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ALUMINUM COLLARS FOR THE SSC

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Aluminum Collars for the SSC

1) Summary

Aluminum alloy collars have performed well in LBL models; there is less loss of prestress on cooldown compared to stainless steel collars and cost can be reduced by about 23M$. It is proposed that an R&D program on improved collars be continued with the main goal of greater magnet reliability as well as lower cost.

2) Brief History

a) The selection of collars with cold iron

The present collar design as described in the CDR has been used in most of the recent LBL models and all of the BNL models of the 40 mm bore "design D" magnet. One of the main reasons for using collars is to provide accurate coil positioning and reliable precompression independent of the split iron yoke which, in older designs, was adjacent to the windings and held in place by an external structural shell.

A major disadvantage of clamping directly in the iron is that the low thermal contraction of the iron relative to the winding allows coil pressure to decrease excessively when cooled to operating temperature. This relaxation could be avoided by assembly of the split yoke with a gap; then, upon cooldown, thermal contraction of an external shell could close the gap and keep the iron shell firmly against the coils, thus preventing loss of prestress. However, to insure precise coil position and proper prestress by this technique might require an extensive development program and costly tooling. In addition, to avoid excessive distortion of the field because of iron saturation, a minimum gap of about 1 cm between the coils and the iron yoke is needed in this high field design (6.6T). Thus, the use of thin nonmagnetic collars does not cause a large decrease in achievable magnetic field strength since the gap would be needed anyway. Interlocking collars were first used in the Tevatron. They proved reliable and economical. In the Tevatron, they were fastened by welding.

b) Keyed collar design

We have used rectangular keys to lock the collars together for improved precision of collar and coil position and ease of assembly; also, disassembly is facilitated in case there is a need for repair, such as damaged electrical insulation, or if the coil is to be shimmed for field quality correction. Two small keys are used on each side, rather than a single larger key, to minimize the depth of the key slot, which maintains adequate collar width in this region. It also avoids intrusion into the iron yoke at the midplane through enlargement of the collar.

In addition to providing adequate precompression of the windings, we required that the collars be stiff enough to completely support the Lorentz forces without yielding or experiencing "excessive" elastic deformation at the operating field. "Excessive" deformation was not precisely defined, but it was estimated, pending magnet test results, that a few mils would be tolerable.

c) Experience at LBL with SSC collars

The initial designs showed that stainless steel collars of 15 mm width and aluminum collars of 25 mm width would have similar deformations when "self-supporting" under magnetic load. The first collars used in design "D" magnets were 25 mm aluminum. They were designed in May 1984 and used in the model magnet, LBL's #D12C-1, which was tested in February, 1985. Two magnets of this design were tested. Collar assembly proceeded as planned and measured deformation at assembly and under operation agreed reasonably with predictions. The first 15 mm wide stainless steel collars (all S.S. collars discussed in this paper are of Armco Nitronic 40 stainless steel) were used in magnet D12C-2. Figure 1-a shows the collar design. They were manufactured using laser machining to avoid the expense and long lead time associated with die fabrication. Again, assembly and collar deformation under load agreed reasonably well with prediction.

Die-punched 15 mm SS collars shown in Fig. 1-b were first used in the 4.5 m model magnets at BNL.[1] These collars were identical in key size and width to the LBL laser-cut collars but differed slightly in keyway design. Ten LBL models were made with these collars. Also, LBL has constructed two magnets using Al alloy (7075) collars punched from the same BNL die. A new die was constructed by LBL with increased collar inner radius to accommodate a 15 mil protective shoe used to prevent insulation damage during collaring, and with a modified keyway design to eliminate the yielding that had been observed. To date, two additional magnets have been built with 15 mm Al collars from this die; the Nitronic 40 collars for the 1.8 m industrial "kit" being made at BNL will be made from this modified die. A new collar is under design at BNL for the next series of 17 m magnet. It will be nearly identical to the former one, but with an improved keyway design and with dimensions to accommodate a protective shoe.

3. Summary of Measurements on Coil Prestress and Collar Deformation

a) Coil prestress goals

A main goal of the collars is to provide sufficient precompression of the windings so that training is minimal. The relationship between training and coil prestress is not well established, however, low prestress is a factor contributing to excessive training. A working design goal is to insure that the windings are always under circumferential compression at the operating field of 6.6 T. This minimum value, based on a frictionless analysis, is 3.6 ksi for the inner layer and 2.9 ksi for the outer layer. To allow for uncertainties, a higher stress, about 1 ksi higher, is used as a design goal.

During assembly, the collar and coil package is squeezed in a press. The maximum stress in the windings, experienced for a short time (few minutes) has ranged up to 26 ksi (MD-1 inner) in LBL model magnets. Creep of the cable insulation is rapid at this pressure and it is judged that a maximum allowable winding pressure of about 15 ksi for production magnets would result in more reliable electrical insulation and more uniform dimensions of the windings.

While the press is loaded, the keys are inserted. As the press is unloaded, the collars expand until the keys are fully loaded. Much of the original assembly pressure is lost as this

TABLE I. Coil Pressure and Collar Deflection Measurements

S.S. Collars 15 mm	Average** Coil Pressure @ Assembly (ksi)	Residual After Collaring (ksi)	% Loss	Average Increase in Collar Diam. after Collaring (mils)	Collar Stiffness (mil/ksi)
D12C-2	18.6	8.7	53.0%	5.0	.57
C-4	15.1	7.9	48.0%	10.0	1.27
C-5	16.6	5.0	70.0%	9.0	1.80
C-6	19.5	8.5	56.0%	9.0	1.06
C-7	20.6	7.7	63.0%	12.0	1.56
C-8	22.5	10.4	54.0%	15.0	1.44
MD-1	16.0	5.5	65.0%	8.0	1.45
-2	16.6	8.1	51.0%	9.0	1.11
-3	17.3	8.3	52.0%	10.5*	1.27
D14B-3	8.0	3.0	63.0%	3.5	1.17
Average			57.5%		
15 mm Al Collars					
D14B-1	23.2*	5.8	75.0%	8.0	1.38
B-2	13.0*	3.0	77.0%	6.5	2.17
B-4	15.0*	5.7	62.0%	7.5	1.32
B-5	16.3*	4.7	71.0%	8.0	1.70
Average			71.3%		
25 mm Al Collars					
D12C-1	20.2	12.0	41.0%	6.5	.54
C-3	20.8	9.1	56.0%	7.0	.77
Average			48.5%		

*Data for inner layer only.

**Average of inner and outer layers. Inner layer pressure is usually greater than outer layer pressure.

"springback" occurs. Further stress reduction occurs due to creep of the insulation and additional stress loss occurs during cooldown. Figure 2 shows the typical stress history for coils with aluminum and stainless steel collars.

During magnet assembly, measurements of the coil pressure and collar deflections are made using a load cell with strain gages[2]. From this data the loss of coil pressure and the collar deformation during assembly, can be determined. These measurements are tabulated in Table I.

b) <u>Springback loss</u>

The "average loss by type" column shows a 57.5% loss for S.S. vs. 71.3% loss for Al, a 13.8% greater assembly loss for 15 mm aluminum collars because of their lower elastic modulus; for example, starting from 17 ksi assembly pressure, this would result in a 2.35 ksi lower residual coil pressure after collaring.

The 15 mm S.S. collars have a measured average stiffness (change in midplane radius/average pressure) of 1.27 mil/ksi as compared to 1.64 mil/ksi for the 15 mm aluminum collars. The ANSYS program predicts 0.7 mil/ksi and 1.78 mil/ksi for the S.S. and aluminum, respectively. The large deflections in many of the S.S. collars are caused by yielding in the keyway region, as was apparent from visual and optical inspection of the collars after disassembly.[3] The notable exception was model D12C-2 which used a collar of a different design.

c) Collar stress analysis

ANSYS modeling of a purely elastic collar shows local stresses in the keyway area well above yield strength.[3] Analysis showed that relocating the keyway would reduce the peak stress by 40%. Second generation collars with this modification have not experienced yielding problems.

d) Properties of 7075 aluminum alloy

Some concern has been expressed about the use of the 7075-T6 aluminum alloy in a structural application where stress concentrations are encountered since it has a high yield strength and thus might exhibit brittleness relative to S.S.; the analytical model predicts very local collar stresses near the keyway corners which would exceed the yield strength of either Al or S.S. at rather low coil loads (about 6 ksi). Other alloys might be satisfactory.

