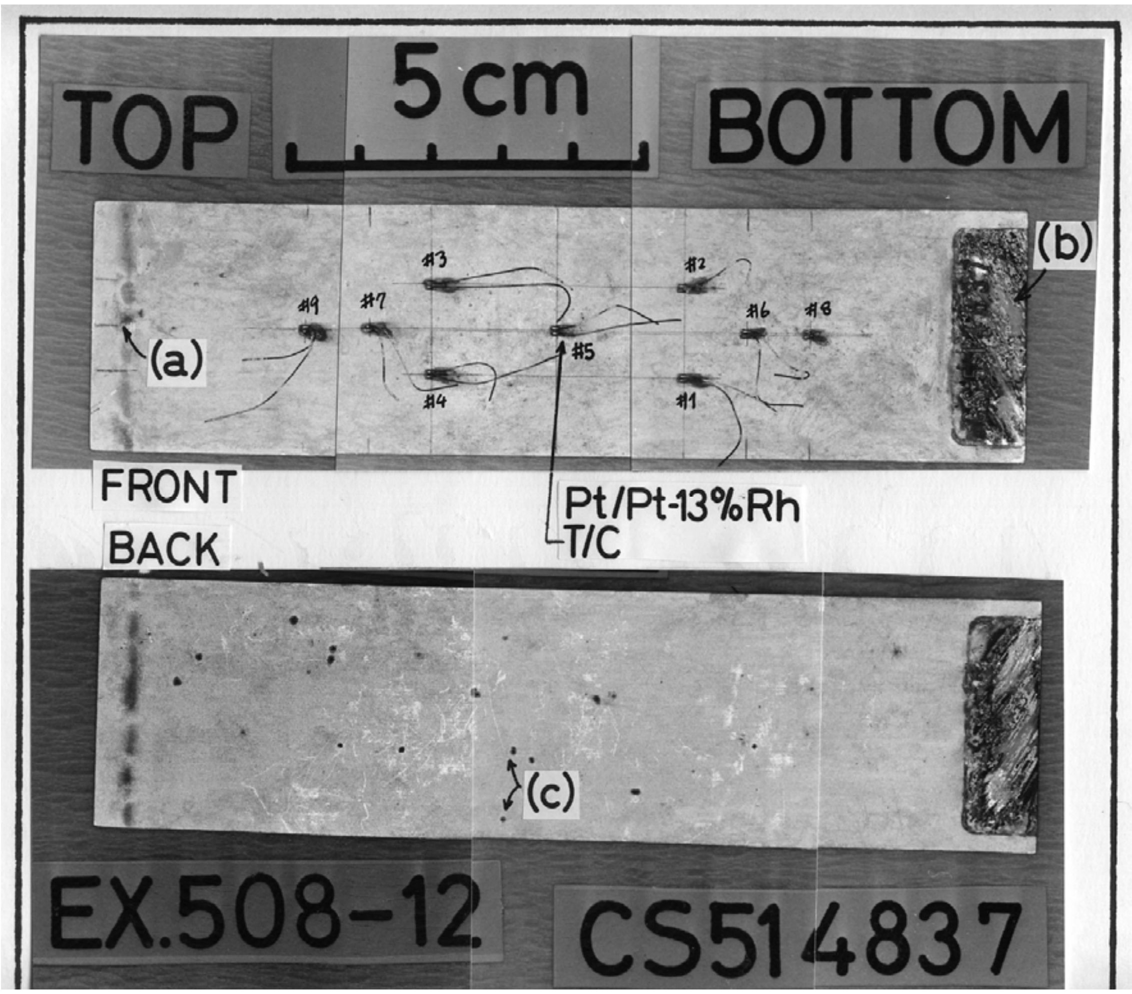

Photo.2 Overview of the test specimen (CS514837) obtained from PIE; the specimen was used for ACRW test in Ex.508-12.

4.2.2 CCI

In **Photo.3**, the overview of the test specimen (JRRJ4851) observed from the PIE is shown. At the plate top and T/C area, the fuel plate was discolored due to the corrosion occurred by the coolant. The trace of the corrosion is also observed at cladding grip end. There are no anomalies in the backside of the fuel. Modified spot welding device could prevent the fuel plate from the pitting. In **Photo.4**, a fuel microstructure is shown. U_3Si_2

fuel particle was tight and dispersed into the aluminum matrix. The author did not find any anomalies from the metallurgical examination and judged that the test specimen was intact.

