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DEVELOPMENT OF CARBON/CARBON COMPOSITE CONTROL ROD FOR HTTR (II)
- CONCEPT, SPECIFICATIONS AND MECHANICAL TEST OF MATERIALS -

January 1998

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– Concept, Specifications and Mechanical Test of Materials –

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A concept and specifications of carbon/carbon composite (C/C) control rod were proposed, aiming at the application of the material to the HTTR. The outer diameter and length of the control rod were kept as the same as those of the present control rod, i.e., 113 mm and 3094 mm, respectively. According to the concept, the rod consists of ten units which are connected in series using bolts. Then, the stresses generated by dead loads in the control rod elements were estimated and compared with the design strengths which were derived from the results of measurements of tensile, compressive, bending and shear strengths of two candidate materials, AC250 (Across Co.) and CX-270 (Toyo Tanso Co.). Design strength was preliminarily determined as one-third or one-fifth of the mean strength. Ratio of the design strength to generated stress for the AC250 (2D) was : Tensile stress in the outer sleeve tube, 66, tensile and shear stresses in the M16 bolt, 8.8 and 8.5, shear stress in the plug support bolt M8, 2.43. These results are believed to indicate the mechanical integrity of the control rod structure. Data available on the candidate materials were also compiled in the Appendix.

Keywords: C/C composite, Control Rod, HTTR, Strength, Young's Modulus.

[+] Department of HTTR Project, Oarai Research Establishment

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炭素複合材料を用いたＨＴＴＲ用制御棒の開発（Ⅱ）
－概念、仕様及び材料の機械試験－

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（1998年１月５日受理）

ＨＴＴＲ用制御棒に炭素複合材料（Ｃ／Ｃ材）を適用することを目的として、制御棒の概念及び仕様の検討、候補材料の強度試験データの取得、及びボルト等の要素に自重によって発生する応力の評価を行った。制御棒の外径及び長さは現行と同様、各々、113mm及び3094mmとした。本概念では、制御棒は10個のユニットから成り、それらをＣ／Ｃ材製M16ボルトで長手方向につなげる構造とした。引張、圧縮、曲げ、せん断等の機械的強度データは２種類の候補材料（アクロス社製ＡＣ250及び東洋炭素社製ＣＸ-270）について室温にて取得した。これらの強度データの平均値の1/3または1/5を暫定的な設計強度とし、暫定値と別途製作した外筒、M16ボルト、Ｍ８ボルト等の要素に自重によって発生する応力計算値とを比較した。ＡＣ250(２Ｄ）の場合、安全率は外筒の引張応力で66、M16ボルトの引張とせん断応力で各々8.8と8.5、端部支持用Ｍ８ボルトのせん断応力では2.43となり、機械的な健全性が明らかになった。なお、付録として、現時点で入手可能な材料データを集録した。

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1. INTRODUCTION

High Temperature Engineering Test Reactor (HTTR) has been under construction at JAERI, Oarai Research Establishment since 1990 and is supposed to attain criticality in the near future. The core of the reactor consists of arrays of stacked fuel or replaceable reflector blocks made of nuclear graphite. In the normal operation condition the maximum temperature of the graphite blocks will be around 1300℃ when the temperature of the helium coolant is 950℃ at the outlet [1]. In order to control the reactivity, control rods are to be inserted into appropriate holes in the core and reflector blocks. In the event of a scram the rods are inserted into the core taking advantage of the gravity. Nine out of 16 pairs of control rods in the reflector region are inserted immediately at the time of scram, while the other seven pairs in the core region are to be inserted 40 minutes later when the temperature of coolant at the outlet becomes lower than 750℃. The two step inserting procedure is employed mainly for the purpose of preventing the control rod sleeves in the core region from overheating. Figure 1 shows an overview of the present control rod system to be applied for the HTTR. The control rod sleeves are made of Alloy 800H. Table 1 summarizes the condition in which the control rods are operated in the reactor.

Since the carbon-carbon (C/C) composite material is believed to be the more heat-resistant than Alloy 800H, it would lesson the restriction imposed on the reactor control procedure, if the control rod sleeve which accommodates boron carbide/carbon pellets is to be made of the composite material. The prominence of the C/C composite has been widely recognized as a high-strength heat-resistant structural material. Effect of neutron irradiation on thermal, mechanical and other properties of the composite has been extensively examined by a number of investigators [2-9] so that the data of the material have been accumulated fairly abundantly enough to commence to ponder on its application to high temperature components of nuclear facilities.

In consideration of this situation a concept of control rod of C/C composite was proposed in quest of the even better performance of the rod for the HTTR [10]. On the basis of the concept, several elements for the control rod were preliminarily prepared from C/C composites and their mechanical strength have been tested both before and after neutron irradiation [10]. The results of the test indicated that the application of C/C composite to the control rod structure was promising. The more systematic effect for the development of C/C composite control rod have been made

on the basis of the result. This report summarizes the results of the above efforts toward the realization of C/C composite control rod for the HTTR.

2. PROCEDURE FOR THE DEVELOPMENT OF C/C COMPOSITE CONTROL ROD AND ITS STRUCTURE CONCEPT

There are quite a few steps to be taken towards the actual usage of C/C composite control rod in the HTTR. These steps include (1) conceptual design, (2) structural design criteria (Analytical code and material database), (3) strength tests on control rod elements, (4) insertion performance test on mock control rod, (5) scram reliability test on mock control rod and (6) detailed design. Among these steps the following R & D were carried out in 1997. With regard to item (1), the kind and level of stresses to be generated were estimated on a preliminary concept of control rod structure. With regard to item (2), preparation of key elements such as outer and inner sleeves and middle and large size bolts was carried out by two potential manufacturers. Moreover, several mechanical strength tests were carried out towards the establishment of database for the material properties. Table 2 summarizes the data requirements for the design of control rod.

Figure 2 shows the concept of the control rod structure. Elements prepared during 1997 are shown in Fig. 3 (a) through (f). The total length and the diameter of the outer tube of the C/C control rod are the same as those of the present control rod of the HTTR. The C/C control rod differs from the present one in the connecting mechanism : The rod consists of ten single sleeves connected in series with each other. Between the outer and inner sleeve tubes compacts of the reactivity controlling material, boron carbide, are to be accommodated. The connecting mechanism consists of the lid supporting plates, upper lids, lower lids, M8 bolts and M16 bolts. The total length of the rod will be 3094 mm.

3. STRESSES GENERATED IN THE ELEMENTS OF A CONCEPTUAL CONTROL ROD AND COMPARISON WITH MATERIAL DATA

3.1 Estimation of Stresses

The weight of the whole control rod mentioned above, including the reactivity controlling material, is estimated to be 55 kg. Here, stresses

generated in the elements are estimated for the case that the dead-weight is loaded to the upper joint of the control rod.

Tensile stress generated in the cross-section of the inner sleeve tube is estimated as about 0.4 MPa on the assumption that a load of 55 kg is applied to the whole cross-section. Similarly tensile stress generated at the connecting bolt M16 is to be about 3 MPa. It is believed that a shear stress will be generated at the top part of M16 bolt. This shear stress will be about 0.4 MPa on the assumption that 55 kg are loaded to the top part of the bolt and the load is sustained by all the threads. Shear stress to be generated at the four lid supporting plug bolts M8 is to be about 3 MPa for each bolt.

3.2 Comparison with Material Data

Preliminary evaluation of the integrity of the rod elements is carried out for the stresses estimated above. The material data shown below, which are based on the results of strength tests are employed here. The details of these results will be described in the next section.

Element	Reference Material	Design strength (MPa)	
sleeve tube	AC250 2D	Tensile	26.4
M16 Bolt	AC250 2D	Shear	3.5
M8 Bolt	AC250 2D	Tensile	20.7
		Shear	7.3

On the basis of the above values, the safety margin for the sleeve tube is estimated as 26.4/0.4=66. Similarly, the margins for tensile stress in M16 bolt and for shear stress at the top part of the bolt are 26.4/3=8.8 and 3.5/0.4=8.5, respectively. The margin for the lid supporting plug M8 bolt is 7.3/3=2.43. These calculations indicate that the structural integrity of the control rod will be maintained on the basis of the present concept.

4. CHARACTERIZATION OF MATERIALS

Mechanical strength tests were carried out. in order to obtain the data on properties of C/C composite materials which may be used for the control rod. In this section the results of the tests are summarized to show the basis for the design strength values which were employed in the previous section.

4.1 Materials, Specimens and Tests

Two C/C composite materials were selected as candidates here. These were AC250 (2D and UD) of Across Co. and CX-270 of Toyo Tanso Co. Bundles of carbon fibers containing matrix material were formed into a preformed yarn coated with resin. As-received yarns or sheets prepared by weaving yarns were hot-pressed to obtain a pre-carbonization product. Then, the product was carbonized and graphitized, being followed by machining.

Specimens for the tensile tests were plate-type ones 2.2 mm in thickness and 25 mm in length. The loading direction was parallel to the fiber orientation. Strain rate was 8×10^{-4}/s. Compressive tests were done on specimens of $10\times10\times10$ mm at a strain rate of 8×10^{-4}/s. Compressive loading axis was perpendicular to the fiber orientation. Three-point bending tests were done on specimens, 2 mm in thickness and 15 mm in width, at a cross-head speed of 0.5 mm/min. The bending load was applied perpendicularly with the fiber orientation. The span was 80 mm. Shear strength tests were done on specimens, 2 mm in thickness and 6 mm in width, with the loading axis parallel to the fiber orientation at a loading rate of 0.1 mm/min. The span was 8 mm.

4.2 Results of the Tests

The data obtained from the above tests are shown in the Appendix of this report. Figures 4 to 7 show the results of tensile, compressive, bending and shear strength tests on AC250 materials, respectively. It is apparent that the unidirectional material (UD) displays the larger values for all the tests but compressive one. It is found that compressive strength of UD material is much smaller than that of 2D one, about a quarter of its own tensile strength. In the case of 2D material, the compressive strength is about two thirds of its own tensile strength. Since the control rod components are subject to various types of stresses, 2D material is believed, generally speaking, to be more appropriate for the control rod use. It is to be noted that, different from the nuclear graphite, the compressive strength is smaller than tensile one both for UD and 2D, and that the bending strength is not so much larger than the tensile one as is the case for the nuclear graphite where bending strength is 1.5 to 2 times larger than tensile one.

Figures 8 and 9 show the results of the compressive and bending tests on CX-270 material, respectively. Compressive strength in the

transverse direction is, as is the case for AC250, much smaller than the bending strength. With regard to the effect of fiber orientation on the compressive strength, the parallel specimens display about 2.5 times larger values than the transverse ones.

Young's modulus of the AC250, UD and 2D, is shown in Fig. 10 where one can see the distribution of the values on the normal probability paper. Two facts are found in the figure : (1) Tensile Young's modulus is the larger than the bending one which is obtained from the stress-strain relationship on the tensile side of the bending specimen, and (2) the modulus of the UD is 2 to 2.5 time larger than that for 2D material. These results seem to be explained reasonably by taking into account the facts that (1) there is a stress gradient along the loading axis during bending test, i.e., the actual stress value in the vicinity of the external surface is smaller than the uniform tensile test, and (2) the number of fibers in the loading direction is larger for UD than for 2D.

Figure 11 shows the results of the measurement of electrical resistivity as a function of density for CX-270. It is to be noted that the density of the material can be controlled within ±3%, and that the resistivity is well correlated with the density in a linear equation. With regard to the density dependence of the strengths, the bending strength of CX-270 seems to be expressed by two linear equations which hold for above and below 1.58 g/cm^3, respectively. This is seen in Fig. 12. As for the compressive strength of CX-270, it is to be noted that there is almost no dependence on the density, which is seen in Fig. 13.

