Super conducting Solenoid Magnet

R&D Program

Presented by

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CONTENTS

- HIGH STRENGTH ALUMINUM STABILIZED SUPERCONDUCTOR (Y.S.> 67 MPa),
- COIL WINDING AND BONDING OUTER SUPPORT CYLINDER,
- PROTOTYPE MAGNET WITH 1/4 LENGTH.
- HIGH E/M RATIO UP TO 15 KJ/KG IN A R&D SOLENOID.
- UNIFORM ENERGY DUMP WITH PURE ALUMINUM STRIP QUENCH PROPAGATOR,
- HONEYCOMB AND ISOGRID VACUUM WALL.

DEVELOPMENT

OF

HIGH STRENGTH AL STABILIZED SUPERCONDUCTOR

- WHY WE NEED IT?:
  - PRESET SUPERCONDUCTORS USED IN CDF, TOPAZ ETC TOO WEAK TO SUSTAIN FORCE AT 2T.
  - FULLY ELASTIC DESIGN DESIRED IN SDC SOLENOID TO MAKE SURE RELIABLE MECHANICAL DESIGN UNDER BOUNDARY CONDITION OF COMPLICATED STRESS:
    $2\tau = S_\phi - S_z \simeq 54\,MPa$. $(39-(-15))$

- GOAL FOR DEVELOPMENT

  Y.S. (0.2%) $\geq$ 60 MPa (minimum)

  $\geq$ 70 MPa (desired)

- HOW TO IMPROVE MECH. CHARACTERISTICS
  - ADDITIONAL MATERIAL (100 ~ 200 ppm)

    Si, Zn, Fe, Cu ...
  - MECHANICAL COLD WORK (10 ~ 20%)

    DRAWING, ROLLING ...

DEVELOPMENT OF CONDUCTOR

Table 2. Design parameters of the aluminum-stabilized superconductor for the SDC and TOPAZ detector.

Al-stabilized superconductor			TOPAZ	SDC
Cu/NbTi Insert				
type			monolith	cable
dimension	thickness	mm	1.8	2.2
	width	mm	3.3	6.4
	corner R	mm	0.2	
Cu/NbTi ratio			1	1
filament diameter		μm	50	20
twist pitch		mm	<30	27
RRR of Cu			>120	>100
Al-stabilized superconductor				
dimension	thickness	mm	3.59/3.61	4.42/4.32
	width	mm	18	43.8
	corner R	mm	0.3	0.4
position of Cu/NbTi			central	central
Ic		kA	>7 at 2.4T	>16 at 5T
RRR of Al stabilizer			>1000	500
yield strength of Al		kg/mm2	---	>6 at 77K
(expected)				>6.5
share strength of Al-SC		kg/mm2	>1	>2

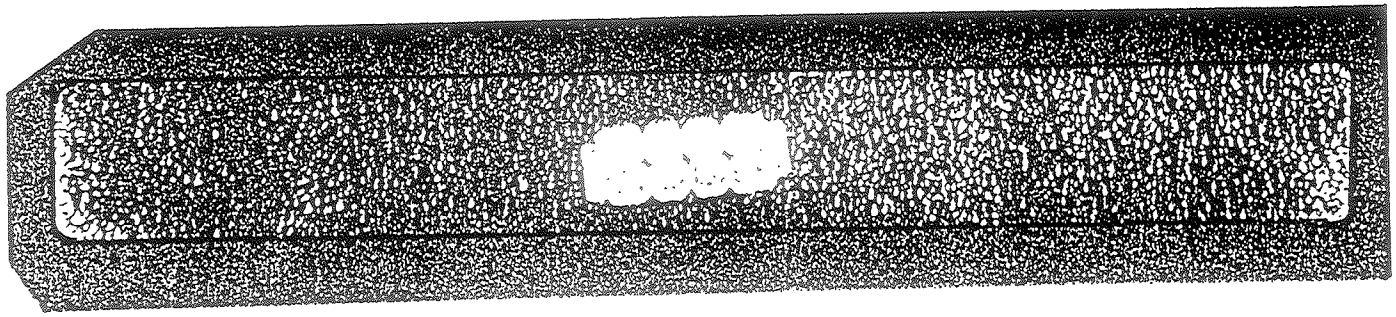


Figure 8. Cross-sectional photograghs of full-sized aluminum-stabilized superconductor for the SDC detector by experimental production.

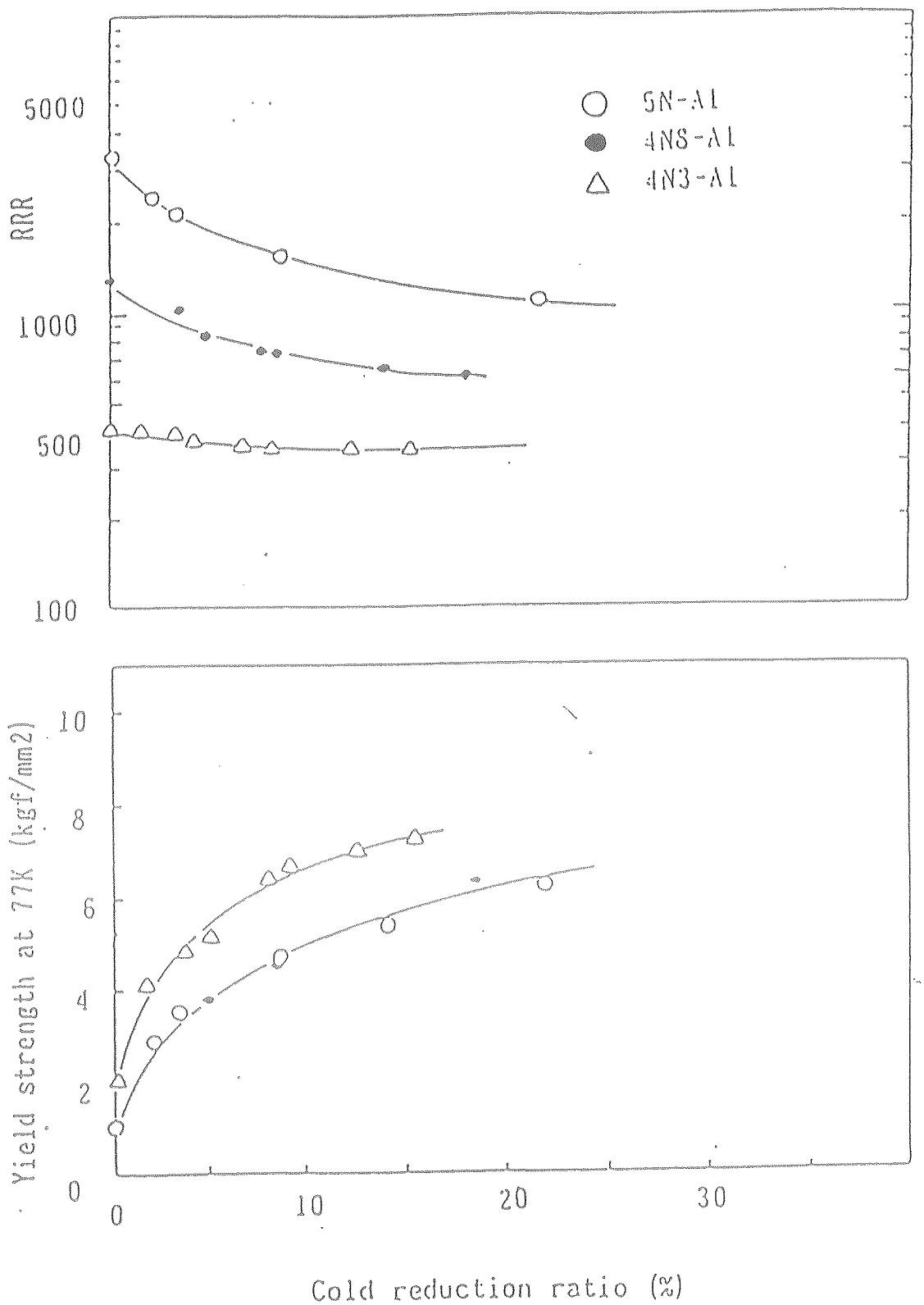


Figure 2. The dependence of yield strength (77K) and RRR about usual high purity aluminum on cold reduction ratio.

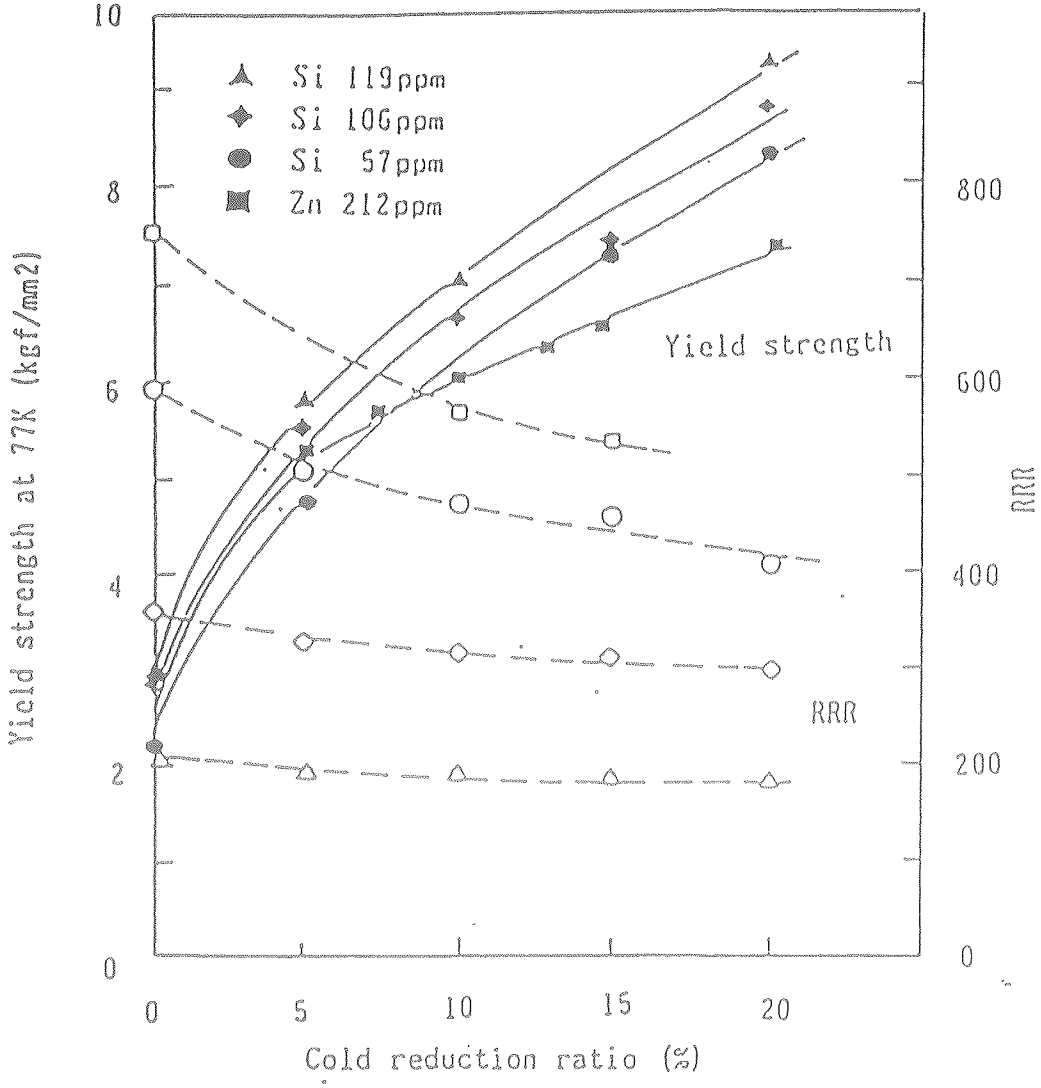


Figure 3. The dependence of the yield strength (77K) and RRR on the cold reduction ratio for Al-Si and Al-Zn.

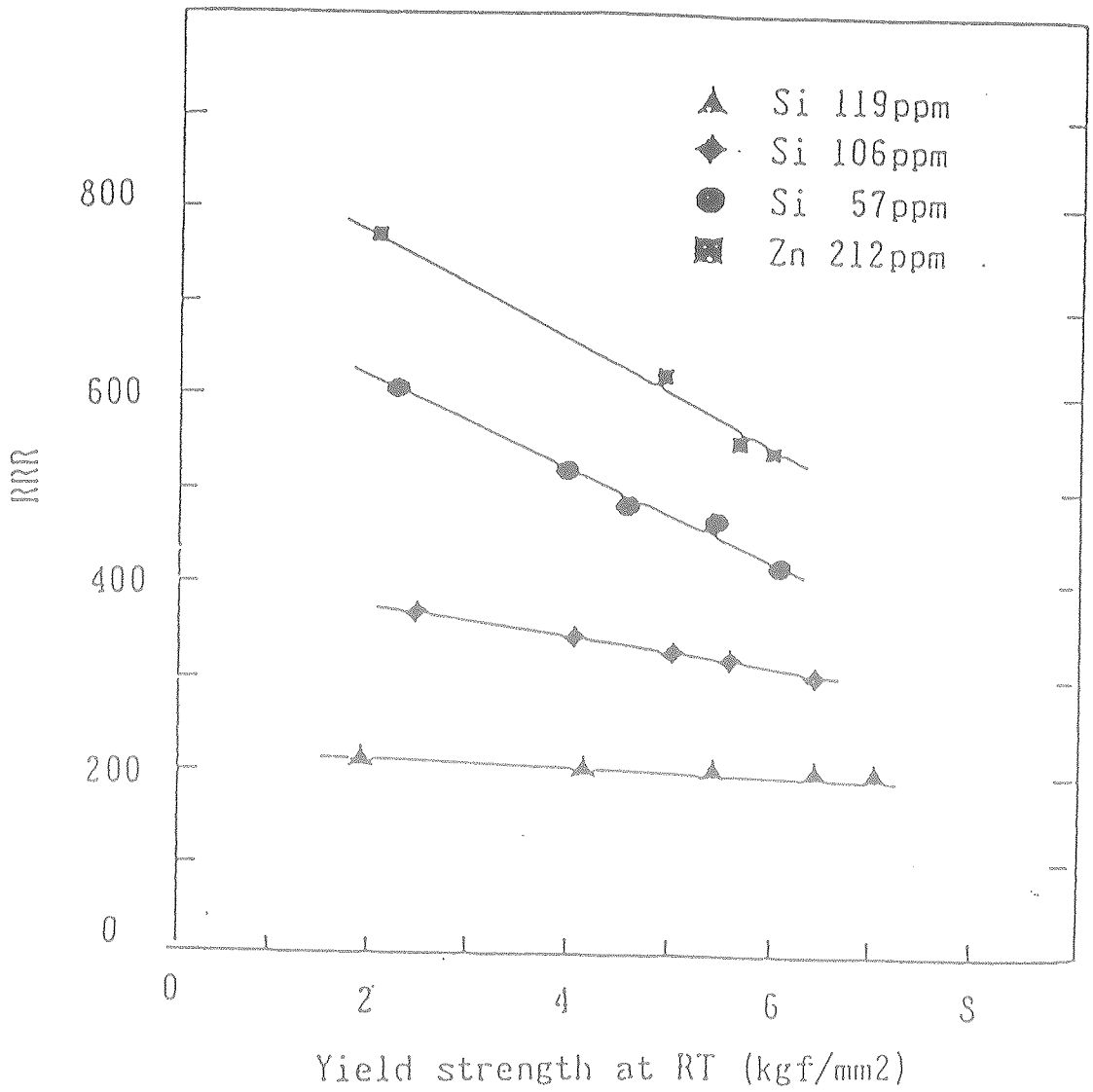


Figure 4. The relationship between the yield strength (RT) and RRR for Al-Si and Al-Zn alloys.

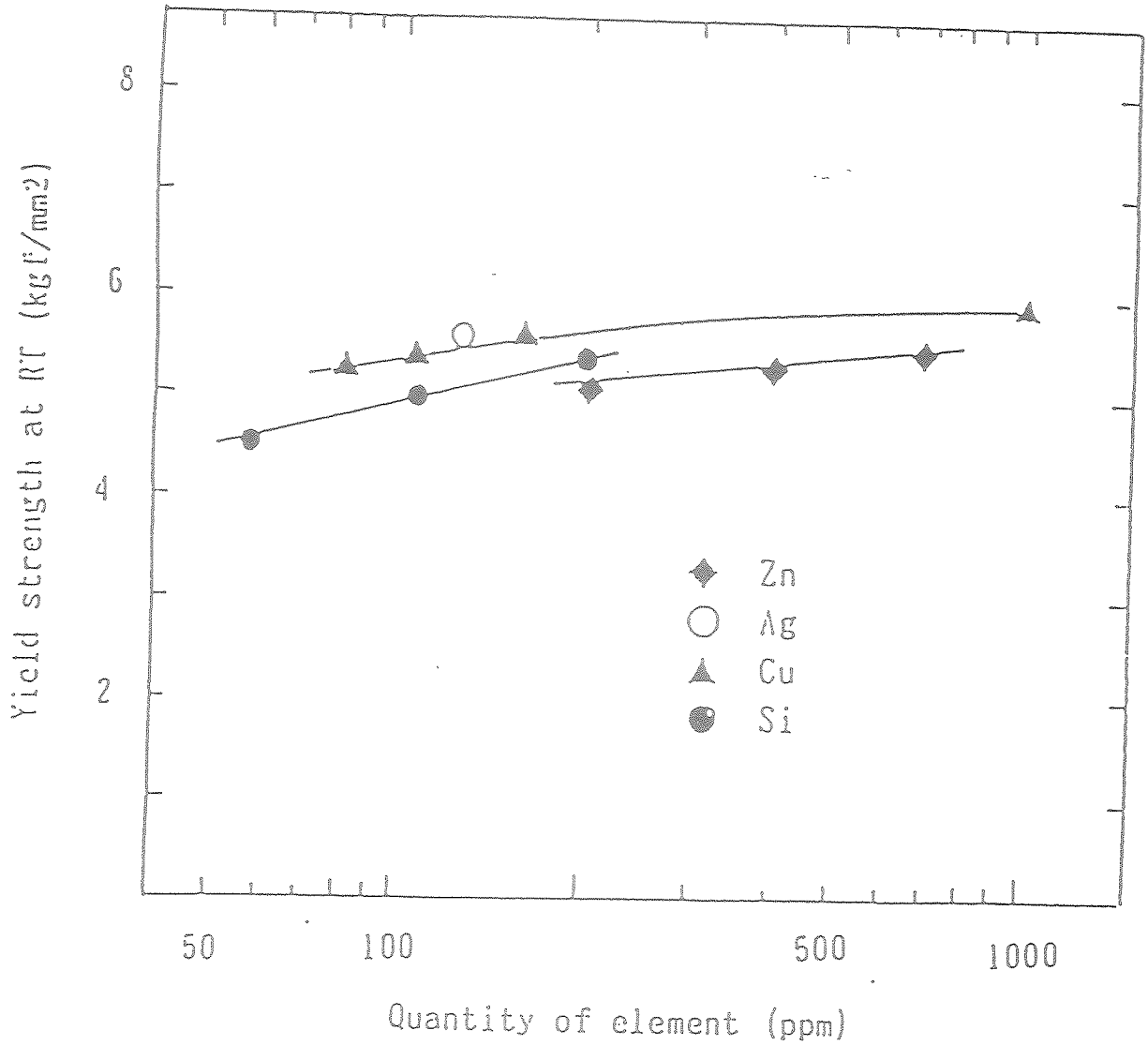


Figure 5. The dependence of the yield strength (RT) on the quantities of added elements after 10% cold-worked.

