Development of Cable-In-Conduit Conductors at MIT

Joseph V. Minervini
MIT Plasma Fusion Center
Cambridge, MA

Workshop on Experience with Testing and Application
of Cable-in-Conduit Conductors (CICC)
Victoria, B.C.
September 24, 1993

OUTLINE

- History of development of CICC at MIT
- Summary of important results
- Present program for development of ITER magnets

- **Original Goals**
  - ❑ Increase superconducting magnet current densities
  - ❑ Eliminate instabilities associated with two-phase helium cooling
  - ❑ Incorporate structure in winding packs of high field, high stress magnets

- **Early Work in Cooling with Supercritical Helium**
  - ❑ 1966 - Kolm, H.H., Leupold, M.J., Hay, R.D., " Heat transfer by the circulation of supercritical helium," Advances in Cryogenic Engineering, **11**, 530, Plenum Press (1966).

- **Early Work in Forced-Flow Cooling of Superconducting Magnets**
  - ❑ 1970 - Morpurgo, M., "The design of the superconducting magnet for the 'Omega' project," Particle Accelerators, Gordon and Breach, **1**, 225 (1970)
  - ❑ 1975 - Vecsey, G., "Forced Cooling of Superconducting Magnets," Proceedings of 5th Int. Conf. on Magnet Tech., (MT-5) Roma (1975)

CABLE-IN-CONDUIT CONDUCTOR (CICC)
aka
INTERNALLY COOLED CABLED SUPERCONDUCTOR (ICCS)
aka
BUNDLE CONDUCTOR
aka
"ROPE-IN-A-PIPE"

- **Earliest Work in CICC**

  - ❑ 1975 - M.O. Hoenig, Y. Iwasa, and D.B. Montgomery, "Supercritical helium cooled 'Bundle Conductors' and their application to large superconducting magnets," Proceedings of 5th Int. Conf. on Magnet Tech., (MT-5) Roma (1975)

- **First Large Coils in CICC - DC Coils**

  - ❑ Westinghouse LCP, Nb_3Sn, React and Wind
  - ❑ MIT 12 Tesla Coil, Nb_3Sn, Wind and React

- **First Pulsed Coils in CICC - DPC Program**

  - ❑ JAERI/DPC-U1-U2, NbTi
  - ❑ JAERI/DPC-EX, Nb_3Sn, React and Wind, Rutherford Cable
  - ❑ US-DPC, Nb_3Sn, Wind and React

- **Latest Tokamak Fusion Applications**

  - ❑ All ITER TF and PF magnets will be CICC
  - ❑ All TPX/SSAT-S magnets will be CICC based on US-DPC desig

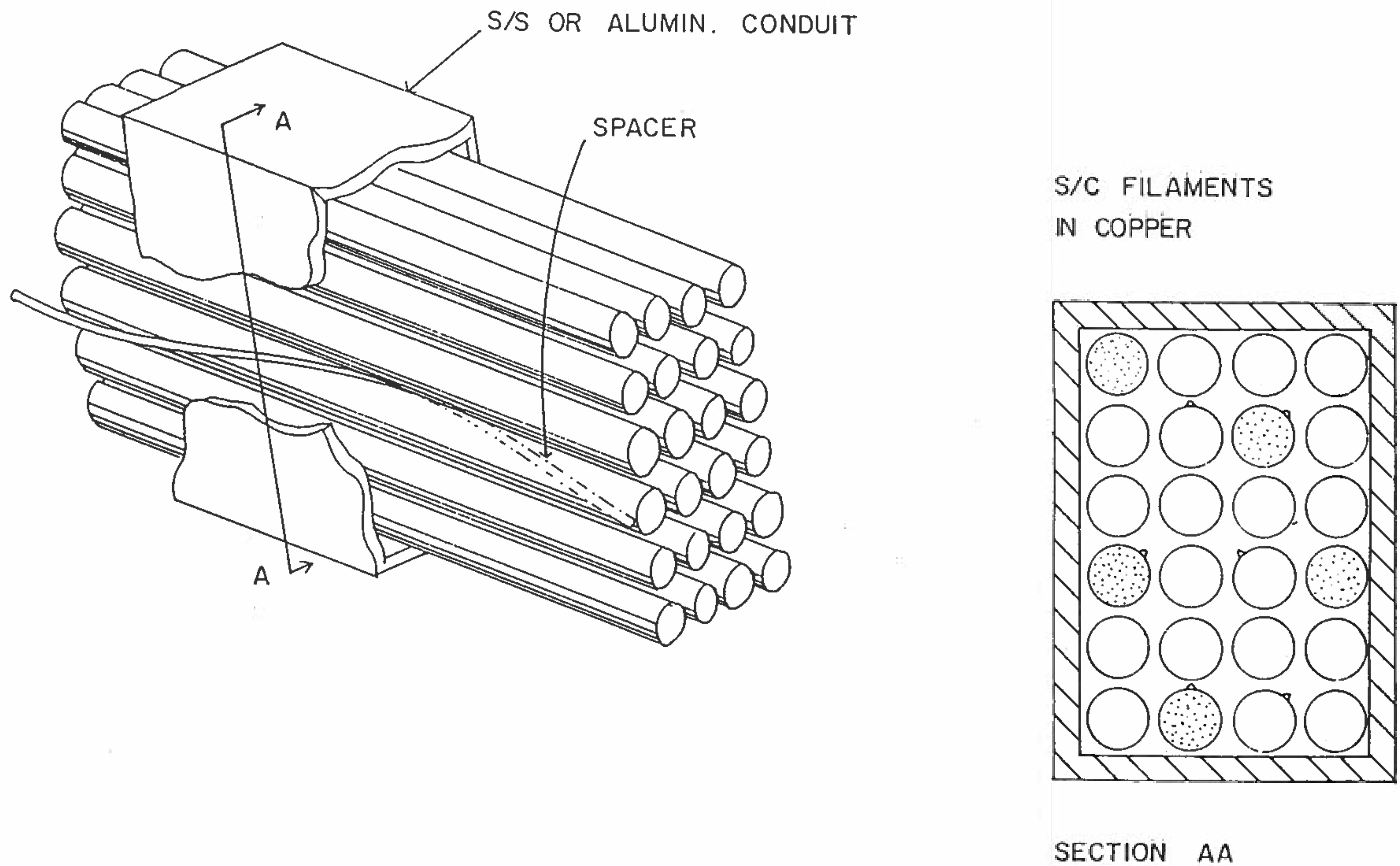
● New Applications for CICC Other then Tokamaks

<u>Other Fusion</u>

- ❑ Wendelstein VII-X - IPP Garching, Germany
- ❑ Large Helical Device, Nagoya, Japan

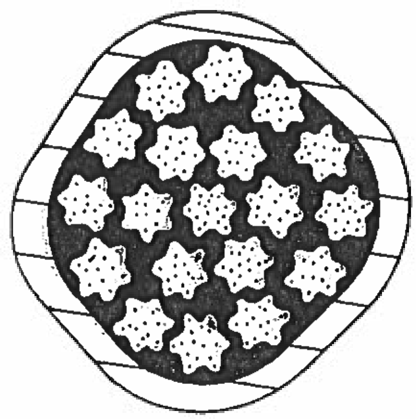
<u>Non-Fusion Applications</u>

- ❑ ENEA 12 Tesla Coil for SULTAN
- ❑ NHMFL/FBNML 40 T Hybrid Coil
- ❑ SMES
- ❑ High Energy Physics - GEM Detector Magnet for SSC
- ❑ MAGLEV
- ❑ MHD
- ❑ ?

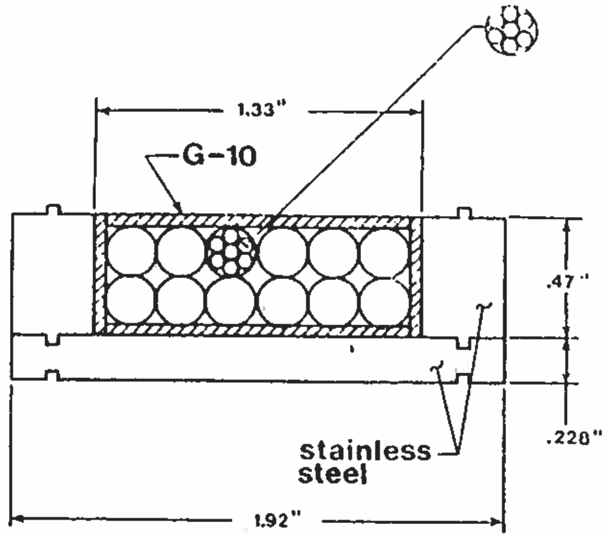


SUPERCONDUCTING CABLE WITH SPACERS BETWEEN STRANDS.

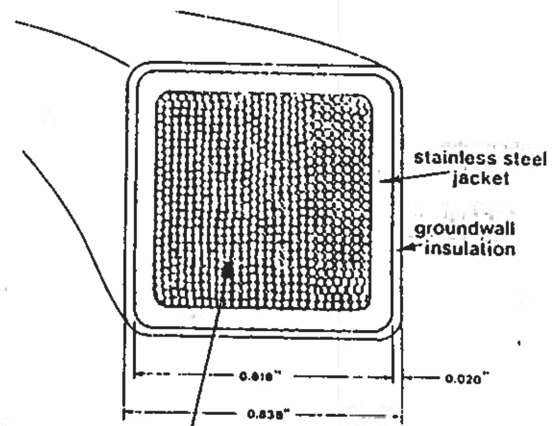
4



FLUTED-WIRE CONDUCTOR IN SQUARED-OFF CONDUIT.

