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DESIGN STUDY OF ADVANCED MODEL

SUPPORT SYSTEMS FOR THE NATIONAL

TRANSONIC FACILITY

GENERAL DYNAMICS CONVAIR DIVISION
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FOREWORD

This report describes the work performed on NASA Contract P.O.L.-99725B by the Convair and Space Systems Divisions of General Dynamics Corporation at San Diego.

This work was administered by the Langley Research Center of NASA, Hampton, Virginia. Dr. C.P. Young, Jr. is the NASA Technical Monitor.

The program was conducted in the Research and Engineering Departments of the General Dynamics Aerospace Divisions, and was managed by S.A. Griffin. A.A. McClain of the Aerotest Group and R. Boswell of the Materials and Process Laboratory were the principal investigators.

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SECTION 1

INTRODUCTION

The inability of conventional wind tunnels to approach or match full scale Reynolds numbers led to the development of the National Transonic Facility (NTF) now in operation at NASA's Langley Research Center. The NTF is a continuous flow, fan driven, high pressure facility, capable of operating at cryogenic temperatures.

A recent design study[1*], investigated the feasibility of developing wind tunnel models of advanced fighter (highly maneuverable) models, for use in that facility. The study indicated that such models could be developed, but pointed out that test conditions (angle of attack/Reynolds number) for certain configurations is likely to be sting limited.

It has been recognized for some time that the sting (or support system) is a very critical part of the model system. Even in conventional wind tunnels, the model designer is frequently faced with the tradeoff of minimizing the sting size, thereby compromising facility and model safety, against a larger sting and the subsequent problems of sting interference effects, and possible distortion of configuration geometry.

In the NTF this problem is accentuated by the severe environment of high pressure/low temperature, designed into the facility to provide the desired high Reynolds number. Compromises in the configuration geometry and/or limiting the test envelope are therefore contrary to the purposes and goals of the NTF and are unacceptable, hence the need for this study of advanced model support systems.

Present day wind tunnel support system technology dictates the use of a high grade steel sting. The low operating temperature (-300F) of the NTF, however, creates a severe environment for both the model and sting, and prohibits the use of most steels used in conventional wind tunnels. Toughness and ductility must be maintained at the low temperatures and this has led to the use of a maraging steel (18 Ni-200). Design studies[1] have shown that the fighter type model when using a 18 Ni-200 sting is likely to have a limited test envelope due to sting divergence. In other words, stiffness is more critical than strength.

1.1 DESIGN APPROACH

The goal of this study has been to investigate advanced sting materials, or combinations of materials that would give an improvement of 25% over 18 Ni-200 in both ultimate tensile strength, and Young's modulus of elasticity, E. Weight is a key factor; the steel sting is approximately 500 pounds, creating obvious handling problems. From this point of view a composite sting would be an attractive solution. From a strength/stiffness point of view, however, the value of the composite sting is questionable. Limited information is available at cryogenic temperatures; in addition, the majority of advanced structural work using composites has been for applications requiring a high

*Indicates reference.

strength/weight ratio, resulting in thin wall designs. The support system needs maximum strength/stiffness and within reason weight is a secondary issue.

Three basic approaches were taken to find a suitable material for the Advanced Sting for NTF:

a. Conventional material sting

b. Advanced composites

c. Hybrid configurations

Each approach had as its goal the following improvements in property levels:

a. Yield strength: 220-250 ksi at room temperature

b. Young's modulus: 32-35 Msi at room temperature

c. Charpy V-Notch (Cvn): 25 ft-lb at -320F

Before we discuss the results of each approach in detail, it would be instructive to first examine some of the known limitations of currently used materials.

1.2 TOUGHNESS VERSUS STRENGTH LIMITATIONS

The current baseline material used in sting applications (18 Ni-200) has a yield strength of 200 ksi, a Young's modulus of 26.5 Msi, and a Cvn toughness of 25 ft-lb at -320F. Our initial goal was to exceed 18 Ni-200 strength and stiffness by 25% while maintaining the 25 ft-lb Cvn toughness at -320F. It may not be difficult to achieve individual (strength or stiffness) requirements; it's difficult, however, to achieve both objectives simultaneously, while maintaining an acceptable toughness. Figure 1-1 shows the generally accepted relationship between strength and fracture toughness for commercially available structural alloys. Note that higher strengths can be achieved but only through loss of toughness.

For a number of years, materials developers have sought to find alloying combinations and microstructures that divert from the general inverse trend as shown in Figure 1-1. Today, precipitation hardening systems of iron, nickel, and cobalt represent the state of the art of high strength/toughness alloys. They form a family of alloys that combines excellent strength, adequate toughness, and relatively high stiffness.

Strength is generally achieved through a combination of solution hardening and precipitation hardening. In some systems, work hardening (i.e., increasing dislocation density through mechanical working) is also used to increase strength, often in conjunction with precipitation hardening.

In Design Approach 1, we examined in greater detail the kinds of refinements that might be made in the iron, cobalt, and nickel systems to achieve our required 25% improvement in strength and stiffness. These refinements included microstructural changes through powder metallurgy and thermal mechanical treatments.

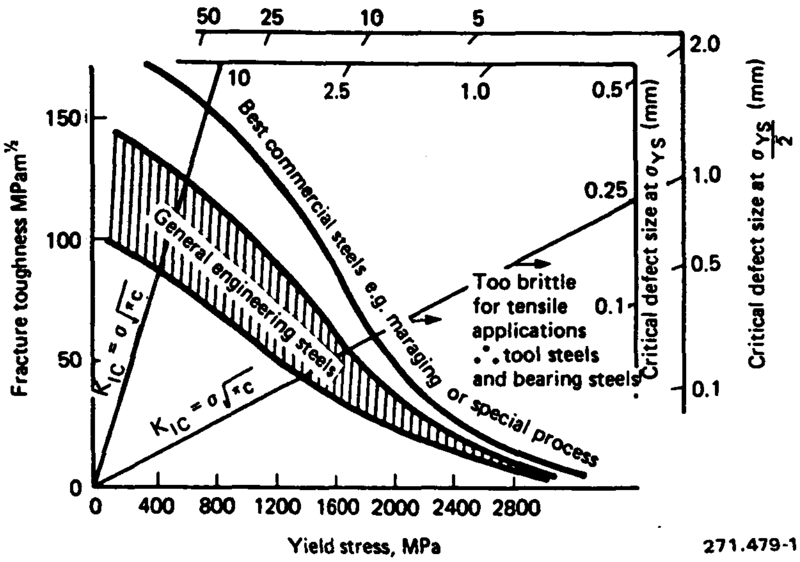

Figure 1-1. Ratio Analysis Diagram for Quenched and Tempered Steels

1.3 STIFFNESS LIMITATIONS OF CONVENTIONAL MATERIALS

In conventional metallic systems, the stiffness is dominated by the basic interatomic bonding of the primary alloy constituent. We can say as a general rule that aluminum alloys have a modulus of 10 Msi, steels have a modulus of 30 Msi, while titanium alloys have modulus in the range of 20 Msi. If one looks for ultra high stiffness systems they generally belong to the VIA, VIIA, and particularly VIIIA elements of the periodic table of the elements. Some high modulus systems include:

Element	Young's Modulus (Msi)	Periodic Table Group
Osmium	80	VIIIA
Indium	79	VIIIA
Ruthenium	68	VIIIA
Rhenium	68	VIIIA
Tungsten	59	VIA
Rhodium	55	VIIIA

A number of filament and whisker/forms have been used to create a variety of resin matrix, metal matrix, and ceramic matrix composites. The principal reinforcements used, however, have been the graphites (35-120 Msi), boron (58 Msi), and silicon carbide (62 Msi) fibers. These reinforcements have been combined with relatively low density matrices (epoxy, polymides, aluminum, magnesium, titanium, carbon) for application primarily in the aerospace industry. Also, falling under Category 1 are the cobalt superalloys including MP35N.

MP35N is a vacuum induction, vacuum arc remelted alloy based on the quaternary of cobalt, nickel, chromium, and molybdenum, which has shown an unusually favorable combination of high strength, stiffness, and corrosion resistance. To obtain high strength, the alloys are cold worked by rolling, swaging, drawing or extruding; additional strength is obtained by aging. MP35N will give us the desired 25% improvement in properties with slight reductions in the required characteristics of ductility, toughness, and corrosion resistance. The primary drawback appears to be that the material is available at the high strength in maximum sizes of 1.5-inch diameter of 1.5-inch thick plate. This study reviews the use of MP35N as a primary sting material.

Our Design Approach 2 for finding a suitable replacement for 18 Ni-200 was to investigate the possible use of composite materials in sting applications. Our goal was to determine if materials already developed for the aerospace industry might be modified or altered slightly to serve as sting materials.

In Design Approach 3, various materials were considered for the hybrid sting, including 18 Ni-200, MP35N, and Kennametal K9, in conjunction with advanced composites. A common problem for all these designs is the thermal stresses due to the use of dissimilar materials. In addition, a highly stiff material such as Kennametal K9 ($E = 90 \times 10^6$) tends to have lower ultimate tensile stress values. When used in the hybrid design it picks up too high a proportion of the load, and does not achieve an acceptable safety factor.

Full scale Reynolds number in the NTF is an established goal, and everything must be done to achieve that objective. The high performance sting will require a unique design approach. A development program, including proof-of-concept tests, will be needed to establish confidence in the design. A fail-safe feature should be a mandatory characteristic of the design, as the safety of the facility must not be compromised.

At the conclusion of this study two configurations will be selected for a development program that will include manufacture, and proof-of-concept testing.

SECTION 2

PROGRAM ORGANIZATION

General Dynamics, through its Convair and Space Systems Divisions, established a team within its Research and Development Departments to conduct the engineering study of Advanced Model Support Systems for the NTF. The Materials and Processes Directorate of the Space Systems Division contributed in the area of advanced composites and special materials and processes suitable for us in a cryogenic environment. The design, thermal analysis, and wind tunnel co-ordination, was performed at the Convair Division. The team organized to conduct the study was led by Mr. S.A. Griffin, who reports to Mr. T. Sammon, Director of Test and Evaluation. The entire organization is under the senior management of Dr. R.F. Beuligmann, Vice President of Research and Engineering.

The program operations chart (Figure 2-1) illustrates the flow of information from the various technical groups through design to the final report.

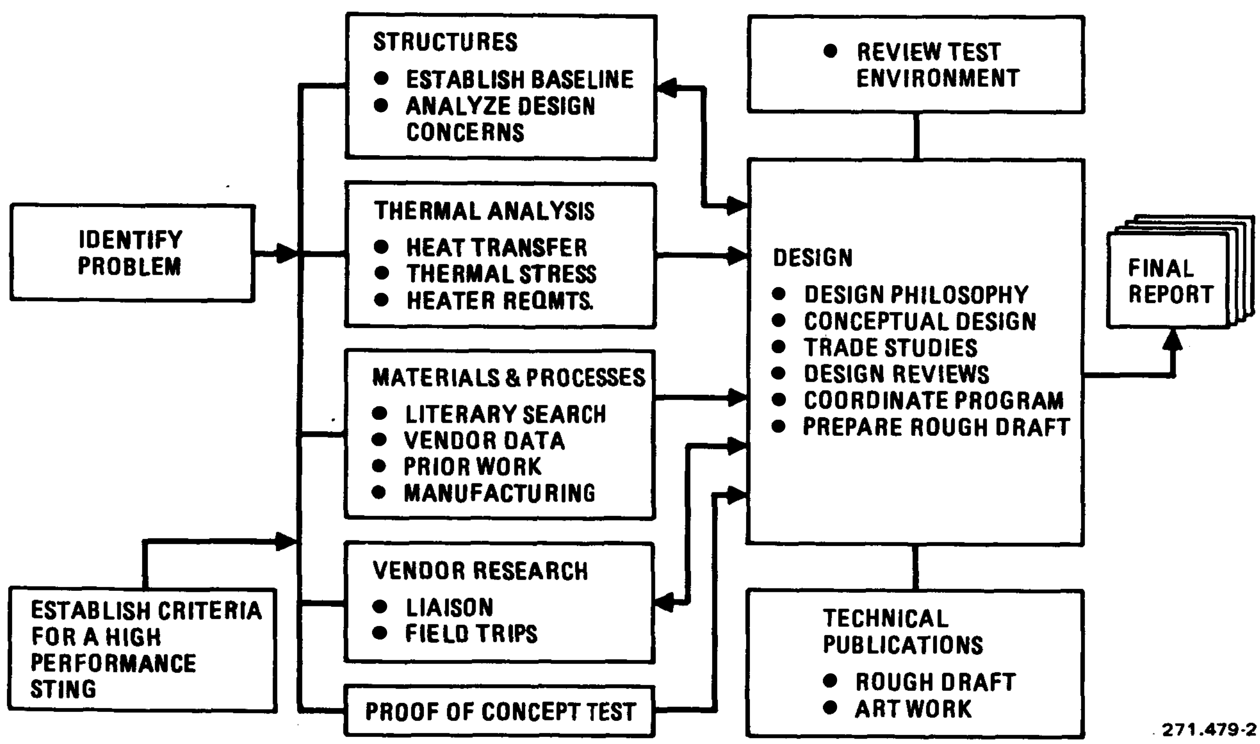

Figure 2-1. Study Plan for NTF Advanced Model Support Systems

SECTION 3

ESTABLISHING CRITERIA FOR A HIGH PERFORMANCE STING

Any sting designed for use in the NASA Langley Research facilities must meet the requirements established in the Wind Tunnel Model Systems Criteria[2] handbook. These requirements include an adequate margin of safety in bending, and torsion, and the following divergence criteria: a safety factor of 2 against divergence demonstrated by in-depth analysis, and where possible, system stiffness verification.

In this study, a goal was established, and a high performance sting was defined as one that could provide an improvement of 25% over the maraging steel (18 Ni-200) sting in ultimate tensile strength and Young's modulus of elasticity, E. These improvements must be achieved without adversely affecting fracture toughness at cryogenic temperatures. A Cvn of 25 ft-lb is desired.

Other desirable features:

- A fail safe feature for a hybrid design
- Reduced weight
- Instrumentation to monitor stress/strain
- Resistance to fatigue (fracture toughness)
- Resistance to corrosion

The structural analysis conducted for this program consisted of two phases. The first phase consisted of a study of the existing sting configuration to establish baseline performance goals. In the second phase, preliminary analysis was performed for several proposed alternative configurations. These configurations included high performance metals, advanced composite materials, and hybrid metal-composite combinations. For both of these efforts, the primary values considered were how the strength and stiffness of the various proposals compared to one another. Fracture toughness was not considered directly in these comparisons but was instead treated as a initial screening mechanism. That is, materials that exhibited poor fracture toughness at cryogenic temperatures were eliminated from consideration before these studies were done to save time and narrow the range of potential candidates.

3.1 BASELINE CONFIGURATION STUDIES

The baseline sting configuration consists of tapered cylindrical tube made from monolithic 18 Ni-200 steel as shown in Figure 3-1. An analysis was conducted of this configuration to establish design goals for strength and stiffness that could be compared to proposed alternatives.

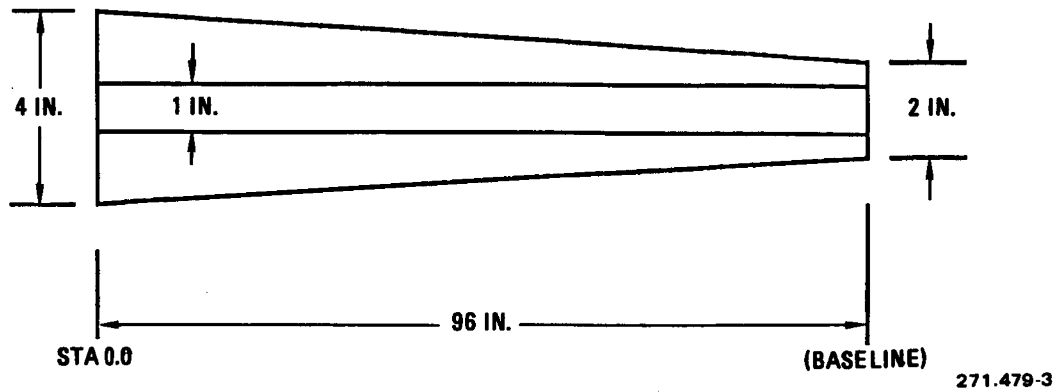

Figure 3-1. Generic Model Sting (Baseline)

3.1.1 STIFFNESS ANALYSIS. Plots of the stiffness versus length were generated for the existing sting and for the goal of a 25% improvement in these properties. The desired values were the AE and EI terms and were calculated from the following equations:

$$AE = \pi\ (R_o^2 - R_i^2)\ (E)$$

$$EI = \pi/4\ (R_o^4 - R_i^4)\ (E)$$

where

$$R_o = 2.00 - x/96.00$$

$$R_i = 0.50$$

E = 26,500,000 psi (MIL-HDBK-5D, Table 2.5.1.0(b))

Substituting in the geometric values from Figure 3-1 gives the values for the baseline configuration summarized in Table 3-1. The values for the desired 25% improvement were obtained by multiplying the AE and EI values by 1.25. The results are shown graphically in Figures 3-2 and 3-3.

Figure 3-4 shows the baseline sting cross section geometry.

3.1.2 STRENGTH ANALYSIS. The baseline sting was analyzed to determine the maximum axial loads and bending moments capable of being carried by this configuration. The loading conditions established in this analysis were then considered to be the design requirements for any replacement model. This was necessary since no formal design requirements were available and by establishing these values as minimum requirements, it ensured that any new sting would be at least as capable as the existing arrangement.

Table 3-1. Baseline Sting Configuration Stiffness Parameters

x (in.)	R_o (in.)	R_i (in.)	AE (lb)	EI (lb-in2)
0.00	2.00	0.50	308,661,000	327,952,000
24.00	1.75	0.50	231,496,000	191,707,000
48.00	1.50	0.50	164,619,000	102,887,000
72.00	1.25	0.50	108,031,000	48,952,000
96.00	1.00	0.50	61,732,000	19,291,000

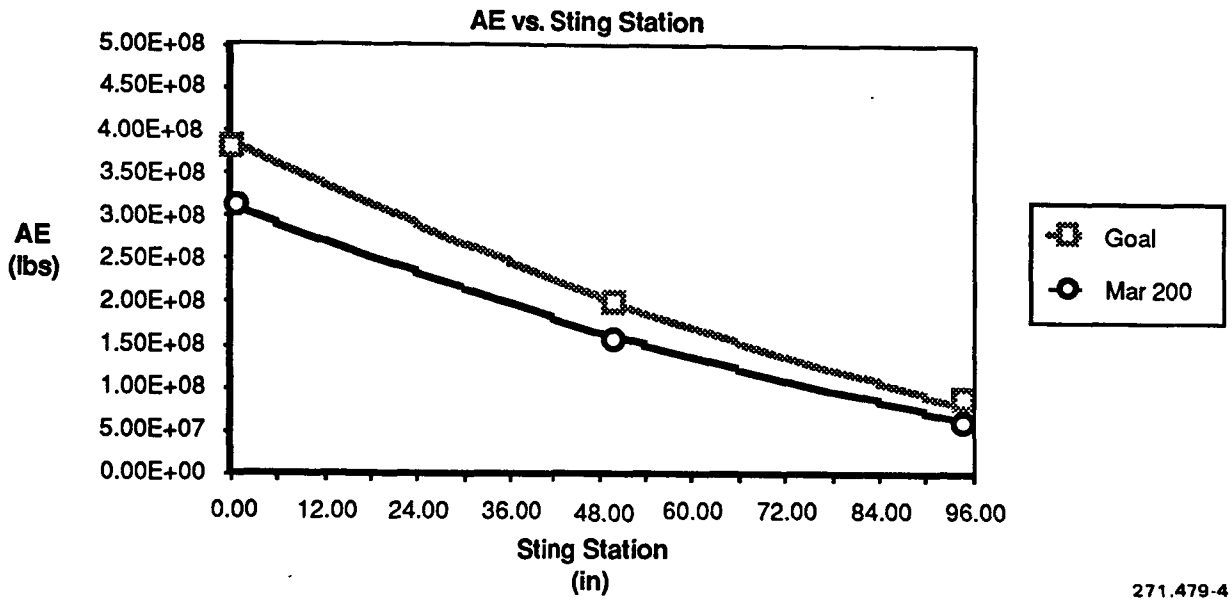

Figure 3-2. Baseline and Improved Sting Configuration Stiffness Parameters, AE

The basic approach taken was to analyze the sections of the sting at the forward and aft ends to determine the maximum allowable axial loads and bending moments. These were then used to create design envelopes for the baseline configuration using 18 Ni-200 and the desired 25% improvement. From this, critical design conditions could be selected for use in the evaluating proposed configurations. A plot of the resulting design envelopes is shown in Figure 3-5 and a summary of the critical design conditions is given in the Table 3-2. Note that in selecting the critical design conditions at the aft end, the maximum axial load at the forward end was used as limiting value. This is because there is no means of introducing additional axial loads into the sting between the forward and aft ends.

