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-Research and Development for Advanced High Temperature Gas-cooled Reactor Fuels and Graphite Components-

(Contract Research)

Yasuhiro MOZUMI, Shohei UETA, Jun AIHARA and Kazuhiro SAWA

High Temperature Fuel and Material Group
Nuclear Science and Engineering Directorate

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JAEA-Technology

独立行政法人日本原子力研究開発機構　研究技術情報部　研究技術情報課
〒319-1195　茨城県那珂郡東海村白方白根2番地4
電話029-282-6387, Fax 029-282-5920, E-mail:ird-support@jaea.go.jp

Intellectual Resources Section, Intellectual Resources Department,
Japan Atomic Energy Agency
2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195 Japan
Tel +81-29-282-6387, Fax +81-29-282-5920, E-mail:ird-support@jaea.go.jp

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Irradiation Sample Fabrications for VHTR
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Yasuhiro MOZUMI※1, Shohei UETA, Jun AIHARA and Kazuhiro SAWA

Nuclear Applied Heat Technology Division,
Nuclear Science and Engineering Directorate,
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

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Fuel for the Very High Temperature Reactor (VHTR) is required to be used under severer irradiation conditions and higher operational reactor temperatures than those of present high temperature gas cooled reactors. Japan Atomic Energy Agency has developed the advanced silicon carbide (SiC) -coated fuel particles having thicker layer thicknesses, and zirconium carbide (ZrC)-coated particles that are expected to preserve their integrity at higher temperatures and burnup conditions than current conventional coated fuel particles. These particles have been fabricated successfully in order to perform irradiation tests at experimental reactors. This paper is summarized fabrication data of irradiation samples.

Keywords: Very High Temperature Reactor (VHTR), Advanced Silicon Carbide (SiC) -coated Fuel Particles, Zirconium Carbide (ZrC)-coated Particles, Irradiation Sample

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※1 Collaborating Engineer

超高温ガス炉のための照射サンプル製造
− 革新的高温ガス炉燃料・黒鉛に関する技術開発 −
(受託研究)

日本原子力研究開発機構　原子力基礎工学研究部門
核熱応用工学ユニット
茂住　泰寛[※1]、植田　祥平、相原　純、沢　和弘

(2008 年 12 月 10 日　受理)

超高温ガス炉（VHTR）の燃料は、現在の高温ガス炉より過酷な照射環境でかつより高温下で使用される。原子力機構は、現行燃料より優れ高温かつ高燃焼度に耐えうると期待される高性能で厚肉な炭化ケイ素（SiC）被覆燃料粒子や炭化ジルコニウム(ZrC)被覆粒子を開発している。試験炉で照射試験を実施するための、これら高性能な炭化ケイ素（SiC）被覆燃料や炭化ジルコニウム(ZrC)被覆粒子の製造に成功した。

本報は、照射試料の製造データをまとめたものである。

本報告書は文部科学省が日本原子力研究開発機構との(委託研究)契約により実施した研究(業務)成果に関するものである。

大洗研究開発センター（駐在）：〒 311-1393　茨城県東茨城郡大洗町成田町 4002

※　1 技術開発協力員

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1. Introduction

Current high-temperature gas-cooled reactor (HTGR) uses Triso-coated fuel particles as shown in Fig. 1. The Triso-coated fuel particle consists of a micro spherical kernel of oxide or oxycarbide fuel and coating layers of porous pyrolytic carbon (buffer), inner dense pyrolytic carbon (IPyC), silicon carbide (SiC) and outer dense pyrolytic carbon (OPyC). The principal function of these coating layers is to retain fission products within the particle. Particularly, the SiC coating layer acts as a barrier against the diffusive release of metallic fission products which escape easily through the IPyC layer and provides mechanical strength for the particle.

The Very-High-Temperature Reactor (VHTR) is one of the most promising candidates for the Generation IV Nuclear Energy System [1]. The VHTR demands the gas outlet temperature of approximately 1000°C for supplying electricity and process heat, e.g., for hydrogen production, as proposed in the Generation-IV International Forum [1]. The VHTR fuel is required to have excellent safety performance up to burn-ups of about 15 to 20% fissions per initial metal atom (FIMA) and fluences of 6×10^{25} n/m^2 (E>0.1 MeV) [1]. Although SiC has excellent properties, it gradually loses strength due to neutron irradiation and mechanical integrity at very high temperatures, especially above 1700°C, by thermal dissociation[2-4]. In the other side zirconium carbide (ZrC) is known as a refractory and chemically stable compound, having a melting point of 3540 °C, and a eutectic melting point with carbon of 2850°C.

JAEA has planed to irradiate the advanced silicon carbide (SiC) fuels having thicker layer thicknesses at OSIRIS reactor in France near future. And also we have joined the irradiation tests of ZrC-coated particles both High Flux Isotope Reactor (HFIR) in Oak Ridge National Laboratory (ORNL) and High Flux Reactor (HFR) in The Nuclear Research & consultancy Group (NRG).

The object of this paper is summarized fabrication data for advanced SiC fuel and ZrC coated particles for VHTR developments.

2. Fabrication of advanced SiC-TRISO fuel

2.1 Fabrication processes of the VHTR fuel elements

The VHTR fuel fabrication process consists of three parts: (1) UO2 kernels fabrication process, (2) PyC and SiC coating processes, (3) Manufacture process of Fuel compacts. These processes are described below.