A mechanical test was done that applied a simulated coil load at 80 K to a short, one-inch long collar pack. At an equivalent coil load of 15 ksi, about 3 times greater that the design load, no failure had occurred. The aluminum collar has a substantial safety factor at the expected operating coil stresses.

Appendix I gives properties of 7075 aluminum and Nitronic 40 stainless steel. Typical properties of Nitronic-40 and 7075 T6 aluminum are summarized as follows:

	300K		4K	
	Al	S.S.	Al	S.S.
Yield Stress ksi	70.6	71	99	169
Ultimate Stress ksi	80.6	113	114	229

There is no reason to believe that brittle-type failure due to crack propagation under cyclic loading will occur. Local yielding without failure occurs during assembly in both S.S. and Al collars at much higher stresses than are experienced at low temperature.

e) Collar deformation during magnet operation

Collar deflection was measured during magnet operation on 5 models and agrees reasonably well with predictions. Measurements are summarized in Table II.

TABLE II.

Radial Deflection of Collars on Horizontal Centerline at 6 Tesla

Model #	Deflection (mils)
15 mm S.S. Collars	
D12C-2	1.7
C-4	1.7
C-5	1.0
C-6	+0.3*
25 mm Al Collars	
D12C-3	1.4

*Model C-6 collars supported by iron yoke.

f) Coil Prestress Loss During Cooldown

Table III is a tabulation of the change in coil prestress between room temperature and 4 K. Figure 3 shows measured coil pressure vs. temperature during cooldown for magnet D12C-7 with S.S. collars; this magnet showed the lowest inner layer pressure loss of all the S.S. magnets tested. Figure 4 shows similar data for magnet D12C-5. Reliable data for models D14B-2 through D14B-5 are not available. The average loss in prestress for the inner coils in S.S. collars is 4.1 ksi and for aluminum collars is 2.0 ksi.

Calculating the coil prestress loss at cooldown is difficult due to the model complexity and uncertainty in material properties as a function of temperature. Two approaches have been tried. A

TABLE III.

Change in Coil Prestress Between Room Temperature and 4K

Model # 15 mm S.S. Collars	Inner Layer (ksi)	Outer Layer (ksi)
D12C-2	-5.0	-1.5
C-4	-5.0	-2.0
C-5	-4.0	-1.0
C-6	-3.8	---
C-7	-3.4	-3.1
C-8	-5.0	-4.0
D14B-3	---	---
15 mm Al Collars		
D14B-1	-2.0	---
B-2	---	---
B-4	---	---
B-5	---	---
25 mm Al Collars		
D12C-3	+2.0	+1.0

program called "Shell" has been used which models the 2D cross section as a series of nested homogeneous rings that can have circumferential and radial stresses. Using a reasonable range of coil properties, the predicted loss ranges from 2,500 psi to 4,800 psi for S.S. Collars, the latter loss occurring with coils having the highest modulus and thermal contraction. Calculated results for the aluminum collars are generally 1,500 psi lower for the same coil properties.

A more elaborate two-dimensional ANSYS model gives similar results: S.S. has about 2000 psi greater cooldown loss.[4] The magnitude of the loss is a strong function of the thermal contraction coefficient of the windings, which is not well known; it depends strongly on the stress state and temperature of the windings. One-dimensional measurements have shown that the effective moduli of windings similar to those of the SSC increase dramatically (factor of about two) when the sample is cooled to 80 K, and that thermal contraction depends strongly on the magnitude of mechanical compression.[5] Independent determinations of thermal contraction of SSC windings in a realistic state of loading has not yet been done, however, the observed cooldown losses can be explained with reasonable values of thermal contraction.

4) Reduction of "Springback" Loss

a) <u>Causes</u>

Significant causes of springback are (1) local yielding in vicinity of keyways, (2) collar rotation caused by pin assembly clearances, (3) assembly fits and clearances around keys, and

(4) circumferential elongation of collars as keys are loaded.

These are addressed separately:

(1) Keyway redesign has eliminated most of the local yielding seen in the S.S. collars.

(2) Edge welding of collar packs to prevent rotation has been observed to reduce springback in the S.S. collars by about 10%;[3] however, a coil model assembled with the stiffer collar pack experienced enough additional stress loss during cooldown to negate much of the gain. Spot welding of adjacent S.S. collars which should be somewhat more effective than edge welding is being proposed and room temperature springback measurements have been made at BNL showing similar behavior; however, cooldown losses with these collars have not yet been reported but a similar increase in cooldown loss would be expected.

(3) Assembly fits cannot be greatly improved without increased assembly costs.

(4) If collars can be loaded circumferentially before keys are fully inserted, the springback could be nearly eliminated. We are examining several promising ways to accomplish this.

b) Test Results on Collars with Tapered Keyways

A simple approach is to load the collars by pushing on tapered keys to assist in drawing the collars closed instead of inserting rectangular keys with clearance. As a test of this idea, the keyways of standard 15 mm Nitronic 40 S.S. collars were machined to have a 6 degree taper (3^{0} per side). A 6 inch collar pack was assembled around a standard coil assembly. At assembly, the collars were compressed until the inner coil pressure was at 16 ksi (read by internal pressure gages), and tapered keys were driven in. The collar press force was adjusted so that coil pressure never exceeded 16 ksi. After the keys were driven home, the press was released and the coil pressures decreased to 11 ksi. This loss of only 5 ksi at assembly is 31% or about half the average loss experienced with the standard unmodified type collars at assembly.

c) Proposed Single Key Design

Another design we are investigating might be more effective than using the present small keys; Fig. 5 shows a single large key designed to properly load the collars with very little springback. By making the key from a ductile magnetic iron (say 5% or 9% Ni), the magnetic behavior of the iron yoke is not affected as would be the case with a nonmagnetic key. These low nickel iron alloys were developed several years ago for cryogenic applications and are ductile, magnetically "soft," and have relatively low cost. Appendix II gives some of the mechanical and magnetic properties of these steels.

5. Magnetic Behavior of LBL Models with Aluminum Collars

a) Historical overview

The first 40 mm bore LBL-SSC dipole design was based on a cold iron 2-in-1 design in which the iron yoke was in direct contact with the graded two layer coil. Four (4) magnets of this type were built and tested at LBL; two (2) with solid iron rings and 2 with bolted split iron blocks.

Eight (8) D12C series of collared magnets were then built, seven (7) with the 3 wedge C5 cross-section. Aluminum collars, 25 mm wide, were used in D12C-1 and D12C-3. Nitronic-40 collars, 15 mm wide, were used in the six (6) other magnets in this series; the first one, D12C-2 had LBL laser-cut collars and the remainder had BNL's die punched collars.

Three (3) MD series, 4 wedge cross section, magnets were built with Nitronic-40 collars and 2 of these were tested at helium temperature.

Aluminum is easier to fabricate, has lower cost, and it was thought that the higher thermal contraction upon cooldown would result in higher coil prestress at helium temperature; therefore, we built several model magnets with 15 mm Al collars. Five (5) D14B series, 4 wedge, magnets were tested at helium temperature. Four (4) of these magnets have 15 mm wide aluminum collars and one (1) has the 15 mm wide Nitronic-40 collars.

b) Training

It seems that training is reduced when the coils have reasonably high, residual, 4 K prestress. Training can be as little as 5% and plateau values reached on the third (3rd) quench or can be as much as 15-20% and require 6 to 8 quenches. These good and bad behaviors have been observed with magnets collared with aluminum and with stainless steel (Nitronic-40) -- the collar material doesn't seem to be the determining factor.

c) Field quality

Since the Young's modulus for aluminum is about one third that of stainless steel, the stiffness is reduced when aluminum is used. The collared magnet, therefore, has a greater shape distortion for aluminum and this can be observed in the magnetic field measurements of the magnets when "free-standing". The major multipole affected is the sextupole, which can be designed out by a small adjustment in design of the wedges. To first order the field quality of the magnets collared with stainless steel and aluminum are equivalent but our best magnetic field quality has been achieved in our latest magnets -- which happen to have aluminum collars.

d) <u>Side shimming experience</u>

Since the aluminum collars are not as stiff as S.S., they are deformed more by the Lorentz forces at operating field. To prevent excessive motion, shims were inserted between the iron yoke and collars at the coil midplane, as shown in Fig. 6, to mechanically restrain the collar from expanding at the midplane. The sextupole field can be adjusted by varying the thickness of these shims. No quadrupole adjustment was attempted. Thin shims were used in this case as a convenience to permit use of the existing collar and yoke designs. In a magnet designed for this method of support, a special shim piece would be used. An example is illustrated in reference 6. One magnet, D14B-2, so shimmed, had a sextupole within 0.5 units of zero. Two magnets achieved sextupoles within 2 units of zero.