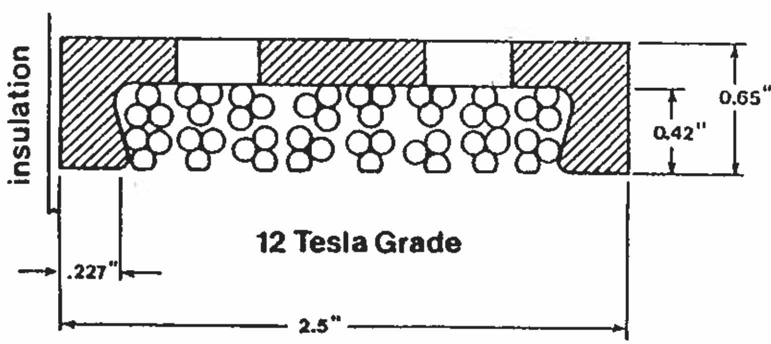


HIGH FIELD REGION (10.5T–12.0T)
CONDUCTOR and STRUCTURE

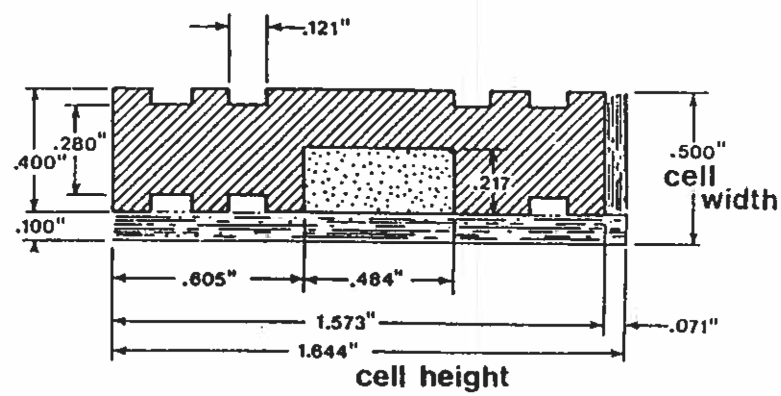


486 strands $(6 \times 3^4 \times 0.7mm\ \phi)$

all dimensions are in inches



Cross Section of CONDUCTOR GRADE



FINNED CONDUCTOR

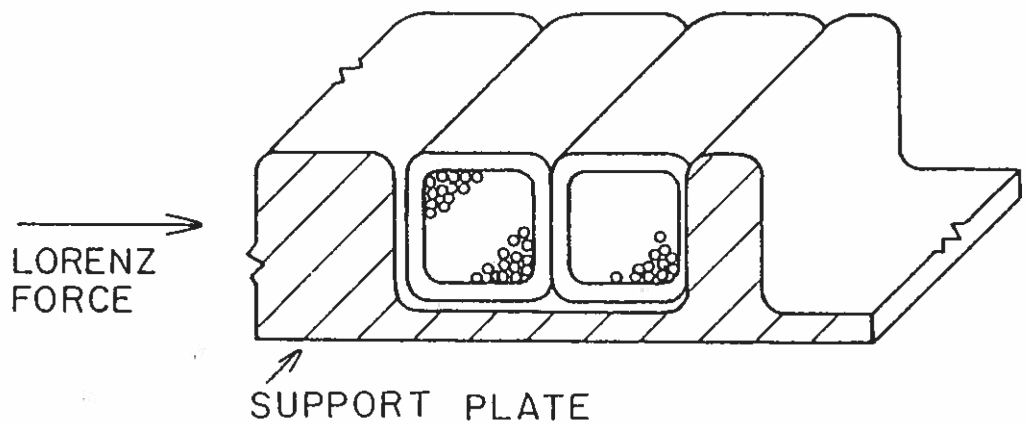
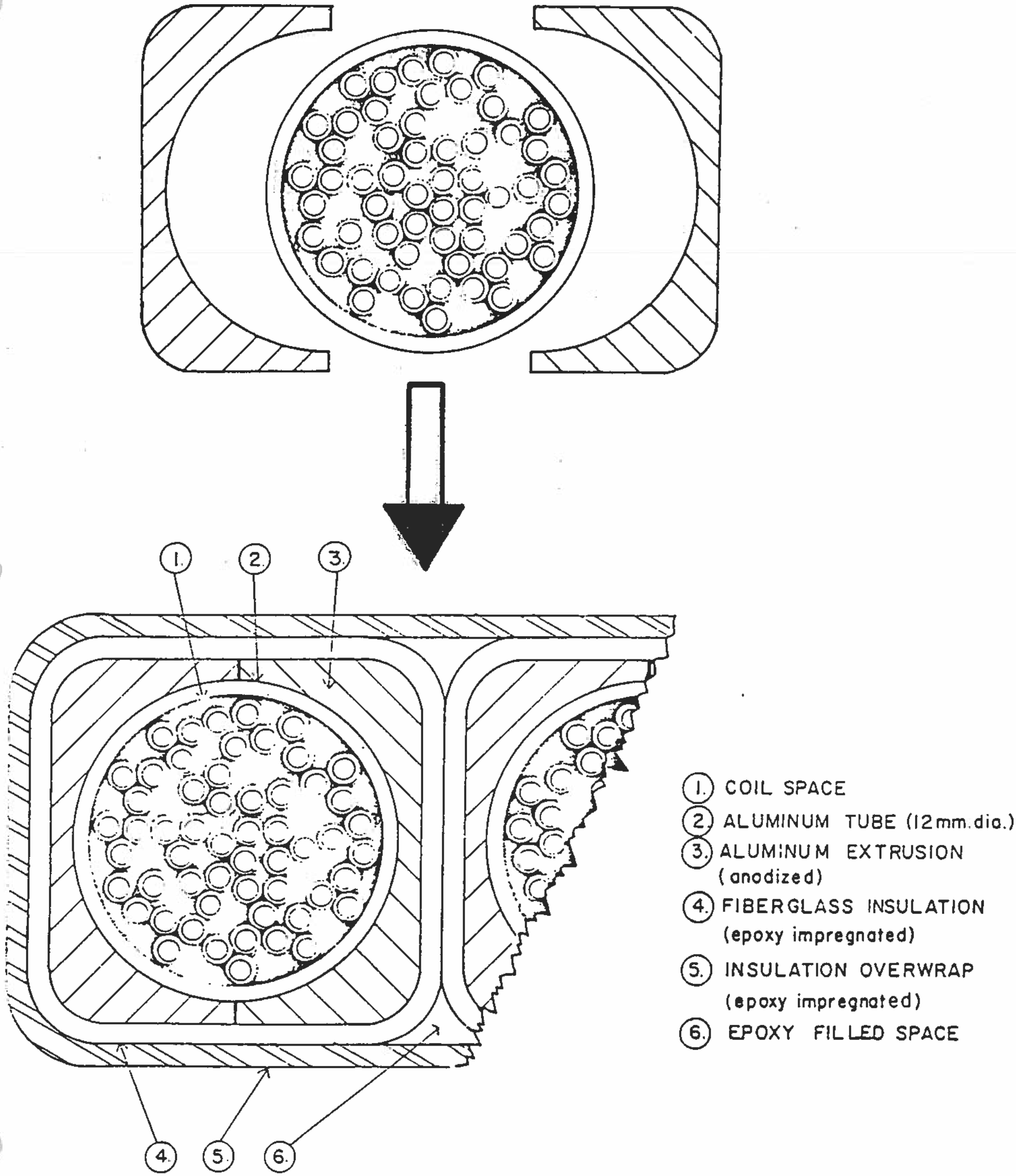
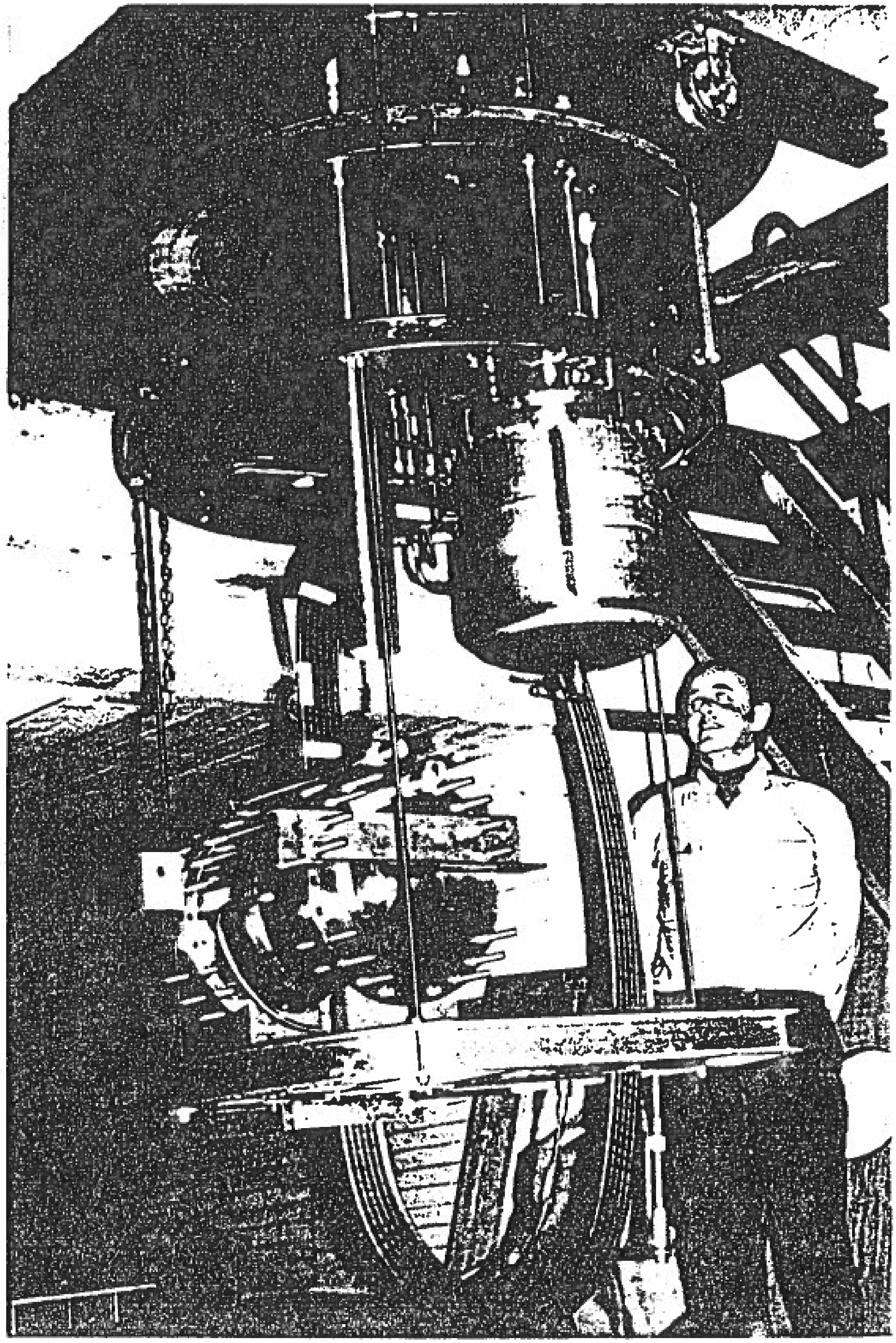
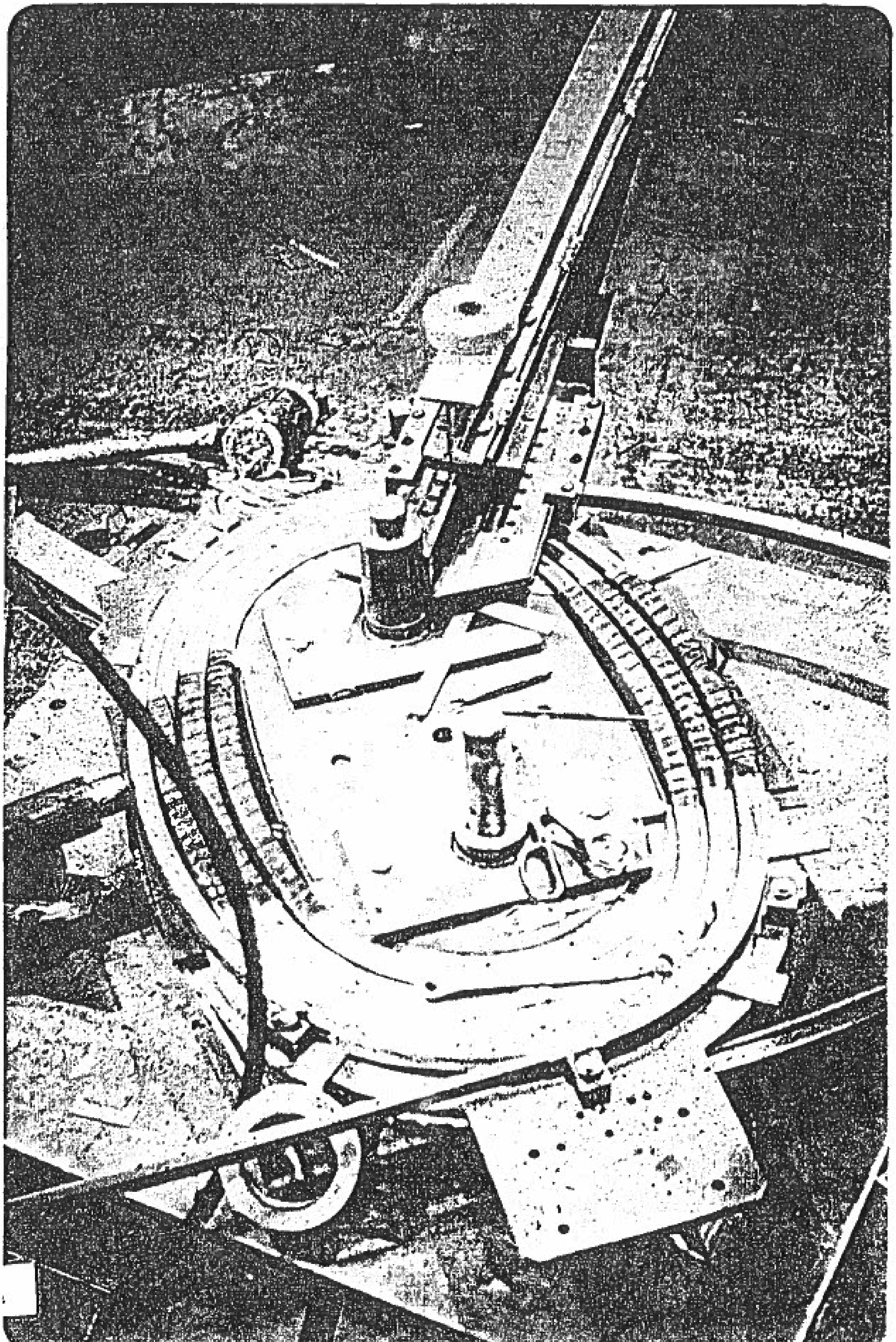


