E. E. Engler / EP13

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Development of Deployable Structures for Large Space Platform Systems

By
R.L. Cox
R.A. Nelson

Part 1 Report

Prepared for the
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

VOUGHT CORPORATION
Post Office Box 225907 • Dallas, Texas 75265

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FOREWORD

This report describes a 9-month study of deployable structures for large space platform systems. The study was conducted by the Vought Corporation for the NASA-George C. Marshall Space Flight Center. The work was performed under Contract NAS8-34678 during the period 29 October 1981 through 31 July 1982, and was monitored by Erich E. Engler, COR, and W. E. Cobb, Co-COR, of the Structures and Propulsion Laboratory. Dr. R. L. Cox of Vought was Study Manager for the program. Mr. R. A. Nelson performed conceptual and design studies and coordinated design effort. Mr. H. C. Allsup conducted interface design studies. Messrs J. B. Rogers, R. W. Simon, and J. J. Atkins performed structural analyses. Mr. D. D. Stalmach conducted thermal and deployability analyses. Mr. J. A. Oren performed new technology and cost studies and directed thermal analyses. Materials studies were performed by Mr. G. Bourland. Mr. R. E. McPartland provided electrical design support.

The authors wish to thank the contributors mentioned above for their dedication and for the excellence of their support to this program. The authors also wish to thank Messrs Engler and Cobb for their guidance and support during the study, and Mr. J. J. Pacey of Vought for his valuable consultation and assistance. Special thanks is due Ms. D. M. Fethkenher who provided secretarial, data management, and publications services throughout the program.

OUTLINE

		PAGE
1.0	INTRODUCTION AND SUMMARY	1
2.0	CONCEPT DEVELOPMENT	25
	2.1 Requirements for Linear and Area Deployable Platforms	25
	2.2 Procedure	41
	2.3 Concept Selection for Screening	45
	2.4 Screening Evaluation and Selection	62
	2.5 Development of Structural and Deployment Concepts	71
	2.5.1 Biaxial Double Fold	72
	2.5.2 Martin Marietta Box Truss	75
	2.5.3 General Dynamics Diamond Truss Beam	79
	2.5.4 Double Fold	84
	2.6 Structural Characteristics	87
	2.7 Utilities Integration Concepts	97
	2.8 Interface Concepts for Utilities and Structure	113
	2.9 Concepts for Interfaces with Payloads and Equipment	127
3.0	MATERIALS SELECTION IMPACTS	131
	3.1 Issues	131
	3.2 Candidate Materials and Mechanical Properties	131
	3.3 Other Materials Characteristics	135
	3.4 Selected Materials	135
4.0	SPECIAL TECHNOLOGY NEEDS	143
5.0	CONCEPT SELECTION	151
	5.1 Evaluation of Configuration Variability	151
	5.2 Cost Trades	158
	5.3 Evaluation of Trade Matrix	160
	5.4 Selection	166
6.0	DEPLOYABLE VOLUMES	167
	6.1 Guidelines and Requirements for Deployable Volumes	168
	6.2 Flexible and Inflatable Concepts	172
	6.3 Deployable Structure Concepts	177
	6.4 Recommended Concepts for Further Work	189
	6.5 Technology Drivers	189
7.0	CONCLUSIONS	191
	7.1 Linear and Area Platforms	191
	7.2 Deployable Volumes	194
8.0	REFERENCES	195

LIST OF FIGURES

		PAGE
1	Elements of Deployable Platform System	2
2	Deployable Volume Mission Candidates	2
3	Deployable Platform Systems Work Flow	3
4	Structural Concepts Evaluated	4
5	Features of Selected BADF Structure	9
6	Deployment/Retraction Concept for BADF	10
7	Utilities Integration Concept for BADF	11
8	Module Deployment Assembly With BADF	12
9	Configuration Variability of BADF	13
10	BADF Subsystem and Payload Interface	14
11	BADF Redeployable Mast on Guide Rails Supports	15
12	Shuttle Compatibility of BADF	16
13	Recommended Concepts for Habitat	19
14	Silo Concept - Deployable Habitat	20
15	Recommended Concept for OTV Hangar	22
16	Flexible Concept Recommendations	23
17	Deployable Volume Launch Benefits	24
18	Review of Focus Missions	26
19	Stiffness Requirements	28
20	Strength Requirements	28
21	Utilities Requirements	29
22	Types of Interfaces	30
23	Structural Interface Examples from Advanced Science and Applications Space Platform	33
24	Structural Interface Examples from SPS TA II	33
25	Structural Interface Examples from GSP Alt. 1, PTF 1	34
26	Structural Interface Examples GSP Atl. 4 - Platform Module 1	35
27	Structural Interface Examples GSP Alt. 4 - Platform Modules #1 and #2	35
28	Max/Min Orbit Temperatures	37
29	Temperature Differential Across Tube	38
30	Options to Minimize Temperature Swing	39
31	Transient Thermal Effects On Strut Material Selection	40

LIST OF FIGURES (CONT'D)

		PAGE
32	Review of Structural Concept Generation and Screening	42
33	System Trades and Concept Selection	44
34	Candidate Deployable Structure Concepts	46
35	Concept 1: Double Fold Configuration	50
36	Concept 1: Double Fold Folded Geometry	51
37	Concept 2: Biaxial Scissors Fold Configuration	51
38	Concept 2: Biaxial Scissors Fold Folded Geometry	52
39	Concept 3: Nested Single Fold Configuration	52
40	Concept 3: Nested Single Fold Folded Geometry	53
41	Concept 4: PETA Configuration	53
42	Concept 5: Diamond Beam Configuration	55
43	Concept 11: Half-Diamond Beam Configuration	55
44	Concept 4: PETA; 5: Diamond Beam; 11: Half-Diamond Beam Folded Geometry	56
45	Concept 6: Box Truss Configuration	56
46	Concept 6: Box Truss Folded Geometry	57
47	Concept 7: Inflatable Double Fold	57
48	Concept 8: Biaxial Double Fold Configuration	59
49	Concept 8: Biaxial Double Fold Folded Geometry	59
50	Concept 9: Pivoted Double Fold Configuration	60
51	Concept 9: Pivoted Double Fold Folded Geometry	60
52	Concept 10: Telefold Configuration	61
53	Concept 10: Telefold Folded Geometry	61
54	Evaluation of Score for Deploy: Stow Volume Ratio Concept 1: Double Fold	65
55	Evaluation of Score for Number of Joints Per Additional Beam Structure Cell Concept 1: Double Fold	65
56	Evaluation of Score for Deployability Index of Merit Concept 1: Double Fold	66
57	Biaxial Double Fold Refold-Deploy Control Cable System	73
58	BADF Structure Folding	73
59	BADF Fold Geometry	74
60	Biaxial Double Fold Surface Diagonals Detail	74

LIST OF FIGURES (CONT'D)

		PAGE
61	Top View of BADF Folded Cell	76
62	Deploy Spring Torques for Biaxial Double Fold	76
63	BADF B Node Details Showing Deployment Spring	77
64	BADF Double Telescope Vertical Strut	77
65	MMC Box Truss Folding Sequence	78
66	MMC Box Truss Refold-Deploy Control Cable System	80
67	Top View of Box Truss Folded Cell	80
68	Square Diamond Beam Deployment	81
69	GDC Diamond Beam Deployment	82
70	Side View of Diamond Beam Folded Cell	82
71	Double Fold Refold-Deploy Control Cable System	83
72	Double Fold Refold-Deploy Geometry	85
73	Deploy Cable and Lever Arrangement for Double Fold	85
74	Top View of Double Fold Folded Cell	86
75	Geometric Properties of Strut Cross Sections	87
76	Simplified Parametric Formulations	88
77	NASTRAN Analysis	89
78	Bending Stiffness Comparison	90
79	Bending Strength Comparison	92
80	Parametric Weight Estimates	92
81	Parametric Comparison of Truss Weight Per Unit Length D/t = 50 .	94
82	Parametric Comparison of Truss Weight Per Unit Length D/t = 75 .	94
83	Parametric Comparison of Truss Weight Per Unit Length D/t = 100.	95
84	Specific Bending Stiffness Comparison of Truss Concepts	95
85	Thermal Distortion Characteristics of Beam	96
86	Minimum Bend Radius of Wire Strands	97
87	Bend Life Test Data on Copper Wire	98
88	Representative Utilities Bundles	100
89	Torque Wrench Test of Wire Cables and Metal Hose	101
90	Torque Wrench Test of 25 mm I.D. Corrugated and Braided Metal Hose at Zero Pressure	101
91	Cable Tray Structure Concept	103
92	BADF Utilities Routing	103

LIST OF FIGURES (CONT'D)

		PAGE
93	BADF "A" Node Details	104
94	BADF "B" Node Details	104
95	Internal Utilities Space Through Original Knee Joints	106
96	Box Truss Knee Joint Concept for Internal Utilities Routing	106
97	Box Truss External Utilities Routing	107
98	Box Truss External Utilities Routing 4 Paths, 12 Bundles	107
99	Utilities In Folded Diamond Beam	108
100	Diamond Beam External Utilities	110
101	Permissible Utility Bundle Diameter for Internal Routing	110
102	Point Comparison Between External and Internal Utilities Routing	111
103	Comparison of Stowage Volume Ratio for Typical Internal Utilities Bundle	111
104	Effect of Internal Utilities Bundle Diameter on Stowage Volume Ratio for Double Fold	111a
105	Effect of Internal Utilities Bundle Diameter on Stowage Volume Ratio for GDC Square Diamond Truss	111a
106	Effect of Internal Utilities Bundle Diameter on Stowage Volume Ratio for MMC Box Truss	112
107	Effect of Internal Utilities Bundle Diameter on Stowage Volume Ratio for BADF	112
108	Electrical Connector Design Considerations	114
109	Electrical Connector Sizing	115
110	Design Considerations for Fiber Optic Connectors and Tees and Electrical Tees	115
111	Fluid Connector Concept	117
112	Catalog of Representative Mechanical Interface Designs	117
113	Interface Mating Approach	119
114	Utility Panel Pull-In	119
115	Node Selection for BADF Utilities Interfaces	120
116	"A" Node Utilities - BADF Internal Routing - Bundle #3	120
117	"A" Node Utility "T" For Routing Bundle To "B" Node at Truss Joint	122

LIST OF FIGURES (CONT'D)

		PAGE
118	"B" Node Utilities - BADF Internal Routing - Bundle #1	122
119	BADF Internal Routing - Bundle #2	123
120	Utilities Interfaces for Double Fold	123
121	Utilities Interfaces for Martin Box Truss	124
122	Box Truss Internal Utilities Cross Routing	124
123	Utilities Interface for GDC Diamond Beam	125
124	Considerations for Utility Branching with External Utilities	125
125	RMS Standard Grapple Fixture Installed At Node	128
126	BADF Subsystem and Payload Interface	129
127	Rotating Joint Interface	129
128	Damping Characteristics of Some Selected Materials	137
129	Calculated Properties of Minimum Gage High Modulus Graphite/Epoxy	142
130	Special Technology Item: Small, No Leak, Low Pressure Drop Fluid Connector	144
131	Special Technology Item: Low CTE Strut and Node Members	145
132	Special Technology Item: High Flexibility Electrical Cables	146
133	Special Technology Item: Super Flexible Fluid Hose	147
134	Special Technology Item: Efficient Fiber Optics Tees	149
135	Special Technology Item: Low Absorption/Emittance Thermal Coating	150
136	Truss Square Butt Joints	152
137	Extension Butt Joint	152
138	Oblique Truss Butt Joints	153
139	BADF Foldable Transition Cell	153
140	Truss-to-Truss Lap Joint Interface	154
141	Module-to-Module Truss Interface	154
142	Deployable Masts (Single Fold)	156
143	Deployable Masts (Double Fold)	156
144	BADF Redeployable Mast on Guide Rails Supports	157
145	BADF & Box Truss Tapered Cells In Spoked Hoop Structure	159
146	Non-Recurring Cost Estimating Approach	159
147	Manufacturing Cost Estimating Approach	161

LIST OF FIGURES (CONT'D)

		PAGE
148	Cost Comparison Methodology	161
149	Launch Cost Estimating Approach	162
150	Design, Development and Production Cost Comparison	162
151	Launch Cost Comparison	163
152	Thermal Protection Approach	169
153	Meteoroid Protection Approach	170
154	Meteoroid Protection	170
155	Telescoping Tube Tunnel	173
156	Convoluted Tube Tunnel	174
157	Goodyear Convoluted Tube Model Dimensions	174
158	Goodyear Moby Dick Flexible Tunnel	176
159	Bladder Materials	176
160	"Folding Doors" Deployable Volume	178
161	"Covered Wagon" Deployable Volume Concept	178
162	Capabilities of Deployable Truss Options	179
163	BADF Silo Truss Cylinder	179
164	Silo Concept-Deployable OTV Hangar	181
165	Attached Bladder Edge Folding Frame	181
166	135° Inside Bladder Frame Bend	183
167	45° Outside Bladder Frame Bend-No Bladder Stretch	183
168	Detachable Bladder Edge Folding Frame	184
169	Bladder Pressure-Load Retention Options	184
170	Bellows Sealed Inside Supports	185
171	Utilities Concept Details	185
172	Two Silo OTV Hangars Stowed In One Half Cargo Bay	187
173	Silo Concept-Deployable Habitat	187
174	Two Silo Habitats Stowed in One Half Cargo Bay	188
175	Concepts For Installation of Equipment in Pressurized Habitat/Storage Volume	188
176	Recommended Concepts for Further Work	190

LIST OF TABLES

		PAGE
1	Major Issues	5
2	Concept Trade Summary	8
3	Deployable Volume Concepts Considered	18
4	Concepts Considered and Rejected for Screening	50
5	Worksheet and Definitions of Preliminary Screening Criteria	63
6	Evaluation of Screening Matrix (Unweighted)	68
7	Evaluation of Screening Matrix (Weighted)	69
8	Selection of 4 Concepts for Additional Study	70
9	Key Issues In Structural and Deployment Concept Design	71
10	Summary of BADF Characteristics	78
11	Summary of MMC Box Truss Characteristics	81
12	Summary of GD Diamond Beam Characteristics	83
13	Summary of Double Fold Characteristics	86
14	NASTRAN Results	90
15	Representative Utilities Exceed ASASP Requirements	99
16	Bending Moment Estimates for Representative Bundles	102
17	Materials Issues	132
18	Selection of Candidate Structural Materials - Metal Alloys	132
19	Selection of Candidate Structural Materials - Organic Matrix Composites	133
20	Selection of Candidate Metal Matrix Composites	133
21	Typical Properties of Candidate Metal and Metal Matrix Materials	134
22	Typical Properties of Candidate Fiber/Organic Matrix Materials	134
23	Outgassing Characteristics of Selected Materials	136
24	Characteristics of Matrix Materials for Fiber Reinforced Composites	138
25	Reinforcing Fiber Materials	139
26	Recommendations for Selection of Metal Alloys	140
27	Recommendations for Selection of Composite Materials	140
28	Trade Matrix	164
29	Concept Trade Summary	166
30	Guidelines and Requirements	168

1.0 INTRODUCTION AND SUMMARY

Studies of future space applications show an emerging need for multipurpose space platform systems. Prior work has focused on the development of generic structural platforms, and on point designs of systems for a few missions such as geostationary communications and scientific experiments. In order for the user community to realize the potential benefits of large structures for early 1990's missions it is important now to develop and demonstrate platform systems which offer both a high degree of versatility and which effectively integrate requirements for utilities, subsystems and payloads. In addition, future missions such as the Manned Space Platform will require both pressurized and unpressurized volumes for crew quarters, manned laboratories, interconnecting tunnels, and maintenance hangars. To minimize launch costs and enable use of volumes greater than those which can be transported by the Space Shuttle Orbiter, it is also desirable to evolve deployable volume concepts. The objectives of Part 1 of the current program have been to review, generate, and trade candidate deployable linear platform system concepts and select and define one or more of these concepts, and to generate candidate concepts for deployable volumes. The platform concepts are based on generic system requirements and selection criteria consistent with three focus missions:

- Advanced Science and Applications Space Platform (ASASP)
- Geostationary Communications Platform (GSP)
- Solar Power Satellite Test Article II (SPS TA II)

Additional supporting objectives are to identify materials selection impacts and special technology needs inherent in the deployable platform system concepts. It is intended that the concepts and technology development requirements will provide the basis for technology readiness of fully integrated deployable platform systems by 1986. The objectives of the deployable volume study are to generate concepts using flexible materials and deployable truss technology, and to select and define promising concepts for subsequent study, including an identification of expected problem areas, design drivers, and technology development requirements.

The elements of a deployable platform system are illustrated in Figure 1, adapted from the Ref. (1) definition study of the ASASP. The core element of the deployable platform system is its automatically deployable/retractable structure. Some of the major system interfaces are the

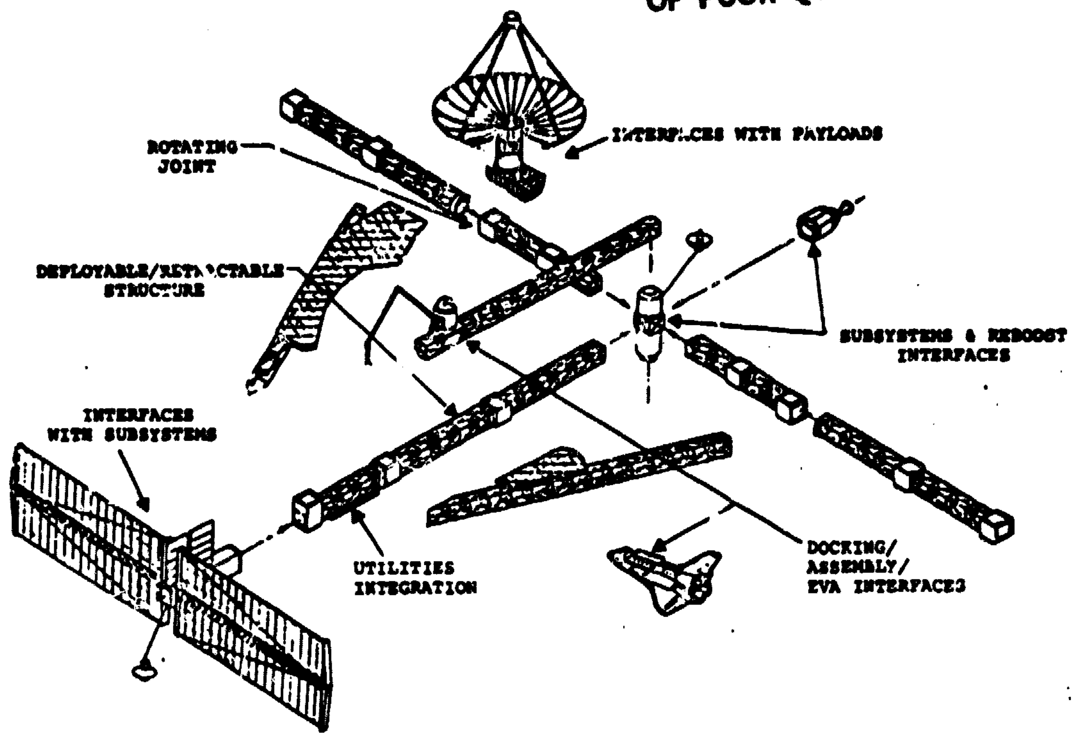

FIGURE 1 ELEMENTS OF DEPLOYABLE PLATFORM SYSTEM

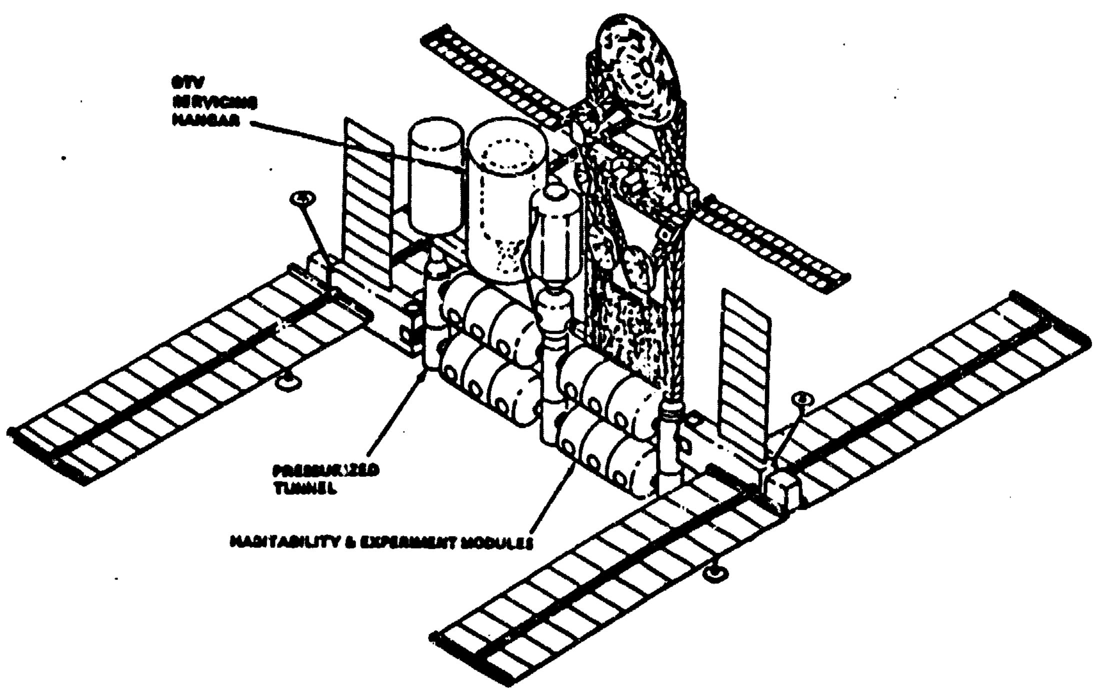

FIGURE 2 DEPLOYABLE VOLUME MISSION CANDIDATES

spacecraft utilities, where full integration with the structure is desired; interfaces with subsystems and payloads; docking, assembly, and EVA interfaces; and various joints and attachments. All aspects of the interfaces are important influences to the deployable platform system design, including physical characteristics, imposed loads, dynamic interactions between the structural and attitude control subsystems, thermal distortion, payload stability requirements, and deployment/assembly operations. Figure 2, from the Ref. (2) NASA-MSFC study, shows a typical space station concept and indicates three potential deployable volume uses : an Orbital Transfer Vehicle (OTV) maintenance hangar, a manned habitat, and an interconnecting tunnel.

