# EXPERIENCE WITH CIC MAGNETS AT ORNL

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Presented at the Workshop on the
Experience with Testing and Application of
Cable-in-Conduit Conductors (CICC)

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R&D Work Done at ORNL toward the Development of Cable-in-Conduit Superconducting Magnets

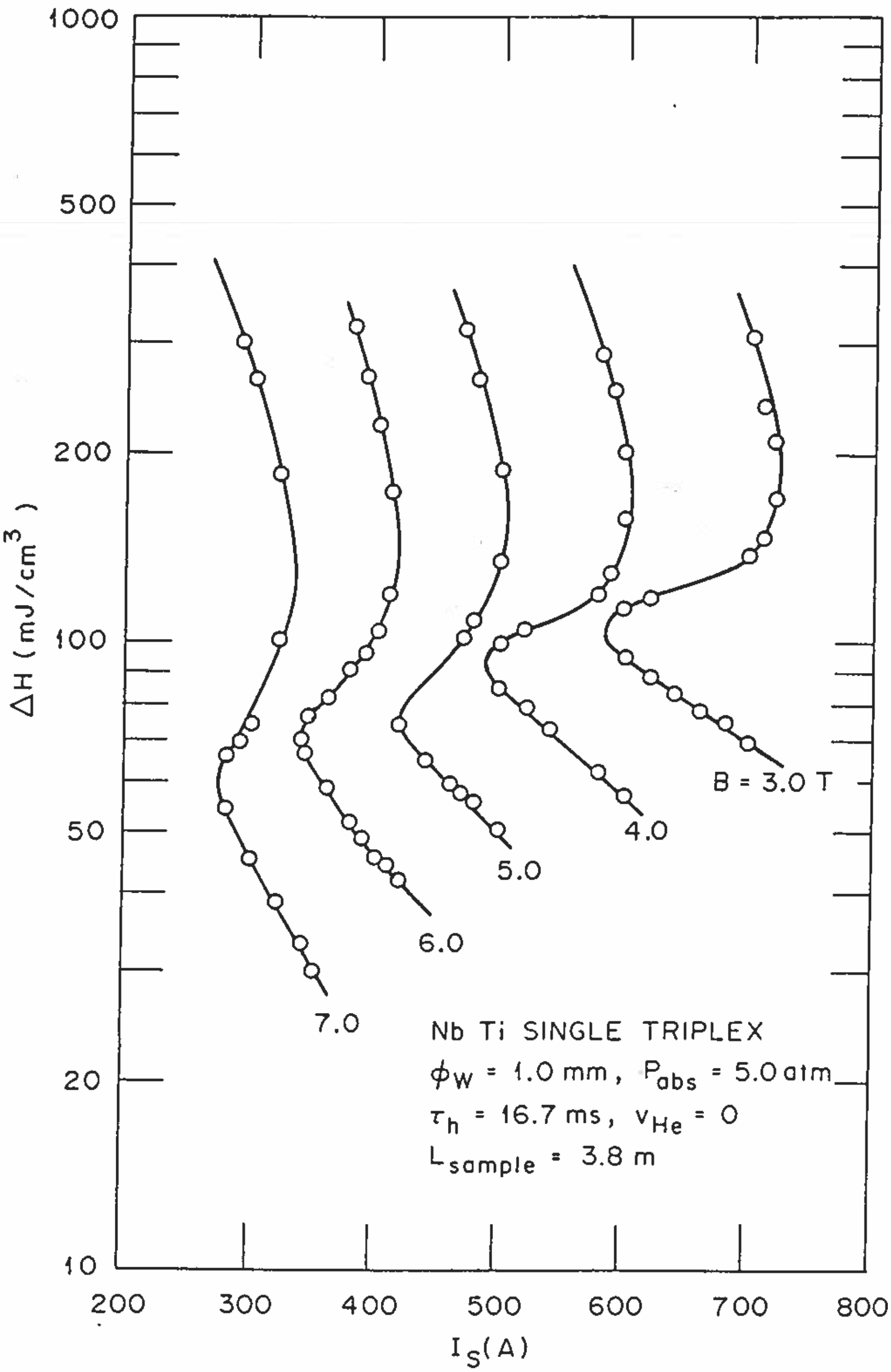
- Small scale experiments:

  - Stability measurements: single triplex CICC of 1 - 5-m long with resistive heater
    1) Multiple stability zone
    2) Limiting currents, $I_{lim}$
    3) Stability margin below $I_{lim}$ ≈ Available helium enthalpy
    4) Parametric measurements

  - Quench simulation experiments: 70-m long Cu-strand CICC
    1) Maximum pressure during a quench
    2) Thermal expulsion velocity of helium

  - $Nb_3Sn$ CICC short sample stability measurement: inductive heaters

  - Normal zone propagation and thermal hydraulic quenchback experiment: 50-m long single triplex CICC
    1) Normal zone propagates in CICC on the order of 1 m/s
    2) When THQ occurred, propagation velocity approached velocity of sound (≈ 100 m/s)


1000
500
200
100
50
20
10
ΔH (mJ/cm³)
200
300
400
500
600
700
800
I_S(A)
B = 3.0 T
4.0
5.0
6.0
7.0
Nb Ti SINGLE TRIPLEX
φW = 1.0 mm, Pabs = 5.0 atm
τh = 16.7 ms, vHe = 0
Lsample = 3.8 m

# R&D Work Done at ORNL toward the Development of Cable-in-Conduit Superconducting Magnets (Continued)

- Theoretical studies:
  - Limiting currents scaling law
  - Peak pressure scaling law
  - Quench pressure, thermal expulsion, and normal zone propagation laws
  - Thermal hydraulic quenchback theory

- Fabrication and testing of CIC magnets:
  - Fabrication and testing of the 10-cm clear bore NbTi CIC magnet
  - Testing of the LCP Westinghouse $Nb_3Sn$ coil
  - Development of Light weight superconducting magnets

# Engineering Equations for Designing CIC Superconductor

- Limiting current:

$$I_{lim} = A_{cs}\, F(f_{Cu},f_{He})\, [(T_c - T_b)\, \rho^{-1}]^{1/2}\, d^{-1} \cdot k_h$$

Heating induced heat transfer factor:

$$k_h = k\, (\ell^2/\tau)^{1/15}$$

- Stability margin for $I < I_{lim}$:

$\Delta H \geq$ He enthalpy

- Maximum quench pressure:

$$P_{max} = G(f_{Cu},f_{He})\, (\rho^2 J_{cs}^4 \ell^3 d^{-1})^{0.36}$$

Fabrication and Testing of a NbTi CIC Magnet

"Design, Construction, and Test of a 113-mm Bore Solenoid with NbTi Cable-in-Conduit Superconducting windings," Miller, Lue, Brown, and Kenney, IEEE Trans. Magn., MAG-17, 2250 (1981).

"Performance of an Internally Cooled Superconducting Solenoid," Lue and Miller, Adv. Cryogenic Engineering, 27, 227 (1982).

"Extending an Internally Cooled Superconducting Magnet to Higher Fields," Lue and Miller, IEEE Trans. Magn., MAG-19, 261 (1983).

"Test Results of Superconducting AC Magnets for Magnetic Refrigeration Experiment," Lue, Luton, Schwenterly, and Wilson, Paper presented at MT-13, Victoria, B.C. Sept. 20-24, 1993.