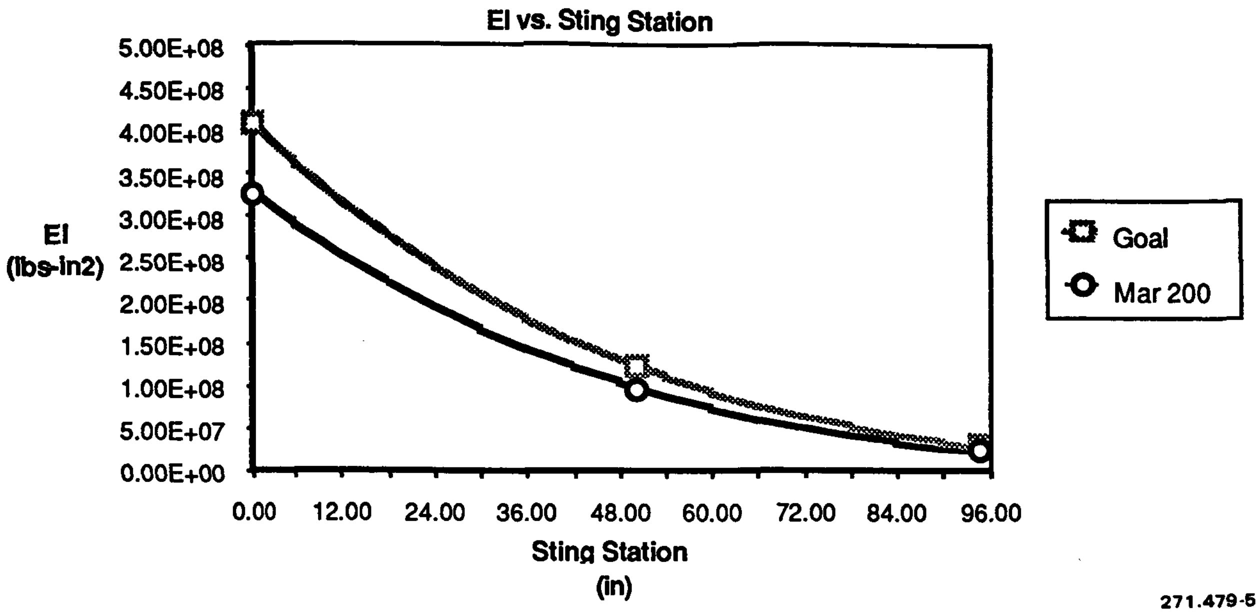

Figure 3-3. Baseline and Improved Sting Configuration Stiffness Parameters, EI

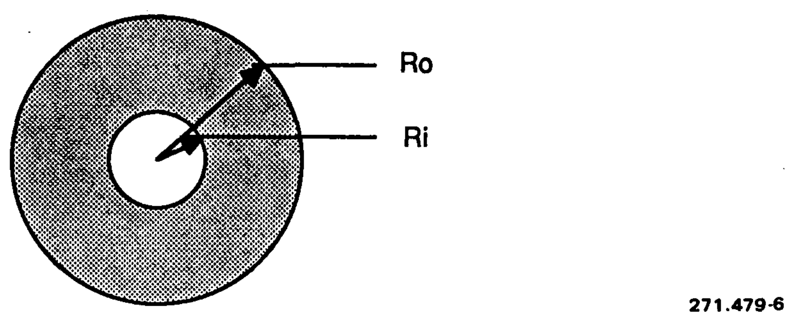

Figure 3-4. Baseline Sting Cross Section Geometry

3.2 CROSS SECTION STRAIN DISTRIBUTION

The axial strains at the cross section at the aft end of the sting were calculated for the critical design conditions. These values were required for analyzing potential sting configurations using hybrid material systems where the stress distribution at a given cross section would no longer be linear. The strain at a given location for a general section subjected to axial loads and bending moments is given by:

$$\epsilon = P/AE + Mc/EI$$

The values for the improved sting configuration were used and were taken from Figures 3-2, 3-3, and 3-5. The results are shown in Figure 3-6.

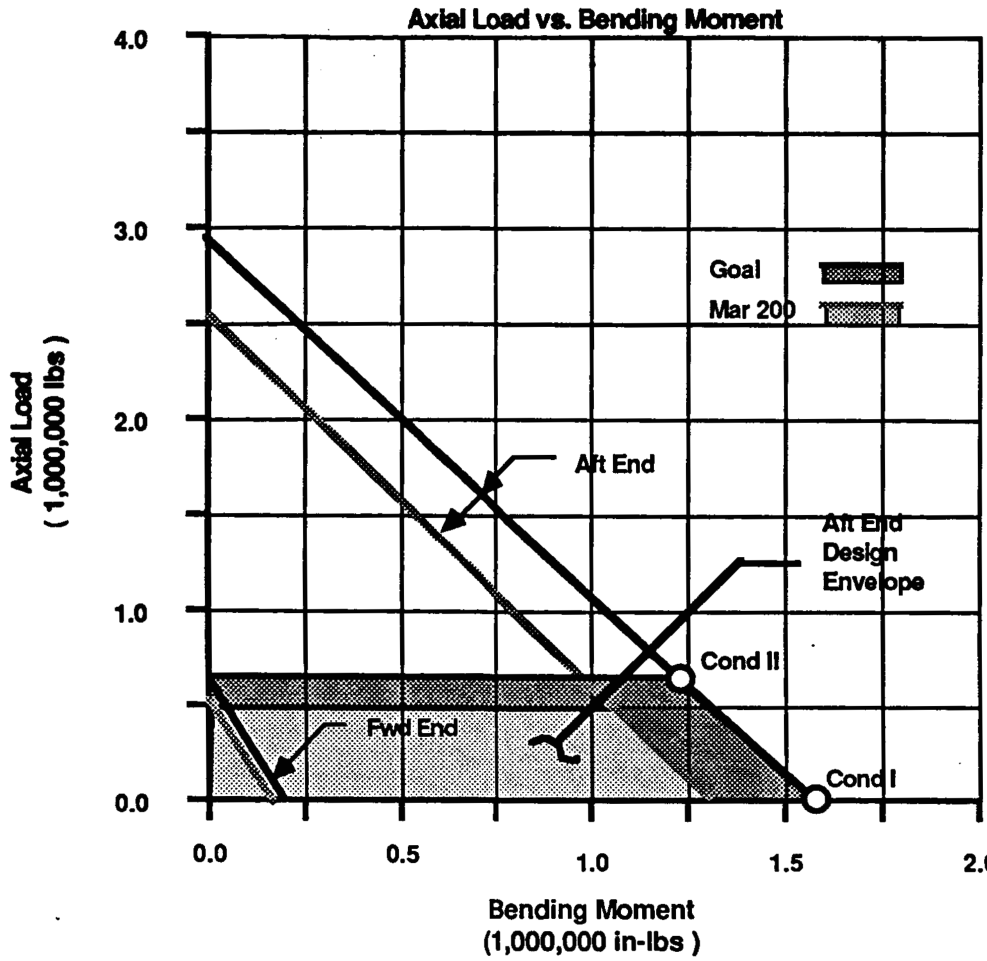

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Figure 3-5. Baseline and Improved Strength Design Envelope

Table 3-2. Critical Loading Conditions for the Improved Sting Configuration

Section Properties

$A = \pi (Ro^2 - Ri^2) = \pi (1.00^2 - 0.50^2)$
$I = (\pi/4) (Ro^4 - Ri^4) = (\pi/4) (1.00^4 - 0.50^4)$

Internal Stresses

$F_{tu} = P/A + MR_o/I$
$P = A (F_{tu} - MR_oI)$
$M = (I/Ro) (Ftu - P/A)$

Material Properties

18 Ni-200
$E = 26,200,000$ psi
$F_{tu} = 200,000$ psi

Goal
$E = 32,750,000$ psi
$F_{tu} = 250,000$ psi

Maximum Allowable Loads - Forward End

Section Properties
$R_o = 1.00$ in.
$R_i = 0.50$ in.

$A = 2.5362$ in^2
$I = 0.7363$ in^4

18 Ni-200
$P_{max} = 507,240$ lb
$M_{max} = 147,260$ in-lb

Goal
$P_{max} = 634,050$ lb
$M_{max} = 184,075$ in-lb

Maximum Allowable Loads - Aft End

Section Properties
$R_o = 2.00$ in.
$R_i = 0.50$ in.

$A = 11.7810$ in^2
$I = 12.5173$ in^4

18 Ni-200
$P_{max} = 2,536,200$ lb
$M_{max} = 1,251,730$ in-lb

Goal
$P_{max} = 2,945,250$ lb
$M_{max} = 1,564,662$ in-lb

Condition	Axial Load (P) (lb)	Bending Moment (M) (in-lb)
I	0	1,564,662
II	-184,075	1,460,872

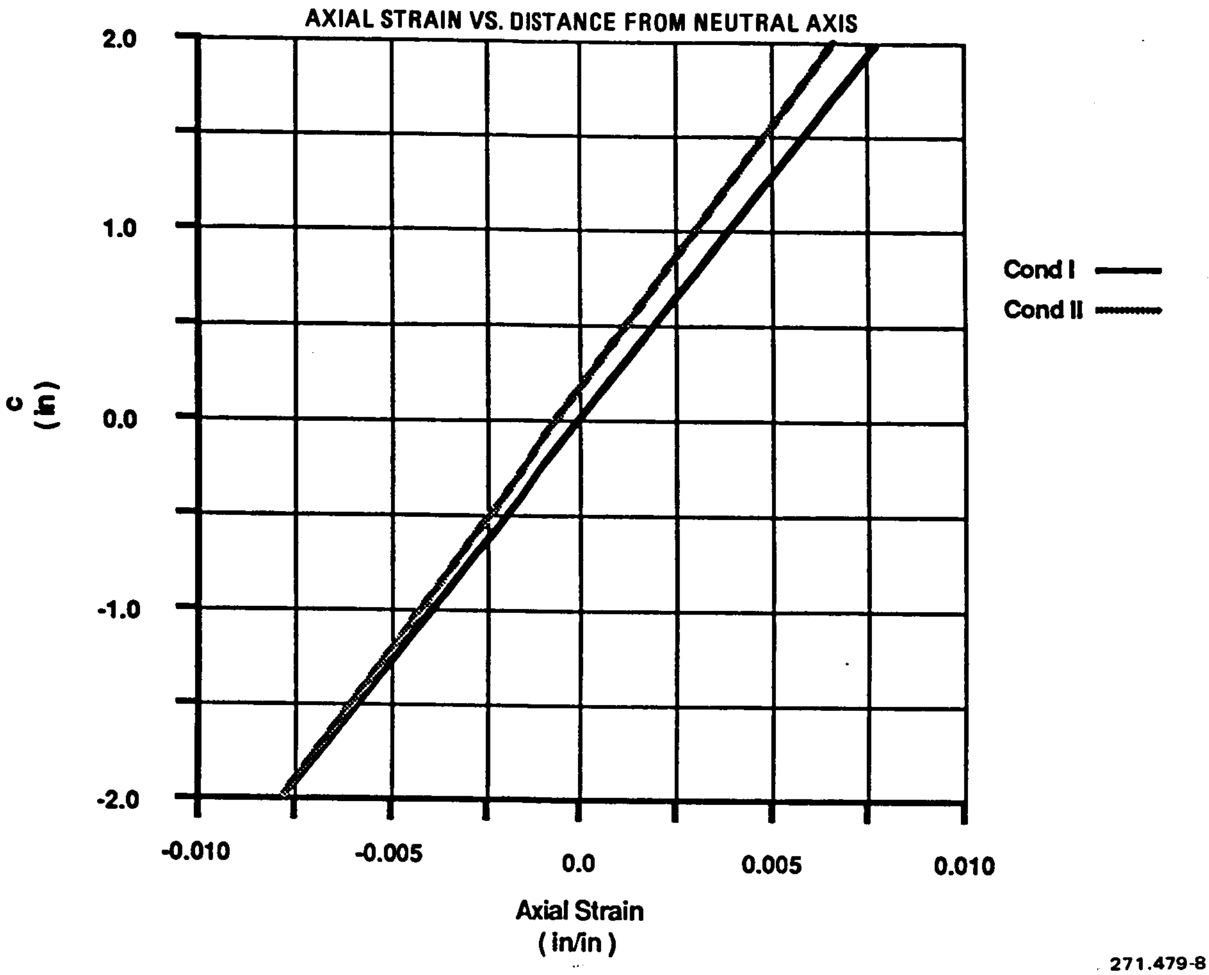

Figure 3-6. Axial Strain Distribution at the Aft End of the Improved Sting Configuration

SECTION 4

CONVENTIONAL METALLURGICAL APPROACH

4.1 GENERAL INFORMATION

For sting applications where high strength and stiffness is a general requirement and where cryogenic fracture toughness is a serious concern, maraging-type steels have been shown to be very effective. Few materials can presently match its combination of 200 ksi level yield strength, 26 Msi Young's modulus, and excellent cryogenic fracture toughness. Commercially available alloys that have properties similar to maraging steels are listed in Table 4-1. As can be seen, a few alloys have higher strength or stiffness or cryogenic toughness, but none exceed maraging steel's properties in all categories. An exception might be alloys such as AF 1410 (a relatively newly developed Air Force alloy) and Inconel 718 or MP35N. With specialized thermal mechanical treatments, possibly 25% improvement in strength and stiffness might be achievable. Satisfaction of cryogenic fracture toughness levels, however, may still present a challenge. Of the alloys listed in Table 4-1, MP35N is perhaps the candidate most closely fitting our requirements.

Table 4-1. Potential Candidate High-Performance Sting Materials

Alloy	Yield Strength (At RT ksi)	Young's Modulus (At RT Msi)	Charpy V-Notch (At -320F, ft-lb)
Maraging 200	200	26.2	28
Maraging 250	250	27.0	10
Maraging 300	290	27.5	10
PH 13-8 Mo H1150M	85	25.0	30
PH 13-8 Mo H950	210	28.6	4
Custom 455	195	29.0	5
AF 1410	230	29.4	15
Inconel 718			
Cold worked & aged		29.0	
MP35N			
Cold worked & aged	285	34.8	16

The high performance metallic material systems considered in this study were compared against the baseline configuration by plotting the strength versus stiffness of these materials on a common chart as shown in Figure 4-1. This provided a simple and easily understandable means of comparing different materials.

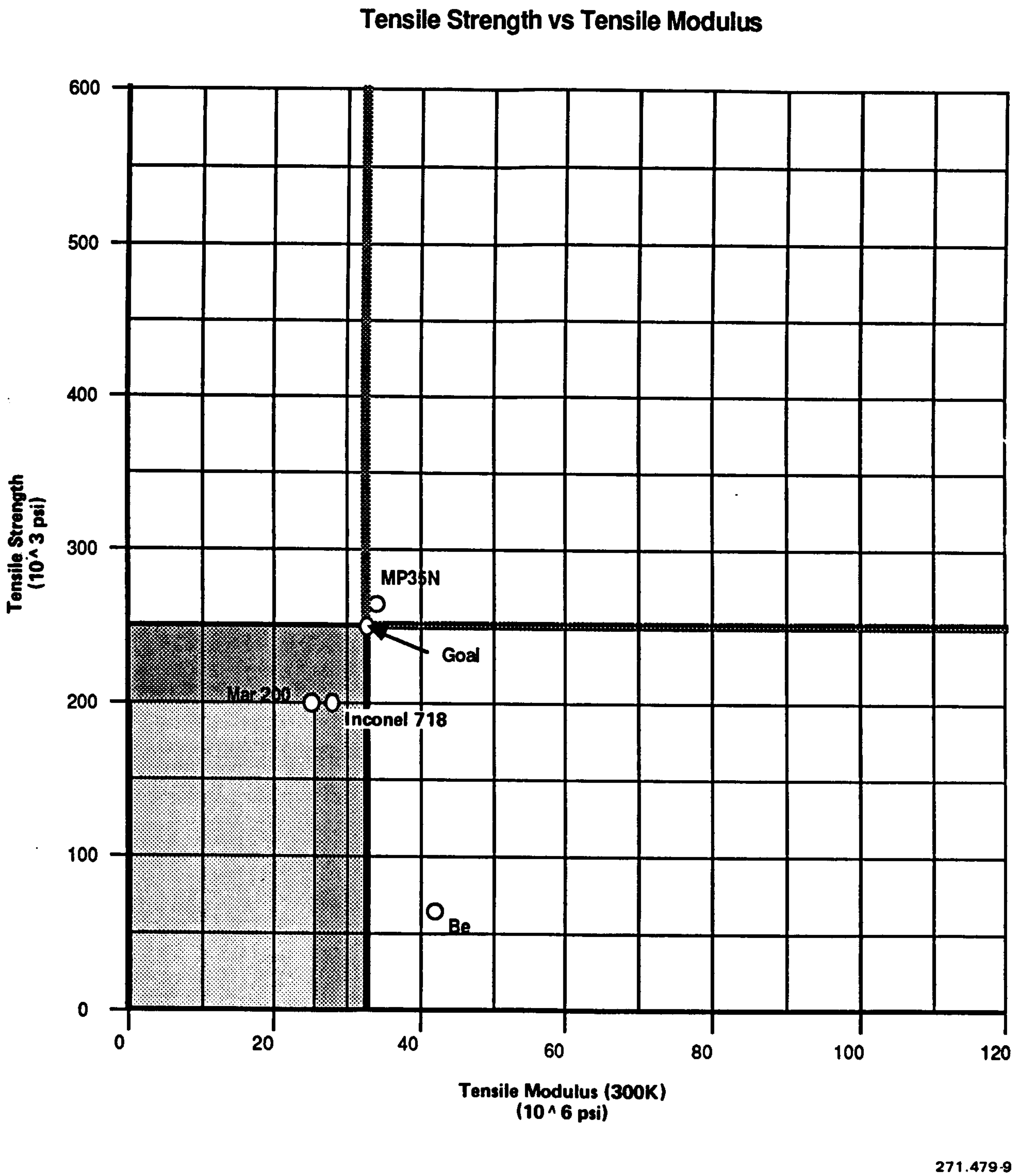

Figure 4-1. Comparison of High Performance Metallic Materials

In viewing the data shown in Figure 4-1, it is important to realize that this chart does not consider the availability of the material in the form required for the sting application. In particular, the data for MP35N is for sections less than 1.25 inches in thickness and does not apply to currently available materials in the size required for this application.

4.2 AN ADVANCED STING USING MP35N

MP35N alloy is a vacuum induction, vacuum arc remelted alloy, comprising 10% molybdenum, 20% chromium, and the balance a combination of nickel and cobalt, normally 35% nickel and 35% cobalt. This alloy has shown unusually favorable combinations of high strength, stiffness, and corrosion resistance. These properties are obtained by cold working the material, either by drawing, extruding, or rolling. Additional strengthening is obtained by aging in the temperature range of 800 to 1200F. The material can be welded, although it should be understood that the high strength properties of the material will be lost in the vicinity of weld.

Typical properties for MP35N are shown in Table 4-2 and compared with other metals.

An outstanding feature of the Multiphase alloy system is the exceptional corrosion and stress corrosion resistance at very high strength levels. This system has matched the strength developed by the high strength steels while maintaining the excellent corrosion resistance demonstrated by the lower strength stainless steels.

An indication of the variation in Cvn with temperature is shown in Table 4-3. This is the result of work done at NASA Marshall Space Flight Center, using a cold-worked MP35N bar for a test specimen.

An example of the change in modulus with decreasing temperature is shown in Table 4-4, using different test specimens.