The study approach and work flow diagram is shown in Figure 3. Part 2 is shown for reference purposes, only, as only Part 1 effort is covered in this document. The current Part 1 work has been a 9-month effort.

Deployable Platform System

Some of the most significant guidelines applied in the deployable platform system study have been:

- Emphasis on new concepts and concepts made up of proven elements.
- Emphasis on generic requirements.
- Area platforms to be made up from a combination of linear beams.

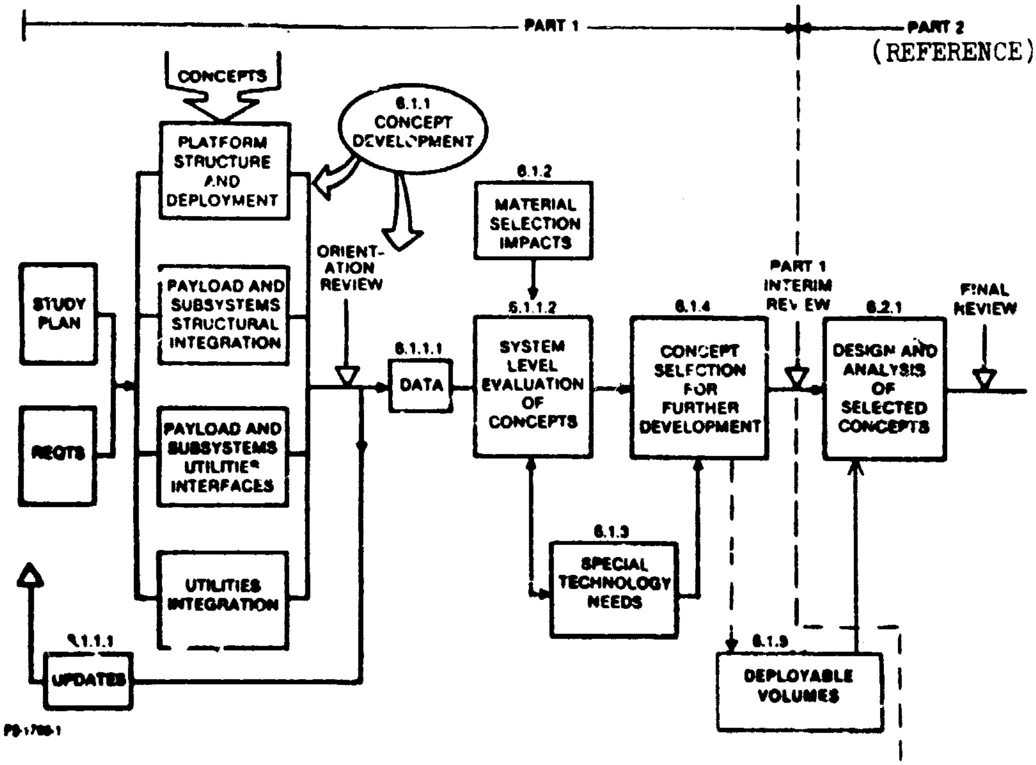

FIGURE 3 DEPLOYABLE PLATFORM SYSTEMS WORK FLOW

- Maximum versatility of the structure/integration concept by
  - provision for future power increases (up to 250 kW)
  - allowance for assembly of various configurations from deployed booms
  - suitability for additional add-on utilities.
- Consideration of limitations to scaling and growth.
- Emphasis on good deployability.

Based on the study objectives, generic mission requirements, and study guidelines, the following deployable platform design objectives were established: Autodeploy/Retract; Fully Integrated Utilities; Configuration Variability; Versatile Payload & Subsystem Interfaces; Structural & Packing Efficiency; 1986 Technology Readiness; Minimum EVA/RMS; Shuttle Operational Compatibility. To meet these objectives five major issues were identified, alternatives considered, and the design approach established. Table 1 lists these and the approach taken.

The procedure involved in conducting the deployable platform system study was initiated with a structural concept generation and evaluation effort. Based on a literature review, personal contacts, brainstorming, and synthesis efforts a large number of potential deployable truss candidates were identified. These were judgementally evaluated against Level "0" criteria and screened to eleven candidates which offered good potential. These eleven candidates are pictured in Figure 4. A more detailed evaluation and screening

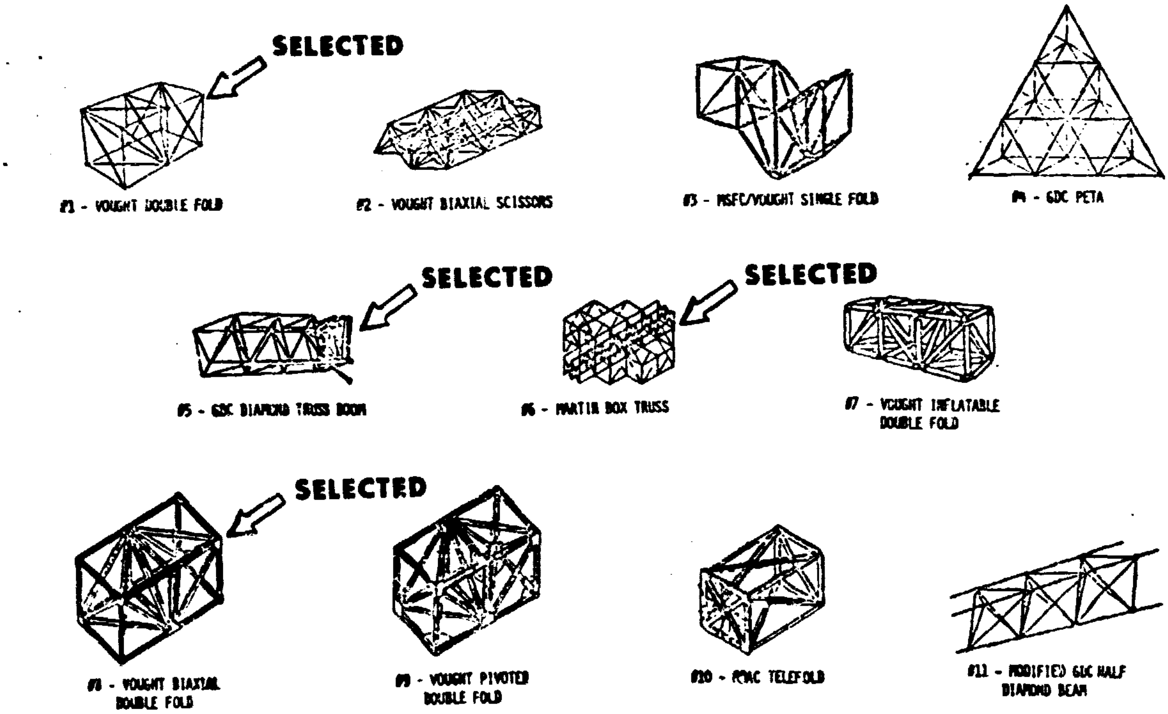

FIGURE 4 STRUCTURAL CONCEPTS EVALUATED

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TABLE 1 MAJOR ISSUES

ISSUE	ALTERNATIVES: SINGLE FOLD	VS DOUBLE FOLD	APPROACH
TRUSS FOLDING	• SMALL DEPLOYED/STOWED VOLUME RATIO (10:1-30:1) • ADEQUATE SOME MISSIONS • LESS COMPLEX • EASIER SUBSYSTEM INTERFACE	• LARGE DEPLOYED/STOWED VOLUME RATIO (50:1-300:1) • ADVANTAGE MOST MISSIONS - CAN ACCOMPLISH ALL • ONLY VIABLE CHOICE FOR LARGE STRUCTURES (10:1 LAUNCH COSTS)	• VOLUME RATIO MAJOR TRADE PARAMETER • PREFER VERSATILITY FOR BOTH

ISSUE	ALTERNATIVES: FULLY INTEGRATED	VS PARTIALLY INTEGRATED	APPROACH
UTILITIES INTEGRATION	• UTILITIES BUNDLES INTERNAL OR EXTERNAL TO STRUTS • MAXIMUM COMPACTNESS • PROVIDES PROTECTION • ADD-ON CAPABILITY • MINIMUM COMPLEXITY	• REELS AND/OR TRAYS INTERNAL OR EXTERNAL TO TRUSS • MINIMUM IMPACT TO TRUSS DESIGN • GENEROUS UTILITY BEND RADIUS FEASIBLE • ADD-ON CAPABILITY	• DESIGN FOR FULLY INTEGRATED • PROVIDE COMPATIBILITY FOR ATTACHMENTS TO STRAP-ON UTILITIES FOR 'TALL-POLE' MISSIONS

ISSUE	ALTERNATIVE: PAYLOAD INTERFACE MODULE	VS PAYLOAD INTERFACE TO TRUSS	APPROACH
PAYLOAD INTEGRATION	• NATURAL GROUPING PAYLOAD INTERFACE EQUIPMENT • SIMPLE MODULE-TO-TRUSS INTERFACE • ENVIRONMENTAL PROTECTION • SIMPLIES ORBITAL OPERATIONS	• ACCOMMODATES SMALL, LESS COMPLEX PAYLOADS WELL • MINIMIZES STOWAGE VOLUME • VERSATILITY IN PAYLOAD PLACEMENT	• DESIGN TO ACCOMMODATE BOTH ALTERNATIVES

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TABLE 1 MAJOR ISSUES (CONT'D)

ISSUE	ALTERNATIVE: SUBSYSTEM MODULE	VS	ALTERNATIVE: STRUCTURAL INTEGRATION	APPROACH
SUBSYSTEM INTEGRATION	• NATURAL GROUPING OF MAJOR SUBSYSTEMS • SIMPLE MODULE-TO-TRUSS INTERFACE • ENVIRONMENTAL PROTECTION • SIMPLIES ORBITAL OPERATIONS		• BEST DESIGN SOLUTION SOME SUBSYSTEM ELEMENTS • ACCOMMODATES DISTRIBUTED SUBSYSTEMS • MINIMIZES STOWAGE VOLUME • SHORTENS UTILITIES SOME CASES	• DESIGN TO ACCOMMODATE BOTH ALTERNATIVES

ISSUE	ALTERNATIVES: FULLY MODULAR	VS	ALTERNATIVES: MODULAR / SCALABLE	APPROACH
MODULARITY	• STANDARDIZED BUILDING BLOCKS • PROVIDE LIMITED CUSTOM TAILORING & SIZING • MINIMIZES DESIGN & FAB COSTS • SIMPLIFIES REUSE • INVENTORY OF STANDARD MODULES FOR MISSION INITIATION & EVOLUTION		• STANDARD DESIGN/ SCALABLE • GREATEST VERSATILITY, LEAST COMPROMISE • LOWEST COST LARGE STRUCTURE MISSIONS • INCLUDES STANDARDIZED BUILDING BLOCKS AS SUBSET	• DESIGN FOR MODULAR/ SCALABLE • DO NOT PRECLUDE USE AS STANDARD BUILDING BLOCKS WHERE BENEFICIAL

procedure was applied to the eleven. Each was scored against 22 individual criteria relating to platform capability, deployability, versatility, subsystem/payload integration, and performance/maturity. By weighting the criteria and comparing the concepts in a matrix, a systematic and traceable selection of the four most promising candidates was obtained. (Section 2.4 of this report presents the detailed scores and weighting factors.) Figure 4 also indicates the four selected:

Biaxial Double Fold (BADF)

Double Fold (DF)

Square Diamond Beam Truss (GDC)

Box Truss (MMC)

Each of these four packaged compactly, offered good potential for automatic deployment/retraction and utilities integration, and appeared to have promise for versatility of application.

The next step of the deployable platform study was to conduct design and analytical trades on the four surviving truss concepts. These entailed design studies of utilities, subsystem and payload integration, and branching/assembly interfaces for evaluation of versatility in assembly of deployed modules into very large structures. Parametric structural and thermal analyses were performed to support the trades, and a materials selection study was conducted with the result that all structural sizing was carried out on high modulus graphite/epoxy typified by GY70/X30. Cost trades were also conducted, which identified differences due to both fabrication and Shuttle launch. Based on the trade results each of the four deployable truss concepts was scored against 26 individual criteria relating to the same five major capability categories applied earlier in screening and enumerated above. Again, weighting factors were assigned and a final ranking was determined. Table 2 is a summary of relative rankings of the four candidate concepts in each of the five major categories. (The detailed trade matrix showing weighting factors and individual scores is given in Section 5.3 of this report.) The Biaxial Double Fold was clearly superior in each major category, and the choice was not vulnerable to the assignment of weighting factors. It was selected for further definition during Part 2. The Table 2 chart also indicates the GDC Square Diamond Beam ranked second, the MMC Box Truss third, and the Double Fold fourth. This result was not so clear, as the totals of the weighted individual scores were within 1% of each other. Thus any firm choice of a runner-up would have to be subject to further evaluations and/or judgemental factors.

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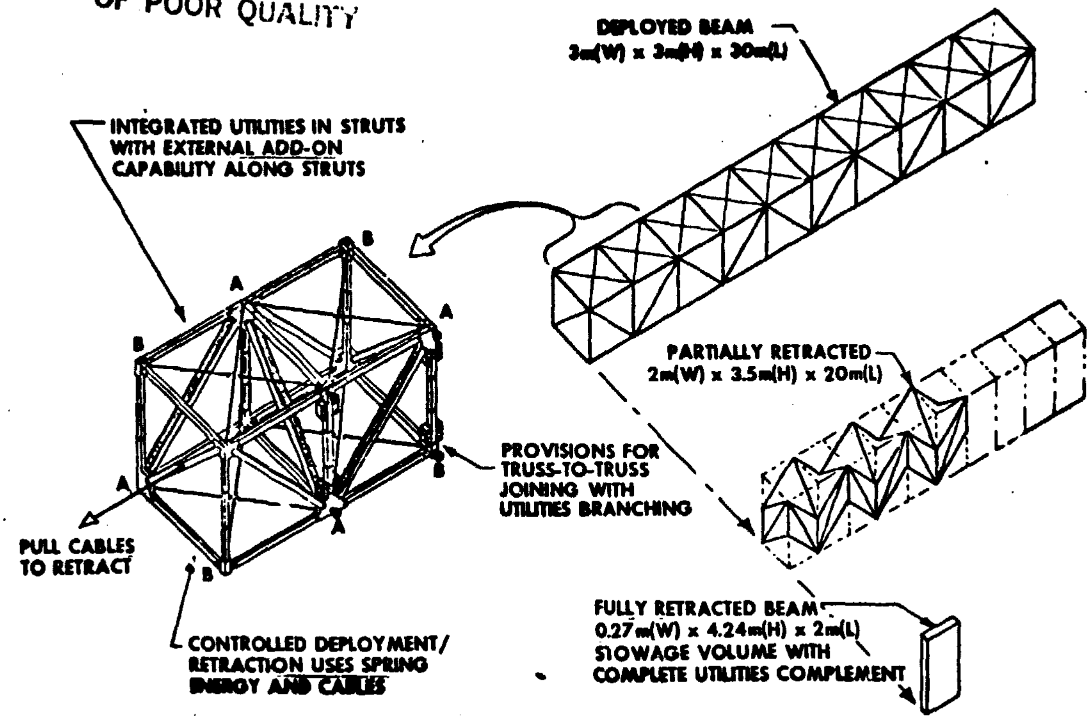
RELATIVE RANKING BY
MAJOR CRITERIA CATEGORY

CLEAR WINNER

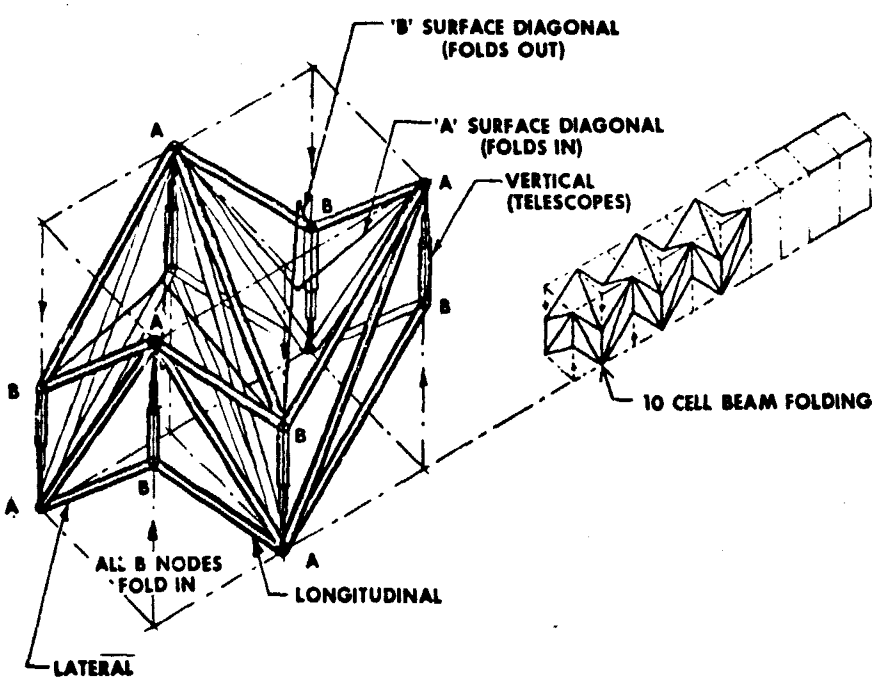
CRITERIA \ CONCEPT	VOUGHT DOUBLE FOLD	GDC DIAMOND BEAM	BIAXIAL DOUBLE FOLD	MMC BOX TRUSS	REMARKS
PLATFORM CAPABILITY	4	3	1	2	TOP DEPLOY/STOW VOL, MOST EFF. AREA PLATFORM ASSY.
DEPLOYABILITY	4	2	1	2	TOP RANKING IN FOUR OR FIVE SUB-CATEGORIES
VERSATILITY	4	3	1	2	DEPLOY AND/OR ASSEMBLE MORE SHAPES WITH LEAST EVA
INTEGRATION	2	4	1	3	CONCEPT CONCEIVED FOR EFF. UTILITIES, SUBYS., & P/L INTEG.
PERFORMANCE	3	2	1	4	FEWEST PIECES MINIMIZE WEIGHT, COST, COMPLEXITY

TABLE 2 CONCEPT TRADE SUMMARY

An overview of the characteristics and capabilities of the selected BADF concept is given by Figures 5 through 12. The general arrangement of a typical 3m square beam with a full complement of utilities integrated inside the struts is summarized by Figure 5A. The ten cubical cells illustrated fold from the 30m deployed length into a 0.27m x 4.24m x 2m package. The sketch also illustrates the folding scheme of the BADF. The truss folds simultaneously in two directions by telescoping the vertical struts and pivoting the bulkhead and side diagonals. All cells in the truss fold at the same time. This folding scheme minimizes the number of joints and the stowage volume. It results in a package height equal to diagonal length (1.41 x length of verticals for a cubical cell). Figure 5B is an enlarged view of a 2-cell unit, showing the folding configuration of the top and bottom surface tension diagonals. Only two types of nodes are involved in the BADF concept; "A" nodes to which all diagonal struts are attached, and "E" nodes. Figure 5A also indicates the method used to energize the deployment and retraction. Deployment is by a combination of energy stored in linear springs located in the verticals and torque springs at the ends of each longitudinal. Tension on



(A) GENERAL CHARACTERISTICS



(B) FOLDING ARRANGEMENT

FIGURE 5 FEATURES OF SELECTED BADF STRUCTURE a cable system provides an opposing force for controlled deployment and retraction. A single reversible cable drive motor actuates the entire deployable truss section. The figure also indicates the utility integration approach, where a full complement of utilities for a large deployable platform system such as the ASASP can be routed through the hollow longitudinal struts. Additional space is available for an equal quantity of add-on utilities mounted external to the longitudinal struts should that be desirable for some subsequent mission. Provisions for utilities and mechanical connectors, which will be necessary for branching of truss sections and payload interfaces, can be located on the sides or end of a truss section.