6. Assembly Procedures with Al Collars

a) <u>Surface friction with aluminum alloy collars</u>

There have been reports of problems with early aluminum collar models; they have been shown to be not fundamental.

The first design B collars at FNAL showed some galling during room temperature assembly; this was corrected by properly removing the burr from the punching operation.

At DESY, where very thick (~ 5 mm) Al alloy collars are used for HERA, small bits of Al "dust" or powder was found in initial models; this was observed on the exterior of the Kapton insulation when the collars were disassembled. A slight lubrication of the collar (a very thin MoS_2-based lubricant) has cured the problem. The method of burr removal is different for the HERA collars and the LBL collars appear to have a smoother surface.

In any case, at LBL we have not experienced galling, production of aluminum chips, or shorts because of the aluminum.

b) <u>Insertion of coil into yoke</u>

To insure that the collared coil assembly is firmly supported by the yoke in a precise position, it is elastically deformed slightly when assembled in the yoke at room temperature so that when cooled, the additional thermal contraction of Al compared to iron (approximately 4 mils on the collar outer radius) does not result in a gap and an uncertain transverse location of the coil within the yoke.

The force required on the diameter of the collared coil to produce this minimum deformation is 1200 lbs./linear inch. To produce 6 mils of radial deformation, for example, about 2000 lbs./in. is required. This deformation at assembly is entirely elastic and does not produce excessive collar stresses.

This has been easily accomplished in the four D14B series aluminum 1-m models built at LBL with the existing collar designs by using clamps to close the yoke.

Full-length models could also be assembled in this manner and the clamps removed after welding; however, it is probably simpler to use assembly tooling that squeezes the entire collared coil the required amount for insertion into the lower half of the yoke; then the assembly/lifting tool is released and the coil is held in the deformed position by the lower half of the yoke. The upper yoke would then be assembled in the usual manner; some slight force may be needed to push the top yoke into place. Subsequent welding of the shell should be the same as with S.S. collars.

Figure 7 shows a conceptual design of a full-length assembly tool that could be used; it is an example design only but it is relatively simple, requires no high precision, and has more than adequate strength. Assembly of such a magnet should not be a significantly more difficult problem than present magnets; however, a tool must be built and the procedure demonstrated.

7. Conclusions

Aluminum alloy has a significant cost advantage, approximately 23M$ for the SSC dipoles. Details on the cost estimate are given in Appendix I. Approximately 2500 lbs. in weight of collar material is saved per dipole. It has greater availability (special mill-runs are not required) and adequate strength.

Its lower stiffness can be easily accommodated if the collars are supported at midpoint by the iron yoke. The iron yoke has sufficient strength and stiffness to support the Lorentz forces. (This method is planned also for the HERA dipoles). This type of support can also be used to reduce magnet-to-magnet sextupole distortions. Four models have been assembled with Al collars supported at the midplane. Central fields up to 8.7T (2K) have been produced. A conceptual design has been made of full-length tooling to facilitate insertion of collared coil into the yoke; it does not appear that such a procedure will significantly complicate the assembly process.

The magnetic behavior of magnets with Al collars should not be significantly different from that of magnets with S.S. collars. The slight difference in the deformation of Al and S.S. is predictable and can be allowed for in the exact design of the wedges. Models that meet field uniformity requirements have been built at LBL. Training behavior seems to be the same for Al and S.S.

The problem of springback losses has not yet been solved satisfactorily with the present collar design using either stainless steel collars or aluminum; the lower cooldown losses of Al are offset by the greater springback losses. But because of lower room temperature pressure, creep during room temperature storage will be less with Al.

However, there may be attractive solutions to the springback problem that require slight modifications in design of the collar but appear to have greater potential for improvement than trying to stiffen the existing design. We propose to construct dipole models using Al collars and tapered keys after further evaluation and detailed mechanical and magnetic design. We believe that the use of aluminum alloy collars for SSC dipole magnets offers sufficient advantages to justify vigorous pursuit of an R & D effort with the goal of securing a more reliable magnet with lower cost.

References

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3) C. Peters, "Design of 15 mm Collars for SSC Dipole Magnets," LBL-21030, March, 1986.

4) S. Marks, LBL Engineering Note M6561, September 8, 1986.

5) R. B. Meuser, S. Caspi, W. S. Gilbert, "Measured Mechanical Properties of Superconducting Coil Materials and Their Influence on Coil Prestress," IEEE Trans. Mag., Vol. MAG-17, 5, pp. 2320-2323, 1981.

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APPENDIX I.

SSC Dipole Collar Cost Comparison
Nitronic 40 - 7075 Aluminum

7075 Al density	=	0.101 lb/in^3	(Marks pg. 6-79)
18,8 S.S. density	=	0.280 lb/in^3	(Marks pg. 6-44)

7075 T6 sheet (.063" thick) Cost = $2.17/lb (Kobliska FNAL)
Nitronic 40 (.059" thick) Cost = $1.57/lb (Armco - LeRoy BNL)

Assuming equal volume of sheet strip required for both S.S. and Al, the material cost ratio is:

$$\frac{\text{AL}}{\text{Nitronic 40}} = \frac{\text{Density Al}}{\text{Density S.S.}} \times \frac{\text{(cost) AL}}{\text{(cost)S.S.}} = \frac{(.101)}{(.280)} \times \frac{(2.17)}{(1.57)} = .498$$

Collar Material Cost per Dipole

Item	No.Required*	Unit Cost($)		Total Cost($)	
		Nitronic 40**	AL	Nitronic 40	AL
Center	20,800	.28	.14	5,824	2,912
End	340	.28	.14	95	48
		Total:		$5,919	$2,960

Total SSC Collar Material Cost

Nitronic 40 collars = ($5919)(7680) = 45.5 M$
Al collars = ($2960)(7680) = 22.7 M$

*From CRD cost estimate
**From CRD cost estimate 304N @ $1.38/lb = $.25/collar, therefore, Nitronic 40 @ $1.57/lb = $.28//collar

APPENDIX II

Some Selected Material Properties

a) 7075 Aluminum

b) Nitronic 40 Stainless Steel

c) 5%, 9% Ni Steel

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Table 21 Typical tensile properties of aluminum alloy 7075

Data from Ref 5-7, 33, 34

Temperature °C	Temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %	Reduction in area, %	Notch tensile strength(a) MPa	Notch tensile strength(a) ksi	Young's modulus GPa	Young's modulus 10^6 psi
Sheet, T6 temper, longitudinal orientation											
24	75	555	80.5	500	72.4	10	...	470	68.4	72	10.5
−73	−100	585	85.1	525	76.2	10	...	...	...	74	10.8
−196	−320	680	98.6	610	88.7	12	...	295	42.5	76	11.0
−256	−423	705	114	705	102	7	...	280	40.4	86	12.5
Sheet, T6 temper, transverse orientation											
24	75	555	80.5	485	70.6	12	...	415	60.5	73	10.6
−73	−100	575	83.2	510	74.1	9	...	...	...	70	10.2
−196	−320	675	98.0	580	84.2	10	...	290	41.9	73	10.6
−253	−423	785	114	685	99.3	9	...	260	37.4	...	...
Plate, T6 temper, longitudinal orientation											
24	75	605	87.4	545	79.2	15	24	790	115	73	10.6
−78	−108	635	92.4	560	81.3	11	18	800	116	79	11.4
−196	−320	715	104	675	97.7	9	13	770	112	...	...
−253	−423	825	120	745	108	10	15	800	116	79	11.4
Plate, T651 temper, longitudinal orientation											
24	75	580	84.2	530	77.1	10	14	715	104	...	...
−78	−108	595	86.2	595	86.0	10	11	680	98.4	...	...
−196	−320	705	102	650	94.4	7	10	565	81.8	...	...
−253	−423	770	112	710	103	5	...	...	...	...	...
−269	−452	825	120	770	112	6	9	555	80.2	...	...
Plate, T651 temper, transverse orientation											
24	75	585	85.0	525	76.3	8	18	655	95.2	...	...
−78	−108	610	88.6	555	80.4	6	12	575	83.2	...	...
−196	−320	695	101	640	92.6	4	8	490	71.0	...	...
Plate, T7351 temper, longitudinal orientation											
24	75	525	76.2	455	66.2	10	22	645	93.4	...	...
−78	−108	575	83.4	500	72.3	10	17	640	93.0	...	...
−196	−320	675	98.2	570	82.5	11	14	580	84.4	...	...
−269	−452	760	110	605	88.1	11	12	650	94.0	...	...