2.2 UO_2 kernels fabrication process

The UO_2 kernels are fabricated in a gel-precipitation process. The process is shown in Fig. 2[5]. After formation of uranyl nitrate solution containing additives, spherical droplets are generated at the vibrating nozzles and fall into ammonia water to be aged to ammonium diuranate (ADU) particles. The reaction products of ammonium nitrate etc. are washed off, then the particles are dried and calcinated to UO_3 particles at 500℃ in air. UO_3 particles are reduced and sintered to UO_2 particles with about 97%T.D. at 1600℃ under hydrogen atmosphere[5].

2.3 PyC and SiC coating processes

Figure 3 [5] shows the fabrication flow diagram of coated fuel particles. Coating layers are deposited on the kernels in a chemical vapor deposition (CVD) process using a fluidized bed type of coater. The Tri-isotropic (TRISO) coating process is divided into four coating processes for the porous PyC, IPyC, SiC and final OPyC layers. Mixing gases of acetylene (C_2H_2) and argon (Ar) are used for the deposition of porous and low density PyC for the first layer; propylene (C_3H_6) and Ar for the deposition of dense PyC for the second and fourth layer; methyl-trichloro-silane (MTS) and hydrogen for the deposition of SiC for the third layer [5].

2.4 Manufacture process of fuel compacts

Figure 4 [5] shows the manufacture process of fuel compacts. First, natural graphite powder, electro-graphite powder and a binder are mixed, and then the mixture makes graphite matrix after fine grinding process. Coated fuel particles are over-coated with the graphite matrix and warm-pressed to make annular cylinder of green compacts. Green compacts are preliminarily heat treated for carbonization at 800℃ under nitrogen atmosphere, then sintered at 1800℃ under vacuum to make fuel compacts[5].

2.5 Specifications and Fabrication of advanced fuels for an irradiation test

The Specifications of advanced UO_2 Kernel, coated fuel particle (CFP) and compact are described on Table 1 compared with first HTTR fuels. Advanced fuels are improved the SiC thicker layer thickness against a high internal pressure of FP and CO gases with higher burnup. Also the fuel kernel become smaller and a buffer become bigger against an accumulated gas pressure. The advanced SiC-coated fuels have been fabricated successfully at Nuclear Fuel Industries (NFI) based on the specifications and processes described above sections. A typical appearance of a fuel compact is shown at Fig.5. These fuels will be used the irradiation test at OSIRIS reactor near future for the VHTR developments.

3. Fabrication of ZrC coated particles

3.1 ZrC coating by bromide process

In previous studies in JAEA, some coating techniques of ZrC have been examined by the chemical vapor deposition (CVD) using zirconium halide vapors such as iodide, chloride and bromide [6]. From the experimental results, it was concluded that the bromide process was preferred to other halide processes experimentally, because it was found to be easier to produce a stoichiometric composition of ZrC.

In the bromide process, the ZrC-coating layer is deposited with pyrolytic reaction of $ZrBr_4$, CH_4 and H_2 at about 1500°C in a fluidized bed. Main reactions of the bromide process can be described as follows [6]:

$$[CH_4] = (C) + 2[H_2] \qquad (1)$$

$$[ZrBr_4] + [H_2] \rightarrow [ZrBr_3], [ZrBr_2] + [HBr] \qquad (2)$$

$$[ZrBr_x] + (C) = (ZrC) + x\,[Br],\ x=2,\ 3,\ \text{or}\ 4 \qquad (3)$$

$$[Br] + 0.5[H_2] = [HBr] \qquad (4)$$

$$0.25(C) + [HBr] = 0.25\,[CH_4] + [Br]. \qquad (5)$$

(In above equations, solid and gas phases are expressed in parentheses and square brackets, respectively.)

3.2 Coating equipment

ZrC coater was constructed at Oarai Research and Development Center of JAEA as shown in Figs. 6 and 7. The ZrC coater was designed with the maximum batch size of 0.2 kg, which is about ten times larger than the previous device used.

The ZrC coater mainly consists of the gas supply equipment, the CVD coater, and the off-gas combustion equipment. In the gas supply system, liquid bromine is vaporized with argon as carrier gas at a temperature of 0 °C, and the bromine gas is introduced into the CVD coater from the bottom. A gas mixture of methane and hydrogen is also transferred into the coater. The CVD coater is composed of the lower and the upper heaters with in-line configuration to trigger ZrC reaction as described in Eqs. (1)- (4). The introduced bromine gas reacts with metallic zirconium sponge loaded in the lower heater, and then produces $ZrBr_x$ gases at about 600°C. The upper heater has a particle fluidizing bed, and ZrC is coated on the surface of the particle at 1600°C in the maximum. The off-gas treatment equipment removes soot, hydrogen bromide, and residual hydrogen.

3.3 Fabrication of ZrC coated particles for irradiation tests

To investigate the fundamental irradiation properties of ZrC, PyC and SiC using several irradiation temperatures under VHTR operating conditions, JAEA has joined the irradiation tests both HFIR in ORNL and HFR in NRG with the total of 18 kinds of particle samples. The fabricated irradiation samples are summarized at Table 2. These consist of Type 1) 5 kinds of inner IPyC /ZrC coatings with ZrO_2 kernels, Type 2) 4 kinds of IPyC/ZrC coatings with Al_2O_3 kernels, Type 3) IPyC/SiC/OPyC coatings with SiC kernels and Type 4) ZrO_2 and Type 5) Al_2O_3 kernels without coating and Type 6) 4 kinds of IPyC /ZrC/OPyC coatings with ZrO_2 kernels. The irradiation conditions 800 and 900 °C, 1100 °C and 1200 °C over 2 x 10^{25} m^{-2} of fast neutron fluences are selected for JAEA samples in the tests.