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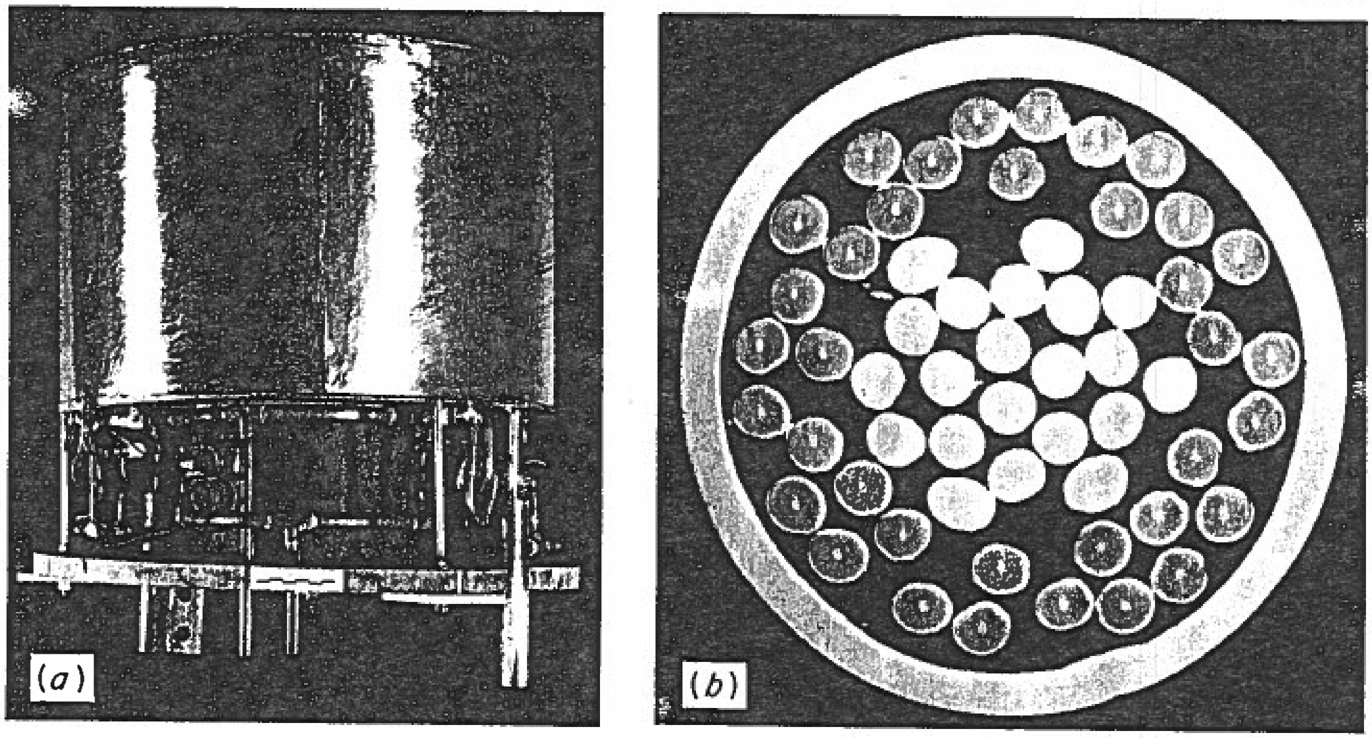
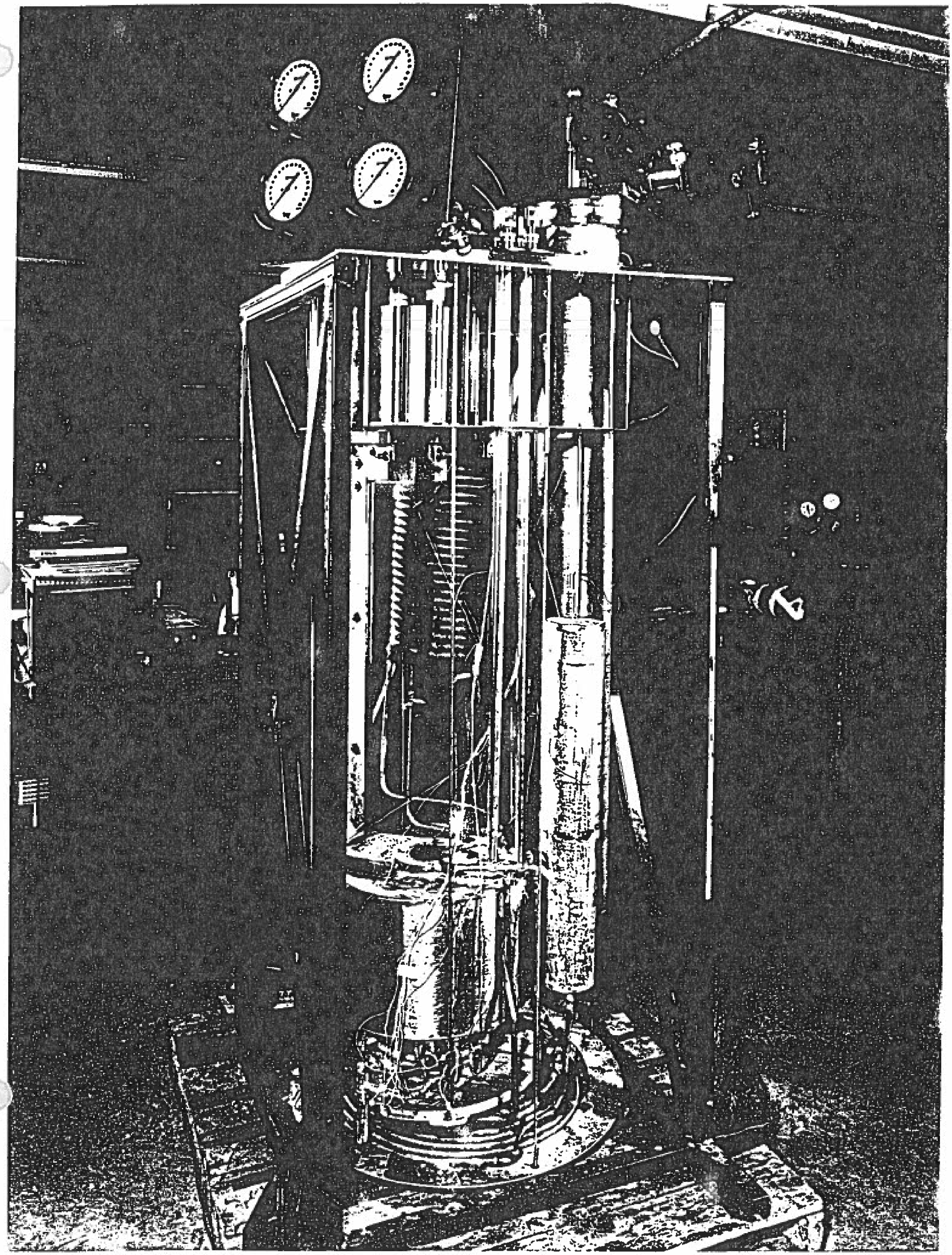


# CABLE-IN-CONDUIT MAGNET PARAMETERS

| Item | Parameter |
|---|---|
| Superconducting strands | 0.72 mm bare NbTi wire |
| Cable pattern | 12 x 3 SC subcables around a 7 x 3 Cu-core |
| Cu/SC ratio | 1.8 : 1 in SC strands<br>3.4 : 1 overall |
| Conductor conduit | 8.56-mm OD 304 stainless steel |
| Void fraction | 43% |
| Refurbished magnet dimensions | 104 mm ID x 445 mm OD x 330 mm Height |
| Hydraulic paths | Series-parallel combination of layers |
| Minimum length | 7.7 m |
| Maximum length | 71 m |
| Maximum central field | 7.5 T |
| Current at Maximum field | 4.8 kA |
| Conductor current density | 8.3 $kA/cm^2$ |
| Stored magnetic energy | 270 kJ |