(a) For sheet in T6 temper, K_t = 30; for plate in T6 temper, K_t = 6.3; for plate in T651 and T7351 tempers, K_t = 16.

Aluminum alloy 7075 is representative of the high-strength nonweldable 7000 series alloys. It is primarily an aircraft and aerospace alloy and has relatively low fracture toughness in the T6 temper. Normally it is not used in applications involving cryogenic temperatures. The choice of 7075-T6 plate for the intertank skirt between the liquid oxygen and liquid hydrogen sections of the external tank of the space shuttle was probably based on the high strength of this alloy. Mechanical fasteners are used in joints between the skirt and the tanks. Tensile properties of 7075 sheet and plate at subzero temperatures are presented in Table 21. Processing of alloy 7075 to the T7351 temper improves its ductility and notch toughness at cryogenic temperatures.

Table 23 Fracture toughness of aluminum alloy plate

Data from 2, 13, 16, 27, 38

Alloy and condition	Room temperature yield strength, MPa	Room temperature yield strength, ksi	Specimen design	Orientation	Fracture toughness, K_{Ic} or $K_{Ic}(J)$ at: 24 °C (75 °F), MPa$\sqrt{m}$	24 °C (75 °F), ksi$\sqrt{in.}$	−196 °C (−320 °F), MPa$\sqrt{m}$	−196 °C (−320 °F), ksi$\sqrt{in.}$	−253 °C (−423 °F), MPa$\sqrt{m}$	−253 °C (−423 °F), ksi$\sqrt{in.}$	−269 °C (−452 °F), MPa$\sqrt{m}$	−269 °C (−452 °F), ksi$\sqrt{in.}$
2014-T651	432	62.7	Bend	T-L	23.2	21.2	28.5	26.1	...	...	...	...
2024-T851	444	64.4	Bend	T-L	22.3	20.3	24.4	22.2	...	...	...	...
2124-T851(a)	455	66.0	CT	T-L	26.9	24.5	32.0	29.1	...	...	...	...
	435	63.1	CT	L-T	29.2	26.6	35.0	31.9	...	...	...	...
	420	60.9	CT	S-L	22.7	20.7	24.3	22.1	...	...	...	...
2219-T87	382	55.4	Bend	T-S	39.9	36.3	46.5	42.4	52.5	48.0	...	...
			CT	T-S	28.8	26.2	34.5	31.4	37.2	34.0	...	...
	412	59.6	CT	T-L	30.8	28.1	38.9	32.7	...	...	...	...
5083-O	142	20.6	CT	T-L	27.0(b)	24.6(b)	43.4(b)	39.5(b)	...	...	48.0(b)	43.7(b)
6061-T651	289	41.9	Bend	T-L	29.1	26.5	41.6	37.9	...	...	...	...
7039-T6	381	55.3	Bend	T-L	32.3	29.4	33.5	30.5	...	...	...	...
7075-T651	536	77.7	Bend	T-L	22.5	20.5	27.6	25.1	...	...	...	...
7075-T7351	403	58.5	Bend	T-L	35.9	32.7	32.1	29.2	...	...	...	...
7075-T7351	392	56.8	Bend	T-L	31.0	28.2	30.9	28.1	...	...	...	...

(a) 2124 is similar to 2024, but with higher purity base and special processing to improve fracture toughness. (b) $K_{Ic}(J)$.

Table 24 Results of fatigue-life tests on aluminum alloys

Data from Ref 2, 40-42

Alloy and condition	Stressing mode	Stress ratio, R	K_t	Fatigue strength at 10^6 cycles, at: 24 °C (75 °F), MPa	24 °C (75 °F), ksi	−196 °C (−320 °F), MPa	−196 °C (−320 °F), ksi	−253 °C (−423 °F), MPa	−253 °C (−423 °F), ksi
2014-T6 sheet	Axial	−1.0	1	115	17	170	25	315	46
		+0.01	1	215	31	325	47	435	63
2014-T6 sheet, GTA welded, 2319 filler	Axial	−1.0	1	83	12	105	15	125	18
2219-T62 sheet	Axial	−1.0	1	130	19	15	22	255	37
			3.5	52	7.5	45	6.5	62	9
2219-T87 sheet	Axial	−1.0	1	150	22	115-170	17-25	275	40
			3.5	52	7.5	48	7	55	8
2219-T87 sheet, GTA welded, 2319 filler	Axial	−1.0	1	69	10	83	12	150	22
5083-H113 plate	Flex	−1.0	1	140	20.5	190	27.5	...	...
5083-H113 plate, GMA welded, 5183 filler	Flex	−1.0	1	90	13	130	18.8	...	...
6061-T6 sheet (a)	Flex	−1.0	1	160	23	220	32	235	34
(b)	Flex	−1.0	1	165	24	230	33	230	33
7039-T6 sheet	Axial	−1.0	1	140	20	215	31	275	40
		+0.01	1	230	33	330	48	440	64
		−1.0	3.5	48	7	48	7	62	9
7075-T6 sheet	Axial	−1.0	1	96	14	145	21	250	36

(a) Surface finish, 150 μin. rms. (b) Surface finish, 20 μin. rms.

Armco Data Sheet
Sheet & Strip

Table 17

Comparative Tensile Properties and Toughness* of Armco NITRONIC 40 and Type 304 at 75 and -320 F (27 and -196 C)

Armco Stainless Steel	% Carbon	Test Temp F (C)	Sensitized **	0.2% YS ksi (MPa)	UTS ksi (MPa)	Elong % in 2" (50.8 mm)	Notch Strength ksi (MPa)	NS/YS	NS/UTS
	0.024	75 (24)	No	62.0 (428)	112.4 (775)	43.0	92.2 (636)	1.49	0.82
→	0.025	75 (24)	No	70.7 (487)	112.7 (777)	44.0	90.6 (625)	1.28	0.80
	0.027	75 (24)	No	67.5 (465)	111.8 (771)	46.0	89.2 (615)	1.31	0.80
			Yes	67.7 (466)	113.1 (780)	44.5	89.2 (615)	1.32	0.79
NITRONIC 40	0.039	75 (24)	No	64.7 (444)	109.1 (752)	45.0	86.9 (599)	1.34	0.80
*	0.040	75 (24)	No	77.1 (531)	118.1 (814)	42.0	94.7 (653)	1.23	0.81
			Yes	77.2 (532)	119.6 (825)	41.5	94.7 (653)	1.23	0.79
	0.045	75 (24)	No	76.1 (525)	116.9 (806)	43.0	94.3 (650)	1.26	0.81
			Yes	75.5 (521)	117.2 (808)	42.0	93.8 (647)	1.24	0.80
304	—	75 (24)	No	43.4 (299)	90.7 (625)	55.0	68.5 (472)	1.58	0.76
and	—	75 (24)	No	36.9 (254)	88.8 (612)	62.5	61.1 (421)	1.67	0.69
304L			Yes	35.7 (246)	89.7 (618)	62.5	61.2 (422)	1.71	0.68
	0.024	-320 (-196)	No	171.1 (1179)	230.1 (1586)	54.0	191.5 (1320)	1.12	0.83
→	0.025	-320 (-196)	No	168.8 (1159)	229.3 (1580)	52.0	192.6 (1321)	1.14	0.84
	0.027	-320 (-196)	No	170.5 (1175)	228.4 (1573)	57.0	189.4 (1306)	1.11	0.83
			Yes	—	227.1 (1558)	30.0	182.7 (1258)	—	0.80
NITRONIC 40	0.039	-320 (-196)	No	162.8 (1119)	223.2 (1548)	63.0	181.7 (1250)	1.12	0.82
	0.040	-320 (-196)	No	182.9 (1261)	232.1 (1588)	50.5	198.3 (1354)	1.08	0.83
			Yes	—	238.7 (1648)	41.5	188.1 (1297)	—	0.79
	0.045	-320 (-196)	No	181.0 (1248)	234.1 (1604)	58.0	192.5 (1327)	1.06	0.82
			Yes	—	225.5 (1552)	22.0	183.1 (1264)	—	0.81
304	—	-320 (-196)	No	79.8 (550)	226.8 (1560)	45.0	113.6 (783)	1.42	0.50
and	—	-320 (-196)	No	74.0 (510)	224.9 (1545)	40.0	100.8 (695)	1.36	0.45
304L			Yes	—	222.6 (1532)	39.5	92.6 (638)	—	0.42