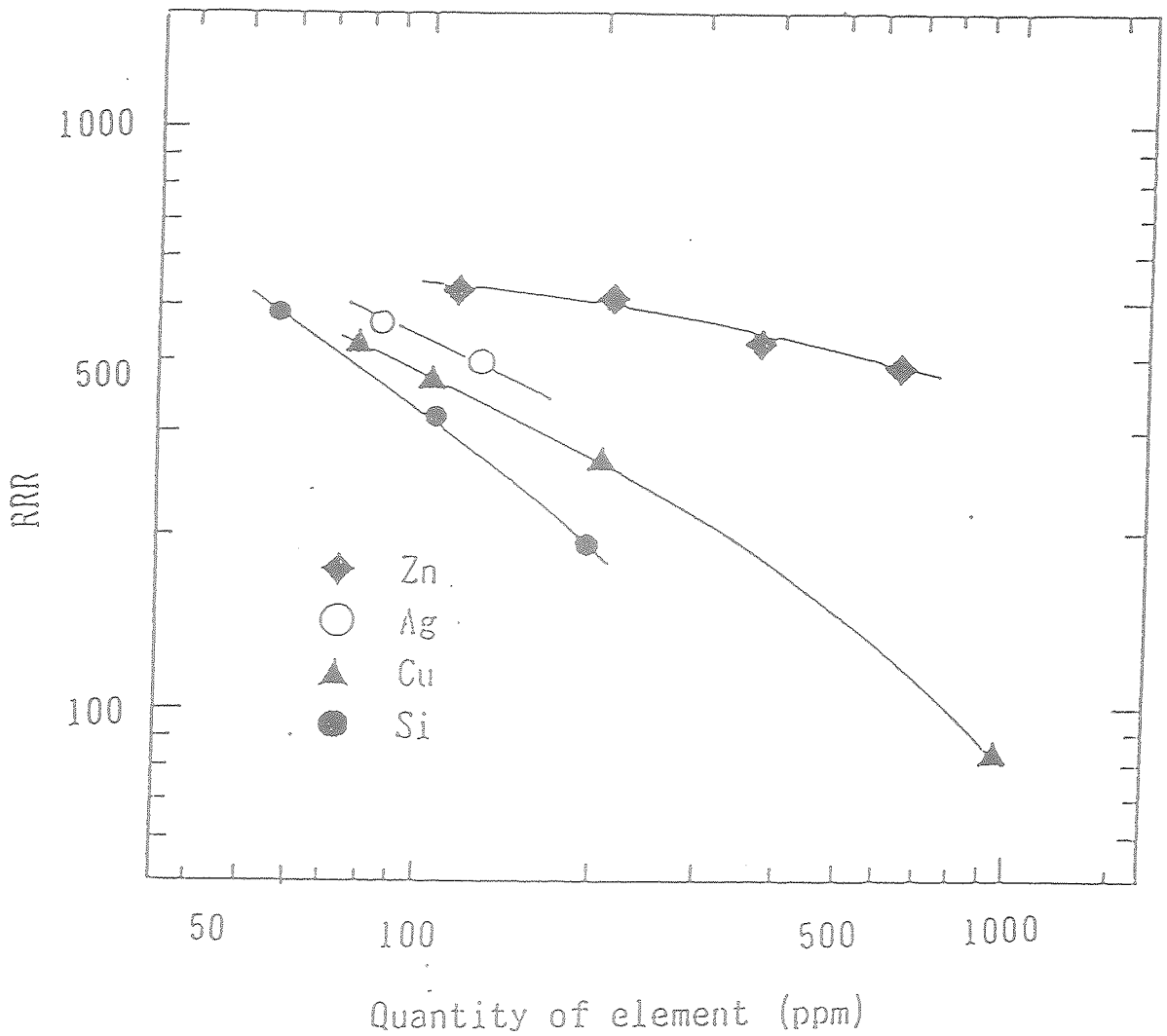
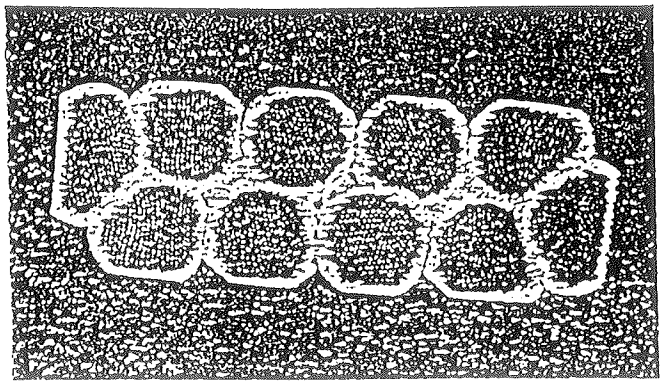
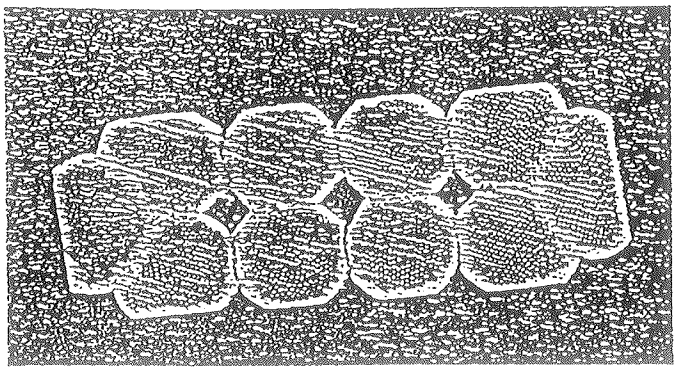


Figure 6. The dependence of RRR on the quantities of added elements after 10% cold-worked.

(1) as extruded



(2) after 10.9% reduced



(3) after 23.2% reduced

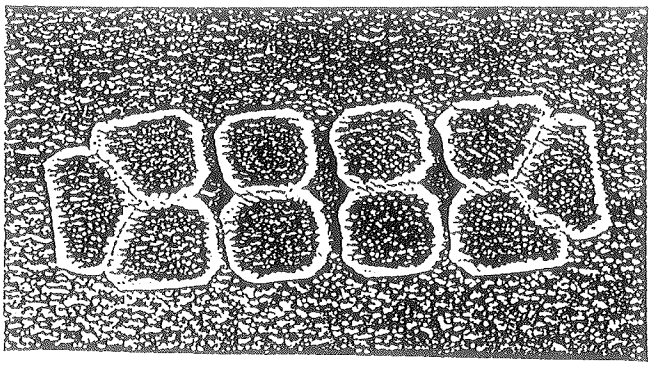


Figure 7. Typical cross-sectional photograghs of 1/3 sized aluminum-stabilized superconductor for the SDC detector as extruded and after cold-drawn.

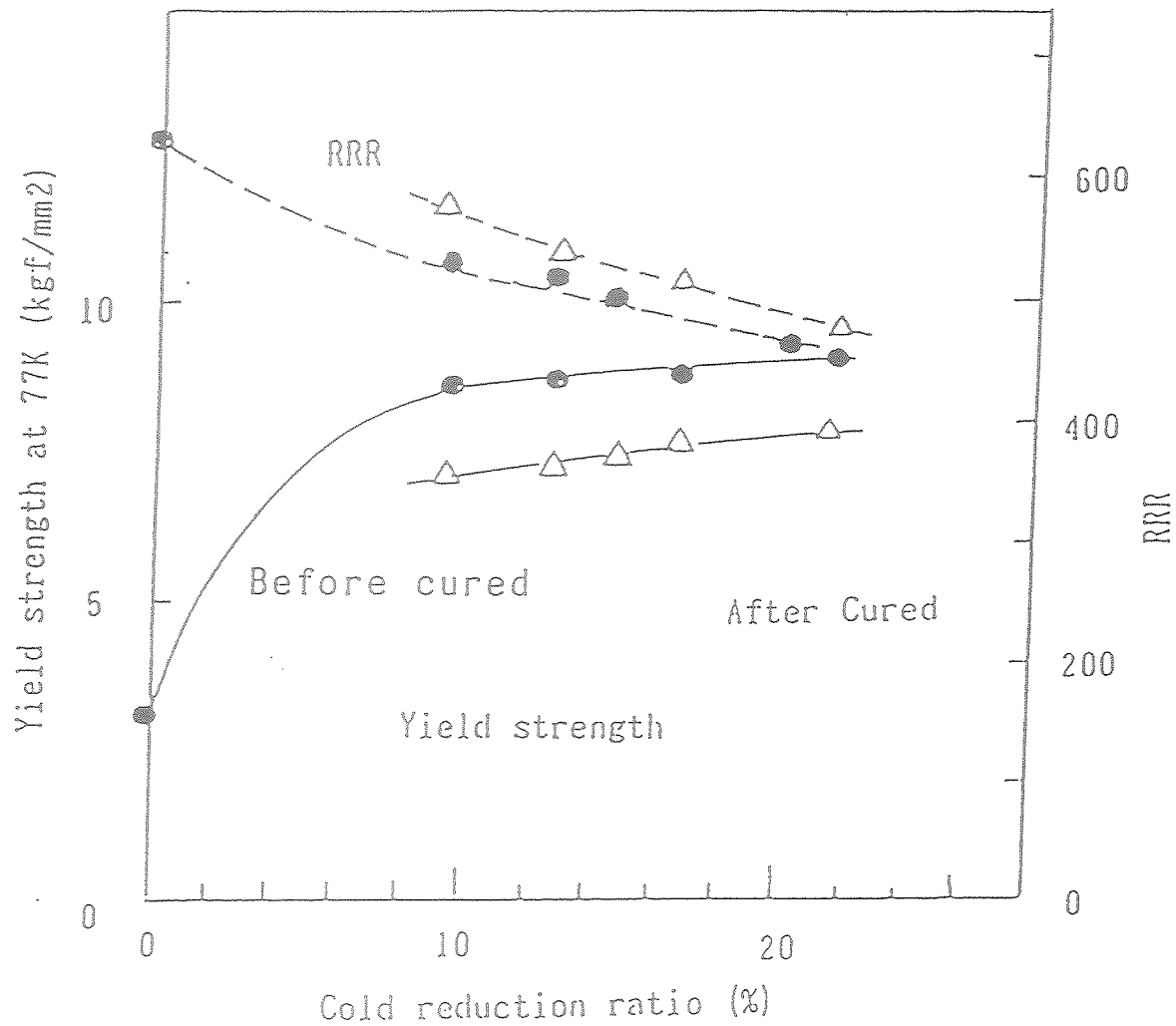


Figure 9. The dependence of the yield strength (77K) and RRR of aluminum matrix on the cold reduction ratio for the full-sized SDC conductor.

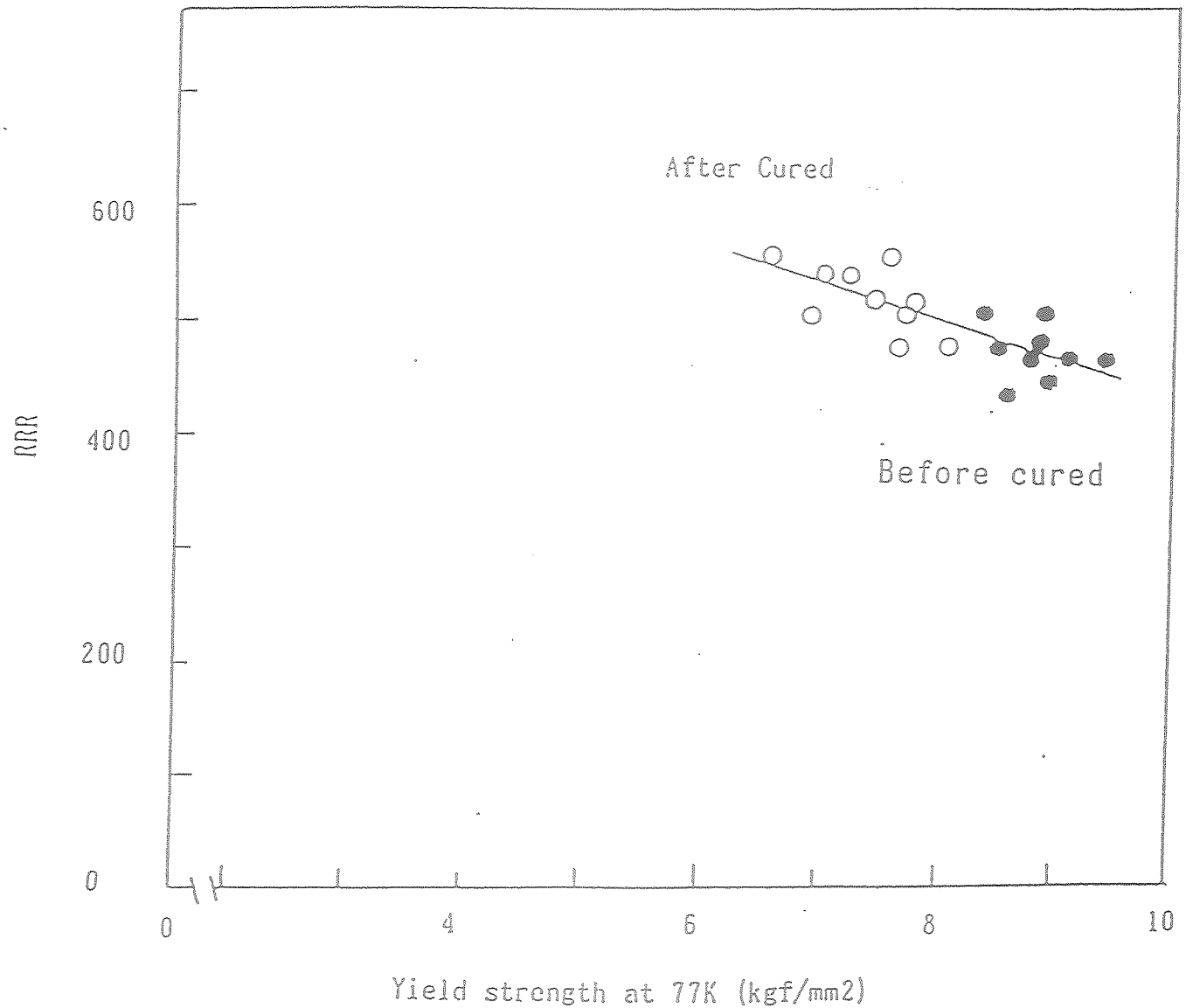
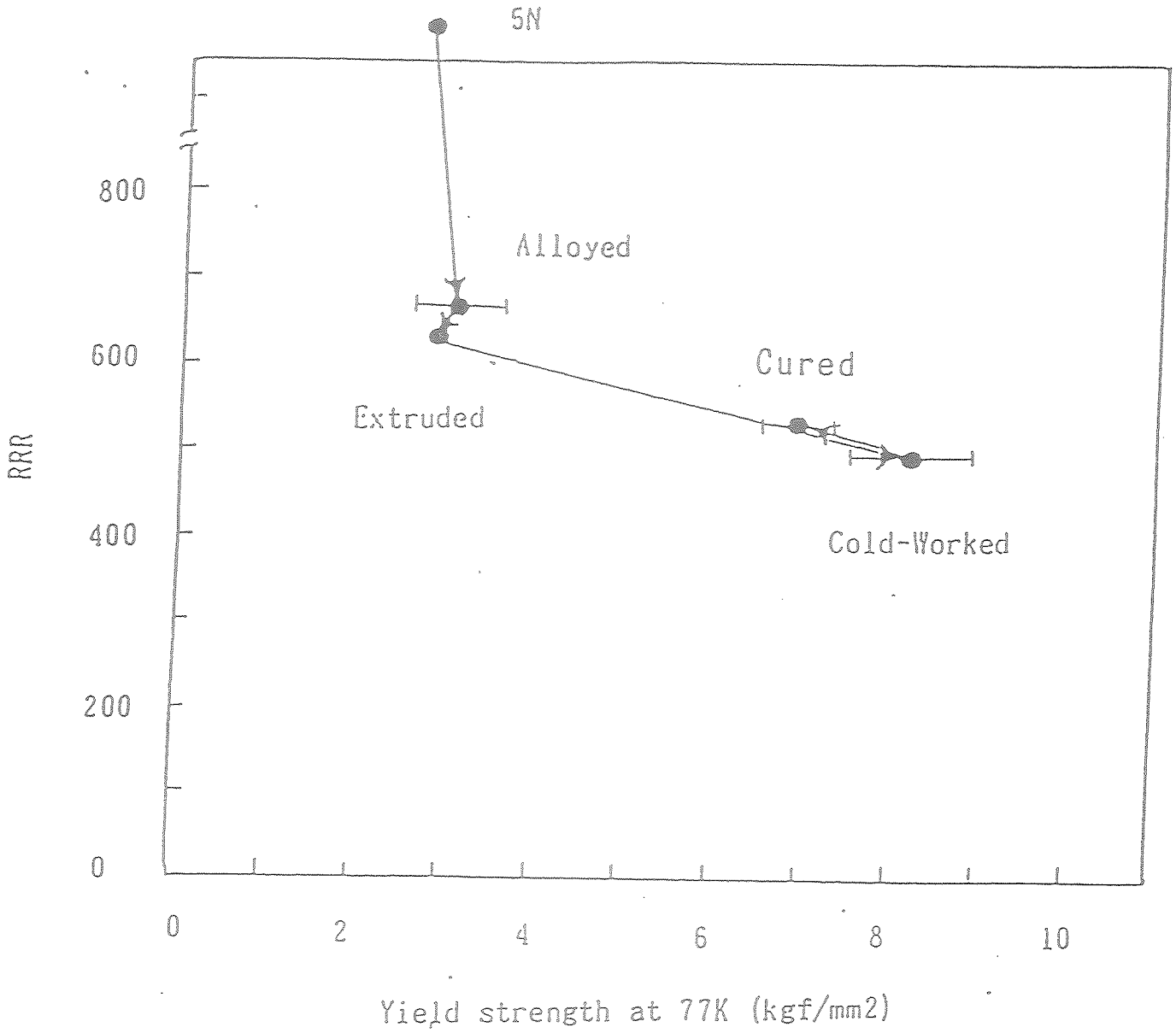


Figure 10. The relationship between the yield strength (77K) and RRR of aluminum matrix on the cold reduction ratio for the full-sized SDC conductor.



Fgure 11. Yield strength (77K) and RRR of aluminum matrix on production stage.

