Fermilab

SDC SOLENOID DESIGN NOTE #118

TITLE: DC Bus for 10 kA SDC Solenoid

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DATE: October 29, 1990

ABSTRACT: The best choice for 10 kA bus for the SDC solenoid seems to be 3-inch nominal double extra strong copper pipe. With the power supply on the surface about 500 feet of bus will be needed. The bus is estimated to cost about $64,000 for material and installation labor. The annual operating cost with 100% duty factor will be about $60,000.

REFERENCES: 1. "Description of a High Current Water Cooled Bus," A.T. Visser, Fermilab TM-1372 (December, 1985); included as Appendix 1 to this design note.

2. Anaconda Copper for Electrical Conductors, Publication C-25, Anaconda American Brass Company (1971), page 52 included as Appendix 2.

GENERAL PARAMETERS AND COSTS PER UNIT AREA AND LENGTH

I calculated the capital and operating costs of water cooled bus per unit copper cross section, per unit length of conductor, for 10 kA and 100% duty factor, following Visser's method:

Parameter	Equation/Value	Units
Operating current	10	kA
Duty factor	8760	h/yr
Copper cross section of bus	S	in^2
Bus weight	3.88S	lb/ft
Maximum expected material cost	3	$/lb
Expected installation cost	3	$/lb
Total material and installation cost	6	$/lb
Installed bus cost	23.28S	$/ft
Current density	10,000/S	A/in^2

Bus resistance at 50°C	9.4/S	μΩ/ft
Bus power loss at 50°C	940/S	W/ft
Bus voltage drop at 50°C	94/S	mV/ft
Cost of bus energy loss; power supply and water pumps	0.08	$/kW-h
Annual energy loss in bus	8234/S	kW-h/ft
Annual energy cost of bus	659/S	$/ft

PARAMETERS AND COSTS PER UNIT LENGTH FOR 1.5 AND 3 INCH COPPER TUBE

Using the dimensions of "double extra strong" copper pipe (see Appendix 2), I calculated the above parameters for 1.5- and 3-inch pipe.

Parameter	1.5"	3"	Units
Outer diameter	1.9	3.5	inch
Inner diameter	1.1	2.3	inch
Water hole diameter	0.4	0.6	inch
Operating current	10	10	kA
Duty factor	8760	8760	h/yr
Copper cross section of bus	1.88	5.466	in^2
Bus weight	7.31	21.2	lb/ft
Maximum expected material cost	3	3	$/lb
Expected installation cost	3	3	$/lb
Total material and installation cost	6	6	$/lb
Installed bus cost	43.77	127.25	$/ft
Current density	5319	1829	A/in^2
Bus resistance at 50°C	5.0	1.72	μΩ/ft
Bus power loss at 50°C	500	172	W/ft
Bus voltage drop at 50°C	50	17.2	mV/ft

Cost of bus energy loss; power supply and water pumps	0.08	0.08	\$/kW-h
Annual energy loss in bus	4380	1506	kW-h/ft
Annual energy cost of bus	350	121	\$/ft

PARAMETERS AND COSTS FOR SDC INSTALLATION

Parameter	1.5"	3"	Units
Total length of bus	500	500	ft
Operating current	10	10	kA
Duty factor	8760	8760	h/yr
Bus weight	3655	10,600	lb
Maximum expected material cost	11	32	k\$
Expected installation cost	11	32	k\$
Total material and installation cost	22	64	k\$
Bus resistance at 50°C	2.5	0.86	mΩ
Bus power loss at 50°C	250	86	kW
Bus voltage drop at 50°C	25	8.6	V
Annual energy loss in bus	2200	950	MW-h
Annual energy cost of bus	175	60	k\$
Water flow, 30°F temp rise	50	18	gpm
Pressure drop in water circuit	300	40	psi

CAPITAL AND OPERATING COST SUMMARY

The capital and one-year operating costs of a number of of bus sizes are summarized below:

Nom. Dia. (in)	Copper Area (in^2)	Capital Cost (k\$)	One-Year Operating (k\$)	Total Cost (k\$)
1.5	1.88	22	175	197

Nom. Dia. (in)	Copper Area (in^2)	Capital Cost (k$)	One-Year Operating (k$)	Total Cost (k$)
3	5.466	64	60	124
4	8.101	95	41	136
5	11.34	133	29	162
6	15.64	182	21	203