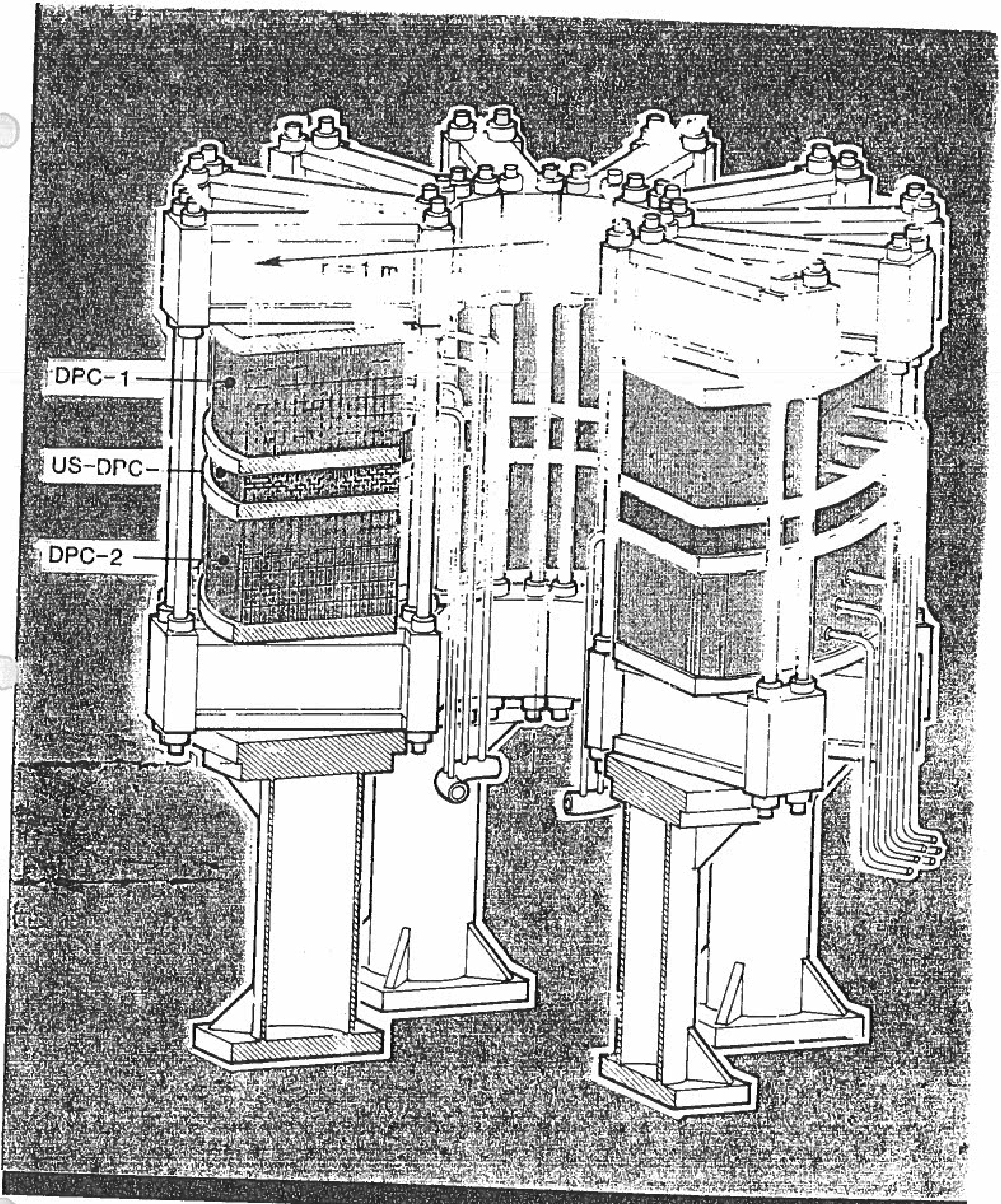
Fig STRUCTURE SUPPORTING TWO CONDUCTORS LAID INTO ONE GROOVE.