For the Type 1) and 2), 6)as shown in Fig. 8 [7], ZrC-coating layer is known as the most pronounced candidate for the advanced fuel particle used in VHTR. In the viewpoint of the coating material, it is essential for the ZrC coating layer to have the stoichiometric composition (of which the carbon to zirconium atomic ratio, (C/Zr) is nearly 1.0), because it shows higher performances with regards to a mechanical integrity, a thermal conductivity and a fission product retention under irradiations than those of one with C/Zr>1.0. The ZrC with C/Zr>1.0 has so-called free carbons as shown in Fig. 9. In the irradiation test, ZrC coatings with some different C/Zr ratio in the range of 1.0 to 1.3 are irradiated in order to study the irradiation effect on ZrC coatings, mainly for mechanical properties such as the hardness and strengths, for the microstructure of both ZrC and free carbons. In addition to the actual industrial viewpoint the coated fuel particle should be received a heat treatment to form the fuel compact, the heated ZrC coated particles at 1,800 °C are also irradiated to compare its behavior with non-heated ones.

The type 3) is SiC-TRISO particles with OPyC coating to compare PyC or SiC properties under the irradiation (a microstructure, PyC dimensional change, PyC anisotropy, etc.) with other samples. Types 4) and 5) are two substrate kernels used for JAEA samples in order to obtain the background data mainly for a dimensional change of each particle under the irradiation. For making PIEs easier, the some of these particles used highly purified Al_2O_3 kernels to reduce radioactivities comparing with ZrO_2 after the irradiation.

4. Conclusion

The advanced SiC-coated fuel particles have been fabricated successfully in order to perform irradiation tests at experimental reactors.

JAEA has developed the ZrC coating conditions under which uniform ZrC coating layers can be obtained by using the new large-scale coater up to 0.2 kg batch. ZrC coated particles were successfully fabricated. These samples have been irradiated at experimental reactors.

Acknowledgements

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Table 1 The specification of the Advanced fuel for irradiation tests planed at OSIRIS

Item	Advanced fuel	1st HTTR Fuel for reference	Sampling rate
Fuel kernel			
^{235}U enrichment (%)	9.9	3.4-9.9	1 sample/enrichment
Diameter (μm)	500	600	1 sample (50 particles) /fuel kernel lot
Sphericity	95% <1.2	95% <1.2	3 samples (100particles/sample)
Density (g/cm^3)	10.63	10.63	3 samples/fuel kernel lot
O/ U ratio	2.00	2.00	1 sample/fuel kernel lot
CFP			
Layer thickness			
Buffer (μm)	95	60	1 sample (50 particles) /CFP lot
I-PyC (μm)	40	30	1 sample (50 particles) /CFP lot
SiC (μm)	35	25	1 sample (50 particles) /CFP lot
O-PyC (μm)	40	45	1 sample (50 particles) /CFP lot
Fuel compact			
Packing fraction (%)	25	30	3 samples/ fuel compact lot
Dimensions			
Outer Diameter (mm)	10	26	All fuel compacts
Inner Diameter (mm)	2	10	All fuel compacts
Length (mm)	12	39	All fuel compacts

Table 2 Coated particles for irradiation tests at HFR and HFIR

No.	Type of particles	Particle D(μm)	Material	Size or thickness (μm)	Density (g/cm^3)	Remarks	lot
1	ZrO_2+PyC+ZrC (ZrO_2 kernel with 4.82% Y_2O_3)	843	ZrO_2	720(diameter)	6.07	C/Zr=1.11 as fabricated	ZrC-06-2022
			PyC	35	1.9		
			ZrC	22	6.45		
2			Same as No.1 sample			C/Zr=1.11 heat treatment at about 1800 °C	ZrC-06-2022HT
3		841	ZrO_2	720(diameter)	6.07	C/Zr=1.03 as fabricated	ZrC-06-2048
			PyC	35	1.9		
			ZrC	28	6.5		
4*			Same as No.3 sample			C/Zr=1.03 heat treatment at about 1800 °C	ZrC-06-2048HT
5*		858	ZrO_2	720(diameter)	6.07	C/Zr=1.35 heat treatment at about 1800 °C	ZrC-06-2003HT
			PyC	35	1.9		
			ZrC	21	6.01		
6	PyC+SiC (SiC kernel)	932	SiC	759(diameter)	Around1.9	as fabricated	91SiCCP
			PyC	12	1.84		
			SiC	38	3.2		
			PyC	45	1.85		
7	$ZrO_2$with 4.82%Y_2O_3	724	ZrO_2	724(diameter)	6.07	heat treatment at about 1800 °C	ZCP-06-M01HT
8						as received	ZCP-06-M01
9	Al_2O_3+PyC+ZrC (99.99% Al_2O_3 kernel)	902	Al_2O_3	755(diameter)	3.89	C/Zr=1.1 as fabricated	ZrC-Al-2003
			PyC	42	1.9		
			ZrC	24	6.5		
10			Same as No.9sample			C/Zr=1.1 heat treatment at about 1800 °C	ZrC-Al-2003HT
11		744	Al_2O_3	642(diameter)	3.89	C/Zr=1.1 as fabricated	ZrC-Al-2001
			PyC	33	1.9		
			ZrC	9	6.5		
12			Same as No.11sample			C/Zr=1.1 heat treatment at about 1800 °C	ZrC-Al-2001HT
13	$Al_2O_3$99.99%	642	Al_2O_3	642(diameter)	3.89	heat treatment at about 1800 °C	7001(600-710)HT
14						as received	7001(600-710)
15*	ZrO_2+IPyC +ZrC+OPyC (ZrO_2 kernel with 4.82% Y_2O_3)	895	ZrO_2	720(diameter)	6.07	C/Zr=1.03 as fabricated	ZrC-07-3002
			IPyC	35	1.9		
			ZrC	21	6.52		
			OPyC	24	1.9		
16*			Same as No.15 sample			C/Zr=1.03 heat treatment at about 1800 °C	ZrC-07-3002HT
17*		902	ZrO_2	720(diameter)	6.07	C/Zr=1.03 as fabricated	ZrC-07-3010
			IPyC	35	1.9		
			ZrC	27	6.52		
			OPyC	25	1.92		
18*			Same as No.17 sample			C/Zr=1.03 heat treatment at about 1800 °C	ZrC-07-3010HT