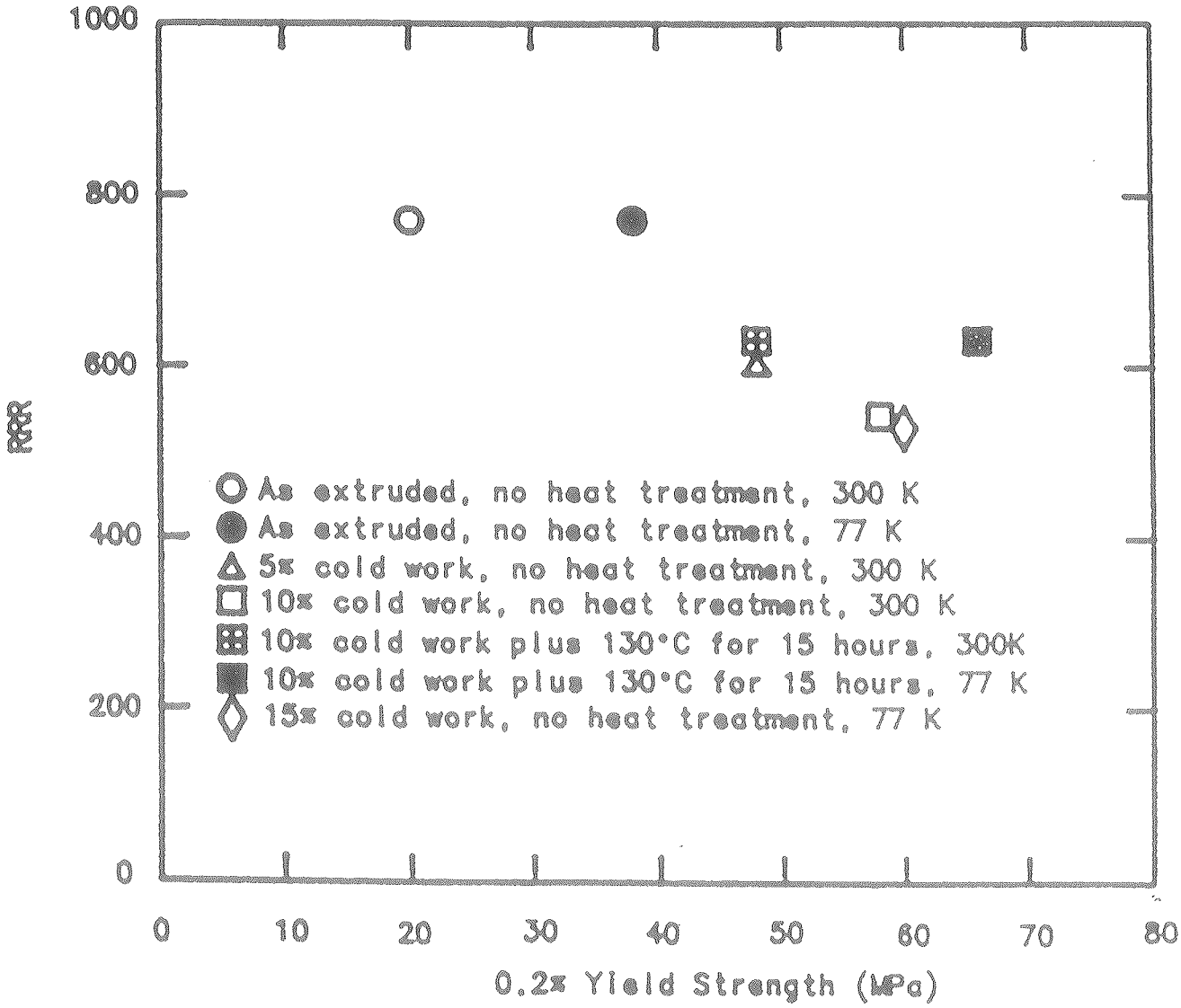
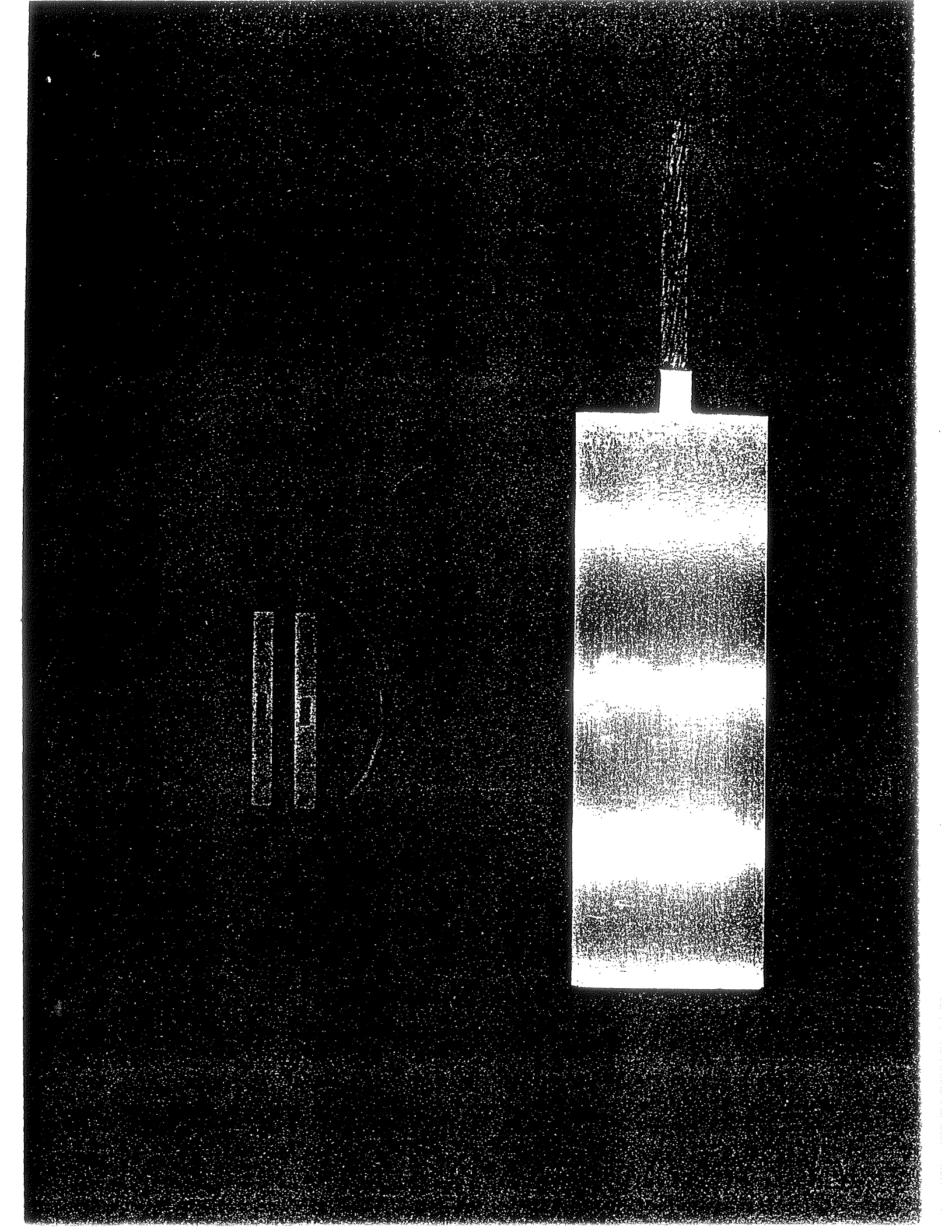
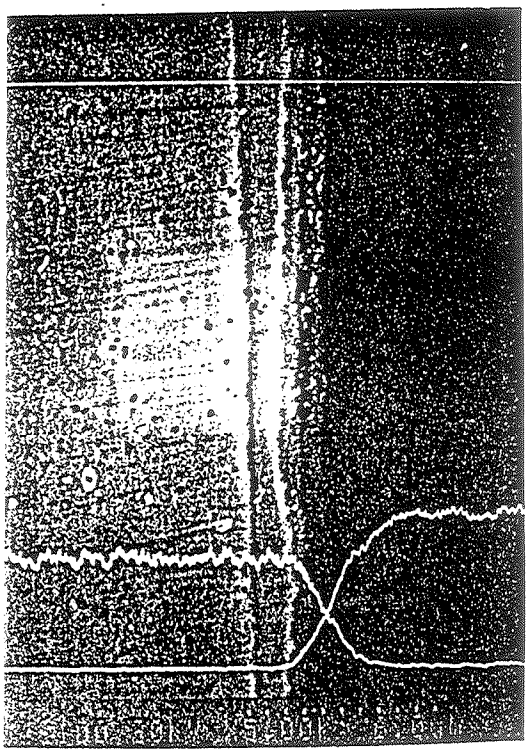


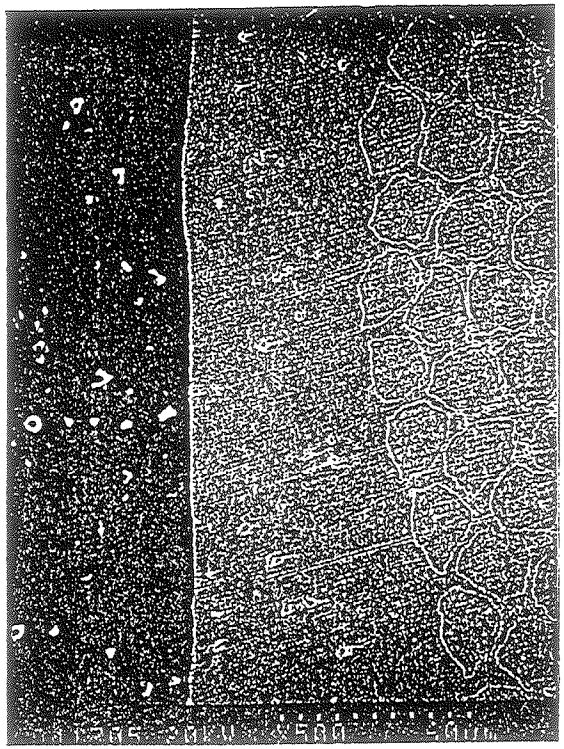
FIG. 5-12. Residual resistivity ratio (RRR) as a function of yield strength in pure aluminum. The operating stress in the conductor is 52 MPa and the minimum acceptable RRR is 500.

Table 3. Mechanical strength and RRR of aluminum matrix on production stages

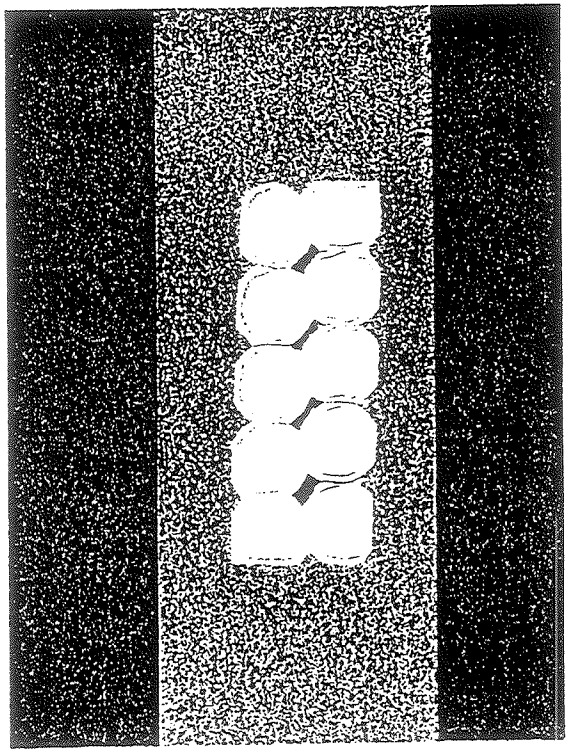
Step	at RT(kgf/mm2)		at 77K(kgf/mm2)		RRR
	σB	σ0.2	σB	σ0.2	
1.5N (based material)		2.3		~3	2,500
2.Alloyed (200ppmZn)			13.6~15.5	2.6~3.6	680
3.Extruded	5.2	2.3	15.7	2.9	630
4.Cold-worked(12%)	6.6	6.5	15.9~17	7.5~8.9	490
5.Curred	6.3~6.6	5.3~5.6	15.6~16.1	6.5~7.3	530
6.Aged at RT(after 6months)			same as above		







×500



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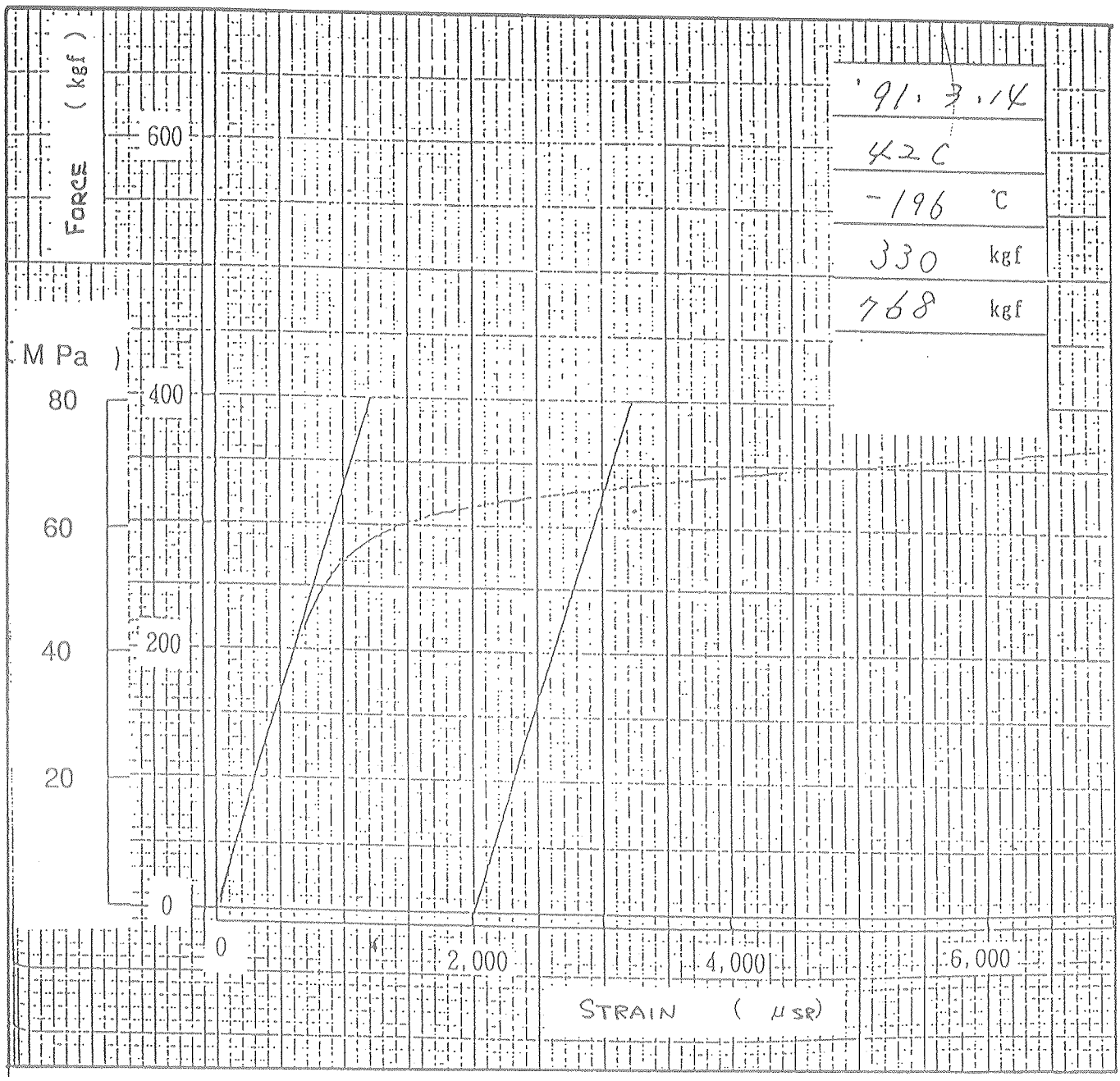
CROSS SECTIONS OF SDC SUPERCONDUCTOR



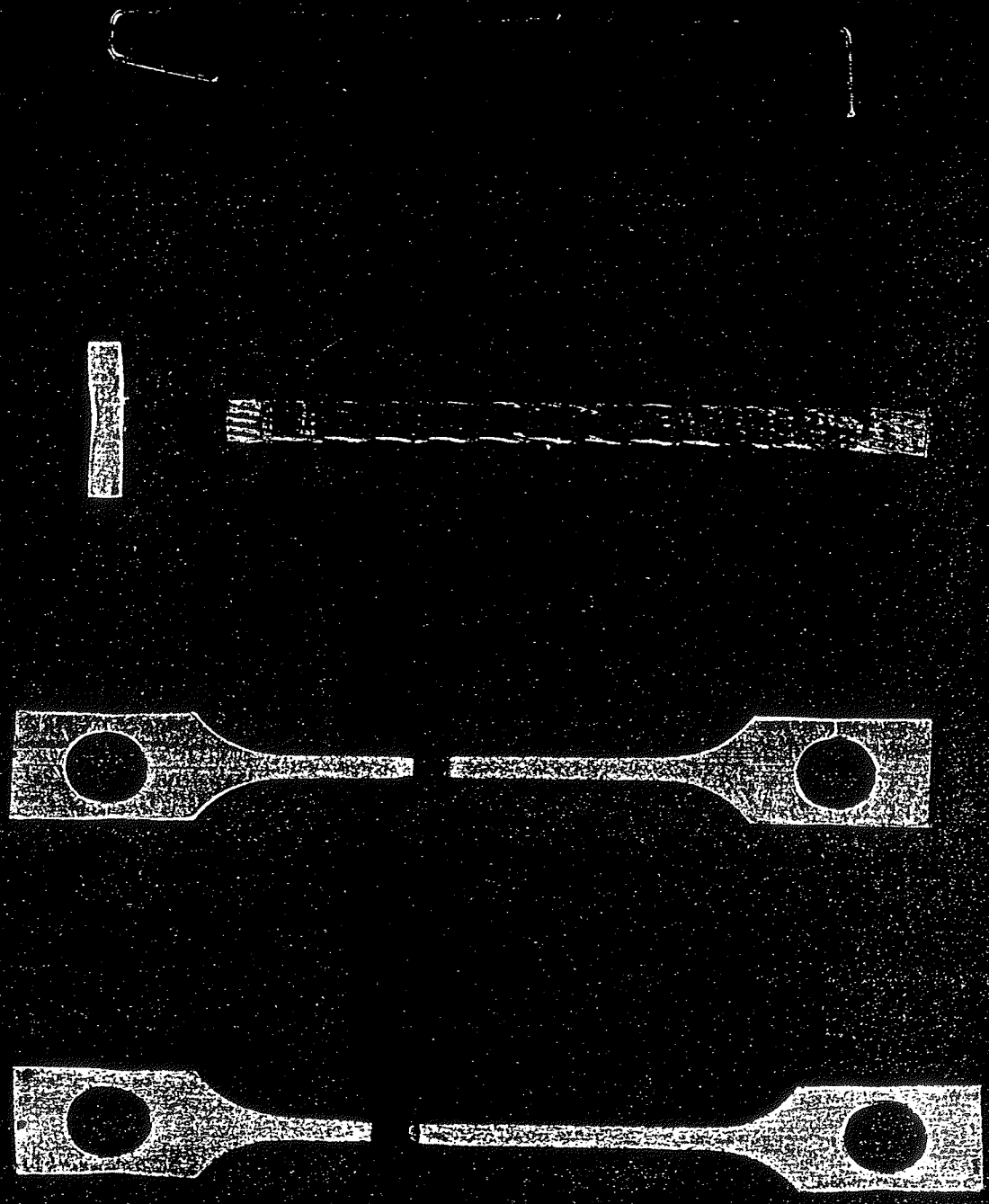
A STRESS- STRAIN CURVE OF HIGH STRENGTH PURE Al (4N)

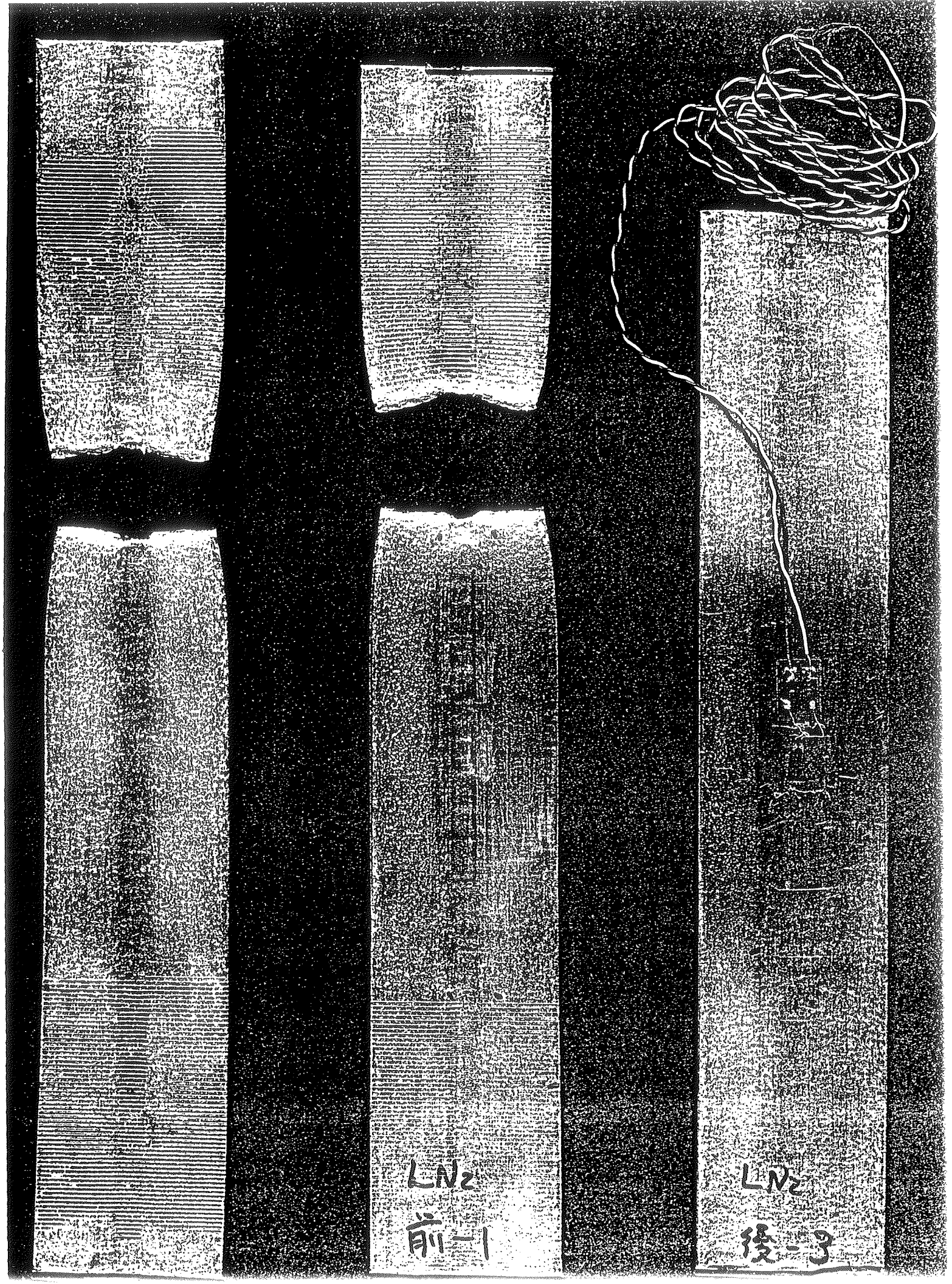
CHARACTERISTICS OF SDC SUPERCONDUCTOR

ITEM	SPEC	before Curing	after Curing
Diamension(mm)			
Strand Dia.	1.277	1.273	
Cable			
thicness	~2.5	2.34	
width	~6.4	6.14	
Conductor			
thickness(L)	(4.42)	4.42	
(S)	(4.32	4.35	
width	43.8	43.8	
corner	≤0.5	0.4	
Al/Cu/NbTi Ratio	27.9/1/1	27.9/0.9/1	
Twist pitch(mm)		27	
IC(A)*1			
at 3.0T		23950	24580 *2
at 4.0 T		19750	20250
at 5.0 T	≥16000	16025	16475
at 6.0 T		12600	13075
at 7.0 T		9225	9500
at 8.0 T		5890	6120
4.2k, $10^{-11}\Omega cm$			
RRR	Al Cu	Al Cu	Al Cu
at 0 T	~600,100	497 95	506 97
at 1.0 T		215 79	243 81
at 2.0 T		162 66	198 67
at 3.0 T		140 55	184 56
at 4.0 T		127 47	178 48
at 5.0 T		118 41	176 42