Figure 6 shows additional details illustrating, to scale, the position of the members before and after folding. In the top view the hollow

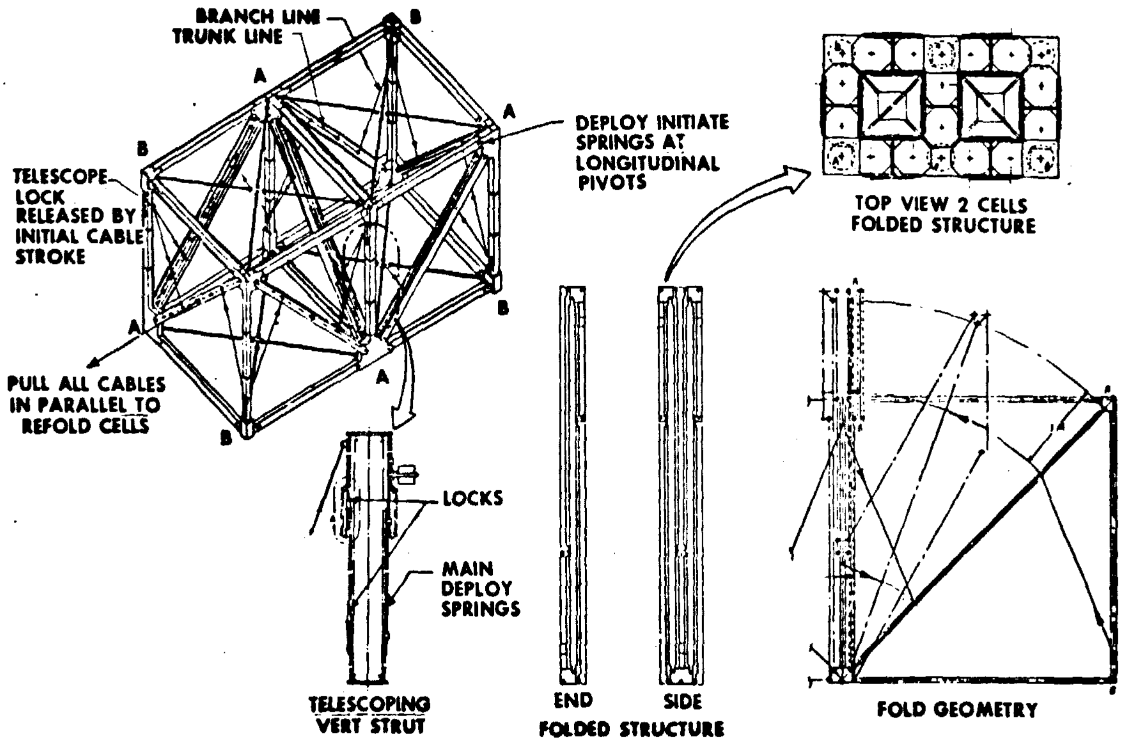


FIGURE 6 DEPLOYMENT/RETRACTION CONCEPT FOR BADF

octagonal cross-section of the longitudinal and lateral struts can be seen, providing space for the internal utilities routing and enhancing the nesting characteristics. Diagonals are of "H" section and can be seen nested around the octagonal struts. Further definition is also given to the telescoping vertical struts and cable system as noted in the figure. The cable system consists of two trunk lines, one running through the face diagonals on either side of the truss, and a triad of branch lines at each vertical. Application of motion to the trunk lines actuates each of the branch triads. All the branches operate in parallel. As motion is imparted to the branch lines a lock is first released on each vertical strut, and then the strut is compressed. The location of the branch line tie-in s on the diagonals is such that a moment is applied to the diagonal strut to assist folding.

Figure 7 summarizes the utility integration and interface concept. The representative utility bundles indicated were derived from ASASP requirements, and provide some additional capabilities above that. The concept

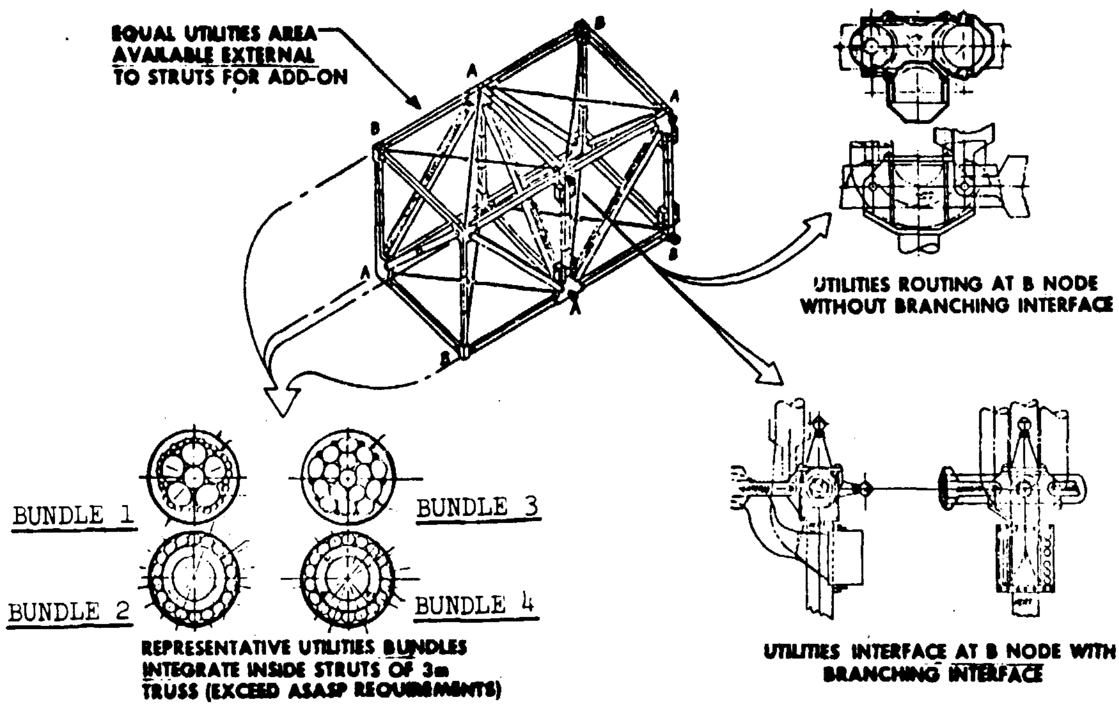


FIGURE 7 UTILITIES INTEGRATION CONCEPT FOR BADF

for routing of utilities through nodes is illustrated by the B-node design sketched in Figure 7. The bundle bend radius to diameter ratio shown is about unity, which was the minimum value used in our design studies. This value was found to be acceptable from our element tests for both bending moment and cycle life (200 cycles or greater) considerations. The interface concept at a

B-node is also shown, where utilities are branched from the opposite A node, routed through the bulkhead lateral strut, and then passed under the utility in the B-node longitudinal to a floating connector fixed to the vertical strut. The connector shown is sized for electrical and fiber optic cables; the design is also compatible with fluid quick disconnects. The interface concept at A nodes is similar, only branching is directly from the A node rather than through a crossover from the opposite side of the truss.

Figure 8 shows the types of truss-to-truss and truss-to-module interfaces possible. With the interface design described in conjunction with

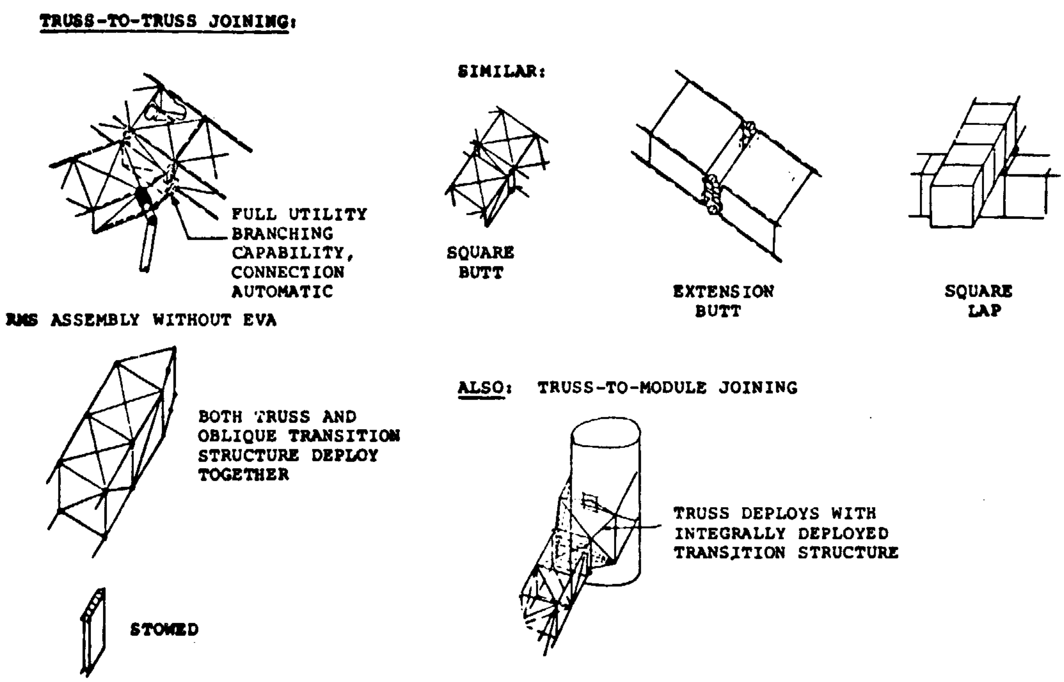


FIGURE 8 MODULE DEPLOYMENT ASSEMBLY WITH BADF

Figure 7, the truss joining is accomplished in two steps. First, the truss branches to be joined are maneuvered together using the RMS until capture and hard lock is accomplished at four nodes by the mechanical node-to-node Autolock Coupler (male side shown in Figure 7). Second, an electrically powered utility connector plate (not shown) pulls together the connectors, with the aid of alignment pins, completing the mating operation. As indicated in Figure 8, various types of square, oblique, and size-change interfaces are possible without the addition of separate interface structure. This results from the peculiar capability of biaxially deploying trusses to integrally deploy oblique or size-change transition structure.

Figure 9 illustrates the capability of the BADF truss to be directly deployed or assembled into a variety of shapes. For example, the indicated fully deployable hoop folds into a diameter about 1/20th its deployed diameter.

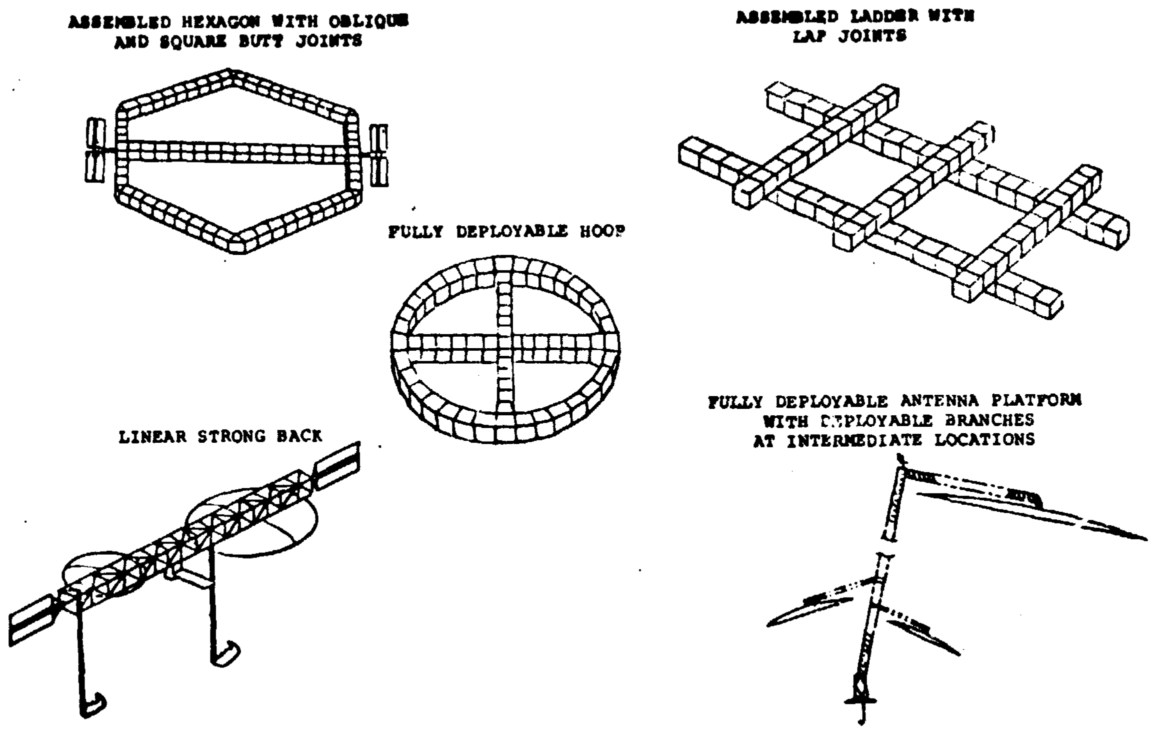


FIGURE 9 CONFIGURATION VARIABILITY OF BADF

This characteristic also makes the BADF a candidate for deploying volume shapes, to be discussed later. Another useful capability is its ability to deploy as a mast, with intermediately situated payloads or deployable branch arms pre-attached and deployed simultaneously. Figure 10 further illustrates this latter capability, where rigid structure such as an equipment item or a

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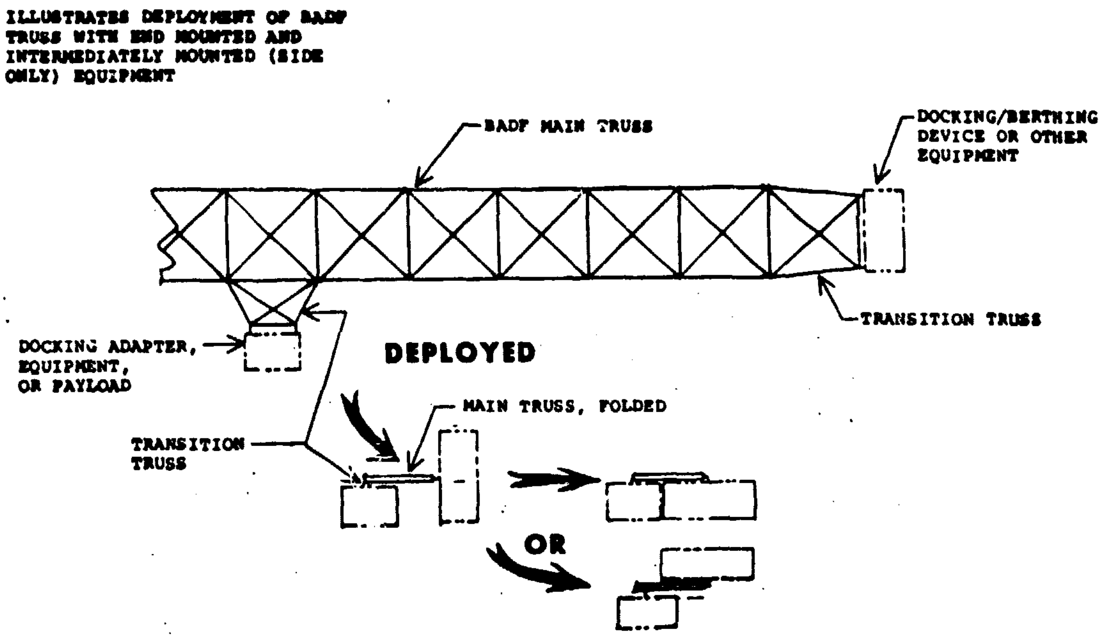

FIGURE 10 BADF SUBSYSTEM AND PAYLOAD INTERFACE

docking adapter is located on one end and a side of the BADF main truss. (The indicated equipment item could as well be another folded truss.) The equipment items are attached to the two ends near the nodes of either a side or an end diagonal of the main truss when stowed. As deployment is completed the equipment interface picks up couplers at one or two additional nodes to complete rigidization of the interface.

Figure 11 shows an additional example of use of the BADF as a redeployable mast on a Geostationary Platform. The truss is folded into a flat pallet configuration, with the ends of the first, third, fifth, etc., bulkhead diagonals positioned in guide rails which are situated transverse to the platform core. As the truss deploys, the second, fourth, etc., bulkhead diagonals rotate 90° and the couplers on the first bulkhead root nodes

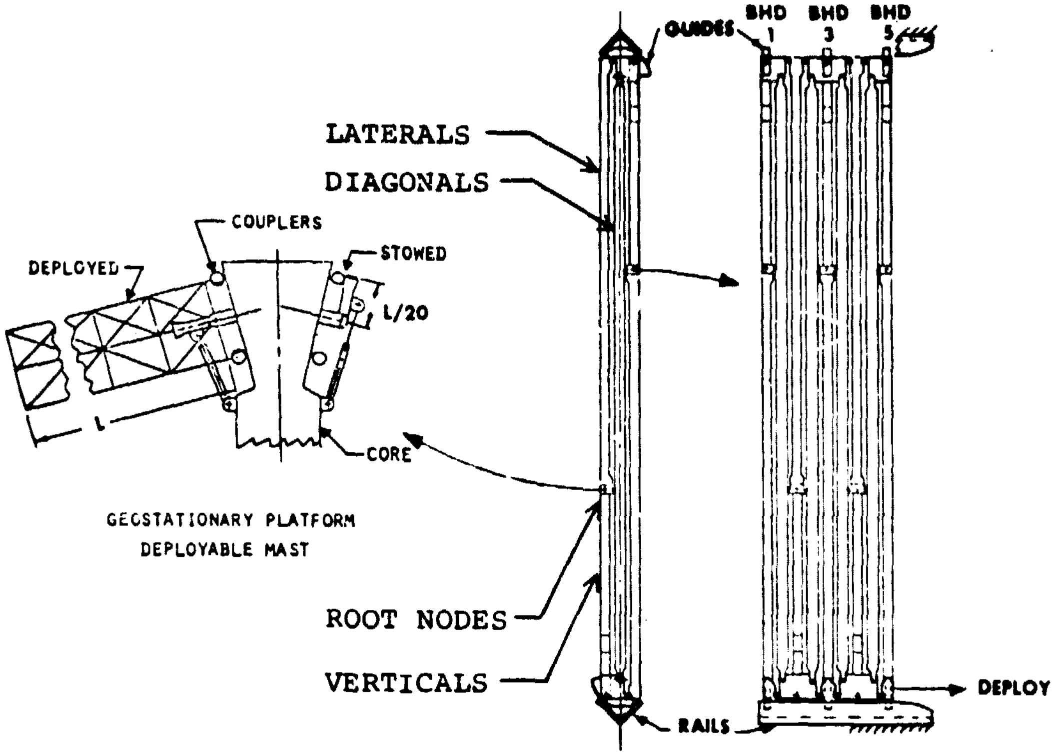

FIGURE 11 BADF REDEPLOYABLE MAST ON GUIDE RAIL SUPPORTS

engage the mating halves on the core structure. Additional rigidity can be obtained from the guide rail, if required, by extending it to maintain contact with the third bulkhead diagonal throughout deployment. The stowed configuration is shown on the right side of the platform core, where an extensible arm and pivot are indicated to provide compact packaging.

Figure 12 shows the capability of these configurations of the BADF to fit in the Shuttle Orbiter cargo bay. As noted, the dimensions shown assume the Shuttle is not weight constrained, which is the case with a full cargo bay in low earth orbit if only a modest amount of utilities are integrated into the structure. The longest single continuous beam of a 3m x 3m truss which can be stowed is 276m. The folded package would be about 0.27m x 4.24m x 17.8m. To obtain a maximum assembled truss length, 44 modules of 3m x 3m x 45m

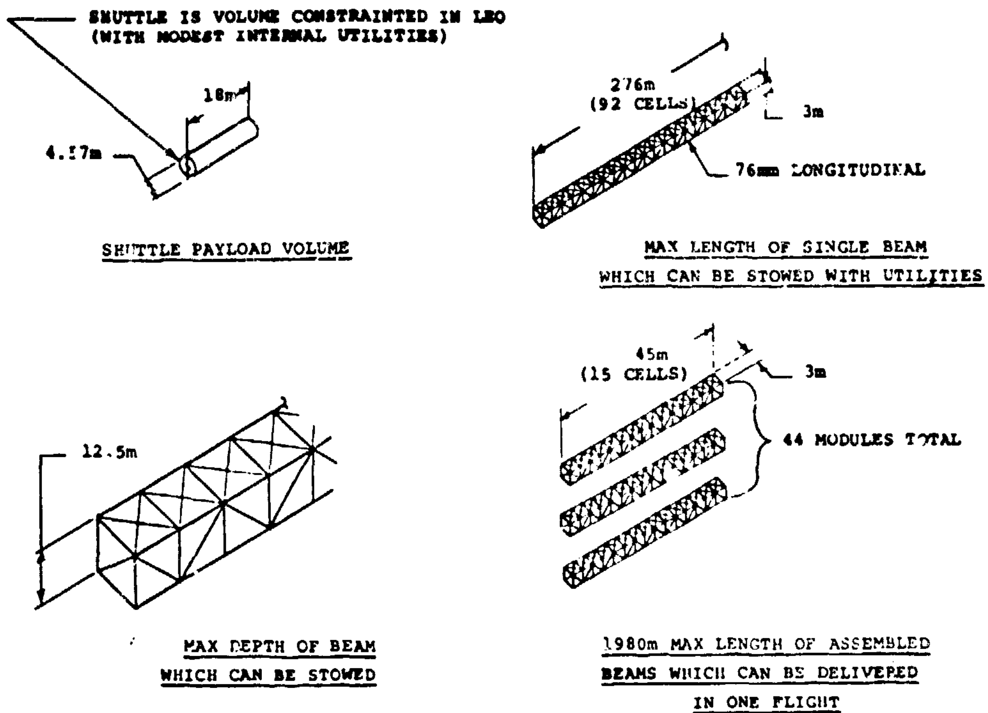

FIGURE 12 SHUTTLE COMPATIBILITY OF BADF

deployed dimensions can be assembled in orbit to result in a total length of 1980m. To fit in the cargo bay the 44 modules are folded and stacked into four packages of eleven: each package 3m x 3m x 4.24m. Also indicated by the figure is the maximum crossection beam of 12.5m square which will fit into the cargo bay.

An important result of the Part 1 study was that six special technology development items were identified and are recommended to enhance the effectiveness of deployable platform system concepts.

- Compact, Low Pressure Drop, No Leak Fluid Q.D.
- Materials and Design Concepts Suitable for Tailored Low CTE in Minimum Gage Struts and Composite Fittings Applications

- High Flexibility, High Endurance Life Electrical Cables Suitable for Small Bend Radius
- Super-flexible Fluid Hose with High Endurance Life and Suitable for Small Bend Radius
- Compact, Low Loss Fiber Optics Tees
- Low Solar Absorptance, Low Emittance Thermal Coatings

In Section 4.0 a description of each of these technology development needs is presented and a development plan is outlined.

