NASA order H-80591

MTI 89TR40

Cryostatless High Temperature Supercurrent Bearings for Rocket Engine Turbopumps

Prepared for:
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Flight Center
Huntsville,AL

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September 1989

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ABSTRACT

This report presents the investigation carried out by MTI on the use of High Temperature Superconducting Materials to magnetically levitate rotating shafts of rocket engine turbopumps in a configuration called "Supercurrent Bearings."

The rocket engine systems examined include SSME, ALS and CTV systems. The liquid hydrogen turbopumps in the SSME and ALS vehicle systems are identified as potentially attractive candidates for development of Supercurrent Bearings since the temperatures around the bearings is about 30°K, which is considerably lower than the 95°K transition temperatures of HTS materials. At these temperatures, the current HTS materials are shown to be capable of developing significantly higher current densities. This higher current density capability makes the development of supercurrent bearings for rocket engines an attractive proposition.

These supercurrent bearings are also shown to offer significant advantages over conventional bearings used in rocket engines. They can increase the life and reliability over rolling element bearings because of noncontact operation. They offer lower power loss over conventional fluid film bearings. Compared to conventional magnetic bearings, they can reduce the weight of controllers significantly, and require lower power because of the use of persistent currents. In addition, four technology areas that require further attention have been identified. These are: Supercurrent Bearing Conceptual Design Verification; HTS Magnet Fabrication and Testing; Cryosensors and Controller Development; and Rocket Engine Environmental Compatibility Testing.

This report is prepared by MTI for NASA under Contract No. H-8059113. The Program Manager is Dr. Dantam K. Rao. Principal contributors to preparation of this report include Dr. James Dill, Mr. Joseph Tecza, Mr. Paul Lewis and Mr. Donald Wilson. The technical monitor is Dr. Rudy Decher, Space Sciences Division, NASA/MSFC, Huntsville, Alabama.

LIST OF FIGURES

1.0 INTRODUCTION

The revolutionary 1987 discovery of High Temperature Superconducting Materials (HTS) has given fresh impetus to examine the feasibility of using them to increase the life of rocket engine bearings, such as those found in HPFTP, LPFTP and CTV turbopumps. Since LH2 propellent circulates at about 30°K in some of these pumps, cryostatless HTS bearings could magnetically levitate the shaft without contact, thus increasing the life and reliability of turbopump bearings.

Basically, HTS bearing is a device that levitates a rotating shaft using some salient properties of superconductors in the levitation mechanism. There are two classes of superconducting bearings: (a) Supercurrent Bearings, and (b) Type II Bearings. These bearings differ by the way they exploit the salient properties of superconductors to levitate the shaft.

Supercurrent Bearings use the ability of superconductors to carry large direct transport currents (D.C.) with no resistance loss. Of course, the usefulness of superconductors does not lie solely in the lossless conduction of transport current, but also in their ability to carry very large currents and produce very high flux fields per given volume of material. In normal applications, these advantages do not come free, as it is necessary to expend energy to cool the superconductors to cryogenic temperatures. An exception, however, is the cryostatless supercurrent bearings for rocket engines being studied here. In this case, these advantages literally come free as the naturally available LH2 and LOX propellants can be used as a cooling medium for superconductors. (The superconductors also offer a means to carry low frequency alternating currents up to about 60Hz with unusually small losses, which is useful for low speed rotors).

Supercurrent bearings employ the superconductors in a flux creating Primary called "Superconductng Magnet" (SM). As shown in Figure 1.1.1, these magnets are nothing but solenoids that contain a closed loop superconducting coil wound on a nonmagnetic core. Either a thick walled disc type (tape pancake) or thin walled tube type solenoids are preferred for bearings. The zero D.C. resistance property of superconductors is used to maintain large persistent currents in these windings. These currents (also called supercurrents), create constant, non-time varying flux lines which are useful in the levitation of the rocket engine shafts. This levitation process will be described in greater detail in section 2. The flux created by these magnets is limited mainly by upper critical flux density (Bc2) as well as by the critical density of transport currents (J_c^t). These values are very high and hence superconducting magnets are useful for high load bearings such as rocket engines.

Type II bearings, (also called Meissner Bearings) on the other hand, exploit the ability of superconductors to repel external fluxes either fully or partially by inducing small persistent eddy currents, called magnetic currents, within the material. These bearings thus use the superconducting material as a "flux repelling secondary" (instead of a flux creating primary). The repulsive forces they produce are mainly limited by the lower critical flux density (Bc1) as well as critical density of magnetic currents (J_c^m), since the magnetic current density is one or two orders of magnitude lower than transport current densities for HTS materials ($J_c^m << J_c^t$) per Greer (1988). Hence the magnetic forces developable by Meissner bearings are one or two orders of magnitude smaller than those created by supercurrent bearings.

The past 30 years of research has not yielded a Meissner bearing of more than 4 psi load capacity over projected area. In fact, the lab demo bearings using High Tc materials at Cornell have not produced more than 0.1 psi magnetic pressure. This magnetic pressure is proportional to the square of magnetic field (Bc2) which is about 0.02T for new materials. Cornell has observed that the magnetic force saturates to a steady level of about 0.1 psi, i.e., beyond about 0.04T. Hence, these bearings will be useful only in light load instrument-like devices such as miniature cryocoolers, microgyros, etc.

In contrast, superconducting magnets can operate at flux density levels of about 5T. Since magnetic pressure $p = B^2/2\mu$, this shows that we can easily achieve magnetic pressures of 1400 psi using the supercurrent approach.

This report deals only with supercurrent bearings since their potential load capacity is within the range of needs of rocket engine bearings. We review literature on Type II bearings only for the sake of completeness.

This report is organized in four major sections:

Section 1 (INTRODUCTION) defines the purpose and scope of the study. It also documents critical requirements of rocket engines that will have significant impact on the design and performance of HTS bearings. An Appendix describes in more detail the requirements to be met by supercurrent bearings in general.

Section 2 (HTS BEARINGS FOR ROCKET ENGINES) presents description of proprietary HTS bearing concepts that were developed by MTI. It also describes the bearing operating mechanism and salient features thereof. It then presents a preliminary feasibility analysis of the bearing to meet the identified requirements of rocket engines. It then deduces the HTS material requirements which are needed by HTS material developers to develop material suitable for representative rocket engine bearing.

Section 3 (CRITICAL TECHNOLOGY AREAS FOR HTS BEARING DEVELOPMENT) identifies critical technology issues that have to be addressed in developing these bearings into a viable rocket engine component in the near future.

Section 4 (PAY-OFFS AND BENEFITS OF HTS BEARINGS) discusses potential pay-offs and benefits that accrue as a result of developing the HTS bearings and compares their projected performance relative to rolling element bearings and active magnetic bearings.

The report includes three Appendices that contain the following peripheral information considered relevant to HTS bearings:

Appendix A describes the prior-art accomplishments in superconducting bearings and related parallel technologies such as maglev trains, Meissner Bearings, etc. Appendix B lists the detailed technical requirements to be met by the supercurrent bearings. Appendix C presents a bibliography of the citations that were examined in preparation of this report.

From the above table it is clear that the low temperature (20°K) of LH2 makes it a better medium for cryogenic operation of superconducting magnets because the wide temperature margin between the temperature of 20°K of LH2 and critical temperature of 95°K of HTS material offers a forgiving design of HTS magnet to accommodate quenching problems. This lower temperature also enables higher operating current density and flux densities as discussed below.

The highest current density of bulk materials, made of Yitrium 1:2:3, so far is 40 A/mm^2 at 1T field at LN2 temperature. Extrapolation of these numbers (presented in section 2.4) to LH_2 temperatures suggest a current density of about 1000 A/mm^2 could be reached by current-art materials. Most of the successful superconducting applications presently use low Tc material with a current density of 200 to 1000 A/mm^2 at 2 to 5T field levels. These numbers indicate that the HTS materials seems to be already having sufficient current density at LH2. This makes de··elopment of HTS bearings for rocket engines a more near-term proposition than what was earlier believed. The range of applications could be increased beyond LH2 to perhaps LN2 temperatures if Thallium based material (Tc = 125°K) matures and is available with required current density in bulk form in the future.

Further, LH2 is more suitable for HTS bearing than LHe or LN2 since it has the highest refrigeration (4629 J/gm vs 1561 or 431) available to cool magnets per Green (1989). Its high heat of vaporization relative to LHe (44 vs 21J/gm) is desirable since it means a small amount of vaporization can remove a larger amount of heat. However, it is inflammable. This characteristic is however not critically detrimental for rocket engine bearings since LH2 is available as system fluid and sufficient care has already been taken to counter the inflammability characteristics.

1.2.1 High Pressure Fuel Turbopump (HPFTP) Bearing

General Bearing Description

Figure 1.2.1 shows current design of HPFTP shaft and bearings. Angular contact duplex pair of rolling element bearings 1 and 2 support the shaft at pump end, while another rolling element pair 3 and 4 supports it at the turbine end. The pump end also has a bumper thrust bearing. The radial bearing pairs are clamped in flexible cartridges that are free to move axially while being restrained from rotation. The angular contact bearing's ability to partially absorb axial loads is utilized to limit the axial travel. This precludes contact between stationary and rotating parts in the pump during the start transient when the balance piston has not yet achieved full operation. The shaft passes through two critical speeds at 18,000 and 30,000 rpm at the rate of 1200 rpm/sec approximately before reaching a steady speed of 37,000 rpm in about 3 seconds.

The pump end bearings are submerged in conditioned cryofluid at 33°K, while the turbine end bearings can see temperatures as high as 83°K during the operation. The fluid pressures are 200 psi at the pump end bearing; 4600 psi at turbine end bearing. The cryofluid flows at a rate of 3.3 lb/s across pump end bearings and at 1.7 lb/s across turbine end bearings.

Worst Thrust Loads

The most damaging load conditions for the bearing occur during the starting and stopping transient periods. Admission of large amounts of fuel into the turbopump at the instance of firing (when balance pistons are inactive) leads to severe thrust loads as well as side loads. These start-up shock type thrust load, while difficult to estimate, could be around 10,000 to 20,000 lb (Tecza 1989) and lasts for about 3 seconds. They ramp up to full level as the shaft speed increases from 0 to 5000 rpm during the initial 1.5 seconds. The value of thrust load drops to near zero when the balance pistons take over for normal operation to reduce the thrust to zero at 10,000 rpm. This thrust is a unidirectional load which tends to move the shaft towards the pump end. (Thrust reversals are observed in HPOTP after 10 secs. per von Pragenau 1982.)