＊Irradiation samples both HFR and HFIR

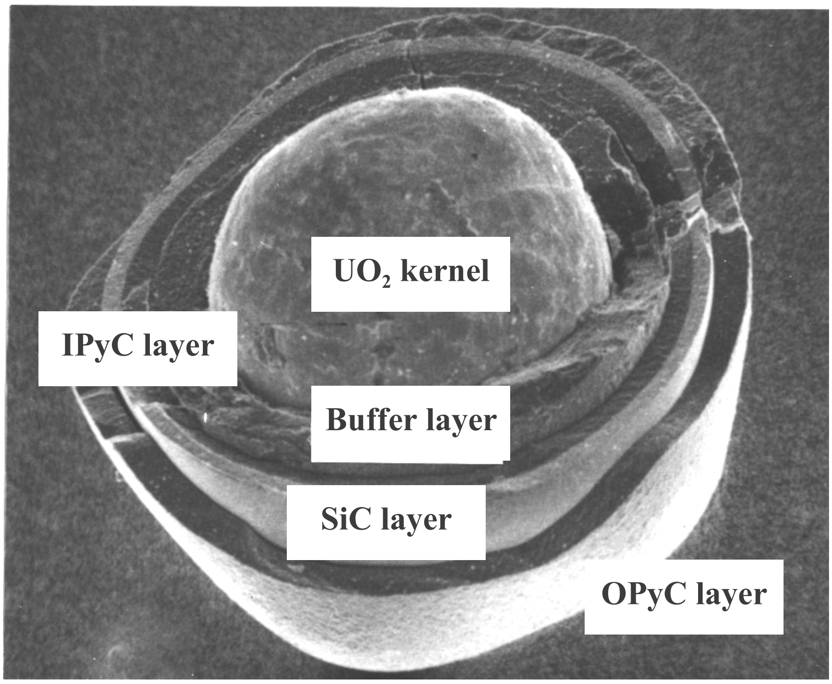


Fig. 1 Triso-coated particle fuel

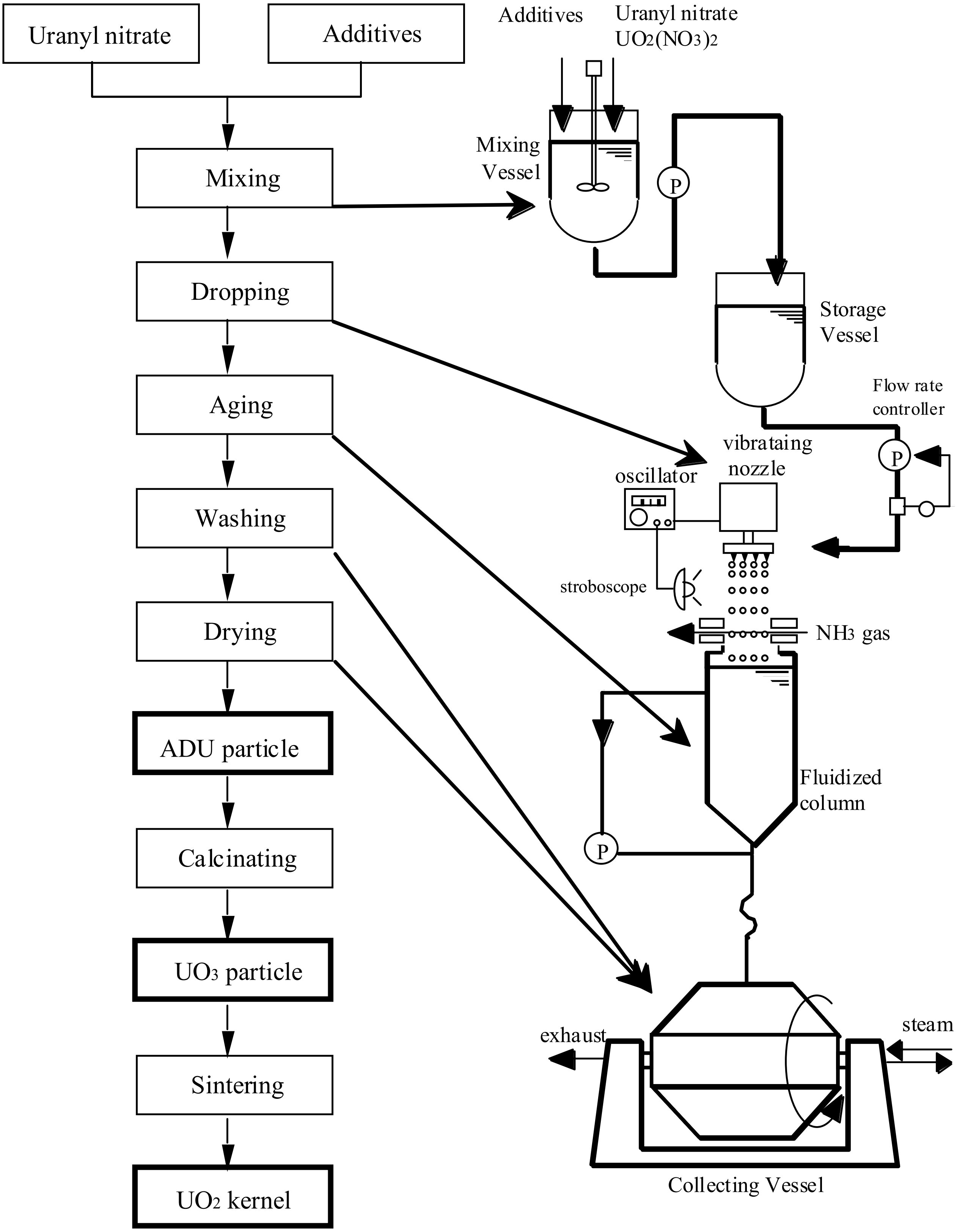
