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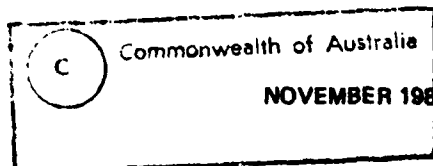COMPOSITE FLIGHT TEST BOOM FOR NOMAD N22B AIRCRAFT

N.C. FROST

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COMPOSITE FLIGHT TEST BOOM FOR NOMAD N22B AIRCRAFT

N.C. Frost

S U M M A R Y

The design, analysis and manufacturing processes are described
for an instrumentation nose boom for a flight test programme
on the Nomad aircraft.

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1. BACKGROUND

The instrumentation of the Military Nomad N22B aircraft for flight testing was undertaken by the RAAF Aircraft Research and Development Unit (ARDU), Edinburgh. Part of this instrumentation involved the measurement of aircraft pitch and yaw angles, and dynamic and static air pressures. These parameters were required to be measured in an undisturbed section of the air stream by mounting the instrument- ation probe (figure 1) on a boom projecting forward from the nose of the aircraft.

An earlier task undertaken by the Advanced Engineering Laboratory (AEL) was the design, stress analysis and manufacture of the fittings, reinforcement and stiffening of the nose baggage compartment of the Nomad to carry an existing boom (figures 2 and 3) for the initial flight trials. A brief description of this work is contained in Appendix I. While this boom met the requirements for rigidity and resonant frequency, it was relatively high in mass and transmitted uncomfortably high vibration loads into the airframe during some phases of the test programme. It was evident that a requirement existed for a lightweight, rigid boom. AEL undertook the development of the new boom.

2. ARDU REQUIREMENTS

The new boom was to be designed to meet the following requirements:

(i)   Lightweight

A design figure of approximately half the mass of the earlier boom was considered desirable.

(ii)   High stiffness

Minimal deflection of the boom during flight manoeuvres was required to reduce angular errors in the read out from the instrumentation which would read angles of attack and yaw relative to the aircraft centreline.

(iii)   A predetermined resonant frequency

It was essential to avoid stimulating vibration of the boom due to coincidence of the boom resonant frequency with aircraft structural resonant or power plant frequencies. Vibration of the boom would have caused structural fatigue and instrumentation environmental problems. A design frequency of 25 Hz was chosen as being achievable consistent with the other requirements and avoiding known excitation frequencies.

(iv)   Structural strength

Since the aerodynamic and inertial loads on the boom were minimal, the boom was to be designed to withstand mistreatment and accidental damage. A vertical design load of 800 N on the end of the boom was considered to cover this.

(v)   Compatibility with existing fittings

It was desirable that the new boom be a quick and easy replacement for the existing one and the fittings and mounting dimensions were to be the same. Refer to Appendix I for a description of the mounting system.

3. DESIGN CONFIGURATION

The two critical requirements were weight and resonant frequency. The
configuration of the boom was constrained by the fittings in the aircraft and
the fitting to the instrumentation probe.   After consideration of the manufact-
uring methods available a circular hollow tapered boom was chosen.   The design
parameters were as follows:

(i)   Length of 2.92 m from bulkhead fitting to probe interface fitting.

(ii)   Diameter 200 mm at aircraft fitting tapering down to 70 mm at probe
interface fitting.

(iii)   Total mass (including probe) no more than 20 kg.

(iv)   Resonant frequency when mounted of 25 ± 2 Hz.

(v)   Design load of 800 N (Proof load 535 N) on the boom end.

4.   PERFORMANCE ANALYSIS

The resonant frequency and mass were determined by a vibration analysis computer
program written for the PDP-11 mini computer.   The resonant frequency was
calculated using the Rayleigh Method and values for wall thickness, material
density and modulus were specified as inputs to the program so that a variety
of materials and thicknesses could be tried.   The program calculated the total
kinetic energy E1 and total strain energy E2 from the following equations:

$$E1 \; = \; \tfrac{1}{2} \sum_{0}^{L} A \, \rho \, (\omega \, y)^2 \; \delta x$$

and

$$E2 \; = \; \sum_{0}^{L} M^2 \; \delta x / 2 \, E \, I$$

where   M = Inertial bending moment

$$= \; \sum \sum A \, \rho \, \omega^2 y \; \delta x \; \delta x$$

ω = frequency rad/s

A = cross-sectional area mm^2

y = deflection at point x mm from tip

x = distance from tip

δx = increment in x = 1 mm

E = tensile modulus of material N/mm^2

I = second moment of area of section mm^4

ρ = density of material

L = length of boom mm

The value of ω for which $E1 = E2$ is the resonant frequency.