The bumper bearing used in HPFTP can withstand this severe initial thrust shock. Superconducting thrust bearings are not attractive candidates for their replacement at present because the load capacity 1591 psi required to support 20,000 lb. load support over 4 in. diameter in a short 1.5 sec. ramp up time is beyond the current magnetic bearing technology level. (While it is unreasonable to and probably impossible to replace the bumper bearing with the magnetic bearing, we believe that there is still a role to be played by the superconducting thrust bearings. Since providing fluid to the balance pistons the "hard mount" and "soft mount" philosophies used in current balancing machines.

The stiffness of supercurrent bearing is largely controlled by the power amplifier gain and design of servocontrollers. Current experience with conventional magnetic bearings indicate that it is feasible to achieve stiffness of up to 500,000 lb/in.

Speeds

The rocket engine bearings typically run at DN values of 2 to 3 x 10^6 mm/mt. These high speeds create large centrifugal stresses in the journal material of superconducting windings, if proposed for the journal magnets. Film coating deposits on the journal could potentially work provided they have sufficiently high current density. The centrifugal stress could be reduced somewhat by using repulsive force approaches to develop compressive stresses in winding to counteract tensile stresses due to rotation.

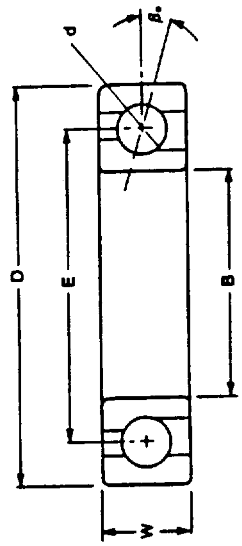
Current Rolling Element Bearing Characteristics

At the pump end, HPFTP currently uses two 45 mm rolling element bearings as shown in Figure 1.2.2. Detailed characteristics of the ball bearings candidates for both high-pressure and low-pressure pumps for both oxygen and hydrogen are given in Figure 1.2.3. The expected life of these bearings for different loading conditions is given in Figure 1.2.4 (a). The values of stiffness that one can expect from ball bearings, given in Figure 1.2.4 (b) indicate about 300 lb/mil per pair. Some available test experience, given in Table 1.2.1, show that the life of these bearings is limited to about six hours.

The outermost rotating part of the bearing has a diameter of about 3 in. The available axial length is approximately 2.2 in. so that the load capacity requirement is 1000/(3 x 2.2) = 151 lb/in^2 of projected area.

Retrofit Mode

In a retrofit mode, it will be necessary to replace current rolling element bearings with magnetic or superconducting bearings within the same geometrical envelope. Current active magnetic bearings using high grade steels with saturation limit of 2.5T which translates to a maximum load capacity of 120 psi



Turbopump	Bearing Position	Internal Geometry				Curvatures*		Speed (rpm)	Boundary Dimensions (mm)		
		H**	d (in.)	E (in.)	β_o	Outer	Inner		B	D	W
High-Pressure Oxidizer	Pump End	12	7/16	2.36	20	0.540	0.530	27,800	40	80	18
	Turbine End	18	13/32	3.38	20	0.540	0.530	27,800	65	105	18
Low-Pressure Oxidizer	Pump End	10	13/16	4.62	20	0.520	0.520	4,800	85	150	28
	Turbine End	10	11/16	3.64	20	0.520	0.520	4,800	65	120	23
High-Pressure Fuel	All	14	7/16	2.78	20	0.525	0.525	33,000	50	90	20
Low-Pressure Fuel	Pump End	10	13/16	4.62	20	0.520	0.520	12,350	85	150	28
	Turbine End	10	5/8	3.34	20	0.520	0.520	12,350	60	110	22

*Race Radius ÷ Ball Diameter
**Number of Balls

Figure 1.2.3 Geometric Data of Bearing's Potential Candidate Bearings for SSME

Note: These are not actual SSME Bearings data.

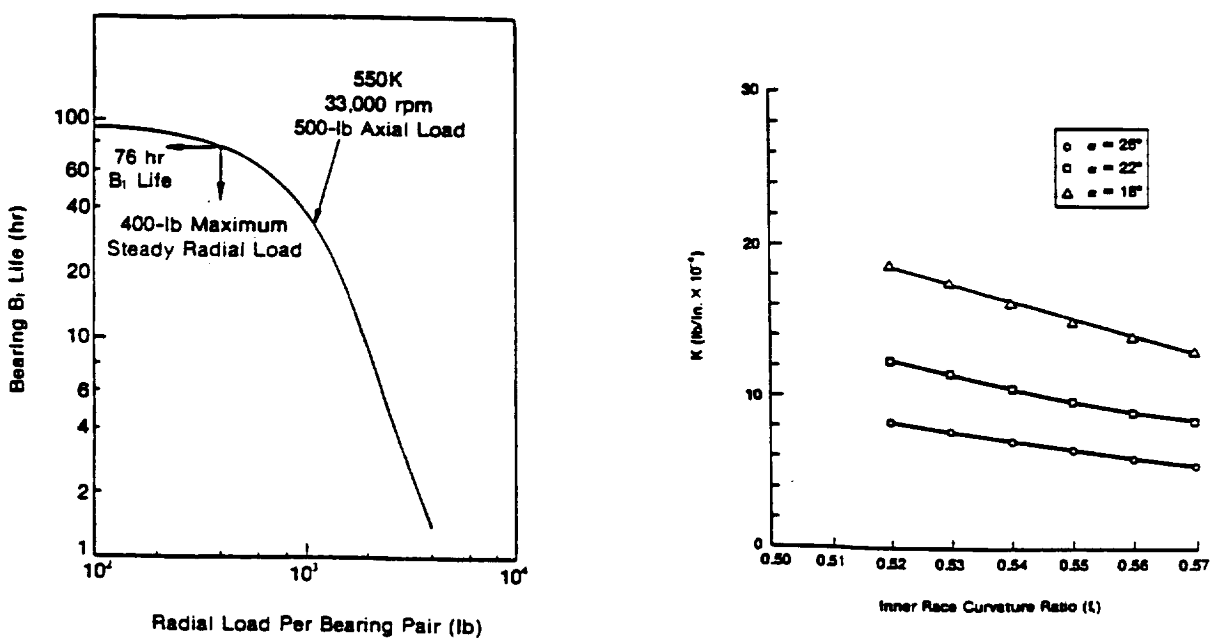


Figure 1.2.4 Typical Design Characteristics of HPFTP Rolling Element Bearings Pair

(a) Bearing B, life (b) Stiffness of Single REB

Table 1.2.1

Summary of LH_2 Bearing Test Experiences

Bearing Type	Bore (mm)	Materials: Ball or Roller	Races	Cage	Load (lbf): Axial	Radial	Speed (10^3 rpm)	Fluid	Experience: Turbo-pump	Test Rig	Maximum Test Hours Per Bearing (No Failure)	Maximum Temp. (°F)	Program
Ball	45	440C	440C	Armalon	800	100	28.3	LH_2	X		6	-350	J-2
Ball	45	440C	440C	Armalon	300	0	34.5	LH_2		X	9	N/A	Nucleonics
Ball	50	440C	440C	Armalon	3,000	N/A	24	LH_2	X		3	N/A	
Ball	60	440C	440C	Armalon	800	100	28.3	LH_2	X		6	-350	J-2
Ball	65	440C	440C	Armalon	2,200	100	31.5	LH_2	X		3	-350	J-25
Three-Tandem Ball	110	440C	440C	Armalon	36,000	N/A	13.3	LH_2		X	0.75	N/A	M-1
Ball	150	440C	440C	Armalon	1,000	0	20	LH_2		X	0.5	N/A	HPPT
Ball	200	440C	440C	Armalon	5,000	0	15	LH_2		X	1.6	N/A	HPPT
Roller	50	440C	440C	Armalon	0	2000	24	LH_2	X		3	N/A	NERVA
Roller	120	440C	440C	Armalon	0	5000	13.3	LH_2		X	1.63	N/A	M-1
Ball	35	440C	440C	Rulon	0-400	150	30	LH_2	X		5.5	-400-+60	RL-10
Ball	40	440C	440C	Rulon	140	200	30	LH_2	X		5.5	-400-+60	RL-10
Ball	45	440C	440C	Armalon	300	0	34.5	LH_2		X	9	N/A	Nucleonics
Roller	30	440C	440C	Plated Steel*	0	300	12	LH_2	X		5.5	-60	RL-10
Roller	40	440C	440C	Plated Steel	0	200	12	LH_2	X		5.5	-60	RL-10

*AMS 4616, plated lead on silver on base metal.

88TR40

The LH2 CTV turbopump model studied by MTI has LH2 at 77°K at turbine end per MTI TR-88-40 and 24-30°K at pump end per MTI TR-63-40. The fluid pressure is expected to be as high as 4500-5000 psi (MTI TR-88-40) and the flow rate is considerably lower (0.5 to 1.5 lb/sec).

The fluid film bearings carry a very light load of 57 lbs. at turbine end (per MTI TR-88-40) or 17 lbs. at pump end (per MTI TR-63-40). The slimmer shaft (1.2 in.dia.) and higher speeds (120,000 to 200,000 rpm) yield considerably high DN of 6×10^6. The total length of a bearing is 0.8 in and bearing housings have a diameter as small as 3.5 in. The load capacity requirement hence is 60 psi = (57/(0.8x1.2) at turbine end per MTI TR 88-40 and 17.7 psi at pump end (17/(0.8 x 1.2)) per MTI TR-63-40. While this load capacity could be met by PM or EM designs, the low geometric envelope is going to be a dominant constraint.

In view of the high speeds and current uncertainty in the mission thrust level of CTV turbopumps, the feasibility of superconducting bearings for this application will not be considered even though its low load requirement makes it an attractive candidate. The bearing load capacity levels for these pumps might be easier to achieve than the large SSME type turbopumps.

1.2.3 Advanced Launch System (ALS) LH2 Turbopump Bearing

These pumps are being developed currently with a view to reduce the cost per engine. A conceptual dimensioned sketch of pump end bearing of ALS system, being evolved by Aerojet under contract from NASA, is shown in Figure 1.2.5. The shaft diameter is 2.75 in. The journal diameter, corresponding to outer race of ball bearings, is 4.5 in. The axial length of the bearing pair is about 2.5 in. The pump end bearing pair is designed to carry a radial load of 470 lb. which corresponds to 470/(45 x 2.5) = 42 psi of load over projected area. This reduced bearing load (compared 150 psi of HPFTP) could be easily carried by the superconducting bearing. The speed of the shaft is 26,700 rpm which corresponds to DN of 3×10^6mm/mt. The low load capacity requirement as well as evolutionary nature of ALS turbopumps makes it a prime candidate for supercurrent bearing development.