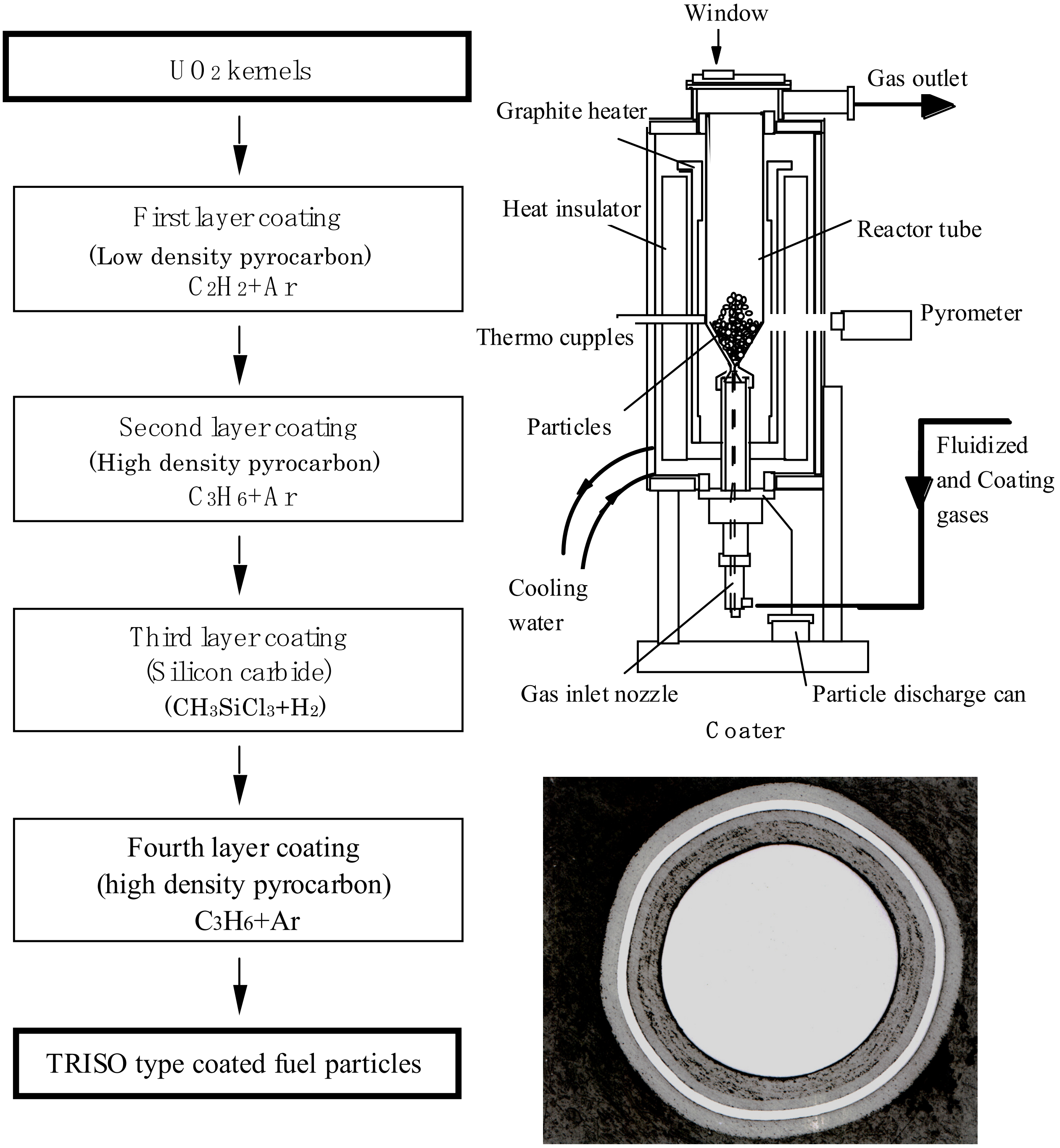


Fig. 2 UO_2 kernels fabrication process [5]



Coater

Polished cross section of coated fuel particle

Fig. 3 PyC and SiC coating processes [5]