COST MINIMIZATION

I minimized the total cost of the bus using a 10-year operating period:

$$C = \text{Capital Cost} + \text{10-Year Operating Cost}$$

$$= (23.28S)(500) + (10)(659/S)(500)$$

$$dC/dS = -3.3 \times 10^6/S^2 + 1.16 \times 10^4$$

Set $dC/dS = 0$ and solve for S,

$$S^2 = 3.3 \times 10^6/1.16 \times 10^4 = 283.1$$

and $S = 16.82\ in^2$, which is close to 6" pipe.

CONCLUSIONS

It would be interesting to know what guidelines other parts of the SSCL are using to size electrical bus. Six-inch pipe seems to be the size to use, but using it in calculating costs at this point inflates the capital cost component. My conclusion is to plan on 3-inch pipe at this time, as the minimum acceptable size.

Appendix 1

Fermilab

TM-1372
2230.000

DESCRIPTION OF A HIGH CURRENT WATER COOLED BUS

A. T. Visser

December 1985

December,1985
Ser.#TM-1372
Cat.2230.000
A. T. Visser

Description of a High Current Water Cooled Bus

Contents

1. General

This note describes the construction of a 2000A to 5000A DC water cooled bus constructed from commercially available catalogue components. This design was first used at Argonne National Lab in 1967. The experimental areas use several thousand feet of this bus. This report concludes that bus current densities of about $1000A/_{inch}2$ are the most economical to use.

2. Construction

The DC bus consists of double extra strong copper pipe, which can be purchased in 20' lengths. A high impact PVC pipe is slipped over the copper pipe for insulation. The copper pipes are joined (brazed) together with straight couplings, 45^o elbows or 90^o elbows. These joints are then insulated with shrink on sleeves. The copper pipe with the PVC pipe over it can be bent with a pipe bender to make offsets and bends up to 90^o. Cooling water flows through the pipe to remove the heat losses. The bus assembly is mounted to structural supports with unistrut clamps fitted around a short length of PVC support pipe. The support pipe has an I.D. slightly larger than the O.D. of the PVC insulating pipe. This allows for movement due to temperature changes. Fig. 1 shows a typical bus section. Short cable jumpers are mostly used to connect the bus to the load. These cables can be connected to special flags which are brazed on to the bus or to a clamped on bus terminal as shown in drawing 6004-ED-76812. The clamped on bus terminal is very handy when the load location changes during the course of an experiment.

The following is a material list of the 5000A bus as used in the experimental areas.

Item	Description	Manufacturer	'85 Price
Copper Pipe	High Conductivity(Alloy 102) Double extra strong Nom. 1-1/2",Hard O.D.~1.9" I.D.~1.1" 20 ft.long,7.24 lbs/ft.	Phelps Dodge	$1.33 per lb.
Coupling	Straight Cat.#5515	Flagg	$18 each
Coupling elbow	45° Cat.#5504	Flagg	$27 each
Coupling elbow	90° Cat.#5501	Flagg	$29 each
End Plug	Home made machined to pipe I.D. with Water Fitting		
Insulating pipe	High impact PVC pipe Nom. 2 inch,Sch.40 O.D. 2.375 inch I.D. 2.067 inch Cat.# 20 ft.long	Carlon	$0.40/ft.
Support Pipe	High impact PVC pipe Nom. 2-1/2 inch,Sch.40 O.D. 2.875 inch I.D. 2.469 inch Cat.#20 ft.long	Carlon	$0.60/ft.
Shrink on Insulation	I.D. min. - 1-1/4 inch I.D. max. - 3 inch Cat.#,SST-30-24, 2 ft.long	Sigma	$19/2ft.
Brazing material	Sil Fos		

Watercooled bus is compact and saves building space, but may not be economical to install below 2000ADC, compared to cables. We have found that the bus can be rather easily dismantled and reused in another place.

We have never been able to reliably use watercooled power cable because of inevitable water leaks within a few years after installation. These leaks are generally caused by the high (~200psi) operating pressures of the cooling water in the Experimental Areas.