The Cvn for the very high strength use shown above does not meet the requirement of 25 ft-lb for impact strength[3]. The lower value of F_y = 217 ksi/ F_{ult} = 227 ksi, however, should give us a better Cvn value. In other words, strength could be tailored during the cold working process to give us a more acceptable Cvn value.

Cobalt superalloys (hcp structure) are described[4] as high cost, limited availability, poor fabricability, lacking design data, etc. MP35N is a cobalt superalloy, and while the above statements are generally correct, recent experiences have shown that the alloy is being used in more and more applications. While we might not recommend it for the whole model system, its use in a high performance sting, with the advantage of a 30% increase in stiffness over 18 Ni-200, would appear to justify further research.

Table 4-2. Mechanical Properties of Various Metals

Material	Temperature (deg K)	Yield Stress (ksi)	Ultimate Stress (ksi)	E (Msi)	ν	α^t in/in/deg F	Cvn ft-lb	K_{IC} ksi-in$^{1/2}$
18 Ni-200	300	205	210	27	0.311	---	35	170
	78	270	280		0.306	3.4×10^{-6}	25	80
18 Ni-250	300	250	260	28.1	0.308	---	20	100
	78	320	330	29.4	0.304	3.4×10^{-6}	10	40
A286	300	100	160	28.4	0.300	---	55	120
	78	120	215	29.4	—	6.8×10^{-6}	50	110
AISI 304	300	35	90	27.4	—	---	155	118
	78	60	230	29.6	—	6.0×10^{-6}	116	—
MP35N	300	215	230	34.5	--	7.1	50	—
	78	---	---	---	--	---	--	—
MP35N	300	240	260	34.5	—	---	23	—
	78	---	---	---	—	---	—	—
MP35N	300	285	295	34.5	--	---	17	—
	78	327	337	35.6	--	---	16	—

Table 4-3. Variation of Cvn for MP35N with Temperature

Test Temp F	(C)	Average Impact Energy (Cvn) ft-lb	(joules)	Impact Energy Range ft-lb	(joules)	Number of Tests
75	(+23.9)	18.90	(25.62)	15.50-23.00	(21.01-31.18)	3
-100	(-73.0)	17.10	(23.18)	14.75-19.25	(20.00-26.10)	3
-200	(-129.0)	15.25	(20.68)	15.00-15.50	(20.34-21.01)	3
-320	(-196.0)	16.10	(21.83)	14.00-18.25	(18.98-24.74)	2
-423	(-252.8)	13.50	(18.30)	13.50-13.50	(18.30-18.30)	2

Table 4-4. Low Temperature Mechanical Properties of MP35N Multiphase Tensile Specimens (0.250 in (0.635 cm) in diameter) Work Strengthened 49% and Aged at 1200F for 4 Hours

TEST TEMP °F (°C)	U.T.S. ksi (GN/M^2)	0.2% OFFSET Y.S.* ksi (GN/m^2)	ELONGATION 1.0 inch (2.54cm) (40%)	REDUCTION IN AREA (%)	MODULUS $X 10^6$ psi (MPa/m^2)	N.T.S. Kt = 5.5 ksi (GN/m^2)	N/U RATIO	NO. OF TESTS
75 (+23.9)	279.3 (1.926)	274.1 (1.890)	9.8	46.8	34.8 (239.9)	356.5 (2.458)	1.28	3
0 (-17.8)	286.0 (1.972)	282.7 (1.949)	10.0	48.6	34.1 (234.4)	– –	–	1
-100 (-73.0)	300.6 (2.072)	295.9 (2.040)	10.0	45.0	34.4 (237.2)	413.1 (2.848)	1.37	2
-200 (-129.0)	314.3 (2.167)	308.0 (2.123)	10.3	46.6	35.5 (244.8)	446.5 (3.078)	1.42	3
-320 (-196.0)	336.7 (2.321)	326.5 (2.251)	11.0	39.5	35.6 (245.4)	478.7 (3.300)	1.42	3
-423 (-252.8)	359.8 (2.481)	344.3 (2.374)	11.8	36.1	36.8 (253.7)	501.4 (3.457)	1.39	3

*YIELD LOAD OBTAINED BY USE OF A CRYOGENIC EXTENSOMETER.

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4.3 MANUFACTURING ASPECTS OF AN MP35N STING

The major factor limiting the availability of MP35N to small sizes is the equipment needed to cold work the material. Our research indicates that the higher values of strength are achieved with extensive cold working; i.e., strength is directly proportional to cold working. Size is also directly proportional; larger sizes are available but strength is reduced because the present equipment cannot cold work the longer sizes to the point of achieving maximum strength. Young's modulus, E, however, is not affected by the amount of cold work, which means that we can trade off size and strength while maintaining stiffness. For example, see Table 4-5.

Table 4-5. Variation of Size and Strength for MP35N Round Bar Stock

Diameter (in.)	Ultimate Tensile (ksi)	E Modulus (Msi)
2.00	220	34.8
2.14	200	34.8
2.25	200	34.8
2.50	195	34.8
3.00	185	34.8

Material cold worked and aged

Machinability tests conducted by an independent laboratory have compared MP35N alloy to Waspaloy, a widely used standard for nickel-cobalt-chromium base alloy machinability. Comparing MP35N alloy work strengthened and aged to the 260 ksi (1793 MPa) ultimate tensile and 240 ksi (1655 MPa) 0.2% yield strength level, and Waspaloy in the mill-annealed condition with approximately 145 ksi (1000 MPa) ultimate tensile and 90 ksi (621 MPa) 0.2% yield strength, Waspaloy has approximately the same machinability in either the solution-treated or solution-treated-plus-aged condition.

MP35N alloy exhibited better machining performance than Waspaloy in all categories of tests except tapping where Waspaloy tapped about 15 ft/min (4.57 m/min) faster for the same tool life of 200 holes.

The Air Force machinability data center files do not provide comparable machining information for other cold-worked austenitic alloys. Further, because of the unique strengthening mechanism for MP35N alloy, it may not be possible to make an extrapolated comparison in machinability performance to precipitation-strengthened alloys, transformation-strengthened alloys, or cold-worked alloys.

Specific setup practices for MP35N alloy are given in Tables 4-6 and 4-7.

Table 4-6. Manufacturer's Recommended Conditions for Machining MP35N Alloy Work Strengthened to 260 ksi (1793 MPa) Ultimate Tensile Stress

Operation	Tool Mat'l	Tool Geometry	Type of Tool	Depth of Cut In. (mm)	Width of cut inches (mm)	Feed	Cutting Speed ft./min. (m/min)	Tool Life	Wear land inches (mm)	Cutting Fluid
Turning	M42 HSS	BR: 0° ECEA: 15° SR: 10° Rel: 5° SCEA: 15° NR: .030" (.762 mm)	⅝" (15.87 mm) square tool bit	.050 (1.27)	—	.010 in/rev. (.254 mm/rev)	30 (9.1)	60 min. plus	.020" (.508)	Soluble Oil (1:20)
Peripheral End Milling	M2 HSS	Helix Angle: 30° RR: 10° CA: 45" x .060" (1.52 mm) Per. Cl: 7°	1" (25.4 mm) dia. 4 flute end mill	.125 (3.175)	.500 (12.7)	.002 in./tooth (.051 mm/tooth)	75 (22.9)	200" (5080 mm) work travel	.005" (.127)	Sulfurized Oil
Drilling	T15 HSS	Point Angle: 118° Helix Angle: 29° Cl: 7° Point: Crankshaft	¼" (6.35 mm) dia. 2 flute drill screw machine length	½" (12.7) through	—	.005 in./rev. (.127 mm/rev)	25 (7.6)	250 holes plus	.012" (.305)	Chlorinated Oil
Reaming	M2 HSS	Straight Flute Chamfer Angle: 45° Relief: 7°	Letter I dia. .272" (6.91 mm) 6 flute HSS reamer	½" (12.7) through	—	.009 in./rev. (.229mm/rev.)	60 (18.3)	195 holes	.006" (.152)	Chlorinated Oil
Tapping	M1 HSS	2 Flute Plug Spiral Point 75% Thread	$\frac{5}{16}$" (7.94 mm) 24 NF tap	½" (12.7) through	—	—	5 (1.5)	235 holes	Tap breakage or undersize thread	Chlorinated Oil

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Table 4-7. Manufacturer's Recommended Conditions for Surface Grinding

Wheel Grade	Wheel Type	Down Feed in./pass. (mm/pass.)	Cross Feed in./pass. (mm/pass.)	Table Speed ft./min. (m/min)	Wheel Speed ft./min. (m/min)	G Ratio	Grinding Fluid
32A46J8VBE	10" x 1" x 3" (254 mm x 25.4 mm x 76.2 mm) Aluminum Oxide Wheel	.002 (.051)	.050 (1.27)	40 (12.2)	6000 (1829)	70	Sulfurized Oil

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Further information on machinability was obtained from the General Dynamics Materials and Processes Laboratory. They compared MP35N with A286 and some of the Inconel materials saying that it can be machined with high speed cutting tools; it isn't, however, a simple material to machine. A sample was obtained of the 0.625 inch diameter bar used, and the ultimate tensile stress was determined to be 285 ksi, and yield stress very similar.

4.4 DESIGN CONCEPTS

Recognizing the limitation in available size for MP35N bar and plate, our study turned to possible ways of building up a sting, using available materials. Two fabrication schemes were considered, one for a round sting, and one for a rectangular sting.

4.4.1 <u>CONCEPTS FOR FABRICATING A ROUND STING</u>. One method is to spiral wind very thin (0.020 to 0.060 inch) MP35N strip around a tube of the same material. The tube would provide the 1-inch instrumentation hole and act as a base for the spiral winding. The strip material would be cold rolled prior to winding. Strip layers would overwrap at various angles (to be determined) to ensure structural strength. The entire structure would then be aged to the desired strength level and machined to size and shape. Three plans were developed to do this and they are described below.

<u>Plan 1</u>

1. Roll, cold work, and spiral wind MP35N strip on MP35N tubing core (see Figure 4-2).

2. TIG, EB, or laser weld each of the spiral wrapped butt joints. Develop depth of penetration.

3. Cold work weld area by shot peen or roll planish.

4. Lathe turn taper on sting.

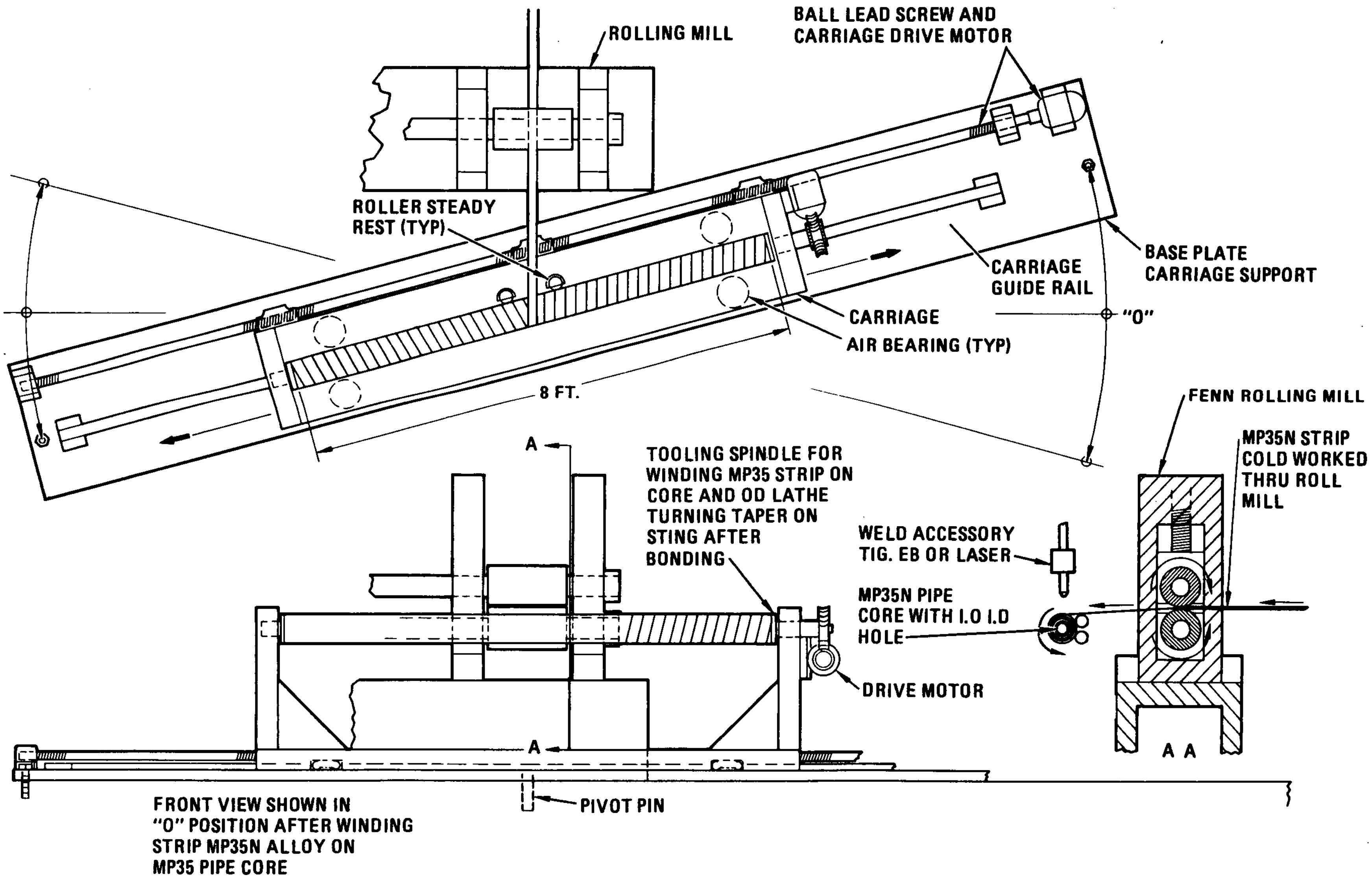

Figure 4-2. Sting Fabrication Concept 1

5. Reweld top layer.

6. Age sting per Latrobe Steel specifications.

Notes: Development data is need for cold working, TIG, EB, and laser welding of MP35N material.

Plan 2

1. Roll, cold work, and spiral wind MP35N strip material and braze alloy on MP35N tubing core (see Figure 4-3).

2. Tack weld as required.

3. Vacuum or retort furnace braze. Match braze alloy to the MP35N aging temperature (about 1000F).

4. Lathe turn taper on sting.

Notes: Development data is need for cold working, brazing alloy selection, tack welding, and furnace brazing MP35N material.

Plan 3

1. Roll, cold work, and spiral wind MP35N strip on MP35N tubing core.

2. Tack weld as required.

3. Diffusion weld entire sting together at a temperature to match the aging temperature.

4. Lathe turn taper on sting.

Notes: Development data is needed for cold working, tack welding, and diffusion bonding of MP35N material.

The spiral wind process is a process that has been used successfully at GDC; it is described in a report[5]. In that particular case, stainless steel (3 inches wide by 0.60 inch thick) was wrapped around a tube, with an adhesive bond used for attachment. Cross plies were used for strength. The finished tube was 1.0 inches in diameter. For the NTF application we must wrap over a 1â inch diameter mandrel using cold rolled MP35N strips, a more difficult task. The cryogenic environment prohibits the use of an adhesive bond and as indicated in the plans above, electron-beam welding, brazing, and diffusion welding are alternate proposals. For either case the manufacturing process must be such that the cold worked properties of the strip are not lost. The manufacturing process must therefore not exceed the aging temperature of MP35N (800 to 1200F).

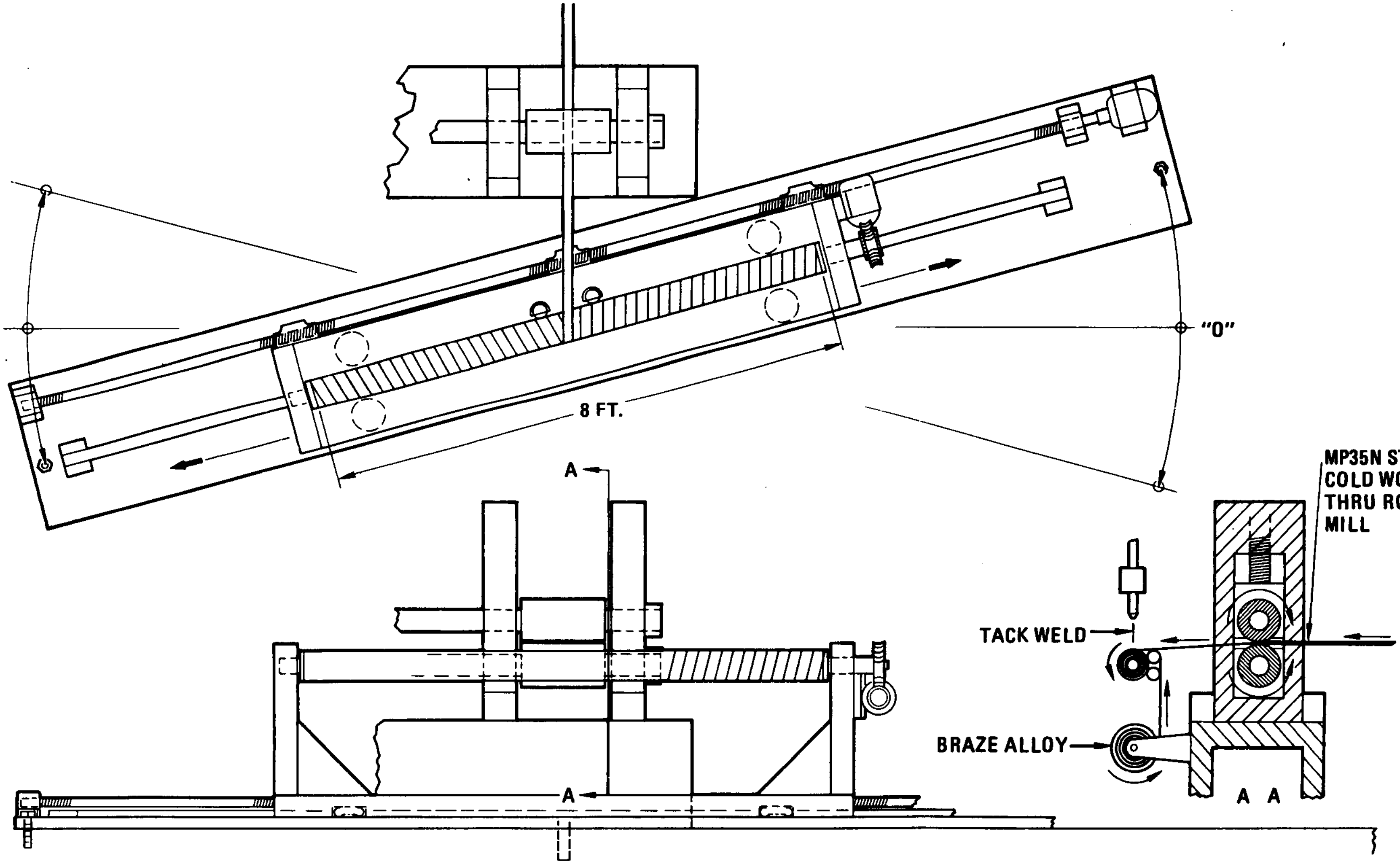

Figure 4-3. Sting Fabrication Concept 2

4.4.2 <u>FABRICATING A RECTANGULAR STING OF MP35N</u>. In this concept, the largest available plate size are used to fabricate a rectangular sting. Two 1-1/2-inch thick by 3-inch deep plates are keyed together on the vertical centerline. The keys will take the major load in the vertical plane, and the method of attachment of the two plates will take the torsional and side loads. The machining task is reasonably straightforward, and the depth of the beam can be tapered using available plate sizes. Various methods of attaching the beams were considered.

- Diffusion brazing
- Diffusion welding
- Adhesive bonding
- Laser welding
- Electron-beam welding

As indicated earlier, MP35N loses it physical properties if the attachment temperature exceeds 1000F, and this is a critical part of the design analysis. The design concept for the rectangular sting is shown in Figure 4-4.