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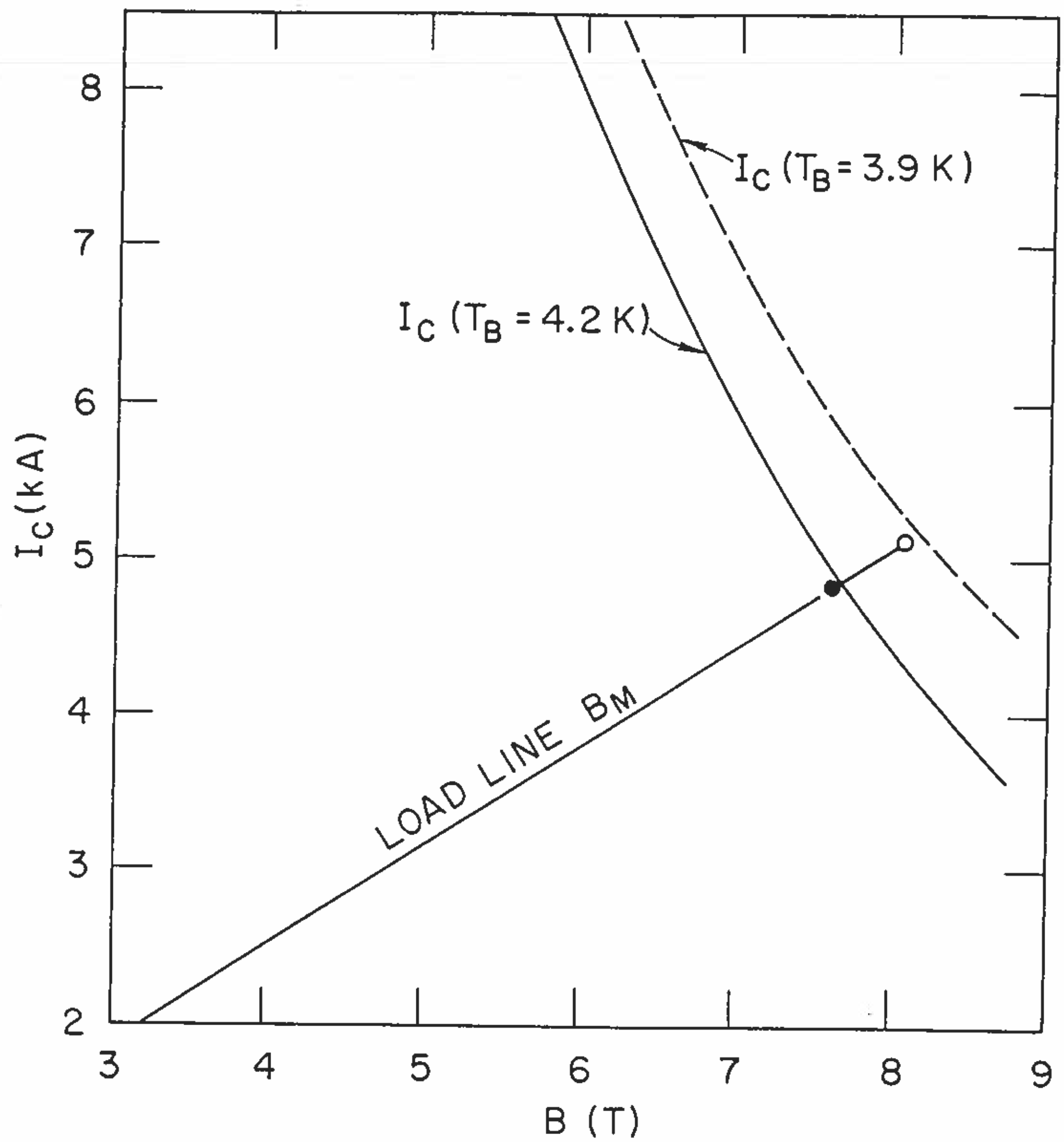
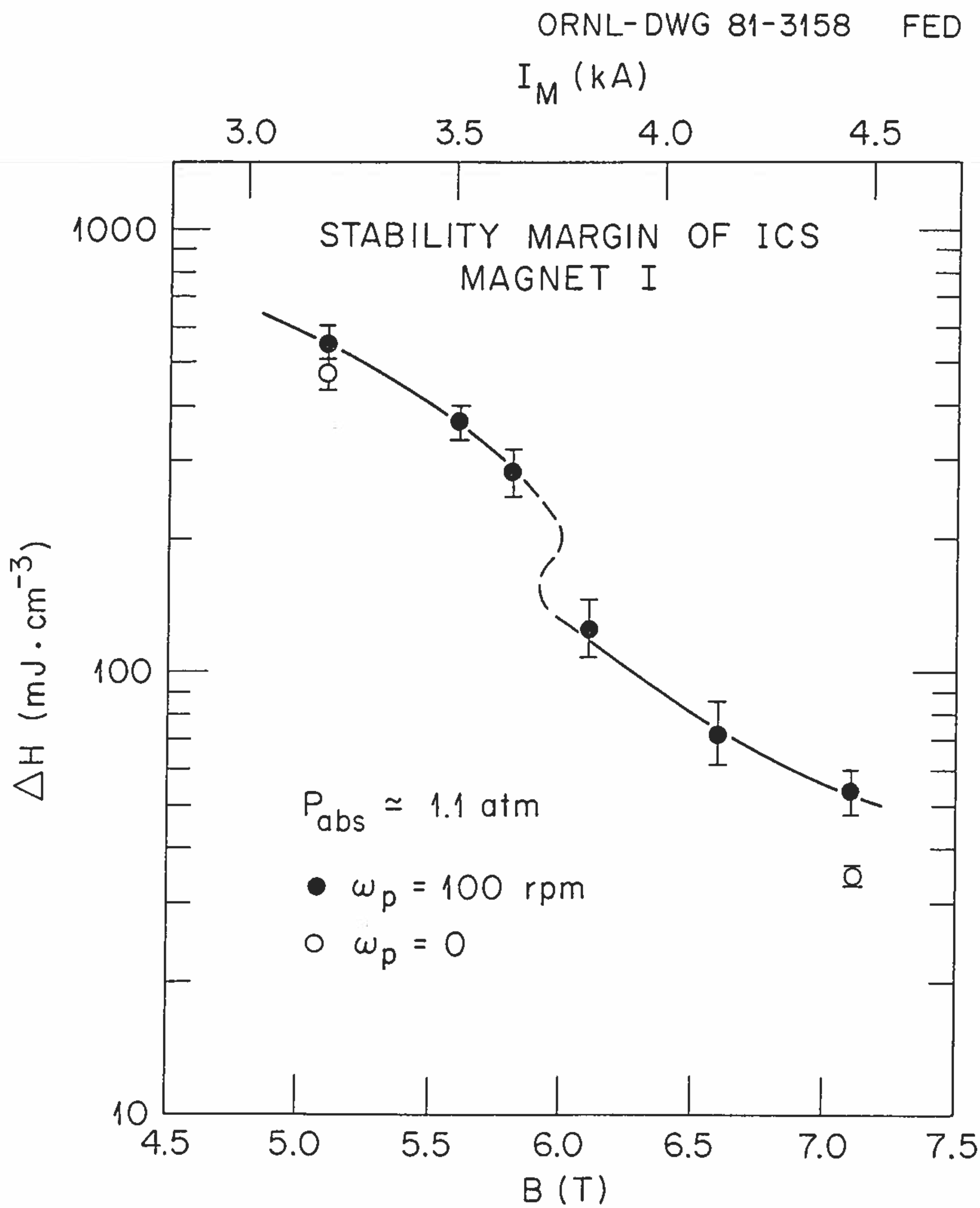


## COIL PERFORMANCE CHARACTERISTICS

| | |
|---|---|
| MAXIMUM CURRENT/FIELD ATTAINED @ 4.2 K | 4815 A/7.68 T |
| MAXIMUM CURRENT/FIELD ATTAINED @ 3.9 K | 5100 A/8.13 T |
| MAGNETIC STORED ENERGY @ 7.68 T | 267 kJ |
| CURRENT DENSITY OVER THE CABLE SPACE @ 7.68 T | 11.3 $kA/cm^2$ |
| MAXIMUM CHARGE RATE (LIMITED BY POWER SUPPLY) | 45 s TO 7.1 T |
| STABILITY MARGINS @ 1.1 atm 4.2 K | 56 $mJ/cm^3$ @ 7.0 T<br>590 $mJ/cm^3$ @ 5.0 T |