Table 1.2.5

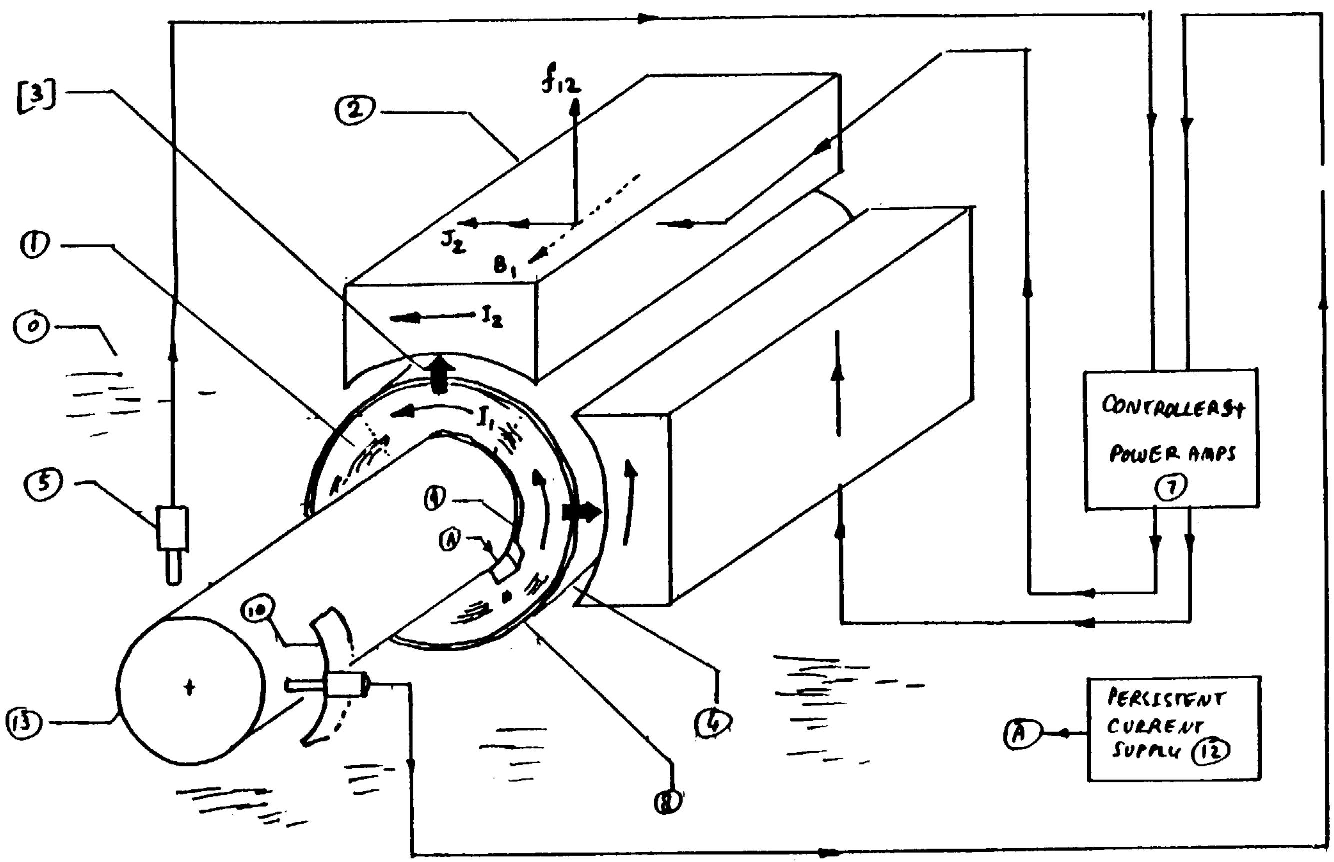
Requirements of Typical Rocket Engine Bearings with LH2 Cryofluid
1) Measured 2) Current Design

No.	LH2 Cryoturbopump	Shaft Dia. (in)	Speeds (RPM)	Radial Load Pump End Brg. Pair	Radial Load Turbine End Brg. Pair
1.	SSME/HPFTP	1.77 in	37K	1000 lb	1600 lb 1)
2.	ALS/Aerojet	2.75 in	27K	470 lb	800 lb 2)
3.	CTV	1.2 in	100-200K	7 lb	50 lb 2)
4.	HPOTP (France)	2 in	30K	1000 lb	--
5.	LTHTP (France)	1 in	190K	14 lb	--

In summary, it is recommended that NASA should concentrate on an approach that integrates superconducting bearings into rocket engines right from the initial design development stages. Designing these bearings right from the conceptual stage will help one to develop a superconducting bearing that is specially suited for rocket engines. A "drop-in" or retrofit approach, on the other hand handicaps the designer to fit these bearings into existing bearing envelopes which have been already selected to suit the special sizes of and shapes of conventional bearings. While this is possible within the current technology, this approach ties the hands of the designer in that it prevents him to efficiently adapt this new bearing technology into rocket engine turbopumps.

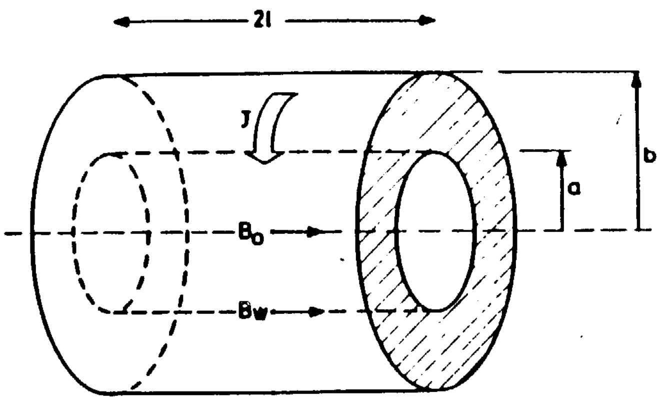
In view of the low load capacity requirement and lower speed requirement of ALS turbopump, and since these pumps are still evolving, they are most attractive candidates for targeting supercurrent development and selecting representative values of bearing parameters for laboratory demonstration.

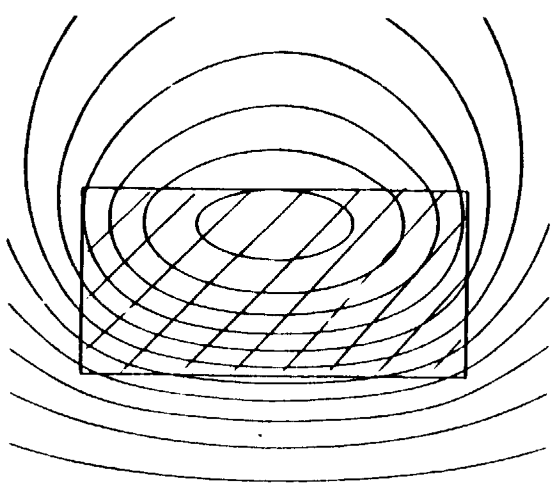
Fig. 2.1.1 CRYOSTATLESS SUPERCURRENT BEARING CONCEPT - SM/CC TYPE



(0) Cryofluid
(1) Supercurrent Magnet (SM)
(2) Controlled Current Poles (CC)
(3) Magnetic Force
(4) Air Gap
(5) Sensor
(7) Controller + P.A
(8) A.C. Loss Shield
(9) Magnet Support
(10) Backup Brg. (not shown)
(11) Persistent Current Switch
(12) Persistent Current Supply
(13) Shaft

Fig. 2.1.2 FLUX DENSITY IN SIMPLE SOLENOID WINDINGS





$$B_0 = JaF(\alpha\beta)$$

$$F(\alpha\beta) = \mu_0\beta\ln\left\{\frac{\alpha + (\alpha^2 + \beta^2)^{\frac{1}{2}}}{1 + (1 + \beta^2)^{\frac{1}{2}}}\right\}$$

$\alpha = a/b$

$\beta = \ell/a$

for $J = 200 \times 10^6 A/m^2$

$a = 30$ mm

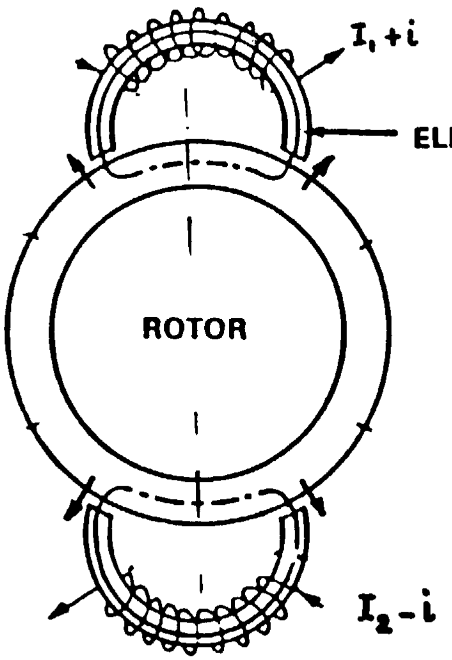
$b = 40$ mm

$2\ell = 80$ mm

$B_o = 1.9T$

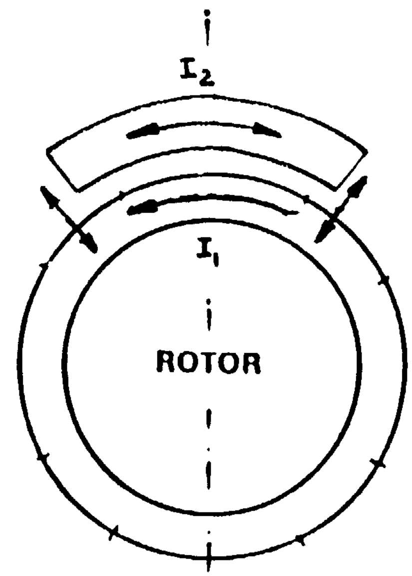
Fig. 2.2.1 COMPARISON OF

NON-SUPERCONDUCTING vs SUPERCONDUCTING APPROACHES



- Attractive Force
  - Needs two electromagnets/axis
  - Needs two power amps per axis (minimum)

