LIMITING DESIGN PARAMETERS FOR COOLED, HIGH SPEED, HIGH CURRENT DENSITY SLIDING CONTACTS

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ABSTRACT

For advanced design of lightweight multi-megawatt dc continuous duty generators, high speed and high current density must be obtained in the sliding contacts. Limiting design parameters must be recognized to direct research and analysis toward a successful design.

A combination of electrical heating and sliding friction produces an intense heat-release in the small volume at the brush-rotor interface, thereby reaching upper temperature limits in a short time period. Coolant selection and application must not degrade other performance criteria while successfully removing heat from the brush-rotor interface. Component design and material selection for the brush, rotor; and coolant must be compatible and meet design limits for stress, temperature, heat transfer, wear, friction, mass, and size. Successful design criteria have been developed to meet each of these design limitations; however, research is continuing to explore higher performance designs.

Introduction

As a machine designer, one must first recognize the specific operational performance requirements of the machine. These requirements must be met within limits for space, weight, and cost without adversely affecting other machine components and the environment. High speed and high current sliding contacts are limited by a baffling array of parameters, as partially illustrated in figure 1. A designer delights in the infinite number of options for size and shape when coupled with the many known material and environmental combinations. Even though there are many industrial and research machines with sliding electrical contacts, no standard design exists such as for pipes, electrical connectors, etc.

Speed and electrical current are the most obvious limits on the design but they are limited by temperature, stress, energy losses, and wear. Selection of a material for the rotor will fix the surface speed limits due to stress in the rotor. Selection of brush material still leaves design options for brush shape, actuator-kinematics, forcing systems, electrical connections, and cooling. For brushes with retraction capability or active forcing methods, the speed of relative motion between the brush and rotor becomes important.

As brush performance demands increase, temperature becomes more important since it affects nearly every measure of performance. Rotor speed is limited by stress which in turn is limited by temperature. Contact resistance, slip velocity, contact pressure and wear are also limited by temperature. Thus temperature is perhaps the most important single parameter which forces the designer to reduce the energy losses or provide adequate cooling.