Deployable Volumes

Several types of deployable volumes were considered in the concept identification task. Table 3 summarizes the concepts, their potential applicability, indicates their principal characteristics and limitations, and identifies those selected for evaluation. The most promising concept for manned habitat and OTV hangar applications was found to be a deployable truss approach with a bladder for pressure containment and an exterior thermal/meteoroid blanket. Two flexible concepts were identified as offering potential for tunnels, a convoluted design and an inflated cylindrical shell design.

Figures 13 through 15 illustrate the recommended concepts for the volume concepts which use deployable trusses. Figure 13 indicates the arrangement of the manned habitat concept. It consists of a deployable truss structure to which a thermal meteoroid protection layer blanket is added on the outside and a pressure bladder on the inside. A rigid interconnecting structure interfaces the deployable truss. This type of deployable volume is applicable to a truss that is bidirectionally deployed, such as the Biaxial Double Fold or the Martin Marietta Box Truss. When the deployed volume is folded, it shrinks in diameter and also in the thickness of the truss structure. On the right hand side of the figure is shown the stowed configuration. Depending on the nature of the truss used, the length of the stowed configuration is either the same as the deployable configuration or longer as is the case with the Biaxial Double Fold. It is shown here that the pressure bladder stows inside the folded structure. It is possible to obtain a 16:1 diameter ratio when deploying the truss structure. This enables a much larger deployed volume to be used in the diameter constraint of the Shuttle cargo bay. Also illustrated in Figure 13 is the deployment and assembly sequence. It is seen that the stowed structure is first expended and that the bladder is secured, then the interconnecting hard structure for the entrance

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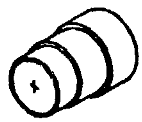
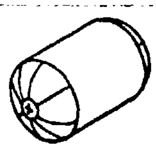
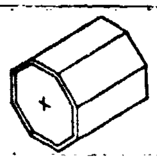
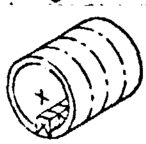
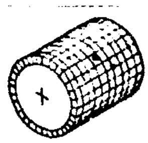
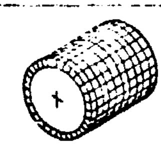
CONCEPT	POTENTIAL APPLICATION			REMARKS
	TUNNEL	HABITAT	HANGAR	
TELESCOPING TUBES 	√	---	---	. CABLES IN PARALLEL ADJUST LENGTH . ROLLING DIAPHRAGM SEALS . AIR LOCK OPTIONAL ON SMALL END . SIMILAR TO SHUTTLE DOCKING MODULE . NOT SELECTED TO PURSUE
FLEXIBLE CONVOLUTED TUBE 	√	√	---	. RIGIDIZED BY FRAMES & LONGITUDINAL CABLES . CABLES ADJUST LENGTH/CURVATURE . 4.5m MAX DIA, 120m MAX LENGTH . SELECTED TO EVALUATE
FLEXIBLE STRAIGHT TUBE 	√	√	√	. UNITIZED STRUCTURES - NO FRAMES/CABLES . NO DEPLOYED SIZE ADJUSTMENT . AS BLADDER FOR HANGAR OR HABITAT WITH INTERNAL/EXTERNAL SUPPORT STRUCTURE . SELECTED TO EVALUATE
FOLDING PANELS 	√	√	---	. LOW DEPLOY : STOW RATIO . MANY SEALS IF PRESSURIZED . TOO SMALL FOR OTV HANGAR . NOT SELECTED TO PURSUE
RIBS AND BACKBONE 	---	---	√	. UNPRESSURIZED HANGAR . THERMAL/METEOROID PROTECTION BLANKET . BACKBONE TRUSS & RIBS FOLD . MINIMAL STIFFNESS & WEIGHT STRUCTURE . NOT SELECTED TO PURSUE
DEPLOYABLE TRUSS SEPARATE BLADDER 	√	√	√	. BADF OR MMC RIGID TRUSS SUPPORT . THERMAL/METEOROID BLANKET SPACED FROM BLADDER BY TRUSS . BLADDER & BLANKET ATTACHED AFTER DEPLOY . SELECTED TO EVALUATE
DEPLOYABLE TRUSS ATTACHED BLADDER 	√	√	√	. MMC TRUSS FOR CONSTANT LENGTH . BLADDER & BLANKET DEPLOYED WITH TRUSS . SELECTED TO EVALUATE

TABLE 3 DEPLOYABLE VOLUME CONCEPTS CONSIDERED

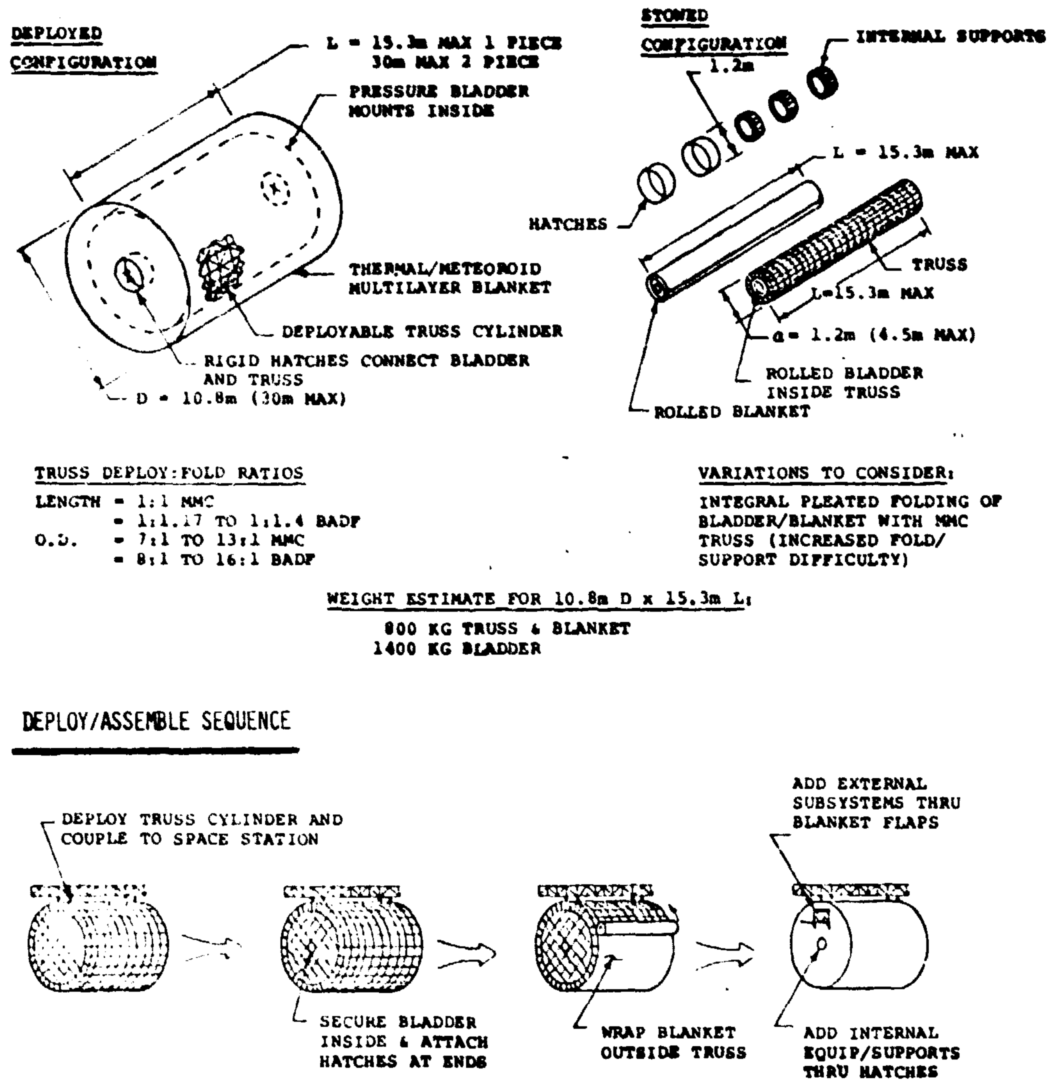


FIGURE 13 RECOMMENDED CONCEPT FOR HABITAT

to the deployed volume is added. Following that, external subsystems are added through access doors in the thermal meteroroid blanket. Internal equipment has to be added through the entrance hatch and therefore it must be of a size that can be inserted through the hatch or it must be deployable.

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Internal structure such as decks is assumed to be deployable structure and would be deployed subsequent to insertion into the volume.

Figure 14 gives a more quantitative illustration of the deployable truss structure. It is possible to simultaneously deploy the cylindrical section and the flat end part. Also shown in Figure 14 is a representative

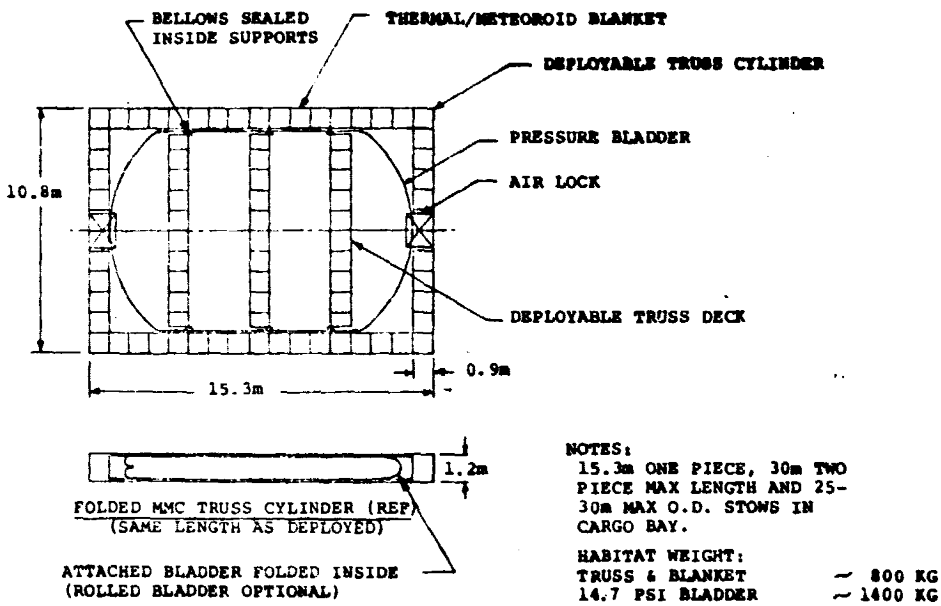


FIGURE 14 SILO CONCEPT - DEPLOYABLE HABITAT

location for the truss deck. Internal structure may be mounted either as shown or horizonally inside the deployed volume. Also illustrated is the bladder concept, where the bladder is inside the structure. With the Martin Marietta Box Truss it would be possible to preattach the bladder internal to the structure because there is no length change during deployment. Also, it may be possible to preattach the meteoroid thermal blanket on the outside of the structure. In this concept all the pressure loads from the bladder are taken as hoop tension in the bladder itself. The structure serves as interface between other Space Station structure as well as a mounting platform.

Figure 15 shows the deployable truss volume concept rendered as an OTV hangar. In order to get the desired length it will be necessary to deploy the structure in two sections. As indicated in Figure 15, the two sections will be linked together similar to a clam shell. For a pressurized hangar a pressure bladder with a seal at the door interface will be provided. For an unpressurized hangar no bladder would be required. With the pressurized hangar concept, stowage of the bladder involves collapsing the seal frame into a folded structure and rolling it inside the pressure bladder. This would require insertion of the bladder into the deployed volume after the volume has been deployed, using EVA and the RMS. The Orbital Transfer Vehicle could be docked onto the structure at one end. Other docking concepts could be used, such as a track or rail down the side on the interior of the deployed volume.

Figure 16 illustrates the two flexible tunnel concepts we recommended for further study. The first concept is the convoluted tube. It is based on a concept developed previously under study by the Goodyear Aerospace Corporation (Ref. 3), and has been demonstrated in scale prototype form. The other flexible concept is a straight cylindrical tube. This tube can be collapsed in diameter and rolled into a smaller volume which allows it to be used for a bladder with deployable structure. It could also function as a separate deployable structure if all the meteoroid and thermal protection were added directly onto the flexible tube. This concept has also previously been studied by Goodyear. A large scale model has been tested.

Figure 17 summarizes the potential benefits of the deployable volume concept to the NASA-MSFC Phase III Science and Applications Manned Space Platform (SAMSP). In the original SAMSP concept five Shuttle launches are required to place the four habitability/experiment modules and OTV hangar into orbit. It is seen from this figure that a greater volume of habitability/experiment space and an OTV hangar can be launched dry in 1/2 of one Shuttle flight using a deployable volume. The equipment used to outfit the deployable habitat/experiment module, packaged at the same density as in the four baseline rigid modules, can be transported in somewhat less than 1-1/2 Shuttle flights. Thus, the total requirement for the deployable modules is two Shuttle flights, compared to five for the equivalent baseline SAMSP modules. A systems trade would be necessary to determine the overall advantage, considering the EVA/IVA operations necessary to outfit the deployable volumes with equipment.

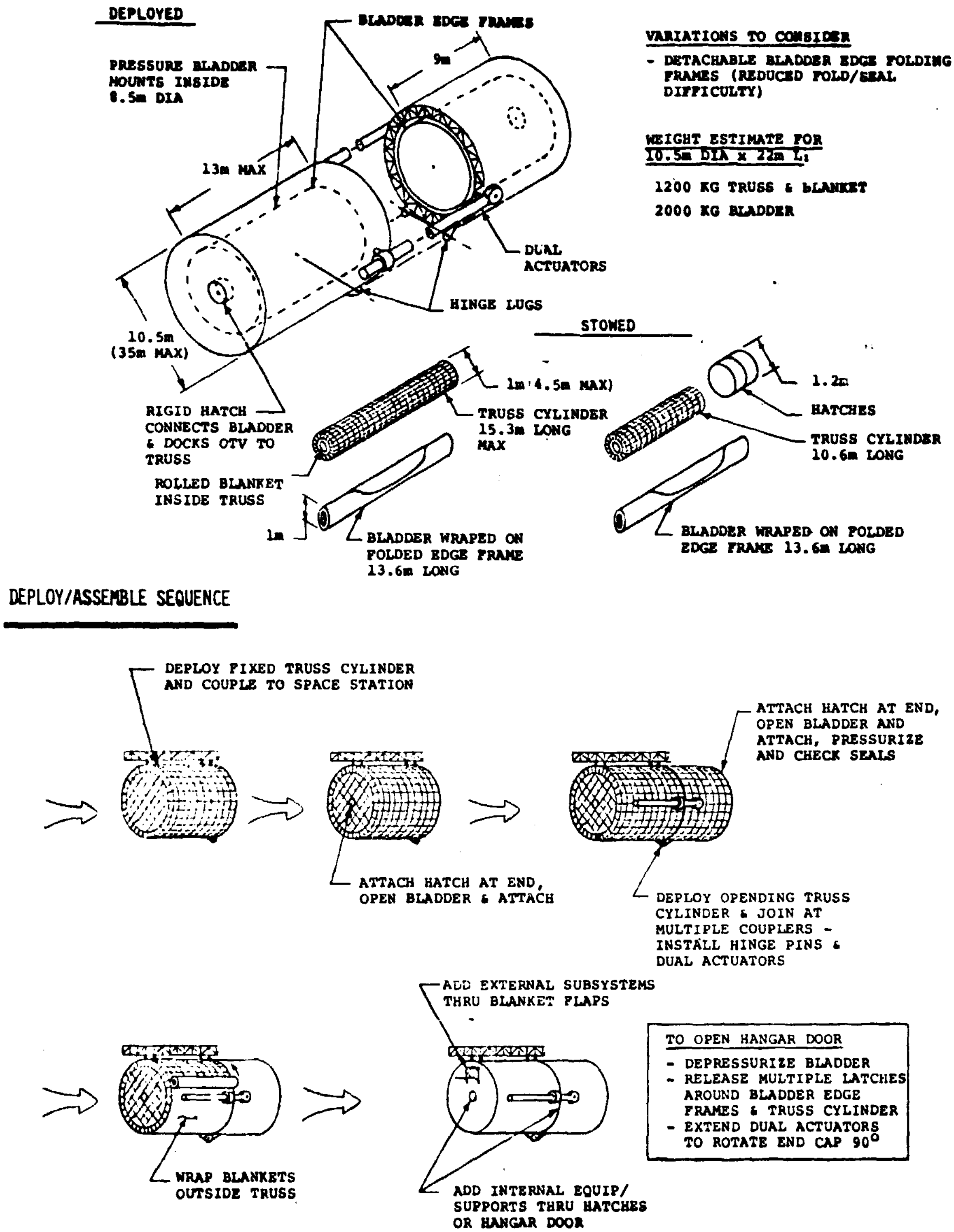
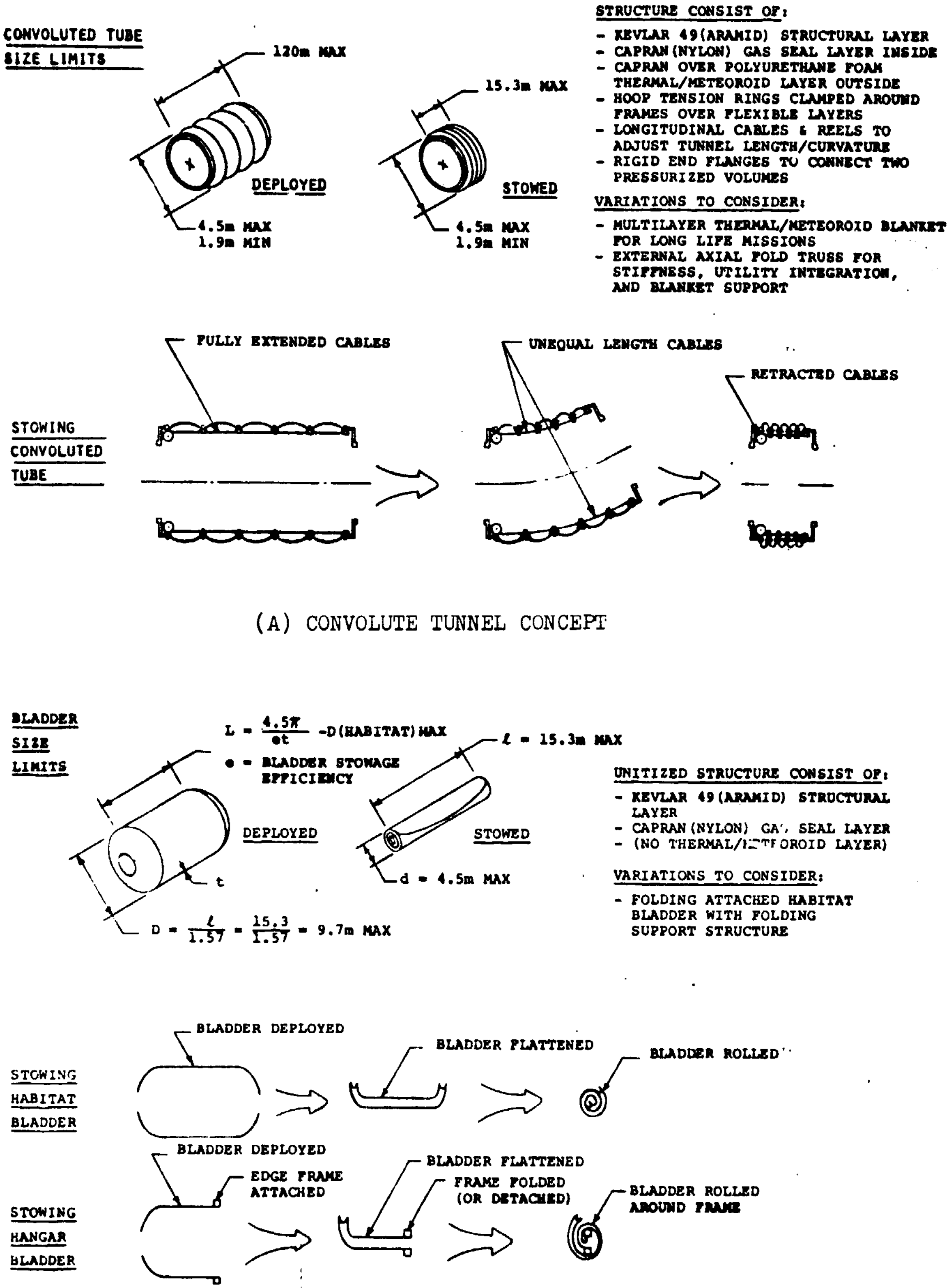