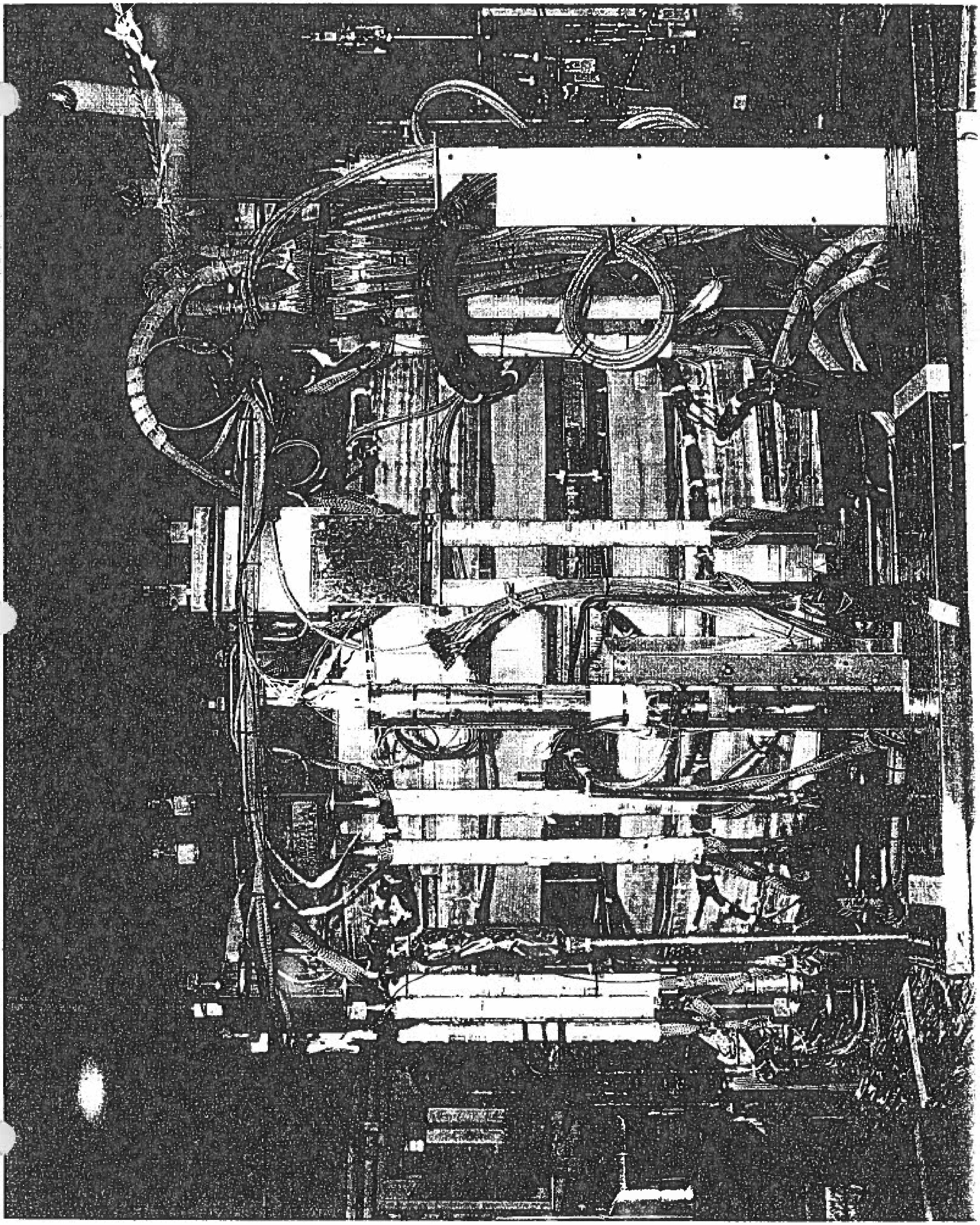
DEE COIL CONDUCTOR ASSEMBLY





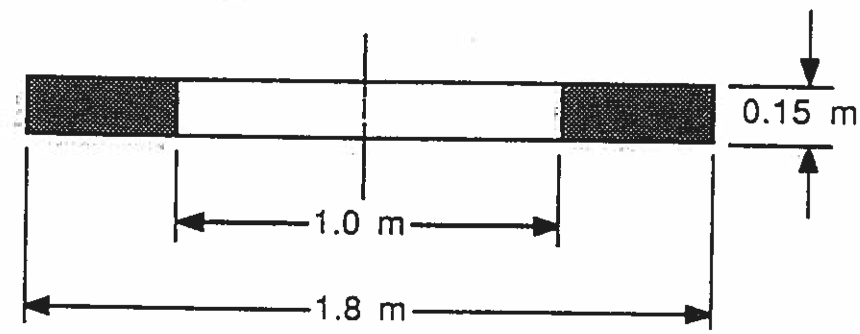


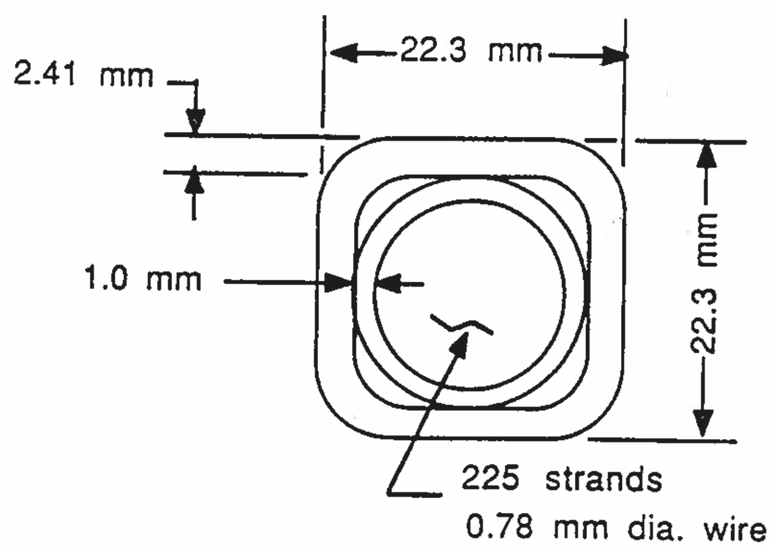
DEMONSTRATION POLOIDAL COIL (DPC) SHOWING
MIT'S TEST COIL-THE "US-DPC" IN PLACE



DESCRIPTION OF US-DPC

Field & ramp rate:	≈ 10 T, 10 T/s
Current:	30 kA
Stored energy:	≈ 8 MJ
Superconductor:	Nb_3Sn (wind and react)
Conduit:	Incoloy 908
Cooling	dual flow supercritical helium





1. The US-DPC experiment

- Dates: Nov. 5 - Dec. 20, 1990
- Goals: manufacturing process evaluation, AC operation to 10 T at 10 T/s; dual-flow cooling evaluation

2. Experiment statistics

- Two cooldowns, approximately 1 week each
- 305 runs: 73 DC and 232 AC
- 50 quenches
- Protection by bridge circuits and inlet flow reversal
- Maximum helium mass flow approximately 60 g/s
- Nominal operating condition of 4.5 K, 6 atm inlet
- Maximum test temperature 14.8 K; minimum 4 K
- Minimum flow 15 g/s
- Single-coil peak field of 5.7 T at 30 kA; 6.6 T at 35 kA
- Series peak field of 8.0 T at 25.9 kA

3. Single-coil DC tests (zero background field)

3.1 System and coil-fabrication checks

- Leak tightness: ok (vacuum vessel ≈3 x 10^{-7} Torr)
- Flow/cryogenic system: ok (4.5 K, 6 atm, 60 g/s)
- Lap joint resistance: ok (≈ 5 x 10^{-10} ohms at 30 kA)
- Protection system: ok (balance circuits; flow reversal)
- Significance: basic fabrication ok

DESCRIPTION OF RAMP-RATE LIMITATION

1. Single-coil AC tests at JAERI

   • Ramps with 3 s flat tops (no quench):

run	ramp rate	peak field	current
139	19 T/s	3.8 T	20 kA
128	4.3	4.3	23
122	2.7	4.7	25
124	0.71	5.7	30
134	0.55	6.0	32

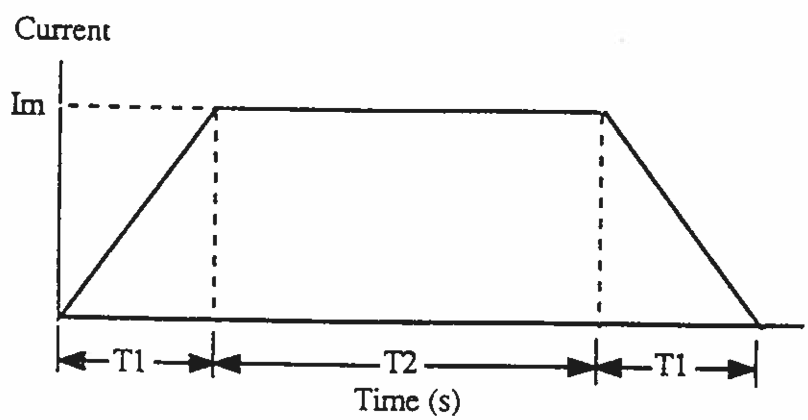
   • Attempts to exceed values listed resulted in quench at or near the transition to flattop

2. Series AC tests

run	ramp rate	peak field	current
265	6.4 T/s	6.4 T	21 kA
266*	11	9.2	30
271	2.3	6.8	22 ramp+half sine
277	6.8	6.8	22 ramp+ripple

* quench at transition to flattop

   • Run 266 - no quench during ramp! Wire went to 100% of critical current



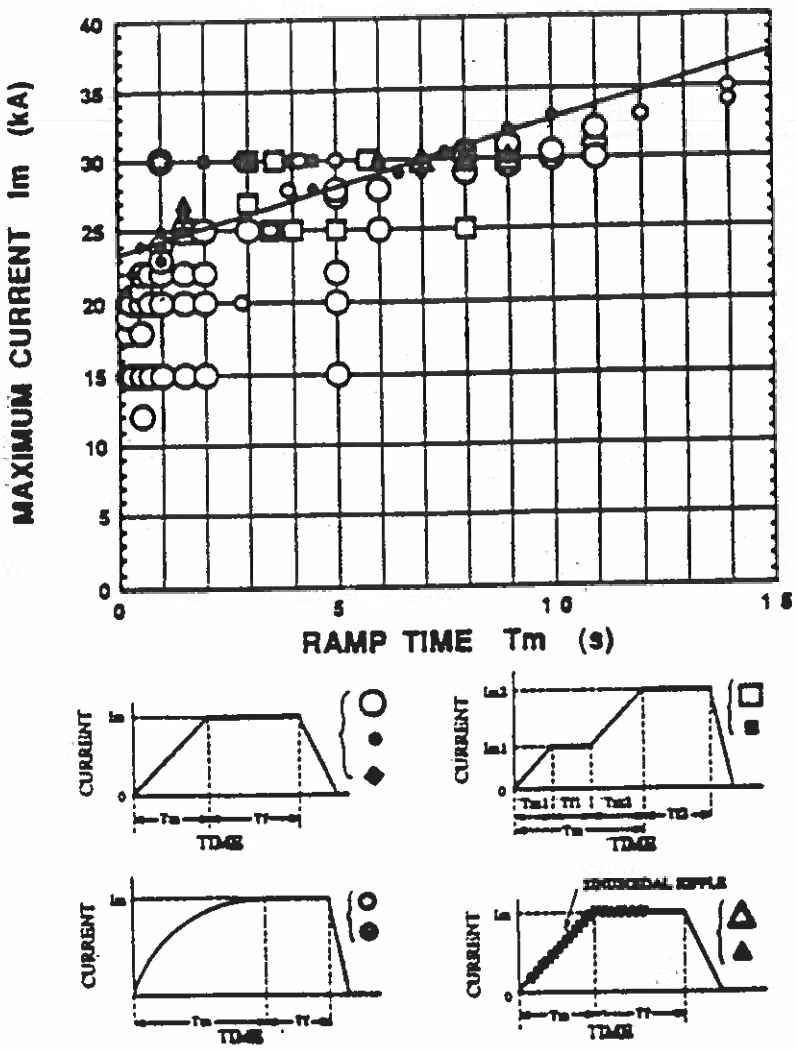
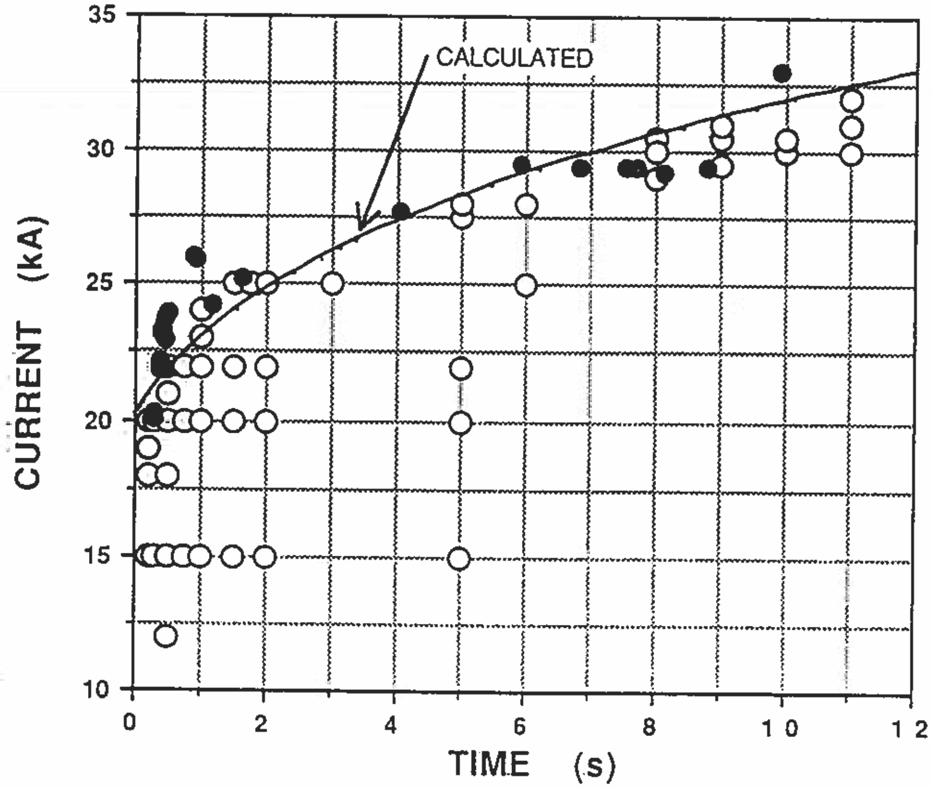


Fig. 7. Current versus ramp time in single-coil mode for four pulses: trapezoids (large circles; diamonds for joint quenches), two-step ramps (squares), ramps with rounded edges (small circles; crossed circles for quenches), and ramps with superimposed ripple (triangles). The solid marks indicate quenches. The circled star shows expected operation. The line is a fit to the solid circles (quenches with trapezoidal waveforms).