3. Selection of an Economical Copper Cross Section for the Bus Conducter

The maximum permissable voltage drop across the bus determines the minimum acceptable copper cross section. A power supply must be able to supply enough voltage to drive the bus and the load at the required current. Bus voltage drop however is often not a problem and the conductor cross section should initially be chosen by weighing the installation cost against the operating cost. A very light bus has high losses and is therefore expensive to run, but costs less to install. The smallest acceptable, from a voltage drop point of view, cross section may not be the best choice.

We have to find out whether a heavy (1000A/$inch^2$) or light (5000A/$inch^2$) bus is preferred from a cost point of view. The following will help to answer this question.

Consider these two cases:

	CASE 1	CASE 2	UNIT
Bus life expectancy	5	10	Years
Average operation current	3000	3000	AMP
Use factor	80	50	%
Bus cross section	S	S	$inch^2$
Bus material cost including misc.	2	2	$/lbs. of Cu
Bus installation cost in experimental area, average difficulty.	2	2	$/lbs. of Cu
Bus weight	3.85S	3.85S	lbs./ft.
Installed bus cost	15.4S	15.4S	$/ft.
Bus resistance at 50°C	$\frac{9.4 \times 10^{-6}}{S}$	$\frac{9.4 \times 10^{-6}}{S}$	Ω/ft.
Bus losses at 3000A	$\frac{84.6}{S}$	$\frac{84.6}{S}$	Watt/ft.
Cost of bus losses including their removal	0.07	0.08	$/KWhr.
Annual cost of bus loss	$\frac{41.5}{S}$	$\frac{29.6}{S}$	$/ft.

Annual bus depreciation	3.08S	1.54S	\$/ft.
Most economical cross section	3.6	4.4	inch^2
Most economical current density	833	682	A/inch^2

The most economical cross section can be estimated from the total annual bus operating and depreciation cost C, which is a function of the cross section S.

For Case 1:

$$C = \frac{41.5}{S} + 3.08S$$

This cost is minimum for $\frac{dC}{dS} = 0$

$$\text{or} \quad -41.5S^{-2} + 3.08 = 0$$

$$S = 3.6 \text{ inch}^2$$

We can similarly determine that $S = 4.4$ inch^2 for CASE 2. The result is interesting. It indicates that current densities in the order of 700 to 1000A/inch^2 are probably the most economical in the long run. Most aircooled installations run at these current densities. We have chosen a cross section $S = 1.88$ inch^2 and operate mostly at current densities from 1000 to 1600A/inch^2.* High current densities do not seem to be economical except for short lived or very lightly used installations. The argument that a light bus is the best (cheapest) is generally not true.

* I	A	J
2000	1.88	1064 A/in^2
3000	1.88	1600
5000	"	2660

4. Bus Parameters

We can list the following parameters for the chosen copper cross section.

Double extra strong copper pipe	Alloy 102, Non-certified
Nominal size	1-1/2"
O.D.	1.9"
I.D.	1.1"
Cross section	1.88 $inch^2$
Weight	7238 lbs./1000'
Installed cost, labor & material (per polarity, 1984)	$30,000/1000'
Resistance at 50°C	$5x10^{-3}\Omega$/1000'
Inductance at 4" center to center, in free air	100μH/1000'
3000A voltage drop	15V/1000'
3000A losses	45KW/1000'
3000A current density	1600A/$inch^2$
Max. water inlet temp.	40°C
Water outlet temp	60°C
Required cooling with water ΔT=20°C, 3000ADC	7.2 GPM/1000'
Pressure drop at 7.2 GPM	18 PSI/1000'
Loss of cooling (overtemp) protection, Klixon	80°C
Short circuit stress at 50,000A, 4" center to center	340 lbs./ft.
Thermal expansion at ΔT=10°C average	2 inch/1000'

Comments

The short circuit stresses can be calculated from:

$$F = \frac{5.4I^2x10^{-7}}{d} \ lbs/ft.$$

d = distance between conductor centers in inches

It is estimated that a power supply can deliver 50,000A of short circuit current. Adequate bus supports need to be used.