*Average of duplicate transverse tests — 0.038" to 0.070" (0.96 to 1.78 mm) thick
Notch strength determined on NASA edge notch specimen 1" (25.4 mm) wide — 60° notch — 0.0007" (0.0178 mm) max root radius
**Annealed material sensitized at 1250 F (677 C) for 1 hour prior to testing

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Table 37 Fatigue-crack-growth-rate data for ferritic steels for compact specimens in T-L orientation

Data from Ref 61, 69

Alloy and condition	Frequency, Hz	Stress ratio, R	Test temperature °C	Test temperature °F	C da/dN: mm/cycle ΔK: MPa$\sqrt{m}$	C da/dN: in./cycle ΔK: ksi$\sqrt{in.}$	n	Estimated range for ΔK MPa$\sqrt{m}$	Estimated range for ΔK ksi$\sqrt{in.}$
3.5Ni steel plate, ASTM A203E, quenched and tempered	20-28	0.1	24	75	1.3×10^{-8}	6.9×10^{-10}	3.2	18-60	16-54
5Ni steel plate,			−78	−108	1.3×10^{-8}	6.9×10^{-10}	3.2	30-70	27-63
ASTM A645,			−101	−150	1.0×10^{-9}	5.3×10^{-11}	3.2	30-60	27-54
austenitized,			−196	−320	1.6×10^{-14}	1.3×10^{-15}	7.6	20-30	18-27
quenched, temperized, reversion annealed	20-28	0.1	24	75	1.1×10^{-8}	5.6×10^{-10}	2.7	25-90	23-82
9Ni steel plate,			−162	−260	1.1×10^{-8}	5.6×10^{-10}	2.7	25-60	23-54
ASTM A553,			−196	−320	2.0×10^{-10}	1.2×10^{-11}	4.0	27-80	24-72
austenitized, quenched and tempered	20-28	0.1	24	75	2.0×10^{-8}	1.0×10^{-9}	2.7	16-70	14-63
			−162	−260	1.0×10^{-9}	5.4×10^{-11}	3.4	17-80	15-72
			−196	−320	4.8×10^{-11}	2.9×10^{-12}	4.4	17-64	15-58
			−269	−452	1.4×10^{-11}	9.1×10^{-13}	5.3	24-35	22-32

For applications involving exposure to temperatures from 0 to −196 °C (+32 to −320 °F), the ferritic nickel steels usually are considered first, if they have sufficient corrosion resistance. Such applications include storage tanks for liquefied hydrocarbon gases and structures and machinery designed for use in cold regions.

Tensile Properties. Typical tensile properties of 5% and 9% Ni steels at room temperature and at subzero temperatures are presented in Table 35. Yield and tensile strengths increase as testing temperature is decreased. These steels remain ductile at the lowest testing temperatures. Minimum tensile properties of all the ASTM steels for subzero applications are designated in ASTM Standard Specifications. Values of Young's modulus and Poisson's ratio at subzero temperatures for ferritic nickel steels are plotted in Fig. 12 and 13.

Fracture Toughness. Ferritic nickel steels are too tough at room temperature for valid fracture-toughness (K_{Ic}) data to be obtained on specimens of reasonable size (Ref 63), but limited fracture-toughness data have been obtained on these steels at subzero temperatures by the J-integral method. Results of these tests are presented in Table 36. The 5% Ni steel retains relatively high fracture toughness at −162 °C (−260 °F), and the 9% Ni steel retains relatively high fracture toughness at −196 °C (−320 °F). These temperatures approximate the minimum temperatures at which these steels may be used.

Fig. 4 Effect of alloying elements on room-temperature saturation induction of iron

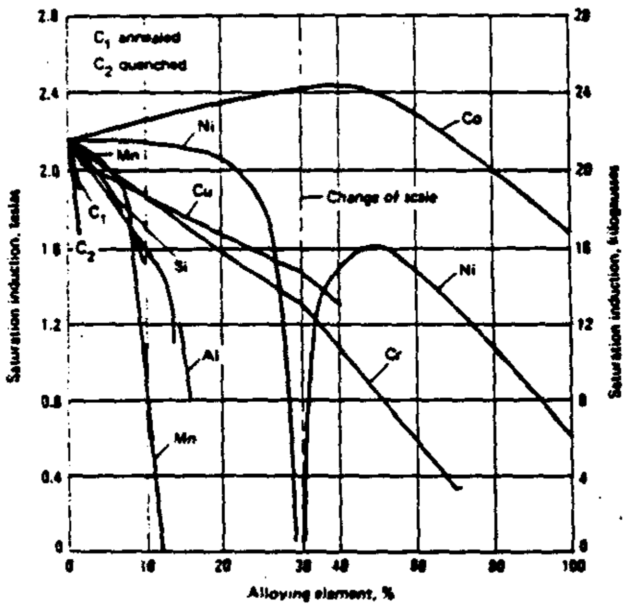

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Table 34 Compositions of ferritic nickel steel plate for use at subzero temperatures

ASTM specification	Compositions of plates up to 50 mm (2 in.) thick, %(a) C	Mn	P	S	Si	Ni	Mo	Others
A203 A	0.17	0.70	0.035	0.040	0.15-0.30	2.10-2.50	...	...
A203 B	0.21	0.70	0.035	0.040	0.15-0.30	2.10-2.50	...	...
A203 C	0.17	0.70	0.035	0.040	0.15-0.30	3.25-3.75	...	...
A203 D	0.20	0.70	0.035	0.040	0.15-0.30	3.25-3.75	...	...
A645	0.13	0.30-0.60	0.025	0.025	0.20-0.35	4.75-5.25	0.20-0.35	0.02-0.12 Al, 0.020 N
A353	0.13	0.90	0.035	0.040	0.15-0.30	8.5-9.5	...	...
A553 I	0.13	0.90	0.035	0.040	0.15-0.30	8.5-9.5	...	...
A553 II	0.13	0.90	0.035	0.040	0.15-0.30	7.5-8.5	...	...

(a) Single values are maximum limits.

Table 35 Typical tensile properties of ferritic nickel steels

Data from Ref 2, 44, 64, 66-69

Temperature °C	Temperature °F	Tensile strength MPa	Tensile strength ksi	Yield strength MPa	Yield strength ksi	Elongation, %	Reduction in area, %	Notch tensile strength(a) MPa	Notch tensile strength(a) ksi	Young's modulus GPa	Young's modulus 10^6 psi
A645 plate, longitudinal orientation(b)											
24	75	715	104	530	76.8	32	72	...	...	200	28.7
−168	−270	930	135	570	82.9	28	68	...	...	205	30.2
−196	−320	1130	164	765	111	30	62	...	...	210	30.7
A353 plate, longitudinal orientation(c)											
24	75	780	113	680	98.6	28	70	945	137	...	...
−151	−240	1030	149	850	123	17	61	...	...	...	...
−196	−320	1130	172	950	138	25	58	...	...	...	...
−253	−423	1430	208	1320	192	18	43	1310	190	...	...
−269	−452	1590	231	1430	208	21	59	...	...	...	...
A553-I plate, longitudinal orientation(d)											
24	75	770	112	695	101	27	69	...	...	...	...
−151	−240	995	144	885	128	18	42	...	...	...	...
−196	−320	1150	167	960	139	27	38	...	...	...	...

(a) K_t = 6.4. (b) Quenched, tempered, reversion annealed. (c) Double normalized and tempered: 900 °C (1650 °F) 1 h/in. of thickness, AC; 790 °C (1450 °F) 1 h/in. of thickness, AC; 570 °C (1050 °F) 1 h/in. of thickness, AC or WQ. (d) Quenched and tempered: 800 °C (1475 °F), WQ; 570 °C (1050 °F) 30 min/in. of thickness, AC or WQ.