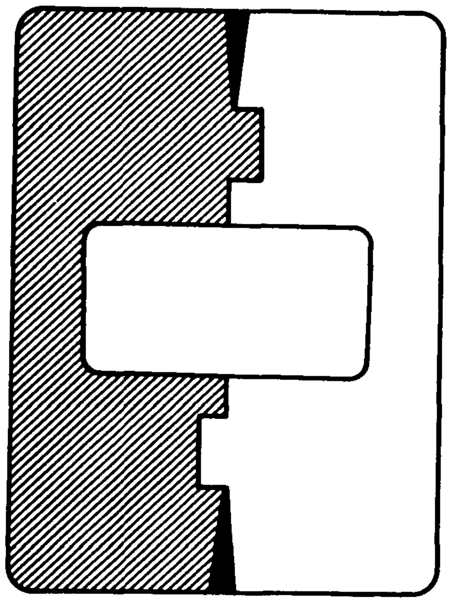

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Figure 4-4. Typical Section of Sting Showing Laser Weld

As can be seen, the MP35N plates are milled to a finished size including the keys and a centerhole for routing instrumentation cables, etc. Available size of MP35N limit the thickness (the reason for the joint) and the length. For example, the maximum size of existing plate is on the order of 1 1/2 inch thick by 24 by 24 inches, possibly going to 2 inches thick with reduced strength, but maintaining stiffness, E. Research indicates, however, that longer length

(4 or 5 feet) could be obtained in the future, but is a function of equipment, demand, etc. It is not unreasonable, therefore, to think in terms of sting 2 to 3 inches wide by 3 to 6 inches deep by 5 feet long, fabricated from two plates. The design concept must therefore be developed in proof-of-concept test.

Attachment method analysis follows.

4.4.2.1 Diffusion Brazing. This process involves the use of a metal foil between the mating surfaces and application of heat and pressure to diffuse the filler metal with the base metal for an effective joint. Care must be taken with surface finish and cleanliness of the mating parts. To maintain the properties of MP35N, the temperature during the diffusion braze process must not exceed the aging temperature (1000F). This limits the braze alloys that can be used as fillers.

4.4.2.2 Diffusion Welding. This is a solid-state welding process that produces coalescence of the faying (or mating) surfaces by the application of high pressure and temperature. The process normally does not include a filler material. Here, because of the temperature limitation, a soft filler would be used as an aid to diffusion, probably copper or silver.

4.4.2.3 Adhesive Bonding. This process was not pursued further because it was not felt to be fail-safe, particularly at cryogenic temperatures.

4.4.2.4 Laser Welding. As stated previously, the desired properties of MP35N are produced by cold working, and it is known that the temperatures associated with welding will return the alloy to the annealed state. Welding therefore is not normally recommended by the manufacturer. MP35N is, however, a weldable material, and in the application shown in Figure 4-4 we felt it to be worth further consideration.

Prior research[1] revealed that laser welding was well controlled, very clean, had very narrow heat affected zones, and little material distortion. At that time the depth of penetration for laser welding was on the order of 0.050 to 0.10 inch maximum. Today the process is more versatile, and weld penetration of up to 0.75 inch has been accomplished. Figure 4-4 shows the design concept; the upper and lower butt joint would be laser welded to a depth not exceeding 0.75 inches. The heat affected zone is not expected to exceed 0.040 to 0.050 inch, which means that a very small area of the structure will be reduced to an annealed condition.

The primary load will be in the vertical plane, and will be taken by the two plates keyed together. The side and torsional loads will be taken in through the welded joint, (annealed-ultimate tensile strength 130 ksi). This design concept would be particularly useful in applications where the vertical load (NF) is large in relation to the side force (SF). The mating surface for this process should fit well, but the finish and cleanliness are not as critical as in the diffusion brazing process.

4.4.2.5 Electron-Beam Welding. This process is much more common and is also a good candidate. The heat affected zone, however, is much larger, resulting in loss of strength, and potential distortion.

4.5 STRUCTURAL ANALYSIS

The sting cross-section shown in Figure 4-4 is a typical design concept. The vertical load is normally larger and is taken equally by the two plates. The keyways help to locate the plates, and take out any asymmetric loading. The centerhole used for routing wiring, tubes, etc., would be rectangular, with the short axis in the vertical plane for increased moment of inertia. The laser welded butt joint would vary in depth up to a maximum of 0.75 inch.

Table 4-8 is a comparison of the fabricated section as shown with a solid section of the same material.

Table 4-8. Comparison of Fabricated and Solid Sections

Load	Fabricated	Solid
Vertical	Strength reduced by depth of weld times 0.050 inch (annealed).	Maximum strength of full section
Side	Taken by shear at welded surface	Maximum strength of full section
Torsion	Similar to side load	As above

An alternate design for the rectangular sting was considered. The main purpose was to use available material for a longer sting. At present the thicker plates are limited in length to 2 feet, whereas sheet stock to thicknesses of 1/4 inch are available in lengths of 6 feet. The alternate design is a laminated beam comprising strips of 1/4-inch sheet built up to the desired width, with the strips cut to the depth required.

The key to fabrication of this type of beam is the joining process. Various methods were described earlier in the section and of those, diffusion welding is felt to be one of the best candidates. As described earlier, a 0.003-inch thick film of copper or silver would be placed between the sheets of MP35N, and pressure applied at a temperature not exceeding 1000F. This process does not include macroscopic deformation, or melting of the filler.

As described in several welding journal articles[6], the process is diffusion welding if the interlayers do not melt. While this process has been successfully accomplished using 18 Ni-200, development would be required using MP35N. The use of comparatively thin sheets of MP35N would facilitate the diffusion welding process. Figure 4-5 shows the concept.

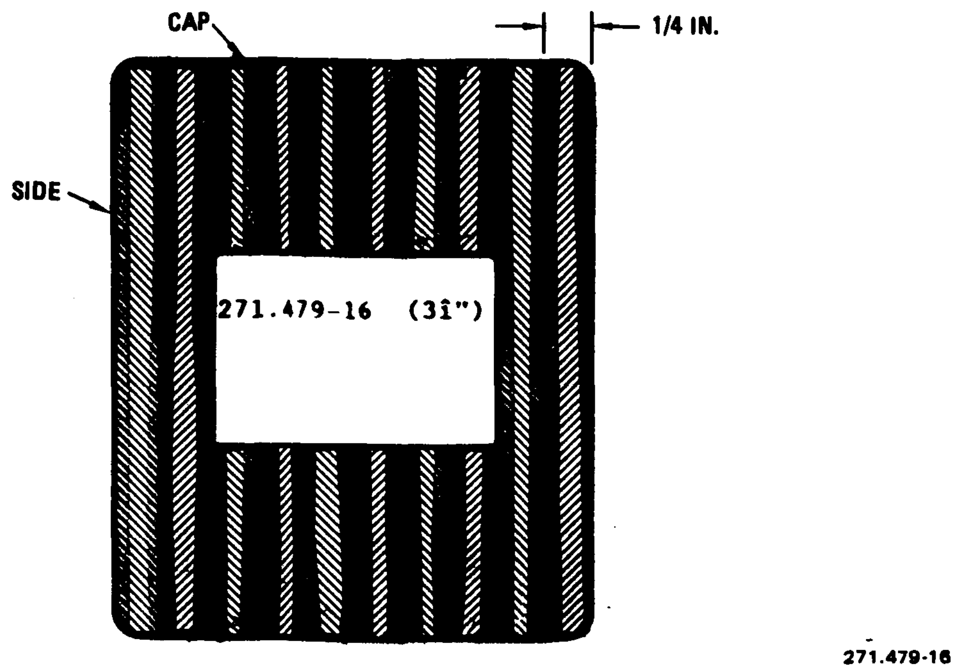


Figure 4-5. Rectangular Beam Using 1/4-inch MP35N Strip

To create a hole in the center for routing model instrumentation, it may be necessary to subassemble the sides, and top and bottom caps. Alternatively, instrumentation could be routed along the sides as shown in Figure 4-6, with an outer cover for protection. As a conservative measure (fail-safe) a pin could be used across the center, laser welded in place for positive clamping of the MP35N strips.

The design using multiple sheets of MP35N is potentially stronger than the two plate approach shown in Figure 4-4 because the thin sheets can be cold worked to the full allowables; in addition, the diffusion welding at 1000F will not reduce the properties.

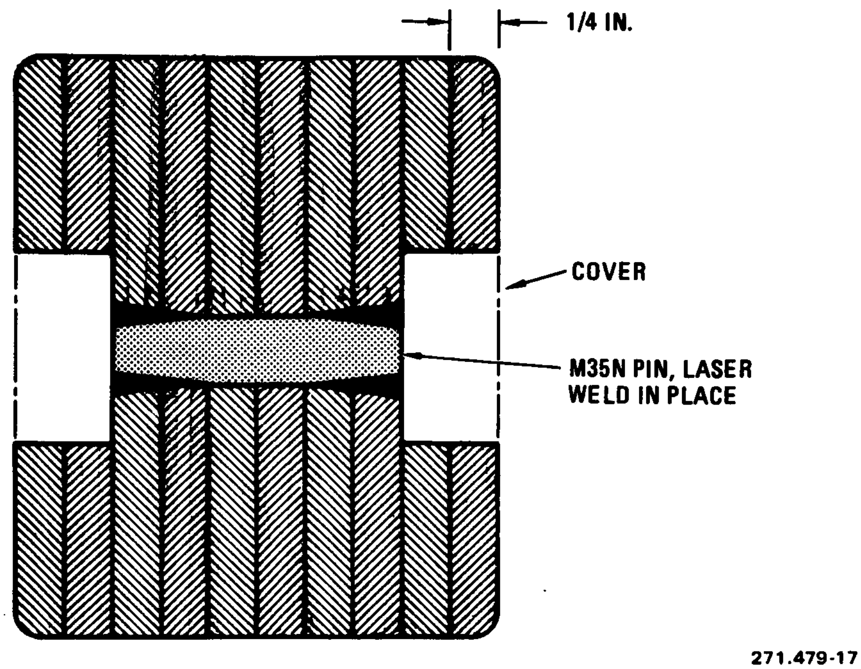


Figure 4-6. Alternate Design Using MP35N Strip

SECTION 5

THE USE OF ADVANCED COMPOSITES FOR A HIGH PERFORMANCE STING

5.1 GENERAL INFORMATION

In viewing the use of composites for use in a high performance sting, it is found that the majority of development work has been done in the area of high strength-to-weight ratios, in other words, relatively thin walled structures. The sting is essentially a solid bar, with a small centerhole, and the generally accepted properties for composites probably do not apply. For purposes of their study, however, our goal was to review composite materials developed for the aerospace industry, and to determine if they could be modified or altered for use in a sting application.

5.2 ORGANIC MATRIX COMPOSITES

In the search for high modulus organic composites, the properties of pitch-based graphite fibers were considered because of their moduli of 70 to 125 Msi. The fibers, as they are currently available, will produce epoxy matrix laminates with moduli of about 70 Msi. However, the tensile strengths of these composites are only 180 ksi. Some of the intermediate modulus PAN-based polyacylonitrile fibers will produce laminates with moduli of about 25 Msi and tensile ultimates of 400 ksi. In compression, however, the PAN-based laminates show ultimates of only 140,000 psi maximum and the pitch-based laminates 40,000 psi and are erratic in performance.

The properties of graphite fiber composites show promise if they can be used in such a manner that they are loaded only in tension.

In this study of advanced stings, the primary load is nearly always in the upward direction. The sting is a cantilevered beam; therefore, the upper side is in compression, and the lower in tension. The feasibility of using an all-composite sting was reviewed on that basis. Unfortunately, there doesn't seem to be any obvious way to blend the material so that we use the high tensile modulus of pitch fibers along with the high tensile strength of PAN fibers. Combining them did not seem to be feasible because of the differences in strain rates between the two types of fibers. Table 5-1 lists candidate materials.

Since the ultra high modulus graphite structures are unpredictable when loaded in compression, and the high-modulus, high strength graphites are not as attractive when loaded in other than tension, any improvement in properties over the metallic materials must be gained by loading them only in tension. These limitations make the design of an all-organic matrix structure very difficult and lead to the alternative of incorporating them into a hybrid design with metallic elements.

Table 5-1. Candidate Sting Materials

Material	E (Msi)	F(tu) (ksi)	CTE (in/in/F)	Advantages	Risks
T-40/Epoxy	25	470	-0.5	Very high strength and modulus. Failure is usually slow, progression not castastrophic. Very low CTE. Not size limited.	Attachment to other materials somewhat difficult. Cryogenic properties not characterized. (CTE < 0)
T-50/Epoxy	35	205	-0.54		
P-75 Epoxy	49	140	-0.97		
P-100/Epoxy	72	180	-1.15		

5.3 STRUCTURAL ANALYSIS

The advanced composite material systems considered for this study consisted primarily of ultra-high modulus graphite fibers in a resin matrix. A survey of the available fiber and matrix materials currently available indicated that this combination would be the only one that could achieve substantial improvements in the sting stiffness properties. Alternative fiber systems such as Kevlar, aluminum oxide, and silicon carbide do not offer the same range of moduli available in the graphite fibers. Alternative matrix materials such as thermoplastics and metals are limited in the fiber volume content that can be achieved. Typically, material systems using these improved matrices are limited to 50% fiber volume compared to the 65% available with epoxy matrices. For the high modulus requirements needed for this application, any improvement achieved by these higher modulus matrices is more than offset by the reduced fiber volume.

In comparing the properties of candidate composite material systems, an approach similar to that used for the high performance metallic materials was adopted. Comparison charts of the strength and stiffness of available materials were created for several levels of each material. These consisted of fiber properties, unidirectional laminate properties, and cross plied laminate properties. The fiber properties represent the theoretical limits achievable with these materials. The cross plied laminate properties reflect the reduced properties required to create a practical design.

5.3.1 FIBER PROPERTIES. A comparison of the strength and stiffness properties of fibers currently available or under development is shown in Figure 5-1. This data represents the results of tensile testing done on individual fibers and was obtained from vendor data sheets.

5.3.2 UNIDIRECTIONAL LAMINATE PROPERTIES. A comparison of the strength and stiffness properties of unidirectional laminates is shown in Figure 5-2. This data was obtained from vendor data sheets and from limited test programs conducted by General Dynamics Space Systems Division. As such, these results tend to represent upper bounds for the properties available for production parts.

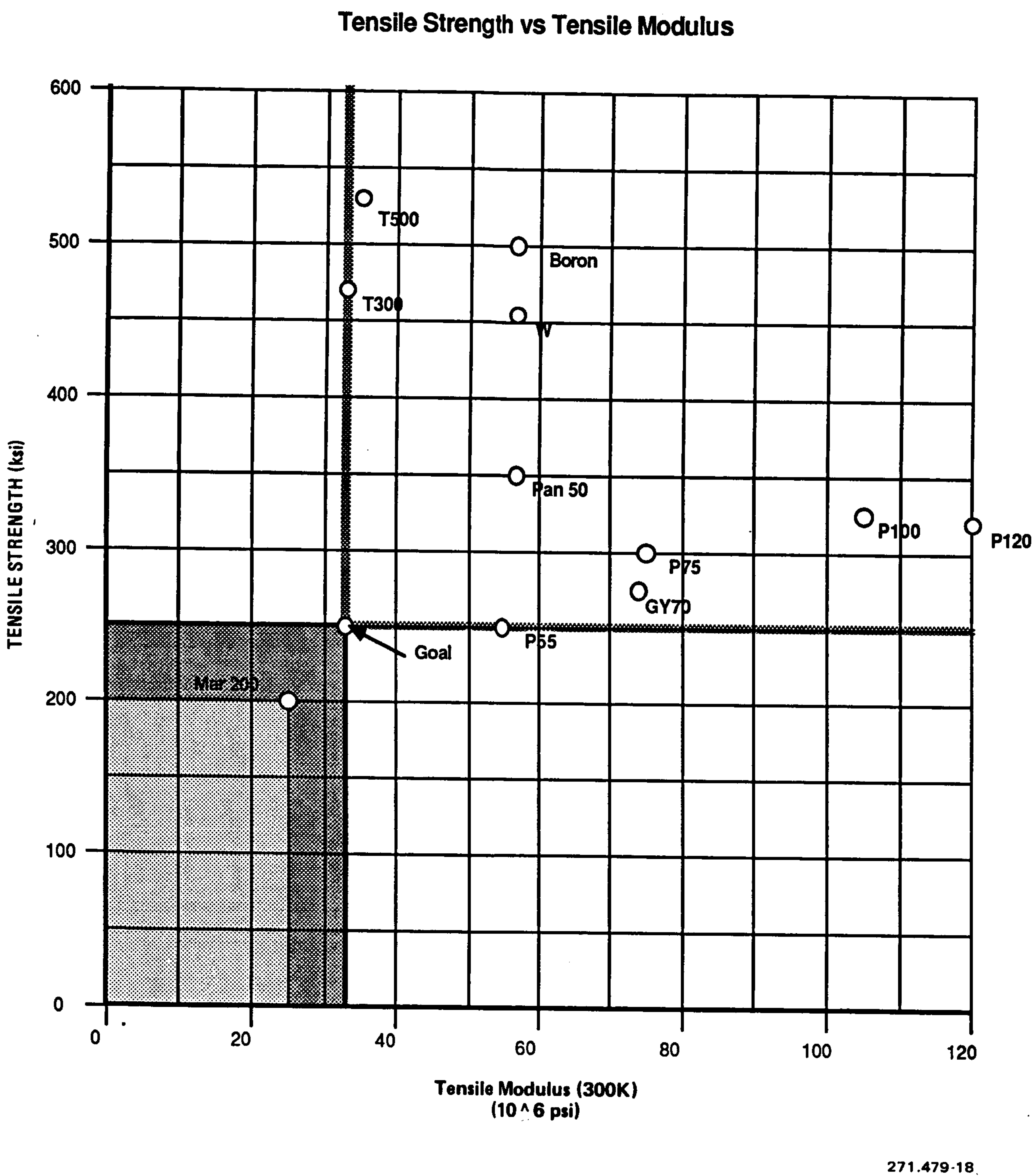


Figure 5-1. Comparison of Composite Fiber Properties

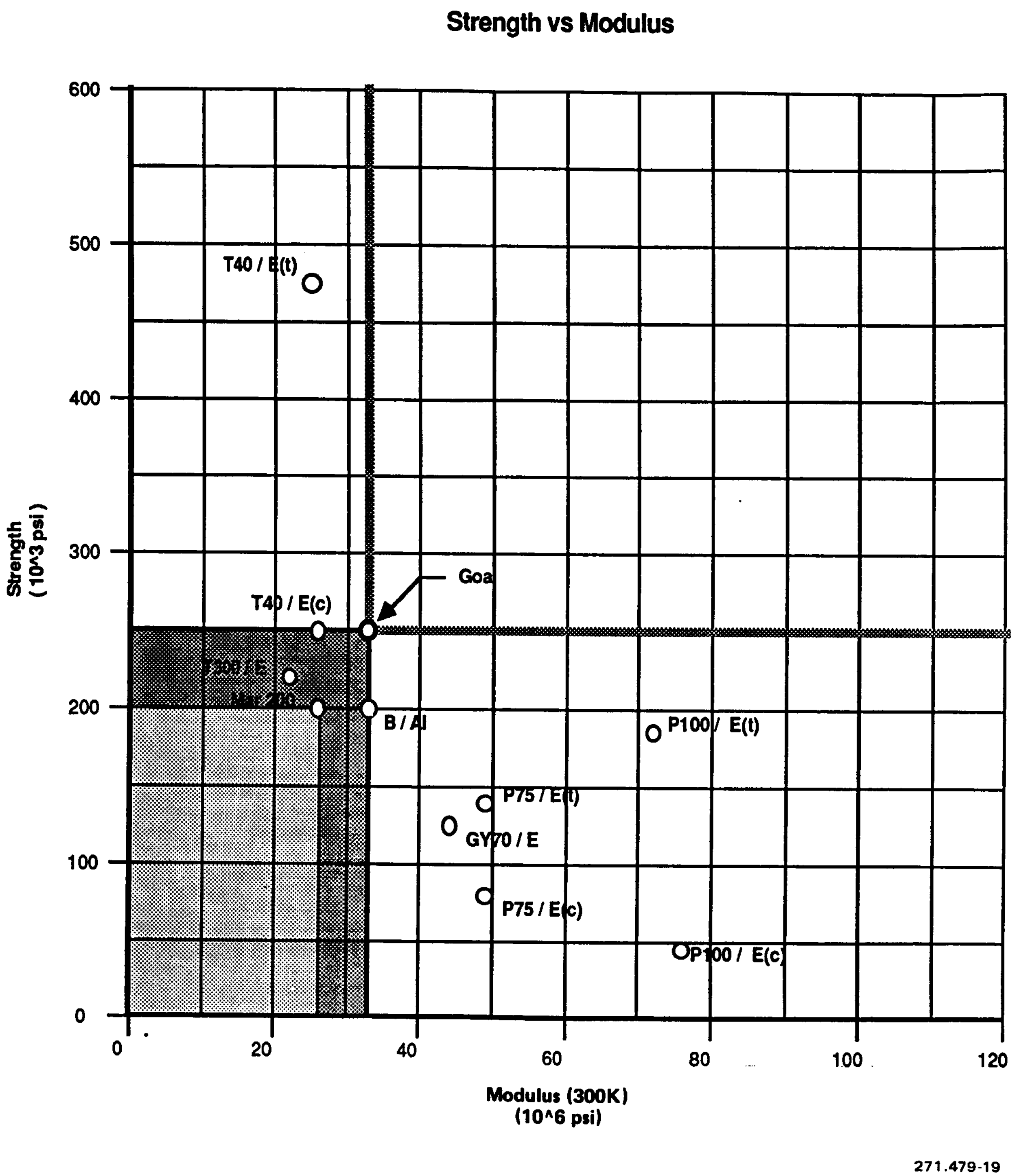


Figure 5-2. Comparison of Composite Unidirectional Laminate Properties

There are two factors to note when comparing this chart to the one for fiber properties. The first is that there is no longer any one system that achieves both improved strength and stiffness properties compared to the existing sting. The second is that the compressive strengths of these materials are substantially less than their tensile strengths. This is especially notable for the ultra-high modulus materials that have only a limited tensile strength to begin with. For these materials, the compressive strength is only one-third to one-half of the tensile strength. This data was confirmed by testing done for an unrelated program and represents a definite limitation on the application of these materials.