In order to determine the deflection along the boom for the 'y' values a sinusoidal deflection curve was assumed. Other curves were tried with no significant changes in the results. A copy of the computer programme listing is contained in Appendix II. A simple stress analysis proved the stress levels were very low for the design loading.

5. MATERIALS

The vibration properties and weight of the boom were analysed with the computer program (see Section 4) for a variety of materials eg steel, aluminium, fibreglass/epoxy laminate, carbon fibre/epoxy laminate and combinations of materials such as fibreglass/epoxy laminate with aluminium and carbon fibre/epoxy laminate with aluminium. Also the physical properties of the two laminates were varied by varying the lay of the fibre and/or the fibre content. The methods used to determine material properties with variations in lay and fibre content are described in Appendix III.

The purpose of this material analysis was to find a material that would give the desired boom properties with the least cost and manufacturing complexity. However after initial programme runs it became evident that the properties of a boom made from carbon fibre/epoxy laminate were not only far superior than the other materials for this application but would be the only material that would allow the boom to meet the design requirements.

6. DETAIL DESIGN

The detail design work consisted of (a) developing a design that enabled the properties of the carbon fibre to be utilized to the full, and (b) the design of fittings and attachments.

The requirements for a 25 Hz resonant frequency and a low mass had to result in a compromise design since the frequency was dependent on both the mass and the bending stiffness of the boom; the frequency being dependent on the inverse of the mass and directly on the bending stiffness. Also the mass and the bending stiffness were both dependent on the second moment of area of the boom cross section.

The compromise design was achieved by optimizing the material properties to give a maximum bending stiffness and then varying the material thickness to give the correct resonant frequency and the mass. This resonant frequency and mass was determined by entering the material properties, ie tensile modulus and density, calculated as described in Section 5, and the thickness of the laminate at each end of the boom into the computer program (see Section 4).

The computer analysis indicated, as expected, that maximum bending stiffness would be achieved with all fibres running longitudinally along the boom, and with maximum fibre content. However, since this type of construction provided minimal torsional strength and stiffness, and was not readily amenable to the attachment of fittings, the boom was redesigned by adding a thin-shell tapered

tube made from 1.2 mm thick aluminium sheet as a base on which to build up the layers of longitudinal carbon fibre.   By trying different thicknesses of carbon fibre laminate in the program, the optimum mass/resonant frequency combination was found.

The end fittings for attachment to the aircraft were designed to attach to the aluminium shell using standard aircraft sheet metal practice.

7.   LAY-UP TECHNIQUES

Lay up techniques for this task were developed by the Materials Division of the Aeronautical Research Laboratory (ARL) at the request of AEL.   They also specified the resin mix.

The carbon fibre used was "Fortafil 5" from the Great Lakes Carbon Corporation, New York, NY.   Properties of this carbon fibre are listed in Table 1.   It was purchased in the form of 40 000 filament tow-tape.   This tow-tape was wound onto a wooden drum 0.775 m diameter x 0.6 m wide covered with Teflon film, the tow-tape turns being positioned side by side.   When the winding was complete, the fibre was sprayed with an impregnating solution consisting of:

   100 g of Epikote 828

   35 g of Diamino Diphenyl Sulphane (DDS) (Araldite HT 976)

   Sufficient MEK to make 200 ml

After a 2 to 8 hour initial drying time the impregnated fibre was cut across the drum, removed and placed on a flat surface for a further 48 hours to dry.   This formed a warp sheet 2.4 m long and 0.5 m wide which was then stored at 0°C until required for lay-up on the boom.   Thirty two pre-impregnated (prepreg) warp sheets were prepared in this manner.

Lay-up of the boom started with a fibreglass tape wrapped around and epoxy bonded to the aluminium tube.   This prevented corrosion of the aluminium caused by electrolytic action between the carbon and aluminium.   Each warp sheet was then shaped to fit the taper of the boom and wrapped around the boom with its joint lines displaced 90° from the joint lines of the previous layer, and impregnated with resin.   Two warp sheets were required per layer.   When it was estimated that sufficient layers had been placed to provide the final thickness required, the boom was wrapped with PTFE shrink tape and then cured.   The cure cycle was:

   (i)   Gel at 180° for 2 hours

   (ii)   Post cure at 200°C for 2 hours

After curing the boom was wrapped with a double layer of fibreglass woven tape with an epoxy resin bond.   This tape wrap protected the carbon fibre from damage and provided a circumferential bond for the longitudinal layers of carbon fibre.