US-DPC SINGLE OPERATION

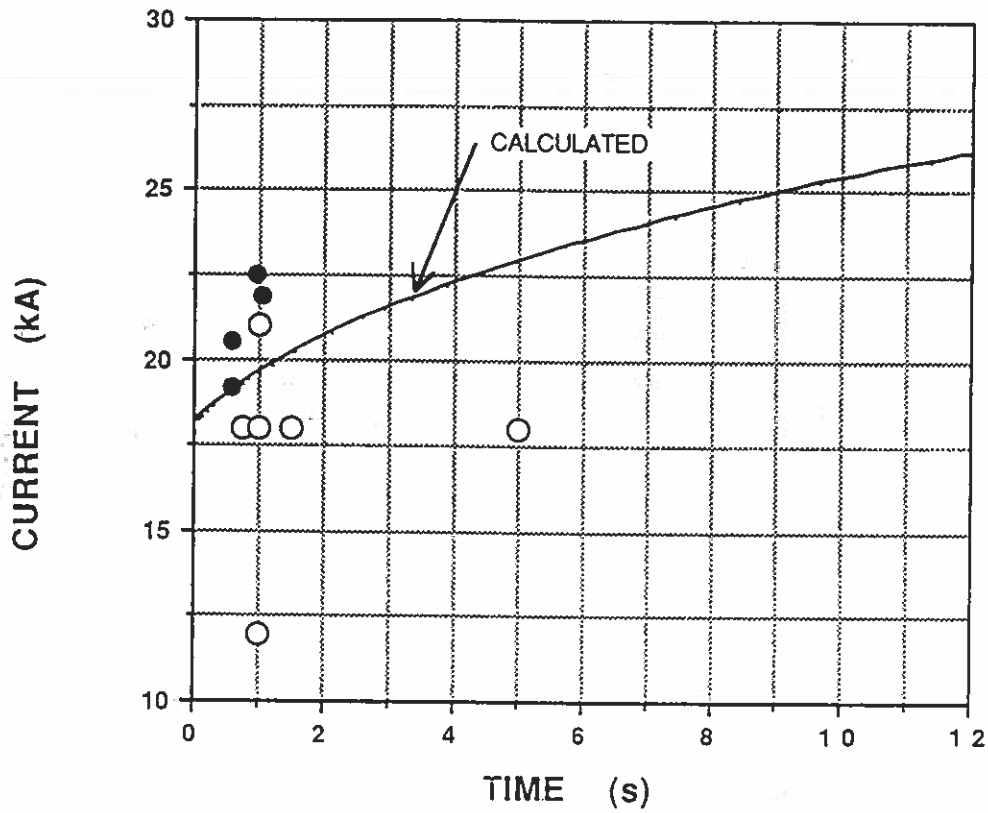
(Quench Data : USVB-56 Vb = 33 mV)

FILE : US-DPC FIT single



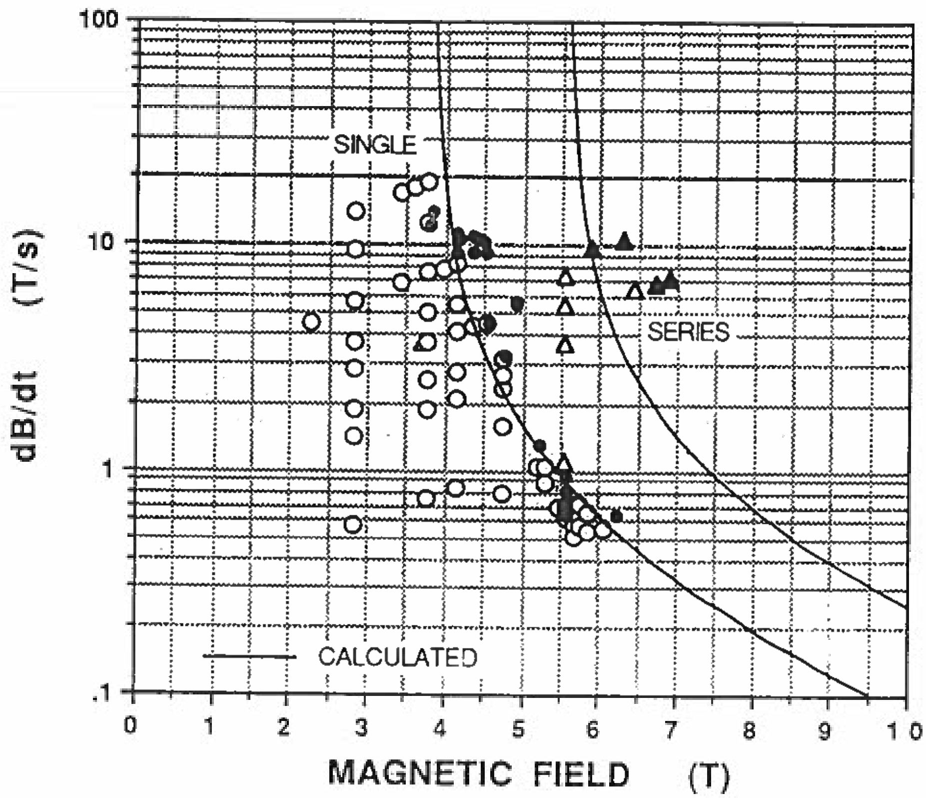
US-DPC SERIES OPERATION
(Quench Data : USVB-56 Vb = 33 mV)

FILE : US-DPC FIT series 14/8-GF



FILE : US-DPC FIT dB 14/8-GF

US-DPC SINGLE AND SERIES TESTS



Summary of Important Results

- *Induced flow* - high transient heat transfer, net mass flow required primarily for steady state heat removal, not for stability (Shanfield)

- *Effect of conduit material and void fraction on critical current* - strain effect on J_c due to different COE of conduit and Nb_3Sn strand (Steeves)

- *Development of strain compatible conduit material* - Incoloy development leading to INCO Alloy 908 (INCO and MIT (R. Ballinger))

- *Wind, react, insulate coil fabrication method* - MIT 12 T coil and US-DPC coil (Steeves, Olmstead and Hoenig).

- *Chrome plating* - to prevent sintering of strands and reduction of cable AC losses (Montgomery)

- *Dual channel cooling* - Used in US-DPC coil for enhanced heat removal (Hoenig)

- *Low resistance joints* - US-DPC coil, including parametric study of materials, processes and geometry affecting joint resistance (Steeves).

- *Stability characterization of Nb_3Sn cables* - experimental and theoretical (Minervini, Steeves, Hoenig, Schultz)

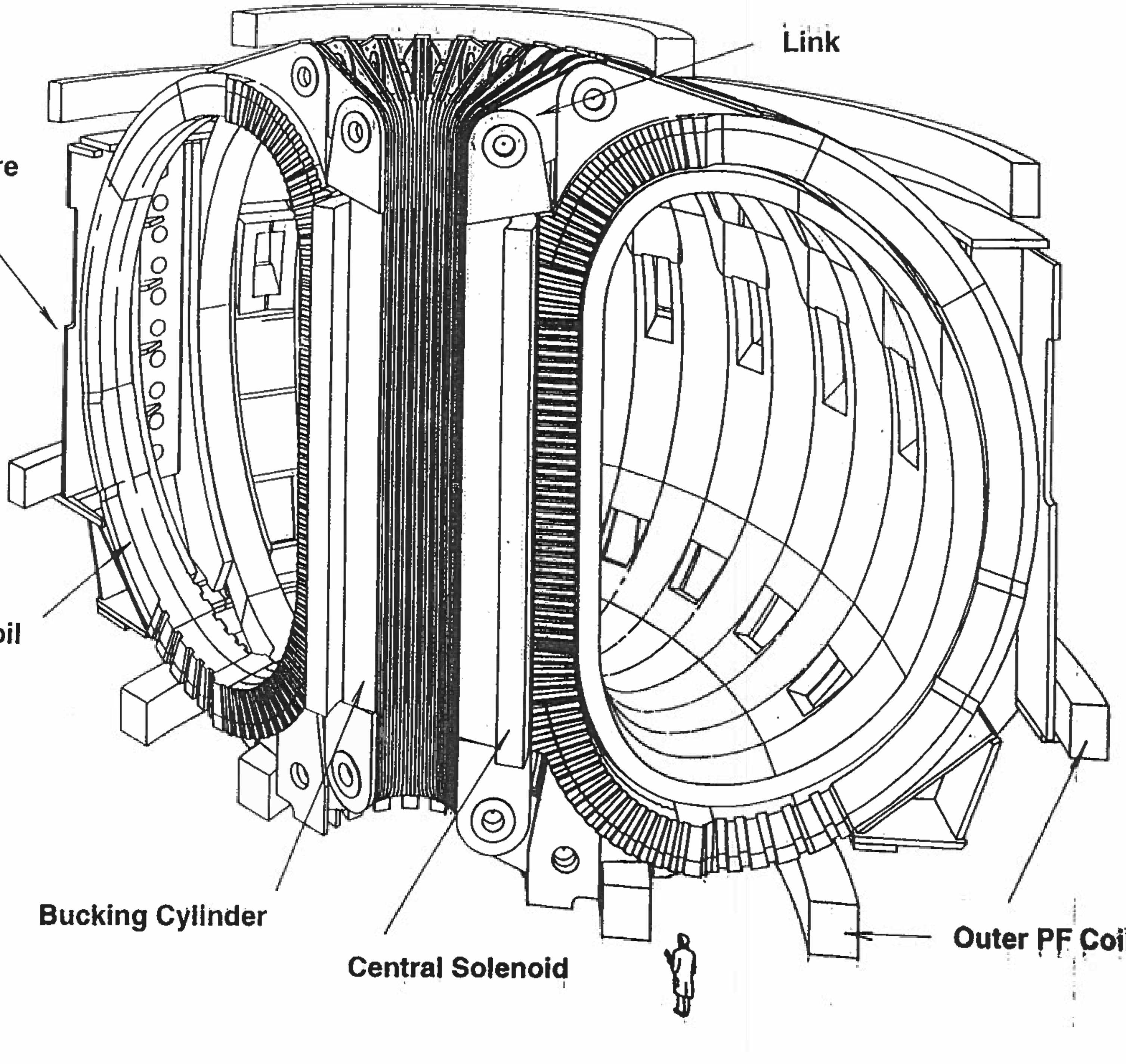
- *Ramp-Rate limitation in pulsed coil operation* - Testing of the US-DPC at JAERI

- *Characterization of inter-strand contact resistance under Lorentz force* - (Takayasu)

- *Calorimetric AC loss for simultaneous full-field and current swings* - (Gung, Takayasu)