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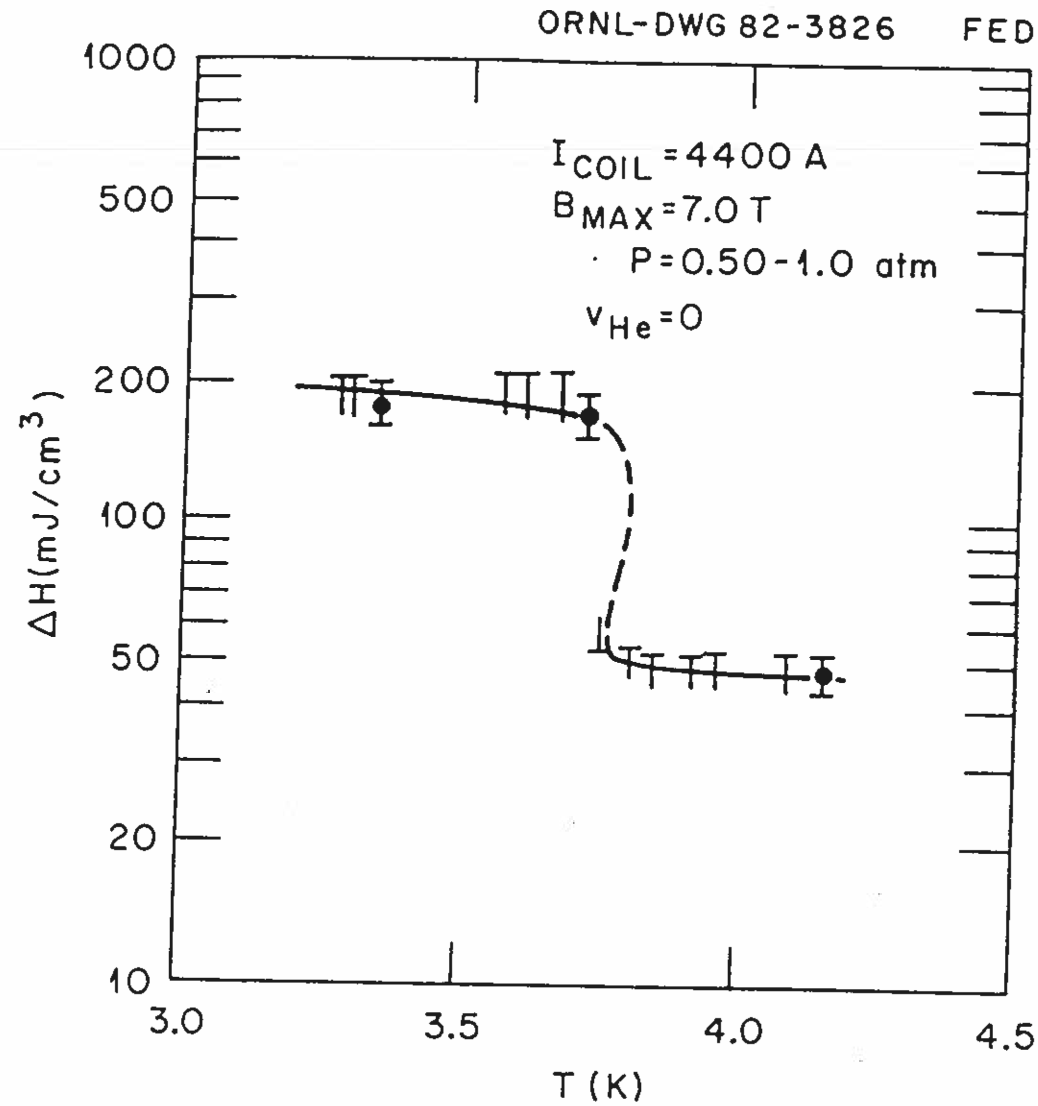
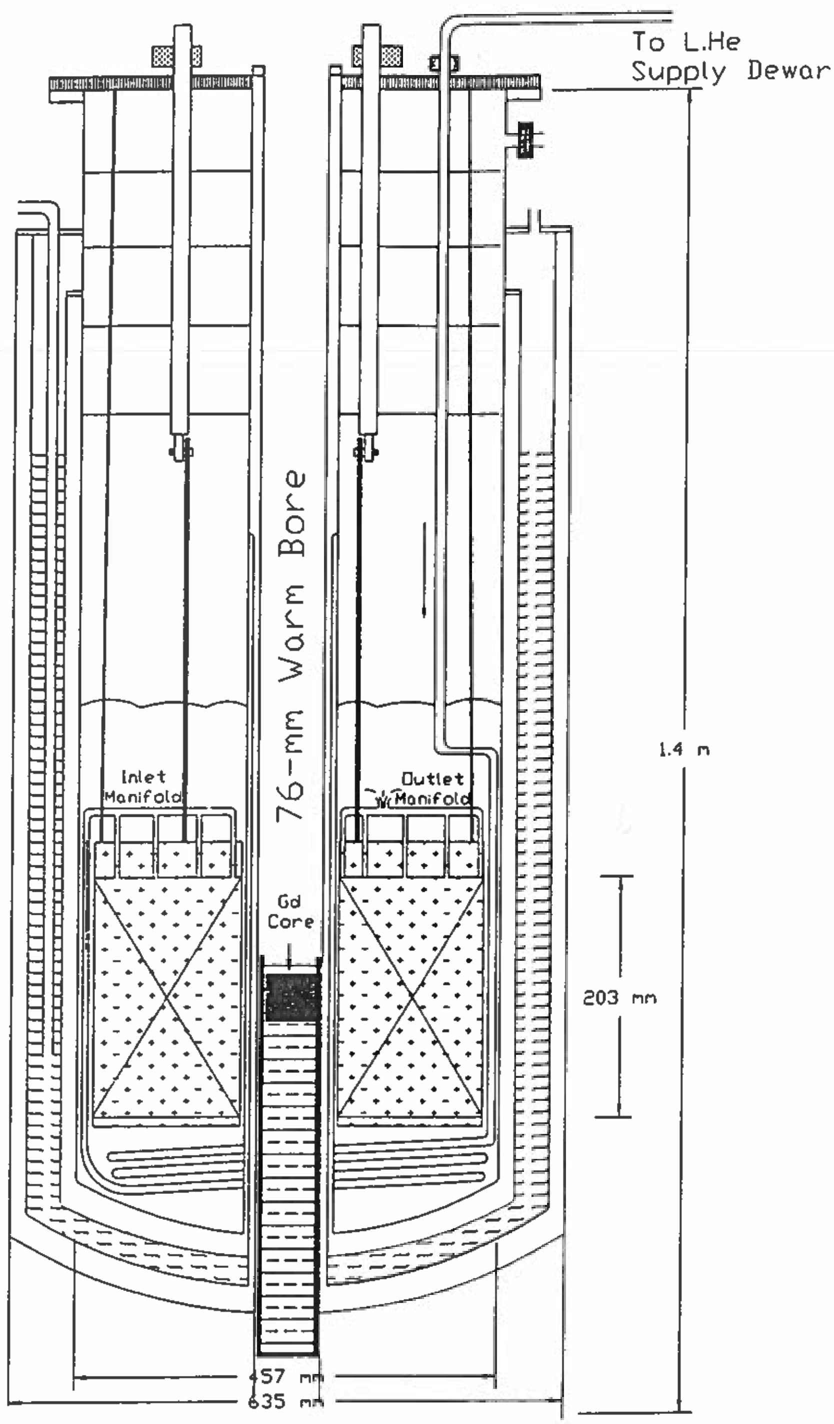
I_M (kA)
3.0
3.5
4.0
4.5
STABILITY MARGIN OF ICS
MAGNET I
1000
100
10
ΔH (mJ · cm^-3)
P_abs ≃ 1.1 atm
● ω_p = 100 rpm
○ ω_p = 0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
B (T)




- Higher stability margin was achieved by lowering the helium temperature.




Liquid Helium Cooling of the
CIC Superconducting Magnet
for a Magnetic Refrigeration Experiment

# PULSE TEST OF THE CIC MAGNET

- 18 s to a maximum field of 7.1 T: .39 T/s
- 10 s up, 10 s down triangular pulsing to 5 T for 15 minutes: .5 T/s
- Magnet quenched only when the helium supply was shut off and the liquid dropped to the level of outlet manifold
- 15 s up, 15 s hold, 15 s down, 15 s hold to 5 T duty cycle for 60 cycles in a magnetic refrigeration experiment

( Ramp rate was limited by the power supply voltage)

## Testing of the LCP Westinghouse $Nb_3Sn$ Coil

"First Tests of the Westinghouse Coil in the International Fusion Superconducting Magnet Test Facility (IFSMTF)," Dresner, Fehling, Lubell, Lue, Luton, McManamy, Shen, and Wilson, IEEE Trans. Magn., MAG-23, 1701 (1987).

"Stability Test of the Westinghouse Coil in the International Fusion Superconducting Magnet Test Facility," Dresner, Fehling, Lubell, Lue, Luton, McManamy, Shen, and Wilson, IEEE Trans. Magn., MAG-24, 779 (1988).

"Hot-Spot Measurements on the U.S.-LCT Coils in the IFSMTF," Lue, Dresner, Fehling, Lubell, Luton, McManamy, Shen, Wilson, Wintenberg, Proceedings 12th Symp. Fusion Engineering, 369, (1988).