FIGURE 15 RECOMMENDED CONCEPT FOR OTV HANGAR



(A) CONVOLUTE TUNNEL CONCEPT

(B) HABITAT/HANGAR BLADDER CONCEPT

FIGURE 16 FLEXIBLE CONCEPT RECOMMENDATIONS

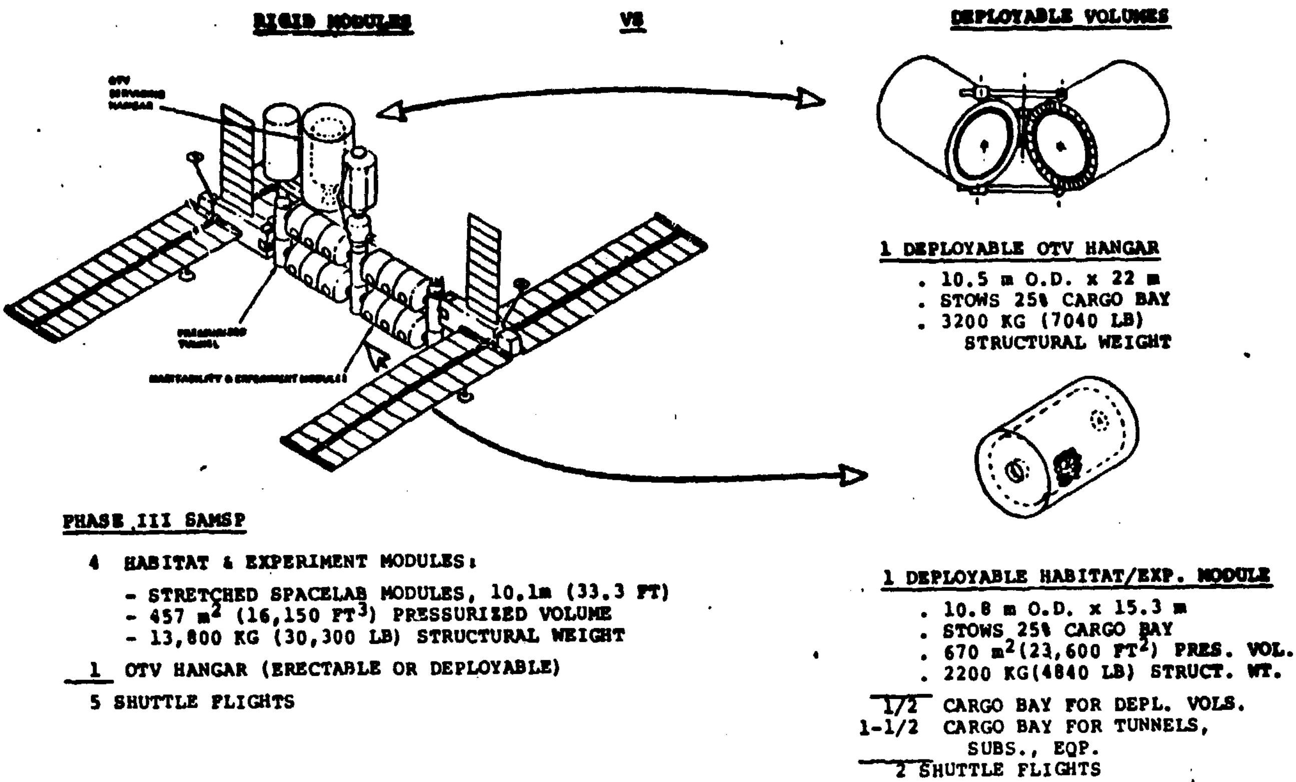


FIGURE 17 DEPLOYABLE VOLUME LAUNCH BENEFITS

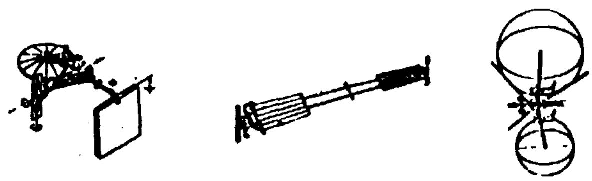
One of the important elements of carrying out the study was the securing of information on prior and on-going work. In addition to literature surveys, National conferences, and our existing library of information at Vought, much information has been provided to us from outside sources. Inputs on Inflatable Structures were provided by L'Garde and Goodyear. Martin Marietta furnished information on their Box Truss design, General Dynamics on the Diamond Truss Beam, and AEC-Able Engineering and Astro Research Corporation on their deployable booms. Significant inputs have also been obtained from NASA-Langley Research Center and Marshall Space Flight Center as well as Boeing, Lockheed, McDonnell Douglas, Union Carbide and Celanese Corporation. All these inputs have enhanced the current study by providing an up-to-date and in-depth basis for evaluating existing designs and evolving new concepts.

2.0 CONCEPT DEVELOPMENT

This section describes requirements, the procedure used for concept development, and the screening, selection and characterization of the concepts. It further includes the integration of utilities, subsystems and payloads into the structural concept design. Supporting efforts carried out under other contract tasks such as materials selection, technology development needs and the final concept selection are covered in subsequent sections of the report.

2.1 REQUIREMENTS FOR LINEAR AND AREA DEPLOYABLE PLATFORMS

The objectives of the requirements task were to establish guidelines, requirements and top level criteria for performing concept selection and trade studies. The emphasis was to develop generic requirements, not specific to any particular mission. However, close consideration was given to the three focus missions defined in the contract Statement of Work. Other sources of information were the supporting systems studies that were done prior to the focus mission definition studies, and other activity on large space platforms available in the literature, as well as standard specifications and handbooks on environments, Orbiter interfaces, etc. Our approach was to identify the available requirements data from these documents, then develop other key information not available in the documentation, as required. The ultimate purpose of the requirements is to provide a minimum group of specifications against which each concept may be tested to assess its limitations during trade studies. The following top level guidelines and requirements were derived from consideration of the missions. First, the structure should perform as a platform. It should be suitable for space structures of size and stiffness in the range of missions examined. Second, it should be deployable. It should have the potential for controlled automatic deployment into a large structure using integral or external mechanisms. It should bascially be deployable with a minimum amount of EVA or RMS operations required. These operations should preferably be limited to module assembling and reconfiguration. Third, the stowed-to-deployed volume ratio should be such that the stowed volume is small enough to commit a minimum number of Shuttle flights. Fourth, the structure should be suitable of utilities integration and interfaces for subsystems and payloads, and should provide acceptable interaction with subsystems. Fifth, versatility is required to accommodate the focus missions or other missions through scaling of the basic structure and/or assembly of standarized modules. Thus it should allow reconfiguration to other missions and objectives. Another guideline which provided direction for this study was that area platforms would be considered as those made up of a combination of linear beams rather than a directly area-deployable structure. In addition, versatility should be provided for increases in power up to as much as 250 kW and to allow various configurations in large structures such as pyramidal shapes, hoop shapes, ladder shapes, or linear beams to be assembled from deployable truss modules. In addition it is desirable to allow capability for subsequent add-on of utilities in excess of those provided integral to the truss structure. Another important guideline was to emphasize deployability. While the principal guideline in the deployable area trusses was to build the area platforms from a combination of linear trusses, it was also recognized that it would be a major advantage if one structure could accommodate a number of missions, such as linear and area platforms, antennas and feed masts. Thus consideration was given to the capability of the structure to deploy as an area as well as a linear platform during initial screening effort. Figure 18 gives an overview of the three focus missions.



	ASASP	SPS	GSP
ORBIT	LEO-500 km	LEO 400-500km	GEO
PAYLOAD TYPE	SCIENCE	MICROWAVE EXP.	COMMUNICATION
OVERALL SIZE OF MAJOR DIMENSION (M)	160 x 82	20 x 215	17 x 27
TOTAL MASS (kg)	80,553	37,864	6,800
PERCENT STRUCTURAL MASS	18	2	23
POWER (kW)	50	490	10
DATA (Mbps)	20	50	ND
POINTING (DEGREES)	1	3-8	0.05-0.1
MINIMUM FREQUENCY TO MEET STIFFNESS REQUIREMENTS (Hz)	0.1	0.004	0.148

FIGURE 18 REVIEW OF FOCUS MISSIONS

The first is the Ref. (1) Advanced Science and Applications Space Platform (ASASP); the second is the Ref. (4) Solar Power Satellite (SPS) Test Article II; and the third is the Ref. (5) General Dynamics Geostationary Platform (GSP), Alternate 1, Platform 1. It can be seen from the figure that ASASP and the SPS Test Article II are both very large structures and both are flown in low earth orbit (LEO). The GSP is a fairly small platform and is separated from the Shuttle in low earth orbit. It is partially deployed in LEO, then boosted to GEO where complete deployment occurs. In the systems studies which defined these three spacecraft, the ASASP and GSP are both baselined as deployable structures (with some assembly required for the ASASP). The SPS Test Article II was baselined in the system study as a space fabricated structure. The objective in the current study, then, was to evaluate its requirements relative to deployable structures. Other than size, some of the significant differences between the three focus missions listed in Figure 18 are the large variations in power and in pointing accuracy. The GSP, which is a communication antenna platform, requires very accurate pointing. The ASASP requires only 1^{o} pointing accuracy because its more stringent accuracy requirements are accommodated by five independent pointing equipment packages mounted in the payload support structure. The SPS Test Article II does not have any inherent fine pointing needs. Also the stiffness requirements are similar for the ASASP and GSP platform, while the SPS Test Article II has a very low stiffness requirement. As the study evolved the SPS requirements were de-emphasized because it is less likely that this mission will evolve in the near future.

In Figure 19 are plotted stiffness requirements derived from the three focus missions as well as two other missions. Because the GSP Alternate 1 is a relatively small satellite and is fully deployable it was desired to also consider a larger version of GSP platform. GSP Alternate 4 (Ref. 5) was chosen as it has the advantage of also being well defined, and is designed to be partially deployed and partially assembled. GSP Alternate 4 is separated from the Shuttle in LEO, then 3 different modules are transported to GEO orbit at which point they are assembled. Other than the additional GEO platform it was desirable to consider the Ref. (6) Science and Applications Space Platform (SASP). This is a more near-term version of the ASASP and has been well defined by systems studies. Its requirements are included in Figure 19. Figure 19 has equivalent truss cube width as its abscissa. (Equivalent truss

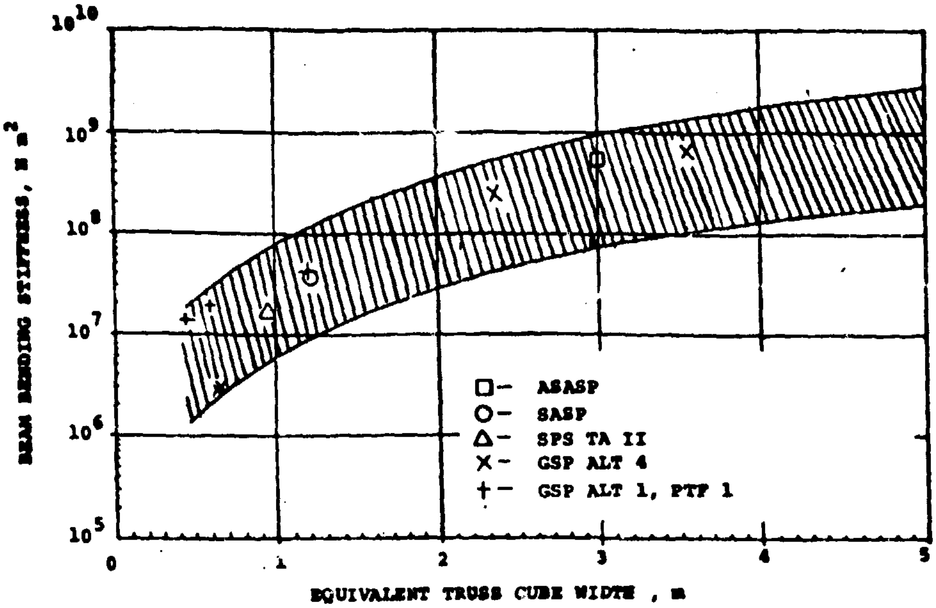


FIGURE 19 STIFFNESS REQUIREMENTS

cube width is defined as the width of a square cross section truss which will just fit inside a circle circumscribed around the truss geometry of interest.) It results that the equivalent truss cube width is 0.707 multiplied by the diameter of the circle that just fits around a diamond or triangular truss. The ordinate in Figure 19 is the beam bending stiffness in Nm^2. The plotted band shows a wide range of stiffnesses, between about 10^6 and $10^9 Nm^2$. It is also seen that the sizes of the equivalent truss cubes are between approximately 0.5m and 3.5m in width. The upper end of the scale is defined by the GSP Alternate 4 and the ASASP. The lower end requirements are derived from both GSP alternates. A similar plot of strength requirements is given in Figure 20. Again the abscissa is equivalent truss cube width in m while the ordinate is beam bending strength in Nm. The band is wide, as can be observed

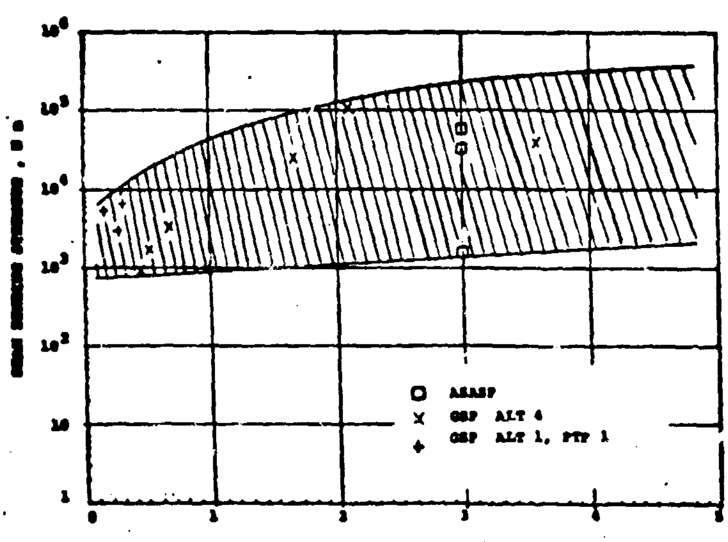


FIGURE 20 STRENGTH REQUIREMENTS

from the figure, and ranges from about 10^3 to 10^5Nm. In most cases stiffness requirements rather than strength requirements sized the structure in the system concepts reviewed. Also in certain cases, especially the ASASP, it was necessary to derive strength requirements in addition to the information contained in the focus mission documentation. The points for ASASP strength were obtained from consideration of orbital acceleration with the maximum payload weights.

Figure 21 shows utilities requirements derived from consideration of the previously mentioned missions. The requirements indicated are for total crossectional area. The maximum utility requirement identified was for the GSP

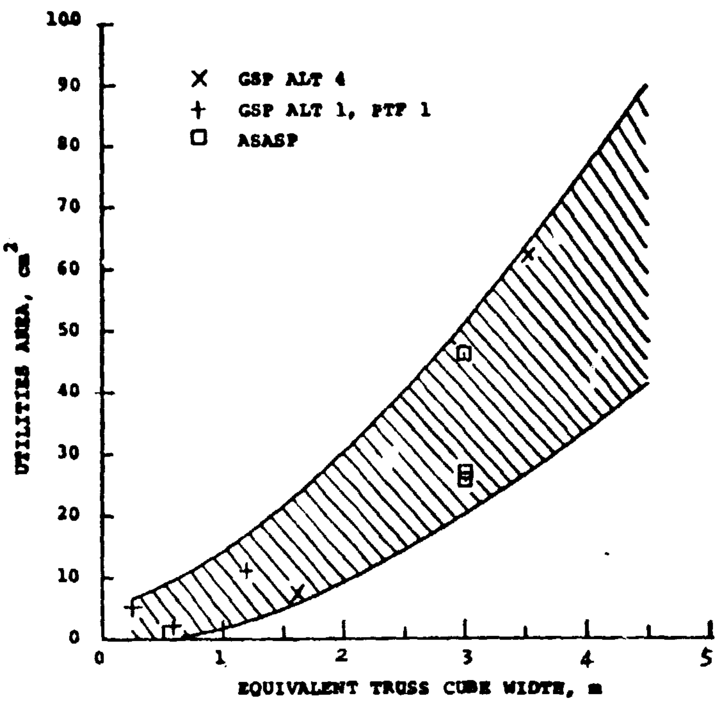


FIGURE 21 UTILITIES REQUIREMENTS

Alternate 4 which required a total area (including fluid, data and power lines) of about 65 sq.cm. The second most severe requirement resulted from consideration of the ASASP. GSP Alternate 1 requirements are very minimal. It was assumed in the current utilities integration studies that total areas could be divided into four separate areas and integrated into each of the four longerons.

Interface requirements were also extracted from a review of the missions. Attention was given to the question, "What type of interfaces contained in these studies are representative of those which might occur in other deployable platform systems, in order that generic requirements might be identified?" By taking the point of view that the deployable structure requirements should keep open to as many future options as possible, the interfaces shown in Figure 22 and listed below were identified:

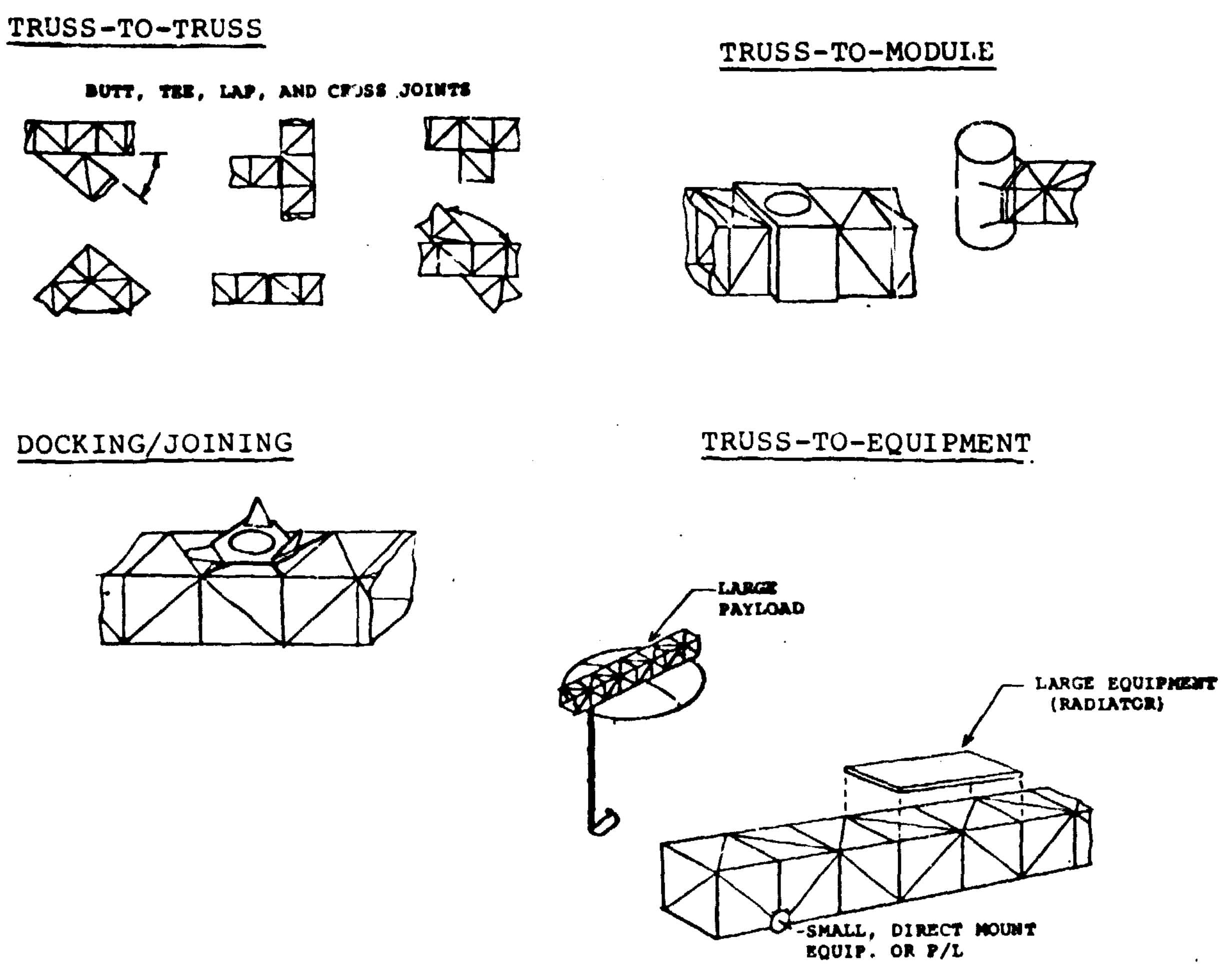


FIGURE 22 TYPES OF INTERFACES

1. Truss-to-Truss Interfaces joining two sections directly, without a docking adapter. Various potential mission applications exist where it would be desirable to build up

large linear and area platforms by assembling deployable truss modules. Interface considerations include the type of coupler used, such as the Autolock or Side Latching couplers previously developed in Ref. (7), interfacing structure to accommodate oblique angles, utility routing and connectors. In addition, the interfacing trusses are not necessarily the same size. Types of joints involved are butt joints and lap/cross joints at various perpendicular and oblique angles.

2. Truss-to-Module Interfaces join a deployable truss section directly to a rigid section such as a subsystem module without a docking adapter. Several potential applications exist in the above missions where deployable truss arms are attached to a central core. Included are both designs in which the arms are attached prior to launch and only deployed on orbit, and designs in which the arms are assembled to the module on orbit using some type of coupler.

3. Docking/Joining Interfaces such as a standardized docking adapter and/or a rotary joint including transition structure. The distinction between this and the truss-to-module interface is that rigid non-foldable interface hardware is involved. This current study is concerned with how the deployable structure accommodates such hardware as this, and therefore uses only existing designs and concepts for docking adapters and rotary joints.

4. Truss-to-Equipment/Payload Interfaces including secondary structure (for example ASASP construction platform), subsystem elements and payload items which lend themselves to direct interfaces with the truss structure. Examples of small items which could be directly mountable to the truss are electrical junction boxes, RMS adapter plates, sensors and small strut/node mounted equipment items. Examples of larger items are radiator panels, antennas, or antenna feeds. In some cases the items will be located at an intermediate point on the structure. And in other cases may be end mounted.

The above interfaces may be accomplished by either of two ways: a) the interface is integrated with the deployable structure which may also be the interfacing item (for example, a deployable antenna payload on a deployable truss), or b) the interface is partially or fully erected or accomplished via RMS/EVA subsequent to the basic structural deployment operation. The latter is especially applicable in the case of large equipment items, payload or module changeout, or spacecraft on-orbit assembly/reconfiguration. To minimize RMS/EVA operations it is desireable that the truss structure/interface design lend itself to automatic deployment in as many cases as appropriate. This is true for both end mounted and intermediately mounted items.