5.3.3 CROSS PLIED LAMINATE PROPERTIES. The strength and stiffness properties of cross plied laminates using several material systems were calculated using the General Dynamics standard laminated plate analysis program SQ5. The results for the longitudinal properties of a high strength system, T40/Epoxy, and high modulus system, P100/Epoxy, are shown in Figures 5-3 and 5-4. Figure 5-3 shows the tensile strength versus tensile modulus for a range of laminates for each material. Figure 5-4 shows the tensile strains to failure versus tensile modulus for these materials. The data in Figure 5-4 is useful in comparing hybrid configurations made from several material systems where the strain across the cross section remains linear while the stress distribution becomes a function of the moduli of the materials. It is important to note that the strength values apply to tensile stresses only. The compressive strength values would be less than half of these values for P100/Epoxy system.

5.4 RELATIONSHIP BETWEEN TENSION/SHEAR STRENGTH FOR A HIGH MODULUS ADVANCED COMPOSITE SYSTEM

To meet the stringent requirements of space hardware, ordnance, electronics and other high modulus applications, manufacturers have developed a new family of prepregs. These Advanced Composite System[7] high modulus prepregs combine state-of-the-art carbon fibers with a new proprietary, toughened epoxy, 350F cure resin. These systems offer, for the first time, an integrated material system designed specifically for the demanding environment of space, and feature microcrack resistance, thermal stability, and mechanical properties needed for advanced composite applications for many aerospace research and development applications. As can be seen in Table 5-2, the shear strength is considerably less than the tensile strength.

5.5 COMPOSITE STING DESIGN

Further research into design/fabrication concepts for advanced composite stings was discontinued based upon the structural/material analysis, particularly the lack of compressive strength. A considerable amount of development work is continuing in the advanced composite field, and this may help us in the future. For the present, however, other opportunities for a high performance sting look more promising.

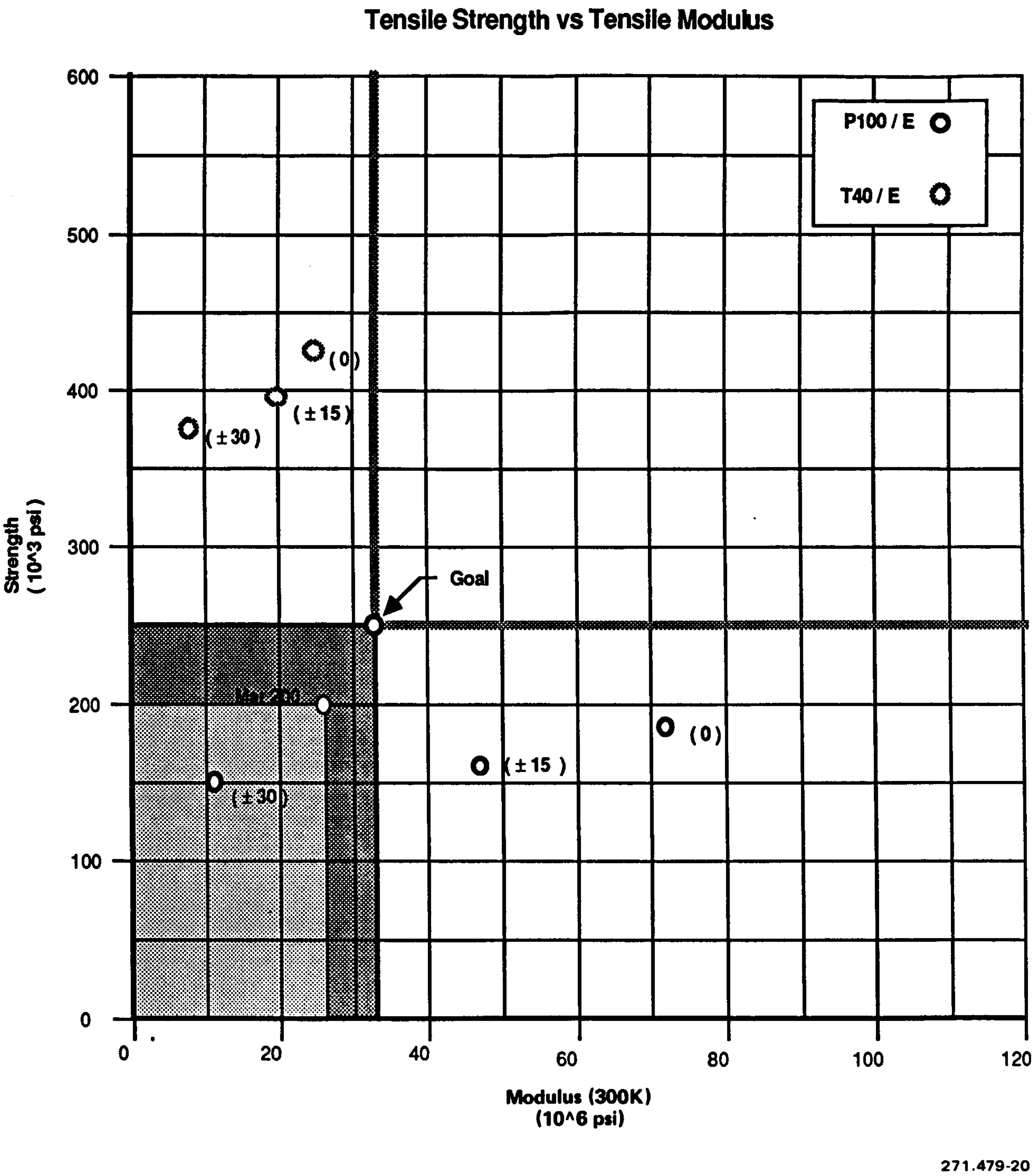


Figure 5-3. Comparison of Composite Cross Plied Laminate Properties

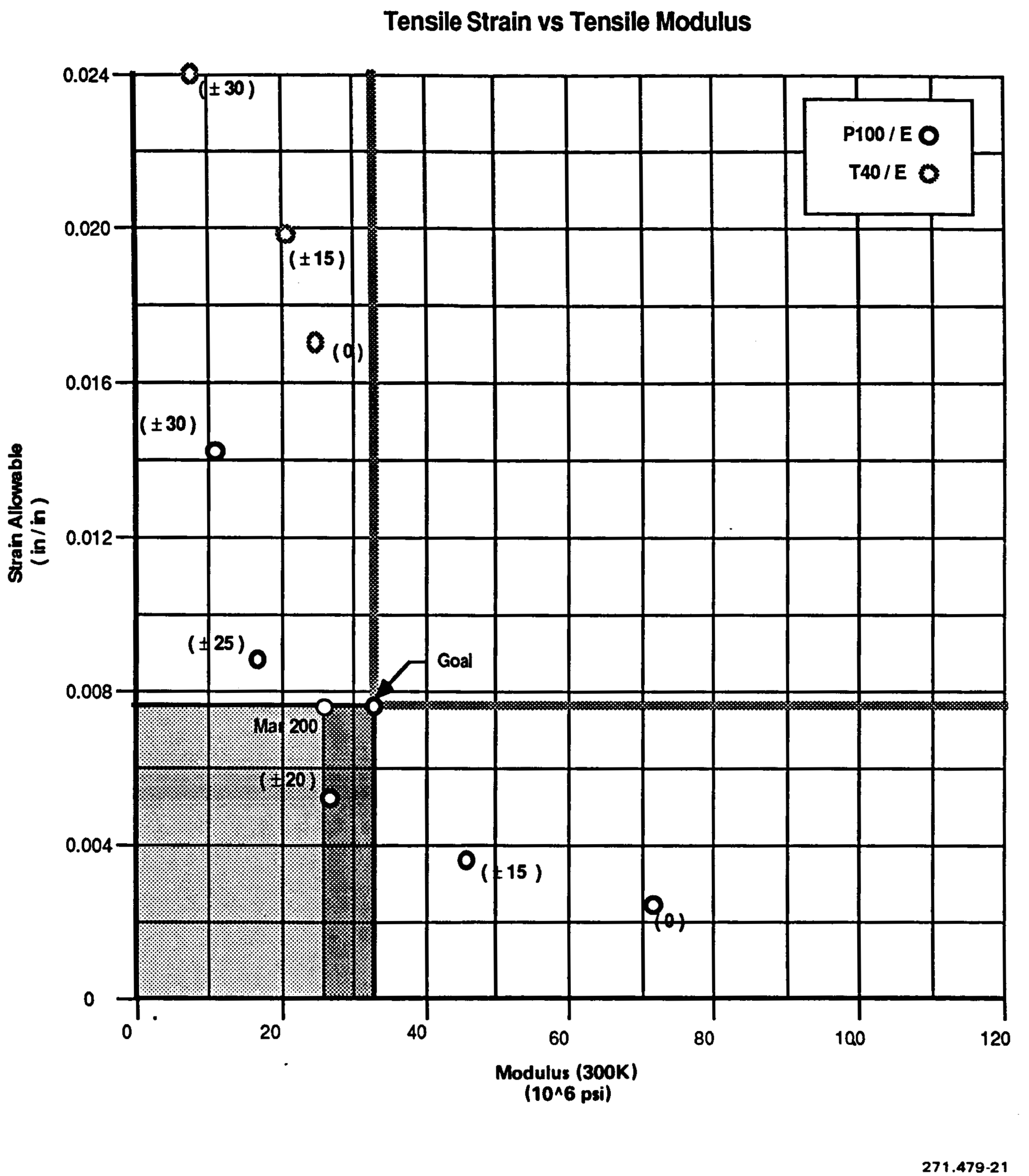


Figure 5-4. Comparison of Composite Cross Plied Laminate Properties

Table 5-2. Typical Composite Properties

Property	P-55	Pitch Fiber P-75	Composites† P-100
Longitudinal Tension (ASTM D-3039)			
Strength (ksi)	135	140	180
Strain (%)	0.38	0.28	0.24
Modulus (Msi)††	35	49	72
Poisson's Ratio	0.34	0.30	0.31
Longitudinal Compression (ASTM D-3410)			
Strength (ksi)	74	64	42
Modulus (Msi)	29	46	76
Coefficient of Thermal Expansion* (10^{-6}/deg C)			
Longitudinal	-0.76	-0.97	-1.15
Transverse	30	30	31

†ERL-1962 prepreg resin. Longitudinal properties normalized to 62 volume percent fiber.

††Measured between 0.1 and 0.2% strain.

*Measure over the range 30 to 100 C.

SECTION 6

HYBRID METAL/COMPOSITE COMBINATIONS

6.1 GENERAL INFORMATION

In a previous wind tunnel model study[1] by General Dynamics the limitation of the sting was recognized and a section describing an "ideal" sting was included: excerpts from that section follow as they form the basis for the research into the feasibility of a hybrid sting.

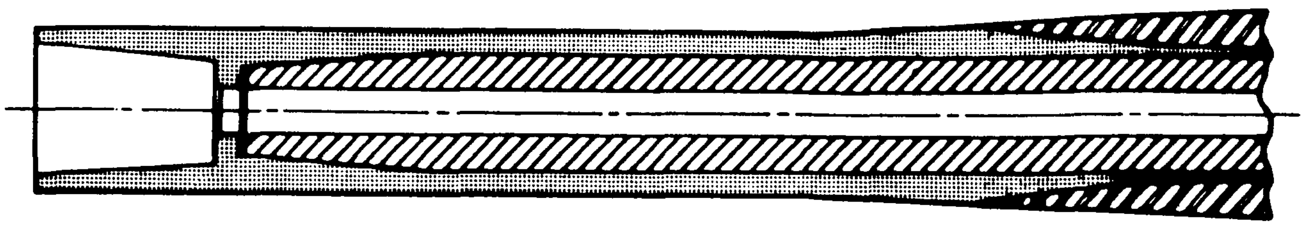
"The primary objective of this section of the study is to identify advanced materials, or combinations of materials, that will provide increased strength and stiffness properties at cryogenic temperatures. Weight is also a key factor; the steel sting is approximately 500 pounds, creating obvious handling problems. From this point of view, composites would appear to be very attractive.

"During the materials research, it was quickly discovered that very little information is available on material properties at the cryogenic temperatures of the NTF. Furthermore, much of the available information is for small billets, and for composite materials for thins sections. For example, considerable research has been done in the aerospace industry on the use of composite materials for space applications at low temperature. High strength boron/aluminum tubes and various graphite epoxies have been developed; in space applications, however, the thrust has been to develop high strength/weight ratios, and therefore the materials are relatively thinwalled. In sting applications, the material thickness is much greater, resulting in questionable material properties, and much higher manufacturing costs.

"One material possessing interesting properties in Kennametal K9, a tungsten alloy with a stiffness three times that of steel. Again, very little information is available for this material at cryogenic temperatures. Kennametal, Inc., conducted a study of the feasibility of using Kennametal K9 as a sting material. The study revealed that the strength and stiffness of K9 was considerably less than the published values when applied to the physical size of material required to manufacture the sting. The properties had been developed from relatively small test samples, and the manufacturer, while initially optimistic, later determined that the desired characteristics of K9 would be degraded to an unacceptable level for an item with the physical size of an NTF sting. Our research also showed that there would be manufacturing problems associated with producing a K9 sting suitable for the NTF. Degradation of material properties due to size was, however, the key factor in determining the unsuitability of Kennametal K9.

"As an alternative to a sting manufactured completely of Kennametal K9, our study turned to the use of Kennametal K9 with its desirable stiffness properties combined with other high strength materials. A K9 outer shell and an A286 inner core was investigated, but again the K9 shell was found to be so large that properties were questionable and manufacture a problem. Using the K9 as an inner core rather than an outer shell was also considered.

"General Dynamics then investigated the use of a high grade steel such as 18 Ni-200, or Kennametal K9, with advanced composites such as boron/aluminum, or graphite epoxies. Finally a combination of Kennametal K9, boron/aluminum, and 18 Ni-200 steel was considered. A common problem (for all these sting designs using dissimilar materials) is that of coefficient of expansion, and the resulting thermal stresses. Figure 6-1 provides a comparison of properties and coefficients and shows a schematic of an "ideal" sting, combining the best available materials. In design, however, it was found that the stiff Kennametal K9 (modulus of elasticity = 90 x 10^6) became too highly stressed, due to picking up too high a proportion of the total load applied to the sting. The very stiff materials tend to have lower ultimate stress values and cannot achieve an acceptable safety factor. For this reason, the stiffness of K9 is unacceptably high when used in a composite sting with other materials of less stiffness. As shown in Figure 6-1, a material with E = 45 x 10^6 is required."



MATERIAL	Fty (ksi)		E (msi)		α = (IN./IN./F) (10^{-6})	
	RT	140 DEG R	RT	140 DEG R	RT	140 DEG R
18Ni-200	208	270	26.2		5.6	
KENNAMETAL K9®	100		94		2.0	
BORON/ALUMINUM	208*	(DIFFICULT TO OBTAIN)	32.2*		1.2 L 5.0 T	
"IDEAL"	160		45		5.0	

*BASED UPON MATERIAL THICKNESS OF 0.080 INCH MAXIMUM.

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Figure 6-1. "Ideal" Composite Sting Support

As pointed out in an earlier section, the search for suitable sting materials is complicated by the need for both high strength and high stiffness plus reasonable cryogenic toughness in one single material. Recognizing that this is a difficult design problem, a reevaluation of the hybrid concept was initiated. The objective was to use the combination of high modulus materials in critical areas, with a high strength/toughness core. The great advantage of this approach is that a large variety of materials might be used for stiffeners because of the safety margin provided by the strong and tough core material. If the high stiffness material should fail, it would not necessarily be catastrophic to overall sting structure. In other words, a fail-safe sting feature is possible.

6.2 HYBRID MATERIAL SYSTEMS USING KENNAMETAL

Hybrid sting configurations incorporating a rectangular cross section have the potential of placing more of the high modulus material where it will be most effective at a location remote from the neutral axis. Potential concepts incorporating metal/metal and metal/composite hybrids were investigated to determine the effects on the sting performance.

A rectangular cross section sting configuration incorporating reinforcing strips of ultra high modulus Kennametal was examined to determine its bending strength and stiffness properties. The geometry considered is shown in Figure 6-2. The analysis approach was similar to that used with the circular metal/composite configuration with appropriate modifications used for generating section properties in the transition from a circular to a square section. These formulas were incorporated into a spreadsheet format to allow trade studies to be performed quickly and reliably. The variables considered were the depth the outside edge of the sting to the start of the Kennametal strip and the thickness of the Kennametal strip. The material properties from Table 6-1 were used and the results are summarized in Figure 6-3.

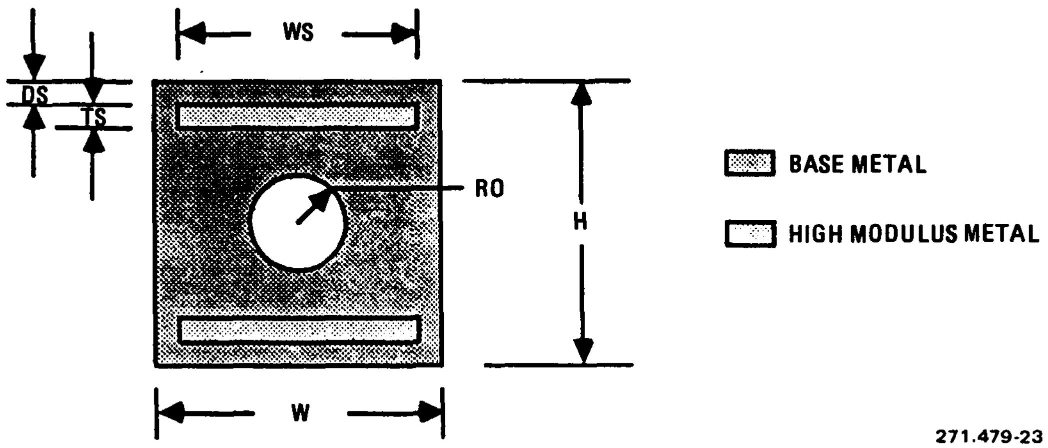

Figure 6-2. Cross Section Geometry for Metal/Metal Hybrid Sting

Table 6-1. Material Properties for Hybrid Sting Configurations

Material	Longitudinal Modulus (psi)	Longitudinal Strain Allowable (in/in)
18 Ni-200	26,200,000	0.007634
MP35N	34,500,000	0.007634
Kennametal	80,000,000	0.001875
T40/Epoxy*	20,000,000	0.017010
T50/Epoxy*	30,000,000	0.006440
P100/Epoxy*	40,000,000	0.003510

*Values for (±15) Laminate

The results in Figure 6-3 again show the tradeoff between strength and stiffness properties. While some very attractive improvements in stiffness are available, they are all accompanied by reduced strength values.