The required cooling water is calculated from:

$$GPM = \frac{KWx3.2}{\Delta T(^{o}C)}$$

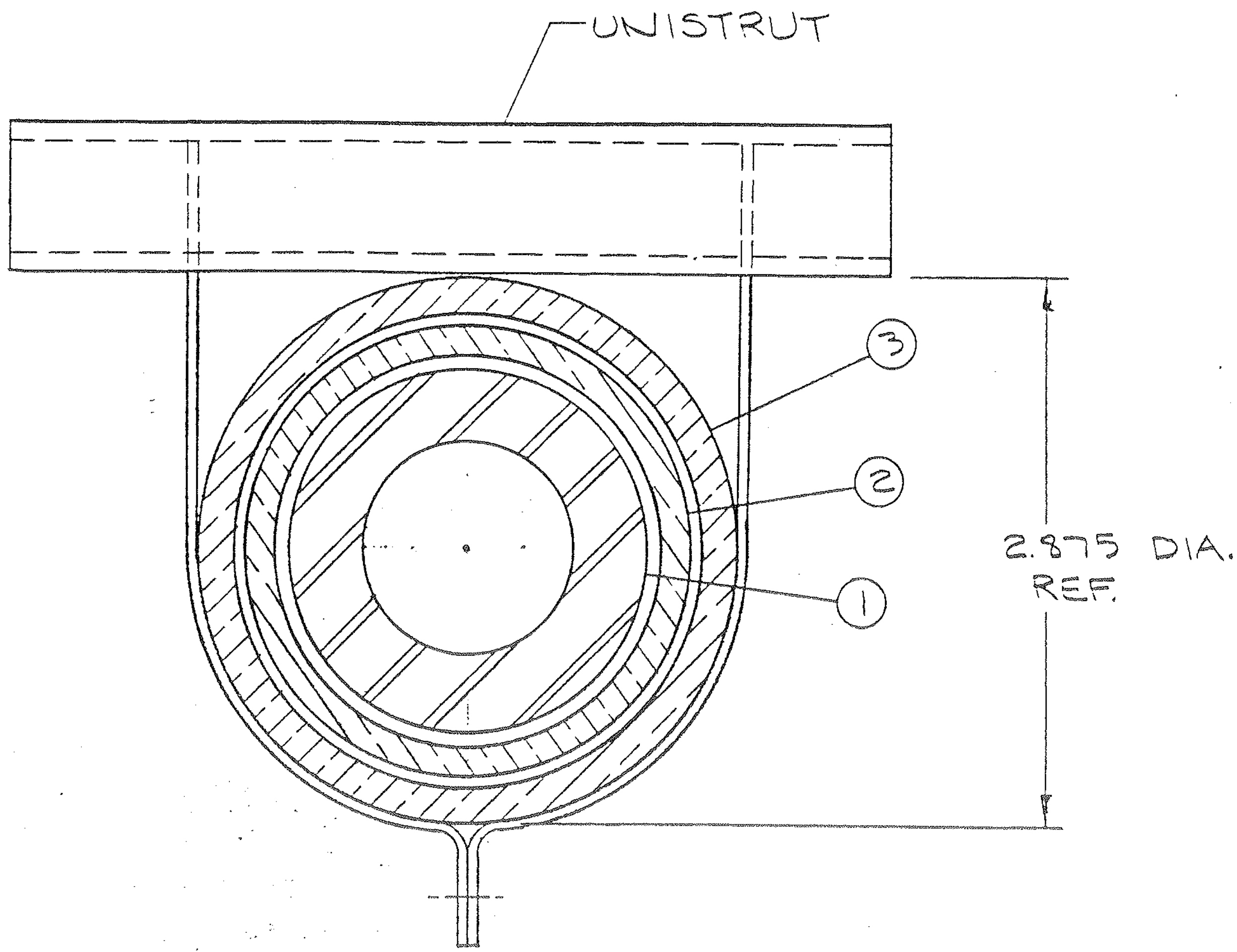
The average bus temperature rise is chosen at 10°C with 20°C water temp rise at the outlet.

Most bus runs installed in the field are about 500' or less. This length of bus will expand about 1". We have not used expansion joints, but use natural bends to take care of this expansion. The bus is not solidly anchored to building structures.

5. Acknowledgement

Stan Orr and Leon Beverly have ordered materials for and installed many feet of bus. They suggested to use heavy shrink on tubing over the field braze joints. A more cumbersome system using split PVC pipe and insulation materials was previously used. The bus material list is taken from their files.