Figures 23 through 27 gives some example interfaces. Figure 23 shows examples from the ASASP. A truss-to-truss direct interface intersecting at an oblique angle is seen between the central deployed structure and the left side portion of the structure. A truss-to-equipment interface at the construction platform is also indicated as are a payload berthing interface, a rotary joint interface, and a direct interface between a truss structure and a rigid module. Examples taken from the SPS TA II are given in Figure 24. Truss-to-equipment interfaces are shown where the solar blanket, junction boxes, and switch boxes interface with the truss structure. An example of a docking adapter interface is also given where the Auxiliary Propulsion System (APS) pod docks into the transverse beam structure. Another docking adapter interface is shown where the interface bridge docks into the longitudinal beams. It should be noted that this docking interface could be replaced with a truss-to-truss butt joint. An example of a lap joint is shown where the transverse and longitudinal beams cross. In Figure 25 interface examples from the GSP Alternate 1, Platform 1 are seen. An interface between a deployable truss and rigid module is illustrated where the Astromast beams interface a central core. An example interface between a deployable truss and a deployable payload is shown by the large dish antennas on the end of the deployed Astromast. In a case such as this it would be desirable to have the deployable structure preattached to the deployable mast and deployed in sequence. Platform Module 1 of the GSP Alternate 4 is useful in showing several important interfaces. This large module has several antennas. An example interface on one of the deployed booms on the solar array is shown in Figure 26 where the equipment interfaces directly with the deployed beam at midpoint. In this case the equipment is a feed array. Also illustrated in Figure 26 is an example interface where an intermediately mounted deployable branch truss interfaces a large truss boom. Here, the branch truss would be deployed in sequence and it would be desirable if it were preattached to the

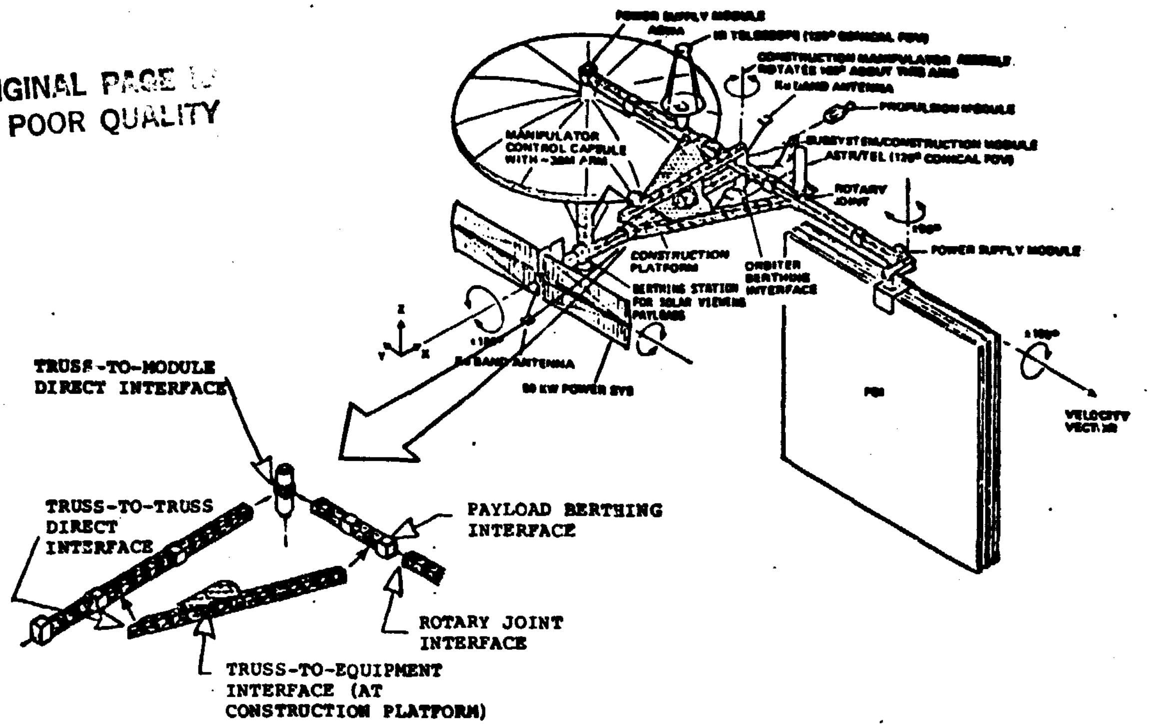


FIGURE 23
STRUCTURAL INTERFACE EXAMPLES FROM ADVANCED
SCIENCE AND APPLICATIONS SPACE PLATFORM

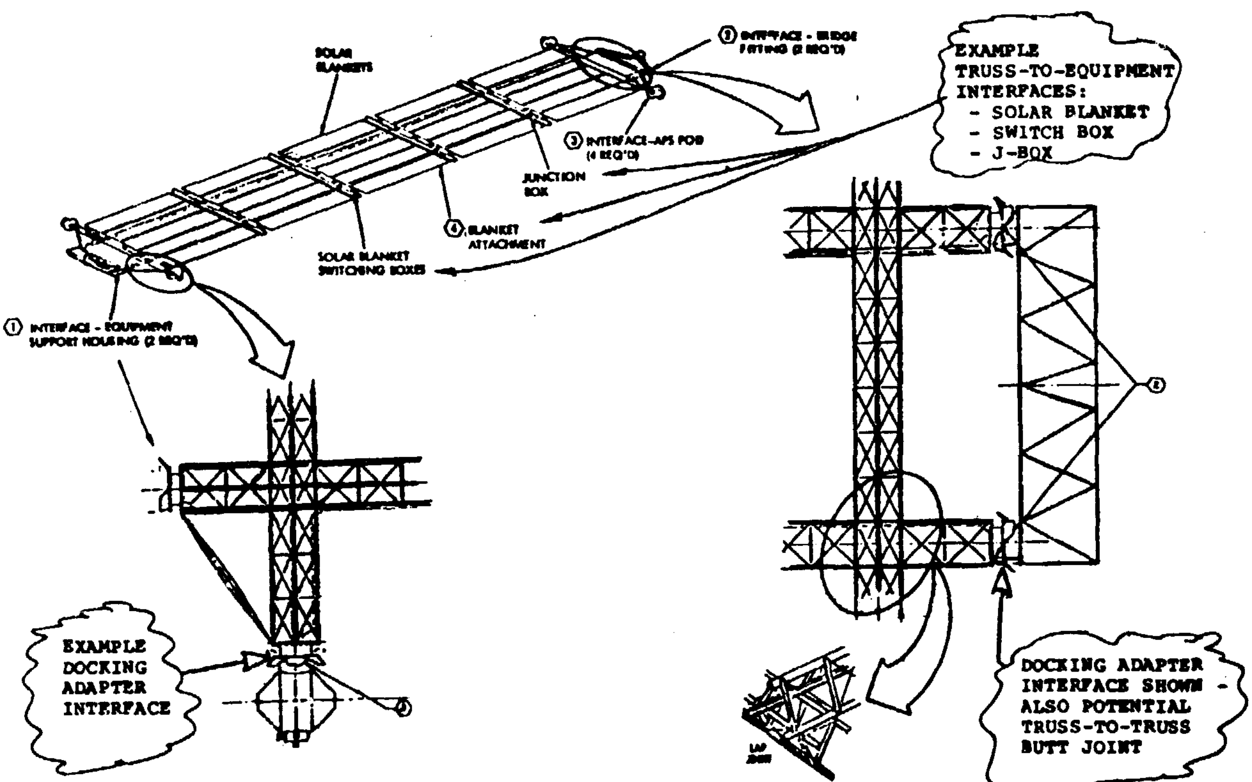


FIGURE 24
STRUCTURAL INTERFACE EXAMPLES FROM SPS TA II

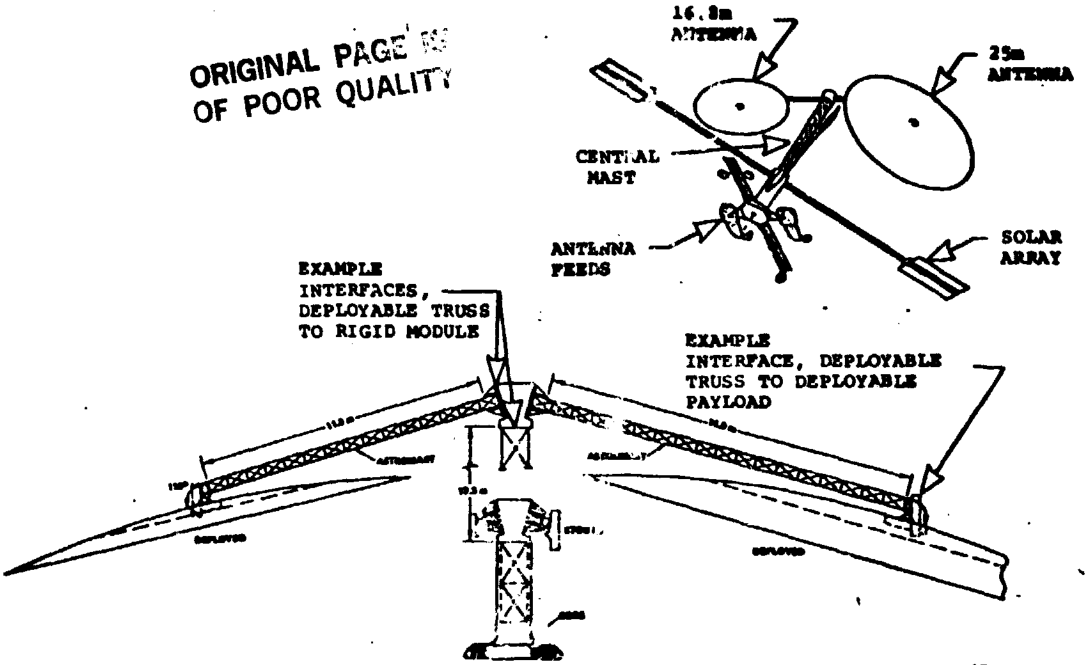


FIGURE 25 STRUCTURAL INTERFACE EXAMPLES FROM GSP ALT. 1, PTF 1

large boom. At the upper portion of this structure is a example truss-to-truss butt joint. Another example interface between a deployable antenna and a truss is also given by Figure 26.

Figure 27, also taken from the GSP Alternate 4, shows the interface between Platform Modules 1 and 2. In that platform system the modules are docked in geostationary orbit, providing examples of both an interconnecting truss between modules and a docking arrangement. On the left part of the figure is an example direct truss-to-module interface, where the truss is preattached to the module. All of these examples illustrate representative truss-to-truss, truss-to-module and truss-to-equipment payload joining which are useful in defining versatility requirements for deployable structure concepts.

Thermal considerations are also important in establishing the design requirements for the deployable structures. A steady state analysis was conducted where the radiation equilibrium temperatures were calculated, including both earth emission and earth albedo. For each of the focus missions the parametric curves given in Figure 28 show the equivalent steady state temperatures plotted as a function of the thermal coating solar absorptance to emittance ratio. In this figure the angle gamma is defined as the angle between the axis of the strut and the normal to the earth surface. The angle lambda is defined as the angle between the normal to the strut axis and the incoming solar radiation direction. A dotted and a solid line are plotted on each of the three figures for different conditions of gamma and lambda. In addition, three different orbital locations are plotted for the

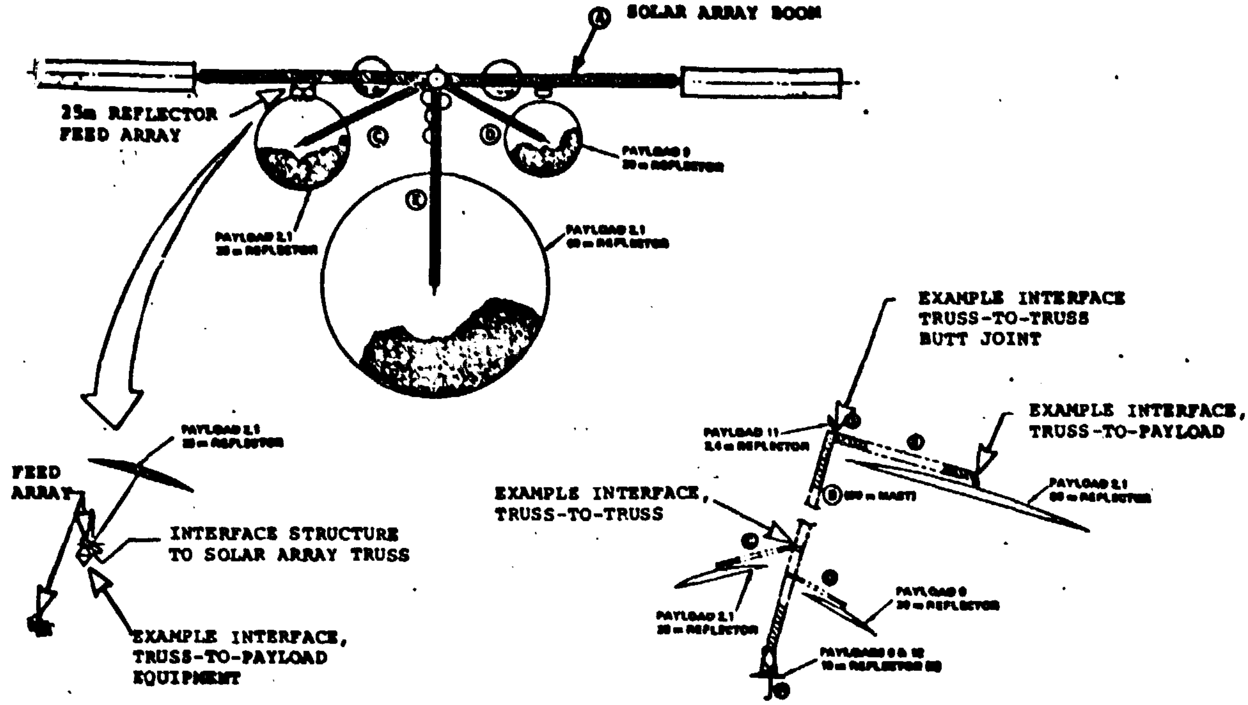


FIGURE 26
STRUCTURAL INTERFACE EXAMPLES
GSP ALTERNATE 4 - PLATFORM MODULE 1

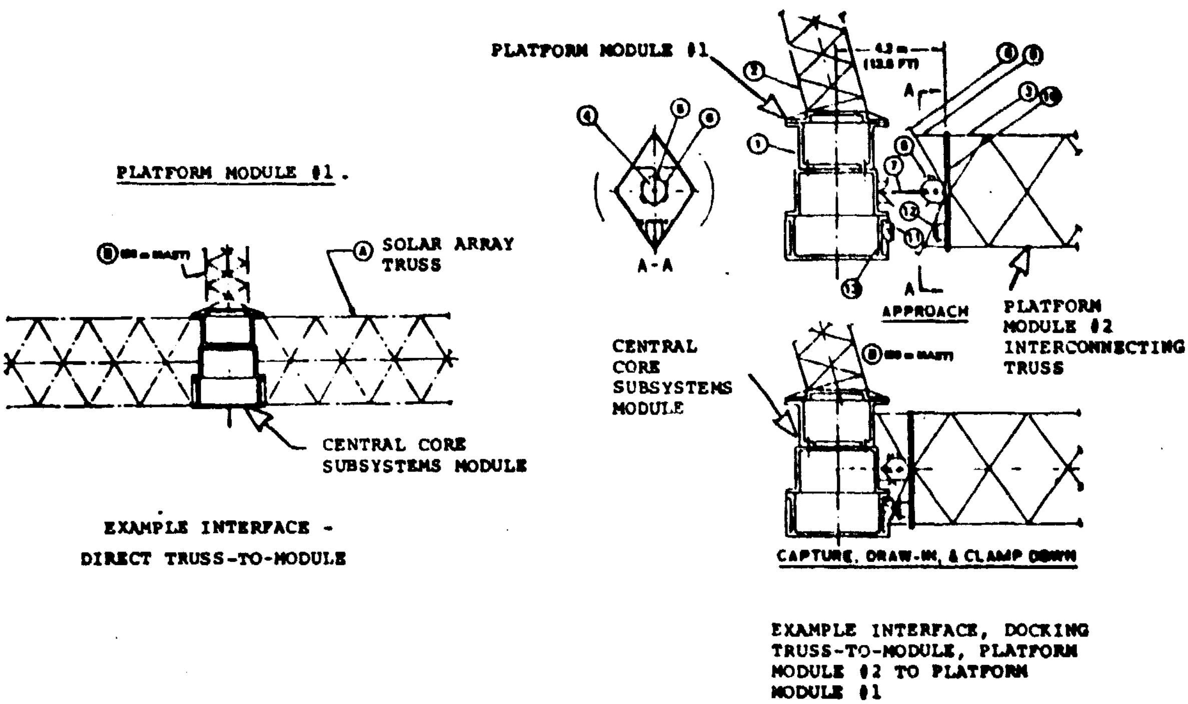


FIGURE 27
STRUCTURAL INTERFACE EXAMPLES
GSP ALT. #4 - PLATFORM MODULES #1 AND #2

central core. An example interface between a deployable truss and a deployable payload is shown by the large dish antennas on the end of the deployed Astromast. In a case such as this it would be desirable to have the deployable structure preattached to the deployable mast and deployed in sequence. Platform Module 1 of the GSP Alternate 4 is useful in showing several important interfaces. This large module has several antennas. An example interface on one of the deployed booms on the solar array is shown in Figure 26 where the equipment interfaces directly with the deployed beam at midpoint. In this case the equipment is a feed array. Also illustrated in Figure 26 is an example interface where an intermediately mounted deployable branch truss interfaces a large truss boom. Here, the branch truss would be deployed in sequence and it would be desirable if it were preattached to the large boom. At the upper portion of this structure is a example truss-to-truss butt joint. Another example interface between a deployable antenna and a truss is also given by Figure 26.

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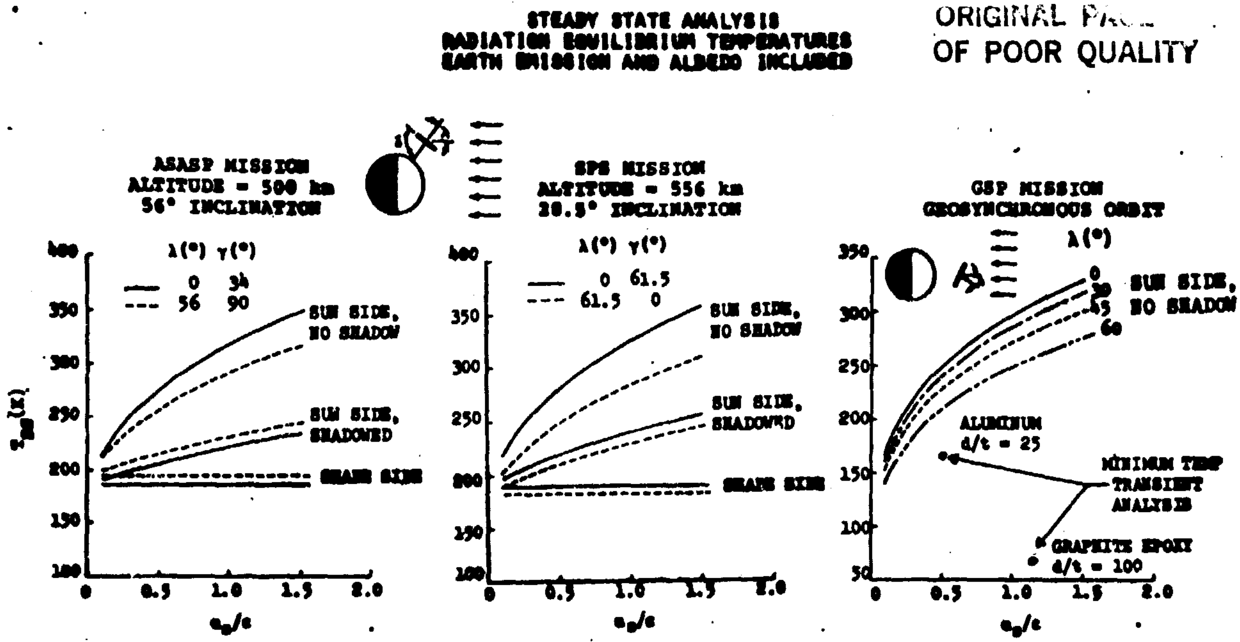

FIGURE 28 MAX/MIN ORBIT TEMPERATURES

two low earth orbit conditions: the shade side, the sun side with shadowing from direct solar irradiation, and the sun side with no shadowing. The hottest condition is the sun side with no shadow and the coldest is the shade side. The difference between the temperature values on the sun side with and without shadowing is an indication of the maximum gradient which would be expected across a truss. For the case of the geostationary platform only the angle relative to the solar flux is varied as the angle relative to the earth is insignificant because of the remoteness of the earth to the spacecraft in geostationary orbit. Also shown on the geostationary platform plot are two transient analysis points from Ref. (8). One is for an aluminum strut with a diameter/thickness ratio of 25 and a thermal coating solar absorptance/emittance ratio of 0.5, and the other is for a graphite/epoxy strut with a diameter/thickness ratio of 100 and a solar absorptance/emittance ratio of 1.15. This shows a minimum temperature condition of about 65°K is reached on the cold side of the earth, with graphite/epoxy. The most severe hot side condition seen on these curves is about 335°K which occurs for the SPS mission with graphite/epoxy struts. It should be noted that the temperatures plotted in Figure 28 are average strut temperatures because of the potential importance of temperature gradients across the strut. An analysis was also conducted to examine that factor based on the method presented in Ref. (9). Figure 29 shows a curve of the temperature