6.3 18 Ni-200/WHISKER REINFORCEMENT

The use of single crystal reinforcing whiskers in a matrix of 18 Ni-200 steel could provide a substantial increase in material properties. In a study[8], SiC whiskers were added during powder metallurgical fabrication of three aluminum alloys. Depending on fiber contents, tensile strength increased up to 60% and the elastic modulus increased to 100%. Fibers of SiC, graphite, and aluminum oxide have been used successfully in both aluminum and nickel base alloys in other studies[9,10]. The proposed approach would attempt to incorporate the composite whiskers during powder metallurgical fabrication of 18 Ni-200. Although sample fabrication and actual testing would be required to determine the feasibility of this approach, the use of powder metallurgy techniques in other margin alloys has been successful, and documented by German and Smugersty[11].

The major difficulties to be overcome with this approach involve whisker-to-matrix adhesion and a loss of toughness in the material. To properly utilize the properties of the whiskers, the matrix and whiskers must not separate under loads. Also, while tensile properties and elastic modulus increase with increasing whisker content, there is also a corresponding decrease in toughness and ductility. Careful experimentation will be required to determine the optimal compromise in properties.

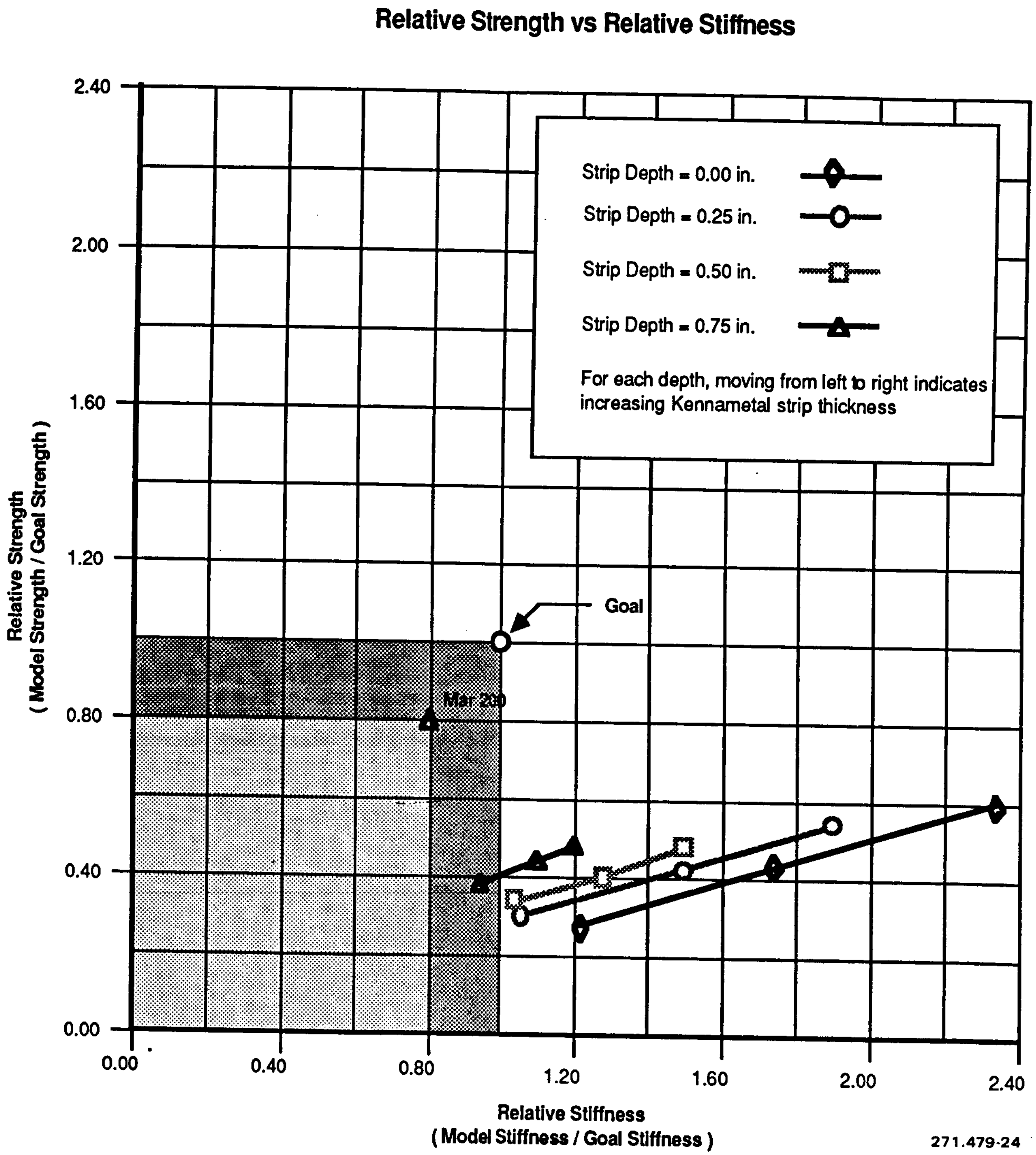

Figure 6-3. Comparison of Hybrid Metal/Metal Stings with Baseline Model Properties

Current examples of material systems that have taken this approach to increasing stiffness are the graphite/epoxies, boron/aluminums, and carbon/carbon composites. Theoretically, the stiffness of these composites should follow a law of mixtures relationship as follows:

$$E_c = E_f V_f + E_m V_m$$

Using this relationship for example you would need only 15 volume percent of tungsten filaments to increase the stiffness of 18 Ni-200 from 27 Msi to 32 Msi, a 20% increase in elastic modulus.

6.4 CLADDING

Cladding is the deposition of a layer of one metallic alloy on a substrate of a second alloy. The laser beam is used to melt both a thin layer on the surface of the substrate and the cladding material, which is introduced as a powder, wire, or thin sheet. Thus, when solidification occurs, a layer of cladding material is deposited with a small region of dilution giving a metallurgical bond. A clad component offers the designer flexibility since it permits combining the properties of two alloys. For this study we reviewed the feasibility of adding a cap of high stiffness material to a conventional sting of high strength but relatively low stiffness. Laser cladding produces homogenous microstructures on metal surfaces. By adding metal powders to the beam work surface, a smooth clad layer can be provided in many shapes and thicknesses. The variety of cladding materials available is extensive and post-cladding machining can be accomplished.

Present day examples of cladding are Inconel 625 over mild steel, and stellite over steel. Inconel 625 was clad on steel substrates by introducing a powder into the focused laser beam with motion controlled by robotic workstation. The Inconel overlay showed very little dilution into the base steel. Successful bend tests and dye penetrant tests were achieved. Deposition rates are about twice the rates achieved by conventional processing. Less heat is introduced so that less distortion is measured after processing.

For the sting application we reviewed cladding a tungsten alloy to 18 Ni-200, using the laser beam process. Stellite has been clad to a thickness of 0.25 inch, and it is preferable to do this to a rectangular rather than a round bar. For comparison, therefore, assume:

a. A bar 3 inches deep by 2 inches wide of 18 Ni-200.

b. A bar 2.5 inches deep by 2 inches wide of 18 Ni-200 with .25-inch tungsten caps added top and bottom.

To compare the relative strength/stiffness of section a. and section b., assume values of:

18 Ni-200-
F_{tu} - 200 ksi and $E = 26 \times 10^6$ psi
Tungsten F_{tu} - 100 ksi and $E = 59 \times 106$ psi

The concept is equivalent to the metal/metal hybrids shown in Figures 6-2 and 6-3. In Figure 6-3 the strip depth would be 0.00 inch. As stated, as you move from left to right the Kennametal thickness is increasing, with the result that increasing stiffness is accompanied by decreased strength.

It should be recognized that cladding a metallic alloy on a second alloy will require some development work, and that all alloys are not suitable for cladding.

6.5 KENNAMETAL STING

Kennametal is a sintered tungsten-carbide material. It has a high modulus of elasticity, moderate strength, but a low Cvn impact resistance.

In relation to this study, Kennametal's high modulus (94 Msi) is its primary asset, while its low Cvn impact strength (Cvn toughness) is perhaps its primary liability.

Previous study work discounted Kennametal as possible sting material largely on its low Cvn value. Since the completion of that study[1], a further review of the material, its properties, and vendor advances in its production, was made. Recent research indicated that certain grades of the material have been used in cryogenic applications as ultra high-stiffness tooling bars.

Kennametal Grade K9 is a possible candidate sting material; its major proper ties are: 1) strength; tensile 146 ksi, compression 590 ksi, 2) coefficient of thermal expansion, 2.0×10^{-6} in/in/deg F, 3) modulus, 83.5×10^{6} psi.

In reviewing the above data, it can be seen that the Cvn impact continues to be the restricting property of the material. However, Kennametal Incorporated indicates that their manufacturing processes are being further developed continually and therefore some improvement in this area may be feasible.

In addition to the limited Cvn impact strength, there are two areas in the manufacturing processes that do not presently meet requirements. Currently, lengths of 2 to 3 feet are the maximum length available of the desired diameter of 1-1/2 to 2 inches. However, at larger diameters (3 to 4 inches), it may be feasible to sinter 4-foot length.

Conceptually, it appears that using Kennametal as a stiffener joined to a conventional material is perhaps a more viable alternative to the single homogeneous Kennametal concept presented above. This concept has the problem of matching stiffnesses to effect an optimum system stiffness that meets the design requirements. There is also the problem of joining the Kennametal to the parent material. There are three techniques that may be considered: oven brazing, adhesive bonding, and mechanical fastening. These will be further discussed in Section 6.9.

6.6 INTERMITTENT STIFFENERS

The coefficient of thermal expansion (CTE) problem associated with the use of dissimilar materials is recognized. The use of intermittent stiffeners of high modulus was considered as a possible answer to the problem. As shown in Figure 6-4, intermittent parallel stiffeners are used to ensure added stiffness, with the breaks staggered so that one stiffener is always working. The CTE problem is minimized by using shorter stiffeners.

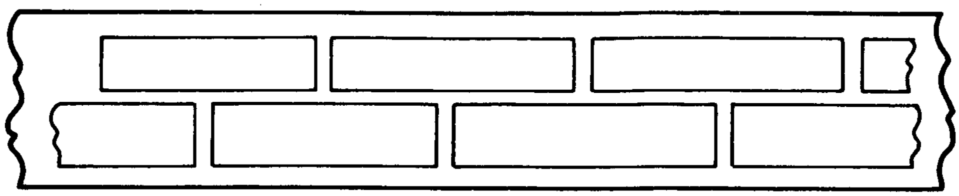

Figure 6-4. Sting (18 Ni-200) with Intermittent Stiffeners (Kennametal)

In this concept the primary sting is 18 Ni-200, and the stiffeners Kennametal. The assembly would be brazed and the final operation would be to age the 18 Ni-200 at 1000F.

This concept is feasible and the smaller sections of Kennametal are readily available. The stiffeners would be used on the compressive side only for the maximum effect. The concept was not pursued further because other concepts promise a more significant increase in stiffness.

6.7 METAL/COMPOSITE HYBRIDS

A configuration consisting of a metal core wrapped with layers of high strength and high modulus fibers was evaluated to compare its strength and stiffness capabilities with those representing the desired improved sting configuration. The geometry of this concept is shown in Figure 6-5.

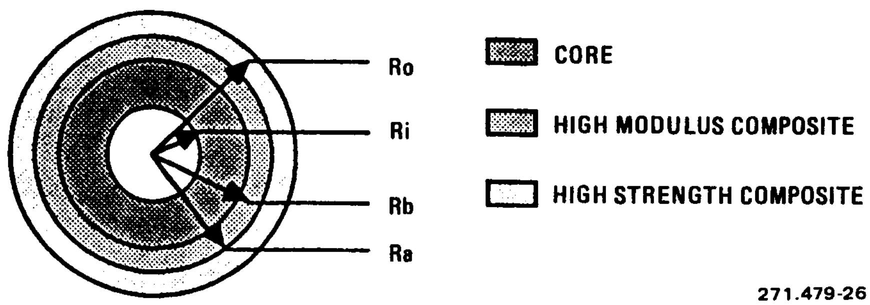

Figure 6-5. Cross Section Geometry for the Metal/Composite Hybrid Sting

This concept offered the following advantages:

a. The metal core could be used to carry the shear and transverse load acting on the sting, allowing the composite materials to be highly oriented in the axial direction.

b. The high strength composite could be used as the outer layer, where it would be capable of carrying the higher strains resulting at that location.

c. The high modulus composite could be placed at an intermediate location, where it would be more isolated from high strain levels.

d. The composite materials are relatively insensitive to fatigue damage, and when damage does occur it results in a gradual degradation in strength and stiffness properties rather than the sudden, catastrophic failure that is associated with thick, high strength metallic materials.

e. The failure modes of the composite and metallic materials are uncoupled. A crack staring in the composite material is unlikely to propagate across the boundary into the metal core.

The disadvantages associated with this concept are:

a. The mismatch in the CTE for the different materials. The composites considered for this application would have CTEs of approximately -1.00×10^{-6} in/in/deg F while the metal would have a CTE of approximately 5.00×10^{-6} in/in/deg F.

b. Under the thermal cycling experienced by the sting, the long term reliability of the bond between the metal and composite is suspect and would have to be established through more detailed analysis than was possible during this initial investigation and would have to be demonstrated through testing.

c. The compressive strength of the high modulus composite material is questionable.

d. Stiffness can be achieved, but with significant loss of strength.

These disadvantages are discussed in detail in the following analysis.

The analysis approach taken to establish the performance of metal/composite hybrid configurations was to calculate the strength and stiffness properties of a cross section at the aft end of the sting and compare those results with the values for the baseline and improved sting configurations calculated earlier.

The critical values were assumed to be the bending stiffness at this section represented by the EI term and the bending strength as determined by the maximum bending moment capable of being carried by the section. The bending stiffness properties for an axisymmetric cross section are determined as follows:

$$EI_{total} = \sum EI_{individual\ segments}$$

where

$$EI_{individual\ segment} = (E)\ (\pi/4)\ (R_o'^4 - R_i'^4)$$

E = Modulus of material

R_o' = Outer radius for a given segment

R_i' = Inner radius for a given segment

The strength calculations involved determining the maximum bending moment capable of being carried by the improved sting configuration and applying this load to the hybrid configuration. The ratio of the maximum strain in each layer created by this load compared to the maximum allowable strain for each layer was then calculated, and the layer with the minimum value for this ratio determined the strength of the sting. The calculations required are as follows:

Maximum Bending Moment

$$M_{max\ improved\ sting} = Ftu\ I/c$$

Ftu = 250,000 psi

$I = (\pi/4)\ (2.00^4 - 0.50^4) = 12.51728\ in^4$

c = 2.00 in

$$M_{max\ improved\ sting} = 1{,}564{,}662\ in\text{-}lb$$

Internal Strains in Hybrid Cross Section

$$\epsilon_{max} = Mc/EI$$

c = Distance from outer fiber of each layer to neutral axis

M, EI from above

These formulas were incorporated into a computerized spreadsheet format that allowed for a rapid evaluation of numerous potential variations in material properties and layer thicknesses. The material properties considered for this study are summarized in Table 6-1. The effects of the thickness of the composite layers was determined by establishing a total thickness of either 0.50 inch or 1.00 inch for all of the composite material and varying the ratio of the thickness of the high strength composite to the high modulus composite within that total thickness. The results of these calculations were plotted on a chart showing the relative strength and stiffness of each concept as shown in Figure 6-6. On this chart a value of 0.80 represents the current sting configuration while a value of 1.00 represents the desired 25% improvement in strength and stiffness properties.

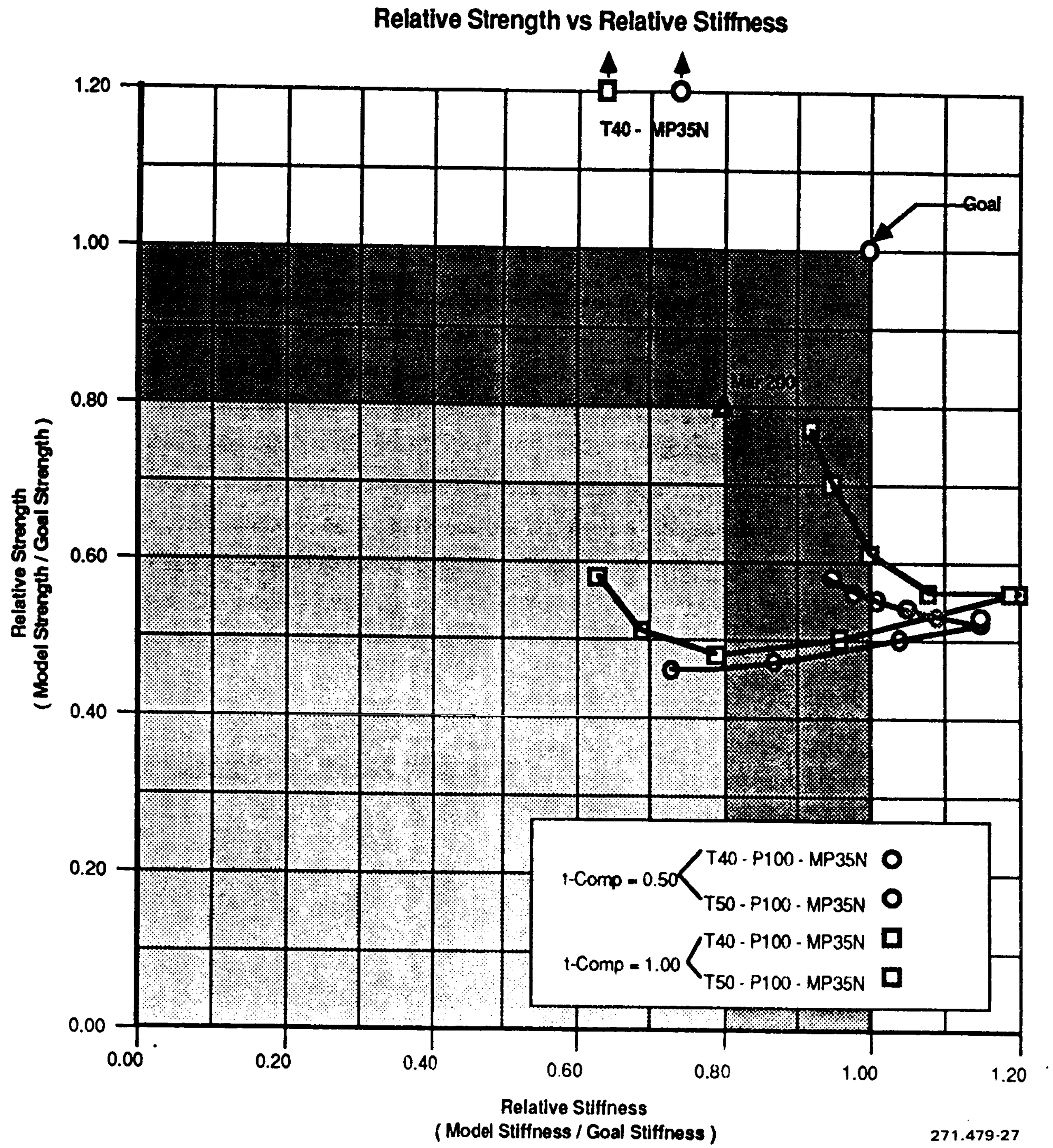

Figure 6-6. Comparison of Hybrid Metal/Composite Stings with Baseline Model Properties

The most notable result shown in Figure 6-6 is the tradeoff in stiffness and strength properties. To achieve the stiffness values desired, significant losses in strength are incurred. One factor that is not accounted for in the data shown is the difference between the tensile and compressive strengths of the composite materials. When these calculations were initially performed, reliable data on the compressive strengths of the high modulus composites was not available. As a result, only the tensile strengths were considered in generating the results. If the actual compressive strengths were considered, the relative strength values for these configurations would be less than half of those shown on this chart. When the data became available indicating that the compressive performance of these materials was poor, the concept was discarded from further consideration. The results are included for the sake of completeness and to show general trends in the behavior of this type of configuration if more acceptable materials become available.