4.3 Design Criteria for the Strength of C/C Composites

It has not been agreed upon the method in which one can determine the design criteria for the strengths of the C/C composite. Here, to determine preliminary values for the strengths measured for the two C/C composite materials, safety factor of 3 or 5 was multiplied to the mean value of each strength. The calculated values are summarized in Table 3. These values were employed when stresses generated in the elements of control rod were evaluated in Section 2. Material properties which have been collected as of the end of 1997 are compiled in the Appendix of this report.

5. SUMMARY AND FUTURE WORK

Towards the development of C/C composite control rod for the HTTR a structural concept of control rod was proposed and the stresses generated in its elements were preliminarily evaluated. Strength tests such as tensile, compressive, bending and shear were done on C/C composite materials, AC250 and CX-270, to obtain material data which were to be used for the above-mentioned evaluation of stresses. Moreover, the data which are available as of the end of 1997 have been summarized in the Appendix of this report. Further work necessary for the development of C/C composite control rod is believed to be as follows:

(1) Establishment of the database for candidate materials: There are strong needs for the mechanical and thermal properties data at higher temperatures as well as the irradiation data including irradiation creep.

(2) Fabrication technology for the rod elements should be established and their mechanical integrity is to be confirmed.

(3) Design of the rod should be made in the more detailed manner in accordance with the process in which the material database progresses toward the completion.

The authors intend to proceed step by step towards the final goal on the basis of the collaboration between the Departments of Materials Science and Engineering and HTTR Project.

REFERENCES

1) S. Saito et al., JAERI-1332, September 1994.
2) S. Sato et al., J. At. Energy Soc. Japan 32 (1990) 1124-1132.
3) T. D. Burchell et al., Proc. 5th Int. Carbon Conf., Essen, Germany, June 22-26, 1992, pp.985-987.
4) T. Maruyama and M. Harayama, J. Nucl. Mater. 195 (1992) 44-50.
5) F. Gao et al., Carbon 31 (1993) 103-108.
6) H. Matsuo and T. Nagasaki, J. Nucl. Mater. 217 (1994) 340-343.
7) C. H. Wu et al., J. Nucl. Mater. 212-215 (1994) 1168-1173.
8) M. Eto et al., ibid., 1223-1227.
9) H. Ugachi et al., Trans. JSME, 62A (1996) 10-17.
10) M. Eto et al., JAERI-Research 96-043 (1996).

Table 1 Service condition for the HTTR.

	Maximum temperature (℃) (Bottom of the lowest sleeve)		Fluence (660 days***) (Bottom of the lowest sleeve)
	Normal operation (950℃) (Location : B+0.75 level)	Scram (Loss of commecial electricity)	
Central control rod	~610*	~1050** (One-step insertion) ~800* (Two-step insertion)	~6×10^{24} n/m^2
R2 control rod	~560*	~900*	~6×10^{24} n/m^2

* : Systematic and random factors conidered.
** : Temperature of control rod guide block.
*** : Lifetime of the control rod is about 5 years (depends of creep property).
B : Top of the core.

Table 2 Items of material testing and necessary database for design.

Test item	Properties	Database
Strength test Fatigue test	Static strength, Fracture strain, Strength distribution, Fatigue strength, Effect of environment and irradiation	Design stress strength, Design yield stress, Design tensile strength, Poisson's ratio, Longitudinal elastic modulus, Allowable fatigue life
Creep test	Creep strength, Creep fatigue	Design creep fracture strength
Thermal expansion		Thermal expansion coefficient
Thermal conductivity		Thermal conductivity

Table 3 Preliminary design criteria for the strengths of C/C composites on the basis of the results obtained in the present study.

Material	AC250 (UD)		AC250 (2D)		CX270	
Safety factor	3	5	3	5	3	5
Tensile strength (MPa)	34.5	20.7	44.0	26.4	75.7	45.4
Compressive strength (MPa)	21.1	12.6	64.9	39.0	(P) 32.3 (T) 96.3	19.4 57.8
Bending strength (MPa)	28.4	17.0	57.1	34.3	53.0	11.8
Shear strength (MPa)	12.2	7.3	5.9	3.5	NA	NA

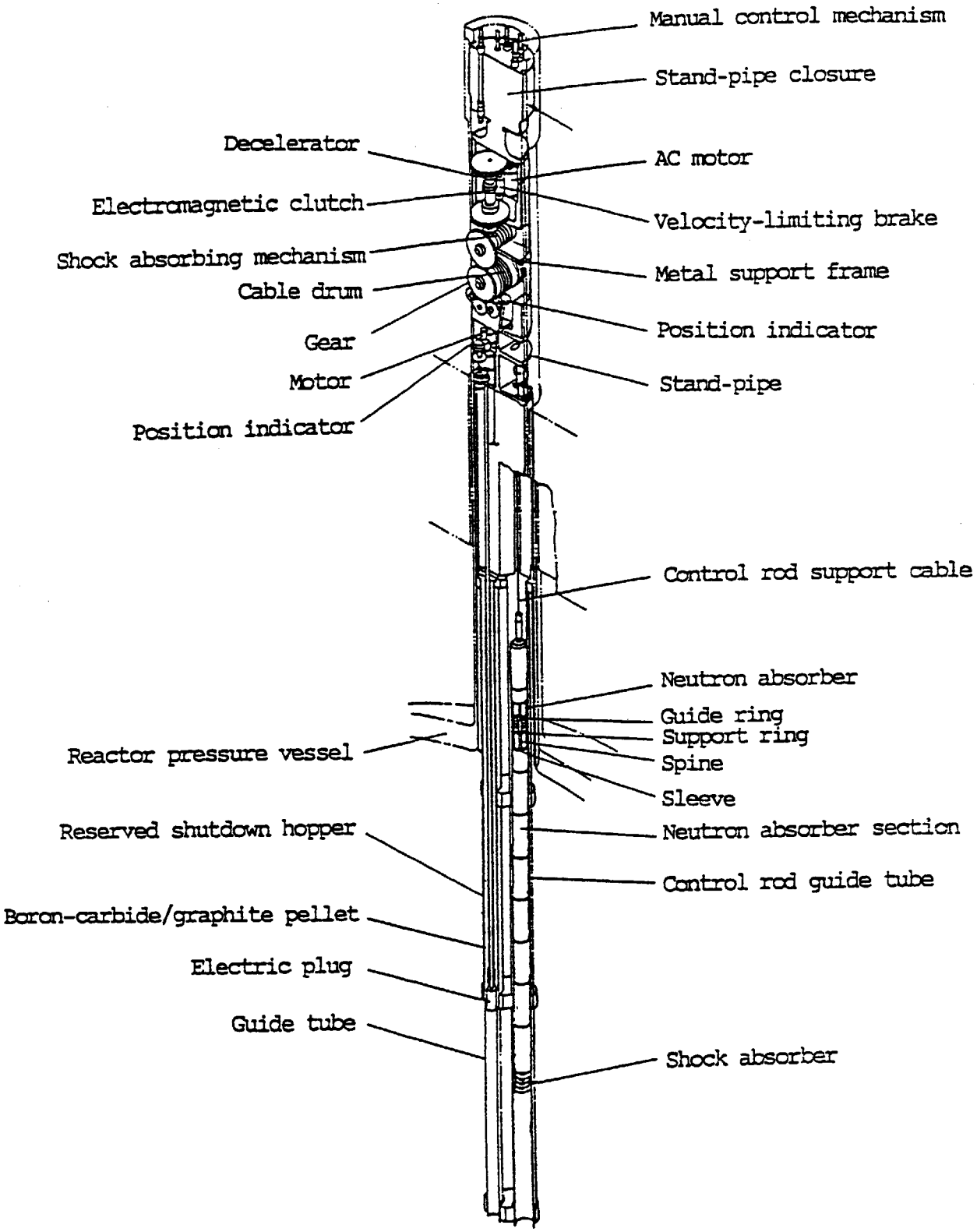
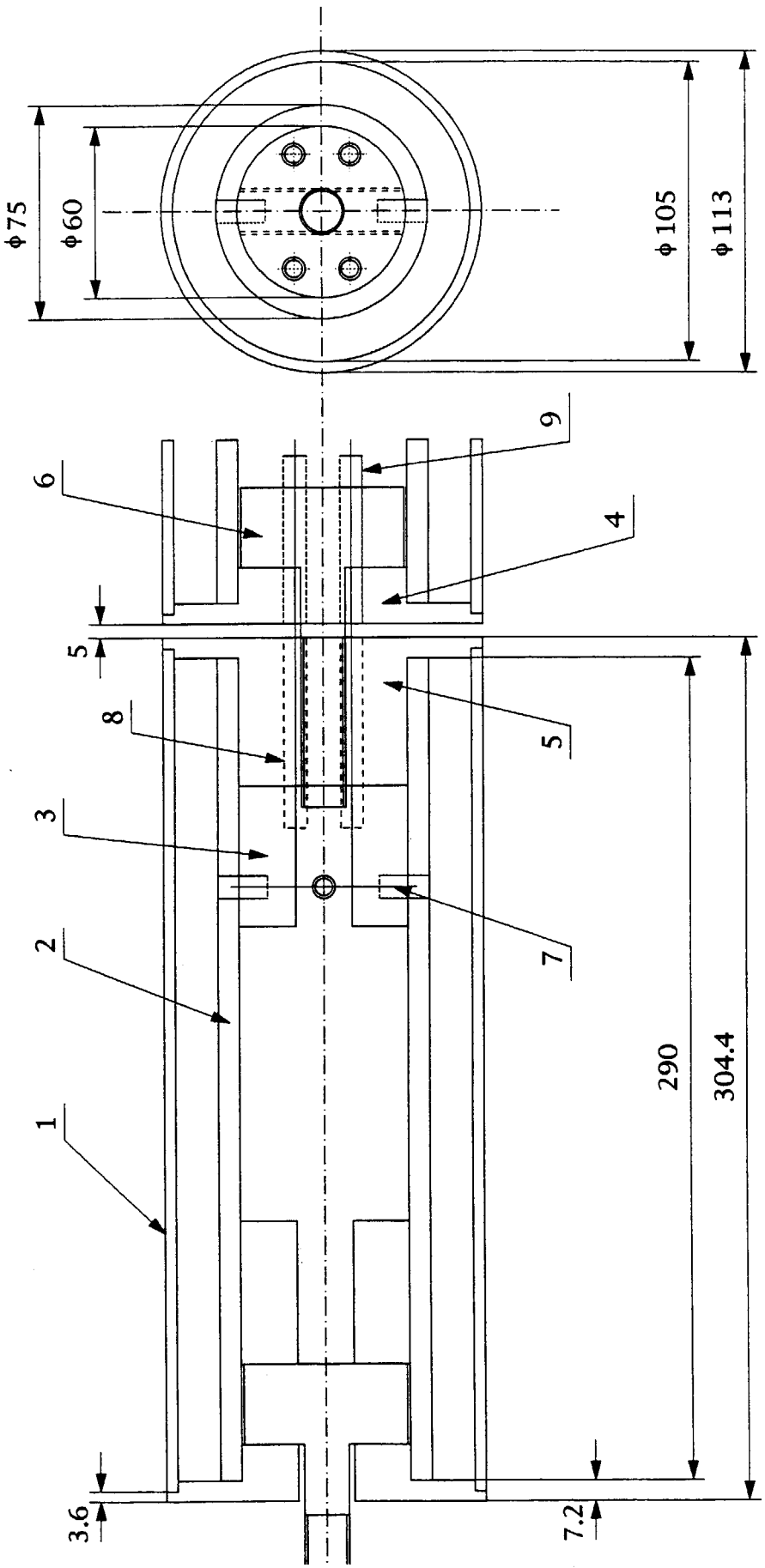


Fig. 1 Reactivity control system of the HTTR.