Table 36 Fracture toughness of 5% and 9% Ni steel plate for compact tension specimens in T-L orientation

Data from Ref 65-70

Alloy and condition	Yield strength(a) MPa	Yield strength(a) ksi	Fracture toughness, K_{Ic} (J), at −162 °C (−260 °F) MPa$\sqrt{m}$	−162 °C (−260 °F) ksi$\sqrt{in.}$	−196 °C (−320 °F) MPa$\sqrt{m}$	−196 °C (−320 °F) ksi$\sqrt{in.}$	−269 °C (−452 °F) MPa$\sqrt{m}$	−269 °C (−452 °F) ksi$\sqrt{in.}$
5Ni steel (A645) quenched, temperized, reversion annealed	534	77.5	196	178	87.1	79.3	58.4	53.2
9Ni steel (A553, Type I) quenched and tempered	689	99.9	...	...	184	167	...	...

(a) At room temperature.

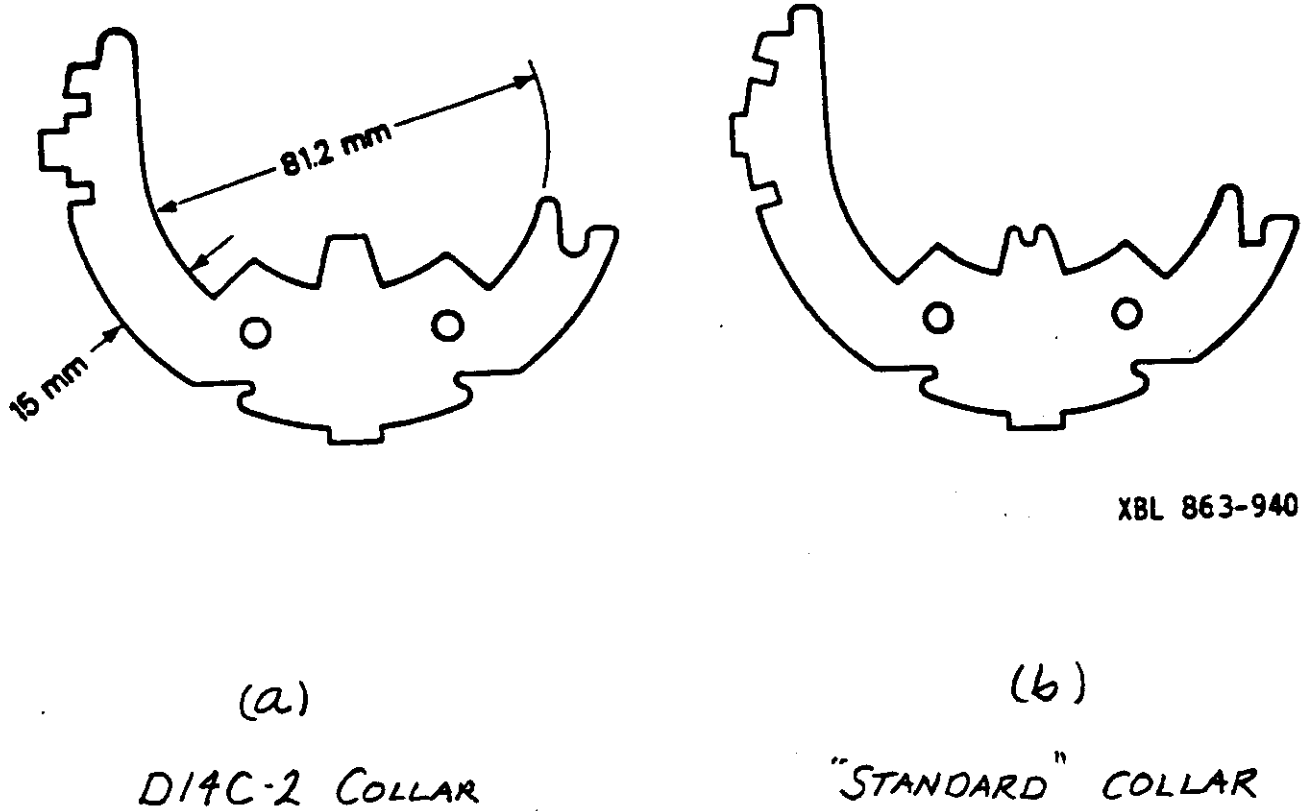


FIG. 1.

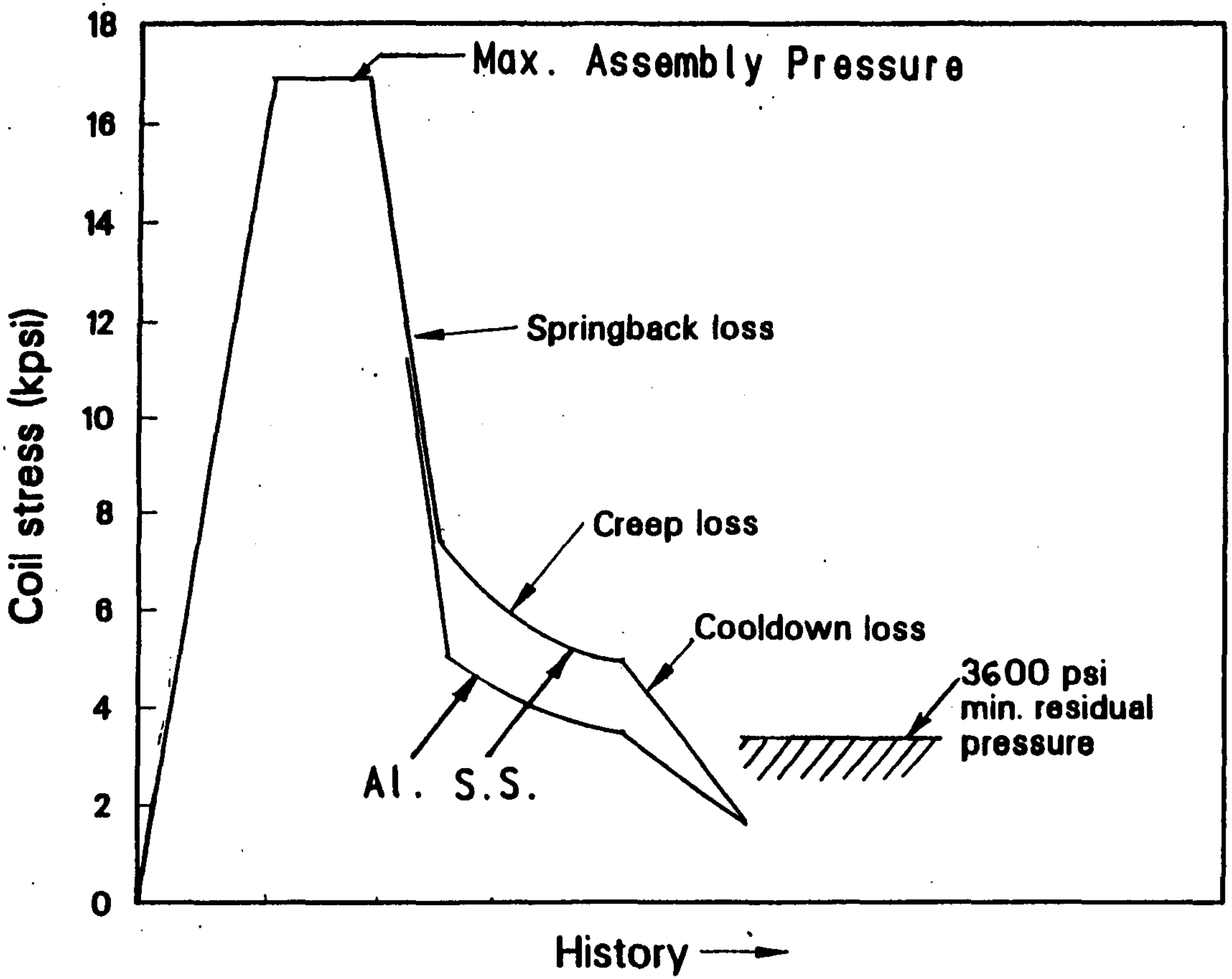

Max. Assembly Pressure
Springback loss
Creep loss
Cooldown loss
3600 psi
min. residual
pressure
Al.
S.S.
Coil stress (kpsi)
18
16
14
12
10
8
6
4
2
0
History

FIG. 2.