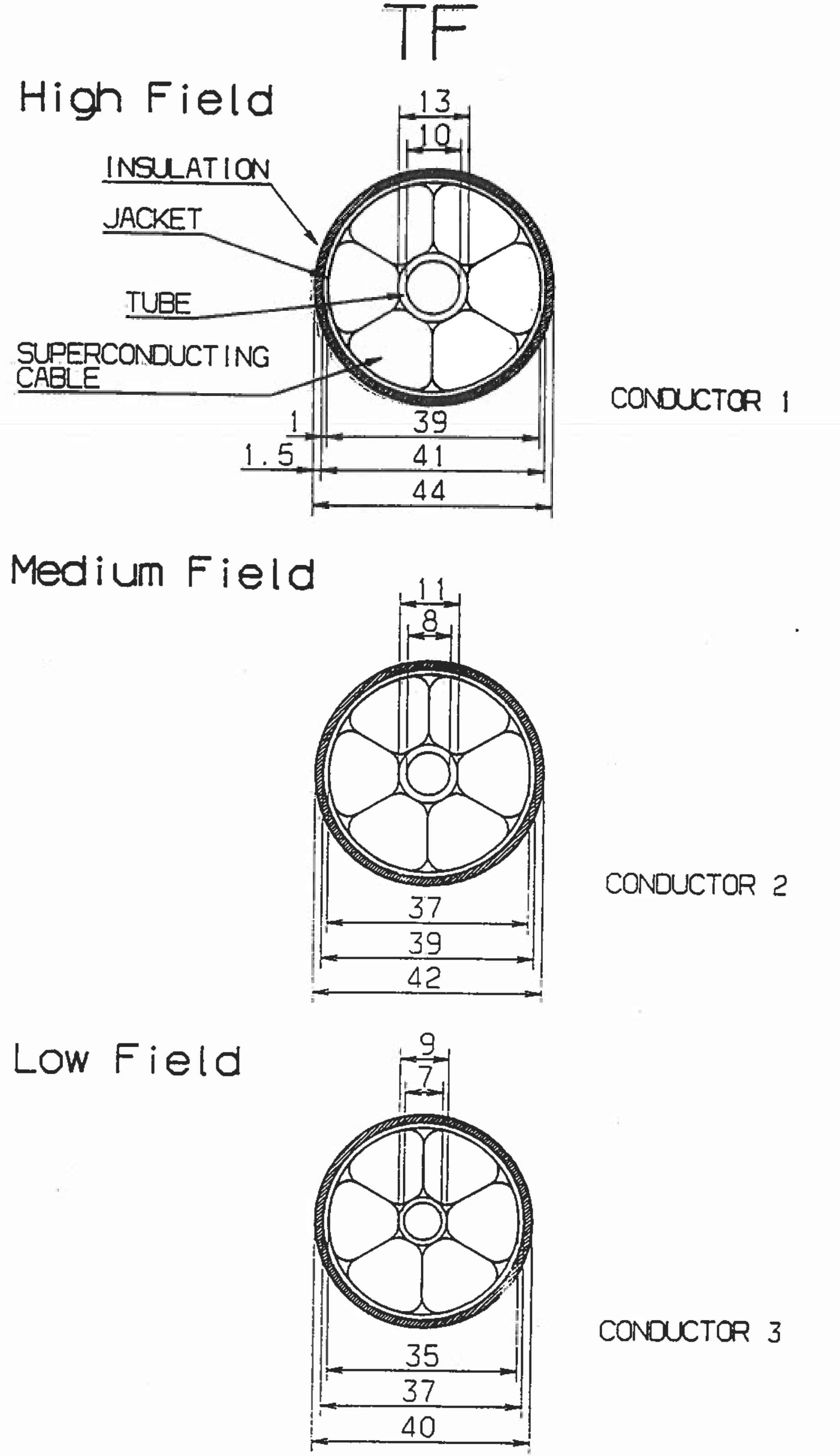
- *Thick walled seamless Incoloy 908 conduit* - development for ITER (INCO, Steeves and Randall)
  - also material characterization and welding development (Hwang, Morra, Jang, Ballinger)

- *GEM conductor development and manufacturing* - Aluminum sheath protection and roll-forming of 18 m diameter turns. (Marston, Smith, Camille, Vieira, Hale, etc.)



ıukia FRAME 1 july 23,1993 16.15.41

1200002_06_1_W_N_930721_YUK_HUG_TF_CONDUCTORS

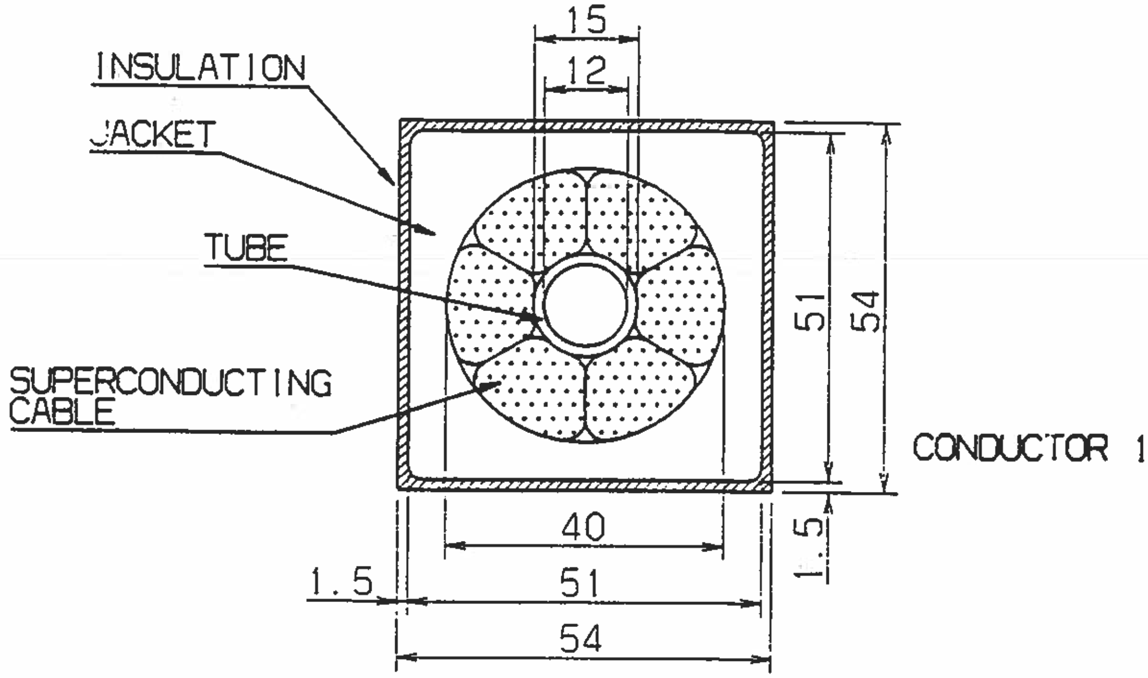


TF CONDUCTORS

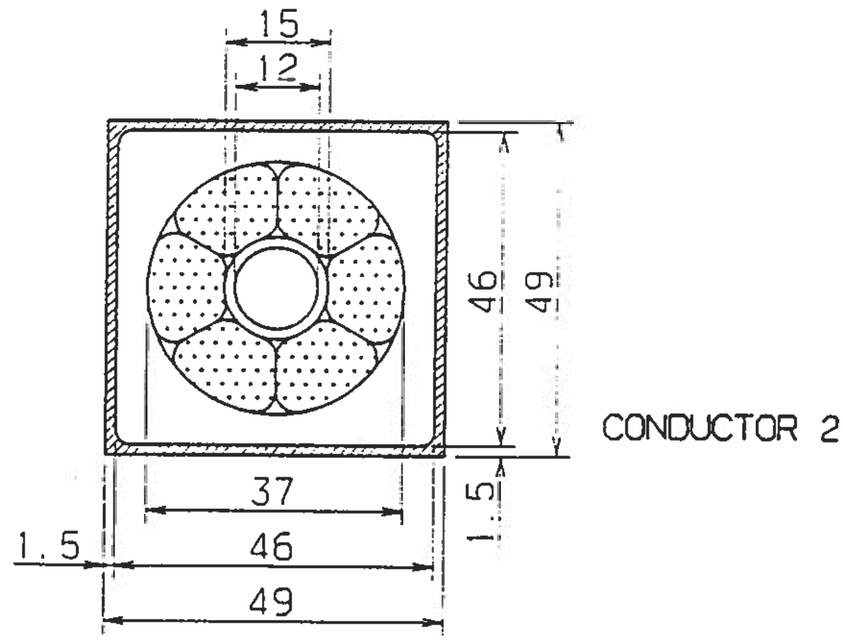
SKETCH/NAKA 9307

CS

High Field



Medium Field



1200004_04_1_W_N_930616_YUK_HUG_CS_CONDUCTORS

Program for ITER Magnet R&D

- Full-size conductor development for TF and CS model coils
  - ❑ strand development and procurement (w/ LLNL)
  - ❑ cable production
  - ❑ conduit production

- Model coil design and manufacturing
  - ❑ *General Dynamics/Westinghouse* as prime industrial contractor

- Full-size conductor and joint testing
  - ❑ Program run by LLNL in FENIX facility

- Supporting laboratory and sub-size conductor R&D program

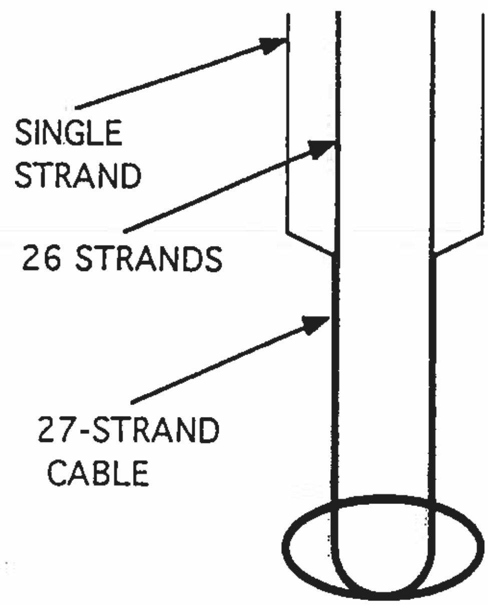
Supporting Laboratory and Sub-Size R&D Program