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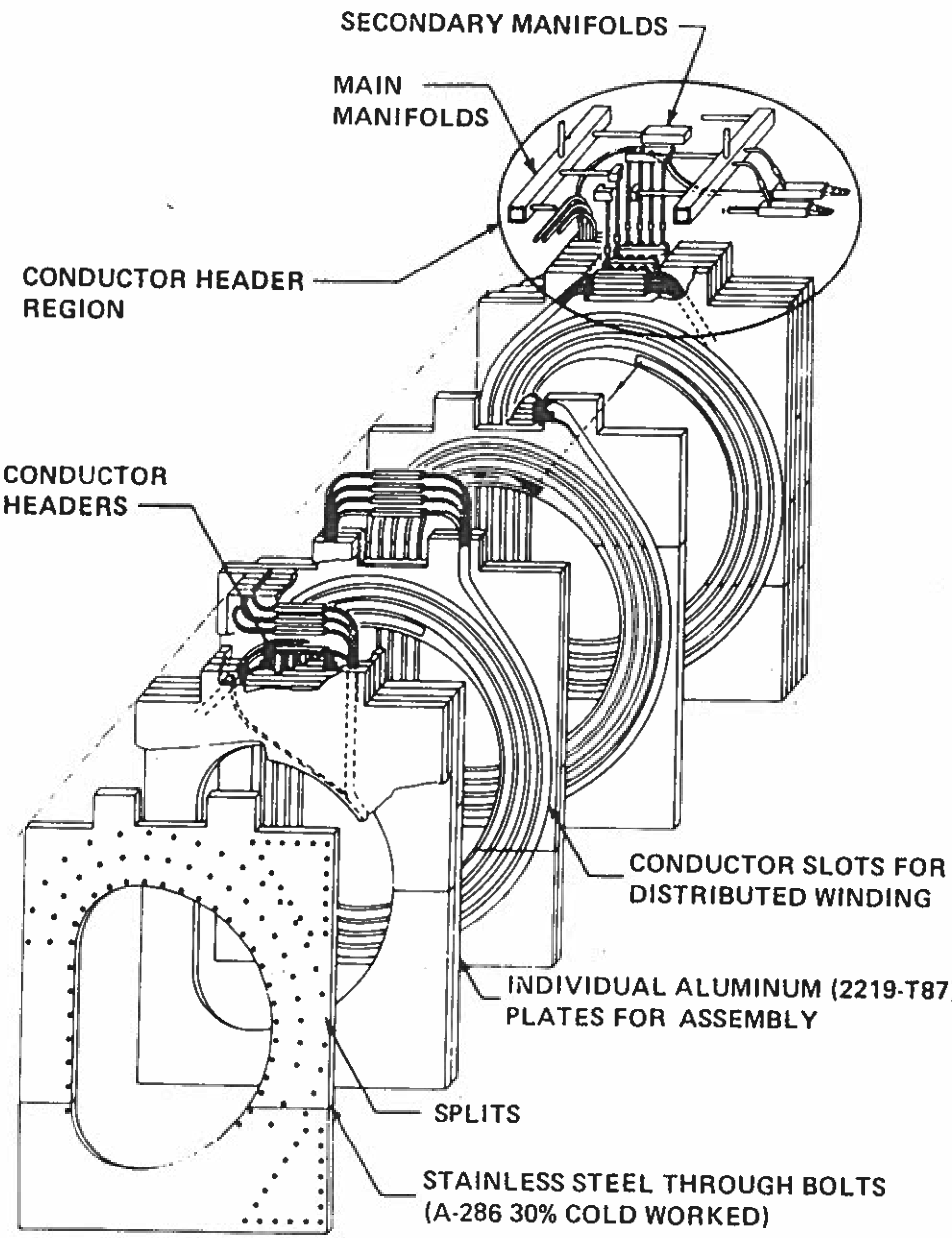
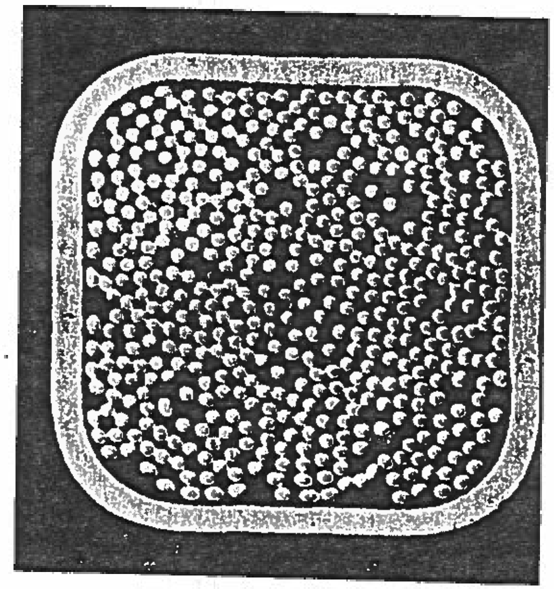


# WH-LCP Coil

- The only LCP coils to use $Nb_3Sn$ superconductor
- Met all design requirements at the rated current and field, including full recovery from an induced normal zone
- No leak was developed in the conductor conduit (4.7 km total length) and the insulation breaks
- The conductor did not meet expectations

# WH Coil Conductor

- Contains degraded regions
- Broad resistive transition scattered throughout the coil
  - Measured 14 pairs of voltage taps, each over two plates with 8.0-K inlet helium

    All showed voltages at I = 12–17.5 kA

    $V_{max}/V_{min} = 4.4$
- Onset of resistivity with increasing current is gradual
  - Power law: $\rho \sim I^n$

    $V \sim (T_c - T)^{-n}$
  - Short samples: n = 30–50
  - Using inductive heater pulses measured helium bubble temperature as it passed the downstream thermometers as well as the voltage in zone 1