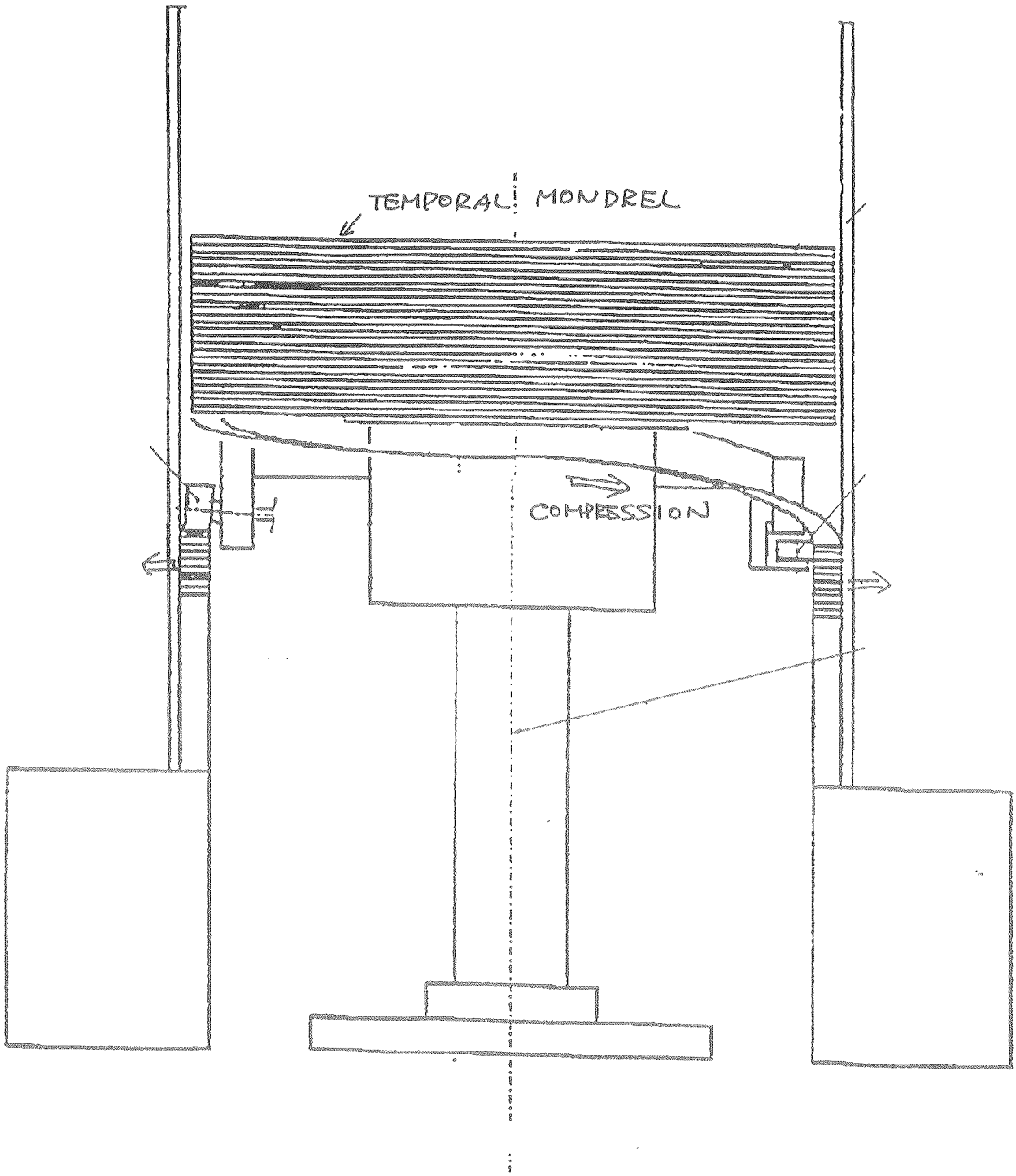
MECHANICAL CHARACTERISTICS OF SDC SUPERCONDUCTOR

ITEM	SPEC	TEST RESULT before Curing			after Curing		
S C Strand		RT	77K	4.2K	RT	77K	4.2K
T.S. [kgf/mm²]		88.9	121.1	150.3			
		(88.7)	(121.0)	(155.7)			
		(89.4)	(121.1)	(144.9)			
		(88.6)	(121.1)				
Y.S.(0.2%) [kgf/mm²]		40.2	47.4	76.9			
		(42.9)	(46.7)	(76.9)			
		(38.6)	(45.0)	(76.8)			
		(39.0)	(50.4)				
Elogation [%]		3.0	1.5	1.6			
		(3.0)	(1.5)	(1.6)			
		(3.0)	(1.5)	(1.6)			
		(3.0)	(1.5)				
Stabilizer		RT	77K	4.2K	RT	77K	4.2K
T.S. [kgf/mm²]		6.3	14.7	30.4	6.0	14.5	30.2
		(6.2)	(14.6)	(30.6)	(6.0)	(14.4)	(30.2)
		(6.4)	(14.7)	(30.1)	(6.0)	(14.5)	(30.2)
Y.S.(0.2%) [kgf/mm²]	6.0	6.0	8.0	9.7	5.2	6.7	7.4
		(5.8)	(8.0)	(10.0)	(5.4)	(6.6)	(7.0)
		(6.2)	(7.9)	(9.3)	(4.9)	(6.7)	(7.7)
Elogation [%]		22.4	53.9	55.0	33.4	61.4	54.7
		(23.0)	(55.4)	(55.0)	(32.8)	(64.2)	(58.6)
		(21.8)	(52.4)		(34.0)	(58.6)	(52.7)
Overall		RT	77K	4.2K	RT	77K	4.2K
T.S. [kgf/mm²]		11.2	17.9		10.7	16.8	30.2
		(11.2)	(17.8)	( )	(10.7)	(16.7)	( )
		(11.2)	(17.9)	( )	(10.7)	(16.8)	( )
Y.S.(0.2%) [kgf/mm²]		10.3	11.2		7.9	8.1	
		(10.2)	(11.0)	( )	(8.0)	(7.7)	( )
		(10.3)	(11.4)	( )	(7.8)	(8.4)	( )
Elogation [%]		10.8	15.6		11.9	16.8	
		(11.0)	(15.3)	( )	(11.9)	(16.8)	( )
		(10.5)	(15.8)	( )	(11.9)	(16.7)	( )
Shearing(Al/Cu)		RT	77K	4.2K	RT	77K	4.2K
[kgf/mm²]	2	3.9	5.8	4.5	3.7	5.7	8.7
		(3.9)	(5.4)	(4.5)	(3.9)	(6.6)	(8.7)