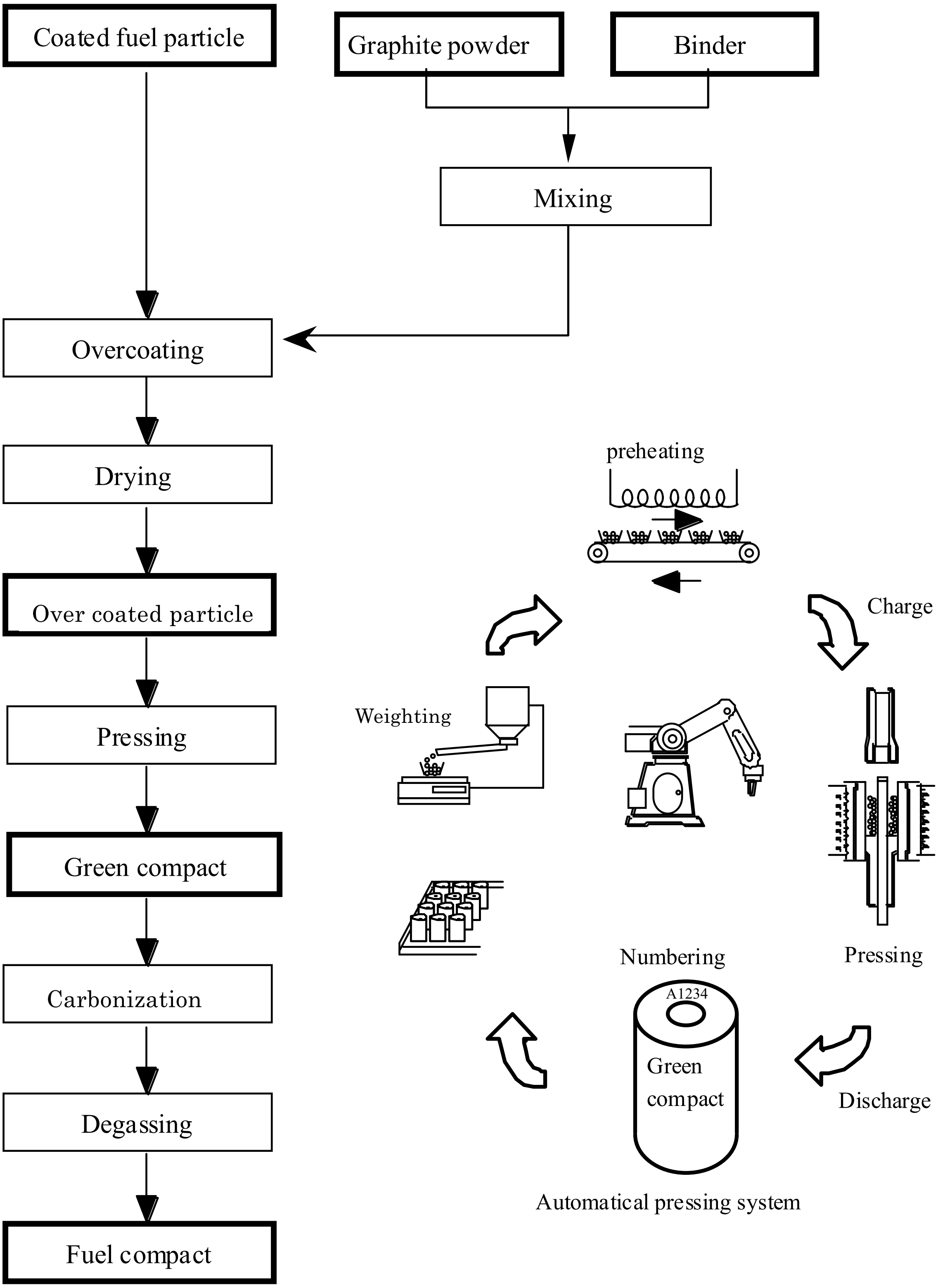


Fig. 4 Manufacture process of Fuel Compacts [5]

Fig. 5 Appearance of a fuel compact

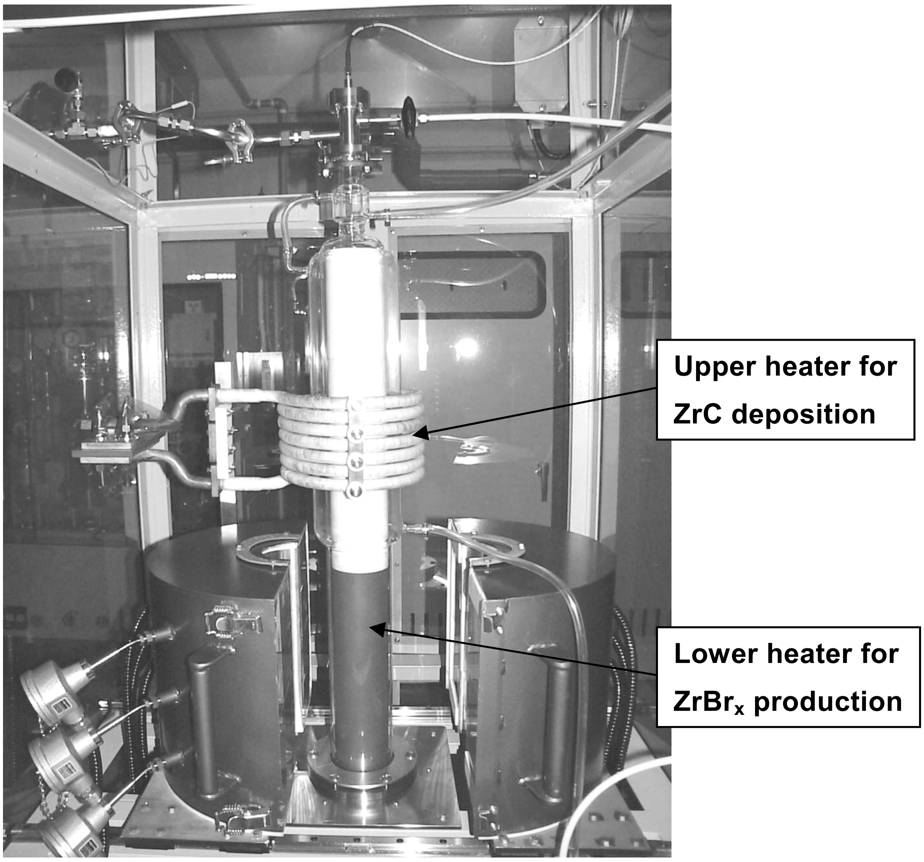


Fig. 6 Appearance of the CVD coater.