The carbon fibre laminate was machined locally to the correct diameter in the region of the clamp fitting and trimmed at each end of the boom.   All raw edges were impregnated with resin.   The boom was finally finish painted.

8. TESTING

Testing of the boom covered three aspects:

(1) Resonant frequency determination

(2) Proof loading

(3) Deflection under load

For the tests the boom was mounted in the same manner as it would be mounted in the aircraft. It was fitted with a dummy probe that simulated the mass of the instrumentation probe.

The resonant frequency of the boom assembly was determined by exciting the boom with an instrumented hammer and monitoring the response of accelerometers mounted at 4 positions along the boom. The signals from the accelerometers were fed to a Hewlett Packard Spectrum Analyser, Type 3582 A.

Proof loading and deflection tests were conducted simultaneously by gradually loading the probe tip to a maximum of 535 N and measuring the deflection of the boom at the same four positions along the boom as the accelerometers were mounted. On completion of the tests the boom was examined for deformation or damage.

9. RESULTS

The resonant frequency of the boom was determined to be 24.8 Hz. The results of the deflection test are shown in figure 6. Examination of the boom showed no permanent deformation or damage and a "coin tap" test did not show up any internal delamination. The final boom mass was 18.13 kg.

10. CONCLUSION

The boom is now in service with ARDU on the test Nomad aircraft and has been used on take off run, take off and flight tests with no adverse vibration effects.

11. ACKNOWLEDGEMENTS

The author acknowledges the assistance of the following:

Dr A.A. Baker and Dr J. Williams, Materials Division, ARL for the development of the method of carbon fibre lay up and the specification of the resin, and technical advice.

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Mr H. Maudslay, AEL, for engineering the manufacture of the boom.

Mr P. Lecons, AEL, forthe initial frequency analysis and evaluation of materials.

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No.	Author	Title
1	Den Hartog, J.P.	Mechanical Vibrations 4th Edition McGraw Hill, 1956
2	Green, A.K. and Bowyer, W.H.	Fibre Reinforced Composites Technical File No. 40, Engineering, April 1977

TABLE 1.   TYPICAL FIBRE OR TOW PROPERTIES (SINGLE FILAMENT TESTS)

TYPICAL FIBER OR TOW PROPERTIES (SINGLE FILAMENT TESTS)

Tensile Strength (KSI on 1" Gage Length)	400
Tensile Modulus (MSI)	48
Density (gm/cc)	1.80
(lbs/in3)	0.065
Tow Cross-Sectional Area (in2)	0.0040
Tow Yield (ft/lb.)	325
Electrical Conductivity (ohm-1cm-1)	1050
Specific Heat (cal/gm/°C)	0.21
Axial Coefficient of Thermal Expansion (10-6/°C)	-0.5
Axial Thermal Conductivity (W/cm°C)	1.44
Oxidative Resistance (%Wt. loss after 700 hrs. at 316°C)	0.0
Surface Area (M2/gm)	0.5
Chemical Analysis · Carbon (%)	99.7
Nitrogen (%)	0.0
Oxygen (%)	0.2
Hydrogen (%)	0.0
Ash (%)	0.1

TYPICAL UNIDIRECTIONAL COMPOSITE PROPERTIES

In a Typical Epoxy @ 60% fiber Volume

Flexural Strength (KSI)	180
Flexural Modulus (MSI)	23.5
Tensile Strength (KSI)	160
Compressive Strength (KSI)	160
Shear Strength (KSI · 4:1 short beam test)	11

APPENDIX I

BOOM MOUNTING SYSTEM

(This description applies to the mounting of the first boom fitted to the Nomad. The same mounting system was used for the composite boom).

The boom was required to be mounted in the nose of the aircraft via mounting points in the forward baggage compartment. The mounting was to provide angular adjustment of the boom for alignment purposes, and for structural reasons was to attach to the existing forward hard points on the side of the baggage compartment. These requirements were achieved by designing a beam that straddled the forward hard points at Fuselage Station 36.94 and supported the boom on the aircraft centreline, and a spherical end fitting which was bolted to the aircraft bulkhead at Fuselage Station 62.71. The beam could be adjusted in the vertical direction by packers under its attachment points, and the ball end adjusted laterally by varying the cup washer thickness. See figure 5.