No.	Component	Material	Quantity
1	Outer tube	C/C	1
2	Inner tube	C/C	1
3	Lid supporting plug	C/C	1
4	Upper lid	C/C	1
5	Lower lid	C/C	1
6	M16 Bolt	C/C	1
7	M8 Bolt	C/C	8
8	M8 Bolt	C/C	4
9	M8 Bolt	C/C	4

Fig. 2 A concept for the control rod structure.

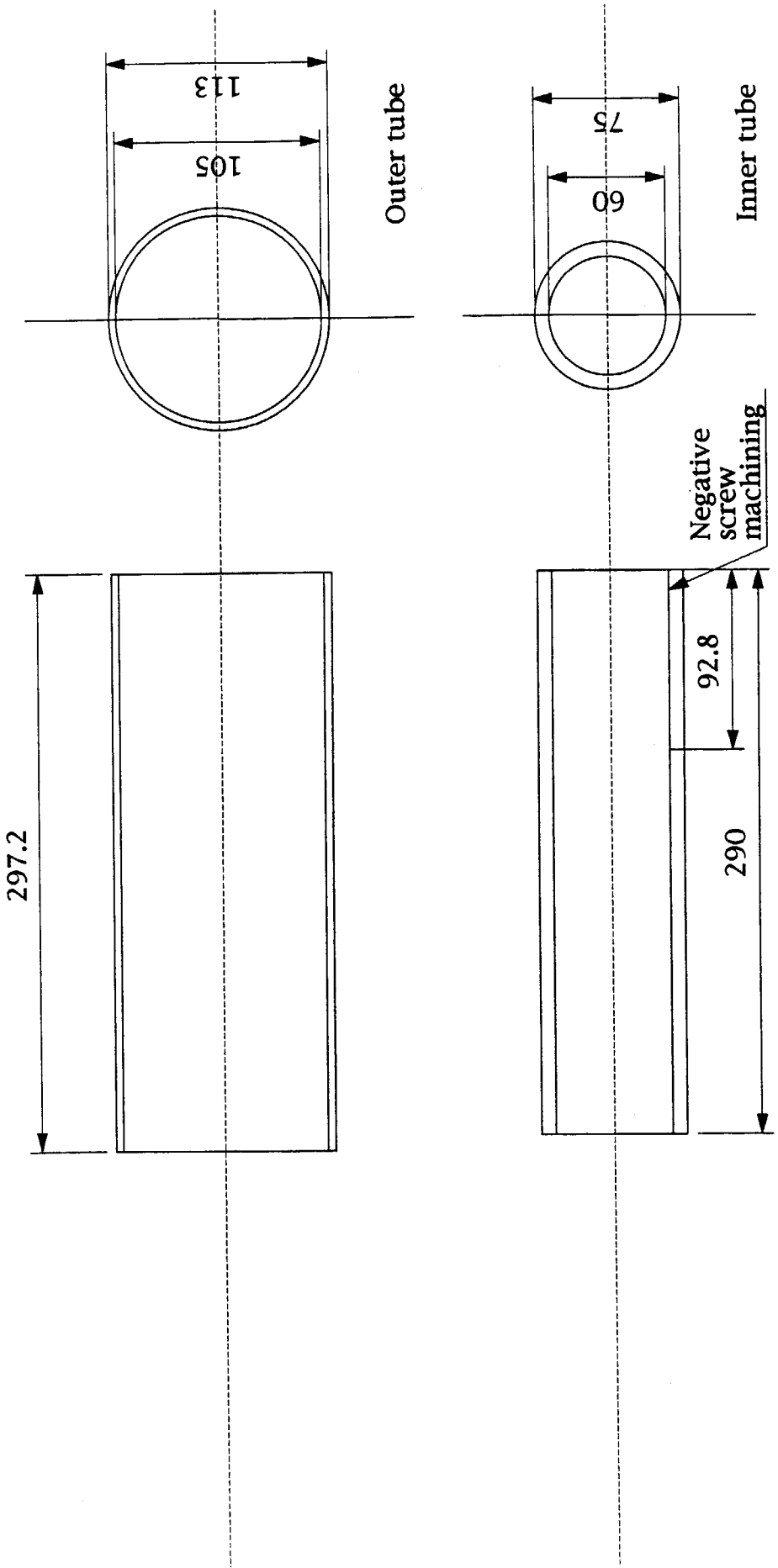
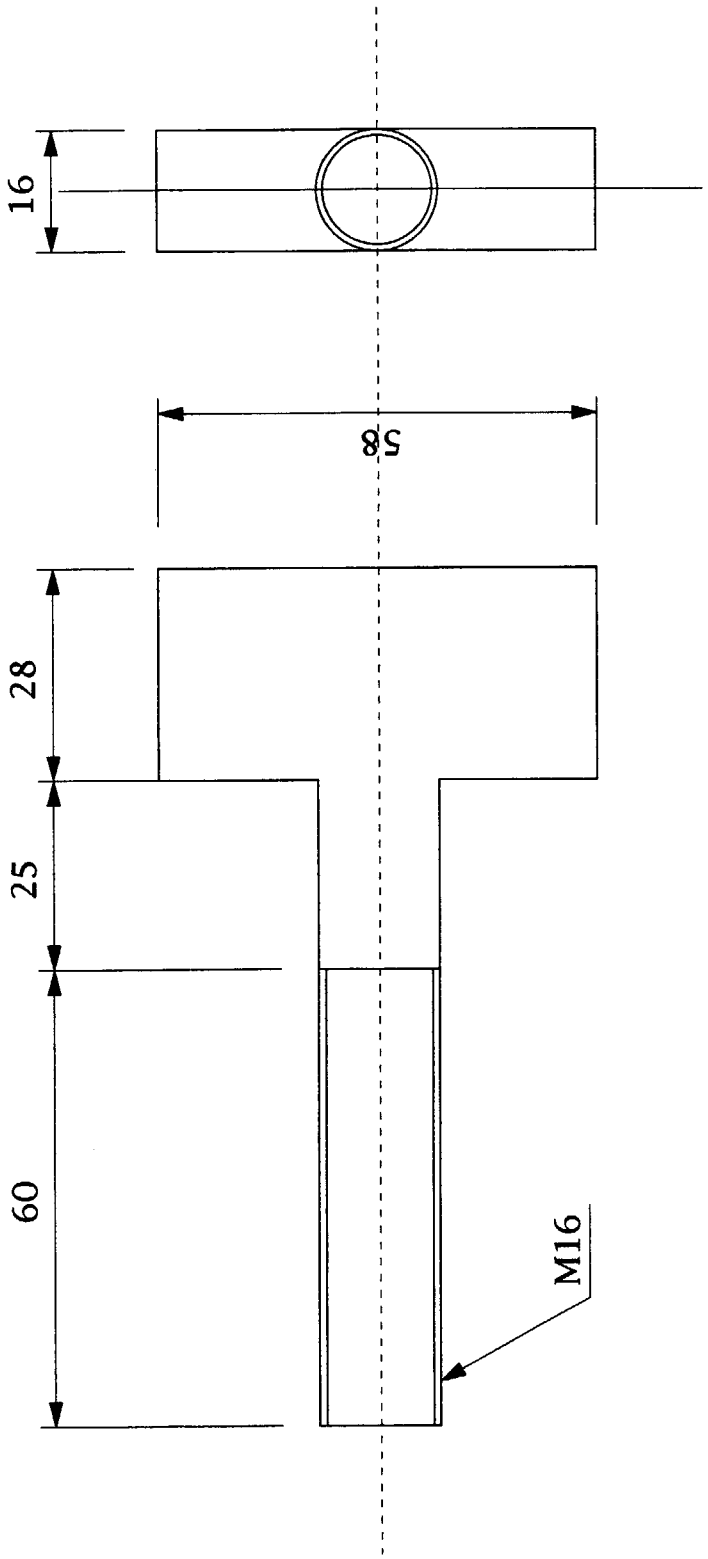


Fig. 3 Some elements prepared from C/C composite.
(a) Outer and inner sleeve tubes