ATV:plm

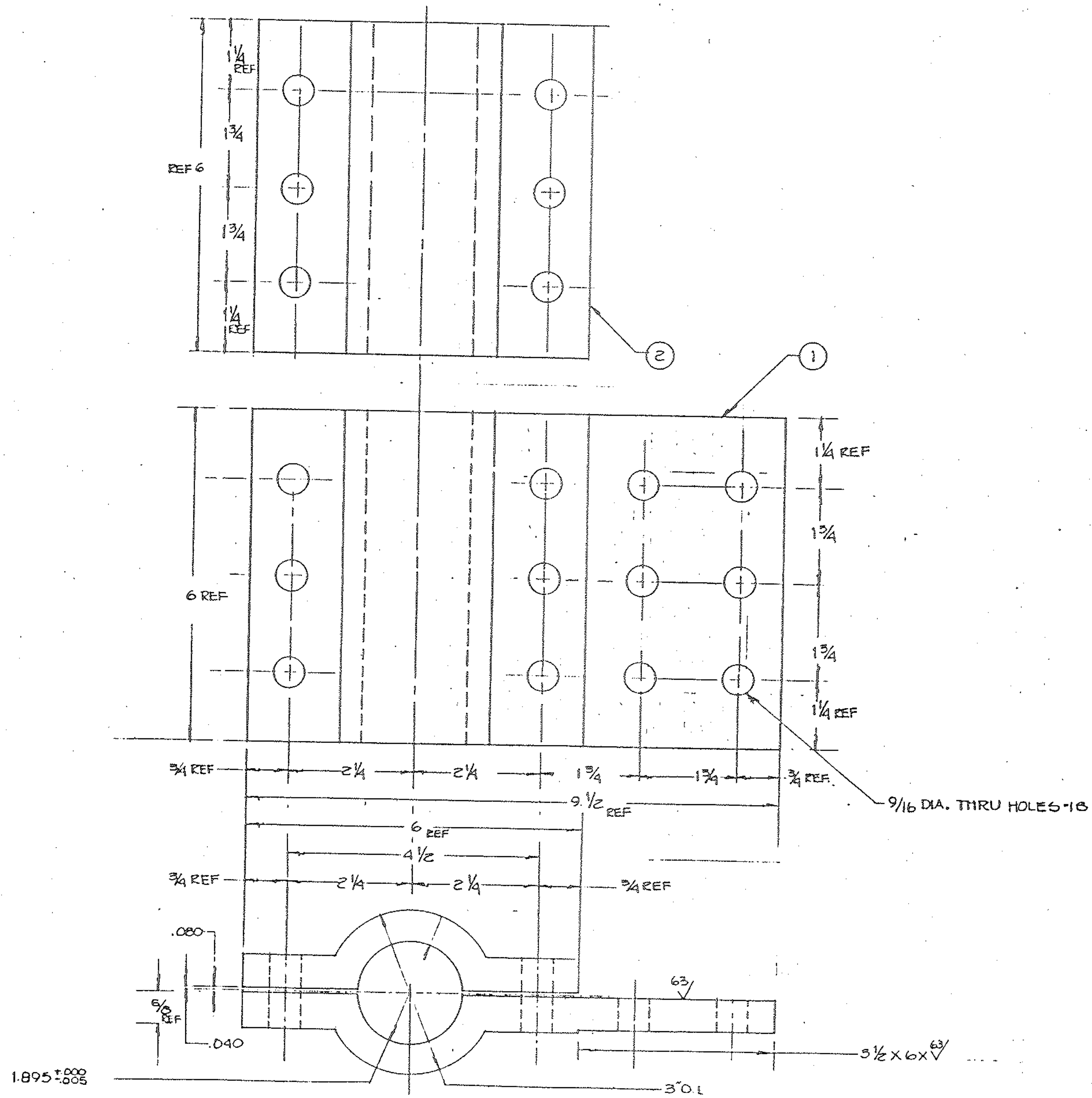


(1) COPPER PIPE

(2) INSULATING PIPE

(3) SUPPORT PIPE

INSULATED WATERCOOLED BUS
TYPICAL CROSSECTION
FIG. 1 FULL SCALE



2	6004-ED-6812 2	BUSS CLAMP CAP	1
1	6004 ED 6812-1	BUSS CLAMP CABLE FLAG	1
ITEM NO	PART NO	DESCRIPTION OR SIZE	QTY REQ

PARTS LIST

UNLESS OTHERWISE SPECIFIED	ORIGINATOR	B. INNES
FRACTIONS ± .005 / DECIMALS ± / ANGLES ±	DRAWN	FERGUSON
1. BREAK ALL SHARP EDGES 1/64 MAX	CHECKED	
2. DO NOT SCALE DWG.	APPROVED	[signature]
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD.	USED ON	1½ WATER COOLED BUSS
√ MAX ALL MACHINED SURFACES	MATERIAL	BRASS CASTING (85-5-5-5 ...)

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

PROTON DEPT
5000 A BUSS TI HAL

SCALE	FILMED	DRAWING NUMBER	REV
FULL		6004-ED-76812	

REV	DESCRIPTION	DRAWN / APPD	DATE

R. FAST

Anaconda Publication C-25 Eleventh Edition

Appendix 2

ANACONDA®
COPPER
for Electrical Conductors

ELECTRICAL PROPERTIES AND USES
OF COPPER AND COPPER ALLOYS

BUS CONDUCTOR SHAPES

WIRE

CONDUIT

SPECIAL PRODUCTS

ANACONDA
from mine to consumer

Anaconda American Brass Company
Waterbury, Conn. 06720

TABLE XVII

ANACONDA HIGH-CONDUCTIVITY COPPER BUS TUBES
STANDARD PIPE SIZES, DOUBLE EXTRA STRONG, HARD

Pipe Size, In.	Nominal Dimensions, In. Outside Diameter	Inside Diameter	Wall Thickness	Nominal Weight, Lb. per Foot	Cross-Sectional Area of Copper Sq. In.	Thousand Cir. Mils.	Moment, of Inertia, In.^{4}	Section Modulus, In.^{3}	Radius of Gyration, In.	D-C Resistance, Microhms per Foot, at 20 C. (68 F) (a)	Skin-Effect Ratio(b
1	1.315	0.599	0.358	4.17	1.076	1370.	0.1405	0.2136	0.3613	7.77	1.04