    n = 4
- Resistive heat load at 23.1 kA, 8.2 T: 750 W

  0.58 mW/cm$^3$ @ v = 25 cm/s

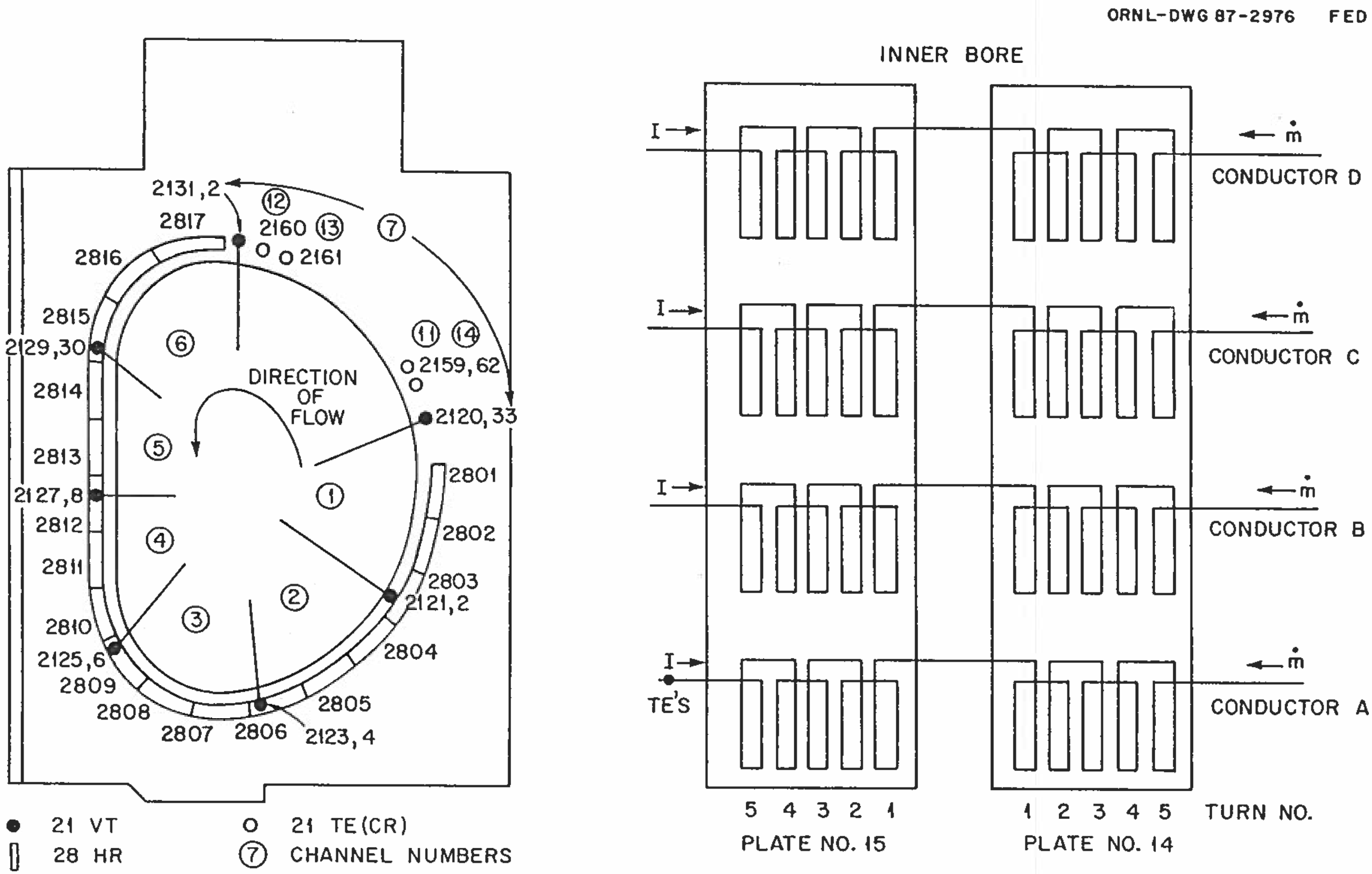
# Stability Measurements of WH-LCP Coil

- Used inductive heaters

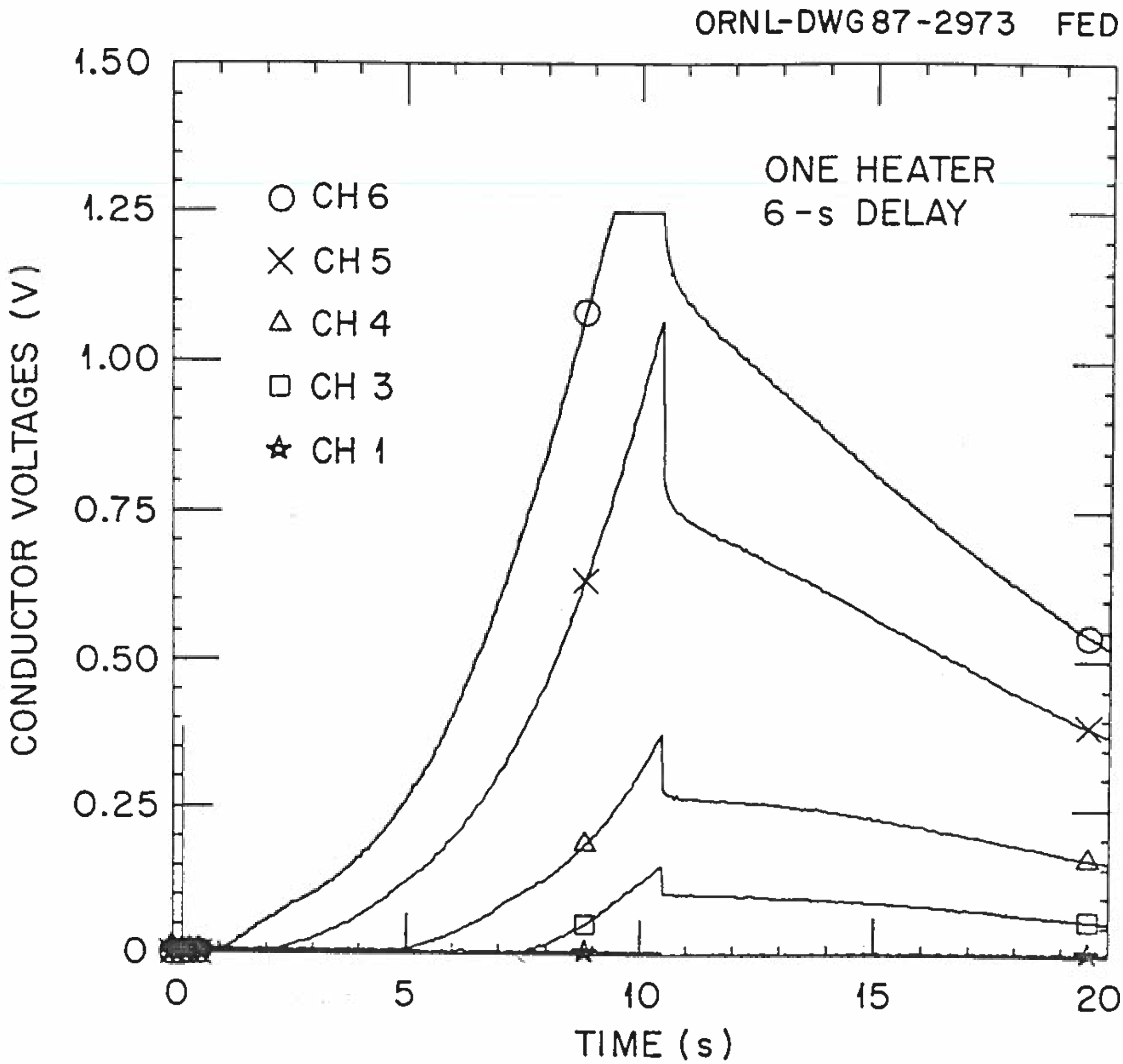
  Calibrated with the resistive heater and the downstream thermometers

- Performed in single coil mode at 100% design current

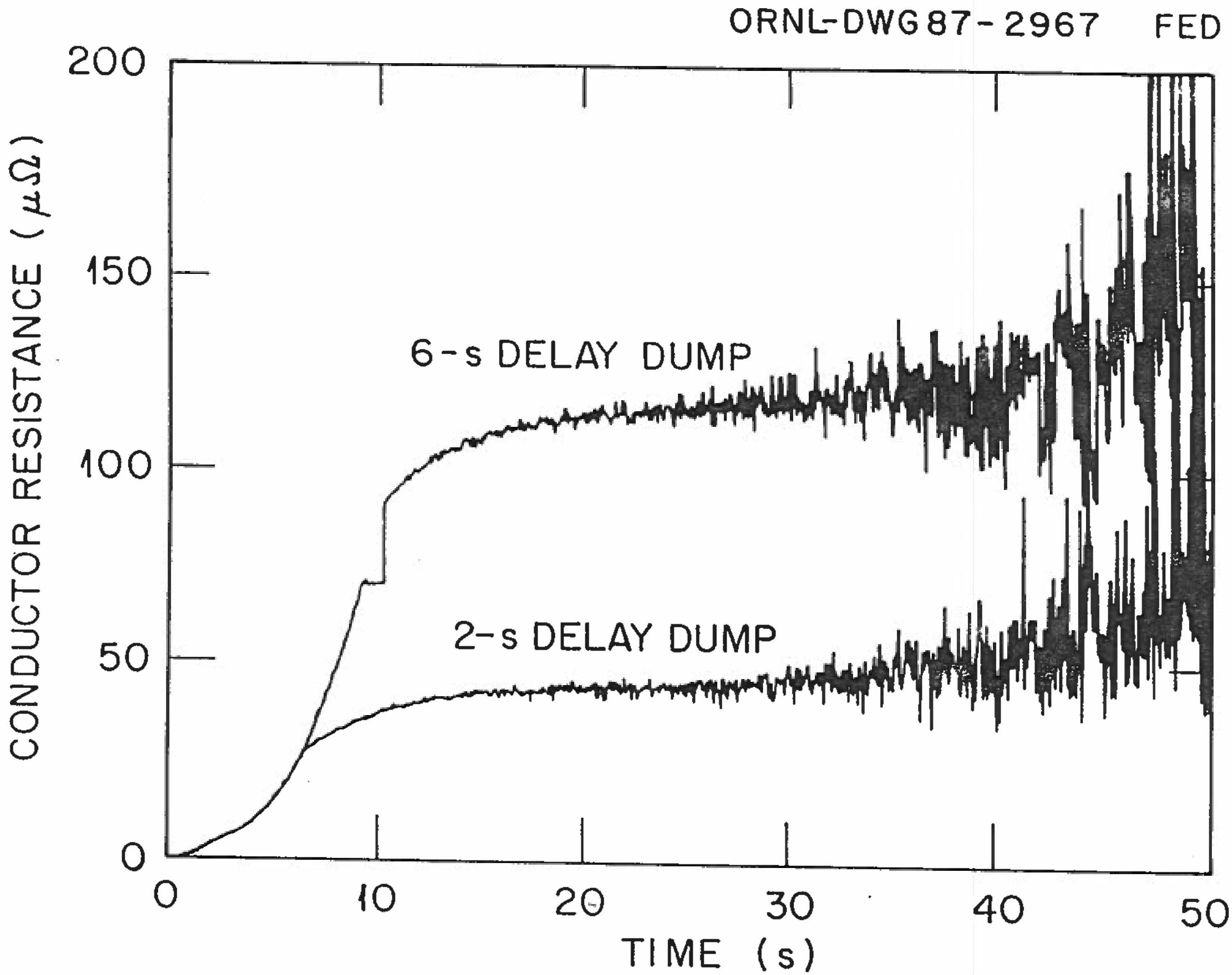
- Measured stability margin: 1.7-1.9 $J/cm^3$