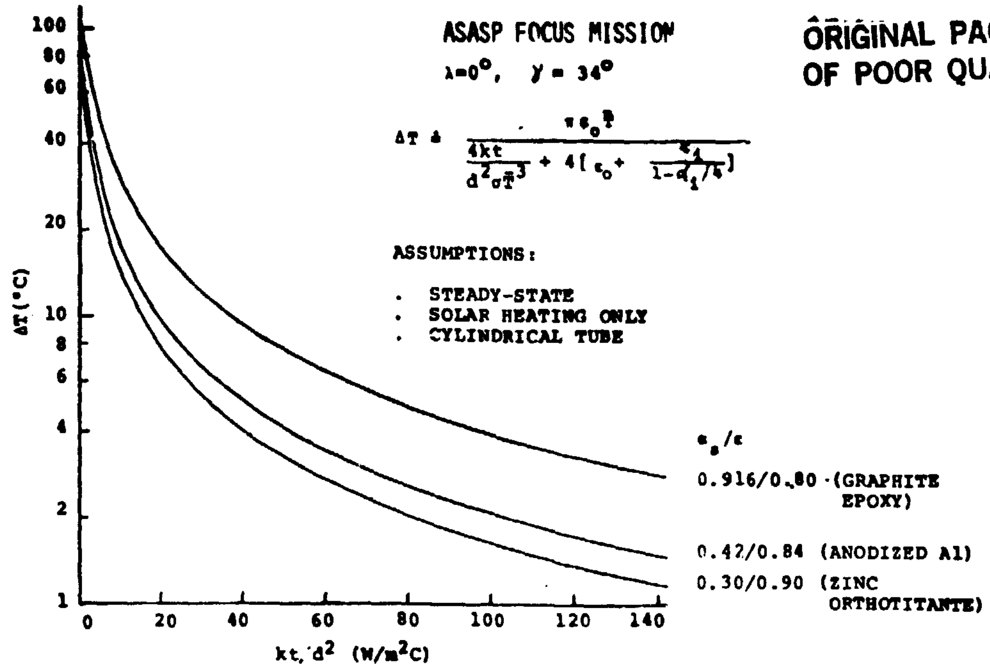

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FIGURE 29 TEMPERATURE DIFFERENTIAL ACROSS TUBE

differential across a tube for a sample mission condition. The abscissa of this plot is a product of thermal conductivity times thickness of the tube divided by the square of tube diameter. The ordinate of this plot is the temperature differential from the hot point to the cold point around the tube. The curve is for three typical ratios of solar absorptivity to emittance. As noted on the figure, the conditions for the analysis assume steady state and solar heating only, so it only strictly applies to those cases. It should, however, be a close approximation for cases with minimum amount of earth heating, and should also be a reasonably accurate approximation for non-steady state maximum temperature conditions. It is seen that as the thermal conductivity or tube thickness is reduced the temperature differential supported is increased. An estimate was made, for purposes of design studies, of the maximum and minimum strut design temperatures. Applying the curve of Figure 29 for a vanishingly thin tube or a very small thermal conducitivty value, it is seen that the maximum possible temperature gradient across the tube is approximately 110°C. Linearly distributing this from the hot-to-cold side the maximum temperature on the hot side of a graphite/epoxy strut is estimated to be about 125°C. On the cold side of the orbit the minimum strut temperature is more uniform and is approximately the average value of 65°K (-210°C). These numbers were used in design studies. Because of the cyclic thermal distortions that can occur due to transient effects it may be desirable to minimize the orbital temperature swing. In Figure 30 some potential options are indicated for doing this. One option is in coating selection, and the two curves on the left show the difference in temperature swing resulting from selection of either anodized aluminum or leafing aluminum/silicone paint. It is seen that use of a paint

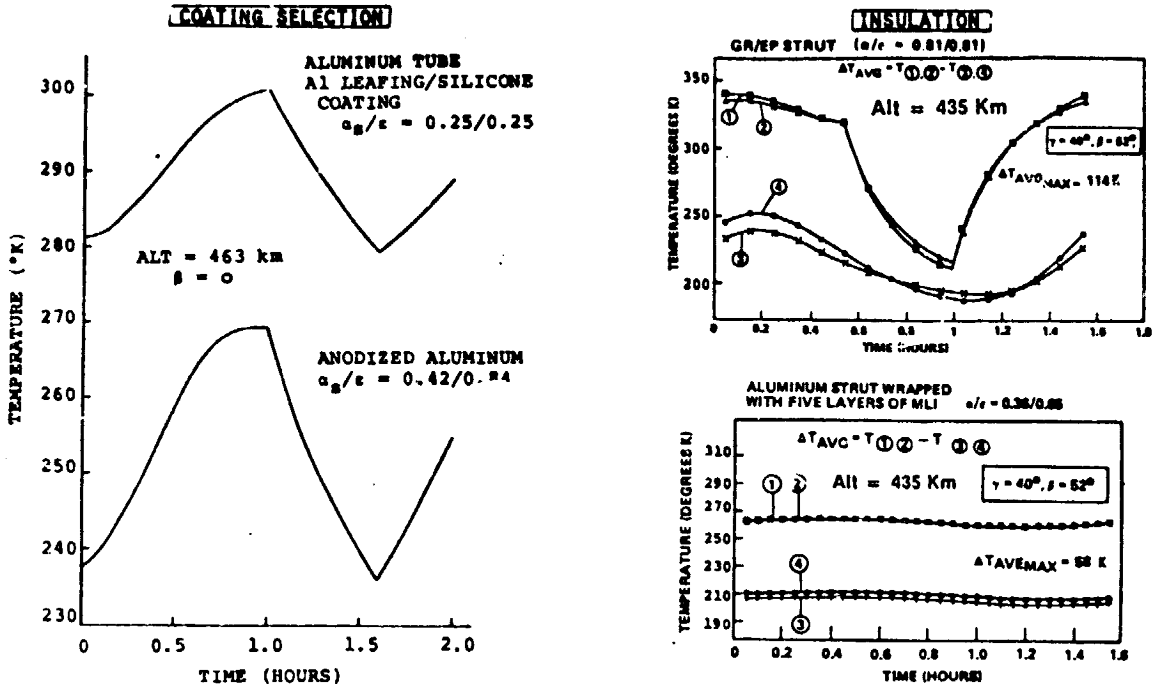


FIGURE 30 OPTIONS TO MINIMIZE TEMPERATURE SWING

with very nearly equal solar absorptance and emittance values of about 0.25 minimizes the temperature swing. However, the maximum temperature is greater than that which would be obtained through use of an anodized aluminum coating which has an absorptance/emittance ratio of about 0.5. The right side of the figure indicates another strategy (Ref. 6) to minimize the swing, where insulation is added to the outside of a graphite/epoxy strut. While temperature distortion across a truss cannot be eliminated, the temperature swing as an orbit is traversed can be virtually eliminated. Figure 31 shows another important consideration in the selection of materials and design of trusses for minimum distortions. If the strategy is invoked to reduce thermal distortions by using fittings that have a thermal coefficient of expansion that is just balanced by a negative thermal coefficient of expansion grahite epoxy, transient effects can spoil this benefit. Differences in thermal mass between the struts and joints results in large transient temperature differences even if the strut has a zero average CTE under isotropic conditions (Ref. 10). Some potential solutions to this problem are indicated in the figure. One would be to insulate the truss to reduce the transient

PROBLEM:

Thermal distortion can not be eliminated by simply off-setting CTE of fittings/struts

CAUSE:

Difference in thermal capacitance between strut and joint results in large transient temperature difference

POTENTIAL SOLUTIONS:

- Insulate truss to reduce or negate transient effects
- Tailor thermal capacitance of joint and strut to be nearly equal
- Tailor thermal control coatings to minimize transient temperature swing

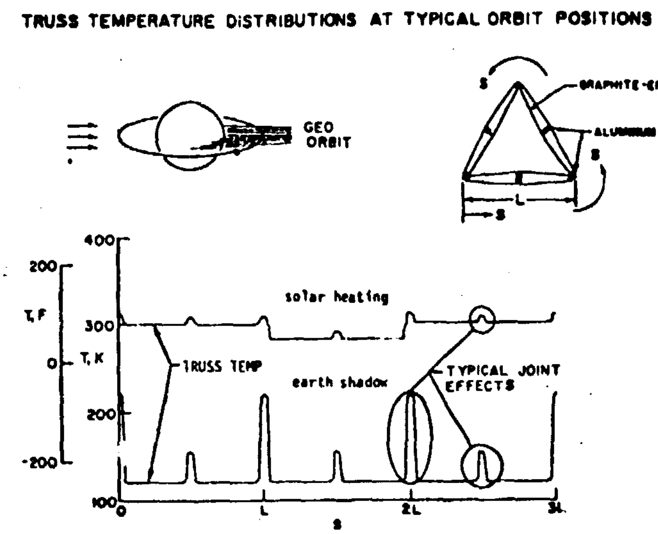


FIGURE 31 TRANSIENT THERMAL EFFECTS ON STRUT MATERIAL SELECTION

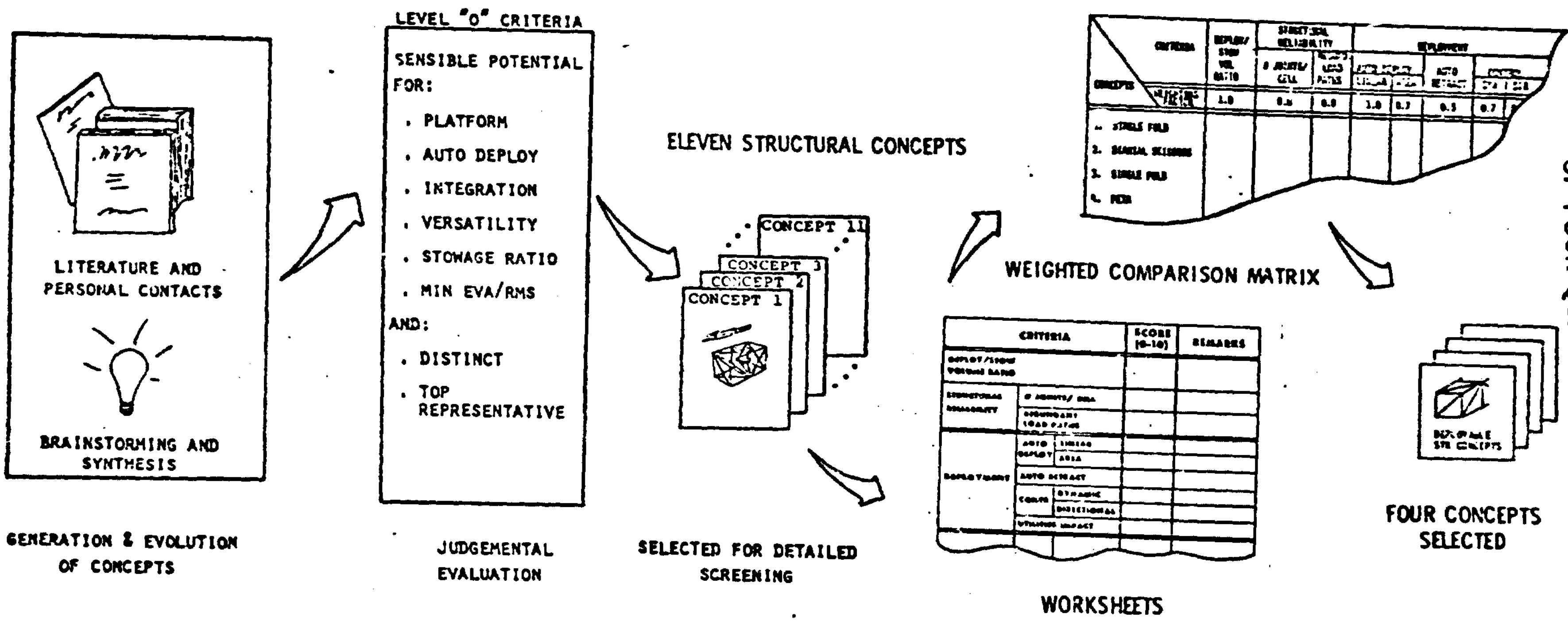
effects. Another would be to tailor the thermal compacitance of the strut and joint to be very nearly equal. Finally, some help can be obtained by tailoring the thermal coating to minimize the temperature swing. The effects are graphically illustrated on the right side of Figure 31, where the joint effects are seen. Because of their high thermal compacitance the minimum temperature reached on the cold side by the joints is much higher than the temperature reached by the strut areas.

2.2 PROCEDURE

This section describes the work carried out in Section 2.0 of this report relative to concept generation, and also covers the work in Section 5.0 of the report on concept selection and trade studies. Figure 32 schematically indicates the work flow process in this effort. The first effort was the generation and evolution of concepts. An information gathering effort was initiated to ensure that the benefits of completed and on-going efforts were incorporated into the study. The information was obtained through existing Vought Advanced Space Library documents as well as the main corporate library resources. A number of personal contacts were utilized and two computerized literature researches were used; Lockheed DIALOG and NASA STAR. Information from current and past national conferences including the 1981 Large Space Structures Propulsion Interaction Conference and the 1981 Large Space Structures Technology Conference. Data were also obtained from NASA Marshall Space Flight Center as well as inputs from the Johnson and Langley Space Centers. The procedure to evolve and generate concepts included brainstorming sessions, review of previous designs, combinations of the best ideas of those designs into new concepts, and further evaluation of existing concepts. After a number of concepts had been generated, a level zero screening was performed in order to reduce the number of candidates to a manageable number and include only those candidates in our more detailed screening matrix which had a reasonable potential for deployable platform systems. The level zero criteria entailed the use of show stoppers against which each concept was weighed without a detailed analysis. These criteria related to the prospect of a concept being sensible to perform the basic mission and/or its potential for a platform. It should have suitable characteristics for controllable automatic deployment and should also have the potential for utilities, subsystem and payload integration. It should possess enough versatility to ensure scaling and accommodation of a wide variety of missions. Its stowed volume, including its deployment mechanism, should be sufficiently small to effectively use the Space Shuttle Orbiter. No major amounts of EVA or RMS assembly should be required. It should be a reasonable candidate for 1986 technology readiness. In addition to judgemental consideration of these criteria, it was required that a concept also pass the judgement call that it be as good or better than

FIGURE 32

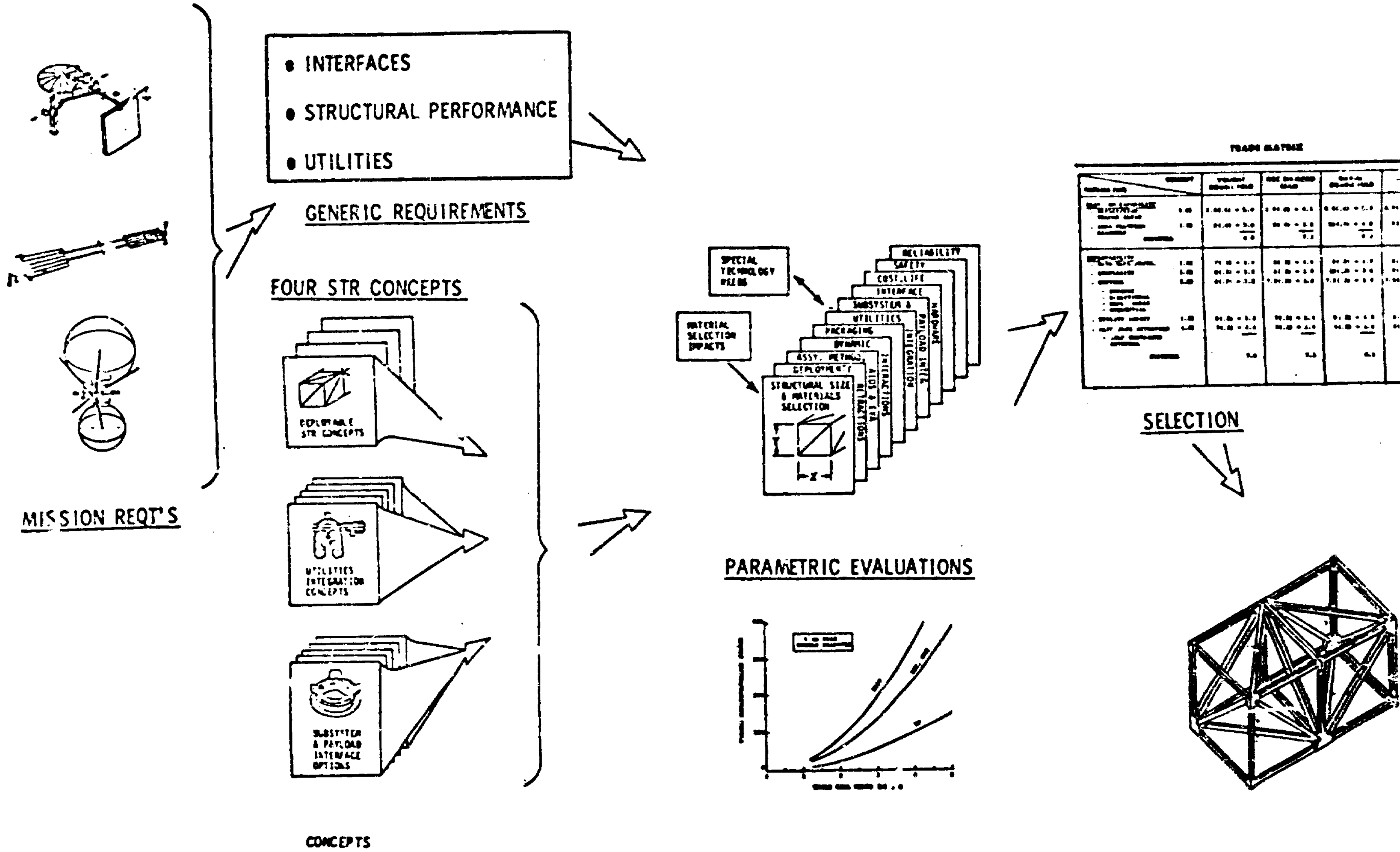
REVIEW OF STRUCTURAL CONCEPT GENERATION AND SCREENING



other similar concepts in its class and that it contain features that make it distinct, in order for it to be selected for inclusion in the preliminary screening matrix. The results of this level zero screening were the selection of 11 structural concepts for more detailed screening. As indicated in Figure 32, worksheets were prepared with specific criteria evaluated for each of these 11 concepts. Subsequent to the evaluation of worksheets on each concept, they were all included in a matrix to compare their characteristics, and weighting factors were assigned. The result of this, then, was that four concepts were selected for detailed trade studies and evaluation. It was considered important in concept generation and screening to provide traceability in evaluation of trade criteria, leading to the utilization of the rather formalized worksheet mentioned above.

As indicated in Figure 33, once the four structural concepts were selected, additional definition studies and concept trade studies utilizing utilities integration concepts, subsystem and payload interface options, and deployment concepts were applied to result in complete system concepts for each of the four candidate structural concepts. As indicated in the figure, a number of parametric evaluations were then conducted and other evaluations including determination of material selection impact, and special technology needs were carried out. The concepts were then compared against the generic requirements involved in the missions and finally evaluated according to trade criteria in a trade matrix. The criteria in this case were similar to those by which the preliminary screening was conducted, only additional subcriteria were added and a more detailed evaluation was possible because the quantitative trades had been accomplished. After comparison in this trade matrix a final selection was made and recommended for further study in Part 2.

FIGURE 33
SYSTEM TRADES AND CONCEPT SELECTION



2.3 CONCEPT SELECTION FOR SCREENING

This section presents the selection of the 11 concepts and the most substantial considerations in each selection. Figure 34 illustrates the selections.

CONCEPT NO. 1 - VOUGHT DOUBLE FOLD

This concept was developed under a prior contract (Ref. 7) on Erectable Structures and has attractive potential on all the level zero criteria. It has been developed to full scale prototype maturity level, is both linear and area deployable, and can be made retractable. It has undergone full size neutral bouyancy test evaluations.

CONCEPT NO. 2 - VOUGHT BIAXIAL SCISSORS FOLD

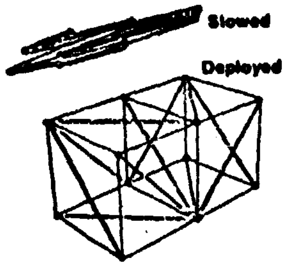
This concept is outstanding in its deployed/stowed volume ratio and has good potential in all the other categories. It also has the fewest joints and latches of any concept other than inflatable concepts. Simultaneous deployment of all the bays occurs. Development has been to a functional scale model maturity level only. It is both linear and area deployable and can be made retractable.

CONCEPT NO. 3 - MSFC/VOUGHT SINGLE FOLD

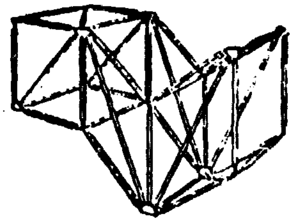
The concept illustrated is a nested single fold version of the Vought Double Fold which was evolved by the NASA Marshall Space Flight Center (Ref. 11). The Single Fold had good potential in all the criteria. It is considerably less compact than the Double Fold and benefits from reduced complexity. Maturity is high with fabrication of the NASA Marshall full scale prototype and testing of the Vought full scale double fold in a single fold mode. The single fold does not deploy into an area platform.

CONCEPT NO. 4 - PARABOLOIDAL EXTENDABLE TRUSS ANTENNA (PETA)

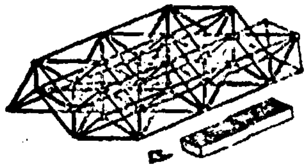
This General Dynamics truss concept (Ref. 12) is an area deployable structure consisting of elemental tetrahedron bays, and uses stored energy in the strut hinges for simultaneous deployment of all bays with a symmetric motion. In addition, it can be configured as a Mod-PETA where a single row of area platform bays is deployed as a diamond crossection linear beam. In the beam version it can also simultaneously deploy all bays or, as further modified by General Dynamics (Ref. 13), be deployed by an auxiliary mechanism into their Diamond Truss Boom. We considered the PETA has attractive potential. It has been matured to the prototype level as an area platform. The Diamond Truss Boom modification, which will be considered separately, has also been developed to a high maturity level.