1¼	1.660	0.896	0.382	5.94	1.534	1953.	0.3411	0.4110	0.4716	5.45	1.06
1½	1.900	1.100	0.400	7.31	1.885	2400.	0.5678	0.5977	0.5489	4.44	1.07
2	2.375	1.503	0.436	10.3	2.656	3382.	1.311	1.104	0.7027	3.15	1.11
2½	2.875	1.771	0.552	15.6	4.028	5129.	2.871	1.997	0.8442	2.08	1.25
3	3.500	2.300	0.600	21.2	5.466	6960.	5.992	3.424	1.047	1.53	1.35
3½	4.000	2.728	0.636	26.0	6.721	8558.	9.848	4.924	1.210	1.24	1.43
4	4.500	3.152	0.674	31.4	8.101	10310.	15.28	6.793	1.374	1.02	1.49
5	5.562	4.062	0.750	44.0	11.34	14440.	33.61	12.09	1.722	0.73	1.69
6	6.625	4.897	0.864	60.6	15.64	19910.	66.33	27.09	2.060	0.53	1.96
8	8.625	6.875	0.875	82.6	21.30	27120.	162.0	47.12	2.758	0.39	2.01

NOTES: Variations from these values must be expected in practice. ASTM Specification B 188, Seamless Copper Bus Pipe and Tube, establishes the outside diameters, the tolerances in terms of weight, and the electrical inspection.

Double Extra Strong Pipe is suited to certain special applications in electrical engineering. The a-c current-carrying-capacity ratings, under accepted conditions of reference, sizes 2½ inches nominal and larger may actually be less than the corresponding sizes of "Extra Strong" pipe. See page 30 and figures 7, 8 and 9. There are no inductive limitations on the use of Double Extra Strong pipe for direct current. Commercial limits on the mechanical properties and conductivity of hard drawn Double Extra Strong Pipe are:

Diameter, In.	Tensile Strength, Min., psi	Elongation in 2 in., Min. Per Cent	Rockwell Hardness, F Scale Min.	Conductivity, Min. Per Cent IACS
Up to 4 in. incl.	35,000	8	75	97.40
Over 4 in.	32,000	20	65	98.40

For equivalent values of resistivity in various units, see page 7.