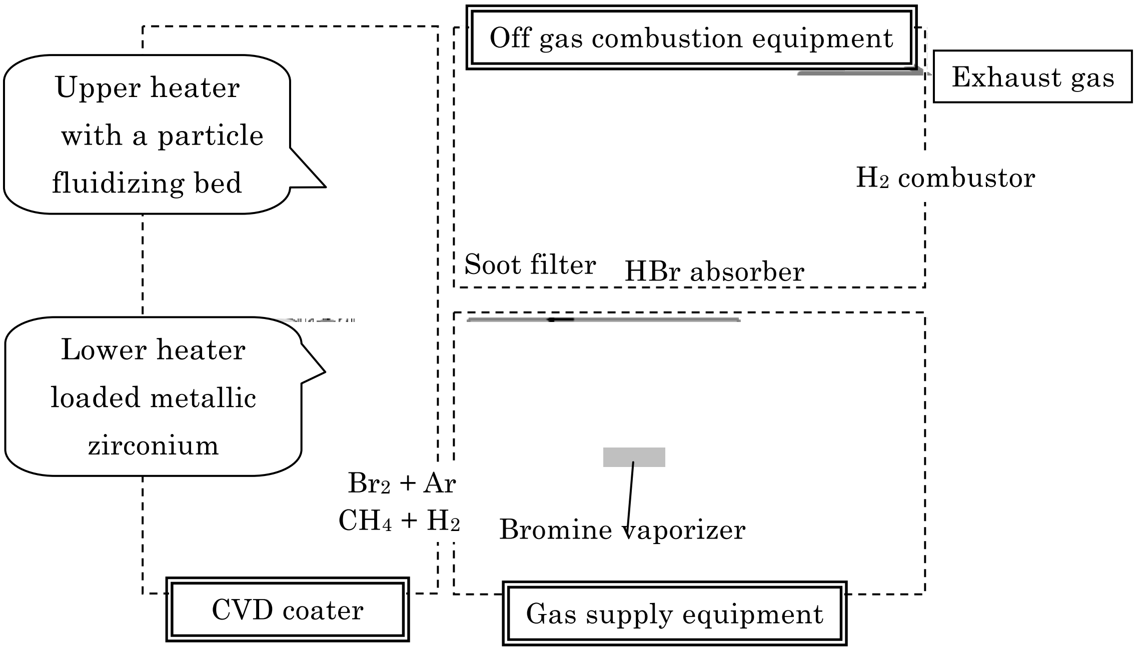


Fig. 7 Process flow diagram of ZrC coater.

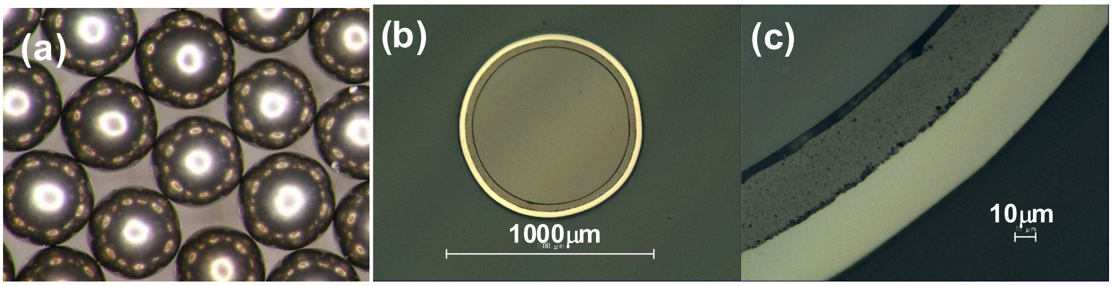


Fig. 8 (a) Appearance and (b) (c) cross sections of ZrC coated particles. [7]

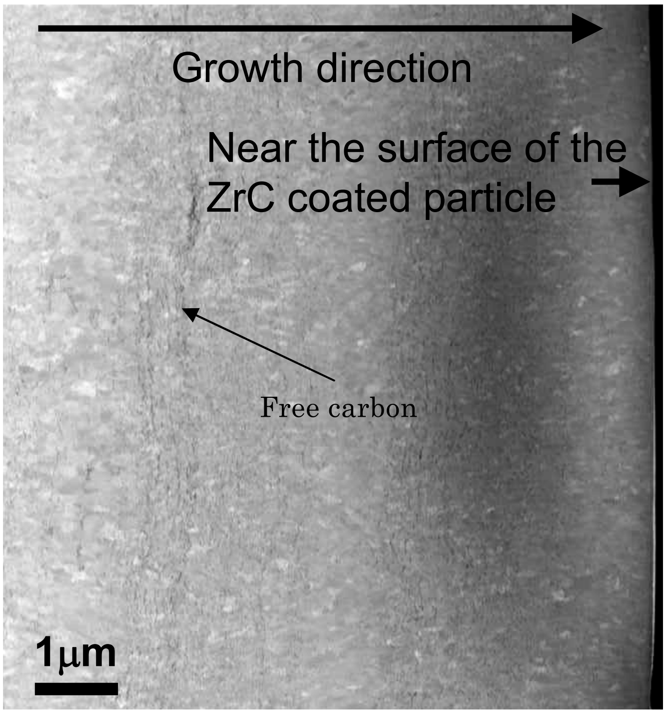


Fig. 9 STEM dark field (HAADF) image of ZrC coating layer with free carbon having high carbon peak by EDX