LN2
前-1
LN2
後-3

COIL WINDING R&D

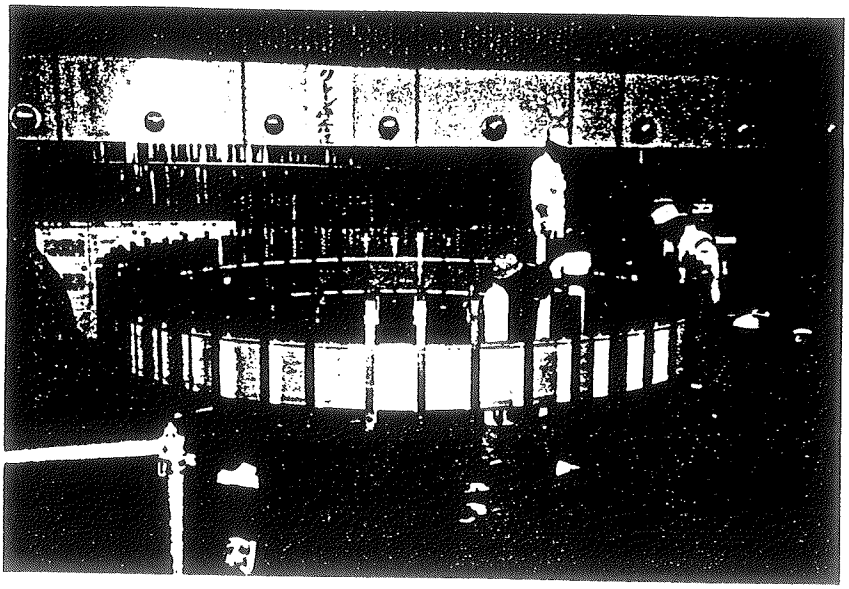


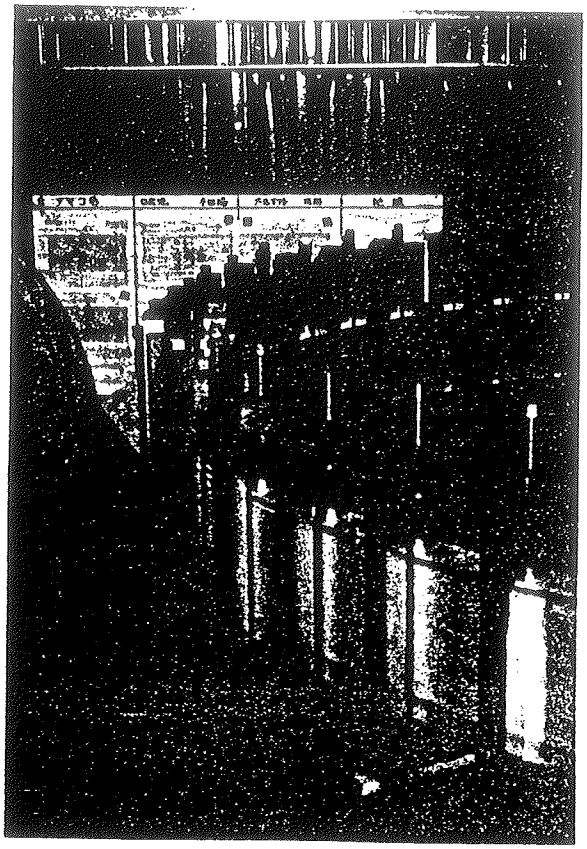
COIL WINDING CONCEPT

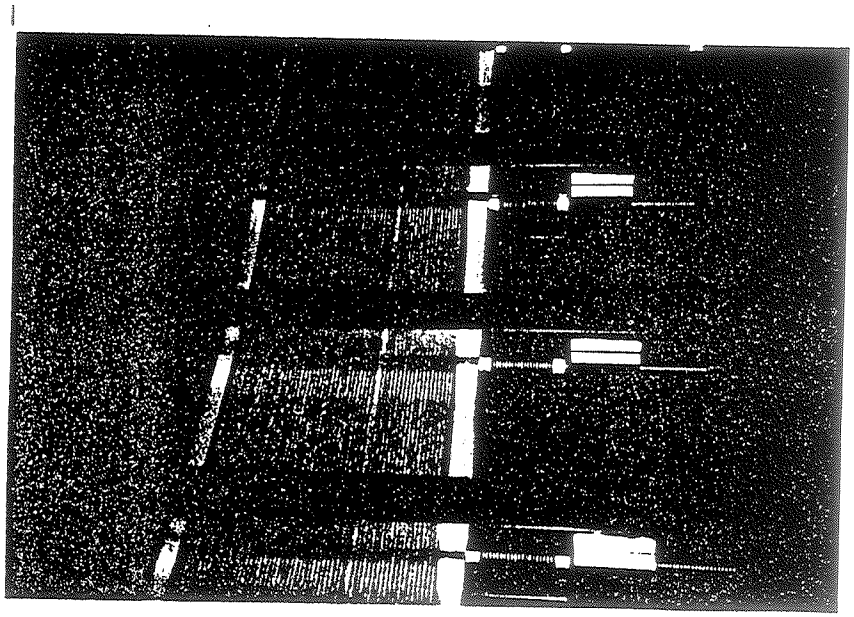
GND INSULATED
SUPPORT CYLINDER

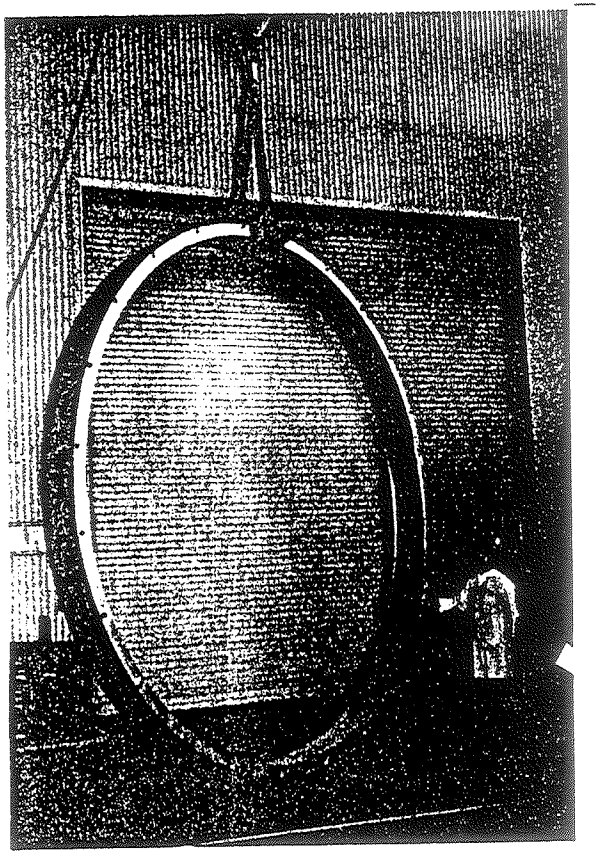
WINDING
PREPERATION

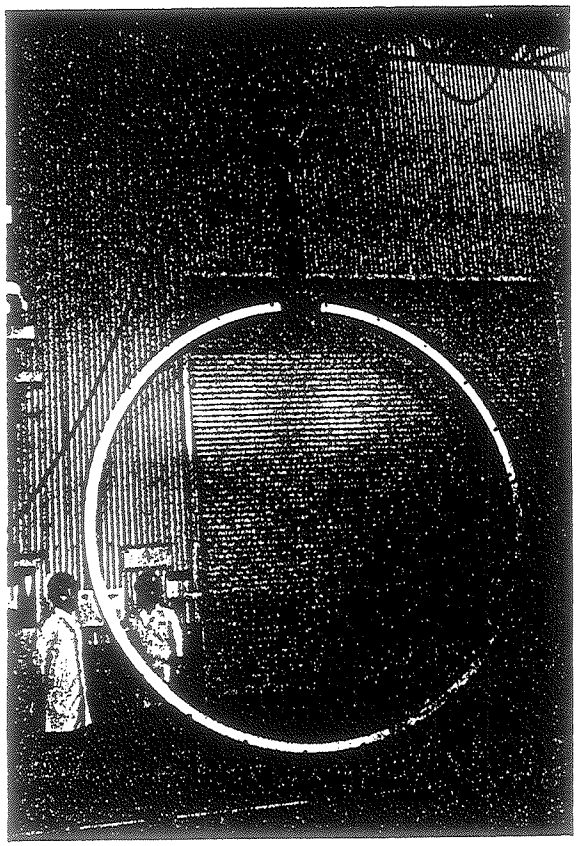
WINDING
STARTED

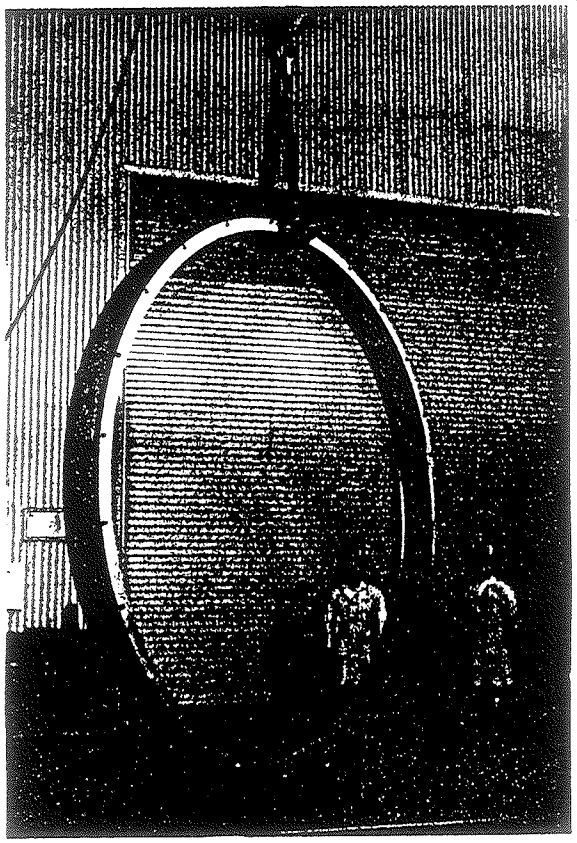


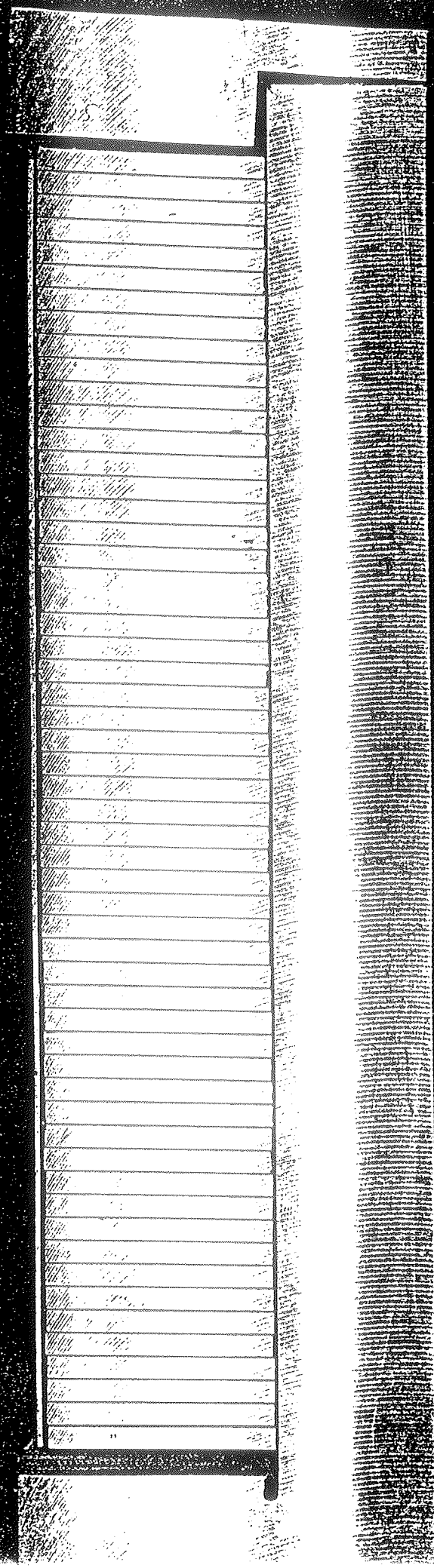


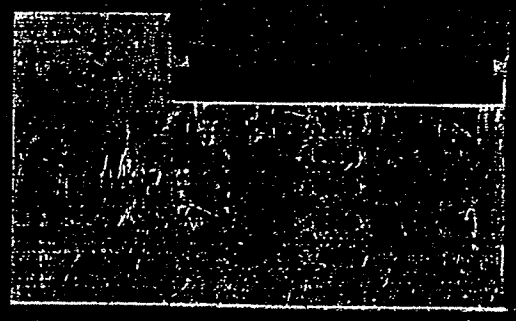


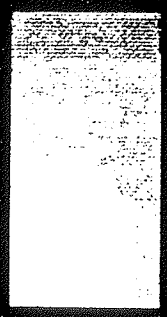


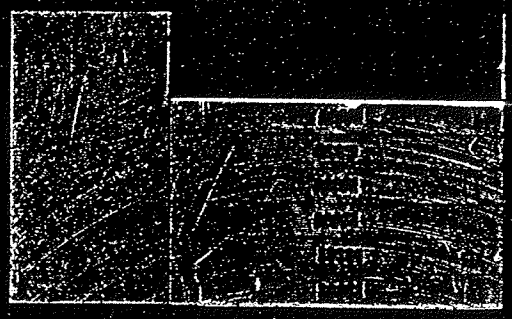


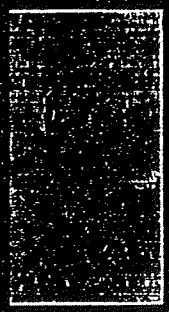


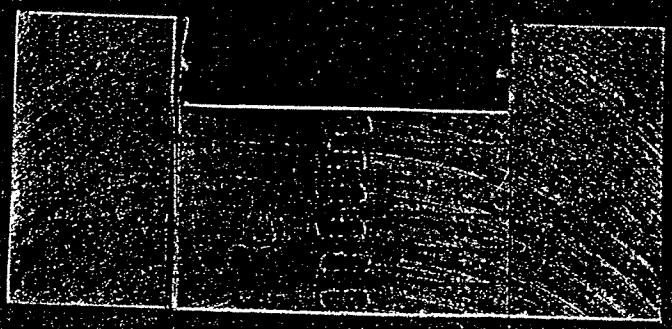








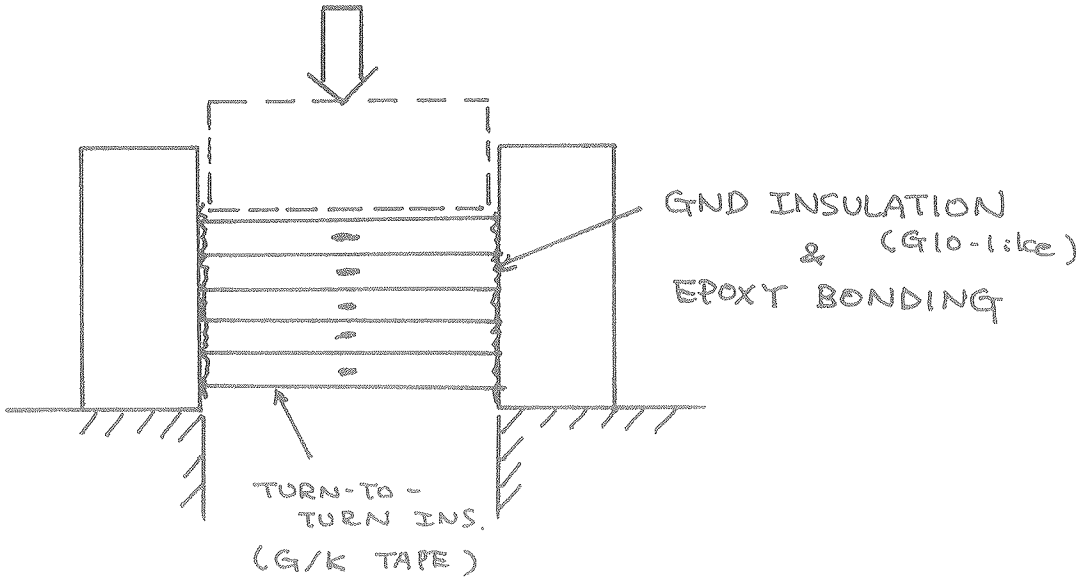




MEASUREMENT OF SHEAR STRENGTH

FOR

EPOXY-BONDING B/W COIL AND SUPPORT CYLINDER



TEST RESULT

	RT	77K	4.2K
LOAD EXPECTED			$\lesssim$ 0.5 MPa
SHORT SPECIMEN	> 15 MPa (N=3)	> 15 MPa (N=3)	
SAMPLE CUT FROM FULL DIA WINDING	> 5 (N=3)	> 5 (N=3)	

PROTOTYPE MAGNET R&D

5.7.1. Prototype coil

The development of a full diameter, one quarter length prototype magnet has been underway since 1991. The purposes of the prototype development are:

- to develop an aluminum stabilized superconductor of high yield strength and RRR;
- to become skilled in the fabrication of a full diameter coil using inner winding techniques;
- to demonstrate that a coil with E/M of about 8 kJ/kg can be quenched safely and without damage or reduced performance; and
- to apply electromagnetic loads to the conductor and outer support cylinder equal to those expected in the detector magnet and to verify the performance under these loads. This can be achieved by operating the prototype to 10–12 kA.

Table 5-16
Design parameters of the prototype R&D solenoid.

Dimensions		
Cryostat	Inner radius	1.70 m
	Outer radius	2.06 m
	Half length	1.17 m
Coil	Effective radius	1.85 m
	Half length	0.95 m
Conductor	Thickness	44 mm
Outer cylinder	Thickness	33 mm
Transparency	Radiation thickness	1.23 X_0
	Interaction length	0.26 λ_0
Electrical parameters		
Central field		1.54
Nominal current		11,250 A
Inductance		0.68 H
Stored energy		48 MJ
E/M		10 kJ/kg
Mechanical parameters		
Effective cold mass		4.5 tons
Total weight		8 tons
Radial mag. pressure (@z =0)		1.73 MPa
Axial compressive force		16.7 MN
Maximum hoop stress		43 MPa
Maximum axial stress		−19 MPa
Maximum shear stress		62 MPa
Peak field in coil		3.8 T
Load line ratio		70%

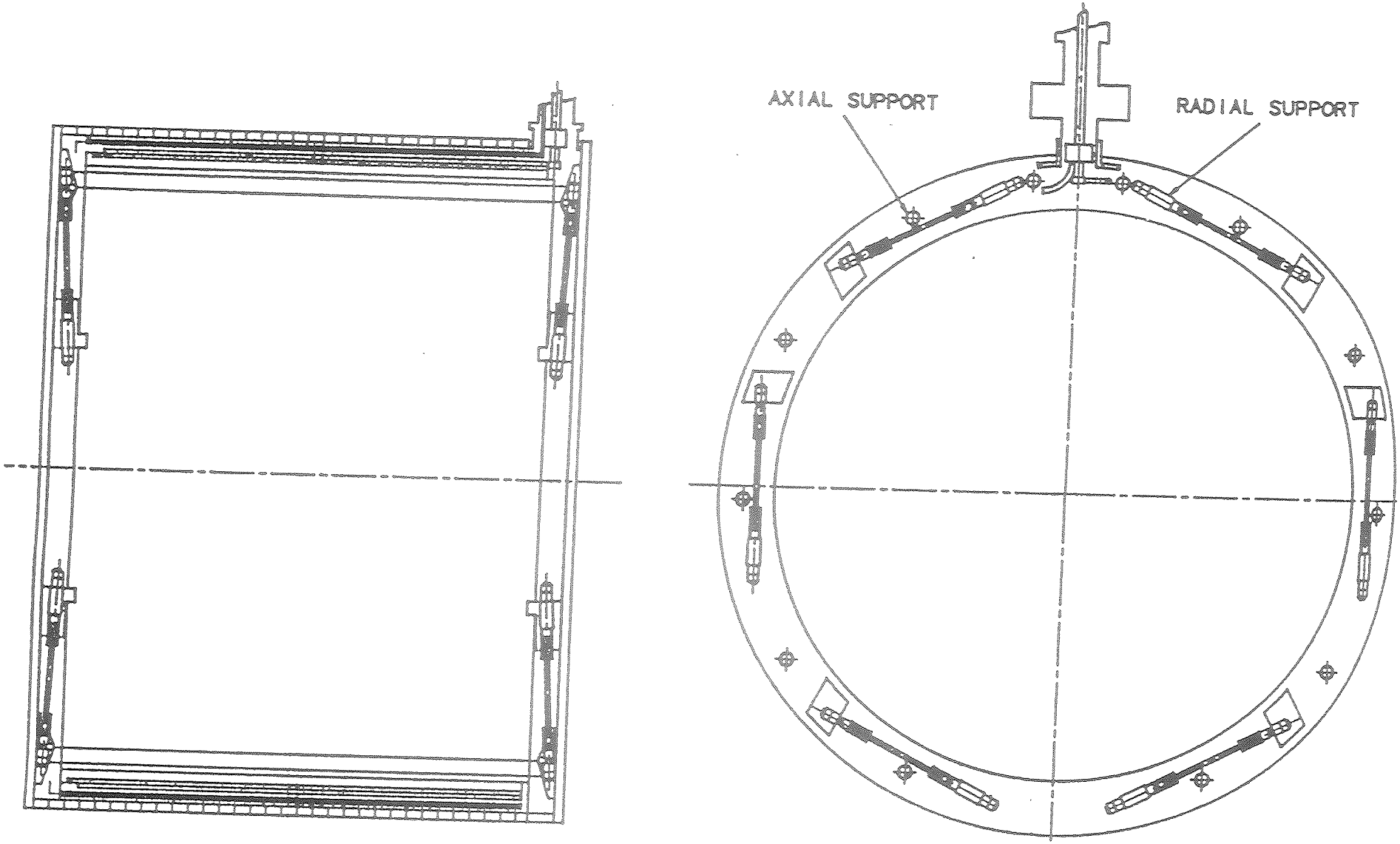


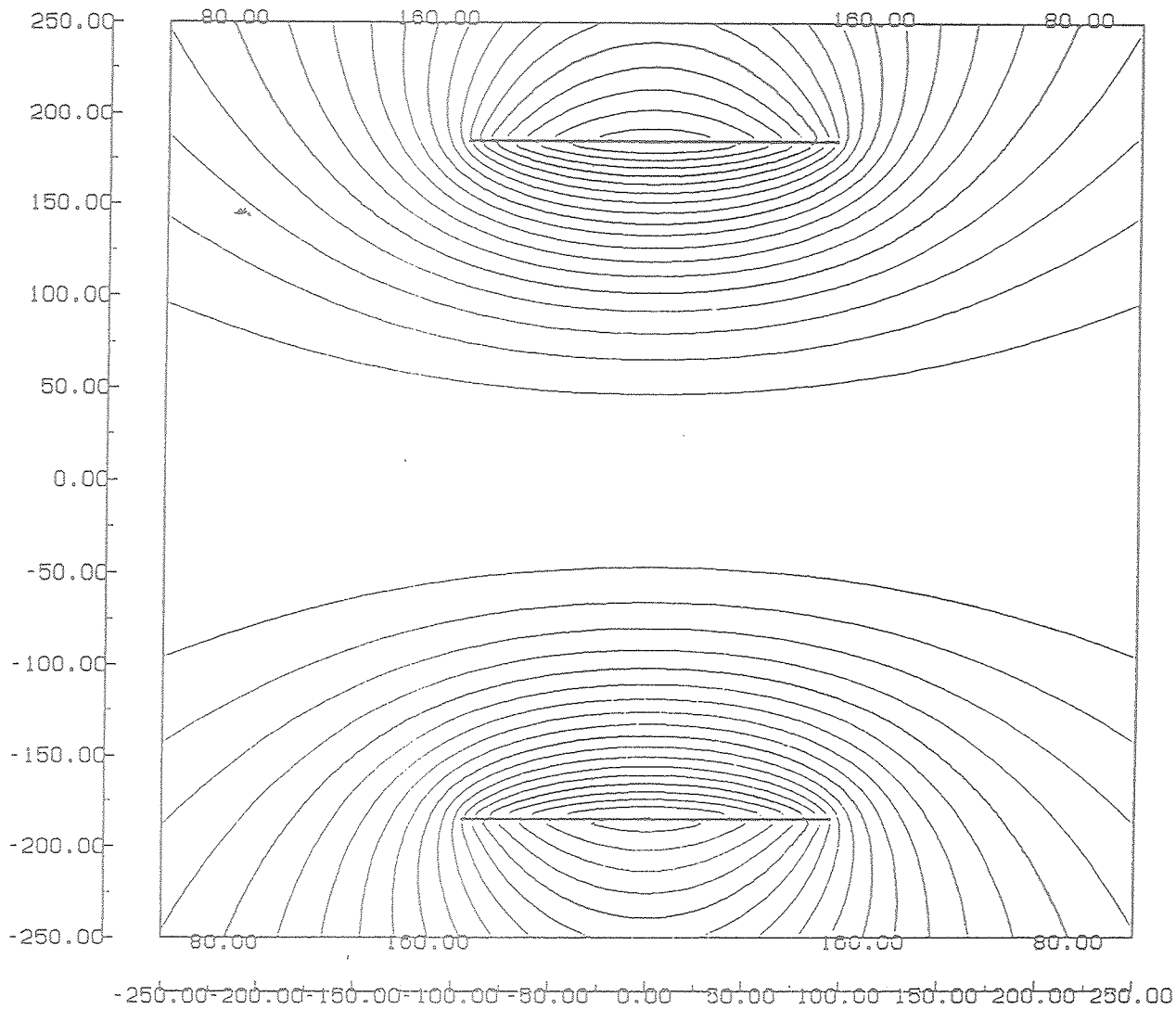
FIG. 5-16. SDC prototype solenoid. Dimensions are given in Table 5-16.