Stiffening of the baggage compartment was required due to its relatively flexible structure and was achieved by two diagonal braces taken from the main longeron at Water Line 74.3 to the two forward baggage tie down hardpoints at Fuselage Station 36.94. The airframe was reinforced at each point of attachment of the braces. Vibration tests indicated a resonant frequency of the boom mounted in the aircraft of 18 Hz with the baggage compartment stiffening fitted and approximately 10 Hz without the stiffening. The resonant frequency of the aircraft fuselage in the vertical bending mode is approximately 18 Hz. Thus the stiffening prevented the baggage compartment flexing and gave a boom/fuselage dynamic behaviour similar to that of the overall fuselage alone.

APPENDIX II

COMPUTER PROGRAMME LISTING

```
10  'NOMAD) INSTRUMENTATION BOOM - ARDU
20  'THIS PROGRAM CALCULATES THE NATURAL FREQUENCY OF AN ALUMINIUM AND CARBON FIBRE COMPOSITE BOOM
30  'TOTAL LENGTH OF BOOM IS 2.83 M  DISTANCE BETWEEN SUPPORTS IS  655 M
40  'E1=TOTAL KINETIC ENERGY, E2=TOTAL STRAIN ENERGY, N=FREQUENCY, L0=CANTILEVERED LENGTH
50  'X=DISTANCE FROM PROBE TIP, Y=DEFLECTION AT X, W=INERTIA INCREMENT, W2=PROBE TOTAL MASS, W3=INERTIAL SHEAR
60  'W4=CARBON LAMINATE MASS, M=MOMENT, A2.A3=DEFLECTION SLOPE OF BOOM AT THE FIRST SUPPORT
70  DIM D(325)
80  INPUT "BASE WALL THICKNESS",T
90  INPUT "FRP MAX WALL THICKNESS",T3
100 INPUT "FRP MIN WALL THICKNESS",T2
110 A2=N     E4=6.9E10   E5=16E10  D1=276?
120 INPUT "FREQUENCY ITERATION START",N
130 FOR I1=A TO 200
140 L0=./2    E1=.M    E2=.M    W0=0   W1=0   W2=0   W3=0   W4=0
150 M=N    R= 037    R1= 037    K2= 1007?    X=0
160 D(J)=1.16.0(21)= 45.0(38)= 65.0(57)= 22
170 I4=./28E-8   D=1552   I5=0  D2=0
180 K1= W0625 K1=K1-A2*L0
190 'X1 ARBITRARY TIP DEFLECTION AMPLITUDE
200 FOR J=1 TO 321
210 IF J>272 THEN 290
220 IF J>40 THEN 300
230 'ARBITRARY SINUSOIDAL DEFLECTION CURVE
240 Y=K1*(1-COS(PI*(L0-X)/2/L0))
250 Y=Y+A2*(L0-X)
260 W=0(J)*N^2*Y
270 W2=W2+D(J)
280 M=M+W3* 01
290 GOTO 510
300 Y=Y1*(1-COS(PI*(L0-X+ 005)/2/(L0- 595))
310 Y=Y+A2*(L0-X+ 005)
320 R=W1+(K2-P1)*(X- 595)/(L0- 595)
330 T1=I2+(T3-T2)*(X- 595)/(L0- 595)
340 I4 =(X-T1-1/2)^2*T1+PI    'SECOND MOMENT OF AREA OF BASE SHELL
350 I5 =(X-T1-1/2)^3*T1+PI    'SECOND MOMENT OF AREA OF FRP
360 W0=(X-T1/2)+11*D+(X-T1-T/2)*1+01   W1=(X-T1/2)*T1*D* 02*PI
370 W0= W2+PI*W0
380 GOTO 480
390 IF J>273 THEN W0=M
400 IF J>290 THEN J.I5=M
410 IF N.A AND J.=273 THEN 420 ELSE 450
420 A2=W1+ 655/3+(E4+14+E5+15))
430 IF (W/<- 0000001).A2 AND A2>(M>+ 0000001) THEN 450 ELSE 440
440 A2=M    J=1    GOTO 140
450 I4=(X-T1-T1/2)^3*T1+PI    15=(X2-T1/2)^3*T1*PI
460 Y=M01+(X-2 72)/2=(X2-2 72)2/ 655-1 31*(X-2 72)/6*(E4*14+E5*15))
470 W0=(X/-T1/2)*11+D+(X-T1-1/2)*T+01   W0= 02*PI*W0   W1=(X-T1/2)*T1*D* 02*PI
480 W2=W2+W2+Y    W4=W4+W1
490 M=M+W0_* 01+W4+ 005
500 M4=M+W4+4/14./+14+14+E5+15))
510 M5.N+P+15.(+4+14+E5+15))
520 W2=N +W
530 X=X+ 01
540 E1=1+M+Y.2
```

```
560 IF I5=0 THEN 570 ELSE 580
570 E2=E2+M4^2*.005/E4/14    GOTO 590
580 E2=E2+M4^2*.005/E4/14+M5^2*.005/E5/15
590 NEXT J
600 IF (E1-.005)<E2 AND E2<(E1+.005) THEN 660
610 IF N=A THEN 620 ELSE 630
620 PRINT "    E1","    E2","  N"
630 PRINT E1,E2,N
640 IF E2>E1 THEN N=N-1.5
650 NEXT N
660 PRINT "BOOM TOTAL PROPERTIES. RESONANT FREQUENCY="N"RADS/SEC"
665 PRINT "                                    MASS="W2+3.05"KG"
670 PRINT
680 PRINT "BASE PROPERTIES:         MASS="W2-W4+3.05"KG"
690 PRINT "                    THICKNESS="T"MM"
700 PRINT "          TENSILE MODULUS="E4"PA
710 PRINT "                DENSITY="D1"KG/CU M"
720 PRINT
730 PRINT "FRP PROPERTIES:          MASS="W4"KG"
740 PRINT "                    THICKNESS="T2"TO"T3"MM"
750 PRINT "          TENSILE MODULUS="E5"PA"
760 PRINT "                DENSITY="D2"KG/CU M"
770 END
```