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	$\mathrm{m^2}$
体積	立法メートル	$\mathrm{m^3}$
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	$\mathrm{m/s^2}$
波数	毎メートル	$\mathrm{m^{-1}}$
密度，質量密度	キログラム毎立方メートル	$\mathrm{kg/m^3}$
面積密度	キログラム毎平方メートル	$\mathrm{kg/m^2}$
比体積	立方メートル毎キログラム	$\mathrm{m^3/kg}$
電流密度	アンペア毎平方メートル	$\mathrm{A/m^2}$
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	$\mathrm{mol/m^3}$
質量濃度	キログラム毎立法メートル	$\mathrm{kg/m^3}$
輝度	カンデラ毎平方メートル	$\mathrm{cd/m^2}$
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)	$\mathrm{m^2/m^2}$
周波数	ヘルツ(d)	Hz		$\mathrm{s^{-1}}$
力	ニュートン	N		$\mathrm{m\ kg\ s^{-2}}$
圧力，応力	パスカル	Pa	$\mathrm{N/m^2}$	$\mathrm{m^{-1}\ kg\ s^{-2}}$
エネルギー，仕事，熱量	ジュール	J	N m	$\mathrm{m^2\ kg\ s^{-2}}$
仕事率，工率，放射束	ワット	W	J/s	$\mathrm{m^2\ kg\ s^{-3}}$
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	$\mathrm{m^2\ kg\ s^{-3}\ A^{-1}}$
静電容量	ファラド	F	C/V	$\mathrm{m^{-2}\ kg^{-1}\ s^4\ A^2}$
電気抵抗	オーム	Ω	V/A	$\mathrm{m^2\ kg\ s^{-3}\ A^{-2}}$
コンダクタンス	ジーメンス	S	A/V	$\mathrm{m^{-2}\ kg^{-1}\ s^3\ A^2}$
磁束	ウエーバ	Wb	Vs	$\mathrm{m^2\ kg\ s^{-2}\ A^{-1}}$
磁束密度	テスラ	T	$\mathrm{Wb/m^2}$	$\mathrm{kg\ s^{-2}\ A^{-1}}$
インダクタンス	ヘンリー	H	Wb/A	$\mathrm{m^2\ kg\ s^{-2}\ A^{-2}}$
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	$\mathrm{lm/m^2}$	$\mathrm{m^{-2}\ cd}$
放射性核種の放射能(f)	ベクレル(d)	Bq		$\mathrm{s^{-1}}$
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$\mathrm{m^2\ s^{-2}}$
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	$\mathrm{m^2\ s^{-2}}$
酸素活性	カタール	kat		$\mathrm{s^{-1}\ mol}$

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

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	$\mathrm{1ha=1hm^2=10^4m^2}$
リットル	L，l	$\mathrm{1L=1l=1dm^3=10^3cm^3=10^{-3}m^3}$
トン	t	$\mathrm{1t=10^3\ kg}$

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	$\mathrm{1eV=1.602\ 176\ 53(14)\times 10^{-19}J}$
ダルトン	Da	$\mathrm{1Da=1.660\ 538\ 86(28)\times 10^{-27}kg}$
統一原子質量単位	u	1u=1 Da
天文単位	ua	$\mathrm{1ua=1.495\ 978\ 706\ 91(6)\times 10^{11}m}$

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	$\mathrm{1\ bar=0.1MPa=100kPa=10^5Pa}$
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	$\mathrm{1\ Å=0.1nm=100pm=10^{-10}m}$
海里	M	1 M=1852m
バーン	b	$\mathrm{1\ b=100fm^2=(10^{-12}cm)2=10^{-28}m^2}$
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	$\mathrm{1\ erg=10^{-7}\ J}$
ダイン	dyn	$\mathrm{1\ dyn=10^{-5}N}$
ポアズ	P	$\mathrm{1\ P=1\ dyn\ s\ cm^{-2}=0.1Pa\ s}$
ストークス	St	$\mathrm{1\ St\ =1cm^2\ s^{-1}=10^{-4}m^2\ s^{-1}}$
スチルブ	sb	$\mathrm{1\ sb\ =1cd\ cm^{-2}=10^4cd\ m^{-2}}$
フォト	ph	$\mathrm{1\ ph=1cd\ sr\ cm^{-2}\ 10^4lx}$
ガル	Gal	$\mathrm{1\ Gal\ =1cm\ s^{-2}=10^{-2}ms^{-2}}$
マクスウェル	Mx	$\mathrm{1\ Mx = 1G\ cm^2=10^{-8}Wb}$
ガウス	G	$\mathrm{1\ G\ =1Mx\ cm^{-2}\ =10^{-4}T}$
エルステッド(c)	Oe	$\mathrm{1\ Oe \triangleq (10^3/4\pi)A\ m^{-1}}$

(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「 ≙ 」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	$\mathrm{1\ Ci=3.7\times 10^{10}Bq}$
レントゲン	R	$\mathrm{1\ R = 2.58\times 10^{-4}C/kg}$
ラド	rad	$\mathrm{1\ rad=1cGy=10^{-2}Gy}$
レム	rem	$\mathrm{1\ rem=1\ cSv=10^{-2}Sv}$
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	$\mathrm{1\ \mu\ =1\mu m=10^{-6}m}$

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