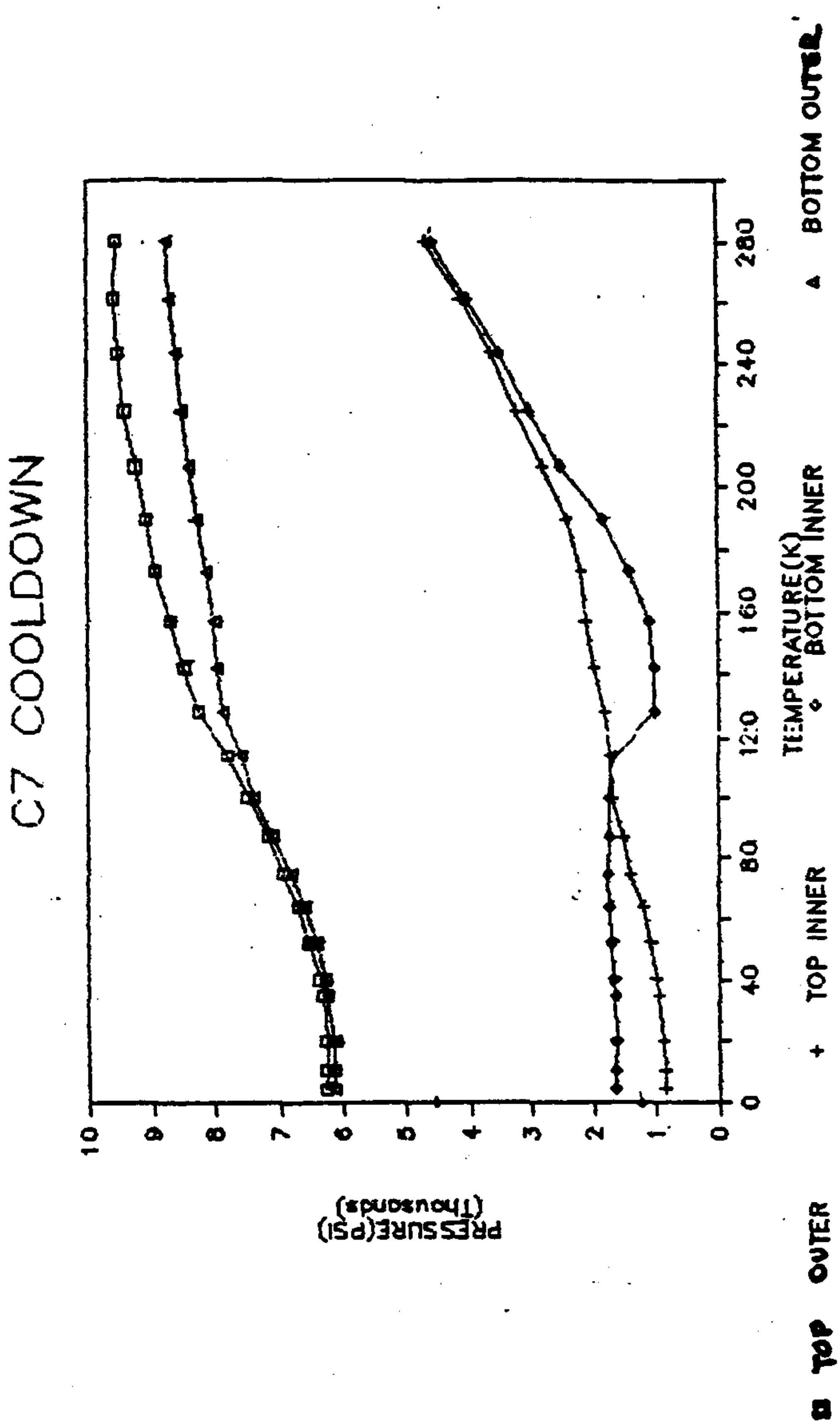

C7 COOLDOWN
PRESSURE(PSI)
(Thousands)
10
9
8
7
6
5
4
3
2
1
0
0
40
80
120
160
200
240
280
TEMPERATURE(K)
TOP OUTER
TOP INNER
BOTTOM INNER
BOTTOM OUTER

FIG. 3.

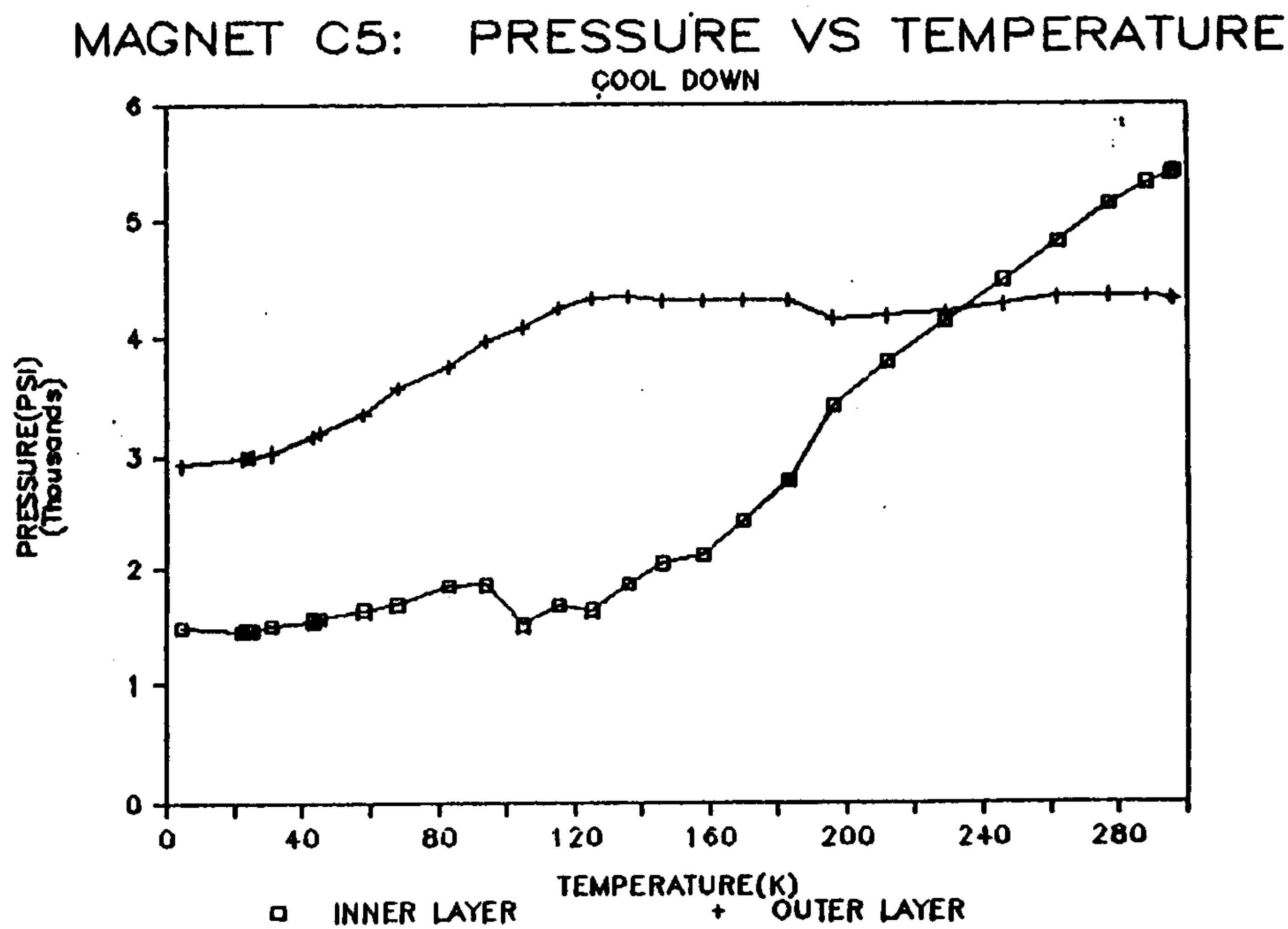
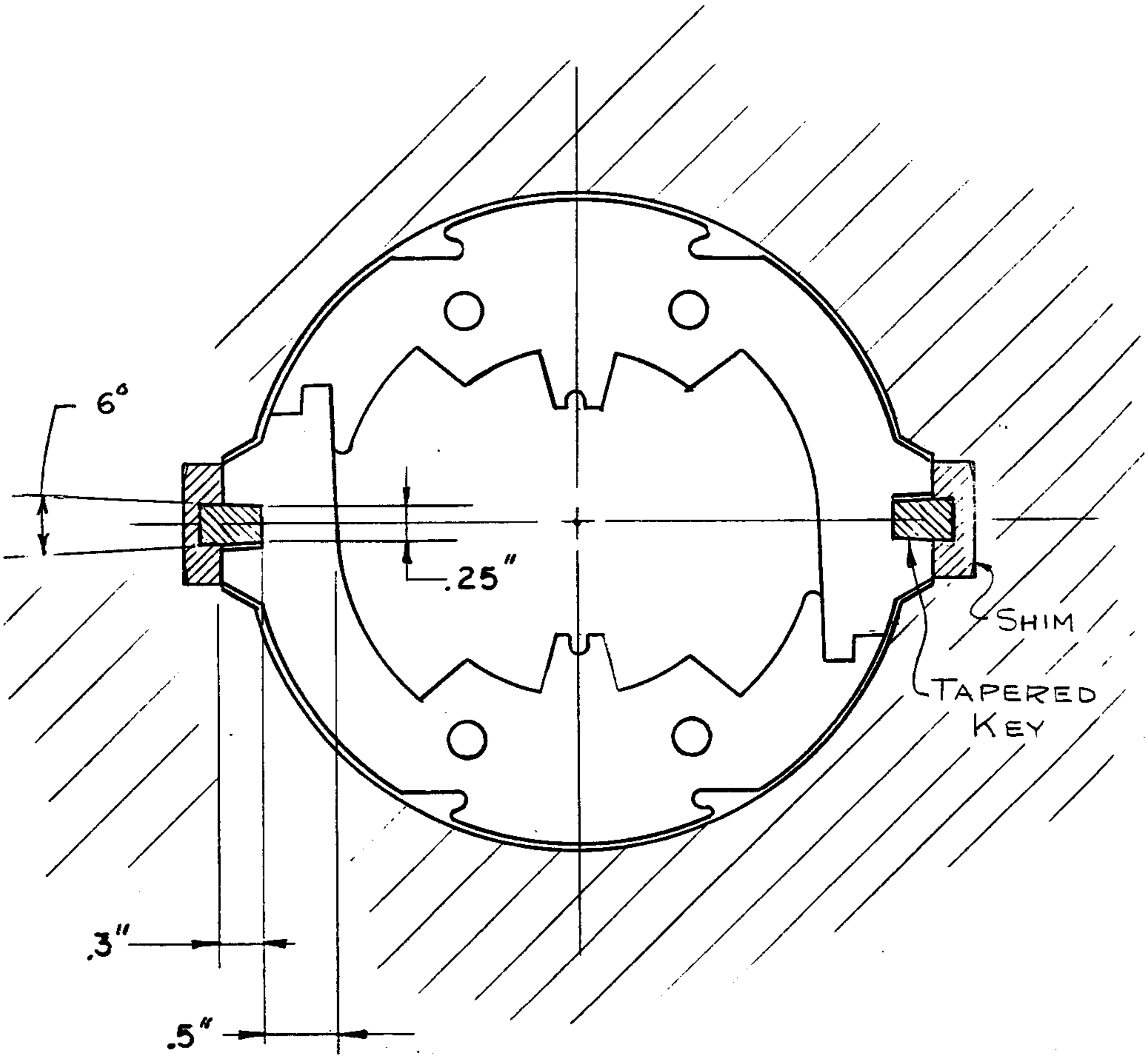