Nonsuperconducting Bearing

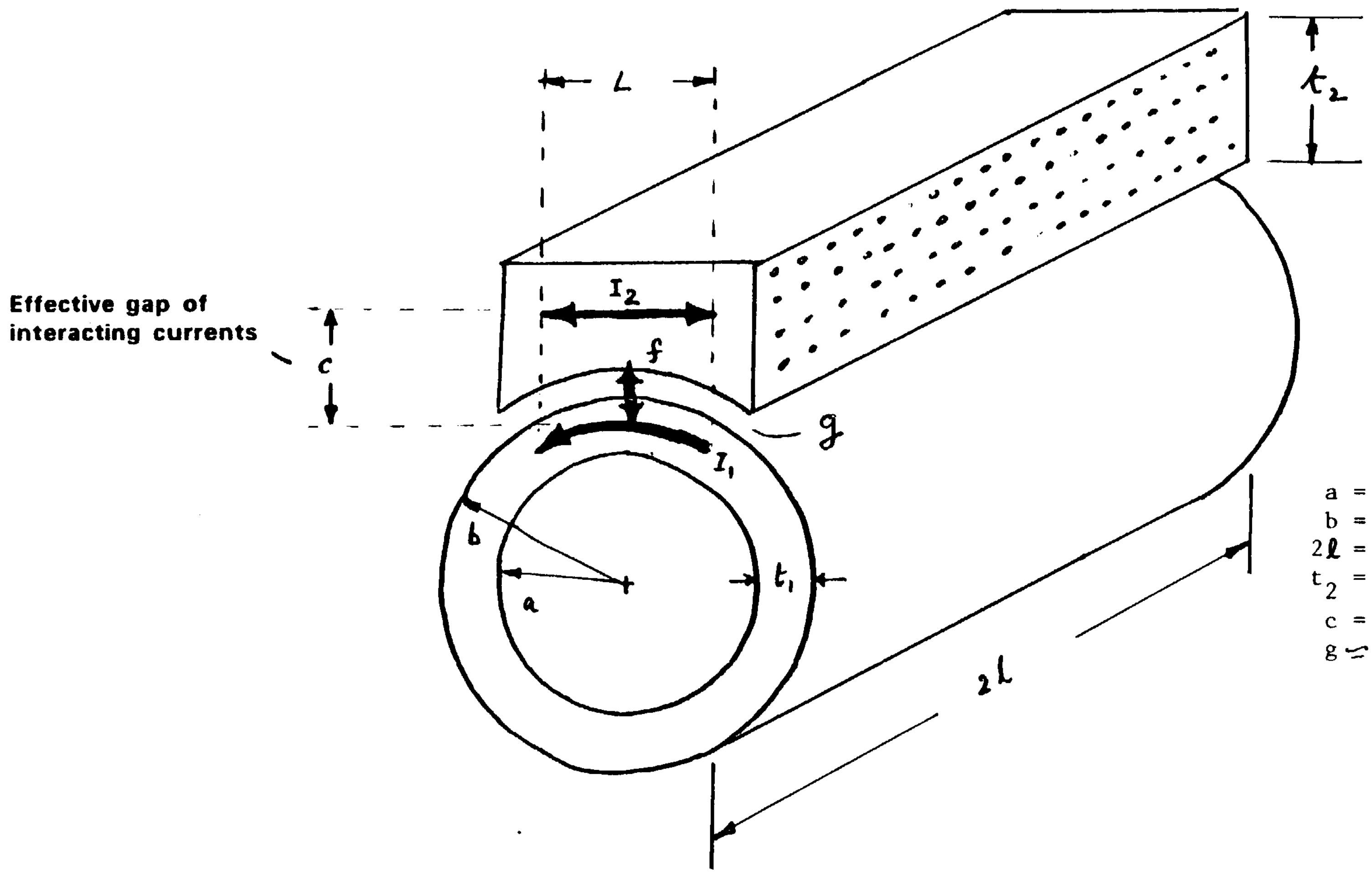


- Attractive/Repulsive Force
  - Needs only one current pole per axis
  - Needs only one power amplifier per axis
- Bias Current = Persistent Currents
- Cryostatless

Supercurrent Bearing

MTI 17778

Fig. 2.3.1 APPROXIMATE "FIRST STEP" FORMULA FOR FORCE
SM/CC CONCEPT



$a = 30mm$
$b = 40$
$2\ell = 80$
$t_2 = 20$
$c = 15$
$g \simeq 0.5$

$$\text{Force } f = \frac{\mu_o}{2\pi}\left(\frac{L}{c}\right) I_1 I_2$$

$$I_2 = I_o + kx + c\dot{x} + d\int x\,dx$$
(Feedback)

I_1, I_2 = Ampere turns in Primary and Secondary

L = Effective length

c = Effective gap

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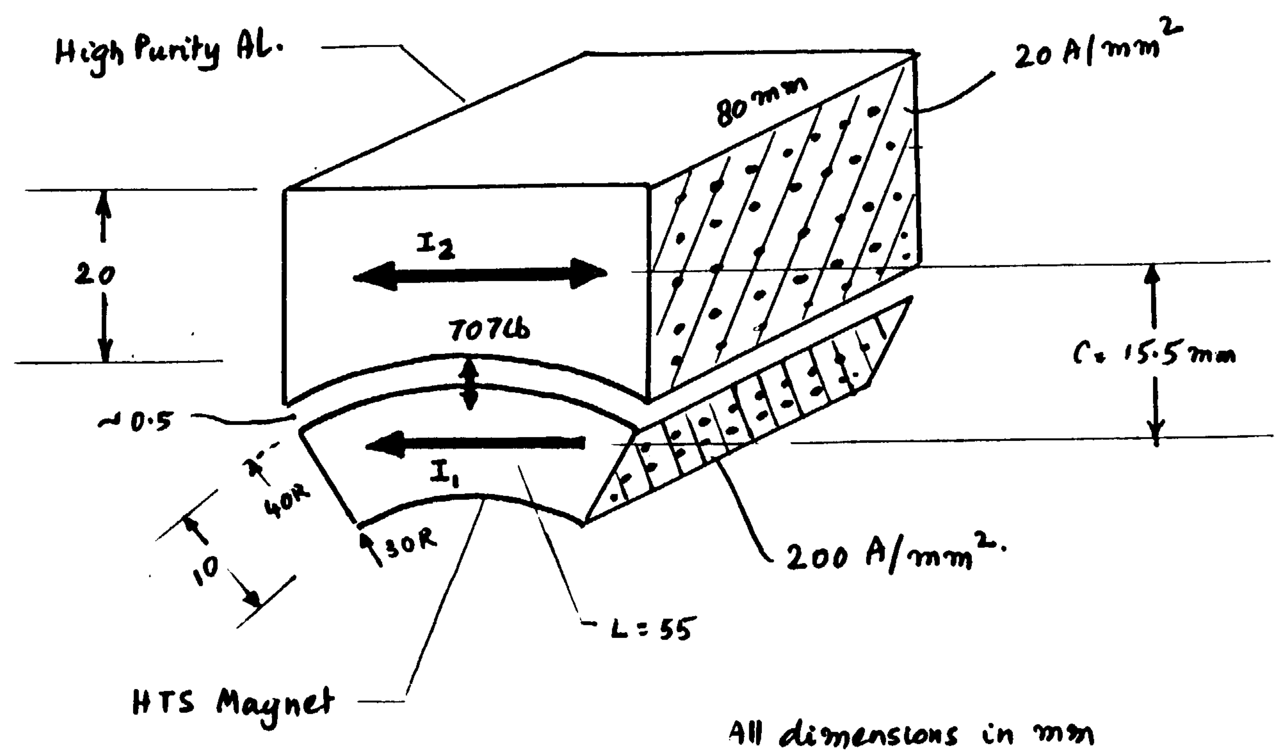
Fig. 2.3.2 ESTIMATION OF CURRENT DENSITY REQUIREMENT FOR A 1000 lb RADIAL BEARING (for HPFTP Rocket Engine)



OPERATING CURRENT DENSITY REQUIRED ≈ 200A/mm^2

OPERATING FLUX DENSITY ≈ 1.9T

Journal DN ≈ 2.96 x 10^6

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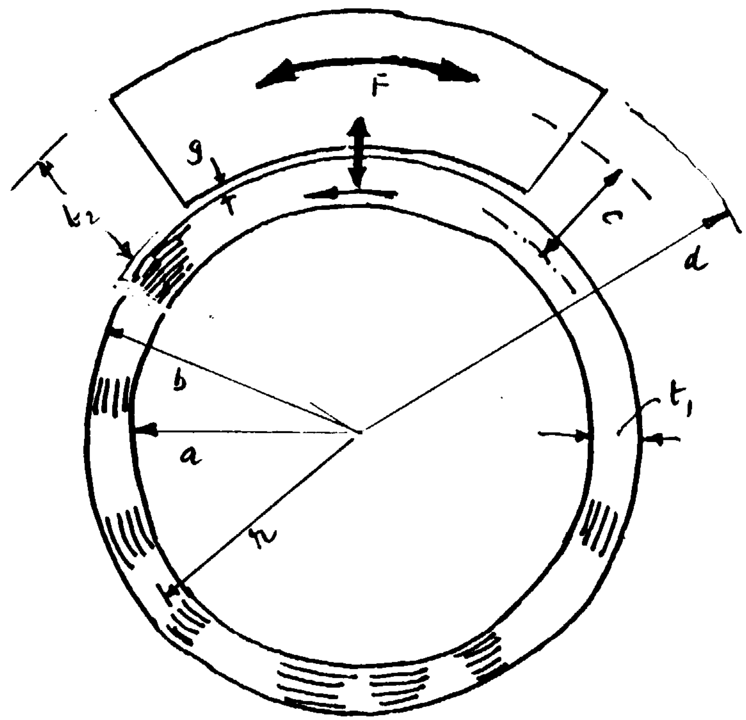
Fig. 2.3.3 Current Density Requirements of CTV LH2 Turbopump Radial Bearing (to carry 17 lb. at pumpend)



length 2ℓ = 1 in = 25mm

<u>Approximate Calculations</u>

$a = 20$ mm (0.78 in)

$t_1 = 3$mm (thickness of solenoid)

$b = 23\text{mm} = a+t_1$

$g = 0.5$mm

$t_2 = 20$mm

$c = 12\text{mm} = (t_1+t_2)/2+g$

$2\ell = 25$mm

$J_1 = 200\ \text{A/mm}^2$

$J_2 = 20\text{A/mm}^2$

$d = a+t_1+g+t_2 = 43.5\text{mm}$ (1.7 in)

$L = 2\pi\ (a+b)/2 \times \frac{1}{4} \times 0.9 = 30.9\text{mm}$

$I_1 = J_1 t_1 2\ell = 200 \times 3 \times 25 = 15000$ AT

$I_2 = J_2 t_2 2\ell = 20 \times 20 \times 25 = 10000$ AT

$$\text{Force} = \frac{\mu_o}{2\pi} \times \frac{L}{c} \times I_1 I_2 = 76\text{N} = 17\ \text{lb.}$$

2 poles: Force = $17 \times 1.414 \doteq 25$ lb.