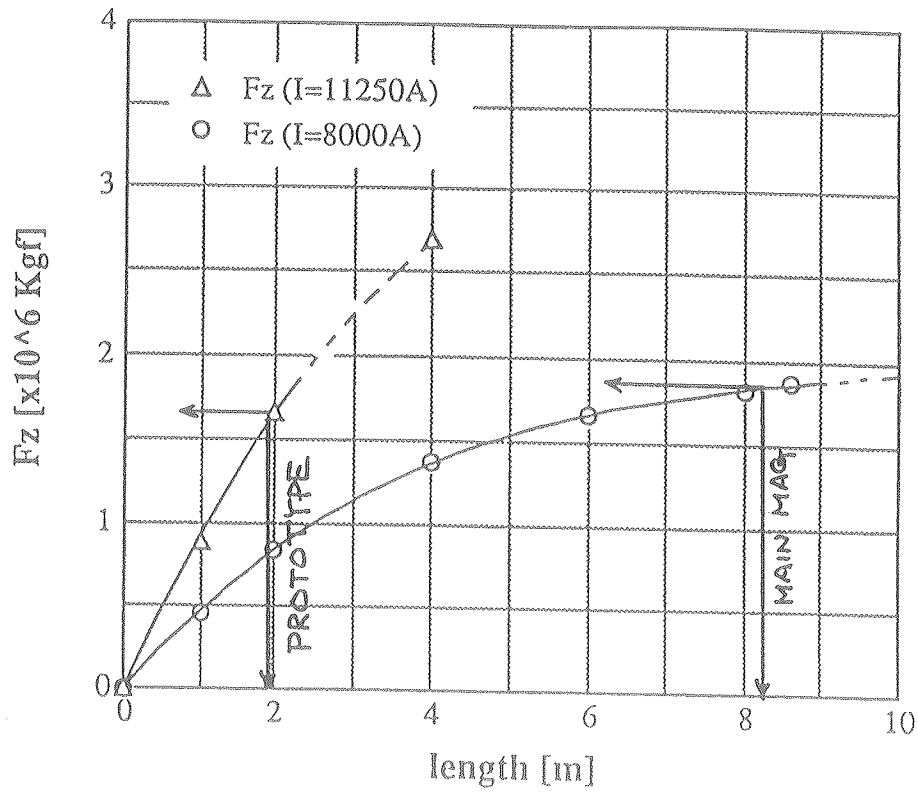
Field Counter Map

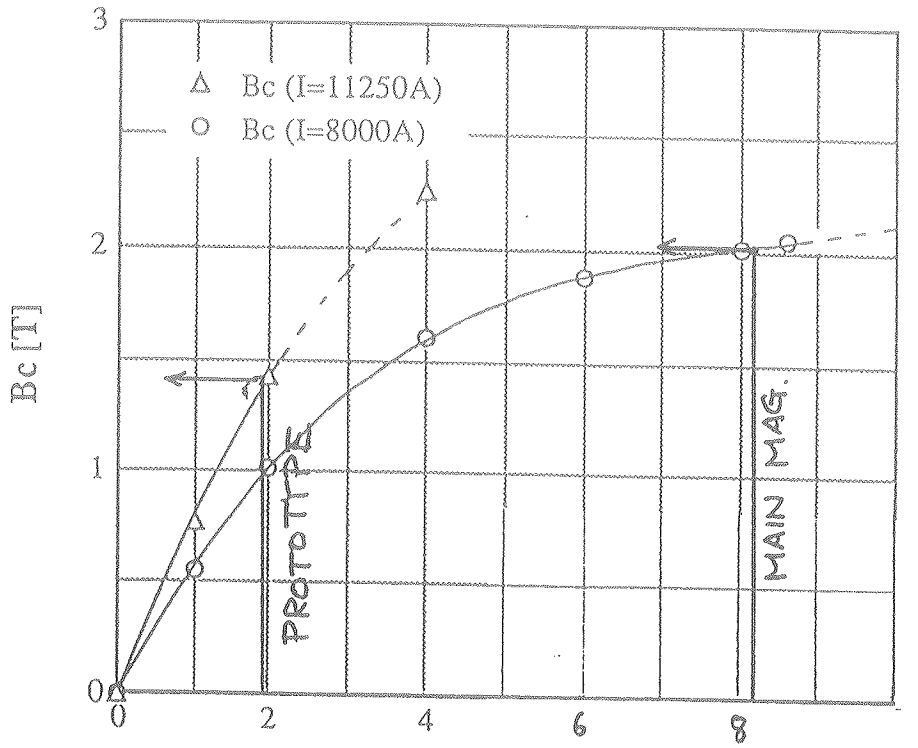
FLUX LINE

SDC PROTOTYPE

PMIN= 0.000E+00 PMAX= 0.311E+03
CMIN= 0.000E+00 CMAX= 0.320E+03 CSTEP= 0.500E-01 NCNR= 17







F_z and B_c vs COIL LENGTH

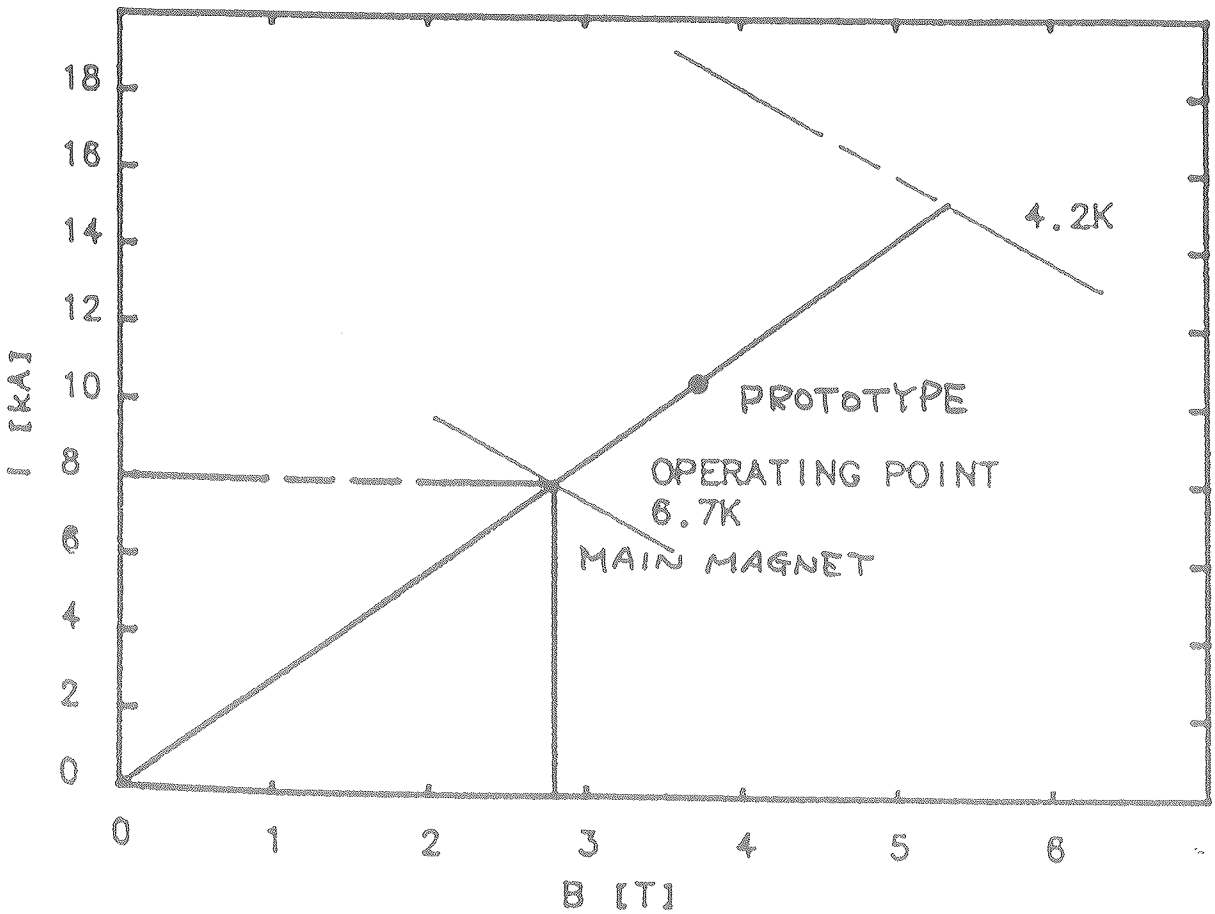
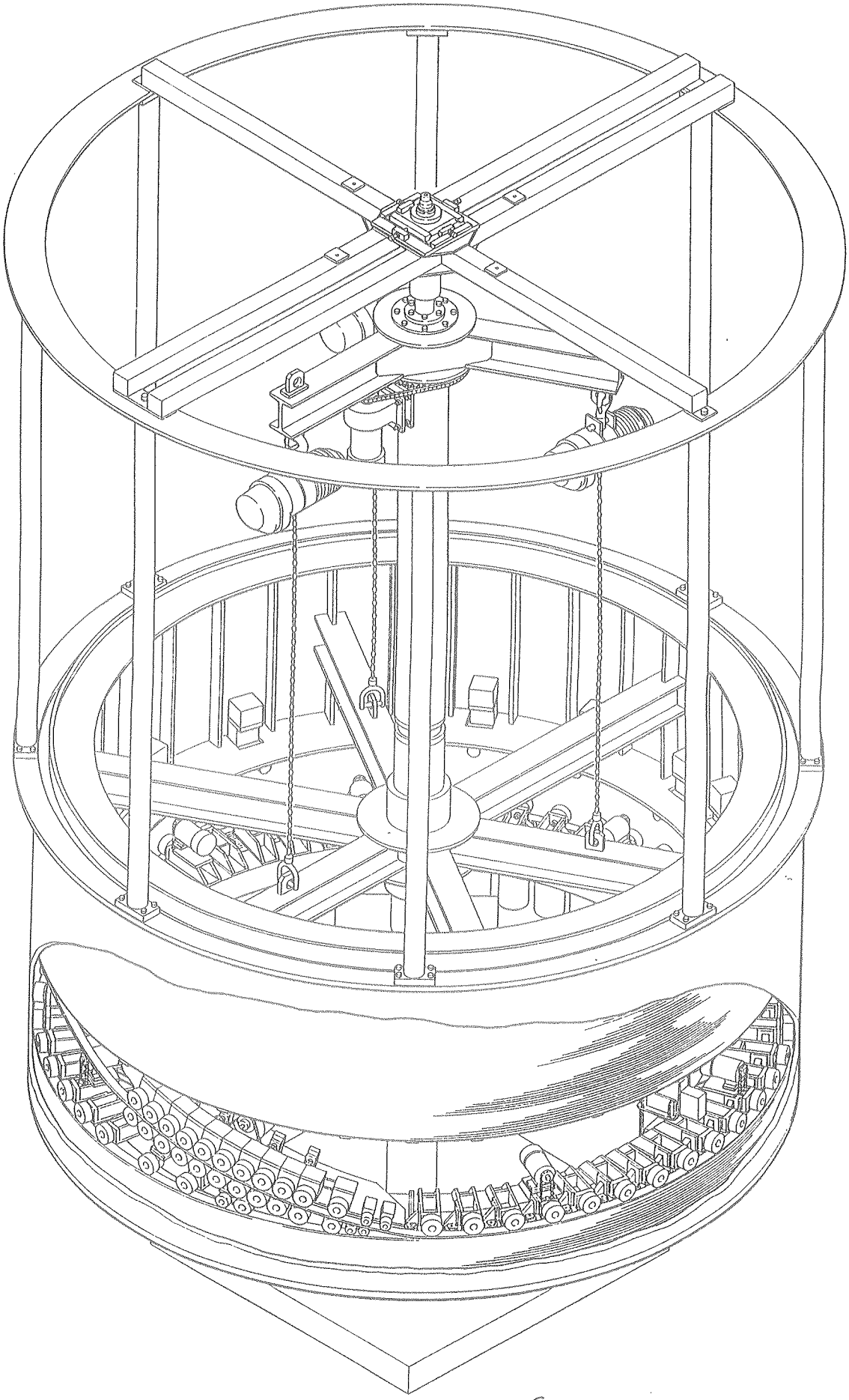
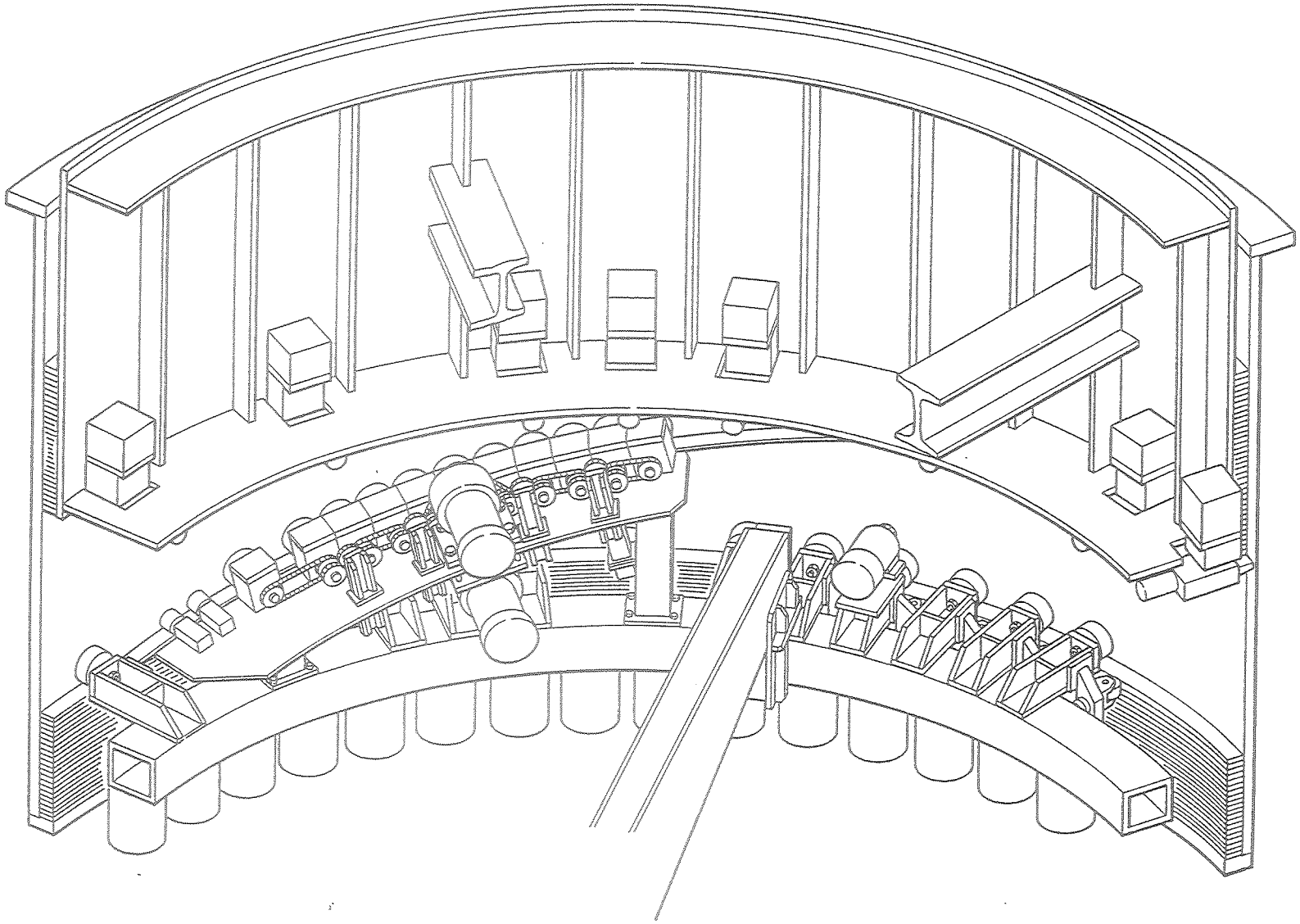
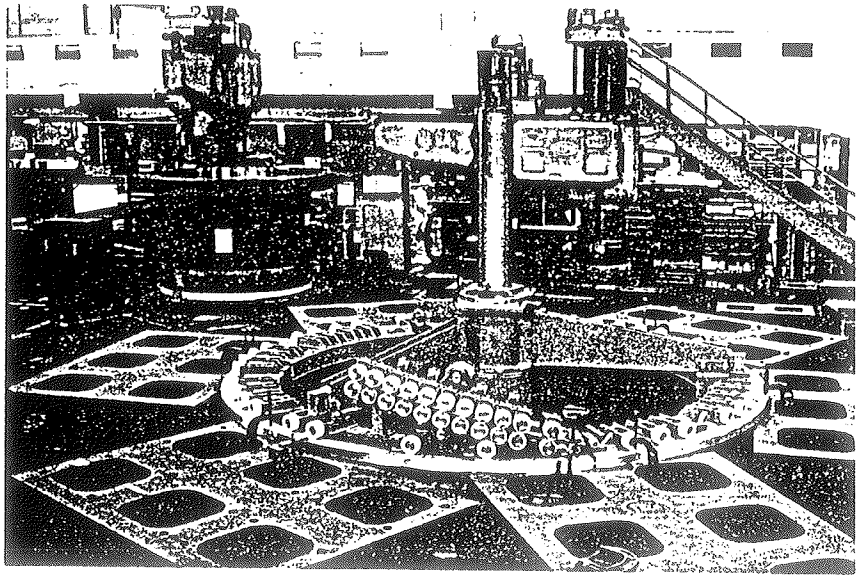


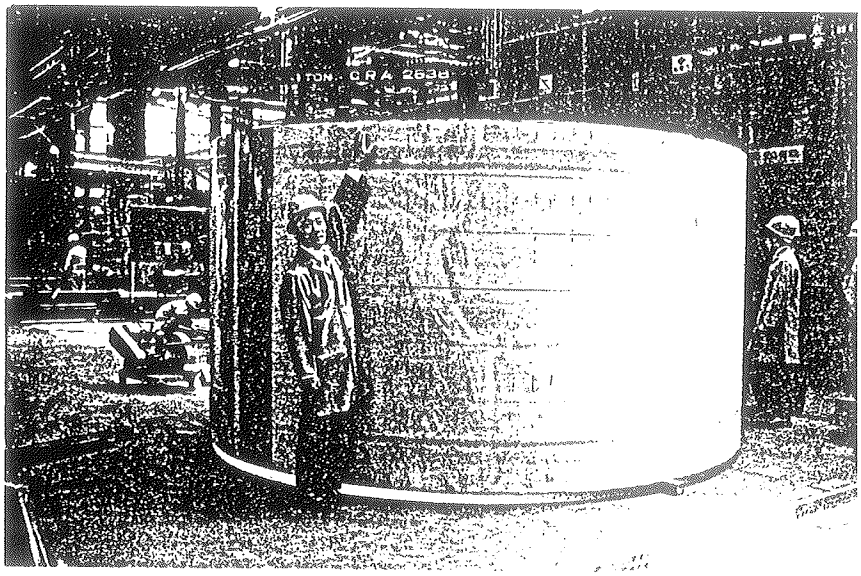
FIG. 5-11. Short-sample characteristics of the SDC conductor and the operating load line.



COIL WINDING MACHINE

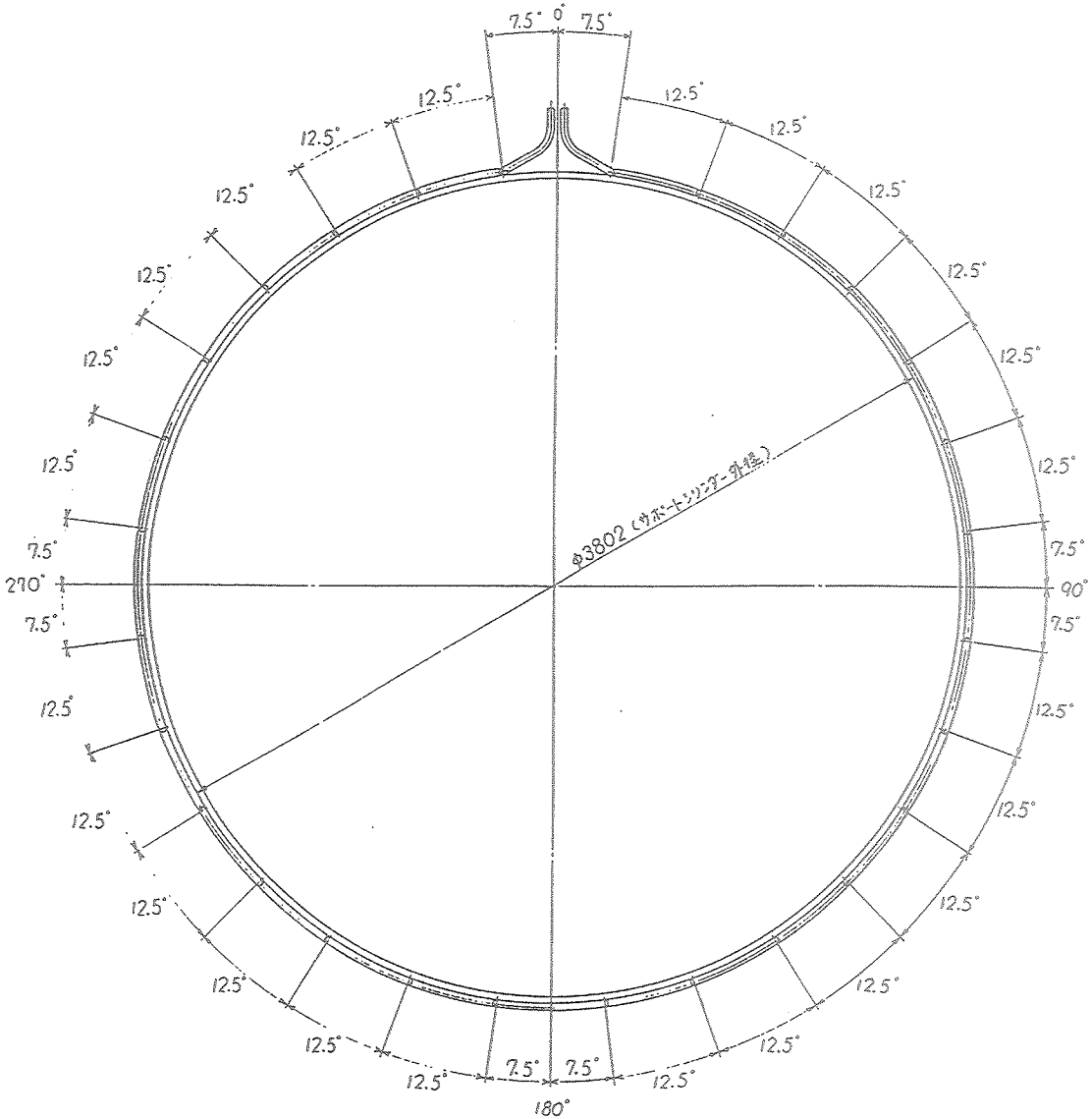


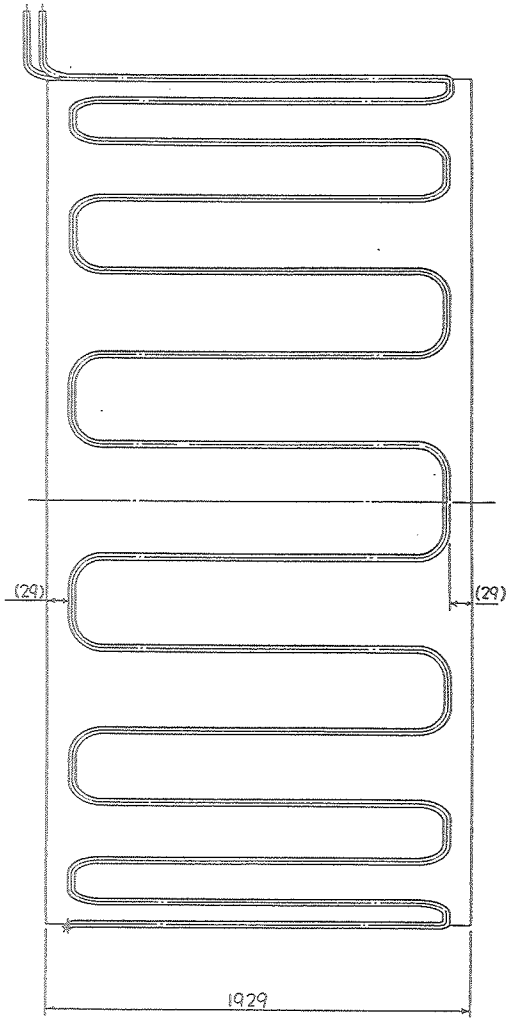




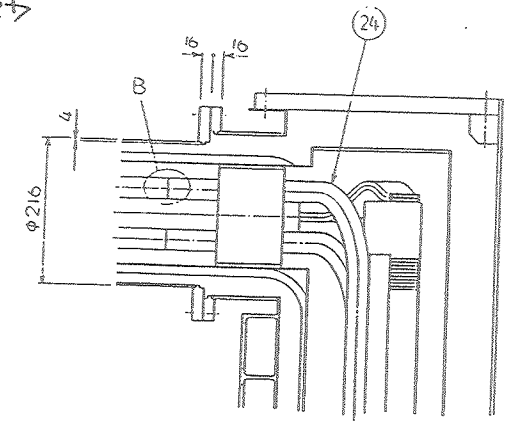
CORE OF WINDING MACHINE & OUTER CYLINDER

17

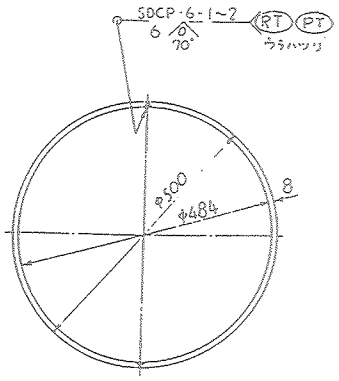

7.5°
0°
7.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
12.5°
7.5°
7.5°
7.5°
7.5°
7.5°
7.5°
270°
90°
180°
φ3802 (サポートシリンダー外径)