APPENDIX III

CARBON FIBRE LAMINATE PROPERTIES

The physical properties of carbon fibre/epoxy laminate depend on the fibre content, orientation of the fibre layers and to some extent the type of resin. The mechanical properties of most significance are stiffness and strength and in order to estimate the performance of the final manufactured article these properties must be predicted for the matrix used.

The stiffness of a unidirectional composite containing continuous fibres (as in the case of the instrumentation boom final configuration), along the fibre direction may be calculated from

$$E_c = E_f V_f + E_m V_m$$

where subscripts c, f and m refer to composite, fibre and matrix respectively. E is Young's Modulus and V is the volume fraction of constituent. This simple rule of mixtures calculation assumes that the fibres and matrix are constrained to deform together; an assumption which is true for all practical purposes. This estimation of modulus only applies along the axis of the fibres. An adequate assessment of stiffness for structures utilising a cross or angle ply construction technique, may be made by resolving the principal stiffness of each layer in the direction of interest, having calculated each layer stiffness from the rule of mixtures approach.

The strength of a composite reinforced with unidirectionally aligned continuous fibres may be calculated from a modified rule of mixtures:

$$\sigma_c = V_f \sigma_f + V_m \sigma_m$$

where σ_c is the UTS of the composite, σ_f is the fibre stress at failure of the fibres, and σ_m is the matrix stress at the fibre failure strain. In practice the value of $V_m \sigma_m$ is small compared to $V_f \sigma_f$ and can be neglected.

Initial estimates of a value for E_c were made assuming a 50% volume fraction. This estimate was used to determine the feasibility of the carbon fibre composite construction for application in this project. When this proved acceptable sample pieces were layed up and test piece cut from them. Tests on these specimens gave a tensile strength of 696 MPa and an elastic modulus of 160 GPa. A burn out test gave a fibre content of 70% by weight (60% by volume).
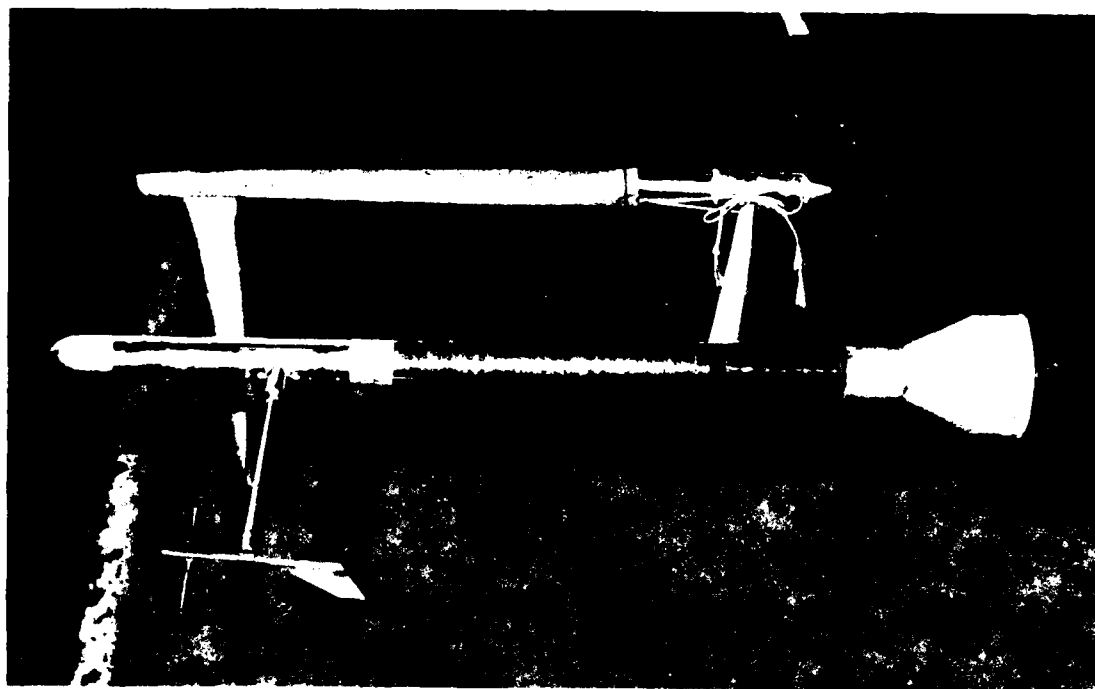
Figure 1.   Instrumentation probe