DN = $46 \times 16000 = 7.36 \times 10^6$ mm/mt
very high DN - critical

2.4 Critical Current Density Capabilities at LH2 Temperatures

For a HPOTP application where bearings see a LOX temperatures of 112°K, the limited J_c (112°K) of 1A/mm^2 achieved so far by bulk high T_c materials seems to be a major technological barrier (unless LHe is pumped around the bearing). However, HPFTP bearings operate LH2 temperatures of 30°K. Detailed below is strong evidence to suggest that current HTS materials and processes are adequate and can achieve current densities as high as 1000A/mm^2 at 30°K temperature. This improvement of current density with temperature makes developing a HTS bearing for rocket engines a more near term application with attractive system benefits such as long life, higher reliability low weight etc. This expected current density of 1000A/mm^2 at 30°K is already within the range of J_c used in most large scale applications.

Analysis conducted by Zhou et.al. (1988) indicate that J_c of polycrystalline sintered Y compound increases with temperature as per data shown in Table 2.4.1. This data is shown as curve AB in Figure 2.4.1. This figure confirms the classical trend that critical current density increases with decrease in temperature.

Table 2.4.1

Critical Current Densities of YBaCuO Material at Various Temperatures

(Bulk, Sintered)

Temperature (°K)	J_c at 1T field (A/mm^2)
77	1
65	3
4	150

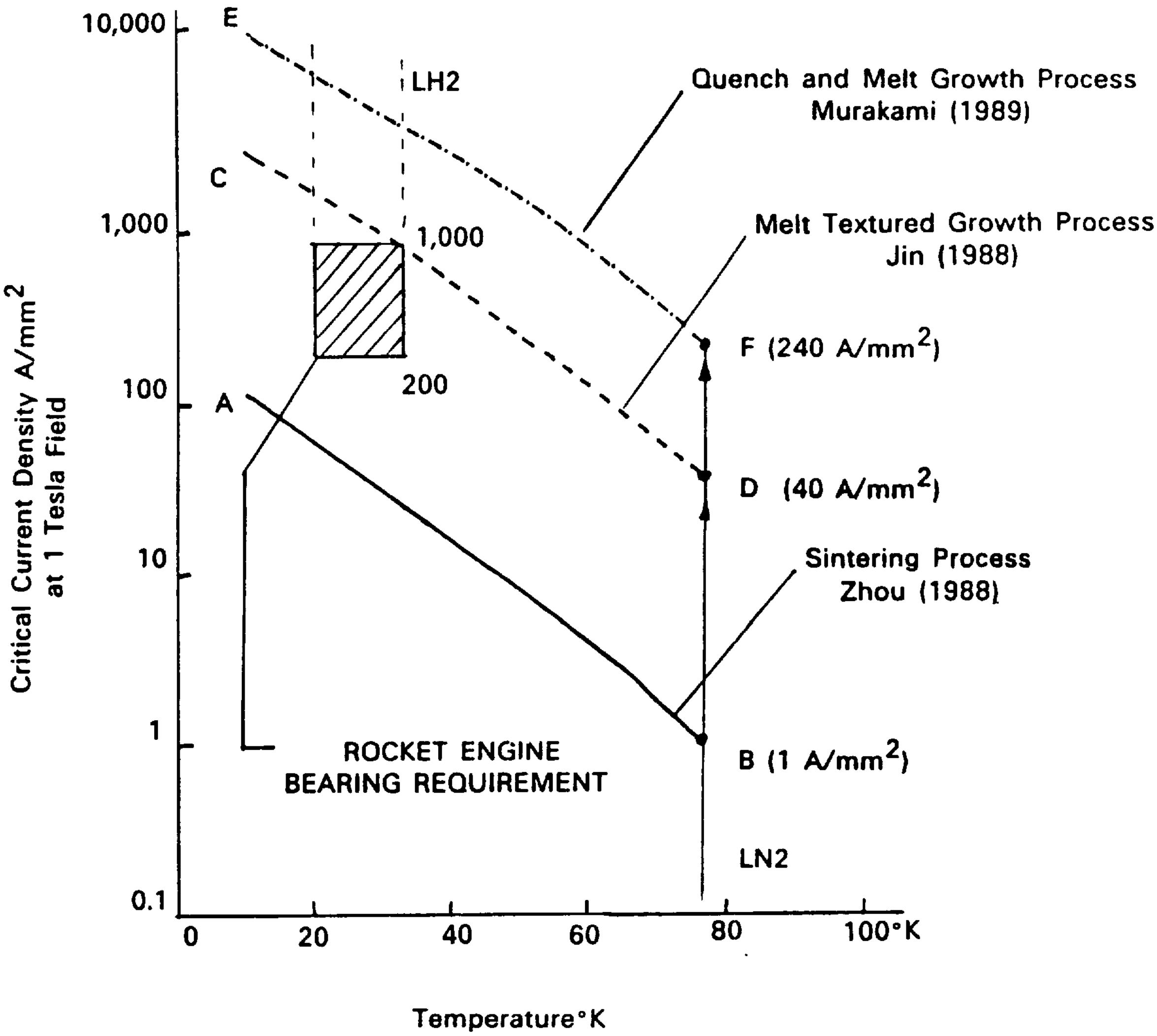
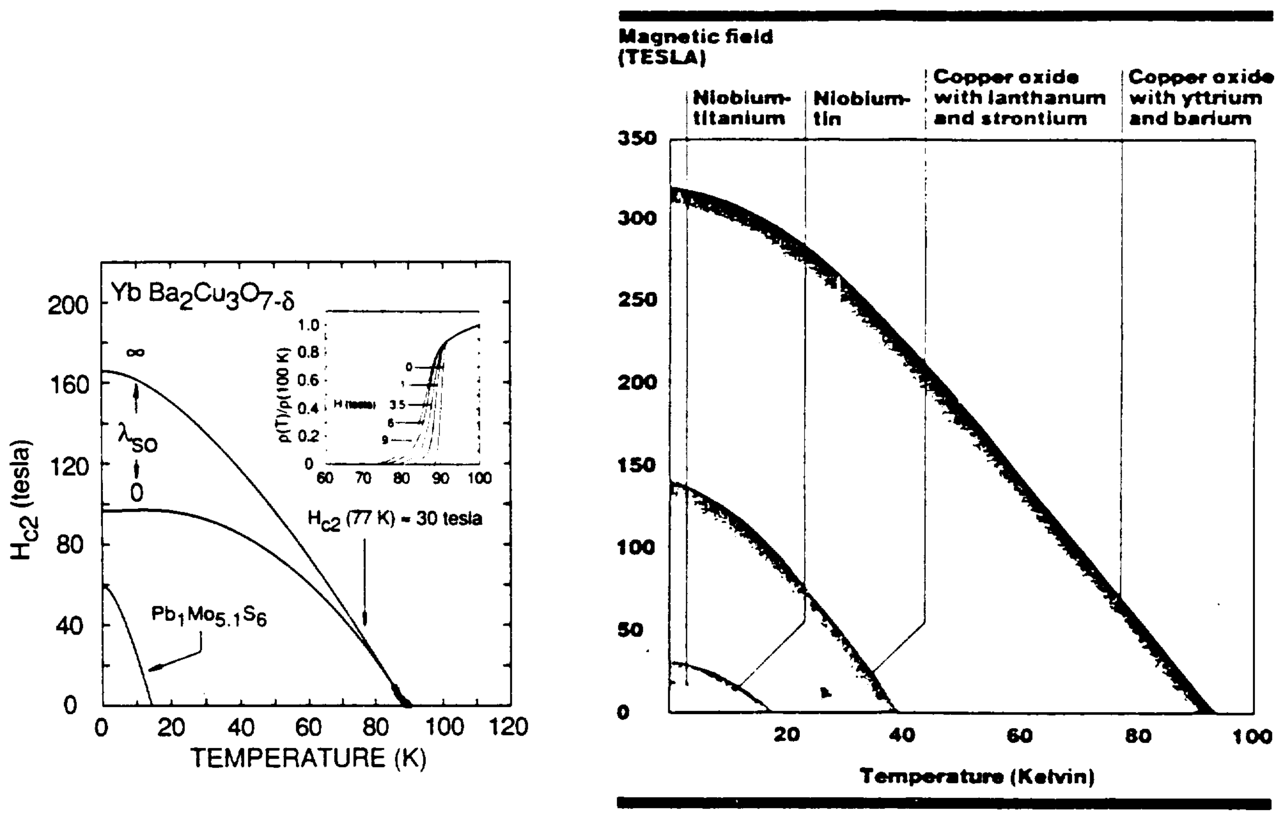


Fig. 2.4.1 Estimated Current Density Capability of HTS Materials at LH2 Temperatures



(a) (b)

Fig. 2.4.3 Upper Critical Fields of YBaCu0 at 30°K
(a) Maple (1987), (b) Forer (1988)

of going to normal. This is consistent even with the most conservative arguments by Green (1988) who projected a B_{c2} of 60T using a WHH theory.

2.4.3 Mechanical Properties of HTS Materials at LN2 Temperature

The properties of HTS materials are still in a state of flux as the processing techniques, which influence them greatly, have not matured fully. The mechanical properties depend on density, porosity and processing method. However, the following mechanical properties at LN2 collected from recent literature should give an indication of how the HTS materials compare relative to low Tc materials.

Table 2.4.3 Properties of YBaCuO at 77°K

(1) Sintered (2) Polymer Impregnated (3) Copper Composite (4) NbT_i at 4°K

	(1)	(2)	(3)	(4)
Young's Modulus	30 GPa	50	86	80
Fracture Stress	50 MPa	--	123	--
Strain to Fracture	0.2%	0.2%	0.2%	0.2%
Density	6.4 gm/cm^3	--	--	6.7
Working Stress Max.	?	?	?	500 MPa (70,000 psi)

This table shows that the fracture stress can be greatly increased by using a 20% copper matrix with YBaCuO. The HTS materials are electrically anisotopic, and no information seems to be currently available on mechanical anisotropy. Considerable work is yet to be done in order to improve and characterize the mechanical properties of these materials. These materials are known to have mica-like lamellar structure with similar strength expectations. Hence improving the mechanical strength is a major challenging task that lies ahead for material developers.

a) Pick a good conductor for the winding of the solenoid (i.e., exploit the property that electrical resistivity reduces considerably with reduction in temperature), then operate the magnet at low temperature. One such magnet, made at Los Alamos, was a spiral of copper sheet in LH2 at 20°K (McClintock 1964). It required 14 KW to obtain a field of 6T in a 2 in. diameter bore. Another magnet, made of high purity Al at 20°K, required 7.2KW to achieve a field of 7T in a 2.5 in. diameter bore. These field experiences indicate that the low resistance of a good conductor at cryotemperatures helps cutting I^2R losses in the solenoid from megawatts range to kilowatts range. But, unfortunately, several kilowatts of power are still required to operate these magnets. This is because it is necessary to drive large currents through the copper wires in the connecting circuitry which are at (noncryogenic) room temperatures.

b) Pick a good superconductor for the solenoid winding (i.e., exploit its zero resistance property to maintain persistent current), charge it and operate the magnet at cryo temperatures. Such magnets, made commercially now to LHe (4°K) temperature, require extremely small power to maintain circulating currents. This is because once started, current sources could be disconnected from the initiating source. This approach thus saves considerable power and is the <u>only</u> accepted means of making high field magnets now.