(29)
(29)
1929

27



A



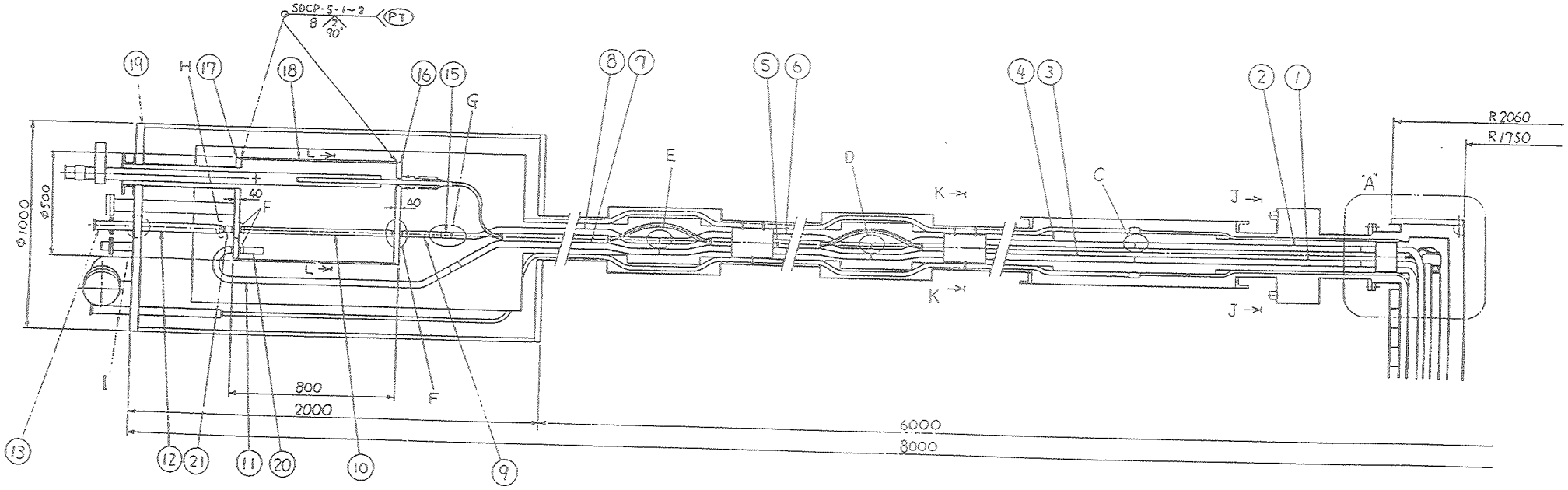
LL
(½2-D)

1. 耐圧試験
16.6 kgf/cm² × 10分 (GNa)

2. φ30×t2(SUS316L) パイプと t8板(SUS316L)について、ボイド付試験も実施します。

溶接開先公差
・角度 ±5°
・ルートギャップ ±2mm

使用条件	
流体	超臨界ヘリウム
設計圧力	11.033 kgf/cm²
	—
耐圧試験圧力	16.6 kgf/cm² (常温)
気密試験圧力	—
設計温度	+40°C ~ -268°C
容積	0.12 m³



RESEARCH FOR HIGH E/M MAGNET

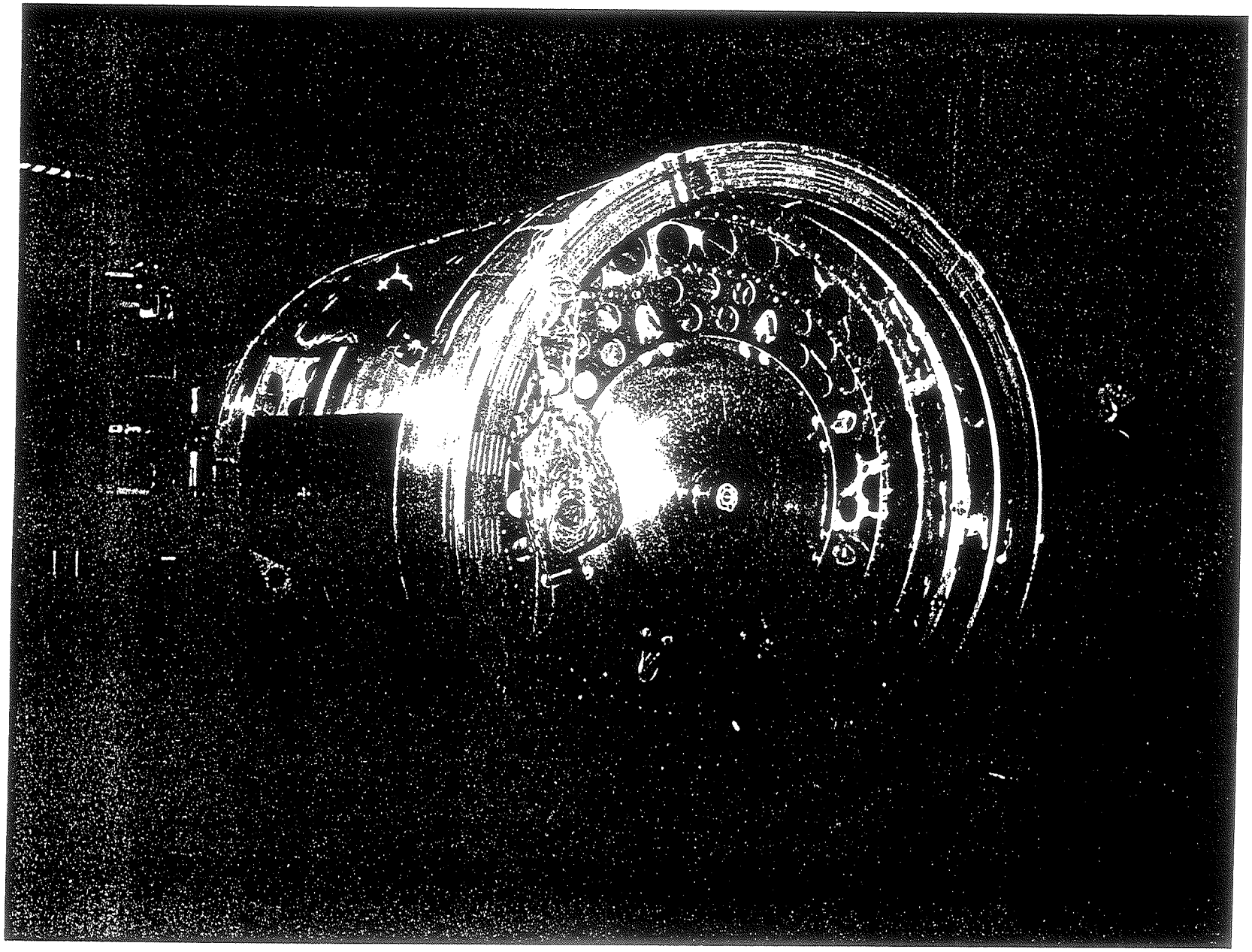
(ASTROMAG TEST COIL)

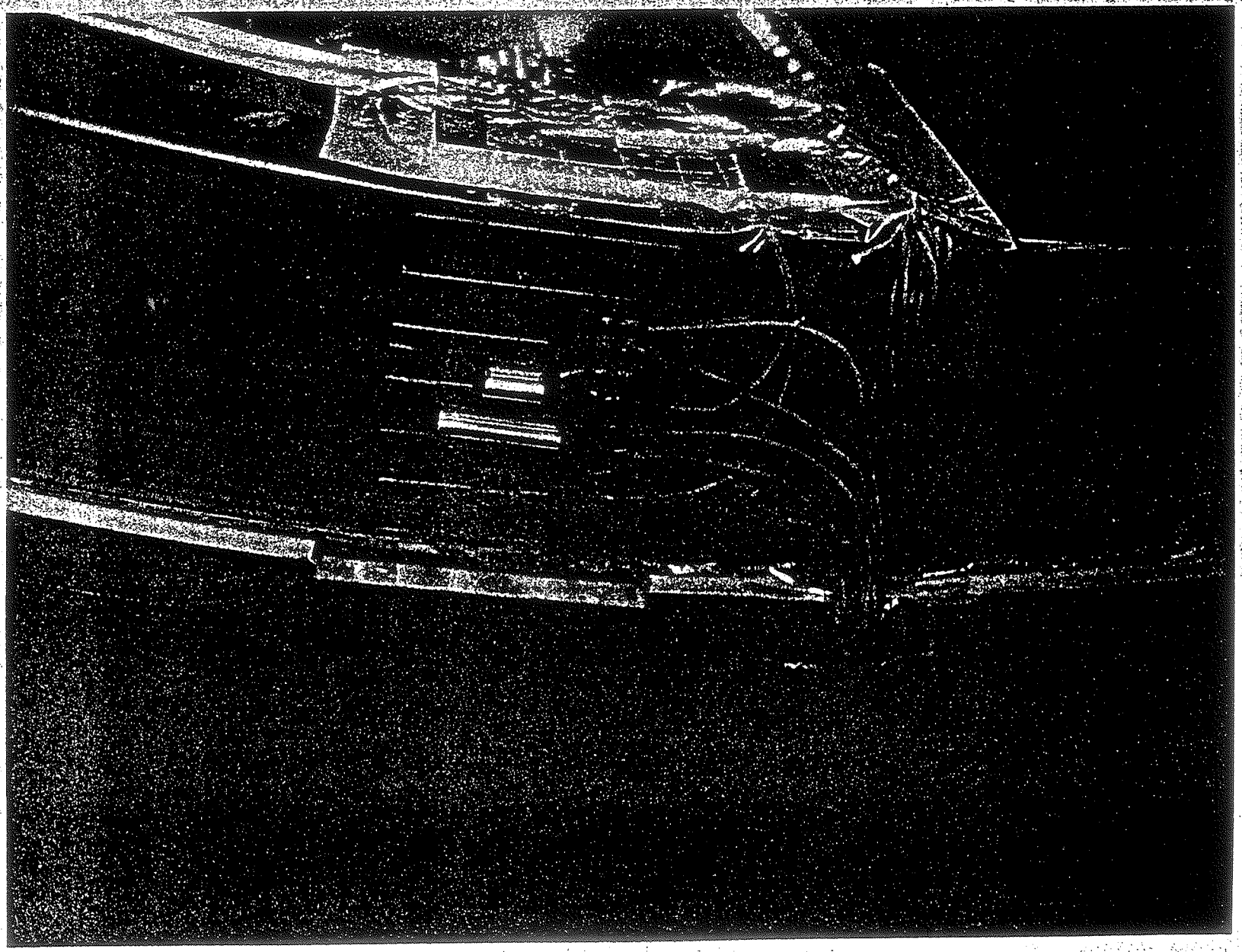
Main parameters of the ASTROMAG test coil

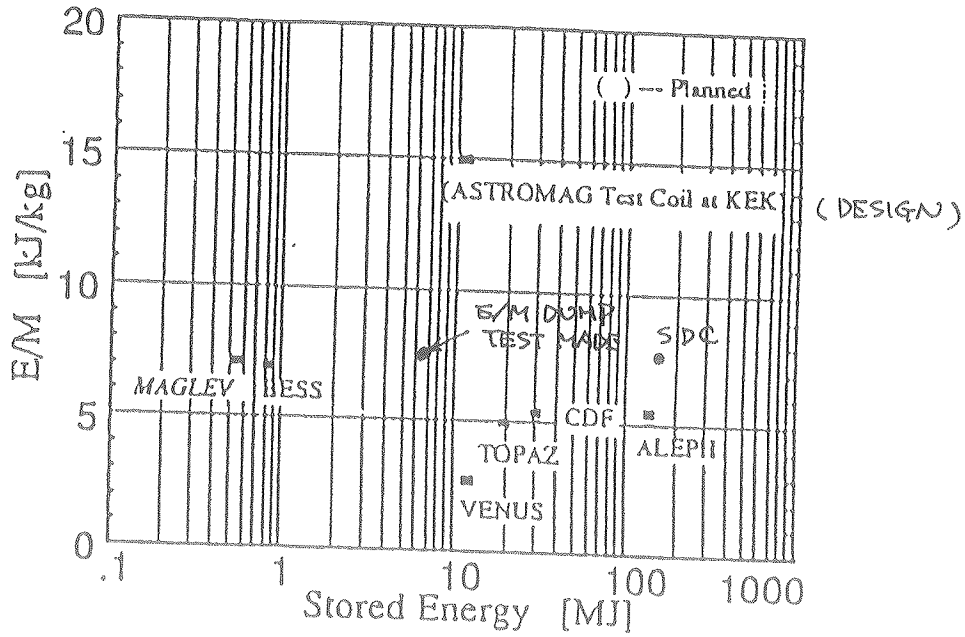
Dimensions	
Coil outer diameter	1.76 m
inner diameter	1.5 m
length	0.19 m
Coil separation (center to center)	2.2 m
Cryostat outer diameter	2.1 m
length	2.6 m
Electric	
Current	800 A
No. of turns	90 × 28
N · I	2.016 MAT
Inductance	32.3 H
Central field	1.5 T
Maximum field in coil	5.6 T
Stored energy	10.3 MJ
Hoop force	140 tonf
Axial repulsive force	27 tonf
Dielectric strength	1000 V turn to turn 2000 V layer to layer
Persistent current switch	
Switching	heater (27 W)
Winding	non-inductive
Current	1000 A
Off resistance	20 Ω
Cooling	indirect cooling
Weight	
Coil mass (1 coil)	330 kg
Cold mass (1 coil) (coil part including support cylinder)	380 kg
Cryostat mass	~1000 kg
Total mass	~2000 kg
Cooling method	indirect cooling

E/M @ 800A 15 kJ/kg

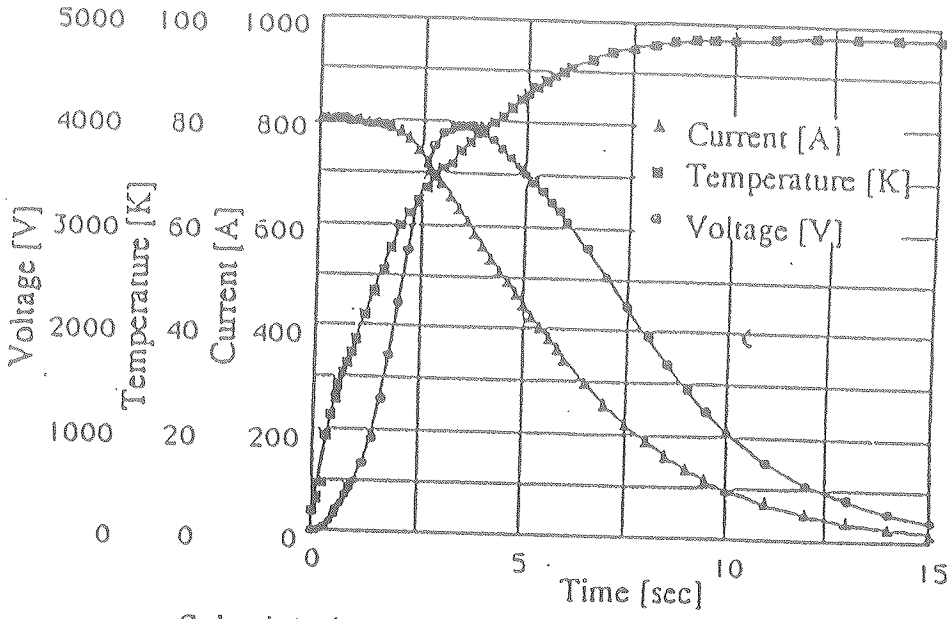
@ 600A 7.5 kJ/kg (TESTED)







E/M in various superconducting magnet.

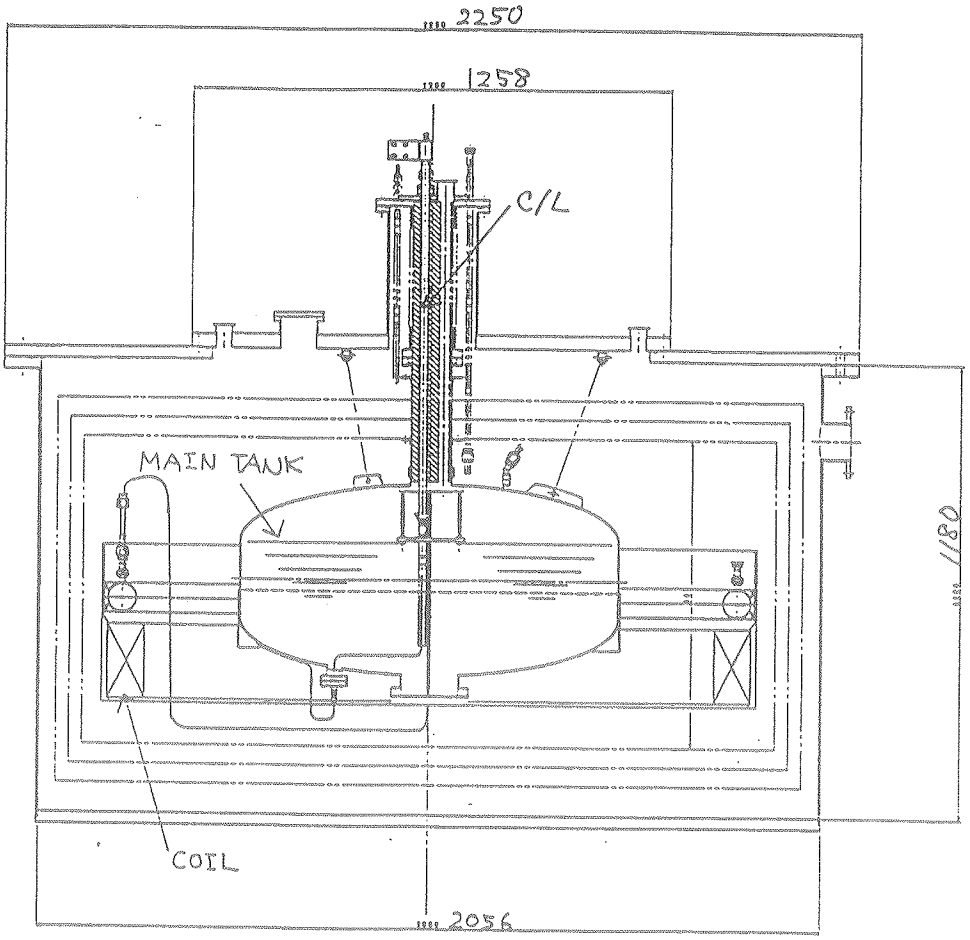


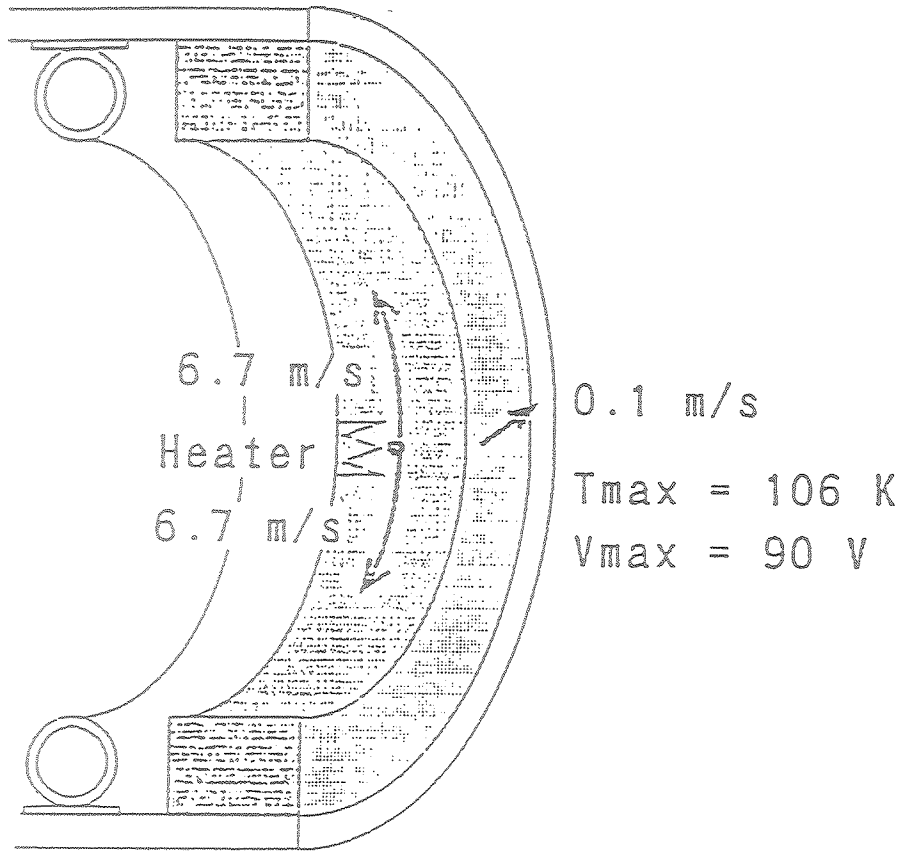
Calculated quench characteristics of the test coil