Figure 2.   Boom Mk 1

Figure 5. Boom installation

COMPOSITE FLIGHT TEST BOOM

COMPOSITE LAMINATE LAYED UPON 1.2mm ALUMINIUM ALLOY SHELL AS FOLLOWS :-

LAYER 1:- SINGLE LAYER FIBREGLASS TAPE WRAP, EPOXY RESIN BOND.

LAYER 2:- CARBON FIBRE ,`FORTAFIL 5´ (GREAT LAKES CARBON CORPORATION)
EPOXY RESIN (65% MINIMUM FIBRE CONTENT BY WEIGHT OR 55%
BY VOLUME).

LAYER 3:- SINGLE LAYER P.T.F.E. SHRINK TAPE WRAP. GEL AT 180°C FOR TWO
HOURS. REMOVE TAPE.

LAYER 4:- DOUBLE LAYER FIBREGLASS TAPE WRAP, EPOXY RESIN BOND. CURE
AT ROOM TEMPERATURE.

END FITTING
TO SUIT PROBE

INTERNAL STRONG RING

2922

END FITTING

STN
62.71

STN
36.94
APPROX.

$\phi 198.5 \pm 0.1$

$\phi 74$

Figure 4. Composite flight test boom

WL 56 0

NOMAD N22B BOOM INSTALLATION

SECTION 'BB'

OXYGEN CYLINDER

STN
62 71

STN
36 94
APPROX.