No.	Component	Material	Quantity
6	M16 Bolt	C/C	1

Fig. 3 Some elements prepared from C/C composite.
(b) M16 Bolt

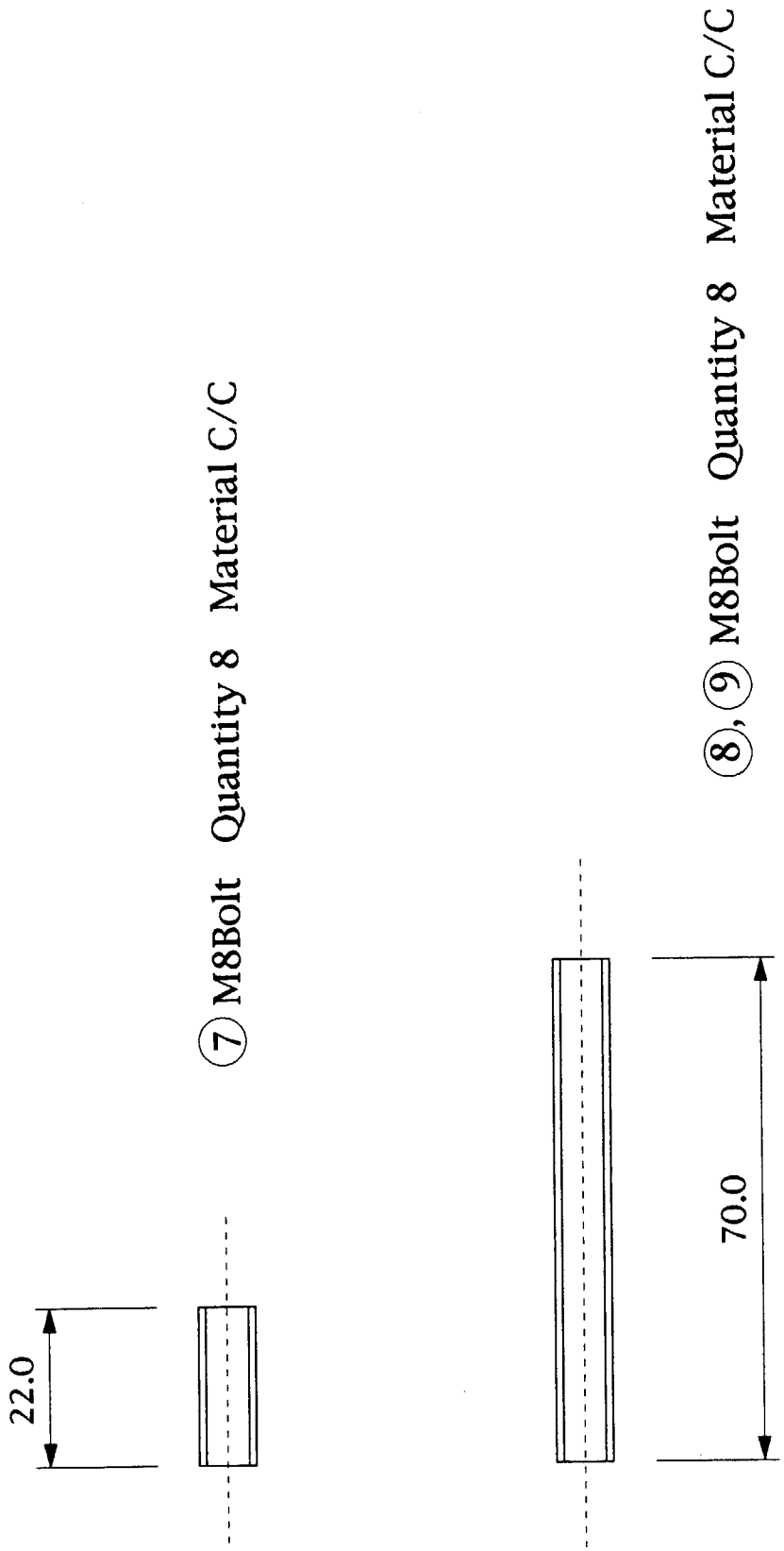
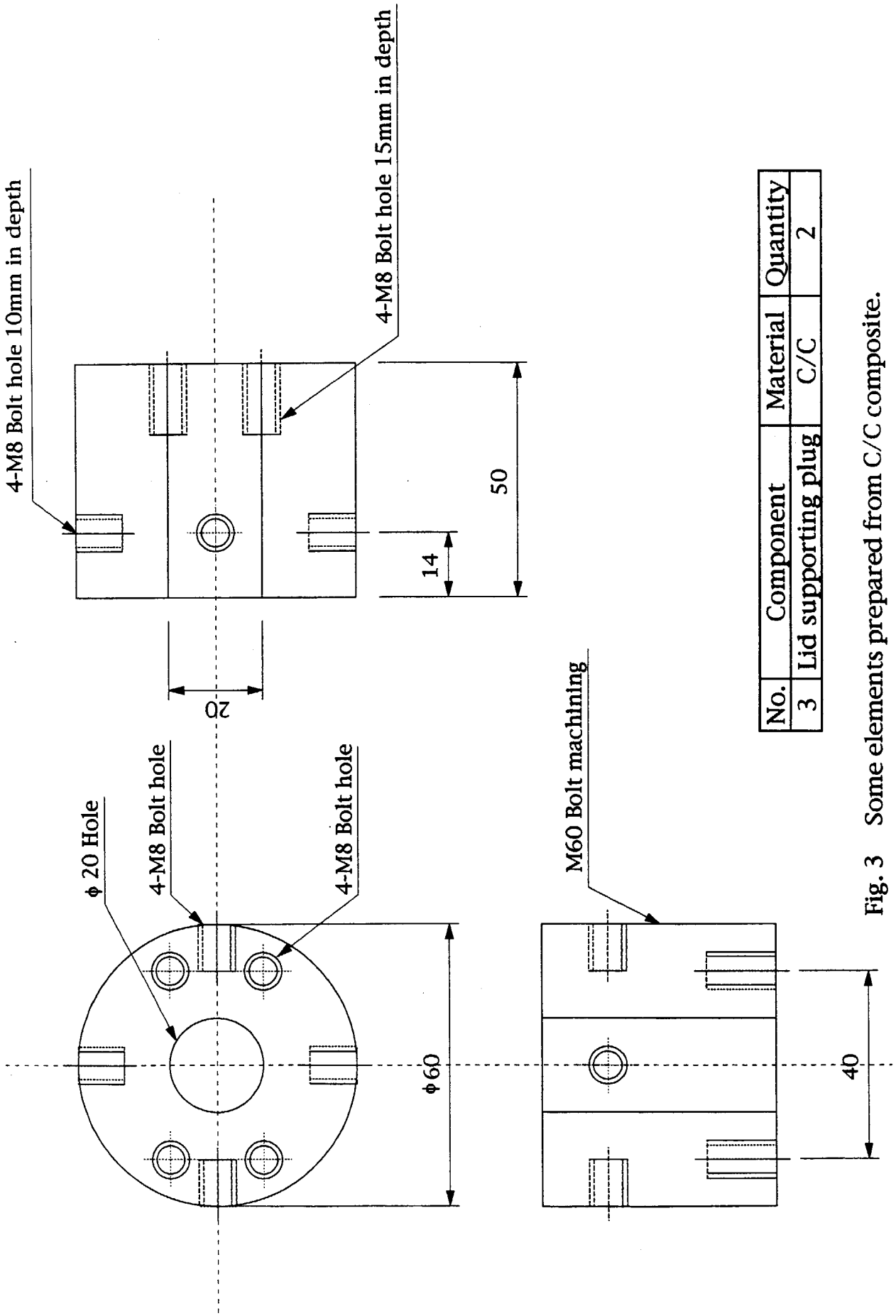
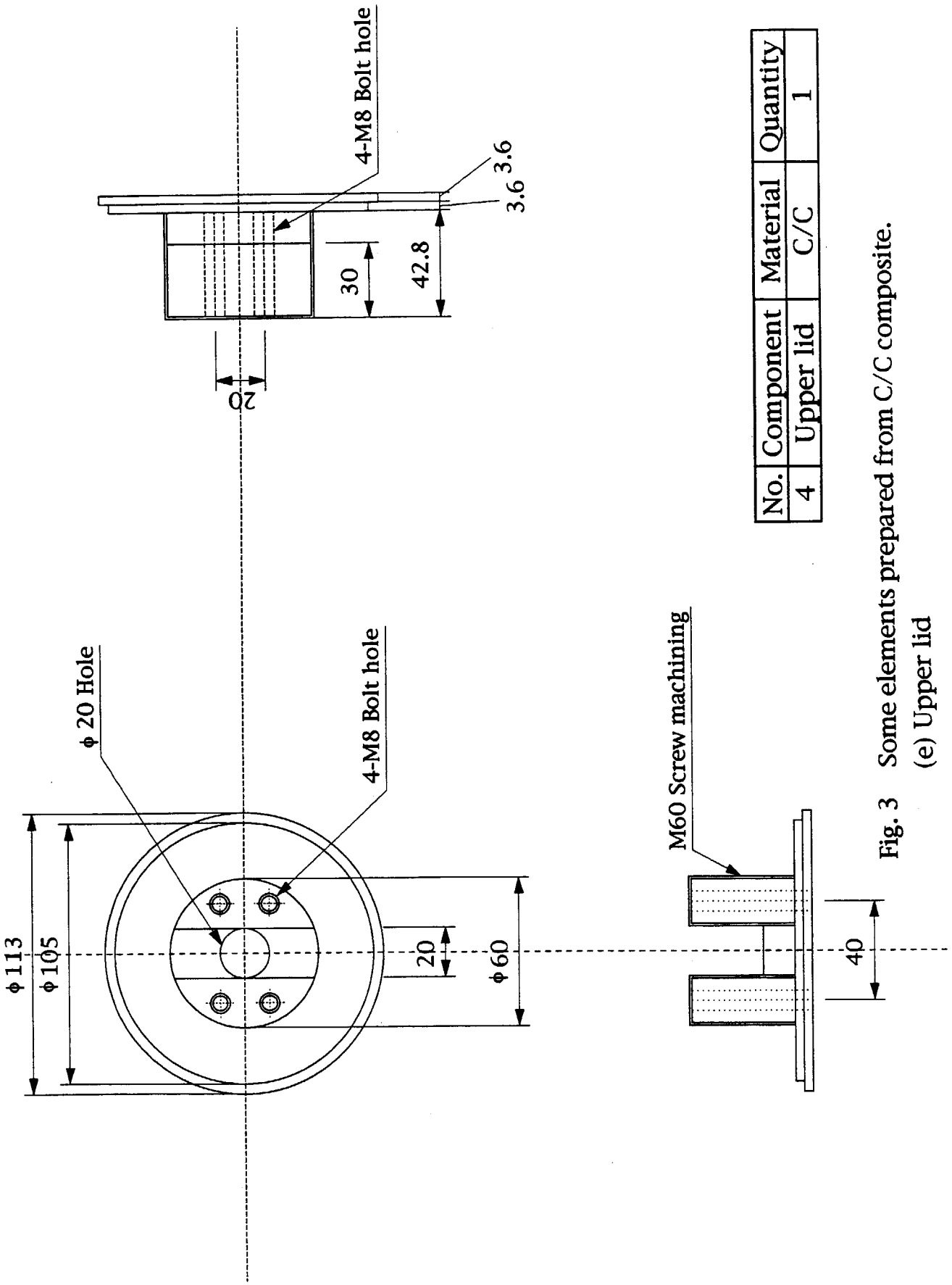


Fig. 3 Some elements prepared from C/C composite.
(c) M8 Bolts



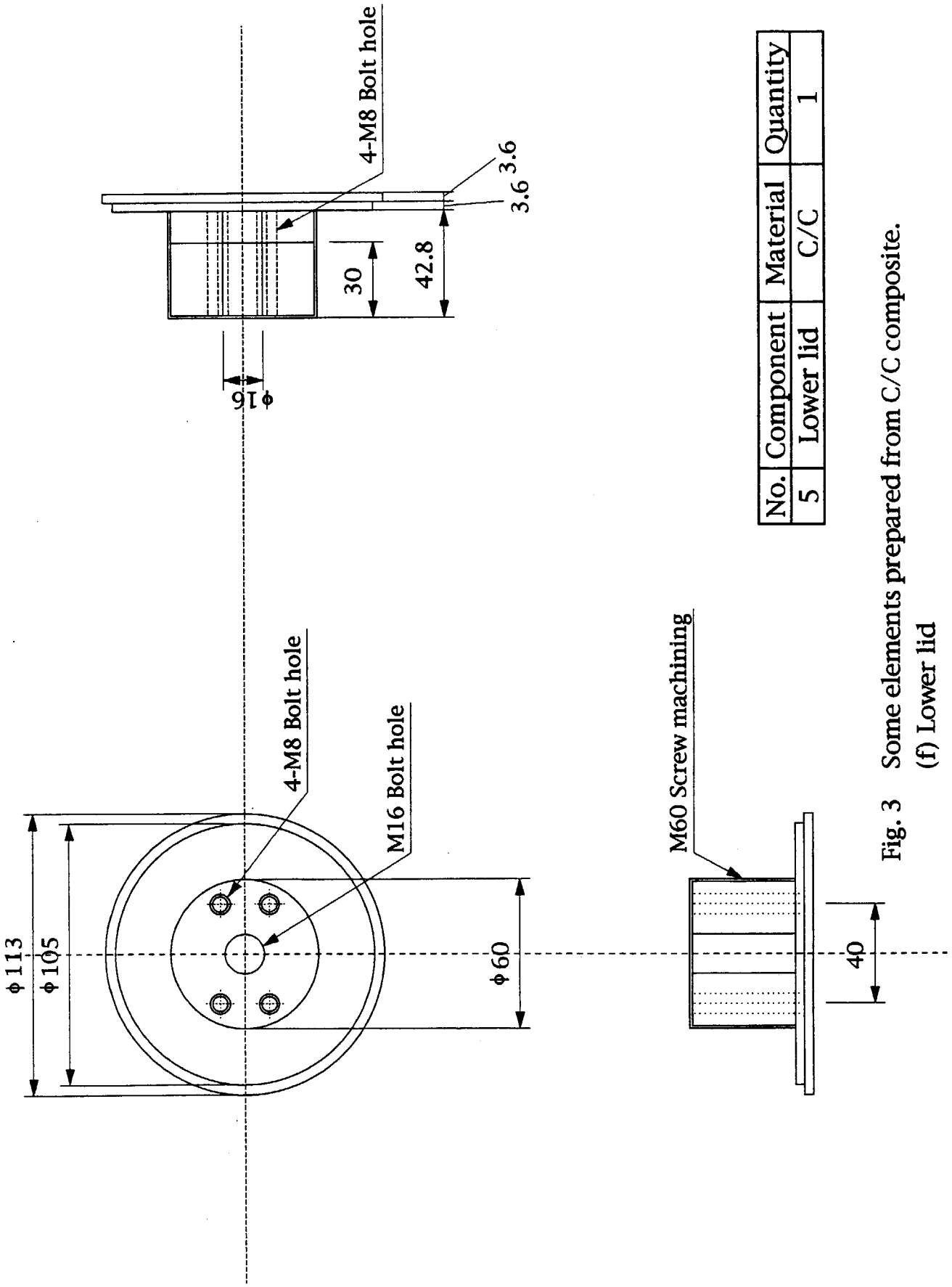
No.	Component	Material	Quantity
3	Lid supporting plug	C/C	2