MAGNET C5: PRESSURE VS TEMPERATURE
COOL DOWN
PRESSURE(PSI)
(Thousands)
0
1
2
3
4
5
6
0
40
80
120
160
200
240
280
TEMPERATURE(K)
INNER LAYER
OUTER LAYER

FIG. 4.



Key to help close collars
(Conceptual design)

FIG 5

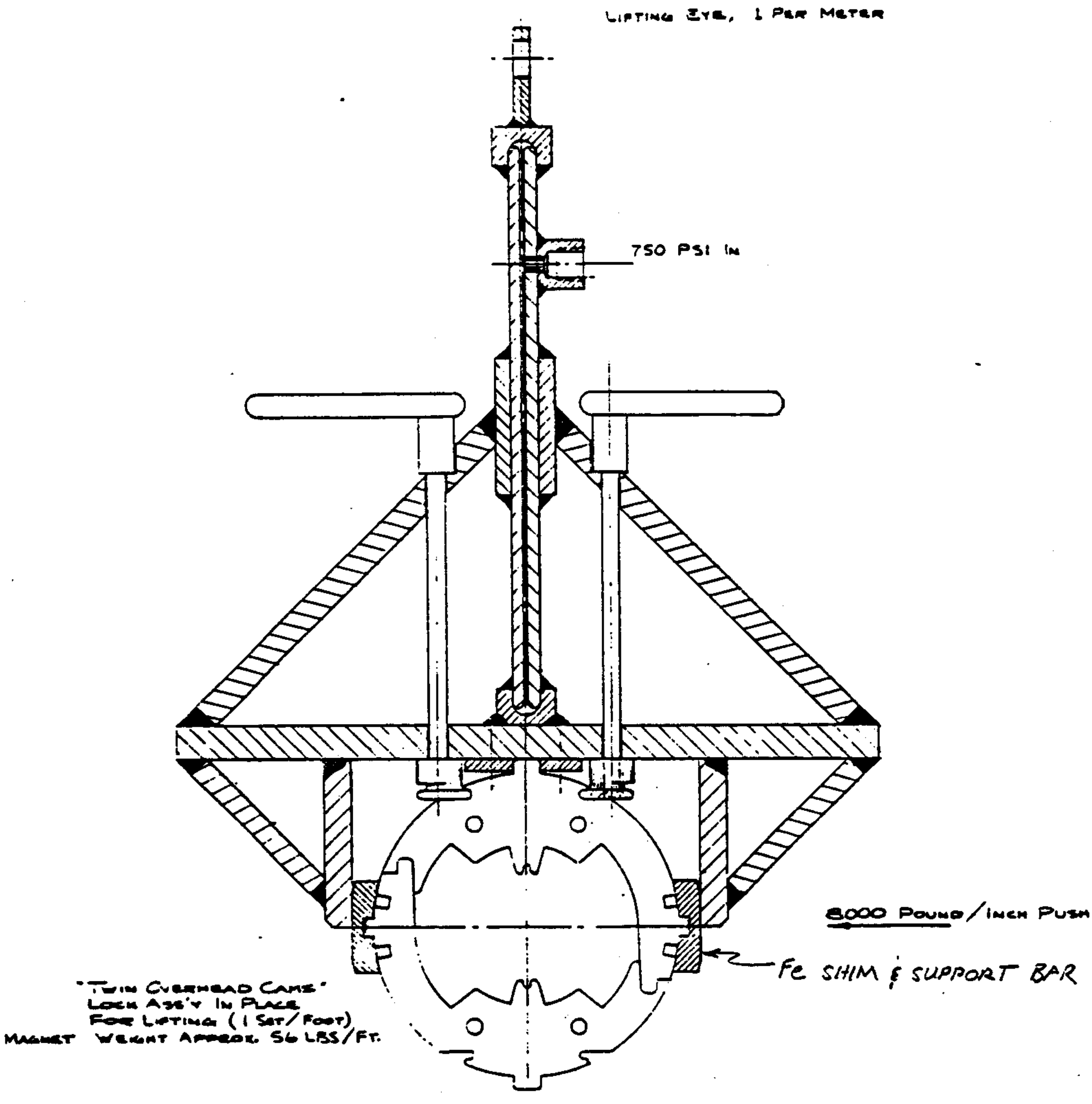

LIFTING EYE, 1 PER METER
750 PSI IN
8000 POUND/INCH PUSH
Fe SHIM & SUPPORT BAR
"TWIN OVERHEAD CAMS"
LOCK ASS'Y IN PLACE
FOR LIFTING (1 SET/FOOT)
MAGNET WEIGHT APPROX. 56 LBS/FT.

FIG. 6.