INSTRUMENTATION
BOOM

CUT HOLE IN NOSE CONE TO
CLEAR ON BOOM. SEAL AFTER
FINAL INSTALLATION OF BOOM

PROBE

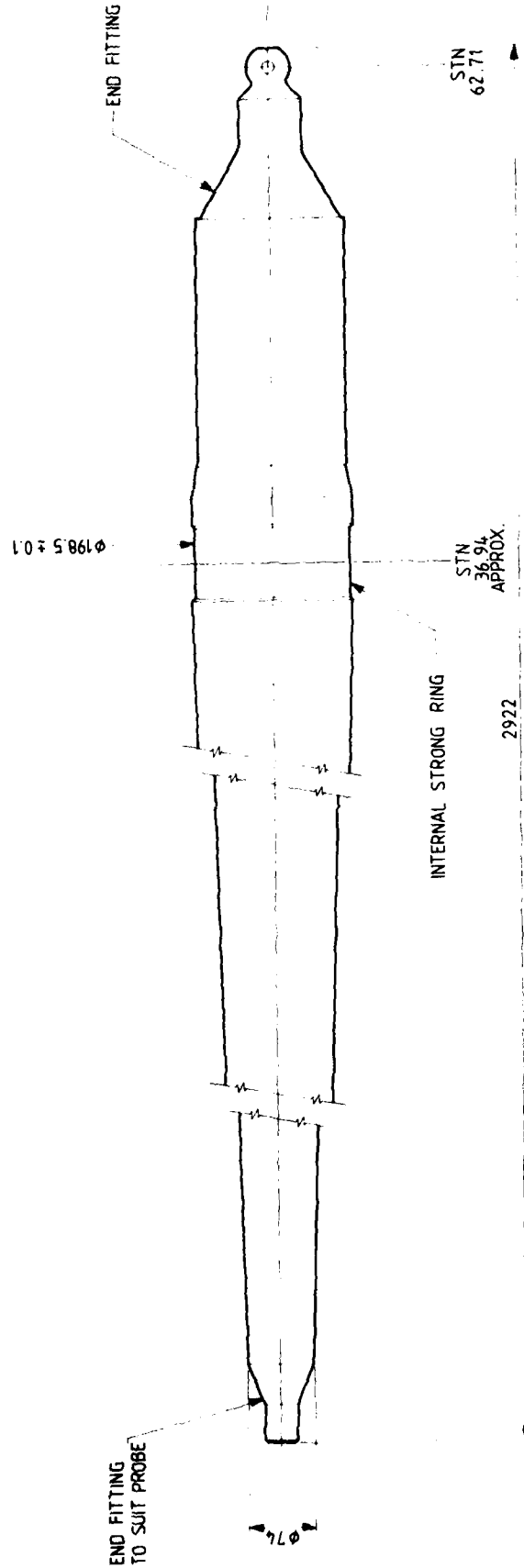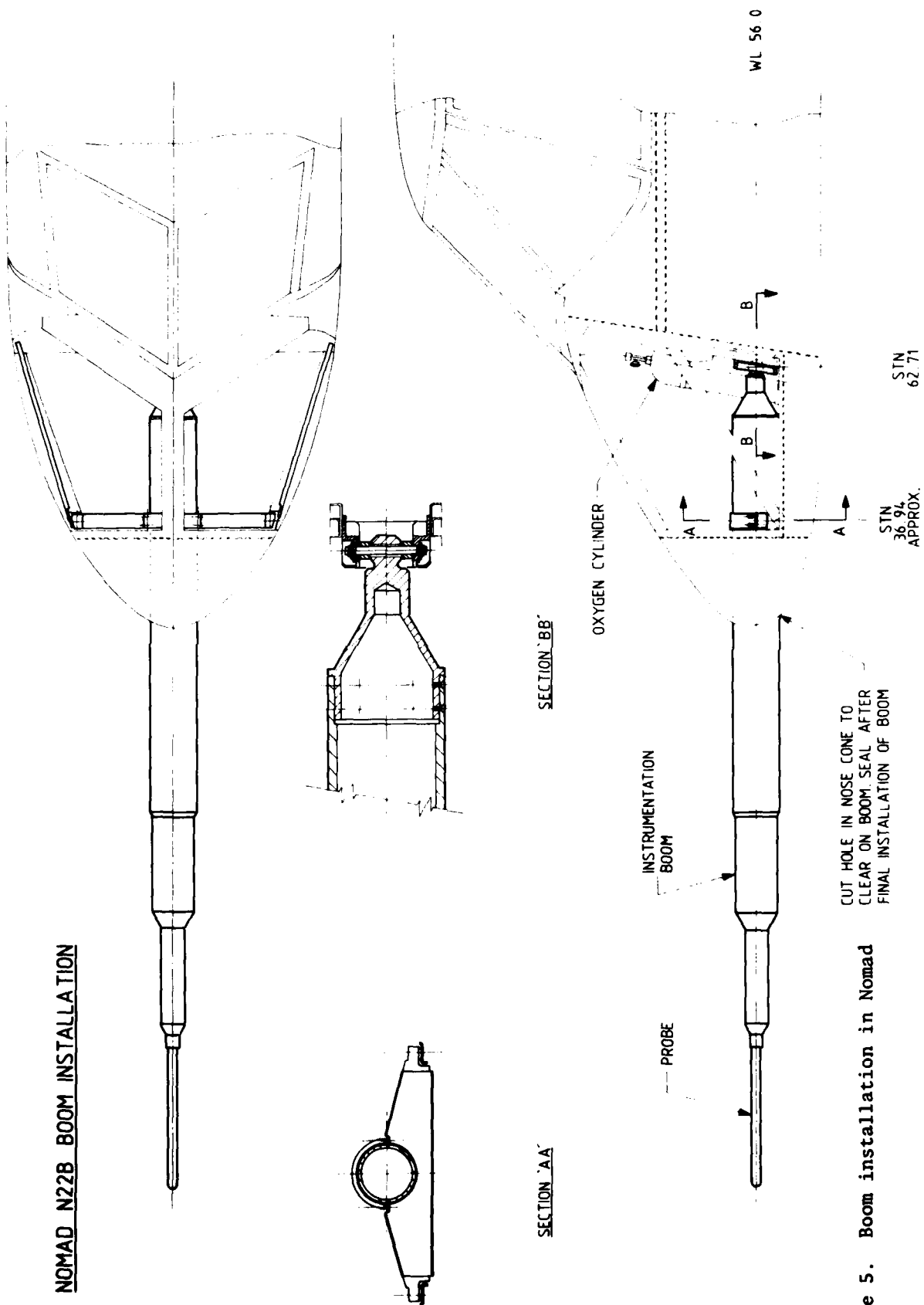SECTION 'AA'