Fig. 3 Some elements prepared from C/C composite.
(d) Lid supporting plug



No.	Component	Material	Quantity
4	Upper lid	C/C	1

Fig. 3 Some elements prepared from C/C composite.
(e) Upper lid



No.	Component	Material	Quantity
5	Lower lid	C/C	1

Fig. 3 Some elements prepared from C/C composite.
(f) Lower lid

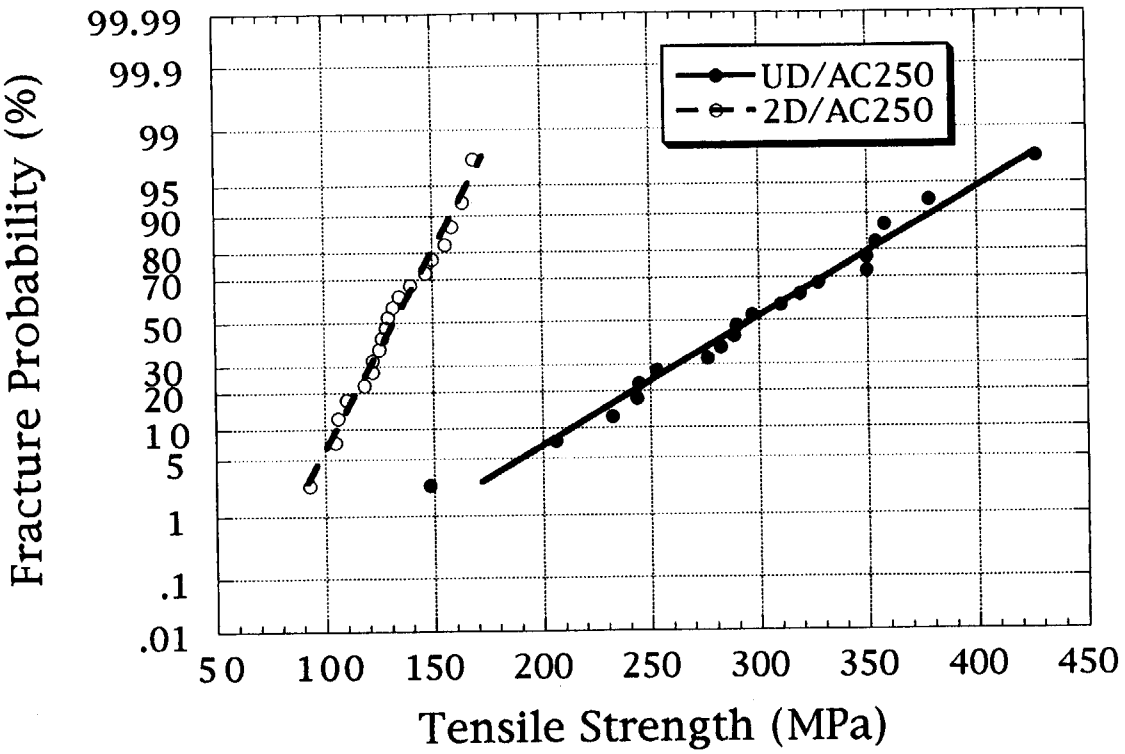


Fig. 4 Normal distribution plots of the tensile strength of AC250, unidirectional (UD) and 2-directional (2D).

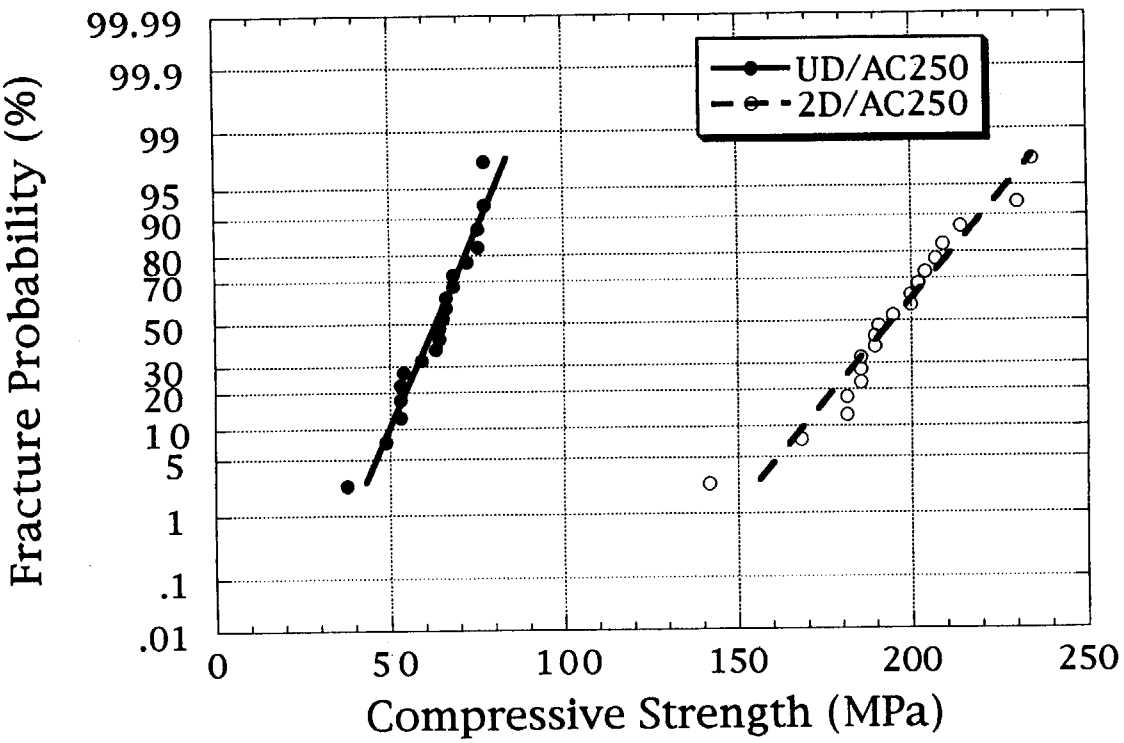


Fig. 5 Normal distribution plots of the compressive strength of AC250, UD and 2D.

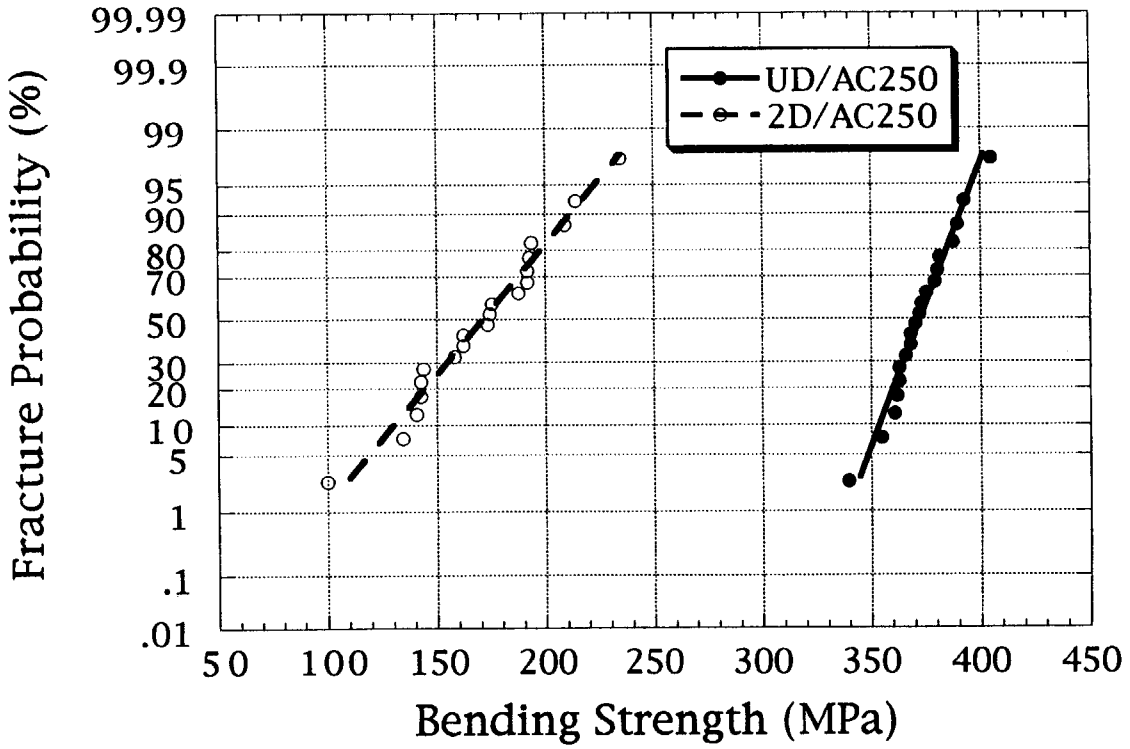


Fig. 6 Normal distribution plots of the bending strength of AC250, UD and 2D.

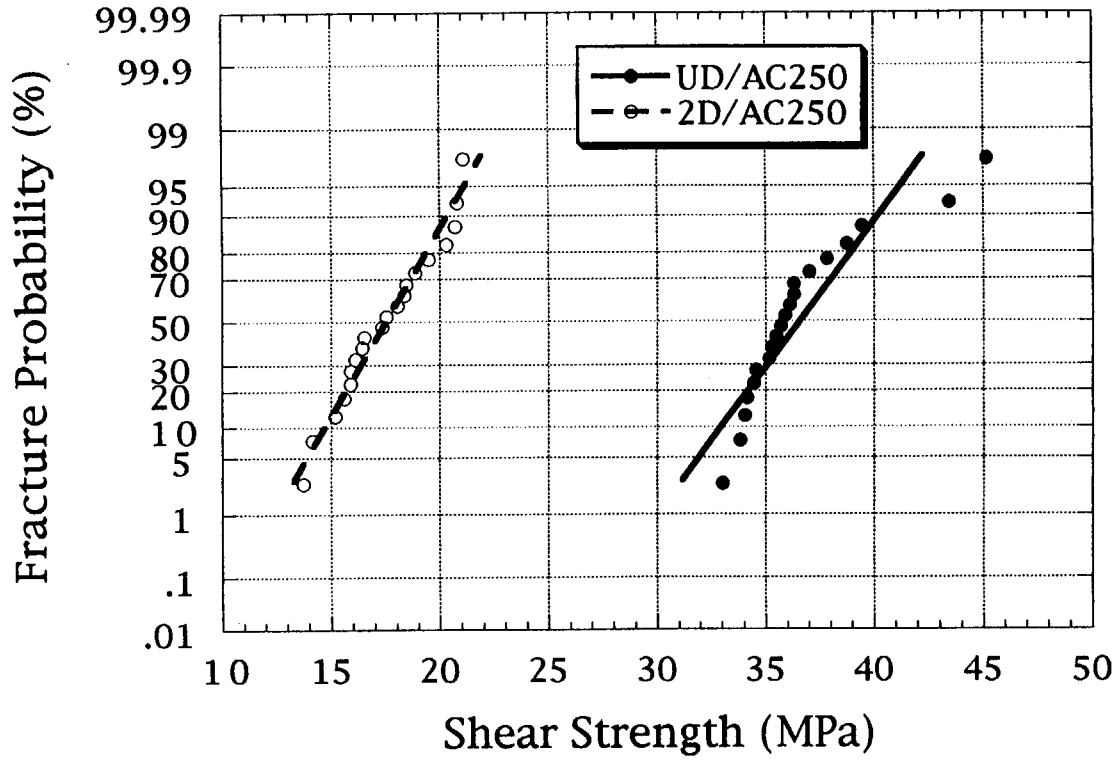


Fig. 7 Normal distribution plots of the shear strength of AC250, UD and 2D.