This preceding analysis indicates that even good nonsuperconductors are not good candidates for high field magnet makers. The HTS magnets essentially extend the operating temperature range from the current value of 4.2°K to higher values, possibly 30 to 40°K.

chemical stability to meet stringent rocket engine environmental requirements are also needed.

3.1 Area 1 - Supercurrent Bearing Development

Goal: The primary goal of programs in this area should be to develop and test optimized supercurrent bearing conceptual designs in the laboratory.

As already mentioned earlier, currently the supercurrent bearing concepts are in an early stage of evolution and not yet proven in the laboratory. The first challenge to be addressed, therefore, should be to determine the best supercurrent bearing design and test the basic magnetic force generation mechanism that is used in levitation of the shaft. Next, steps should involve laboratory demonstration of the optimized bearing concept. The major objective of building a lab demonstrated bearing should be to determine how the bearing's macro behavior parameters such as load capacity, stiffness and damping depend on the superconductor's controllable parameters such as currents, flux densities, temperatures etc.

In order to achieve these goals and objectives, a three-year basic technology development program is recommended. It should consist of three phases:

Phase I: Develop optimal bearing concept. Test the magnetic force generation mechanism in the optimal bearing concept (year 1).

Phase II: Develop and test the performance of supercurrent bearings under non-rotating conditions in the laboratory (year 2).

Phase III: Test the performance of the supercurrent bearings under rotating conditions in the laboratory (year 3).

Phase II - Non-Rotating Performance Tests of Supercurrent Bearing

Task 4 Laboratory Bearing Design

The goal of this task is to develop a detailed design of a radial or thrust supercurrent bearing for laboratory evaluation. This laboratory bearing should be designed to carry loads, stiffnesses and damping capacities that are representative subscaled values of rocket engine bearings. This should preferably incorporate commercially existing low Tc superconducting magnets.

Task 5 - Controller Design

The goal of this task is to design and develop a controller that integrates and controls the laboratory bearing designed in the preceding task into a bearing test apparatus. The controller design should include PDI control algorithm design and current amplifier design, together with selection of an optimal sensor.

Task 6 - Bearing Fabrication

This task should fabricate the supercurrent laboratory bearing using existing low Tc magnets.

Task 7 - Bearing Testing

The goal of this task should be to test the performance of the laboratory bearing under non-rotating conditions. The primary focus of laboratory bearing testing is to understand the mechanism A.C. power losses, as well as to analyze potential electrothermal instabilities (quenching) caused by the JxB oscillatory forces on the HTS materials. The bearing testing should include stationary tests (zero speed). Both persistent current and nonpersistent current tests should be conducted in order to evaluate the performance of superconductors under dynamic load conditions.

Phase III tasks should continue the effort of Phase II and test the performance of the bearing under rotating conditions.

A recommended program schedule to develop and demonstrate supercurrent bearings in the laboratory is given in Figure 3.1.

3.2 Area 2 - HTS Magnet Fabrication and Testing

"HTS Magnet Fabrication and Testing" refer to the challenging tasks of design, fabrication and testing of a small-size HTS magnets needed for the bearings. The HTS magnet is a basic component that is required in many of the projected HTS applications such as energy storage, MRI, motors and generators etc. Goals of programs in this area should be to design, fabricate and test HTS magnets which are relatively stress-insensitive, easily manufacturable, and quench resistant under dynamic loads and thermal excursions. Since technology programs to develop HTS magnets are already under way (Reed and Sovey 1988), no additional program outline will be presented in detail in this report.

As per 2.4.4, HTS material are known to be extremely brittle, and unlikely to carry more than a few tenths of percent of strain. Assuming that no major breakthrough in mechanical properties of HTS material is likely to occur, significant quantities of strong support case, made of high strength structural material, will be needed to limit the strain in HTS magnet coil. This in turn will increase the weight of stator, thus reducing the total system benefit. Approaches, therefore, will be needed to design and fabricate a lightweight, yet strong HTS magnet support structure that will limit the strains in them to less than a few tenths of a percent.

One critical issue that deserves special attention is complex electrothermal instabilities as that can occur in superconducting bearings. These instabilities are caused by the interaction between supercurrents in the windings (J) and the oscillatory components of impinging external fields (B) caused by mechanical vibration of the rotor. The temperature rise caused by the frictional micromotion of wires or tapes due to this JxB force can create a microregion of "normal" superconducting material. This microregion tends to propagate due to I^2R heat released by the increased resistance in the "normalized" superconducting material. A fundamental understanding of the conditions under which such electrothermal instabilities occur in HTS materials

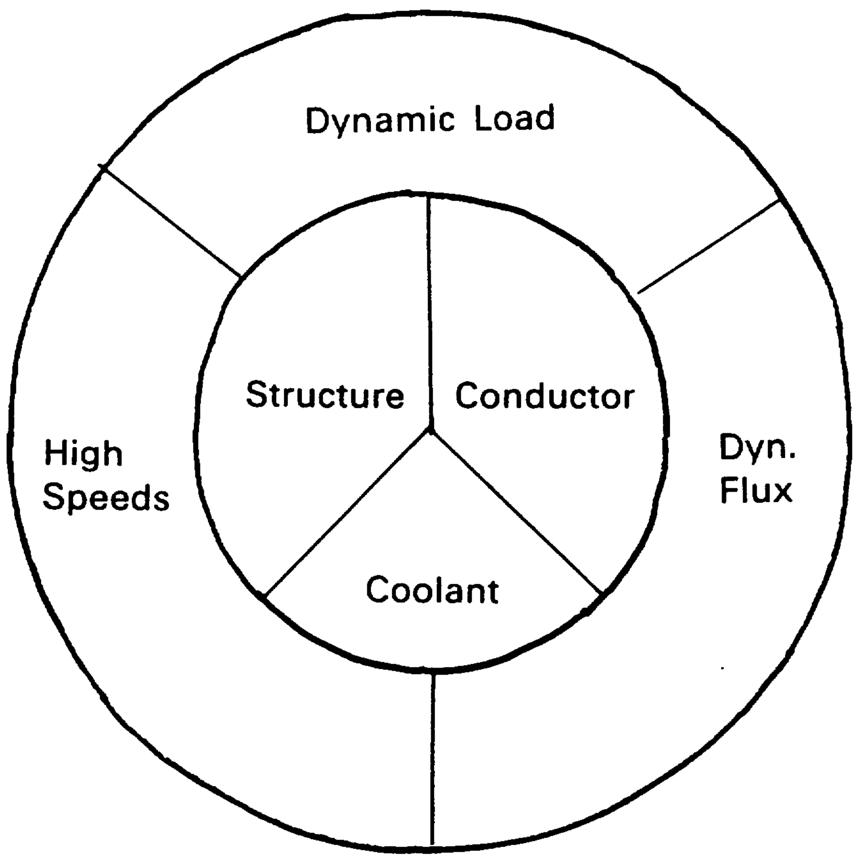


Fig. 3.2.1 Basic Constituents of Superconducting Magnet for Supercurrent Bearings

Other considerations include pressure range, sealing, low noise circuitry, ruggedness, cross axis motion sensitivity, higher dynamic range and resolution also need to be improved.

Candidate sensors for cryogenic operation include:

- Eddy current sensors
- Capacitive sensors
- Fiber optic sensors

Eddy Current Sensors

These sensors (also called proximity probes or inductive sensors) work on the principle that a high-frequency sinusiodal command voltage sent through a proximity coil close to the target shaft of electrically conducting material locally induces eddy currents in the shaft. These eddy currents change the inductance of magnetic circuit, which is measured by the self-turning oscillator. The use of these sensors to cryogenic fluids is limited by the fact that eddy currents locally heat the cryofluid. The local boiling of cryofluid introduces drift in the sensitivity that affects performance.

Capacitive sensors

The capacitance sensor utilize the variable capacitance of due to change in the plate gap or dielectric constant of the medium. The absence of electrical runout noise and insensitivity to the magnetic field make these attractive candidates for cryogenic applications. However, cryofluids like LN2 or LH2 are known to boil at the boundaries of rotating components, introducing changes in the dielectric that lead to noise in the probe signal. For operation in cryofluids, these sensors hence do seem to need improvements.

Controllers

In the supercurrent bearings, force-current relation is linear and hence the control strategy need not use bias currents for linearization. Appropriate control strategies as well as controller design implementations thereof need to be developed. The controller design strategies would be closer to the servo control techniques developed for vibration control using electrodynamic

4. A lift-off circuit must initially center the shaft before it starts rotating.

5. The temperature rise (ΔT) must be such that the temperature of the magnet is well below the critical temperature, Tc.

There are two approaches to meet these requirements: In the first approach, the thermal conditioning equipment meeting these needs could be made available as a system component. In the second approach, a simple static pressure head, sufficient to prechill LH2, could be used for ground-based applications (but it meets only the first two requirements).

(Unlike rocket engines, an application like LHe cryocooler bearing does not necessarily have prechilling equipment. The bearing in such cases are required to operate in a wide temperature range of 300°K room temperature to 4.2°K LHe temperature. In such applications, superconducting bearings can be advocated only if prechilling methods e.g., a static pressure head are included as auxiliary equipment in the system. An alternate approach is to use back-up bearings for load support for temperatures above LH2. This approach has an advantage of exploiting the back-up bearings, but they may wear very rapidly if subjected to frequent starts and stops, reducing the system benefits.)