The instrumented turn 1, conductor A, plate 14 of the WH coil.




Voltages of the heated zone and adjacent zones in the one-heater, 6-s delay test of WH. Plateau at 1.25 V is instrument saturation. Abrupt drops mark initiation of dump.




Comparison of heated-zone (6) conductor resistance for the 2-s and 6-s delay dump.

## HOT-SPOT MEASUREMENTS ON WH COIL

- One heater, 2-s delay: $T_{HS} = 114$ K
- One heater, 6-s delay: $T_{HS} = 205$ K
- 9 heaters, 6-s delay: $T_{HS} = 193$ K

"Development of Light Weight, High Current Density, Superconducting Magnet"

Lue, Lubell, Luton, Frame, Paulaskas, and Blake

Paper presented at MT-13, Victoria, B.C. Sept. 20-24, 1993

# APPROACH

- Cable-in-Conduit Superconductor:

  - Produce high field at high current density

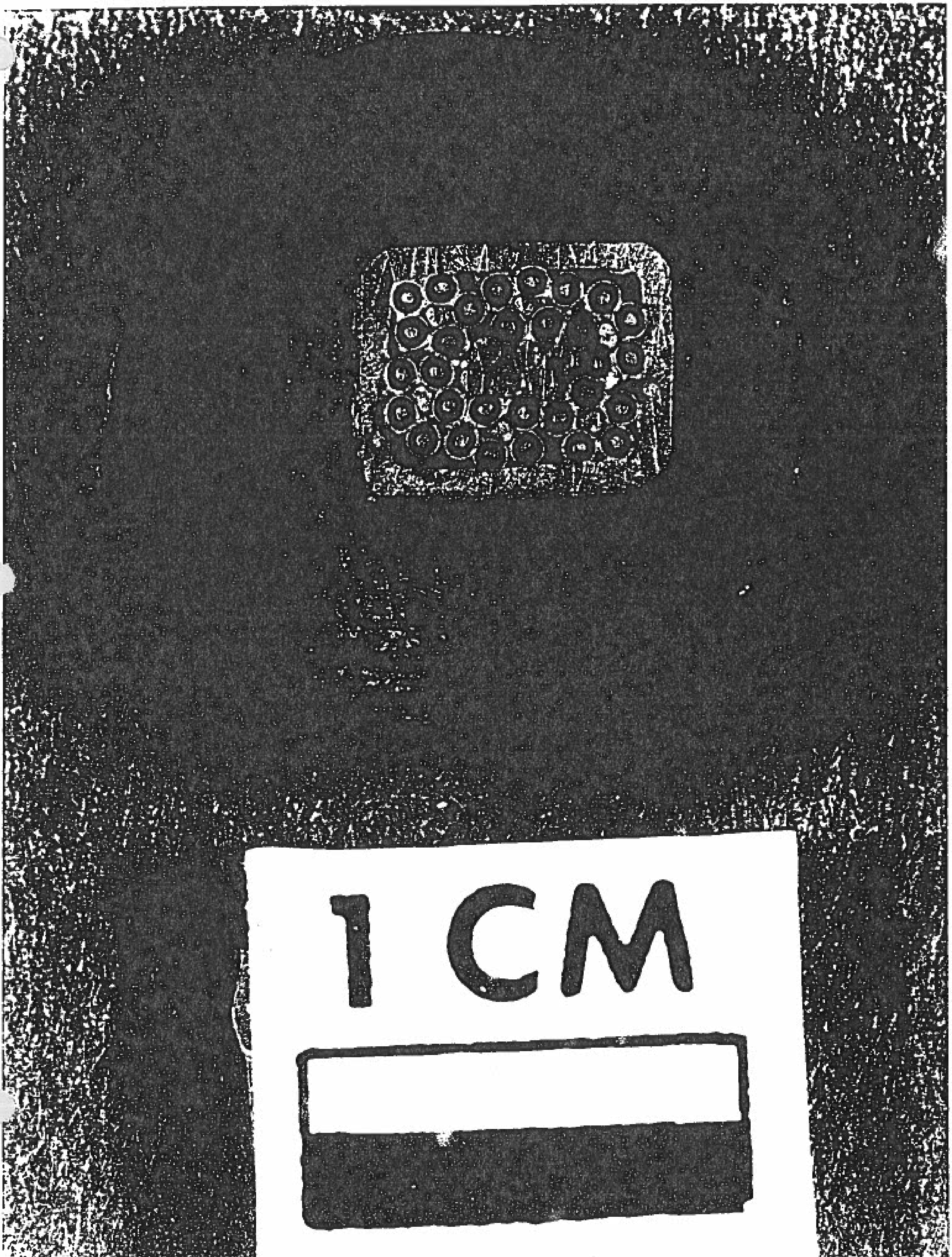
  - Al-conduit to reduce weight and ease the winding

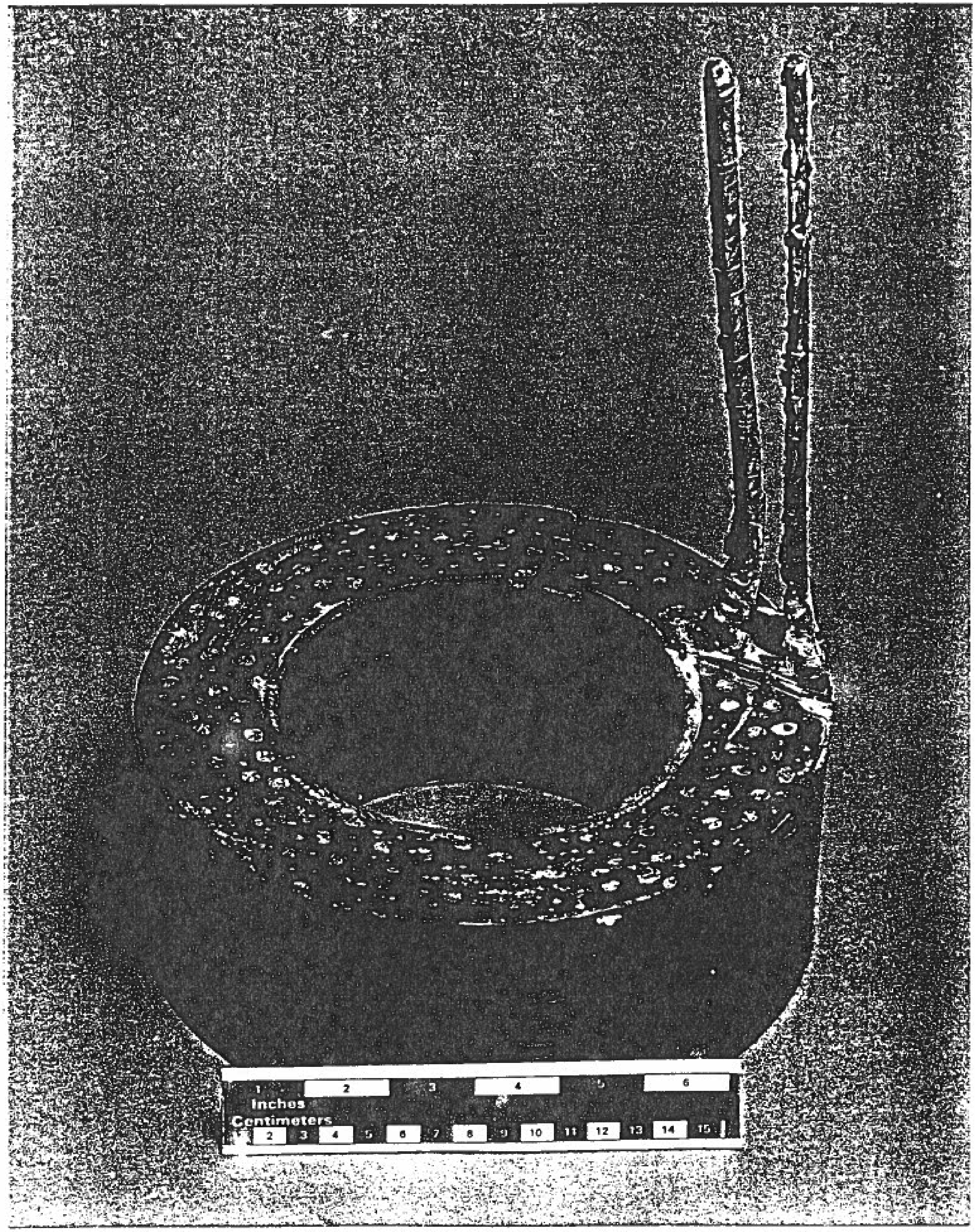
- Polymer matrix composite (PMC) structure:

  - Provide the strength of stainless steel at 1/3 the weight

# Test Coil Parameters

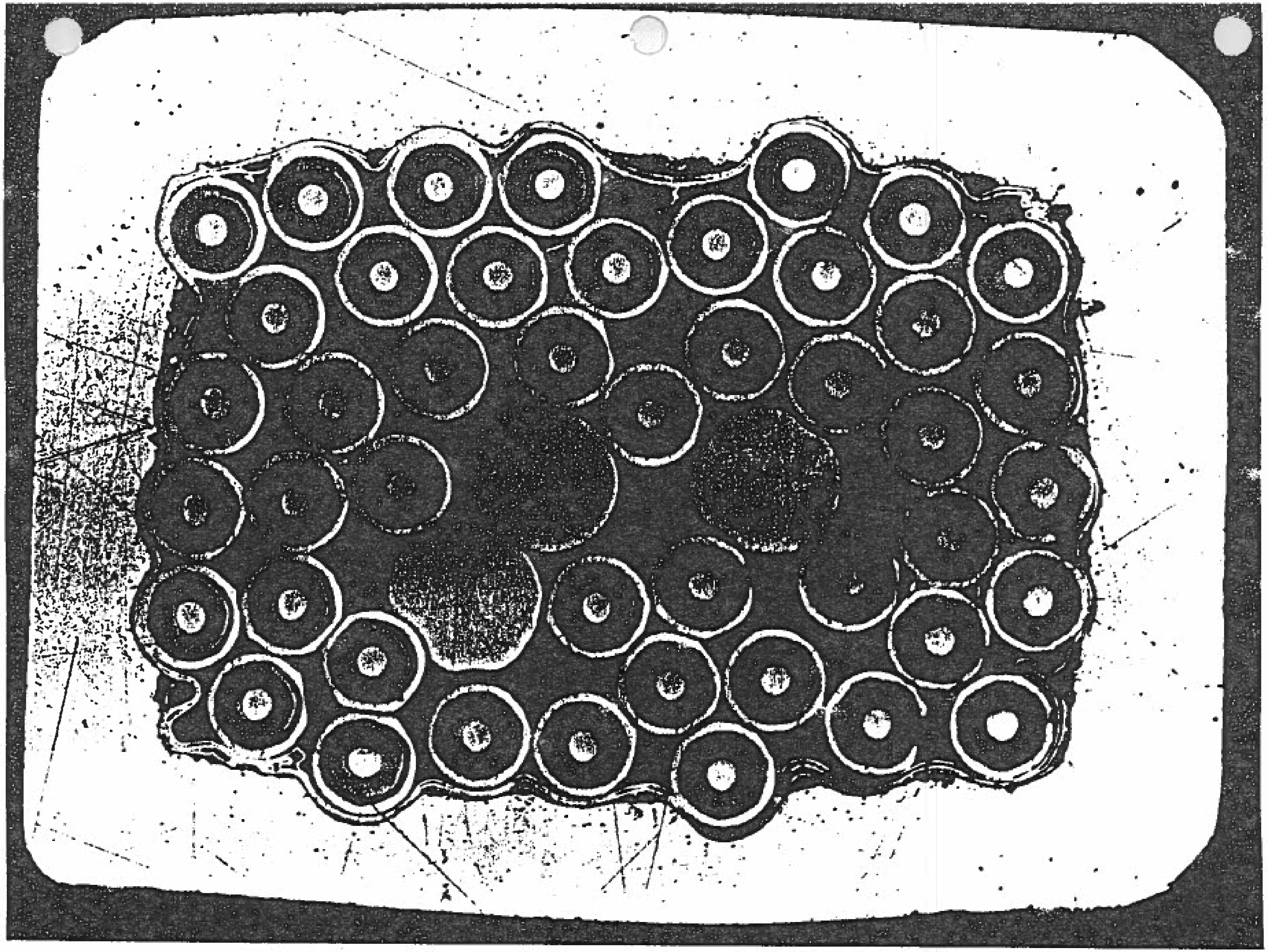
| | Coil #1 | Coil #2 |
|---|---|---|
| Superconducting strands | 0.808 mm SSC wire | 0.526 mm Fermi wire |
| Strand Cu/SC ratio | 1.52 : 1 | 1.5 : 1 |
| Cable pattern | 6 x 5 SC subcable around a Cu-core | 9 x 6 SC subcable around a Cu-core |
| Conductor dimension | 7.2 mm x 5.8 mm | 7.2 mm x 5.8 mm |
| Conduit thickness | 0.64 mm | 0.64 mm |
| Void fraction | 28% | 26% |
| Coil dimensions | 12.7 cm ID x 21.6 cm OD x 8.1 cm H | 12.7 cm ID x 21.3 cm OD x 5.6 cm H |
| Estimated $I_c$ @ 8 T, 4.2 K | 7.0 kA | 6.0 kA |


1 CM


1 2 3 4 5 6
Inches
Centimeters
2 3 4 5 6 7 8 9 10 11 12 13 14 15

# Light Weight Demo Magnet

| Item | Parameter |
|---|---|
| Superconducting strands | 0.809 mm SSC wire |
| Strand Cu/SC ratio | 1.46 : 1 |
| Cable pattern | 5 x 3 x 3 SC sub-cable around a triplex Cu-core |
| Conductor dimension | 9.4 mm x 6.7 mm |
| Conduit thickness | 0.9 mm |
| Void fraction | 26% |
| Magnet design dimensions | 60 cm ID x 90 cm OD x 32 cm H |
| Estimated $I_c$ @ 8 T, 4.2 K | 11.2 kA |
| Design current | 7.0 kA |
| Design conductor $J_c$ | 11 kA/cm$^2$ |
| Maximum field on conductor | 8 T |
| Stored magnetic energy | 4 MJ |



Al-Conduit Cable-in-Conduit Superconductor. 1-km continuous length of this conductor has been made.

# SUMMARY 1

## 5 Steps Used to Reduce the Weight of a Superconducting Magnet

- Reduce magnet cross section: Employing cable-in-conduit conductor to achieve high current density
- Reduce conductor weight: Using Al-conduit instead of SS-conduit
- Increase packing factor: Forming the conduit into rectangular shape
- Reduce structure weight: Using polymer matrix composite instead of stainless steel
- Eliminate the bobbin: Potting the magnet and removing the mold to achieve a bobbinless coil

# SUMMARY 2

## Major Technical Problems encountered

- Mismatch in the thermal expansion coefficients of the PMC and the conductor would cause undesirable thermal stress on the conductor and limit the effectiveness of PMC as a structure.

- Continuous extrusion of Al-conduit on a cable needs be perfected to produce a flawless long length conductor