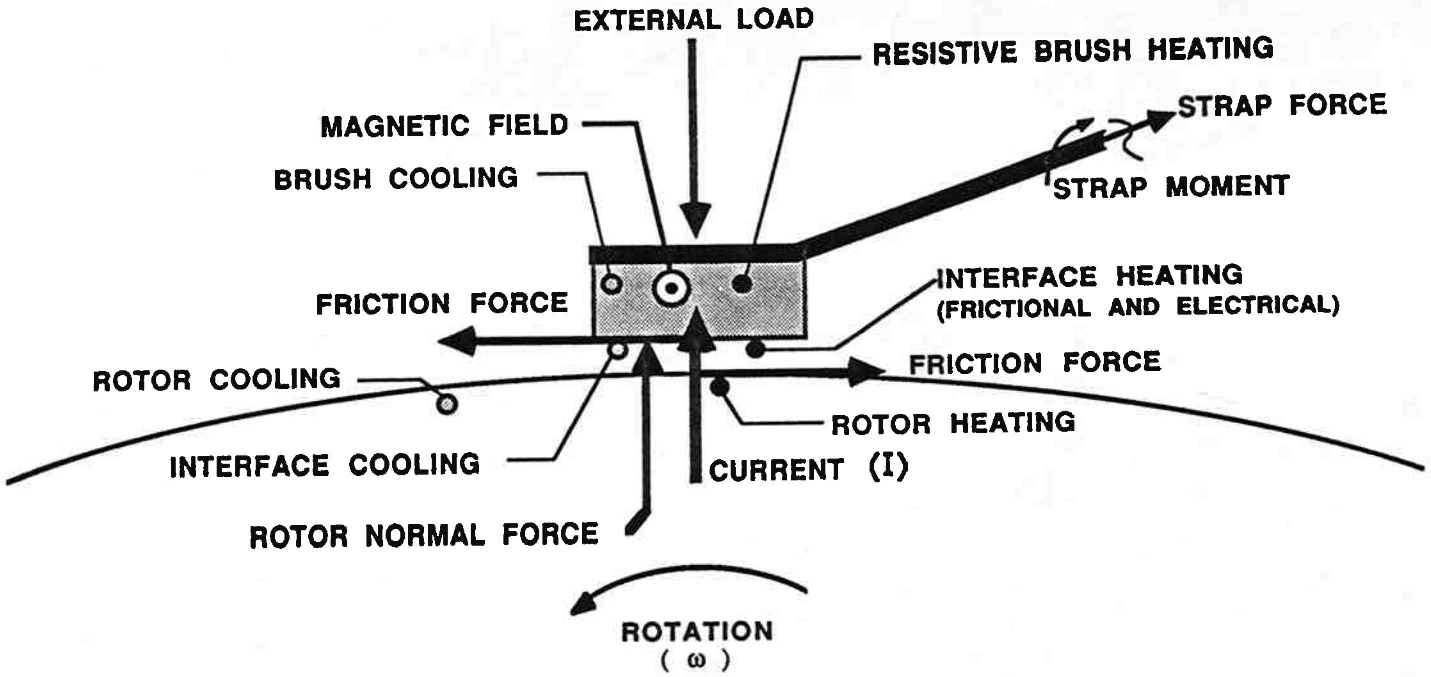

Figure 1. Design parameters at brush rotor interface

Wear Limits

Temperature effects on wear are well documented but the data are sensitive to many variables, thereby making general design limits difficult to ascertain. One of the best presentations is by Hannan and Taylor[1], whereby wear on an electrographite brush sliding on a copper rotor is experimentally determined as

$$\omega' = 1 + 4.6 \times 10^{-9}(\Delta T)^4,$$

where

ω' = ratio of the wear rate at a given temperature rise (ΔT) above room temperature to wear rate at room temperature

ΔT = temperature rise at interface, °C.

This equation for wear was generated as a curve fit to specific data but is still quite significant in that it points out the importance and limiting nature of the temperature rise. Other material combinations exhibit similar characteristics with limiting interface temperatures. Thus, if adequate cooling can be applied to the interface, dramatic improvement in the wear can be achieved at high performance levels.

Energy Losses

Energy losses at the interface are the most severe design limitation; thus, if they could be eliminated, most of the design problems would disappear. Interface losses are attributed to frictional resistance due to relative motion, and electrical resistance due to current flow, as determined by

$$P_t = \mu N v + I^2 R_{eff}.$$

The location and nature of these losses is such that they are difficult to remove since they occur in the contact zone where relative motion exists. Projected power dissipation levels (fig. 2), as given by Walls[2], show the magnitude of this heat flux.

The two terms in the energy equation are not independent, but it is possible to minimize energy lossses by noting that R_{eff} increases with slip velocity (v) but it decreases with increasing contact load (N). Unfortunately, different optima exist for each load and speed and designers have a tendency toward optimization at the lower current levels, where it is not nearly so important as at high current levels. This tendency is sometimes justified if the machine is to run for relatively long time periods at little or no load, whereby frictional losses can preheat brushes before current is applied. For this reason, electrical motoring of a pulsed generator is less attractive than hydraulic motoring. From figure 2 at 1.5 MA, electrical losses would be 15 times frictional losses, thereby indicating a large saving potential by increasing normal pressure.

Cooling of Brush and Rotor

Cooling must be provided for any brush-rotor interface. For most pulsed duty, the cooling is provided by the rotor and brush mass acting as heat sinks. Duration of the duty cycle is extremely important, as well as the ability to transfer heat from the contact surface into the brush and rotor. Without direct transpiration cooling, the heat transfer away from the interface is highly material dependent.