We examine the thermal conditioning capabilities of typical rocket engine systems as shown in Table 3.2.1 below. This table shows that high load applications, such as HPFTP, ALS etc. carry prechilled LH2 at 33°K at the pump end. The low load application such as CTV and LTHTP engines also carry LH2 at 33°K at the pump end. But since the CTV system requirements and layouts seems to have not been finalized, whether fluids are conditioned or not could not be ascertained.

4.0 PAY-OFFS AND BENEFITS OF HTS BEARINGS

This section aims at establishing the potential benefits that accrue from developing and using HTS bearings for rocket engines. Currently, rocket engines mostly use rolling element bearings even though foil bearings and fluid film bearings are targeted potential candidates.

4.1 Advantages Over Rolling Element Bearings

While rolling element bearings currently used in rocket engines provide performance adequate for one mission, excessive surface wear caused by insufficient lubrication during the worst transient start and stop conditions seriously limits their life. To develop a truly long life, multimission turbopump (whether a main propulsion engine as ALS or space-based CTV) it is necessary to use bearings that eliminate surface contact and associated wear.

HTS bearings are such noncontacting suspension devices which offer significant system benefits for future rocket engines. These benefits follow from the fact that these bearings exploit the cold temperatures of propellents to levitate the rotor. In contrast, other bearing approaches such as REB literally "fight" the cryotemperatures. The performance of HTS bearings improves as temperatures reduce to liquid hydrogen levels, while that for rolling element bearings degrade with temperature.

While HTS bearings cannot compete with ball bearings in size and weight, they can improve the life, reliability and reduce power loss, as described below.

1. Long Life. Wear due to mechanical contact of rolling element bearings severly limit their life to at most one mission. Wear levels as high as 5 mils are measured after 2 hrs. of testing of current HPOTP bearings. HTS bearings have no mechanical contact or associated wear or friction; hence, considerable increase in the life of rocket engines can be expected from their use. (See Fig. 4.1)

2. High Reliability. REB's can suffer from surface cracks due to stress concentrations at point contacts. Such mechanical failure can reduce their reliability. Since HTS bearings have no rubbing surfaces, the possibility of developing cracks in bearings is remote. The 30°K operating temperature is well below the 95°K critical transition temperature of the HTS materials. This wide margin allows for bigger heat disturbance without quench possibility. This reduced chance of quench also increases its reliability. In addition, the voice coil approach linearizes the force-current relation, which simplifies the control electronics and hence increase the reliability. (The reliability of the bearing, is controlled by that of electronic hardware. But general consensus is that solid state electronic devices are more reliable than mechanical devices with moving parts.)

3. Low Maintenance. Cryofluids are poor lubricants for rolling element bearings. The increased wear and tear results in expensive tear down maintenance programs as in SSME. The same cryofluids, on the other hand, facilitate noncontact operation in the HTS bearings by cooling the superconducting magnets. This noncontact operation reduces the maintenance effort.

4. Multimission/Intermittent Operation Capability. Uneven surface wear of rolling element bearings can potentially increase the starting torques and hence reduce the possible number of starts achievable by them. HTS bearings on the other hand do not create any wear debris, and hence the starting torque does not change from one mission to the next mission. This increases the multimission start capability. Further, the persistent current magnets are on full time alert; they can be used for zero speed static suspension of the rotor during intermittent, no-load, sleep mode period.

   This is especially important for space station based rocket engines since it does not penalize system power requirements. This enables low power, intermittent operation of space-based multimission engines.

4.2 Advantages Over Nonsuperconducitng Magnetic Bearings

Major System Benefits of Superconducting Bearing

For a radial bearing, the requirement is to control two degrees of freedom shaft motion. Electromagnets in stator attracting iron in the rotor (used in conventional magnetic bearing) can generate attraction or tensile force only and hence add one additional constraint. Thus, for any n degree of freedom system considered together, the minimum number of electromagnets will be n + 1, the one additional electromagnet arises from restriction to attraction force (Bradfield et.al. 1987).

If the two translational degrees of freedom of the shaft at the radial bearing location are controlled independently, then two attractive forces are required to control each axis. The total requirement will then be four electromagnets, each with its own power amplifier. This 4 electromagnet/4 power amplifier per radial bearing approach has been adapted for ground-based active magnetic bearings. This approach is least suitable for space-based magnetic bearings because of severe weight and power penalties imposed by four power amplifiers and associated power supplies.

[If two translational degrees of freedom of the shaft at the bering location are controled together, then three electromagnets, each with its own power amplifier, are sufficient, reducing their number from 4 to 3. This offers 25'/. saving in weight and power. This approach has been adapted by Bradfield (1987). However, since magnet axis are not orthogonal (they are at 120°), microprocesser-based control algorithm will be required to derive 3 drive signals from 2 sensor signals, increasing the control complexity.]

Instead of using attraction forces, super-current bearings can employ voice coils approach that can generate both attractive and repulsive forces. Thus, for any n degree of freedom system considered together, only n voice coils will be needed.

If two translational degrees of freedom of shaft are considered (whether independently or together) then a supercurrent radial bearing will require only

Figure 4.2.1

HT SUPERCONDUCTING BEARING'S PAY-OFFS TOWARD A BETTER MAGNETIC BEARING

Characteristic	Longer Life	Higher Reliability	Lower Weight	Lower Power	
Non-contacting	■	■			
Simplified Controls	■	■	■	■	
Ironless Design		■	■		
Propellent as Cryofluid		■	■		
Zero Resistance			■	■	
Higher Flux Design			■	■	
Higher Current Density			■	■	

permanent magnet, in the flux path, we can ward off this apparent weakest link. The real weakest link will then be iron used for channelling the flux. Thus, even for PM/EM designs, the 180 psi magnetic pressures across pole faces could be reached.

The supercurrent bearing's magnetic stress is limited by critical flux density (B_{c2}), current density (J_c), permissible stress and strain as well as fracture toughness. As outlined in section 2.4, 5T HTS magnets at 30°K are feasible and can develop a magnetic stress of 1400 psi. Thus, the magnetic pressures in air gap could theoretically be increased at least by 8 times by using superconducting magnets without iron cores. (Use of iron to channel the flux makes it the weakest link, reducing magnetic pressures to 180 psi.)

2. Reduced Weight and Size. Ironless designs of SM save the weight of the iron core. Since the weight of a material required to convey a given current is inversely proportional to current density, improving the current density of the HTS materials will reduce the weight of the winding by the same order of magnitude. Both these factors will reduce the size of the stator, enabling one to better fit the bearing into the geometrical envelope of the rocket engine.

   The higher flux density of superconductors also reduces the strength of control currents needed which in turn makes lesser demands on power supply sources. This reduced weight of control electronics contributes significantly to the total weight saved.

3. Reduced Power. The AMB requires a large D.C. power supply source to produce the D.C. bias currents. Supercurrent bearing reduce this power need by four-ways. Firstly, lossless conductivity affords the persistent currents to carry D.C. loads with virtually zero power. Secondly, the force between conductors is proportional to the product of persistent currents and controlled coil current. Because the currents in the superconductor dissipate no power, that current should be as high as possible while current in the normal conductor, which dissipates power, should be as low as possible. This reduces the

4.3 Pay-off Summary

Preceding analysis indicates that the HTS bearings have considerable pay-off potential relative to rolling element bearings or nonsuperconducting magnetic bearings. Figure 4.3 presents the salient major pay-offs of the supercurrent bearings.

Figure 4.3

PAY-OFF SUMMARY

- Rolling Element Bearings Have Limited Life Due to Mechanical Contact
- Fluid Film Bearings May Have Higher Power Losses Due to Viscous Drag. Characteristics Fixed (No Active Control)
- Non- Superconducting Magnetic Bearings Suffer From Heavy Weight of Control Electronics
  - HTS Bearings Increase LIfe by Non-Contact Operation
  - They Reduce Power by Using Persistent Currents & Large Gaps (Reduction of 80% in Required Current Supply)
  - They Reduce Weight by Using Fewer Power Amplifiers and Possibly by Eliminating Iron Laminations.

A1.1 Ironless Concepts

These superconducting bearing concepts use an SM primary (usually on stator) as a flux creator and a controlled voice coil secondary (usually on rotor) to create the Bli magnetic force.

Machine Tool Spindle: Kirtley and Downer (1988) and Anastas et.al. (1988) proposed a superconducting bearing for a 500 rpm spindle to achieve high position accuracy needed for machining large optical surface. It uses one SM primary on the stator and a secondary on the rotor that consists of four non-superconducting, controlled moving coils on each side of the SM to create the bearing force as shown in Fig. A1(a). Active feedback loops adjust currents in these coils to develop forces that ensure stability and safe operation. The figure shows that the effective magnetic gap between poles of primary and secondary coils is very large, which reduces the load capacity of the arrangement. This concept also needs a copper A.C. loss protective shield that prevents time varying magnetic fields from entering the superconducting magnet. The potential heavy weight of this screen offsets the basic light weight advantage of superconducting magnets. This bearing has a weight to force ratio of 466 lb/587 lbs or 1/1.26. This shows the severe weight penalty since for conventional magnetic bearings, the weight to force ratio is about 1/50 (Girault 1988). In summary, this design needs considerable improvements from magnetic and bearing perspectives before it can be fabricated.

Control Moment Gyro: Downer and Eisenhaure (1988) and Downer et.al. (1987) proposed a superconducting gimbal bearing for a CMG. It uses forces between a secondary with 12 normal, controlled voice coils mounted on a spherical case of LHe Dewar and a SM primary that rotates inside the LHe Dewar, as shown in Fig. A1(b). Twelve active feedback loops achieve stabilization and control. Its primary advantage is that using spherical casing as a cryostat reduces the number of components and hence increases the reliability. However, use of more number of feedback loops than number of controlled degrees of freedom (12 vs 5) increases the control overhead and reduces the reliability. The large magnetic gap between the primary and voice coils reduces the load capacity and makes this also a non-optimized design.

- Too large magnetic gap reduces the load capacity. Efforts should be made to reduce the gap.

A1.2 Iron Core Concepts

Another method (called 'mixed mu' method) proposed by Homer in UK was originally intended for maglev applications (Paul et.al. 1984). This method creates an attractive force between a SM primary in the stator and ferromagnetic secondary sleeve on the rotor. Stabilization of this force is accomplished by using a superconducting diamagnetic screen attached to the primary, as shown in Fig. A1(c). Motion of the rotor induces persistent eddy currents in the screen. These currents interact with the primary currents, creating the needed stabilizing repulsive forces. The primary advantage of this arrangement is that the use of ferromagnetic material on the rotor creates a robust design efficient even at high speeds. It also generates a force that is independent of speed, and hence is available even at zero speed, which facilitates lift off approaches. There are, however, a number of critical developmental issues to be addressed. This concept showed poor stiffness because Meissner currents, which control stiffness are, small. It also showed little damping because the spring action is dominant. Potential screen losses due to control field perturbations will require a complete 3-D analysis of electromagnetic fields, which increases the complexity of design.