Recognizing the problem of the difference in CTE between the two materials, and the reliability of the bond at cryogenic temperatures, it was decided to investigate the feasibility of heating the bond line. The objective was to maintain the bond line at -100 to 0F, as this condition would allow the use of a number of high quality adhesives. Controlling the temperature at the bond line causes a gradient across the composite material (possibly 0 to -300F), and possible thermal stress problems. This should not be a significant problem because of the low CTE (-1.00×10^{-6} in/in/deg F).

6.8 SUMMARY OF THERMAL ANALYSIS

A thermal analysis of a cryogenic wind tunnel cylindrical sting has been completed. The proposed sting consists of a hollow metal core cylinder wrapped with graphite epoxy as shown in Figure 6-7. During a wind tunnel test the sting is subjected to operational temperature as low as -300F with resulting high heat transfer coefficients, thereby inducing thermal stresses.

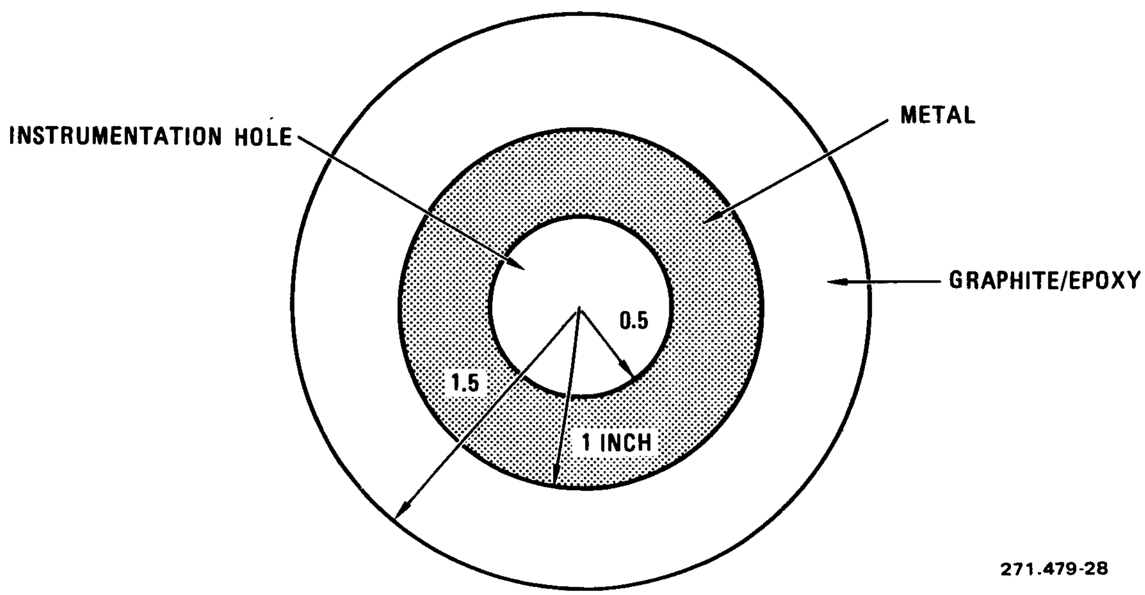

Figure 6-7. Cryogenic Wind Tunnel Advanced Sting Cross Section

The objectives of this analysis were to:

a. Determine the worst case temperature gradients. These gradients will be use to perform radial and axial thermal-stress analyses.

b. Determine the heater sizing requirements to keep the metal core at 0 or -100F.

Analysis results show that:

a. The temperature of the epoxy will drop quickly as assumed at the beginning with a maximum temperature between the metal and the epoxy of 130F. The metal temperature then decreases until the whole sting reaches the equilibrium temperature of -300F after about 15 minutes.

b. To maintain the core temperature at -100F a heater power of 6632 Btu/hour (1944 watts) is required (no safety factor). (26 watts/sq in)*

c. To maintain the core at 0F the heater power must increase by 70% to 11,290 Btu/hour (3310 watts) (no safety factor). (44 watts/sq in)*

d. The thermal conductivity of the epoxy is available only at two or three temperatures in the range of interest. Since the heater power is proportional to the thermal conductivity, it is recommended that a factor of safety of 2 be employed to size the heater; doubling the above numbers.

e. It is important to assure good contact between the heater and the sting to avoid burning the heater.

6.8.1 DISCUSSION. Two analytical models were employed. A transient model provided the temperature distribution and gradients versus time. A steady-state model was used to size the heater required to keep the metallic core temperature at a fixed value of -100F or 0F. In both models it was conservatively assumed that the surface temperature of the epoxy would equal the nitrogen gas temperature of -300F.

6.8.1.1 Transient Analysis. The sting thermal model shown in Figure 6-8 consists of 10 metal nodes and 10 epoxy nodes. Node 20 is connected to surface node 3001, which is kept at a fixed temperature of -300F. The computer program QMAG** was used to perform this analysis.

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*Includes a safety factor of 2.

**The input data file for the sting QMAG Model is the DECK called STING of the program library ZRECI in SD9EAI catalog.

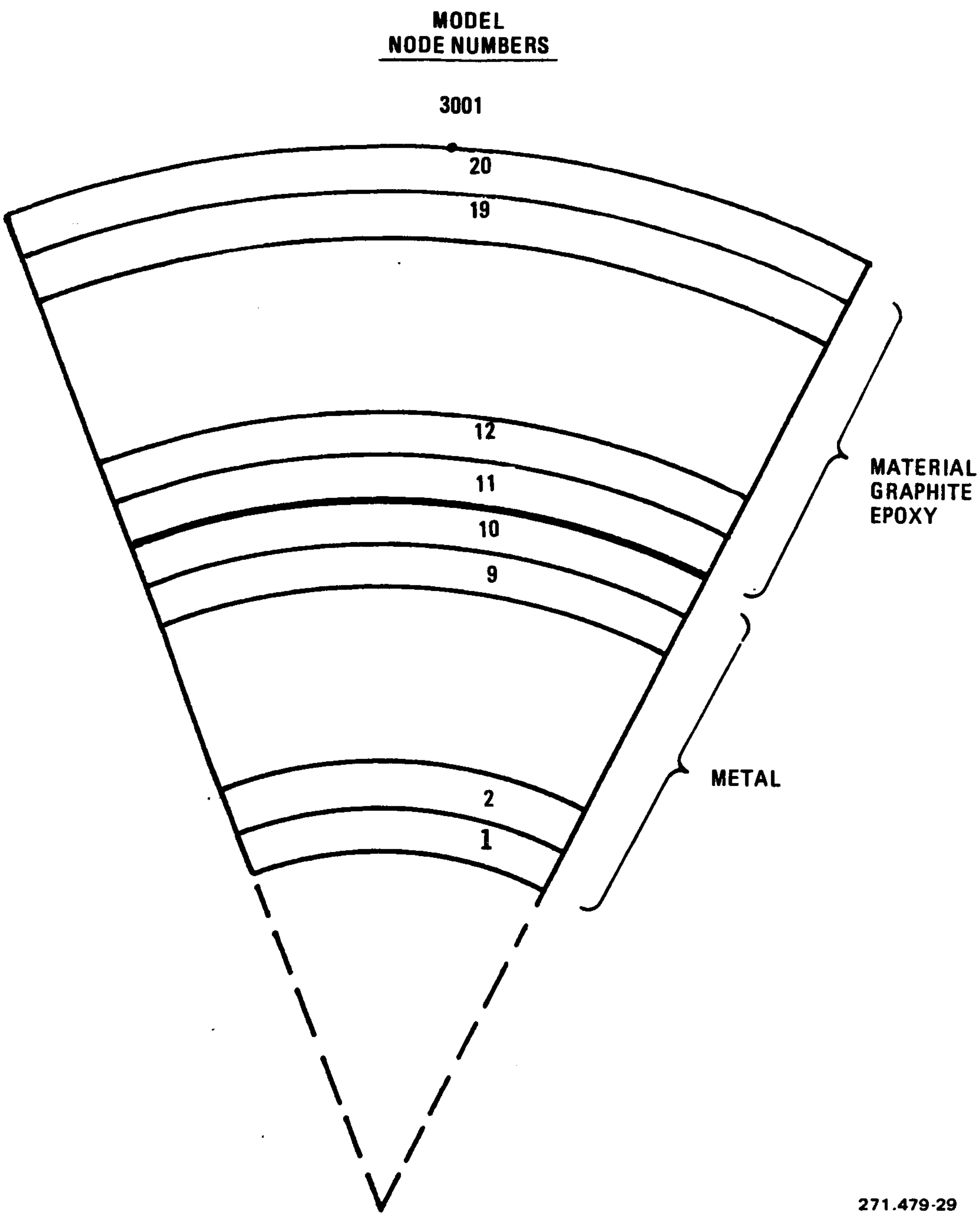

Figure 6-8. Cryogenic Wind Tunnel Advanced Sting Thermal Conduction Model Segment

Analysis results plotted in Figure 6-9 show node temperature versus distance from the center of the sting as (shown as node number) and time. Figure 6-10 shows the average temperature of the epoxy alone, the metal average temperature, and the combined average temperature. Notice that the average temperature of each material is weighted by its heat capacity, i.e.,

$$T = \sum_i m_i \, Cp_i \, T_i / \sum m_i / \sum m_i \, Cp_i$$

where m_i, Cp_i, and T_i are the mass, specific heat, and temperature of node i of specific material. Figure 6-10 also shows the difference between the graphite and metal average temperatures. This temperature difference reaches a maximum value of 130F after 30 seconds.

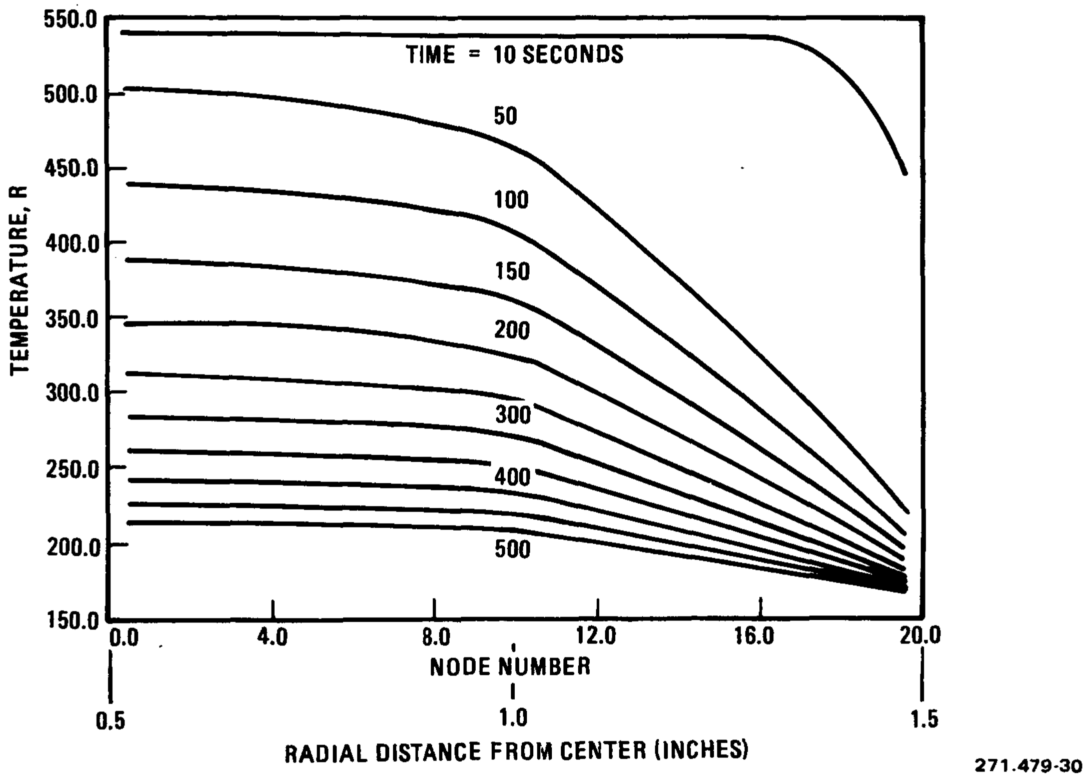

Figure 6-9. Cryogenic Wind Tunnel Advanced Sting Temperature Distribution Versus Node Number and Time

6.8.1.2 <u>Heater Sizing Steady-State Model</u>. The heat input required to maintain the metal core at a fixed temperature was determined using a computer steady-state model and an analytical solution. Both approaches were used with good agreement between the two results.

To maintain the surface between the metal core and the graphite epoxy at a fixed temperature T_h, the heater must provide the conduction heat flow between T_h and the colder surface temperature T_c.

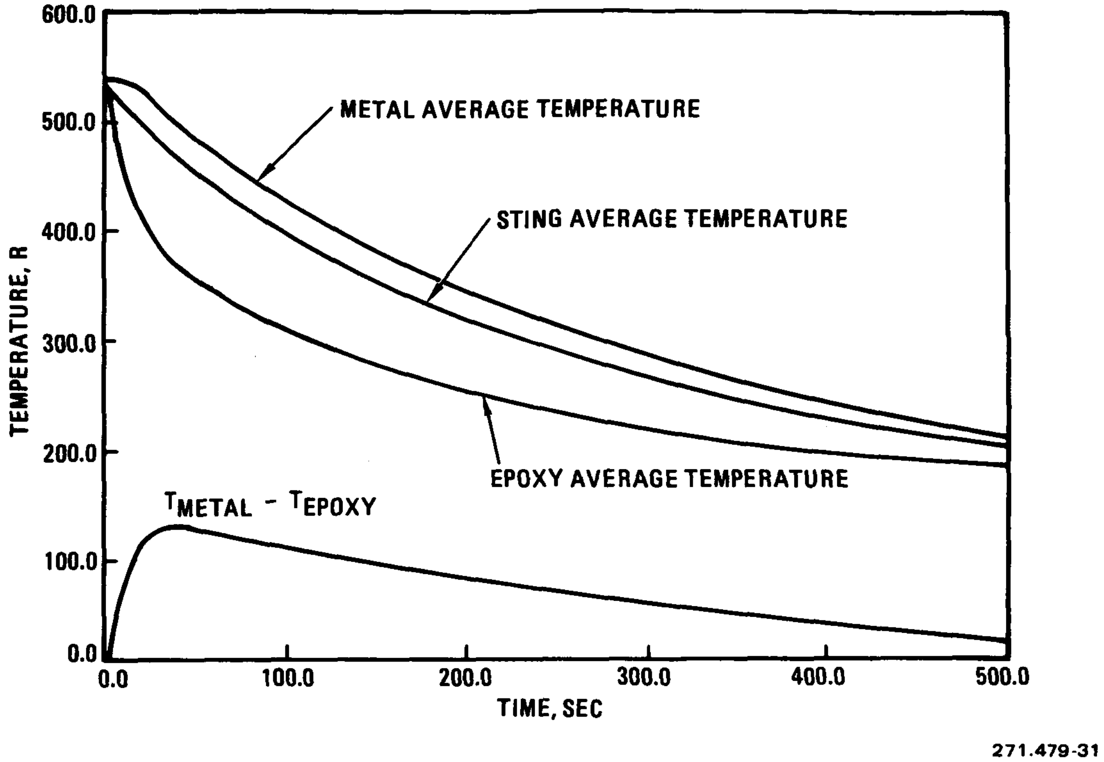

Figure 6-10. Cryogenic Wind Tunnel Advanced Sting Temperatures Versus Time

From Figure 6-11:

$$Q = -2\pi r \ell k(T)\ dT/dr \qquad (1)$$

where Q is the heat conduction, r is the radius, ℓ is the sting length, and k is the thermal conductivity of the epoxy.

From Eq 1

$$Q \int_{r_1}^{r_2} dr/r = -2\pi\ell \int_{T_h}^{T_c} k(T)\ dT \qquad (2)$$

Integrating Eq 2

$$Q = 2\pi\ell \int_{T_c}^{T_h} k(T)\ dT/\ln\ (r_2/r_1) \qquad (3)$$

The thermal conductivity integral for the epoxy between -300 and -100F is 214 Btu/hr-ft, giving a heater requirement of

$$Q = 2\pi \times 2 \times 214/\ln\ (1.5) = 6632\ \text{Btu/hr}$$

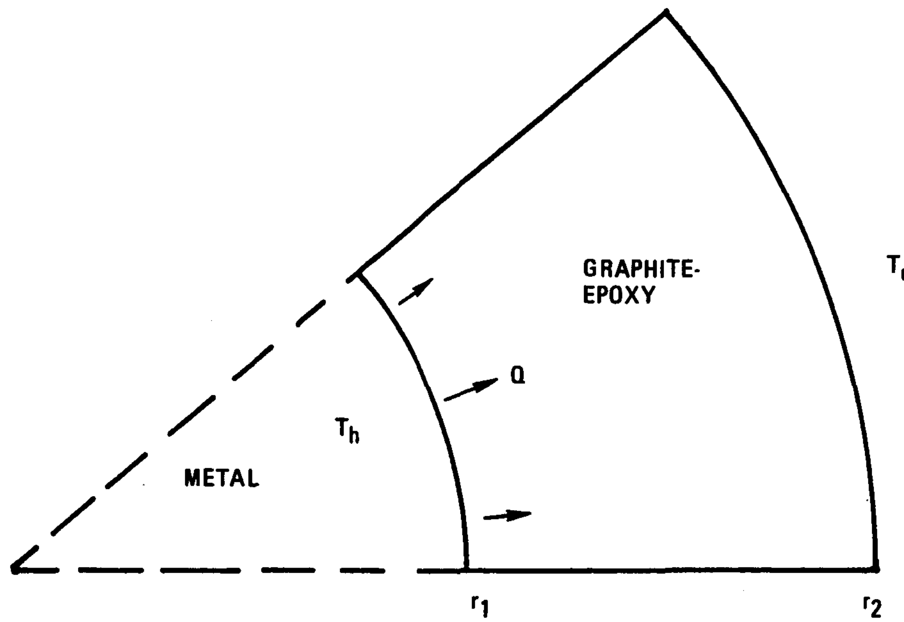

Figure 6-11. Cryogenic Wind Tunnel Advanced Sting Analytical Solution Geometry

A steady-state thermal analysis was also accomplished employing the QMAG program and gave a heater requirement of 6585 Btu/hr, which is less that 1% apart from the analytical result. To keep the metal core at 0F requires a heater power of 11,290 Btu/hr.

Note that the heater load is proportional to the thermal conductivity integral of the graphite epoxy. Since the thermal conductivity is available only at two or three points in the range of interest, the integral was not expected to be of high accuracy. A factor of safety of 2 is suggested in the design of the heater. It is also very important to assure good thermal contact between the heater and the sting to avoid burning the heater. Also note that these results are one-dimensional in nature and do not accommodate heat losses to the model being tested or to the sting support structure. If such losses exist, the result would be increased heater power requirement.

Assuming that the heater covers 50% of the surface to be heated and taking the case of controlling the surface at -100F, the heater would be sized on the basis of 52 watts/sq in, and would be 0.30 inch thick. It would be wound in a spiral around the inside of the graphite epoxy.

6.8.2 METAL/COMPOSITE HYBRIDS. The final configuration considered consisted of a rectangular cross section reinforced with high strength and high modulus composite materials on one side only as shown in Figure 6-12. By selectively reinforcing one side, the sting could be oriented so that the composite materials would experience primarily tensile loads and only light compressive loads. This would solve the problem with the low compressive strengths present in the high modulus composites.