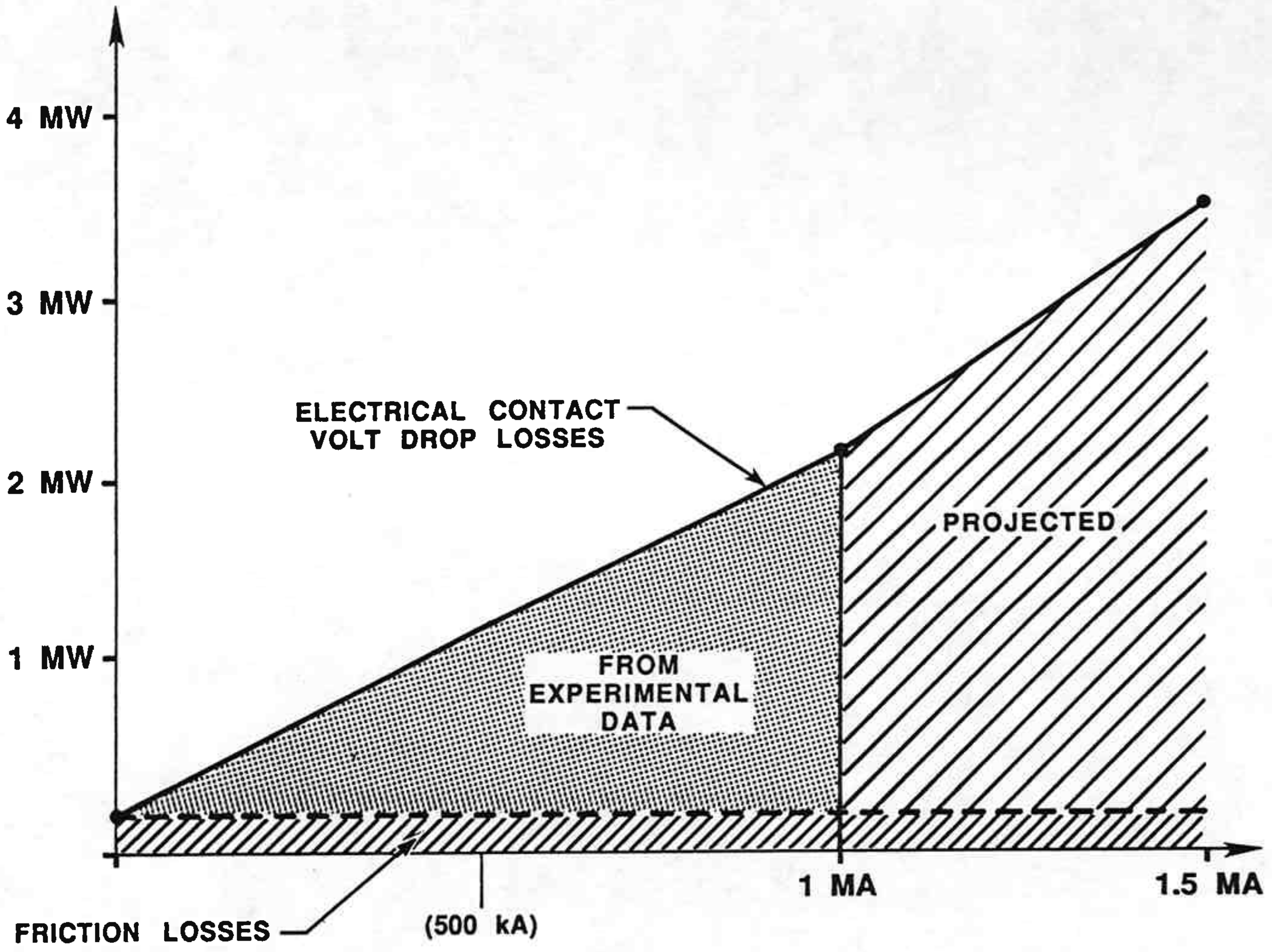

Figure 2. Projected power dissipation levels

Brush Material Parameters

Many of the basic material constants are easy to obtain to a high degree of accuracy from the literature and can be used in the early screening process. At this point one should note that there are an infinite number of alloys and mixtures that are suitable for brush applications; however, the basic elements seem to dominate the material constants. Table 1 gives a list of physical constants for nine materials that contain properties which are significant for brush operation and cooling. It is difficult to select a brush material on a single parameter such as electrical resistivity, but it is an important property of the material.

If the electrical resistivity were the only parameter used for selection of a brush material, the choice would be silver followed by copper, gold, and aluminum. Very quickly one finds faults with each. Silver and gold are expensive and have a lower melt temperature than copper. Copper has a high coefficient of friction and aluminum oxidizes rapidly.

Thermal diffusivity, α, defined as $\frac{K}{\rho C}$ can be used to determine how fast heat will soak into the brush or rotor. Silver has the highest value of diffusivity followed by graphite, gold and, copper, in that order.

As soon as cooling becomes important, other parameters must be considered. Column 8 in table 1 is a first approximation by using the product of thermal conductivity and the melting point divided by the electrical resistivity without weighting functions. Thermal conductivity is the most important single parameter in any heat flow process such as cooling if the heat generated is to be removed anywhere other than the point of generation.