A2 Wind Tunnel Model Suspensions

A recent wind tunnel suspension (Boom, Eyssa et.al. 1984,85) proposes to develop the magnetic suspension force between a stationary primary consisting of 6 constant flux superconducting coils plus 8 control flux coils and a moving secondary consisting of one constant flux superconducting coil (mounted inside the core of the wind tunnel model) and two NdFeB PM's (in its two wing sections). Stabilization is achieved by modulating SM flux with that from control coils, whereas control is accomplished by 8 channels of active feedback. Use of superconducting coil in the secondary reduces the control current requirements (Britcher 1984, 1983, 1985). The coils, however, require nearly 100 MW of power per ton of lift force (Broom, Eyssa et.al. 1984) and weigh about 10 tons. This is too large compared to the typical 1 kW/ton required for maglev trains (Nasar using conducting loops to generate counteracting eddy currents in the track. No control mechanism is proposed, and this approach does not seem to have been reduced to practice.

Danby and Powell (1988) recently described various null flux configurations which need the lowest track material and highest stability. The system consists of a quadrupole primary on train reacting against a dipole track secondary containing multiturn loops.

A "mixed mu" levitation has also been actively studied in Britian (Paul et.al. 1984, Homer, 1976). As already mentioned earlier, this method uses attractive force between superconducting primary and steel sheet secondary. Stabilization of this attractive force is accomplished by a superconducting loop attached to the track (instead of a conducting loop as proposed by Danby et.al. 1974). Absence of mechanism to control lift force makes this approach less attractive, and less promising than the first approach.

Guderjahn et.al., (1969) proposed to use repulsive force between superconducting magnet Primary on the rocket and eddy currents induced in an aluminum channel secondary to suspend and launch high speed rocket sledges. Lateral instability of these repulsive forces is countered by aluminum channels that enclose the primary. This proposal does not seem to have been reduced to practice.

Hull and Carney (1989) recently proposed an electromagnetic launch system in the form of a railgun for launch of non-fragile payloads from Earth to Orbit. EM launch system is said to consume less power and lower the payload launch cost which stands at $2500/lb for conventional rockets.

A novel, efficient SM/EM approach will be to support the dead load of the train by attractive forces between a SM primary on train and iron track secondary. Decoupled EM attracting the track could counteract and support the dynamic load. This approach results in a large reduction of control currents reducing control overhead. Use of SM to support dead train load reduces power consumption. It also permits large gaps, overcoming the major technology barrier for using mature attractive electromagnet approaches. This approach seems to have not alone has strong system penalty overtones. In addition, these bearings have discouragingly low stiffness. Damping capacities are extremely low which required add-on approaches. The load capacities achieved never exceeded 4 lbs/in^2 of projected area. These projects were dropped slowly after initial wide publicity impending emergence of such "cryogenic gyros" (Anon. 1960) raised undue hopes.

Everitt and Worden (1979, 80,82) developed linear Meissner bearings using a superconducting constant flux winding primary in which current flows in opposite directions in adjacent superconducting wires that are wound parallel to the axis of the cylinder. Repulsive force is created between this stationary primary and a moving superconducting sleeve secondary on the rotor. Their review of literature indicates that attempts have been made to develop Meissner bearings for the following applications (in addition to gyro development programs at JPL, G.E. and Stanford), but most of these are limited to laboratory demonstrations:

- Gimbals (Mustov 1986)
- Proof mass suspension (Mobley et.al. 1975)
- Superconducting accelerometer for earth use (Goodkind 1979, Tuman 1971)
- Superconducting microgravity accelerometer for space purpose
    - for thrust monitoring (Lockard 1977)
    - for gravity mapping (Forward and Miller 1967, Paik 1980)
    - for testing the equivalence principle (Everitt 1980)
- Gravity Wave Antenna (Boughn 1975)

Marutani (1986) recently compared the performance of a Meissner thrust bearing with theoretical prediction and found satisfactory agreement.

A4.2 Type II Bearings (High Tc)

Recent discovery of high Tc materials renewed the dormant interest in Meissner bearings after decades of failure to develop quality Meissner bearings. These materials exhibit anisotropic superconductivity, and have strong type II behavior, and are operated mostly in the partial flux penetration region ($B>B_{c1}$). Validated analytic models to estimate the strength of induced eddy currents (and hence repulsive force) have not been developed so far. Analytic to 159 psi as claimed by various authors, e.g., Marinescu et.al. (1989). An exception, however, is the mixed-mu system described earlier. In this case the magnetic pressure is mainly generated by the attractive force between electromagnet and ferromagnetic material, and it can be large.

B1 Static Load Support Requirements

1.1 Lift-Off Force: The mechanism shall generate a lift-off force that keeps the rotor centered when it is stationary and non-rotating.

1.2 Coastdown Force: The mechanism shall generate the coastdown forces and ensure that vibrations/excursions of the rotor are within bearing clearances during shut-down.

1.3 Static Force: The mechanism shall deliver static forces that resist time-invariant loads such as self-weight, dead loads and side loads due to impeller hydraulics and keep the static equilibrium point close to the center of the bearing.

B2 Dynamic Load Support Requirements

2.1 Restraining Spring Force: The mechanism shall create a restraining force that will limit the response of the journal (to external dynamic loads such as unbalance) to within bearing clearance.

2.1.1 Stability: The restraining force generated must always oppose the motion of the rotor to ensure stability. Instabilities such as fractional frequency whirl must be avoided.

2.2 Damping Force: The mechanism should generate a positive damping force that can dissipate vibratory energy and enable the shaft to pass through critical speeds. Heat dissipation path should preferably not contain the cryofluid. (Since the cryofluid is heated at a later stage in rocket engines, this is not a critical requirement for rocket engine application. But for other applications such as superconducting generator, this is an obligatory requirement.)

2.3 Drag Force: The drag force on the rotor in the direction of rotation shall be minimal, and lift to drag force ratio must be high.

B4 Thermal Conditioning Requirements

4.1 Prechilling: The stator magnet region must be prechilled to insure that the magnet does not go normal at any time during starting or stopping.

4.2 Temperature Rise: The power loss due to bearing operation should be low enough that there is negligible temperature rise in superconducting magnets. The heat shall be dissipated non-locally to ensure negligible temperature rise.

4.3 Starting Thermals: Any sudden starting or stopping thermal transient shall be controlled so that the magnet does not become normal.

B5 Space Operation Requirements

5.1 Micro g Operation: The bearing shall operate in any orientation in an earth environment, as well as in micro g environment without deteriorating performance.

5.2 Space Vacuum: The coils shall be canned. Wire insulation shall not outgas in space to such an extent that they can distort due to heating up of wire. The can shall be designed to withstand pressure and thermal gradients.

5.3 Launch Shock: The bearing shall be caged during the launch (for applications other than launch vehicles).

5.4 Shaft Protection: A failed bearing shall not automatically result in a failed shaft. A shaft protection device, such as catcher bearing, slow rampdown circuits, etc. must be incorporated.

7.1.2 Decoupled Bias: The control flux must not pass through the supercon ing magnet to avoid exposing superconducting wires to alternating flux fiel

7.2.1 Compressive Stresses: The magnet shall be designed so that conductors always be subjected to compressive stresses and take advantage of the compression strength of ceramics.

7.2.2 Minimal Dynamic Forces: The superconducting magnet must ideally subjected to dynamic stresses from the rotor to avoid friction induce quenching of superconductors.

7.3 Magnet Explosion: The magnet shall be protected from explosion d sudden short circuit or quenching, so that magnet energy is dissipated sl

7.4 Safety Margins: The current density and flux density chosen shall below critical values to ensure safe operation. There must also be wid margin between critical transition temperature and operating temperatu magnet.

7.5 High Frequency Operation: The magnet shall be designed to ensur will perform without degradation in specified frequency range.

7.6 Magnet Shield: The magnet flux shall be shielded so that it does r fere with the system fields naturally present in target applicatior superconducting generators or sensitive instruments.

7.7 Fluid Flow: The viscous drag due to fluid flow in the annular g stator and rotor should add to its damping and load capacity, not sul it.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Cryostatless High Temperature Suppercurrent Bearings for Rocket Engine Turbopumps		5. Report Date September 1989
		6. Performing Organization Code 0440-39273
7. Author(s) Dr. Dantam K. Rao Dr. James F. Dill		8. Performing Organization Report No. MTI89TR40
		10. Work Unit No. 42
9. Performing Organization Name and Address Mechanical Technology Inc. 968 Albany-Shaker Rd. Latham, NY 12110		11. Contract or Grant No. H-80591 B
		13. Type of Report and Period Covered Contractor Report (May-July 1989)
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Huntsville, Alabama		14. Sponsoring Agency Code

15. Supplementary Notes
MSFC Technical Monitors: R. Decher and E. Urban

This report presents the investigation carried out by MTI on the use of High Temperature Superconducting Materials to magnetically levitate rotating shafts of rocket engine turbopumps in a configuration called "Supercurrent Bearings."

16. Abstract
The rocket engine systems examined include SSME, ALS and CTV systems. The liquid hydrogen turbopumps in the SSME and ALS vehicle systems are identified as potentially attractive candidates for development of Supercurrent Bearings since the temperatures around the bearings is about 30°K, which is considerably lower than the 95°K transition temperatures of HTS materials. At these temperatures, the current HTS materials are shown to be capable of developing significantly higher current densities. This higher current density capability makes the development of supercurrent bearings for rocket engines an attractive proposition.

These supercurrent bearings are also shown to offer significant advantages over conventional bearings used in rocket engines. They can increase the life and reliability over rolling element bearings because of noncontact operation. They offer lower power loss over conventional fluid film bearings. Compared to conventional magnetic bearings, they can reduce the weight of controllers significantly, and require lower power because of the use of persistent currents. In addition, four technology areas that require further attention have been identified. These are: Supercurrent Bearing Conceptual Design Verification; HTS Magnet Fabrication and Testing; Cryosensors and Controller Development; and Rocket Engine Environmental Compatibility Testing.

17. Key Words (Suggested by Author(s)) High Temperature Superconductors, Magnetic Bearings, Supercurrent Bearings, Cryoturbopumps, HPFTP Turbopump, ALS Turbopump, HTS Magnets, Superconducting Bearings, HTS Materials		18. Distribution Statement Unclassified	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of pages 88	22. Price*

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

END DATE FEB. 16, 1990