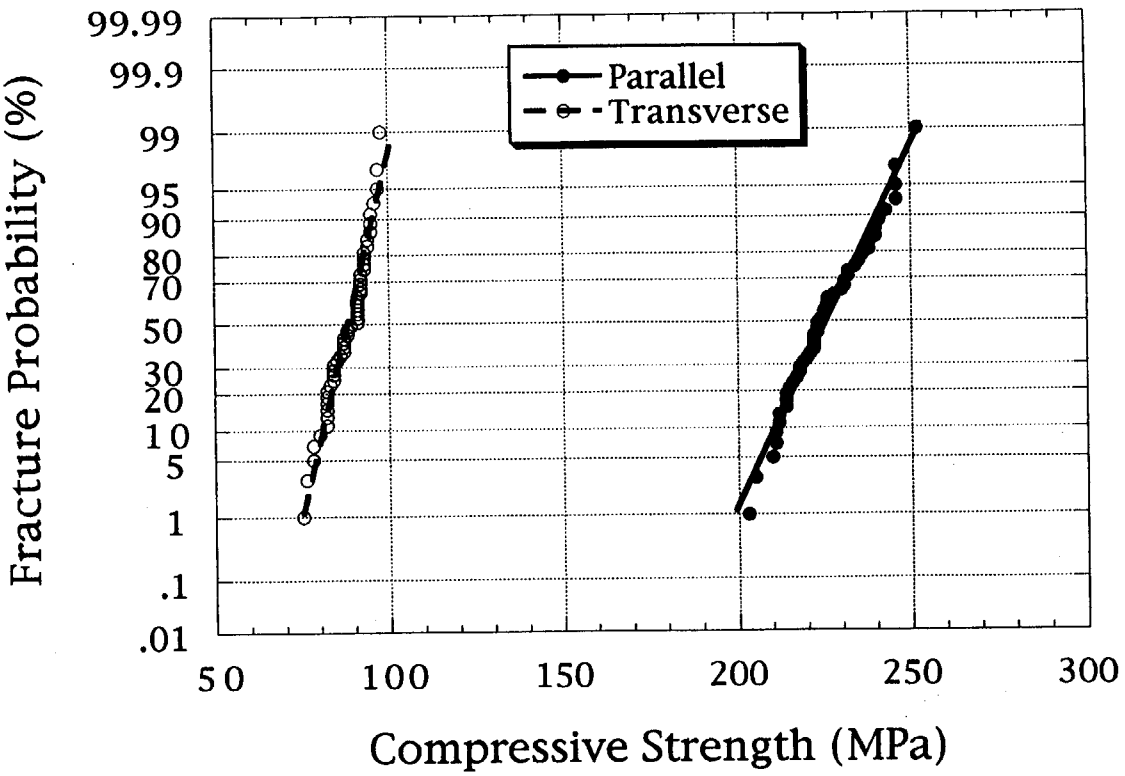


Fig. 8 Normal distribution plots of the compressive strength of CX-270.

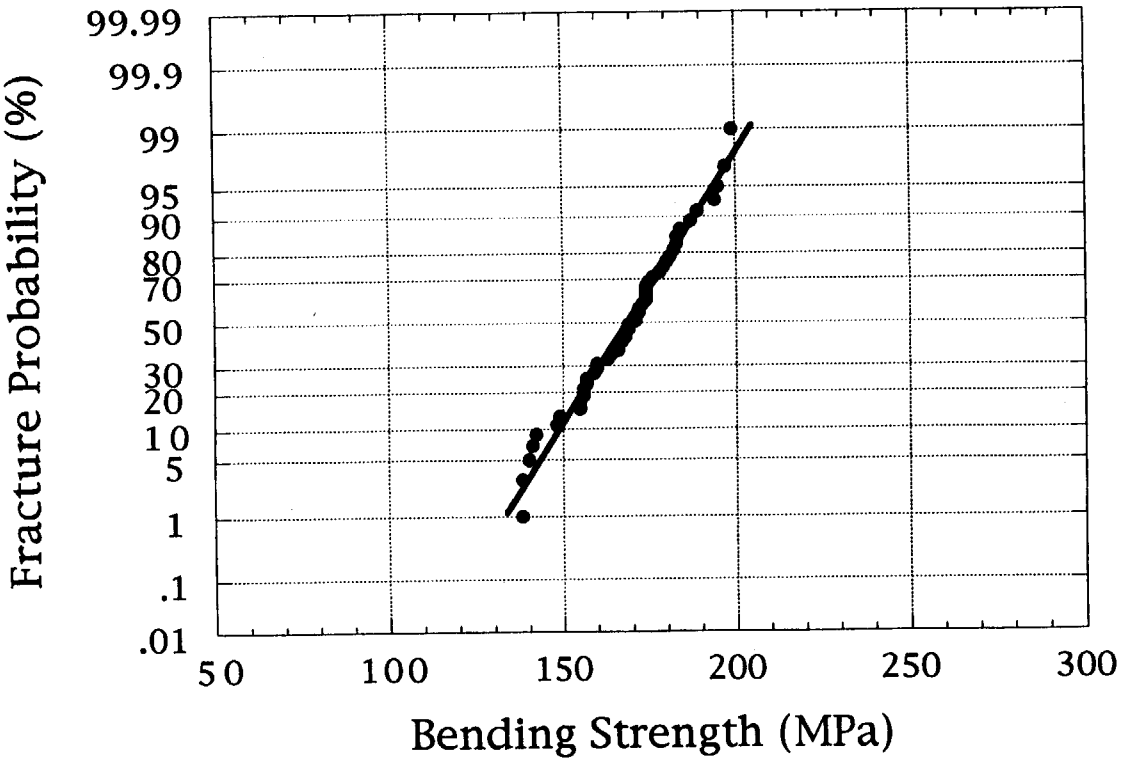


Fig. 9 Normal distribution plots of the bending strength where the loading axis is transverse to the fiber orientation.

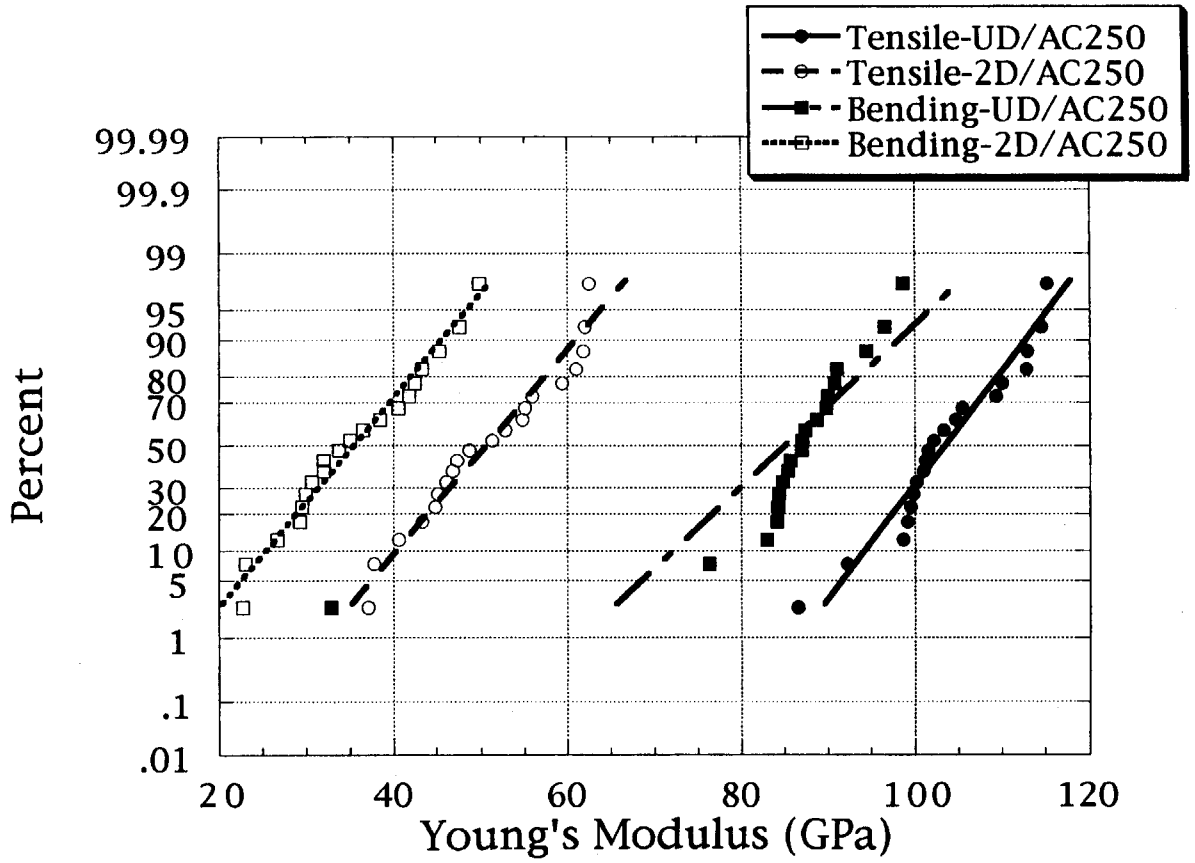


Fig. 10 Normal distribution plots of the Young's modulus of AC250, UD and 2D, obtained from tensile and bending tests.