Table 1. Brush material parameters

	1	2	3	4	5	6	7	8	9	10
MATERIAL	MELTING POINT °F	THERMAL DIFFUSIVITY (α), m^2/s	ELECTRICAL RESISTIVITY MICROHM-CM	SPECIFIC HEAT CAL/G °C @ 25°C	SPECIFIC GRAVITY	THERMAL CONDUCTIVITY W/cm °C @ 25°C	MELTING POINT °C	$\frac{6x7}{3}$	4x5	$\frac{6x7x4x5}{3}$
Copper	1,983	$116x10^{-6}$	1.673	0.092	8.96	3.98	1,084	2,578	0.824	2,124
Silver	1,760	$171x10^{-6}$	1.59	0.057	10.50	4.27	961	2,580	0.598	1,542
Tungsten	6,150	$69x10^{-6}$	5.65	0.032	19.3	1.78	3,400	1,071	0.617	660
Gold	1,945	$127x10^{-6}$	2.35	0.031	19.32	3.15	1,063	1,424	0.598	851
Iron	2,797	$23x10^{-6}$	9.7	0.108	7.87	0.803	1,536	127	0.850	107
Molybdenum	4,750	$55x10^{-6}$	5.2	0.06	10.22	1.4	2,620	705	0.613	432
Beryllium	2,345	$65x10^{-6}$	4.0	0.436	1.85	2.18	1,285	700	0.806	564
Aluminum	1,220	$98x10^{-6}$	2.655	0.215	2.70	2.37	660	589	0.580	342
Graphite	4,531+	$136x10^{-6}$	830-210	0.17	1.58	1.52	2,500+	4.6	0.258	1.2

Strong evidence of surface melting is evident in all high current density-high slip speed brush research. One might even argue that the boiling point is a better indicator of the real temperature of the source process. Electrical resistivity is used in the denominator since it is an indication of the amount of heat generated. Column 8, table 1, shows silver and copper to be virtually tied for best index, followed by gold and tungsten at approximately half value.

Another cooling index is the ability of a material to store heat. Column 9, table 1, shows the product of the specific heat and specific gravity. Surprisingly, all of the metals were relatively close in value.

Column 10, table 1, the product of columns 8 and 9, shows copper far ahead, followed by silver, then gold and tungsten. This rating would classify a material by its ability to store heat generated by electrical resistance up to its melting point.

Brush Coolant Parameters

Table 2 is an effort to compare several potential coolants for high performance brushes. For transpiration cooling, the most significant parameters are the latent heat of evaporation shown in column 6 and the specific gravity shown in column 1. Column 7, table 2, shows the product of these two properties multiplied by the specific heat, column 1, with water leading all other coolants by 3 to 1 or better. Glycerine was second, followed by methyl alcohol and ethelyene glycol. The ability of the coolant to conduct heat is shown in column 8, table 2, which is the product of the specific gravity, thermal conductivity and the boiling point. Again water is best followed by glycerine and ethelyene glycol, but the relative differences have been reduced. Column

Table 2. Brush coolant parameters

	1	2	3	4	5	6	7	8	9
COOLANT	SPECIFIC GRAVITY	DIELECTRIC CONSTANT	SPECIFIC HEAT kJ/kg·K	THERMAL CONDUCTIVITY W/m·K	BOILING POINT K	LATENT HEAT OF EVAPORATION kJ/kg	EVAPORATIVE 1·3·6	CONDUCTIVE 1·4·5	ELECTRO-EVAPORATIVE $\frac{1\cdot3\cdot6}{2}$
Water	1.00	78.5	4.18	0.609	373	2,260	9,446	227	120
Alcohol, Methyl	0.79	32.6	2.54	0.208	337.8	1,100	2,207	55	68
Carbon Tetrachloride	1.59	2.23	0.866	0.104	349.6	194	267	57	119
Ethelene Glycol	1.10	37.7	2.36	0.26	470	800	2,076	134	55
Freon R-12	1.32	2.0	0.97	0.071	243	165	211	23	105
Glycerine	1.26	40	2.62	0.28	463	974	3,215	163	80
Octane	1.07	9.8	2.15	0.13	398	298	685	55	70

9 is column 7 divided by the dielectric constant, column 2. The electro-evaporative numbers shown in column 9 are virtually the same for water, carbon tetrachloride and Freon (R-12).