(a) D-C Resistance for minimum conductivities shown above.
For conversion of resistance to temperatures other than 20 C, see page 49.

(b) Skin-effect ratio calculated at 60 cycles per second and 105 C copper temperature (see page 23).

TABLE XVIII

ANACONDA HIGH-CONDUCTIVITY COPPER BUS TUBES
THREADLESS PIPE SIZES, HARD DRAWN

Nominal Pipe Size, In.	Nominal Dimensions, In. Outside Diameter	Inside Diameter	Wall Thickness	Nominal Weight, Lb. per Foot	Cross-Sectional Area of Copper Sq. In.	Thousand Cir. Mils	Moment of Inertia, In.^{4}	Section Modulus, In.^{3}	Radius of Gyration, In.	D-C Resistance, Microhms per Foot at 20 C. (68 F) (a)	Skin-Effect Ratio (b)	60-Cycle Current Rating Amperes (c) Indoor 30 C Rise	Indoor 65C Rise	Outdoor 65C Rise
½	0.840	0.710	0.065	0.613	0.1583	201.5	0.01197	0.02849	0.2750	53.27	1.00	300	495	610
¾	1.050	0.920	0.065	0.780	0.2011	256.1	0.02450	0.04667	0.3490	41.58	1.00	390	610	740
1	1.315	1.185	0.065	0.989	0.2553	325.0	0.04999	0.07603	0.4425	32.76	1.00	475	750	900
1¼	1.660	1.530	0.065	1.26	0.3257	414.7	0.1037	0.1250	0.5644	25.68	1.00	590	940	1100
1½	1.900	1.770	0.065	1.45	0.3747	477.1	0.1579	0.1662	0.6492	22.32	1.00	670	1050	1200
2	2.375	2.245	0.065	1.83	0.4717	600.6	0.3149	0.2652	0.8170	17.73	1.00	825	1300	1500
2½	2.875	2.745	0.065	2.22	0.5738	730.6	0.5667	0.3942	0.9938	14.57	1.00	980	1550	1700
3	3.500	3.334	0.083	3.45	0.8910	1134.	1.301	0.7435	1.208	9.39	1.00	1340	2100	2300
3½	4.000	3.810	0.095	4.52	1.165	1484.	2.223	1.111	1.381	7.18	1.00	1600	2550	2750
4	4.500	4.286	0.107	5.72	1.477	1880.	3.564	1.584	1.554	5.66	1.00	1900	3000	3250
5	5.562	5.298	0.132	8.73	2.252	2867.	8.304	2.986	1.920	3.71	1.00	2550	4000	4400
6	6.625	6.309	0.158	12.4	3.210	4087.	16.79	5.069	2.287	2.61	1.00	3275	5200	5600
8	8.625	8.215	0.205	21.0	5.423	6903.	48.09	11.71	2.978	1.54	1.00	4750	7500	8200
10	10.750	10.238	0.256	32.7	8.440	10740.	116.2	22.71	3.711	0.992	1.02	6450	10200	11100
12	12.750	12.124	0.313	47.4	12.230	15570.	236.6	39.03	4.399	0.689	1.04	8200	13000	14200

NOTES: Variations from these values must be expected in practice. ASTM Specification B 188, Seamless Copper Bus Pipe and Tube, controls electrical and tensile properties, dimensional tolerances, appropriate tests and inspection.

(a) D-C Resistance for hard-drawn temper per ASTM B 188.
Diameters up to and including 1", conductivity 96.6% IACS, minimum.
Diameters over 1", conductivity 97.4% IACS, minimum.
For equivalent values of resistivity in other units, see page 7.

For conversion of resistance to temperatures other than 20 C, see page 49.

(b) Skin-effect ratio calculated at 60 cycles per second and 105 C copper temperature (see page 23).

(c) Calculated, based on 40 C ambient, mill finish, indoor service, and freedom from external magnetic influences. For determining current ratings at other temperature rises, see page 18. Outdoor ratings calculated from formulas in "Heat Transmission" by W. H. McAdams, McGraw-Hill, New York, 1954.