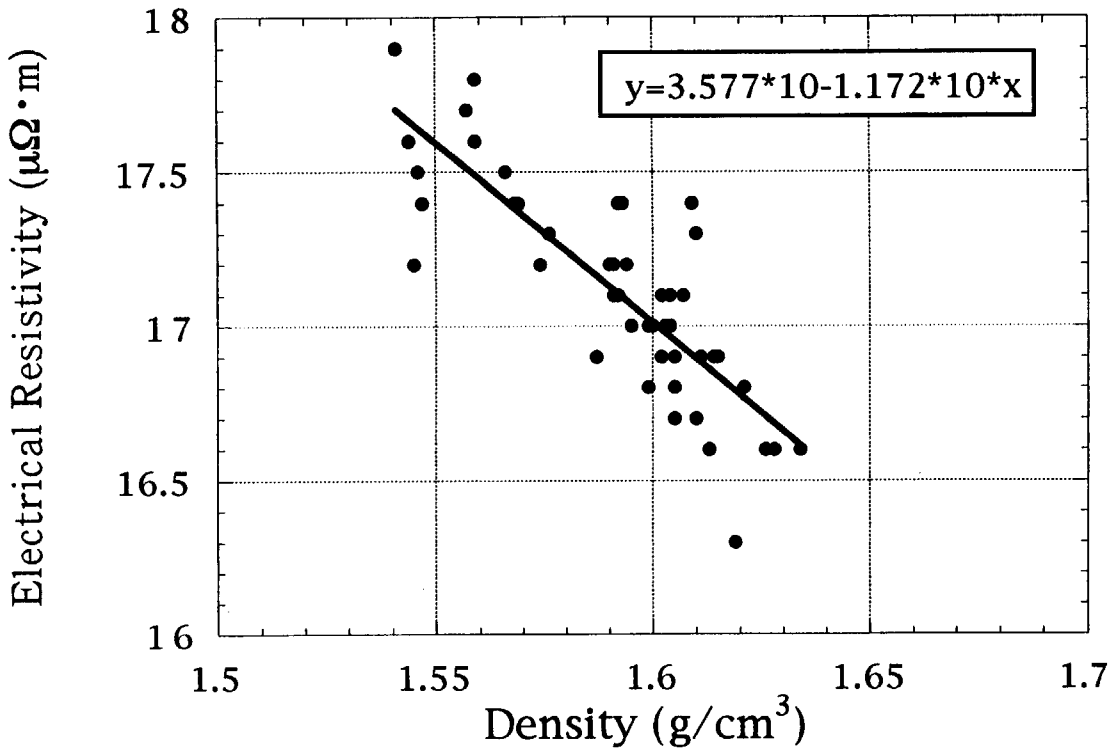


Fig. 11 Electrical resistivity of CX-270 parallel to the fiber orientation as a function of density.

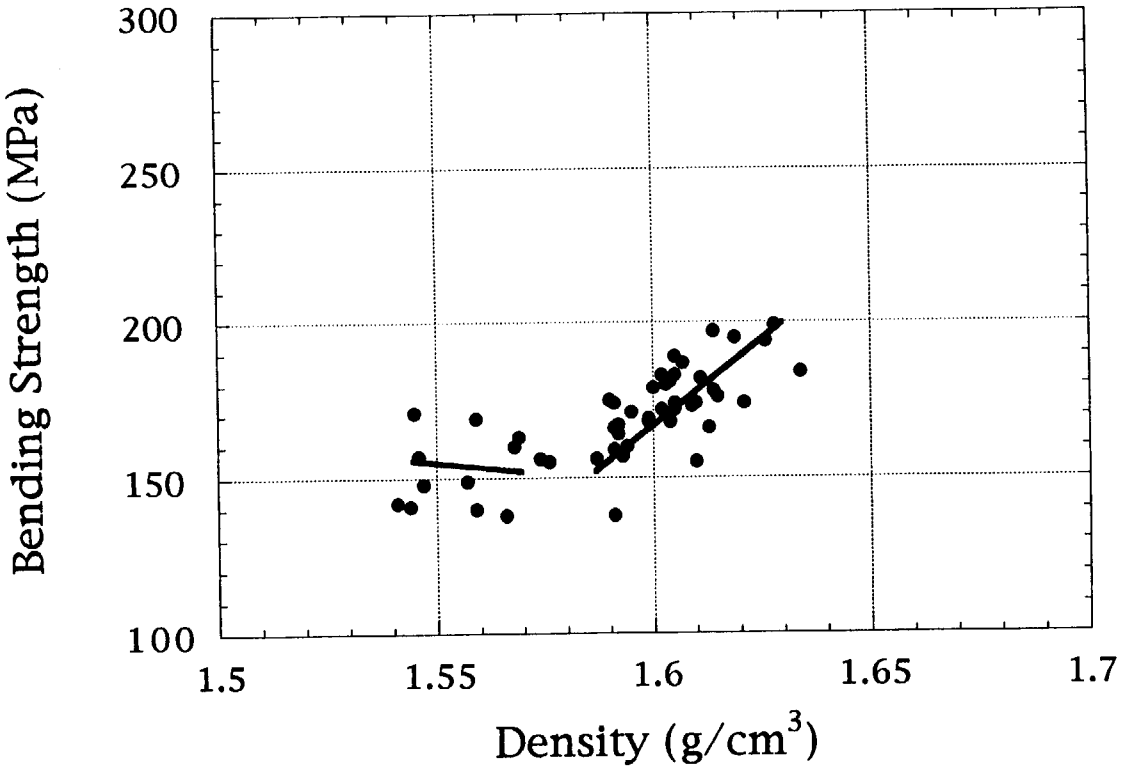


Fig. 12 Density dependence of bending strength of CX-270.

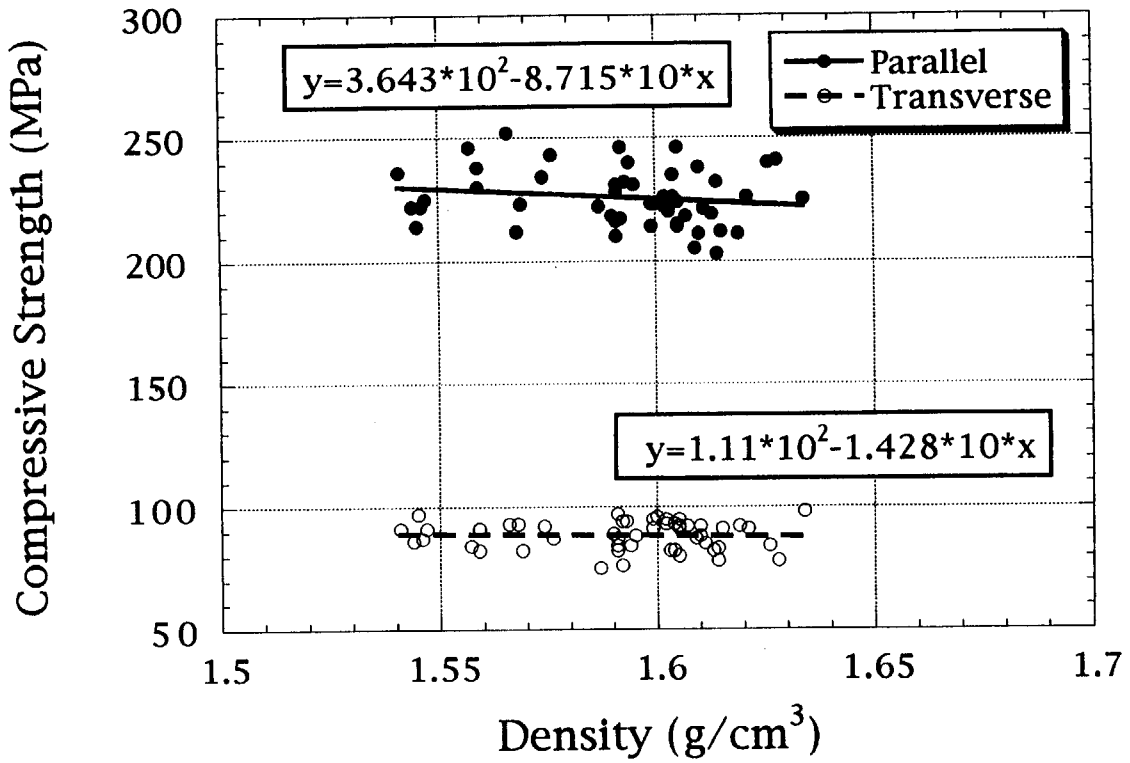


Fig. 13 Density dependence of compressive strength of CX-270.

APPENDIX :

Compilation of Available Data

Table A. 1 Digital data on the strengths of C/C composites, AC250 and CX270

Table A. 1 -(1) Tensile strength of AC250, UD and 2D.

Specimen No.	UD				2D			
	Thickness (mm)	Width (mm)	Tensile Strength (MPa)	Tensile Young's Modulus (GPa)	Thickness (mm)	Width (mm)	Tensile Strength (MPa)	Tensile Young's Modulus (GPa)
1	2.165	25.07	349.8	101.2	2.158	25.13	169.3	61.05
2	2.190	24.99	349.8	98.7	2.170	25.13	118.3	48.69
3	2.188	25.06	206.0	92.3	2.085	25.26	122.4	46.10
4	2.195	25.02	232.5	105.5	2.160	25.12	105.0	55.93
5	2.224	25.01	353.8	114.6	2.103	25.12	159.1	61.86
6	2.113	24.98	276.3	112.8	2.135	25.05	106.1	54.79
7	2.138	25.15	282.5	102.2	2.162	25.10	134.6	45.17
8	2.102	25.05	357.9	110.0	2.199	25.10	139.7	44.84
9	2.118	25.11	289.6	103.3	2.163	25.11	149.9	59.42
10	2.135	24.99	327.3	99.5	2.192	25.14	146.8	62.52
11	2.245	24.94	378.3	99.8	2.215	25.06	164.2	62.06
12	2.192	25.01	288.6	100.2	2.212	25.11	110.1	46.83
13	2.265	25.11	243.7	104.7	2.055	24.98	129.5	52.83
14	2.148	25.11	147.9	101.0	2.078	25.18	122.4	51.28
15	2.159	24.70	244.7	86.6	2.044	25.10	125.4	37.08
16	2.100	25.12	427.3	112.9	2.018	25.11	131.5	43.37
17	2.084	25.08	296.7	99.1	2.010	25.04	156.0	47.33
18	2.235	25.08	252.9	109.3	1.998	25.14	128.5	40.60
19	2.218	25.05	319.2	101.5	2.117	25.13	92.8	37.73
20	2.208	25.04	310.0	115.3	2.144	25.12	126.4	55.04

Table A. 1 -(2) Compressive strength of AC250, UD and 2D.

Specimen No.	UD			2D		
	Thickness (mm)	Width (mm)	Compressive Strength (MPa)	Thickness (mm)	Width (mm)	Compressive Strength (MPa)
1	10.44	10.41	77.50	10.40	10.43	189.7
2	10.41	10.39	72.40	10.34	10.39	189.7
3	10.44	10.34	75.46	10.38	10.30	201.9
4	10.47	10.30	53.02	10.43	10.40	230.5
5	10.44	10.39	77.50	10.42	10.34	203.9
6	10.44	10.40	54.04	10.37	10.39	168.3
7	10.39	10.36	63.22	10.41	10.44	185.6
8	10.41	10.45	65.26	10.47	10.48	190.7
9	10.41	10.32	68.32	10.35	10.39	199.9
10	10.33	10.43	64.24	10.42	10.95	207.0
11	10.46	10.39	64.24	10.42	10.42	194.8
12	10.38	10.47	53.02	10.46	10.34	181.5
13	10.42	10.43	53.02	10.42	10.42	234.5
14	10.46	10.34	37.73	10.35	10.48	199.9
15	10.36	10.36	68.32	10.44	10.33	214.1
16	10.39	10.41	66.28	10.39	10.34	209.0
17	10.25	10.35	75.46	10.40	10.43	185.6
18	10.41	10.35	59.14	10.35	10.38	185.6
19	10.38	10.38	66.28	10.46	10.32	181.5
20	10.45	10.43	48.95	10.48	10.42	141.7

Table A. 1 -(3) Bending strength of AC250, UD and 2D.