Heat Conduction Feasibility

Any form of cooling other than direct injection of coolant at the surface will require surface generated heat to be conducted to the receiver. The conduction process is driven by a thermal gradient, °C/cm. Maximum values of the thermal gradient are assumed to be the melt temperature of the brush material-boiling point of water divided by a distance from the sliding surface. If this distance from the sliding surface is too small, no amount of coolant can cool the brush by indirect methods. From the heat conduction equation:

$$Q = KA\frac{\Delta T}{x},$$

where

Q = heat load, watts per brush = 4.4×10^3

(anticipated lead for cooled brush)

A = conducting area, cm^2 (minimum area - 1 cm^2)

$$\frac{\Delta T}{x} = \frac{\text{melt temperature - boiling temperature of water}}{\text{distance } x}$$

T = temperature, °C

x = length of heat flow, cm

K = thermal conductivity, W/M °C.

Thus the length of heat flow for 4.4×10^3 watts per brush through an area of 1 cm^2 equals 0.89 cm for copper, 0.84 cm for silver, 0.26 cm for iron, and 0.83 cm for graphite.

The numbers show that 4.4 kW can be transmitted to a coolant through the brushes with relatively small flow distances (0.8 cm for copper, silver, and graphite). These numbers could be larger since some heat will go to the rotor. If half of the heat is removed through the rotor, then these numbers become 1.6 cm, which is sufficient. Graphite is interesting since it is a high temperature material and has relatively good thermal conductivity, which is one of the reasons it is used in nuclear reactors.

Liquid Heat Transfer

If the heat is successfully transmitted through the brush material, a coolant must remove the heat at a very short distance from the brush active surface A study by Dr. H. P. Liu produced heat transfer coefficients for convective transfer through channels using water on the brush at the active surface. Maximum transfer coefficients occurred for nucleate boiling (an order of magnitude above the liquid phase).

Using convective heat transfer with:

$$h_{NCB} = 0.163 \times 10^6 \frac{W}{m^2 \text{ °C}}$$

Q = 4.4 kW load

A = area, m^2(2 cm^2 is possible)

ΔT = temperature difference (assume 100°C which is near max heat flux)

$$Q = h_{NCB} A \Delta T = 0.163 \times 10^6 \frac{(2)}{(100)^2} = 0.326 \times 10^4 W.$$

Note:

Q = 3.26 kW vs 4.4 kW design load

Other coolants with documented high heat transfer coefficients are freon and alcohol. Handbook values for boiling liquids go up to 50,000 BTU/hr ft^2 °F. Using a value of 25,000 would remove 2.84 kW from the brush.

Melt and Resolidify

Melting material at the interface of two solids with relatively high sliding velocities has been well documented by a number of researchers. Some of the best early papers were presented by Bowden and Taber[3] dated 1950. Basic evidence which supports this theory includes:

1. relative sliding velocities above 200 m/s,
2. appreciable normal load between brush and rotor, 6.9×10^4 - 21×10^4 N/m^2,
3. copper bands formed on steel rotor during tests at CEM-UT, and
4. energy released at interface due to electrical heating is up to ten times frictional heating.

Recent research by A. K. Stiffler[4] has applied this theory to guns with rotating copper bands melting in a steel gun barrel. Application of the Reynold's equation for hydrodynamic lubrication was successful using the melt mass as a liquid feed. Surface melting accounted for the continuous presence of a liquid layer which was used to accurately calculate the coefficient of friction. Calculated and measured values of the coefficient of friction were quite low (0.026) compared to design values (0.1 - 0.2) for brushes. The significance of this research is that low coefficients of friction can be obtained with a relatively thick melt zone but high wear rates will occur if most of the melt material is lost. Fortunately, the thickness of the melt layer is such that it can resolidify before reaching the next brush if sufficient cooling is available. The exact time required to reach melt is a function of many variables but usually in the order of 10^{-8} s. In the case of electrical brushes, it is conceivable to establish a melt from friction prior to the flow of current. In either event, sufficient surface energy is available to establish a thin melt zone very rapidly.

Progress in Brush Design

Considerable progress has been made in high performance brush design over a period of years. Early research at CEM-UT began with the first homopolar generator design, in 1972, using Delco-Remy starter brushes at 0.08 kA/cm^2. Figure 3 shows how the design limits for velocity and current have been pushed up over a period of 15 years. Sliding velocity for the first unit was actually planned to be over 200 m/s but was not achieved due to bearing and motoring problems. During the past ten years, sliding velocity has limited most designs due to the lack of sufficient cooling. Continuous duty machines are limited to significantly lower values for the same reason. Other solid armature sliding contact applications, such as railguns, are operating at velocities above 1,200 m/s with current densities above 500 kA/cm^2 at CEM-UT and are being rapidly pushed to higher limits.