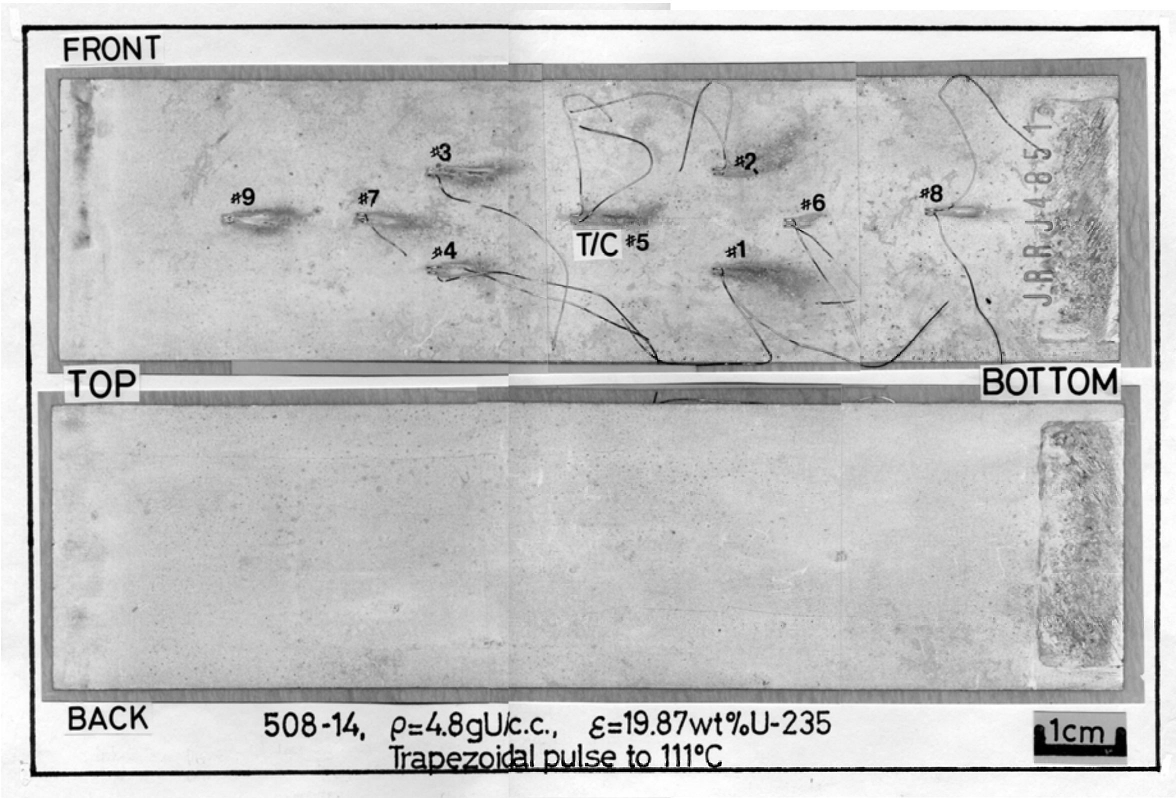

Photo.3 Overview of the test specimen (JRRJ4851) obtained from PIE; specimen was used for CCI test in Ex.508-14.