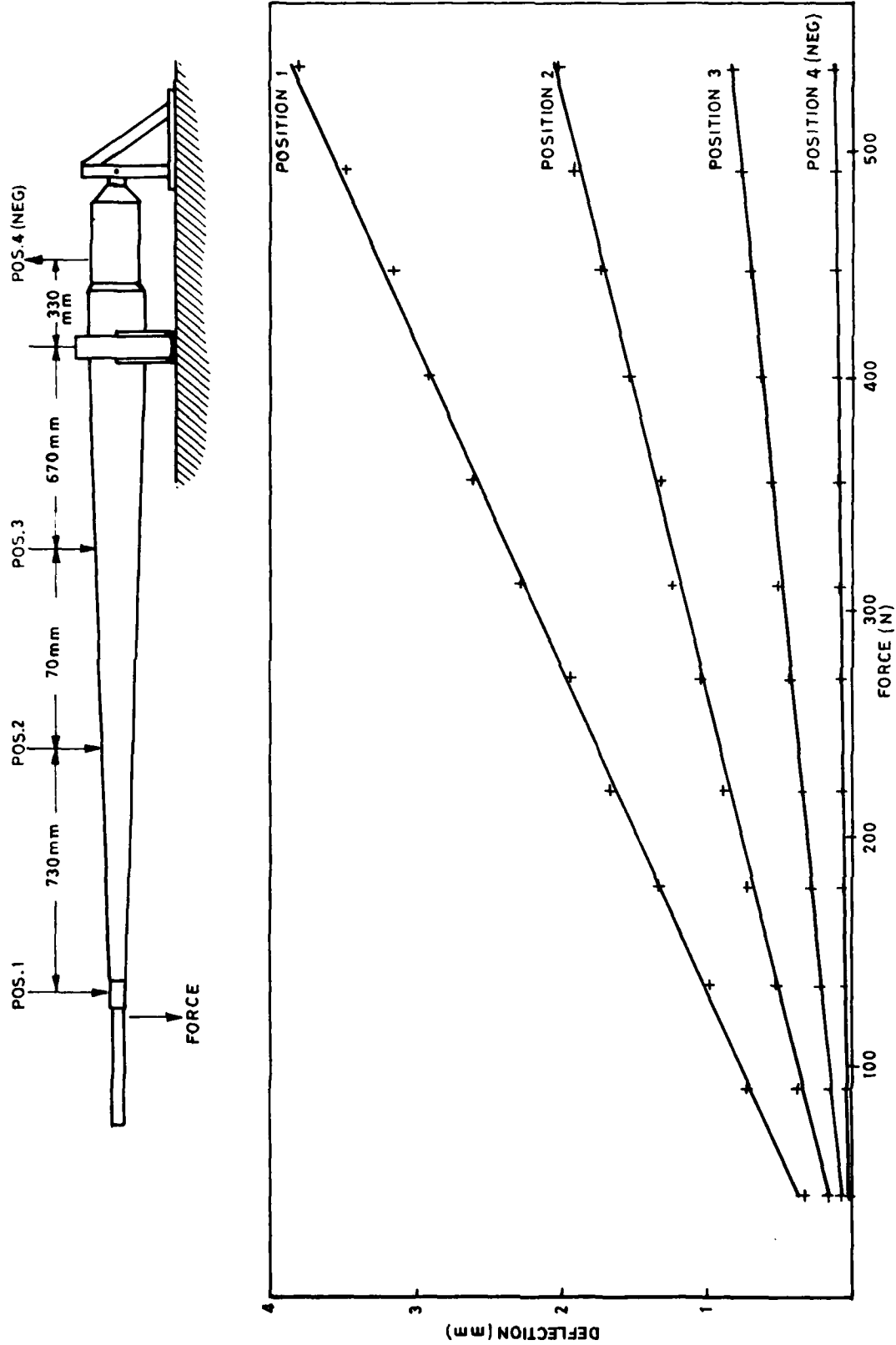Figure 5.   Boom installation in Nomad

Figure 6. Load-deflection curves

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