Specimen No.	UD				2D			
	Thickness (mm)	Width (mm)	Bending Strength (MPa)	Bending Young's Modulus (GPa)	Thickness (mm)	Width (mm)	Bending Strength (MPa)	Bending Young's Modulus (GPa)
1	2.165	15.32	339.6	76.32	2.135	15.09	174.4	31.97
2	2.228	15.24	373.2	90.04	2.108	15.29	140.7	33.75
3	2.182	15.19	404.8	87.06	2.112	15.28	191.7	45.34
4	2.240	15.26	363.0	87.47	2.119	15.23	191.7	42.49
5	2.225	15.30	363.0	87.02	2.118	15.19	214.1	47.60
6	2.215	15.17	379.3	96.55	2.123	15.20	209.0	49.85
7	2.120	15.24	366.1	90.80	2.113	15.22	143.8	40.58
8	2.139	15.25	361.0	91.10	2.100	15.19	175.4	29.93
9	2.158	15.24	362.0	88.77	2.188	15.21	142.8	35.01
10	2.112	15.11	381.4	94.52	2.160	15.25	99.9	29.49
11	2.196	15.18	368.1	85.46	2.125	15.19	187.6	31.98
12	2.215	15.21	380.3	98.71	2.095	15.27	162.1	22.78
13	2.147	15.28	392.6	32.81	2.115	15.28	193.7	26.72
14	2.215	15.22	372.2	84.85	2.085	15.29	158.1	23.09
15	2.248	15.22	375.2	89.86	2.078	15.11	192.7	41.86
16	2.263	15.24	370.1	83.03	2.198	15.21	173.4	38.48
17	2.252	15.25	389.5	84.20	2.188	15.27	142.8	30.67
18	2.196	15.07	354.9	84.32	2.178	15.19	134.6	29.29
19	2.203	15.14	368.1	85.78	2.167	15.28	162.1	36.49
20	2.240	15.29	387.5	84.39	2.173	15.13	234.5	43.34

Table A. 1 -(4) Shear strength of AC250, UD and 2D.

Specimen No.	UD			2D		
	Thickness (mm)	Width (mm)	Shear Strength (MPa)	Thickness (mm)	Width (mm)	Shear Strength (MPa)
1	2.197	5.98	39.46	2.248	5.96	20.80
2	2.101	6.03	36.30	2.088	6.00	14.17
3	2.125	5.82	35.89	2.090	6.01	18.35
4	2.098	5.94	35.69	2.070	6.00	15.91
5	2.195	6.02	45.17	2.082	5.95	15.91
6	2.110	5.94	37.83	2.238	5.98	18.86
7	2.106	6.03	36.30	2.064	6.06	16.11
8	2.090	5.88	35.18	2.087	6.07	21.11
9	2.102	5.90	37.01	2.194	6.05	17.54
10	2.093	5.91	34.06	2.112	6.01	16.42
11	2.112	5.85	34.16	2.283	5.95	20.70
12	2.114	5.85	36.10	2.078	5.97	15.19
13	2.090	6.03	34.57	2.103	5.99	18.05
14	2.178	5.96	38.75	2.215	6.07	18.46
15	2.192	6.02	43.44	2.222	6.04	20.29
16	2.105	5.86	33.85	2.088	5.97	17.34
17	2.096	5.99	33.04	2.240	5.96	19.48
18	2.088	5.92	35.28	2.180	6.12	15.60
19	2.100	5.93	35.49	2.076	5.96	16.52
20	2.082	6.02	34.47	2.078	6.05	13.77

Table A. 1 -(5) Young's modulus of AC250, UD and 2D, obtained from tensile and bending tests.

Specimen No.	Tensile Young's Modulus (GPa)		Bending Young's Modulus (GPa)	
	UD	2D	UD	2D
1	101.2	61.05	76.32	31.97
2	98.7	48.69	90.04	33.75
3	92.3	46.10	87.06	45.34
4	105.5	55.93	87.47	42.49
5	114.6	61.86	87.02	47.60
6	112.8	54.79	96.55	49.85
7	102.2	45.17	90.80	40.58
8	110.0	44.84	91.10	29.93
9	103.3	59.42	88.77	35.01
10	99.5	62.52	94.52	29.49
11	99.8	62.06	85.46	31.98
12	100.2	46.83	98.71	22.78
13	104.7	52.83	32.81	26.72
14	101.0	51.28	84.85	23.09
15	86.6	37.08	89.86	41.86
16	112.9	43.37	83.03	38.48
17	99.1	47.33	84.20	30.67
18	109.3	40.60	84.32	29.29
19	101.5	37.73	85.78	36.49
20	115.3	55.04	84.39	43.34

Table A. 1 -(6) Compressive and bending strengths, density, electrical resistivity of CX-270.

Density (g/cm^3)	Electrical Resistivity ($\mu\Omega\cdot m$)	Bending Strength (MPa)	Compressive Strength (MPa) Parallel	Compressive Strength (MPa) Transverse
1.545	17.20	171.0	214.0	97.00
1.544	17.60	141.0	222.0	86.00
1.547	17.40	148.0	225.0	91.00
1.619	16.30	195.0	211.0	92.00
1.603	17.00	180.0	220.0	82.00
1.602	17.10	172.0	226.0	93.00
1.590	17.20	175.0	218.0	89.00
1.568	17.40	160.0	212.0	93.00
1.605	16.70	172.0	215.0	91.00
1.541	17.90	142.0	236.0	91.00
1.610	16.70	174.0	238.0	88.00
1.569	17.40	163.0	223.0	82.00
1.602	16.90	183.0	222.0	95.00
1.609	17.40	173.0	205.0	87.00
1.614	16.90	178.0	203.0	83.00
1.593	17.40	157.0	232.0	94.00
1.628	16.60	199.0	241.0	78.00
1.621	16.80	174.0	226.0	91.00
1.613	16.60	166.0	219.0	82.00
1.605	16.90	174.0	214.0	80.00
1.591	17.10	174.0	228.0	97.00
1.604	17.10	181.0	226.0	93.00
1.546	17.50	157.0	222.0	87.00

Table A. 1 -(6) Compressive and bending strengths, density, electrical resistivity of CX-270. (contn'd)

Density (g/cm^3)	Electrical Resistivity ($\mu\Omega \cdot m$)	Bending Strength (MPa)	Compressive Strength (MPa) Parallel	Compressive Strength (MPa) Transverse
1.576	17.30	155.0	243.0	87.00
1.566	17.50	138.0	252.0	93.00
1.574	17.20	156.0	234.0	92.00
1.605	16.90	183.0	224.0	95.00
1.592	17.10	164.0	246.0	94.00
1.605	16.80	189.0	246.0	92.00
1.626	16.60	194.0	240.0	84.00
1.607	17.10	187.0	218.0	92.00
1.594	17.20	160.0	240.0	84.00
1.587	16.90	156.0	222.0	75.00
1.592	17.40	167.0	217.0	76.00
1.591	17.20	138.0	210.0	84.00
1.611	16.90	182.0	221.0	85.00
1.599	17.00	168.0	223.0	91.00
1.559	17.60	169.0	230.0	91.00
1.599	16.80	169.0	214.0	95.00
1.610	17.30	155.0	211.0	92.00
1.614	16.90	197.0	232.0	78.00
1.591	17.10	166.0	216.0	82.00
1.559	17.80	140.0	238.0	82.00
1.600	17.00	179.0	223.0	96.00
1.604	17.00	168.0	235.0	82.00
1.615	16.90	176.0	212.0	91.00

Table A. 1 -(6) Compressive and bending strengths, density, electrical resistivity of CX-270. (contn'd)

Density (g/cm^3)	Electrical Resistivity ($\mu\Omega\cdot m$)	Bending Strength (MPa)	Compressive Strength (MPa) Parallel	Compressive Strength (MPa) Transverse
1.595	17.00	171.0	231.0	88.00
1.557	17.70	149.0	246.0	84.00
1.591	17.10	159.0	231.0	87.00
1.634	16.60	184.0	225.0	98.00

Table A. 2 Room temperature strength data on AC250 and CX-270.

Material	AC250 (UD)	AC250 (2D)	CX-270	
Tensile strength (MPa)				
Mean	103.5	131.9	227	
S.D.	7.2	20.3	(Catalogue value)	
Minimum	86.6	92.8		
(Sample size)	(20)	(20)		
3-Point bending strength (MPa)				
Mean	85.2	171.3	169.0	
S.D.	13.0	31.2	15.3	
Minimum	32.8	99.9	138.0	
(Sample size)	(20)	(20)	(50)	
Compressive strength (MPa)			Parallel	Transverse
Mean	63.2	194.8	88.0	226
S.D.	10.3	20.0	5.8	11.5
Minimum	37.7	141.7	75	203
(Sample size)	(20)	(20)	(50)	(50)
Shear strength (MPa)				
Mean	36.6	17.6		
S.D.	3.0	2.1		
Minimum	33.0	13.8		
(Sample size)	(20)	(20)		
Young's modulus (GPa)	Tensile	Bending		
Mean	103.5	85.2	102	
S.D.	7.2	13.0	(Catalogue value)	
Minimum	86.6	32.8		
(Sample size)	(20)	(20)		

For AC250 (UD) Charpy impact strength : 23.5 kJ/m^2, Shore hardness : 24. (Catalogue value).

Table A. 3 Room temperature physical properties of AC250 and CX-270 (Catalogue values).

Material	AC250 (UD)		CX-270	
	Parallel	Transverse	Parallel	Transverse
Thermal conductivity (W/mK)	68.6	10.5	35	5
Thermal expansion coefficient (10^{-6}/K)	0.6	8.2	<1	8
Specific heat (J/g K)	0.75 1.88(1200℃)		NA	
Density (g/cm^3)	1.7		1.592±0.024* (Minimum 1.541, Sample size 50)	
Electrical resistivity (μΩ·m)	17		17.1±0.33* (Minimum 16.3, Sample size 50)	

*) Measured values.

Table A. 4 Chemical composition of AC250 and CX-270 (ppm).

Material		Fe	Al	Ni	Cr	Cu	V	Na	Ca	Mg	K	Mo
AC250	Unpurified	3.00	0.82	2.40	0.40	0.02	8.80	0.38	4.20	0.10	0.18	0.34
	Purified	0.01	0.02	<0.01	<0.01	0.03	0.01	0.01	0.01	<0.01	<0.01	<0.01
CX-270	Unpurified	1.6	<0.08	<0.1	0.43	<0.08	<0.07	<0.05	<0.04	<0.02	<0.1	<0.2
	Purified						NA					

国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	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
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名称	記号
分，時，日	min，h，d
度，分，秒	°，′，″
リットル	l，L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10^{-19}J

1 u=1.66054×10^{-27}kg

表3　固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	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
エネルギー,仕事,熱量	ジュール	J	N·m
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	A·s
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å=0.1nm=10^{-10}m

1 b=100fm^2=10^{-28}m^2

1 bar=0.1MPa=10^5Pa

1 Gal=1cm/s^2=10^{-2}m/s^2

1 Ci=3.7×10^{10}Bq

1 R=2.58×10^{-4}C/kg

1 rad=1cGy=10^{-2}Gy

1 rem=1cSv=10^{-2}Sv

表5　SI接頭語

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

（注）

1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。

2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。

3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s(N·s/m^2)=10 P(ポアズ)(g/(cm·s))

動粘度　1m^2/s=10^4St(ストークス)(cm^2/s)

圧力	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7 erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal= 4.18605J（計量法）

= 4.184J（熱化学）

= 4.1855J（15℃）

= 4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)

= 75 kgf·m/s

= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

DEVELOPMENT OF CARBON/CARBON COMPOSITE CONTROL ROD FOR HTTR (II) – CONCEPT, SPECIFICATIONS AND MECHANICAL TEST OF MATERIALS –