3. PERFORMANCE TEST RESULT ON EACH COIL

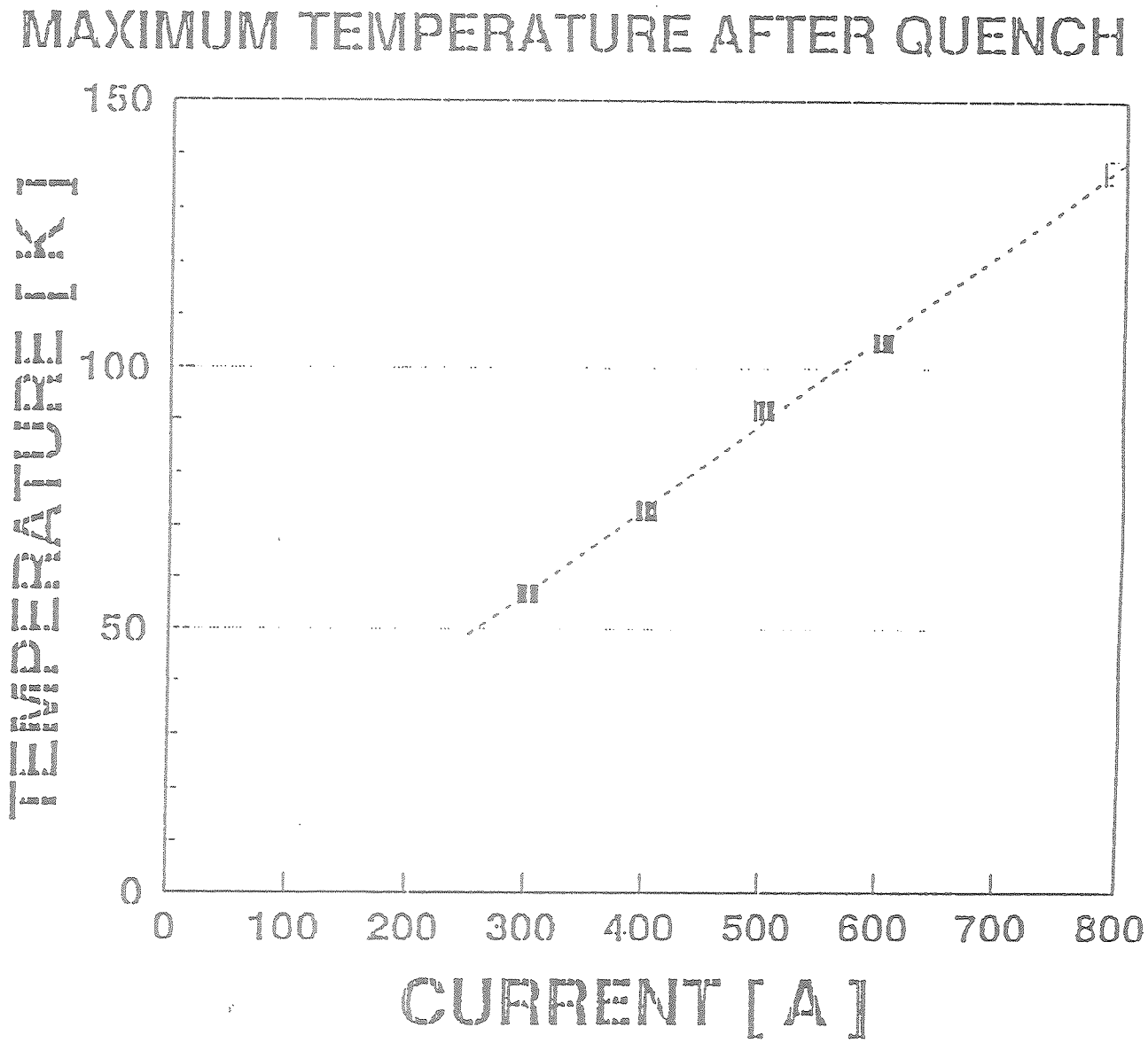
Before coupling the two coils in a horizontal cryostat as shown previously, each of them has been examined on its magnetic performance in a vertical cryostat.

The coil is surrounded by triple stage radiation shields. The LHe is transferred from a main tank to the sub-tank.

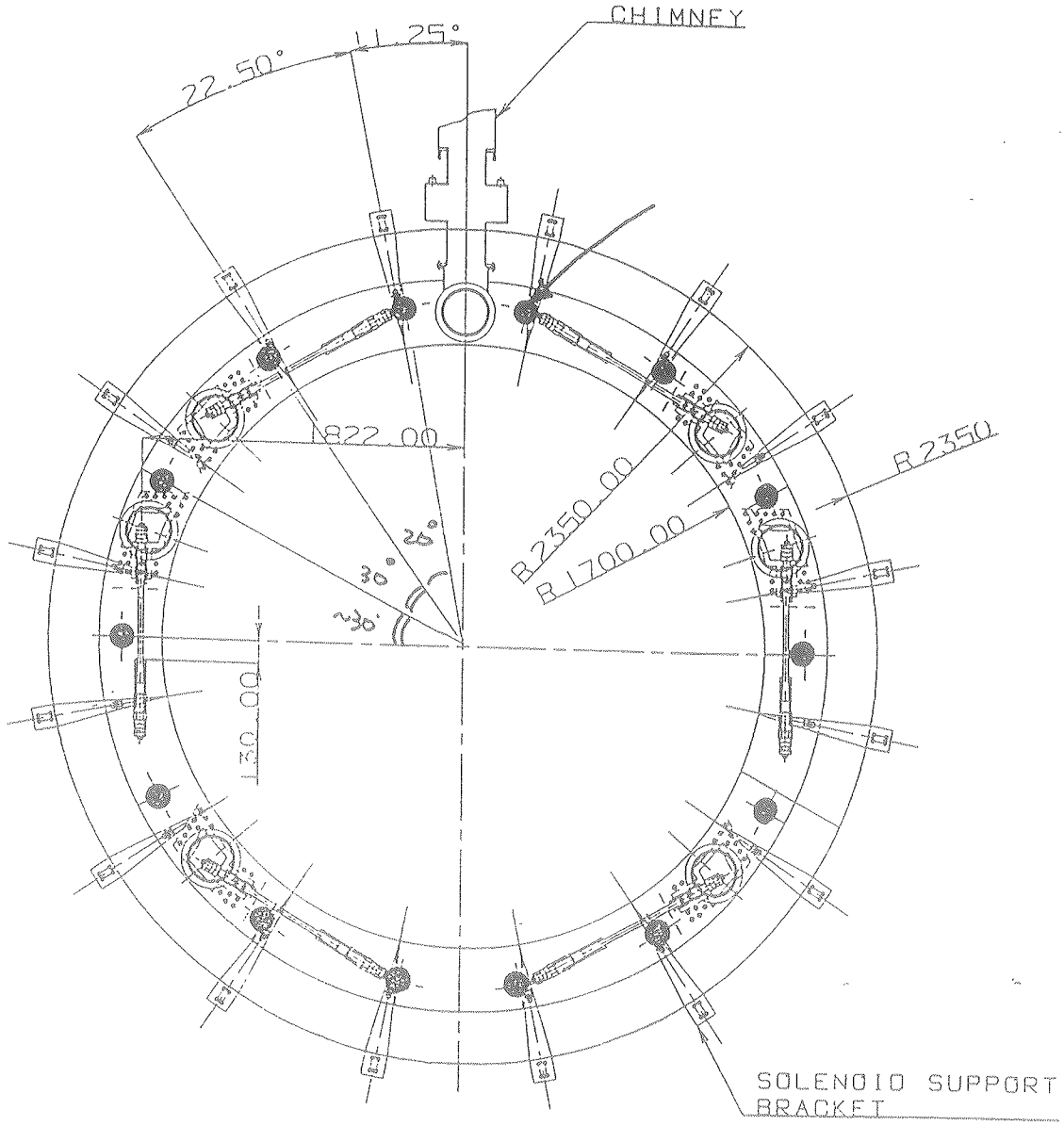




QUENCH CHARACTERISTCS @ 600 A

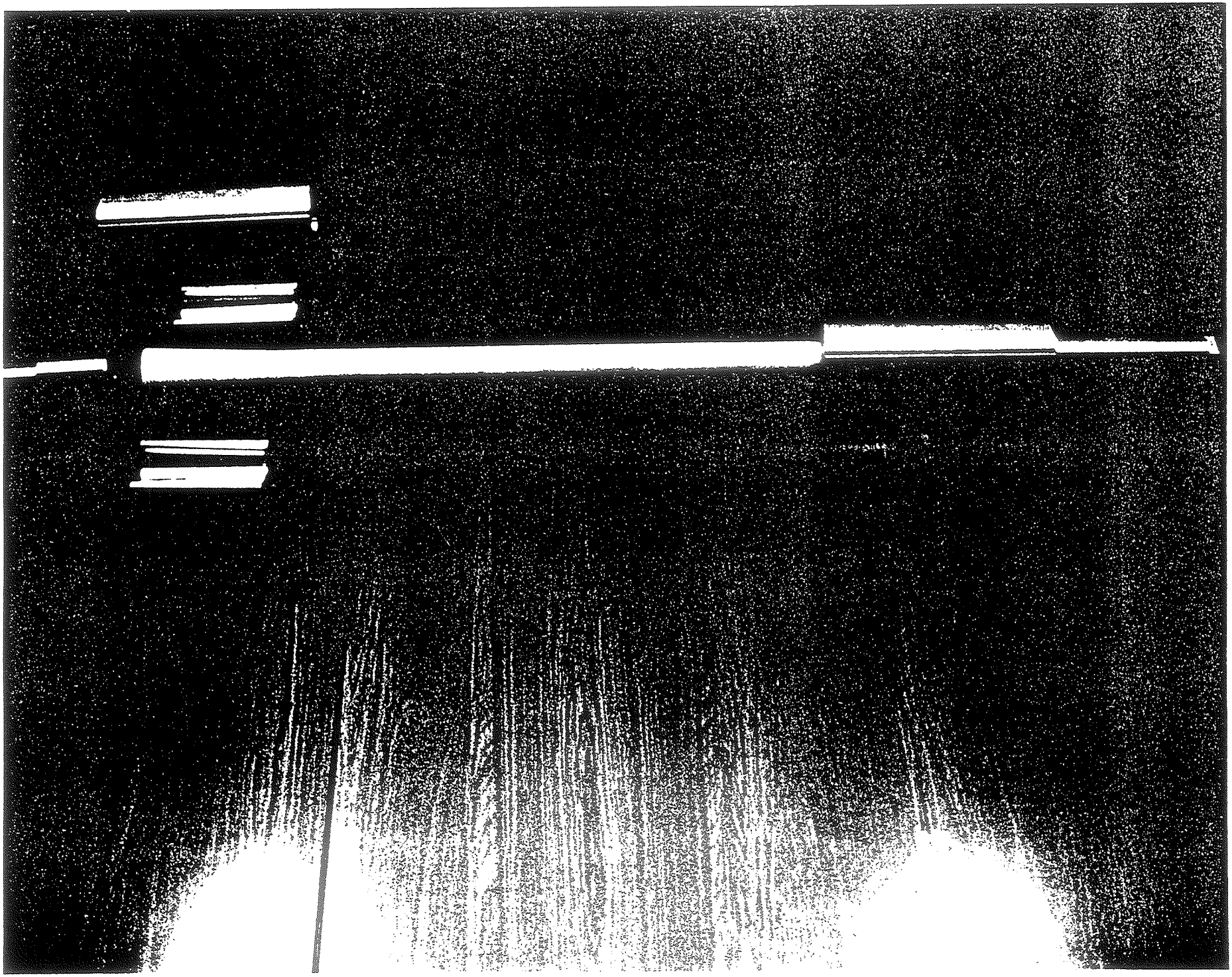

MAXIMUM TEMPERATURE AFTER QUENCH
TEMPERATURE [K]
150
100
50
0
0
100
200
300
400
500
600
700
800
CURRENT [A]

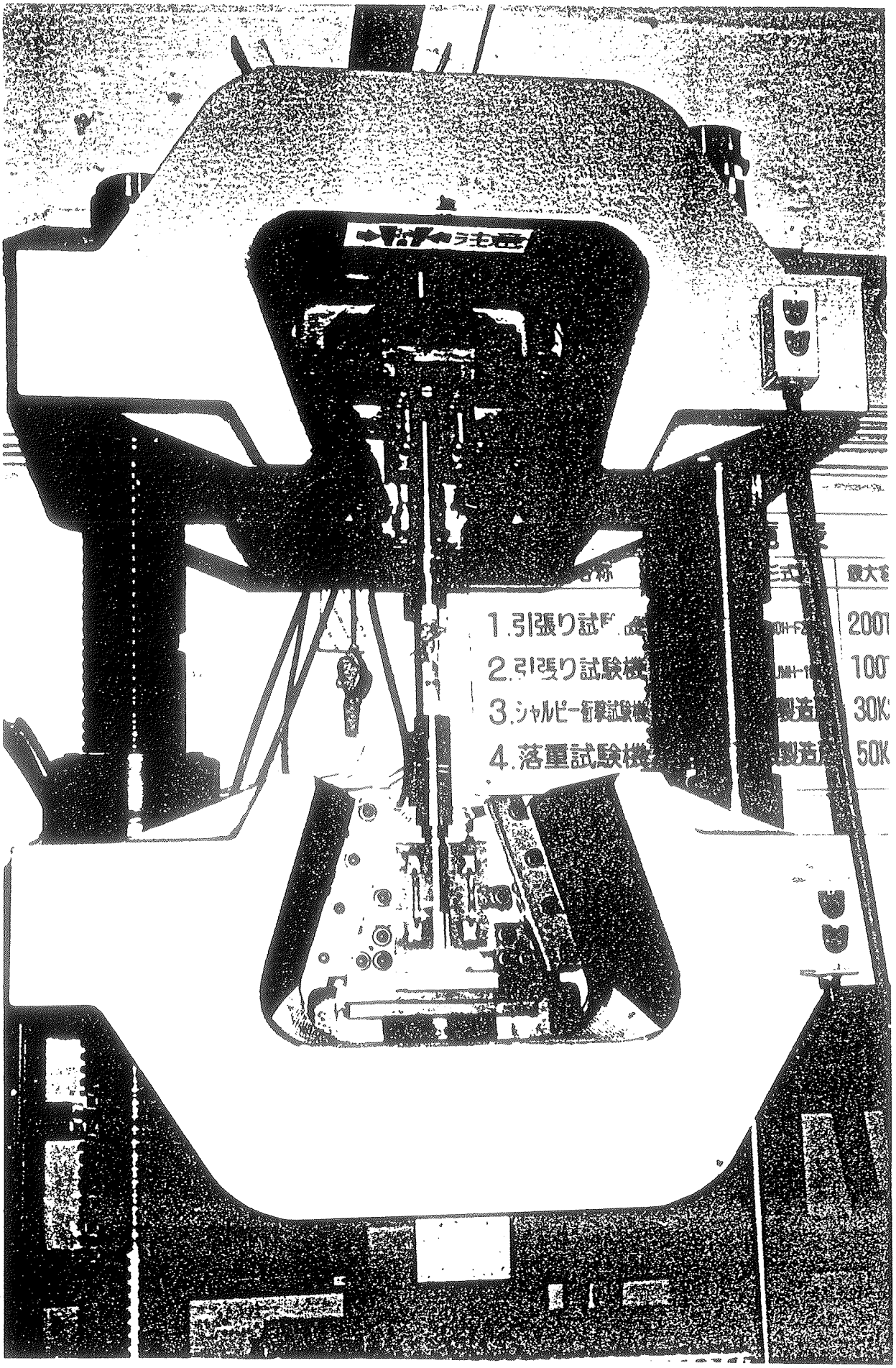
R&D FOR COIL SUPPORT

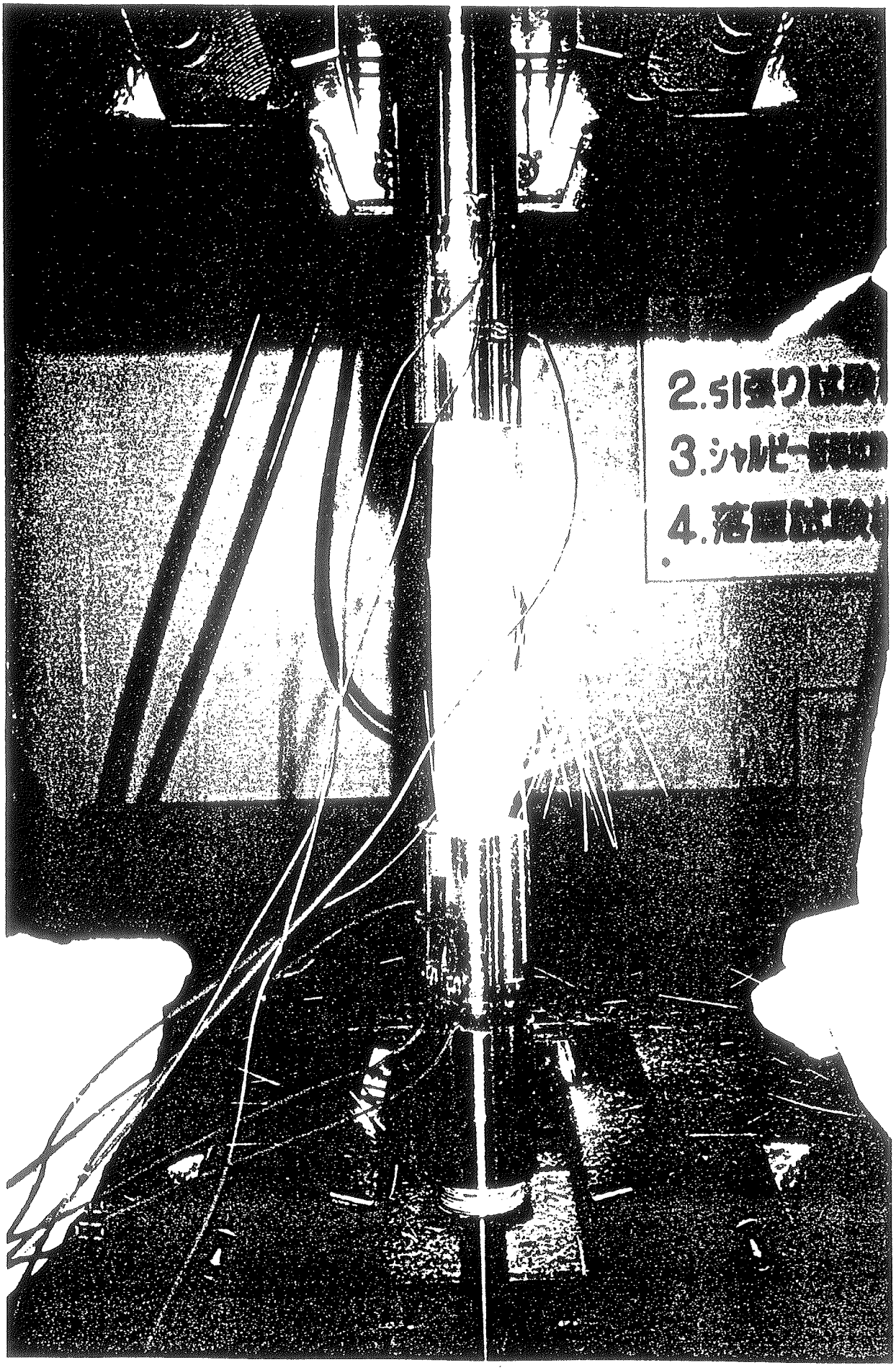


RESULT OF TENSILE TEST

T.S. (77K) = 750 MPa
(RT) = 650 MPa




1.引張り試
2.引張り試験機
3.シャルピー衝撃試験機
4.落重試験機
200T
100T
30K
50K


2.5引張り試験
3.シャルピー衝撃
4.落重試験

SUMMARY

FOR

PROGRESS OF THE SDC SOLENOID R&D

1. DEVELOPMENT OF HIGH STRENGTH ALUMINUM STABILIZED SUPERCONDUCTOR HAS BEEN SUCCESSFUL TO REACH Y.S. = 80 MPa WITH RRR = 500.

2. COIL WINDING MACHINE DEVELOPMENT IN PROGRESS,

3. EPOXY BONDING STRENGTH B/W COIL AND CYLINDER HAS BEEN VERIFIED TO BE SUFFICIENTLY STRONG ENOUGH TO SUSTAIN AXIAL MAGNETIC FORCE OF 1300 TONNES

4. ENERGY DUMP TEST INTO A MANGET WITH AN E/M RATIO OF 7.5 KJ/KG HAS BEEN SUCCESFULLY MADE. THE RESULT HAS BEEN CONSISTENT WITH OUR PRESENT DESIGN CONCEPT FOR THE SDC SOLENOID.

5. HONEYCOMB AND ISOGRID R&D IS IN PROGRESS.

6. PROTOTYPE MAGNET DEVELOPMNET IS BEING CARRIED OUT AND TO BE COMPLETED IN JFY1994.