Conclusions

Actively cooled sliding contacts for high speed and high current density are feasible and will extend present design limits for pulsed duty into the

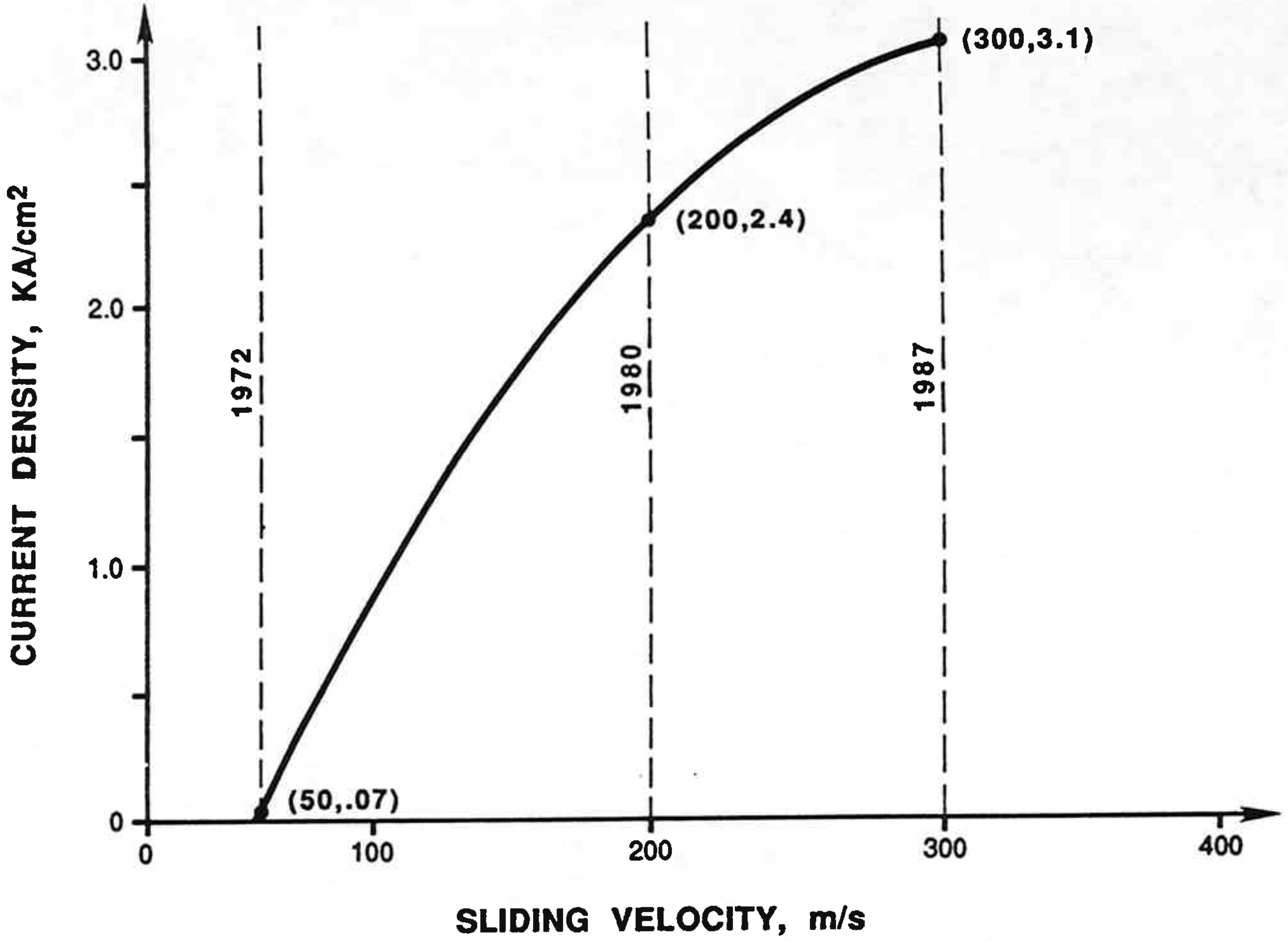

Figure 3. Historical design limits