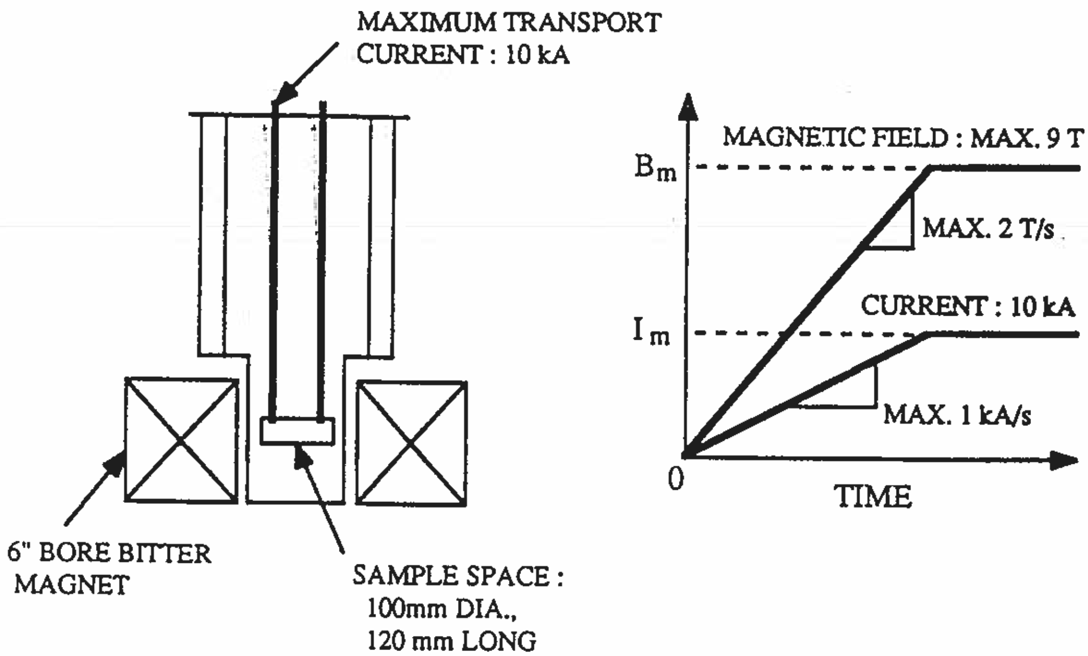
- Materials database
  - ❑ Conduit physical, mechanical and processing properties (MIT & NIST)
  - ❑ Insulation physical, mechanical, radiation and processing properties (R. Reed, CTD, NIST, ...)

- Sub-Scale Tests and Measurements
  - ❑ Strand characterization (MIT, UW, BNL, NIST, LLNL)
  - ❑ Stability and ramp-rate
  - ❑ Quench detector development

Focus is on:

→ simultaneous ramping of both current and field
→ study of current distribution in cable during ramping
→ effect of Lorentz force on contact resistance and AC losses

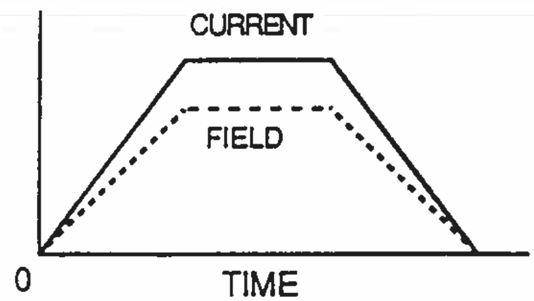

SINGLE
STRAND
26 STRANDS
27-STRAND
CABLE


MAXIMUM TRANSPORT CURRENT : 10 kA
6" BORE BITTER MAGNET
SAMPLE SPACE : 100mm DIA., 120 mm LONG
MAGNETIC FIELD : MAX. 9 T
B m
MAX. 2 T/s
CURRENT : 10 kA
I m
MAX. 1 kA/s
0
TIME

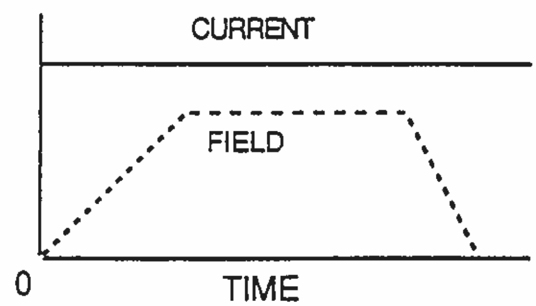
RAMP RATE LIMITATION EXPERIMENTS USING 27-STRAND CABLE

Experimental Method

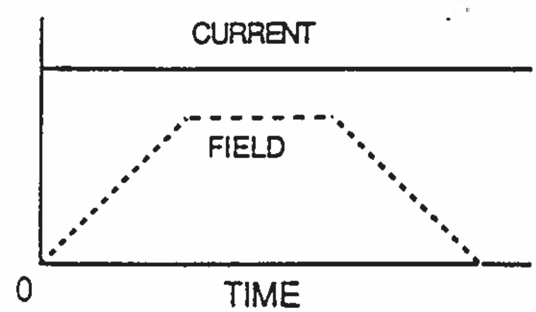
a. US-DPC Simulation

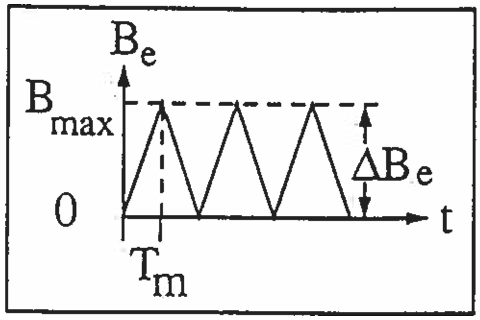


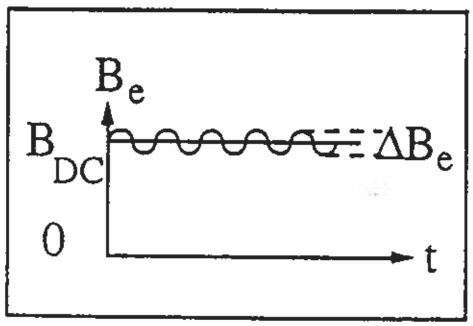
b. Ramp-down Field with DC Current

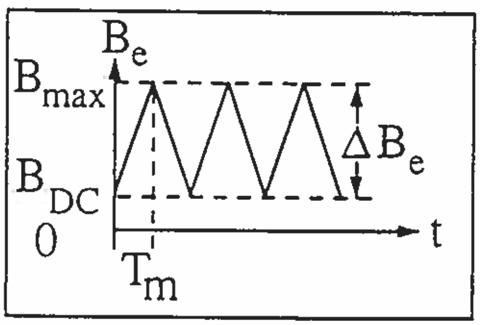


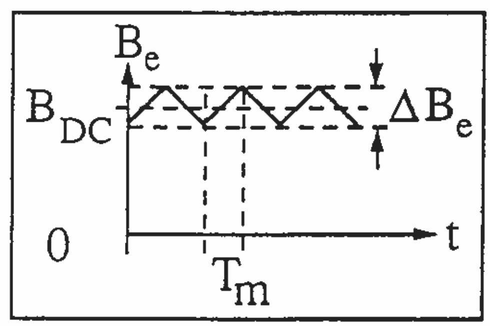
c. Ramp-up Field with DC Current

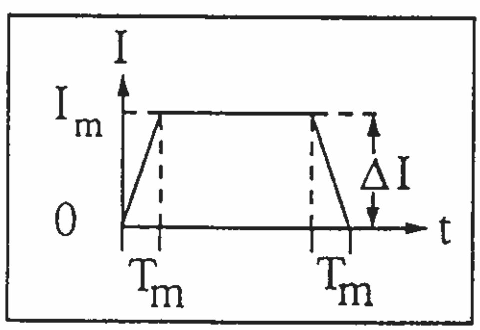



B_e
B_max
0
ΔB_e
t
T_m

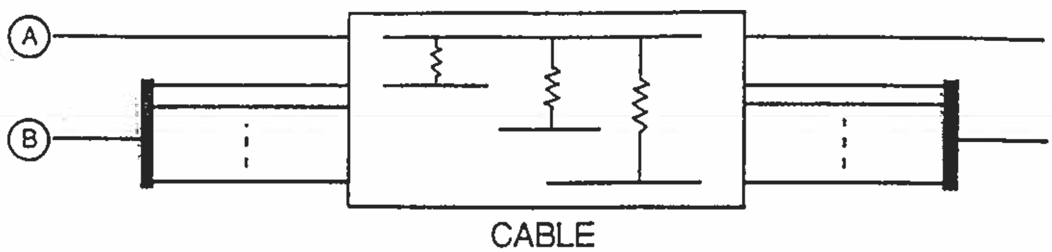

B_e
B_DC
ΔB_e
0
t


B_e
B_max
ΔB_e
B_DC
0
t
T_m


B_e
B_DC
ΔB_e
0
t
T_m


I
I_m
ΔI
0
t
T_m
T_m

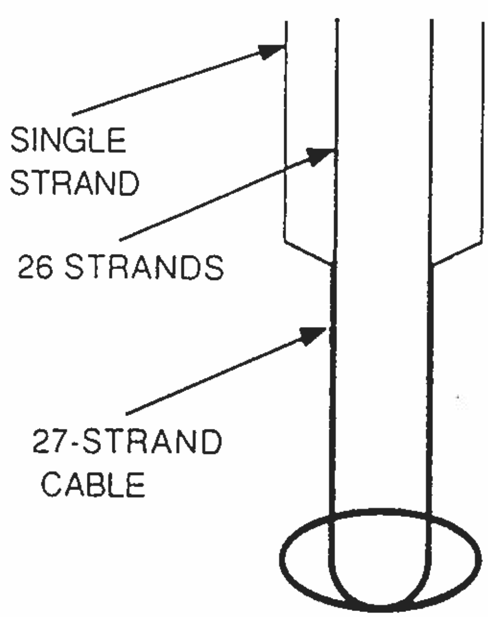
CONTACT RESISTANCE BETWEEN STRANDS



CONTACT CONDUCTANCE

$$G = \frac{1}{R} \qquad \text{(mho/m)}$$

R = Measured resistance R for 1 m cable between "A" and "B".