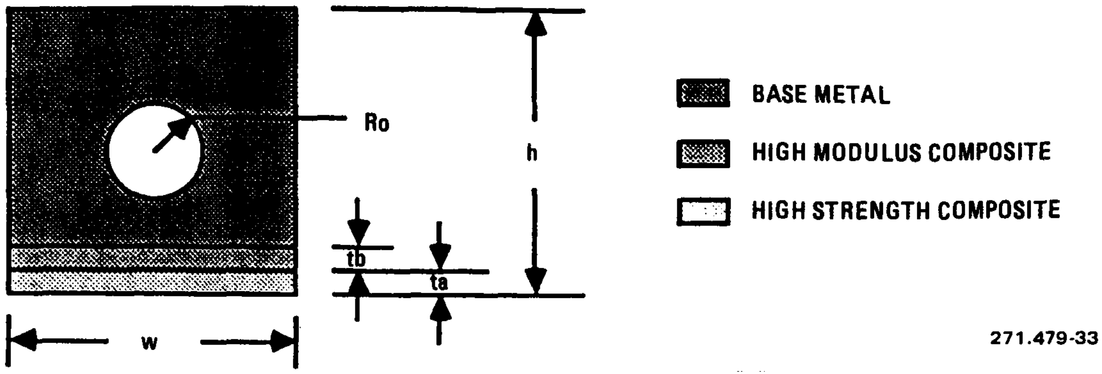

Figure 6-12. Cross Section Geometry for Metal/Metal Hybrid Sting

Analysis approach similar to that discussed previously was used and the results are shown in Figure 6-13. The variables considered were the total thickness of the composite caps and the ratio of the thickness of the high modulus composite to that of the high strength composite.

The results are similar to that of the other hybrid configurations in that increased stiffness is accompanied by reduced strength. An additional problem with this configuration is the possibility of secondary failure modes due to the mismatch between the CTE of the composite and the CTE of the metal. By selectively reinforcing one side, temperature changes incurred during the curing of the composites would create internal stresses in the sting that would tend to create warpage in the finished product. This would become even more severe in the transition to the cryogenic temperatures encountered in the NTF. The effects of these temperature changes would have to be more fully analyzed than was possible during this limited study, and the long term reliability of the bond would need to be established through testing.

A thermal analysis was not done for this configuration, but one could assume similar heater requirements as for the circular sting. This would have to be confirmed with a more detailed analysis.

6.9 FLOATING STIFFENERS

As briefly discussed in Section 6.5, the use of Kennametal stiffeners joined to a conventional (18 Ni-200 or MP35N) sting, perhaps presents a viable approach to reducing sting support deflection.

Also as stated, the joining method is quite critical to the success of the system. Kennametal, being a sintered tungsten-carbide material, is somewhat limited in processes suitable for successfully joining it to other materials. Oven brazing is one process that has been used successfully. However, in this application the brazing temperature (approximately 1200F) is too high in relation to the normal aging temperature 900F of the 18 Ni-200 steel. Secondly, adhesive bonding may be considered and bonding fillers such as American Cyanimide's FM-1000 or equivalent film have been used at temperatures as low as -300F. Adhesive bonding, however, may be strength limited in the

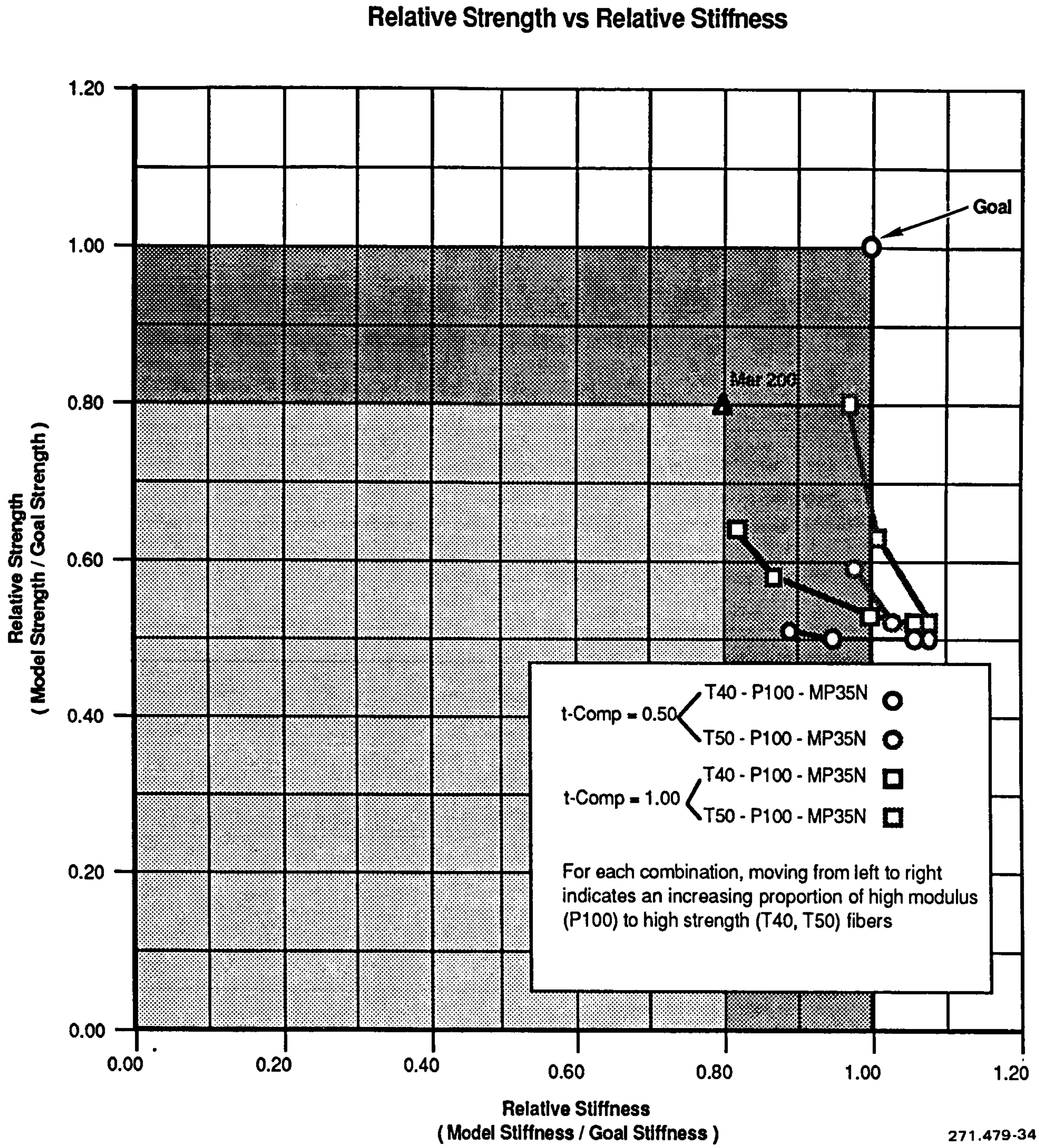

Figure 6-13. Comparison of Hybrid Metal/Composite Stings with Baseline Model Properties

shear directions of the bond system. The limitation is due primarily to the differential CTEs of the materials.

Mechanical fastening also offers an approach to joining the materials considered. In this application, a close sliding fit of the mating diameters is required at the forward end of the sting. At the aft end, a tapered joint secured by bolts may provide the "fixity" between the mating parts. As the sting is deflected and/or subjected to temperature, the parts will have "relative freedom" to move in the axial direction.

Two design concepts using sliding stiffeners have been considered. The first employs a concentric inner rod made of Kennametal. The outer member is of 18 Ni-200 or equivalent steel as shown in Figure 6-14.

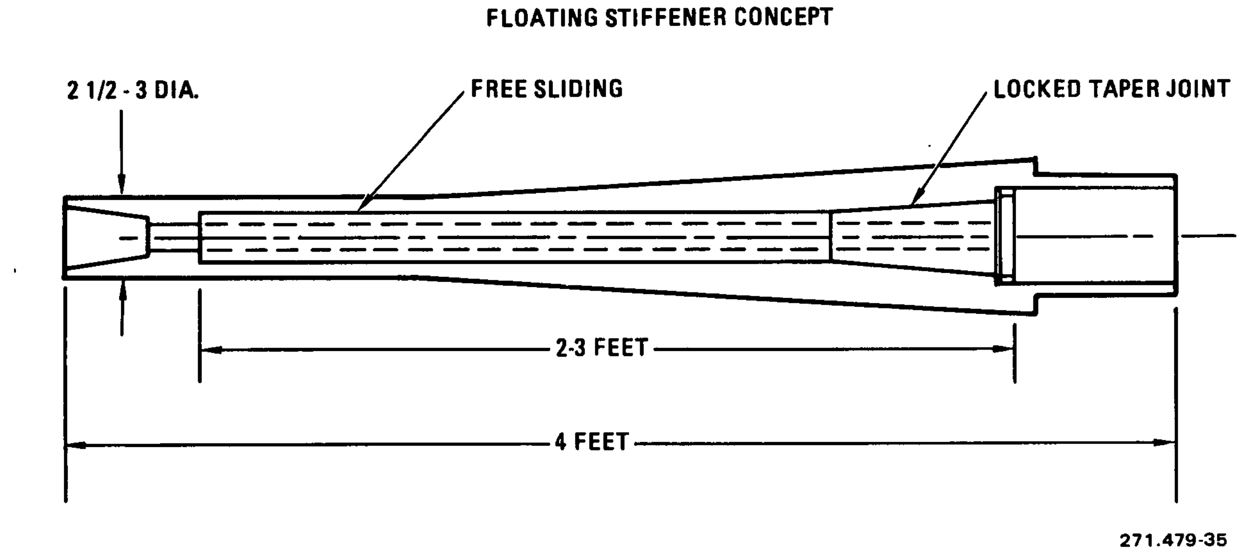

Figure 6-14. Conventional Steel (18 Ni-200) with Kennametal Inner Rod

Engineering analyses will be required to optimized the stiffness-to-strength ratio of the system, while minimizing temperature effects due to CTE differentials.

The concept employs conventional manufacturing and materials processes that should facilitate the production of hardware.

The second concept considered locates the stiffer Kennametal sliding member eccentrically to the centerline of the system. The Kennametal is located on the compressive side due to its high compressive strength. The sliding motion designed into the system will minimize the CTE problem.

To investigate the concept, a test specimen was fabricated using existing materials. A beam of rectangular cross section was grooved on its compressive side along the upper centerline, as shown in Figure 6-15. Two rods (one steel and one Kennametal) were fitted to the groove to provide "fixity" at one end, while sliding along its length.

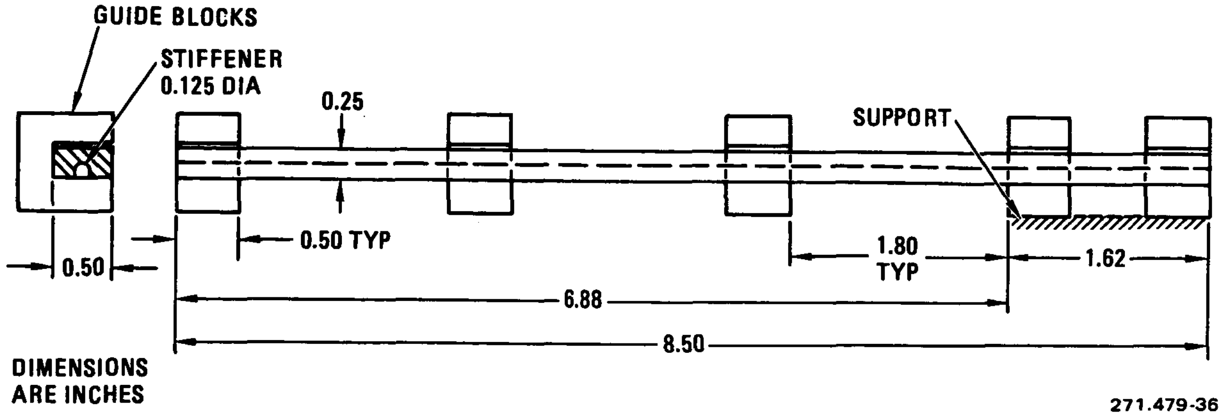

Figure 6-15. Proof of Concept, Floating Stiffener

Deflection tests were conducted in the following sequence:

1. Beam without a stiffener
2. Beam with a steel stiffener
3. Beam with a Kennametal stiffener

The results are show in Figure 6-16. The Kennametal stiffener shows a definite improvement in the reduction of deflection for a given load, thereby indicating an improvement in the stiffness-to-strength ratio. Further development in this area is required to fully substantiate the viability of this concept.

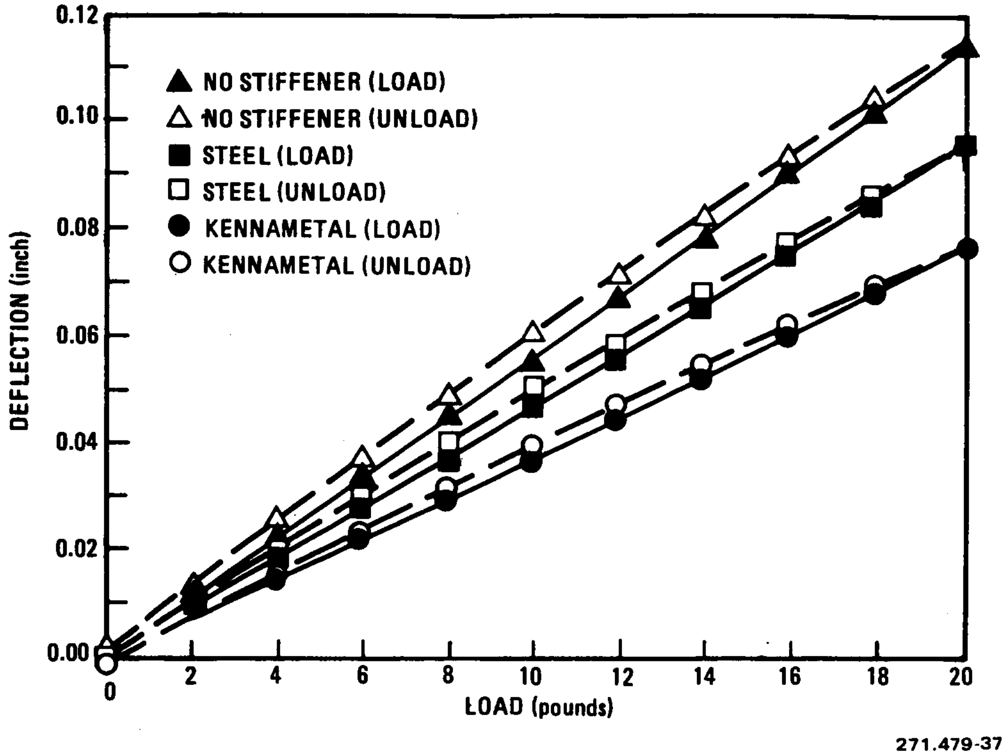

Figure 6-16. Experiment - Floating Stiffener - Deflection Versus Load

SECTION 7

CANDIDATES FOR PROOF-OF-CONCEPT TESTS

In this study the use of advanced materials for high performance stings was investigated. In doing so three separate areas were reviewed:

- Conventional Metals
- Advanced Composites
- Hybrid Configurations

The objective of increasing the values of the ultimate tensile strength, and the modulus, E, of 18 Ni-200 by 25%, while maintaining toughness values, is not an easy task. An innovative approach is required.

For conventional metals, the research was directed toward the multiphase superalloys. Advanced composites, while promising as fibers, have limitations in laminate form particularly when a combination of high strength and high stiffness is required. Hybrids look promising, but the use of dissimilar materials, and the subsequent thermal stress problems due to differences in the coefficient of expansion, raises question with respect to the integrity of the design.

This study has identified a number of concepts that appear promising, yet are questionable because "it hasn't been done before." To achieve our objective, it becomes necessary to select the candidates with the best chance of success, and to further develop those concepts by building hardware, and to subject each design to proof-of-concept tests under environmental condition.

The recommended configurations are:

1. MP35N - laserweld/diffusion weld
2. 18 Ni-200 with a high modulus composite strip on the tension side
3. 18 Ni-200 with a Kennametal floating stiffener

In configurations 1 and 2, the proposed test article is a constant cross-section 3 inches by 2 inches wide and 2 feet long. Configuration 3 is 2-1/2 inches in diameter by 2 feet long with a Kennametal insert.

SECTION 8

CONCLUSIONS

- There is no simple solution. Each of the concepts described in this report will require further development of the manufacturing process.

- Proof-of-concept tests are necessary, and must be done under cryogenic conditions.

- Advanced composites, particularly the ultra-high modulus graphite laminates are unpredictable when loaded in compression.

- Hybrid concepts appear to be promising if the differences in CTE can be overcome. Some past tests have shown that CTE problems, while expected, did not occur. Proof-of-concept tests will verify this.

- Vendor/expert response to questions, usually are: "It's impossible," or "It's no problem." The real answer is in between.

- Some superalloys are candidates but are very limited in available sizes; building them into the desired shapes/sizes will require fabrication process development. In the long term, the mill will produce larger sizes, if there is sufficient demand.

- In hybrid concepts, the adhesives available are suspect at cryogenic temperatures. It is possible to heat the bond line; however, this could introduce temperature to the balance and create an undesirable gradient.

- The superalloys are cold worked to obtain a high ultimate tensile stress, and modulus, E. If they subsequently are subjected to temperatures in excess of 1000F, they lose those properties.

- The cost of superalloys such as MP35N is high - $50 to $100/lb.

- The high performance sting would be approximately 5 to 6 feet long, and adapted into an existing sting. The taper joint between the balance/conventional sting and the high performance sting must also be evaluated.

- A fail-safe feature in the sting is desirable.

SECTION 9

REFERENCES

1. S. A. Griffin, D. S. Madsen, and A. A. McClain, Design Study of Test Models of Maneuvering Aircraft Configurations for the National Transonic Facility, NASA Contract Report 3827, August 1984.

2. Wind Tunnel Model Systems Criteria, LHB 1710.15, NASA Langley Research Center, August 1986.

3. Technical Report - MP35N, Latrobe Steel Co., Latrobe, PA 15650, Report No. 56081, September 1983.

4. R. L. Tobler, Materials for Cryogenic Wind Tunnel Testing, NBSIR 79-1624, May 1980.

5. K. B. Meyer, Fabrication of a High Strength Tube by Spiral Winding, GDC-MRR-80-004, December 1980.

6. A3.0-80, American Welding Society, August 1979.

7. Advanced Composite Systems, Union Carbide Corporation Data Sheet - ACS, Chicago, IL 60606, 1986.

8. D. L. McDaniels, Analysis of Stress-Strain, Fracture, and Ductility Behavior of Aluminum Matrix Composites Containing Discontinuous Silicon Carbide Reinforcement, NASA Lewis Research Center, Cleveland, OH, NASA TM83610, March 1984.

9. P. J. Mazzei, G. Vandrmen, and M. J. Hakins, Powder Fabrication of Fiber-Reinforced Superalloy Turbine Blades, Westinghouse Canada Limited, Turbine and Generator Division, Hamilton, Ontario, Canada, November, 1976.

10. D. Webster, "Properties and Microstructure of Metal Matrix Composites," Advances in Composite Materials, Proceedings of the Third International Conference of Composite Materials, Paris, France, Vol. 2, Pergamon Press, Oxford, 1980, pp. 1165-1176, August, 1980.

11. J. E. Smugersty and R. M. Gesman, "Hot Isostatic Pressing of Maraging Steels," National Powder Metallurgy Conference 7th-8th, pp. 69-82, 1978-1979 Proceedings.

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16. Abstract

It has long been recognized that the sting (or support system) is a very critical part of the model system. The designer is frequently faced with the tradeoff of minimizing sting size, thereby compromising facility and model safety, against a larger sting and the subsequent problems of sting interference effects. In the NASA Langley Research Center National Transonic Facility (NTF), this problem is accentuated by the severe environment of high pressure/low temperature, designed into the facility to provide the desired high Reynolds number. Compromises in the configuration geometry and/or limiting the test envelope are therefore contrary to the purposes and goals of the NTF and are unacceptable, hence the need for this study of advanced model support systems. This paper documents the results of an investigation aimed at improvements of 25 percent in both strength and Young's modulus of elasticity as compared to high strength cryogenically acceptable steels currently being used. Various materials or combinations of materials were studied along with different design approaches. Design concepts were developed which included conventional material stings, advanced composites, and hybrid configurations. Results of the study indicate that significant improvements in both strength and stiffness are possible and various promising design concepts are presented. Candidate configurations are recommended based on best chance of success and proposed proof-of-concept tests under environmental conditions.

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