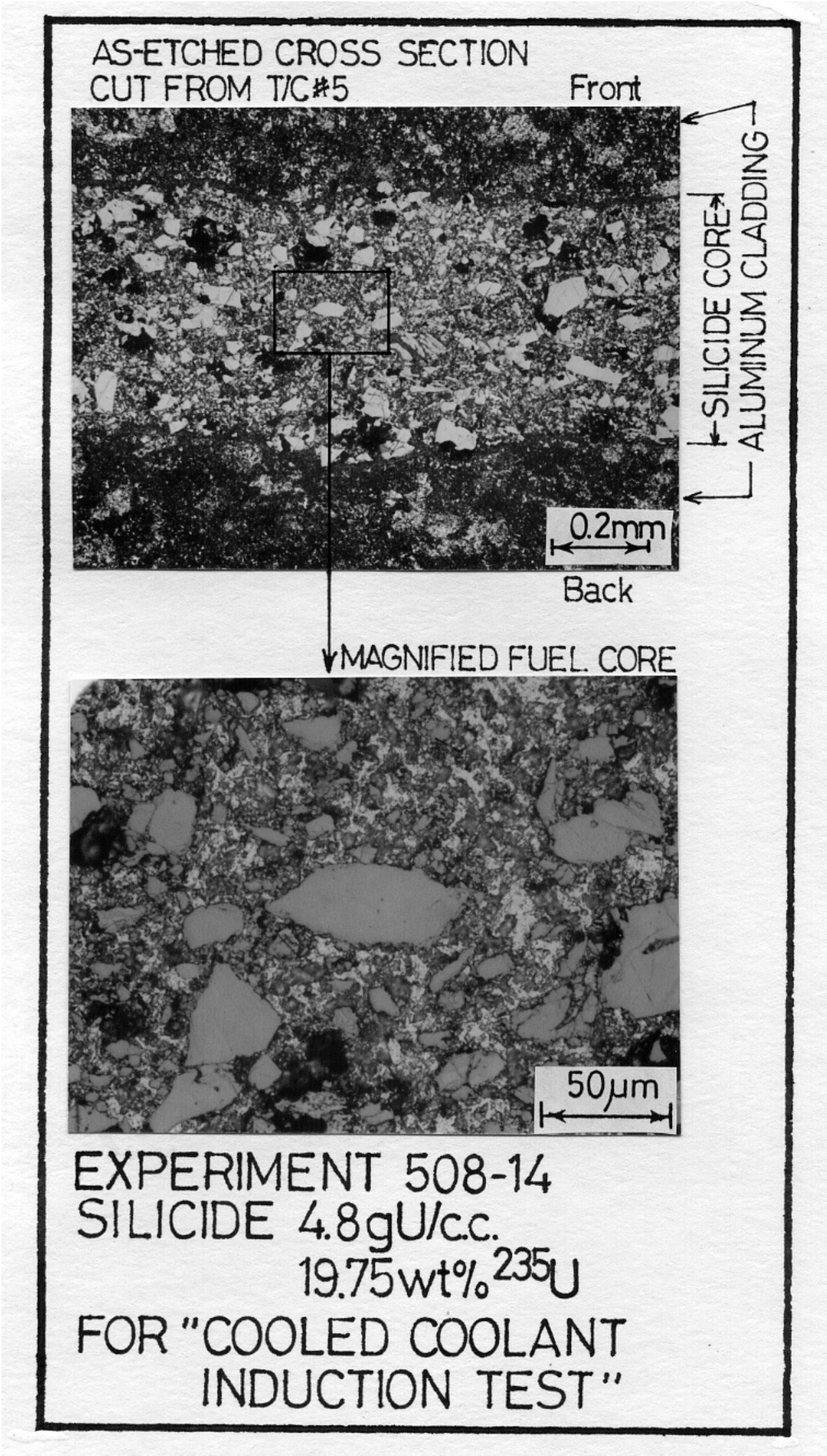

Photo.4 Fuel microstructure of the test specimen used for CCI test in Ex.508-14.

5. CONCLUSIONS

- PCST for the ACRW was 137 ℃ and that for the CCI was 111 ℃. Corresponded value by the EUREKA-2 code calculation used for the JMTR licensing was 110 ℃ for the former and 53 ℃ for the latter. The experimental data were more conservative than those of the code.
- Not only PCST of ACRW but also PCST of CCI did not exceed the DNB temperature revealed as 174 ℃. The two cases are judged to be the safety side from the view point of the minimum DNBR known as one of the judging criterion for the JMTR silicide fuel.
- Post irradiation examination revealed that no damage not only in the ACRW but also in the CCI occurred. The two cases are also judged to be safety side from the view point of the fuel damage described as one of the judging criterion for the JMTR silicide fuel.
- Because the experiment data for ACRW and CCI were judged to be the safety side, the judgment made by the EUREKA-2 computer prediction was more safety side due to the reason mentioned above (1).

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度[(a)]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率[(b)]	（数字の）　1	1
比透磁率[(b)]	（数字の）　1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(b)]	rad	1[(b)]	m/m
立体角	ステラジアン[(b)]	sr[(c)]	1[(b)]	m^2/m^2
周波数	ヘルツ[(d)]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度[(e)]	℃		K
光束	ルーメン	lm	cd sr[(c)]	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能[(f)]	ベクレル[(d)]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[(g)]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で”radioactivity”と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} sA
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}$ mol

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^9	ギガ	G	10^{-12}	ピコ	p
10^6	メガ	M	10^{-15}	フェムト	f
10^3	キロ	k	10^{-18}	アト	a
10^2	ヘクト	h	10^{-21}	ゼプト	z
10^1	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	$1ha=1hm^2=10^4m^2$
リットル	L，l	$1L=11=1dm^3=10^3cm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1eV=1.602\ 176\ 53(14)\times10^{-19}J$
ダルトン	Da	$1Da=1.660\ 538\ 86(28)\times10^{-27}kg$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$1ua=1.495\ 978\ 706\ 91(6)\times10^{11}m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1MPa=100kPa=10^5Pa$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$1\ Å=0.1nm=100pm=10^{-10}m$
海里	M	1 M=1852m
バーン	b	$1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s$
ストークス	St	$1\ St=1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1cd\ cm^{-2}=10^4cd\ m^{-2}$
フォト	ph	$1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx$
ガル	Gal	$1\ Gal=1cm\ s^{-2}=10^{-2}ms^{-2}$
マクスウェル	Mx	$1\ Mx=1G\ cm^2=10^{-8}Wb$
ガウス	G	$1\ G=1Mx\ cm^{-2}=10^{-4}T$
エルステッド[(c)]	Oe	$1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}$

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「$\triangleq$」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R=2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu=1\mu m=10^{-6}m$

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