CONTACT RESISTANCE OF A SINGLE STRAND
IN 27-STRAND CABLE

Data from "RAMP #11 RESIST-TB"
FILE : RAMP #11 RESIST R v I-GF

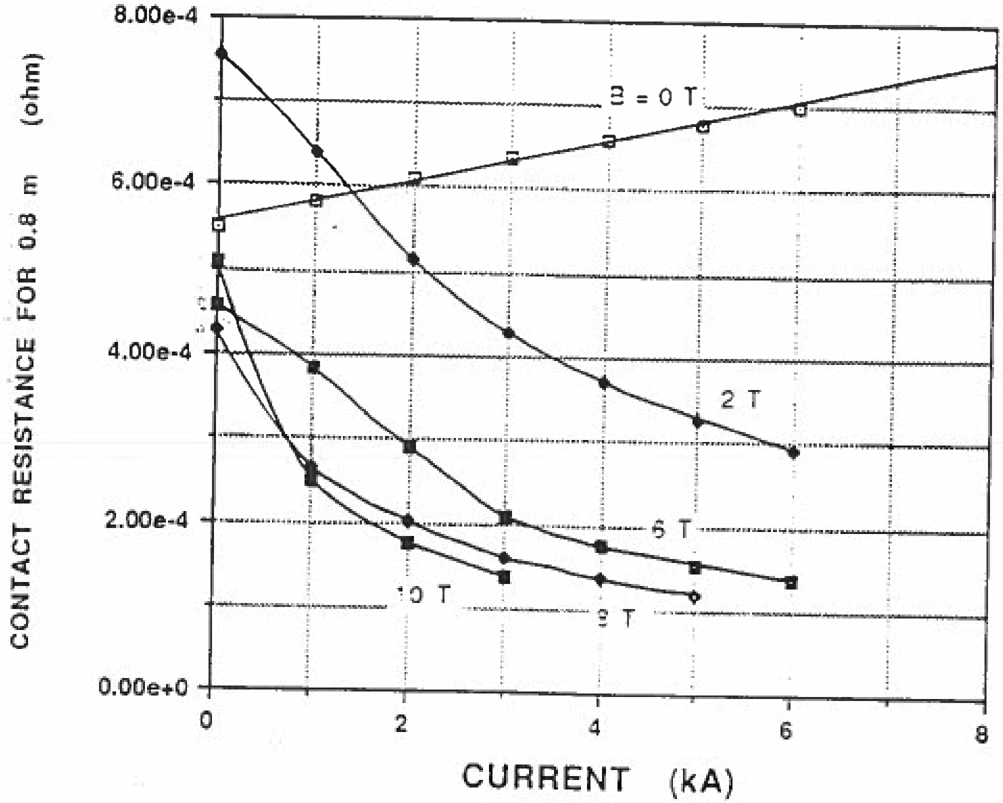


Fig. 1

CONTACT RESISTANCE OF A SINGLE STRAND
IN 27-STRAND CABLE

Data from "RAMP #11 RESIST-TB"
FILE : RAMP #11 RESIST v I-GF

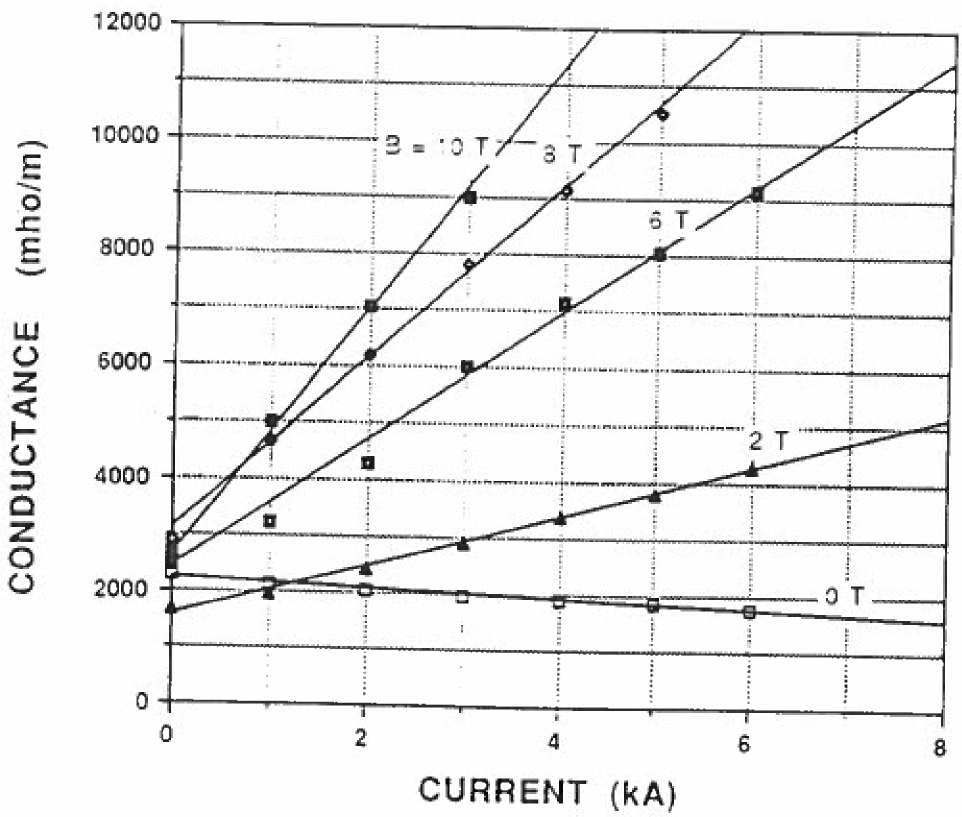


Fig. 2

CONTACT RESISTANCE OF A SINGLE STRAND IN 27-STRAND CABLE

Data from "RAMP #11 RESIST-TB"
FILE : RAMP #11 RESIST-GF

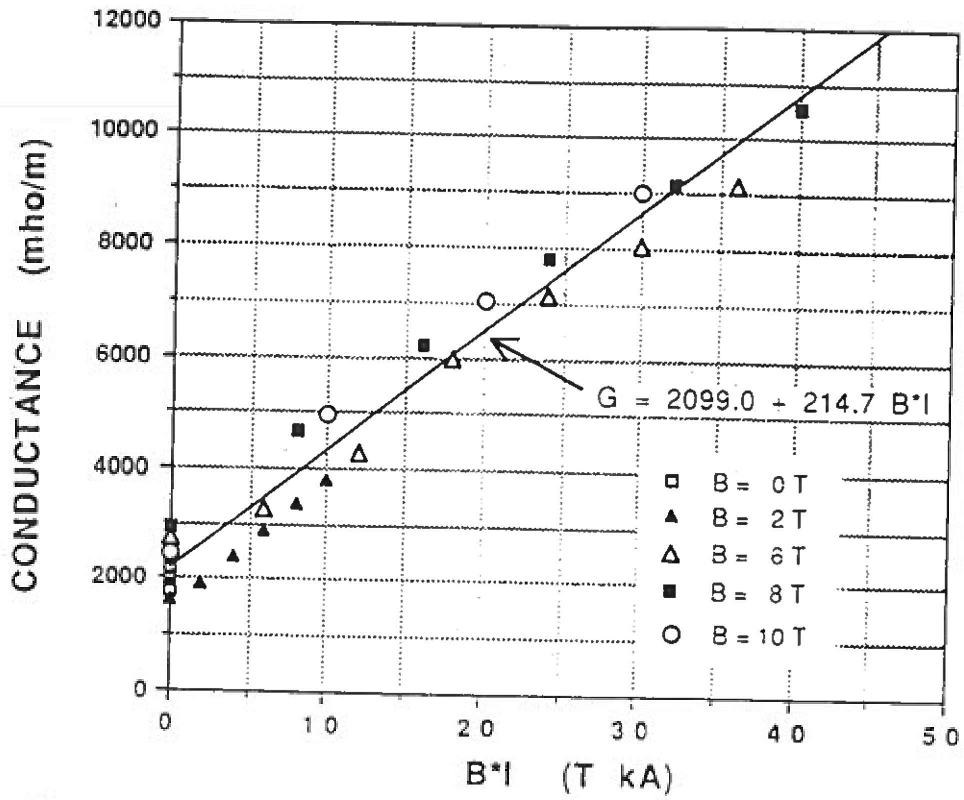
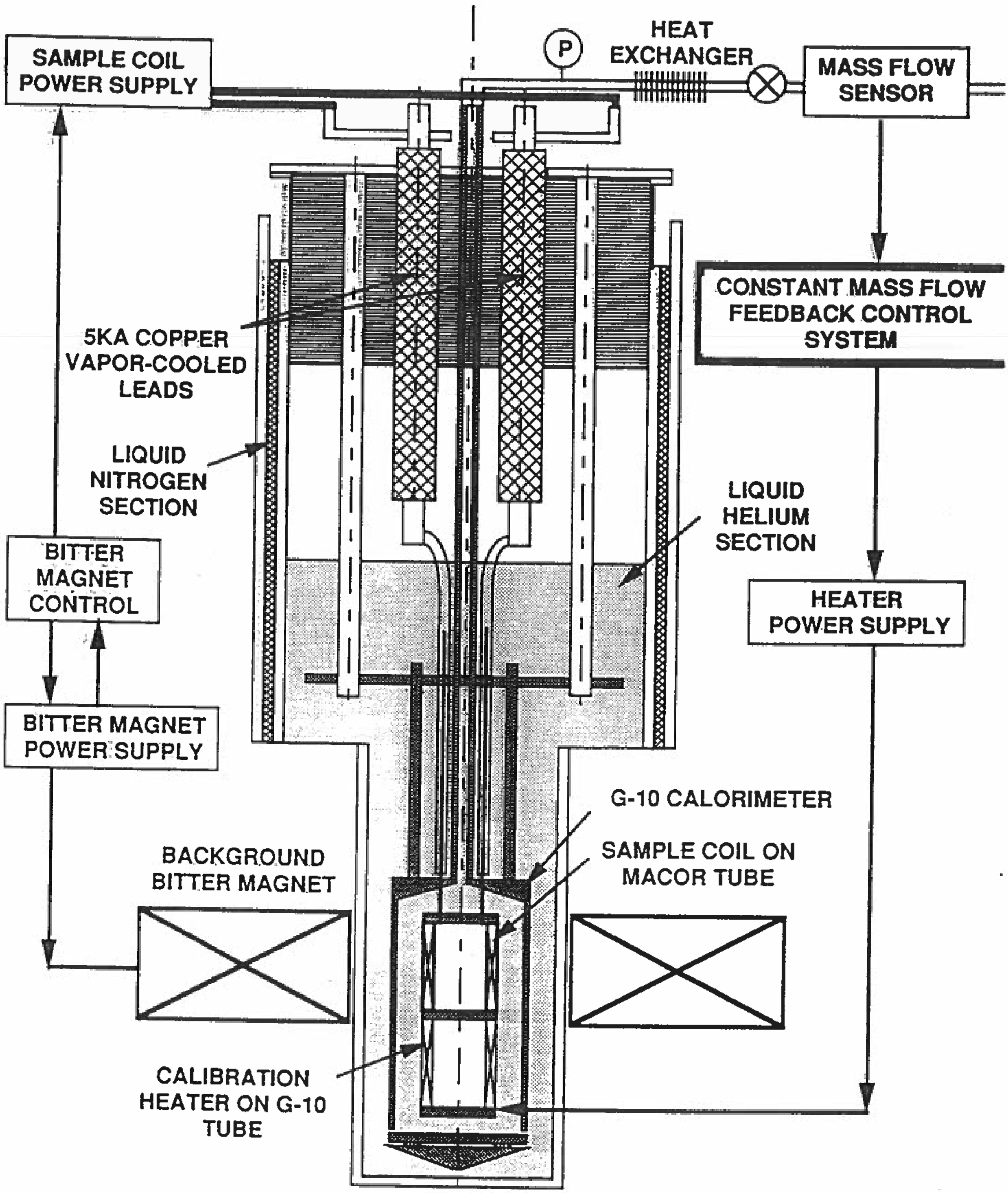


Fig. 3



EXPERIMENTAL SETUP OF ISOTHERMAL CALORIMETRIC AC-LOSS MEASUREMENT WITH CONSTANT-FLOW CONTROL SYSTEM