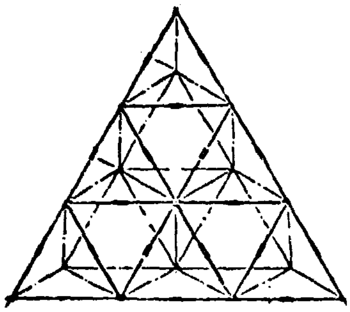
#1 - VOUGHT DOUBLE FOLD



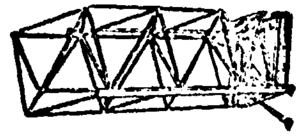
#3 - MSFC/VOUGHT SINGLE FOLD



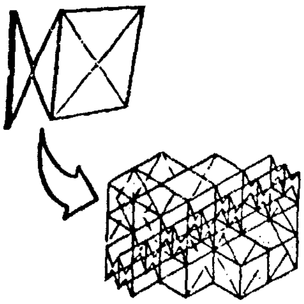
#2 - VOUGHT BIAXIAL SCISSORS



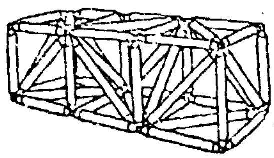
#4 - GDC PETA



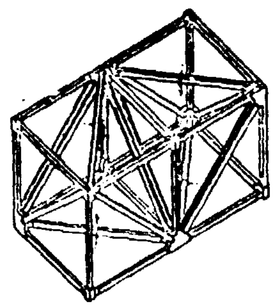
#5 - GDC DIAMOND TRUSS BOOM



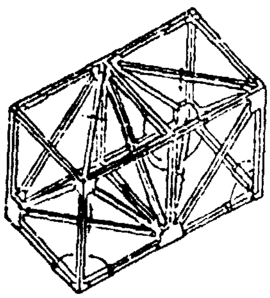
#6 - MARTIN BOX TRUSS



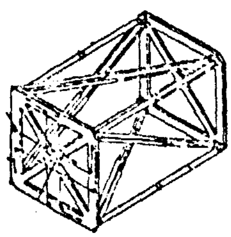
#7 - VOUGHT INFLATABLE DOUBLE FOLD



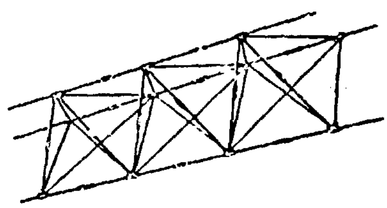
#8 - VOUGHT BIAXIAL DOUBLE FOLD



#9 - VOUGHT PIVOTED DOUBLE FOLD



#10 - MDAC TELEFOLD



#11 - MODIFIED GDC HALF DIAMOND BEAM

FIGURE 34 CANDIDATE DEPLOYABLE STRUCTURE CONCEPTS

CONCEPT NO. 5 - DIAMOND TRUSS BOOM

This evolution by General Dynamics of their PETA, as described above, is a highly efficient structure which packages very compactly. It is deployed in a sequenced symmetric axial motion. When considered as part of the PETA family the potential for a competitive mast linear platform or area platform is provided. Its high maturity level includes a full size graphite composite structure and deployment mechanism prototype, and the design of a retraction mechanism (Ref. 14). The Diamons Truss Boom has been the subject of several systems studies primarily focused toward antennas.

CONCEPT NO. 6 - MARTIN BOX TRUSS

This Martin Marietta design (Ref. 15) deploys into either linear or area configurations using stored energy in the strut hinges. By control of the release of individual electrical mechanical latches, a sequenced deployment of an area platform is obtained. First, rows are deployed in the symmetrically balanced sequence, then columns. In the linear case it is deployed in a sequenced symmetric axial motion like a mast. Deployed/stowed volume ratio is very good. The major limitation is stiffness in configurations using flexible diagonal tension tapes. For current studies it was assumed that the rigid telescoping diagonal tape design is used on all six sides of a cubic cell in order to achieve a truss stiffness equivalent to the other concepts. The Box Truss maturity level includes several systems studies focused mainly on large antennas, and the fabrication of a full scale graphite/epoxy cube. The Box Truss has good potential relative to all the criteria, can be made retractable, and can be used as a mast, linear platform, or area platform.

CONCEPT NO. 7 - INFLATABLE DOUBLE FOLD

This truss and deployment concept was generated by Vought based on past deployment rigidization techniques such as those developed by L'Garde (Ref. 16), Goodyear (Ref. 17) and Hughes (Ref. 18). The rectangular truss structure is deployed by inflation of the struts between the nodes which have rigid sockets at their centroids to provide a pattern of hard points. The structure is folded near the nodes similar to the Double Fold structure except the diagonals are folded together rather than telescoped apart. During the final phase of deployment the structure is rigidized by such a method as pressure stressing a wire grid or metal foil (an integral part of the tube layup) slightly beyond yield to set the shape. There is no retraction. The

Inflatable Double Fold can deploy into linear or area platform configurations. Its maturity level is conceptual.

CONCEPT NO. 8 - BIAXIAL DOUBLE FOLD

This new Vought concept is a rectangular truss structure evolved from the Double Fold and replaces the telescoping diagonals with telescoping or strut/slider verticals. The rigid H section diagonals nest between folded longitudinals and laterals. An improved, very compact stowed/deployed volume ratio results. This concept also has next to the least number of joints. Deployment of all cells is simultaneous. The Biaxial Double Fold (BADF) is suitable for either area or linear platforms and can be made retractable. While its maturity level is conceptual, it appears to have an attractive potential and is an evolution of a relatively mature design.

CONCEPT NO. 9 - PIVOTED DOUBLE FOLD

This is also a new Vought concept and is a rectangular truss structure similar to the Biaxial Double Fold except, rather than telescoping the verticals, the longitudinals and laterals are hinged at the 30% length points. This concept avoids all telescoping members and can be deployed by stored energy in the hinges to form a linear or area platform. It can be made retractable. Stowed/deployed volume ratio is intermediate between the double fold and biaxial double fold. Maturity level is conceptual.

CONCEPT NO. 10 - TELEFOLD

This McDonnell Douglas truss was selected as the best candidate of purely axially folding accordion concepts. It has been designed to an intermediate level of detail as part of the SASP system study. It has good compaction, stable and symmetric deployment kinematics, and is attractive in areas relating to linear platforms. Maturity level is to the preliminary design phase, including a cable deployment/retraction mechanism.

Other concepts considered were the Vought Accordion Fold (Ref. 7) and the Rectangular K-Brace Longitudinal Fold concept (Ref. 19).

CONCEPT NO. 11 - MODIFIED HALF DIAMOND BEAM

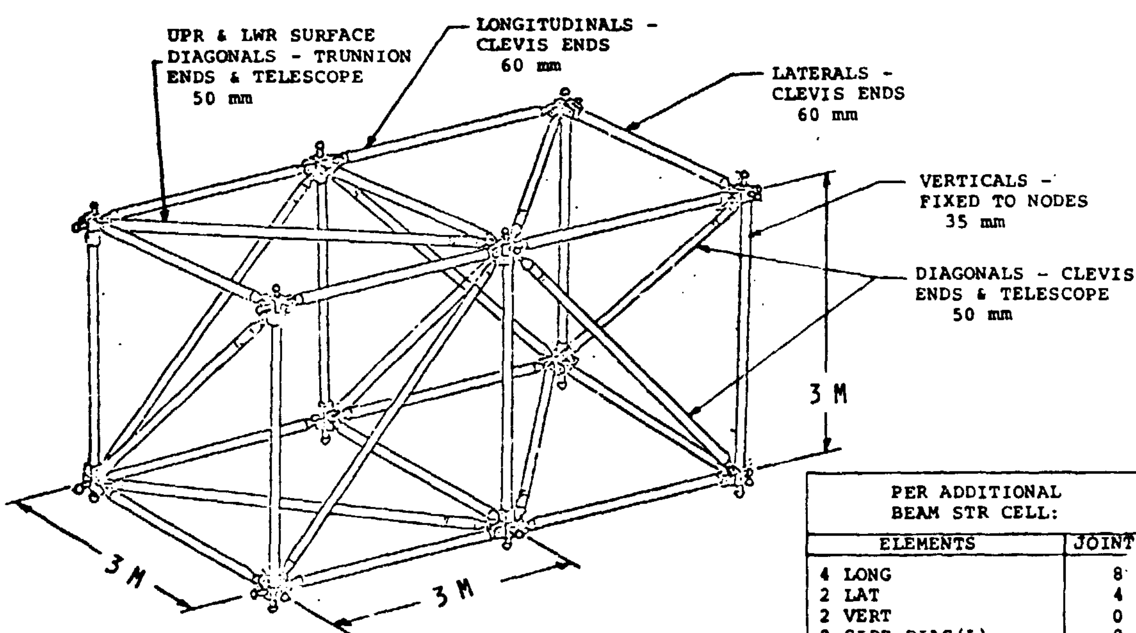
This triangular, linearly deployable truss was selected as the most attractive mast type candidate other than the square or diamond crossection candidates already included. The Half Diamond is a General Dynamics concept, essentially one-half of their diamond truss beam. For our screening it was modified to add rigid member diagonals on the square cell faces formed by splitting the diamond. Rigid diagonals are necessary to provide sufficient stiffness to permit a versatile potential for platform applications. The rigid diagonals could be an adaptation of the dual telescoping Telefold diagonals, the telescoping rigid tape Box Truss diagonals, or nested hinged struts. In selecting the modified half diamond beam, a wide range of alternate candidates were also considered. The Modified Half Diamond beam was selected to be representative and one of the most attractive concepts because of its suitability to obtain high stiffness by incorporation of rigid diagonals, its structural efficiency, relative simplicity, linear non-rotating deployment, capability for both deploy and retraction and good compaction. Its maturity is considered relatively high, as it is evolved from other relatively mature structures. Its potential for integration of payloads, systems and utilities is also good.

Table 4 summarizes various concepts which were considered by either personal contacts, past Vought work, or the literature and were not included in the list of those selected for further study. The rationale for their non-selection is also included in the table.

The 11 concepts selected for screening are described in Figures 35 through 53, which give additional detail on the concepts nd evaluation results in certain areas. For purposes of uniformity evaluation, a representative design of a 3-meter cell was defined. In addition, to provide an equal basis for stiffness comparisons, a strut length to radius of gyration ratio of 150 was used for longitudinals and laterals which resulted in a 60 mm diameter. A strut length to radius of gyration ratio of 250 for other elements was used, which resulted in a 50 mm diameter diagonal, and a 35mm diameter vertical. These dimensions result in equal stiffness in bending for all concepts. Figure 35 shows the Double Fold. It illustrates the 3-meter face size and gives a summary of the joints involved; 36 joints and 13 element types. The weight of 13.6 Kg is also summarized. Figure 36 showns a crossectional view of the Double Fold in the folded configuration. This illustrates the folded dimensions and also the deployed/stowed volume ratio of 78:1. As illustrated in Figure 37 for the Biaxial Scissors Fold, the estimated weight is 9.9 Kg. There are 20 joints per cell and 7 distinct elements per cell. The Biaxial Scissors Fold has an extremely compact stowage ratio of 223:1. Figure 39 shows the NASA-MSFC Nested Single Fold which has 9 distinct elements and 20 joints. Its weight is estimated at 13.6 Kg. Figure 40 shows its deploy/stow length ratio of 26:1 which is equivalent to the volume ratio of 13:1. In Figure 41 the General Dynamics PETA concept rendered

TYPE	CONCEPT	RATIONALE
TETRAHEDRON TRUSS-AREA DEPLOYABLE	BOEING ARTICULATED TETRAHEDRON TRUSS	SIMILAR TO CONCEPT 4: GENERAL DYNAMICS PETA WHICH REPRESENTS THIS TYPE.
BOX TRUSS - LINEAR DEPLOYABLE	VOUGHT SINGLE FOLD	SIMILAR TO CONCEPT 3: NESTED SINGLE FOLD WHICH REPRESENTS THIS TYPE.
BOX TRUSS - AXIALLY DEPLOYABLE	VOUGHT AXIAL ACCORDIAN FOLD K-BRACE LONGITUDINAL FOLD	SIMILAR TO CONCEPT 10: MCDONNELL DOUGLAS TELEFOLD WHICH REPRESENTS THIS TYPE. IT WAS CHOSEN DUE TO ITS GOOD COMPACTION AND STABLE DEPLOYMENT KINEMATICS.
TRIANGULAR TRUSS - LINEAR DEPLOYABLE	ASTRO/ABLE ARTICULATED MAST CABLE CROSS-BRACED TRANSV. & LONG. FOLD GD DELTA BEAM MAST HARRIS TELESCOPING MAST K-BRACE LONG. FOLD LOCKHEED REDEPLOYABLE Y-MAST LOCKHEED TAPERED TUBE MAST SEASAT SCISSORS/DELTA TRUSS TETRA-BEAM MAST	CONCEPT 11: MODIFIED GD HALF-DIAMOND BEAM WAS CHOSEN TO REPRESENT THIS TYPE. IT WAS MODIFIED TO USE DUAL TELEFOLD DIAGONALS, THE RIGID TELESCOPING AND FOLDING DIAGONALS ON THE MARTIN BOX TRUSS, ON THE SQUARE CELL FACE TO OBTAIN HIGH STIFFNESS. IT WAS CHOSEN DUE TO ITS GOOD COMPACTION, STABLE, NON ROTATING DEPLOYMENT KINEMATICS, GOOD STIFFNESS, AND CROSS COUPLING EASE AT THE SQUARE CELL FACES TO ERECT LARGE AREA PLATFORMS. ORIGINAL PAGE IS OF POOR QUALITY

TABLE 4 CONCEPTS CONSIDERED AND REJECTED FOR SCREENING



PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
4 LONG	8
2 LAT	4
2 VERT	0
2 SIDE DIAG(L)	8
2 UPR & LWR DIAG(L)	12
1 BULKHEAD DIAG(L)	4
13 TOTAL	36

13.6 Kg WT

FIGURE 35 CONCEPT 1: DOUBLE FOLD CONFIGURATION

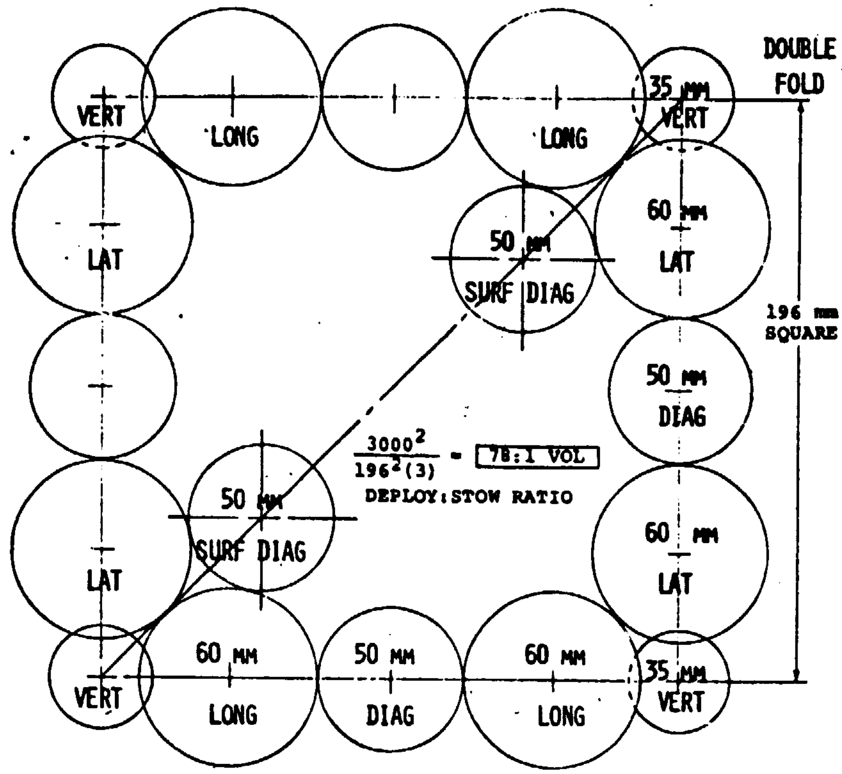
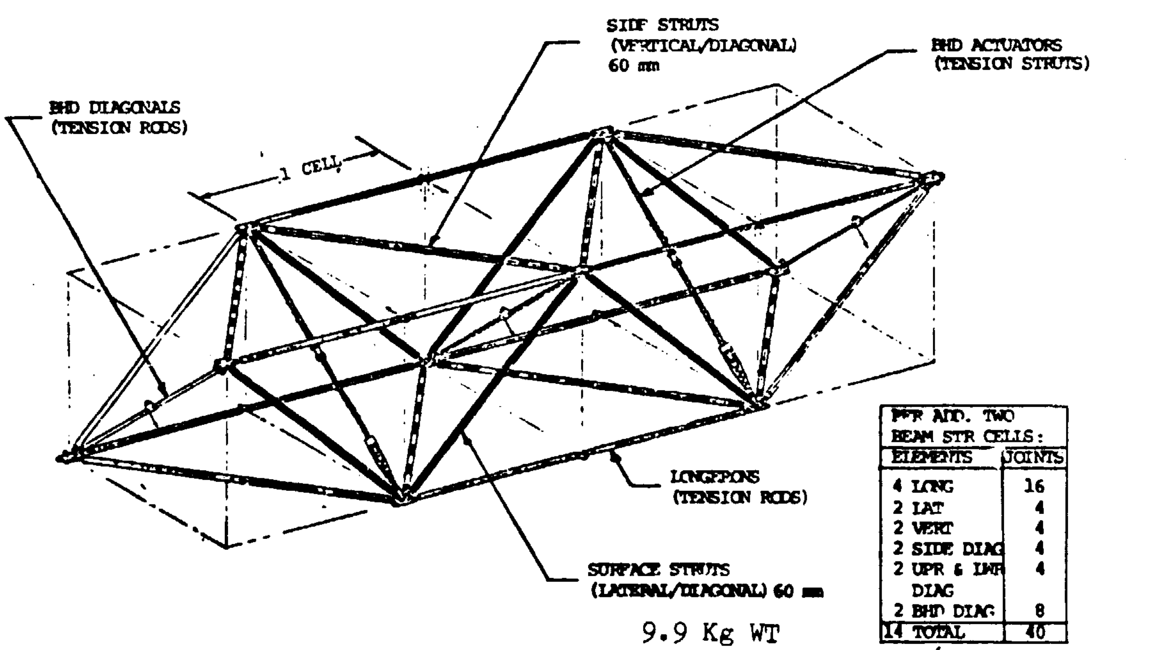


FIGURE 36 CONCEPT 1: DOUBLE FOLD FOLDED GEOMETRY



PER ADD. TWO BEAM STR CELLS:

ELEMENTS	JOINTS
4 LONG	16
2 LAT	4
2 VERT	4
2 SIDE DIAG	4
2 UPR & LWR DIAG	4
2 BHD DIAG	8
14 TOTAL	40

7 ELEMENTS, 20 JOINTS PER CELL

FIGURE 37 CONCEPT 2: BIAXIAL SCISSORS FOLD CONFIGURATION

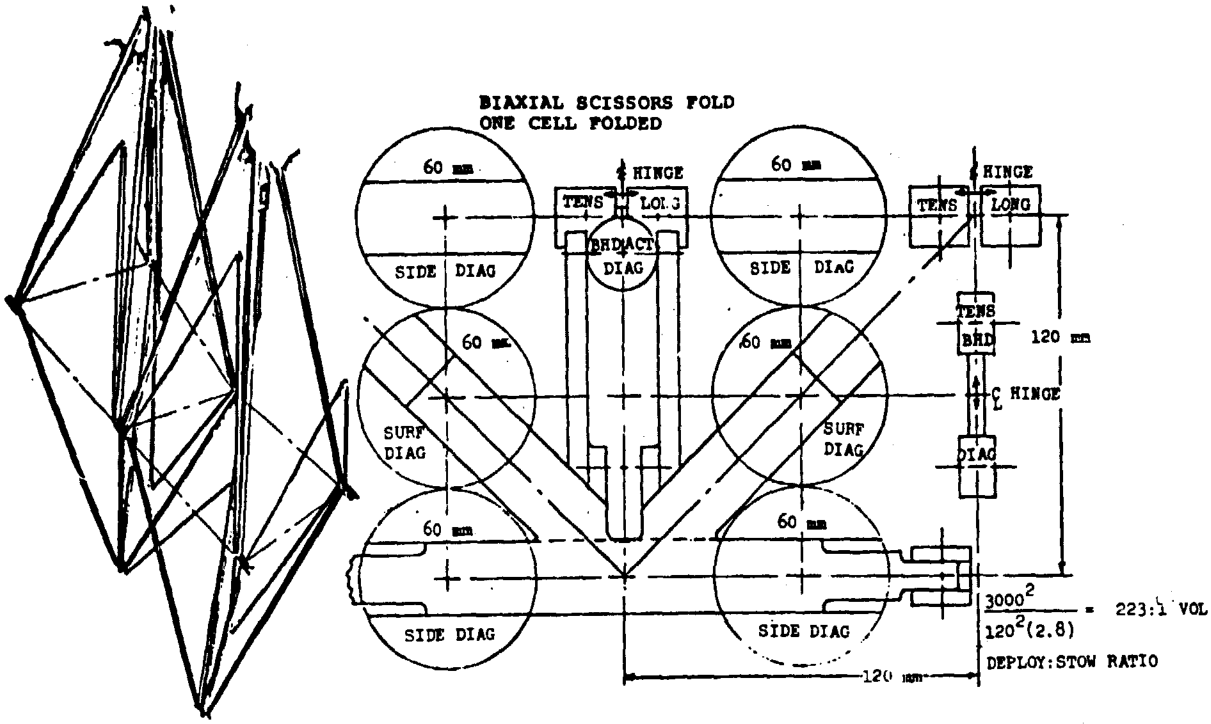
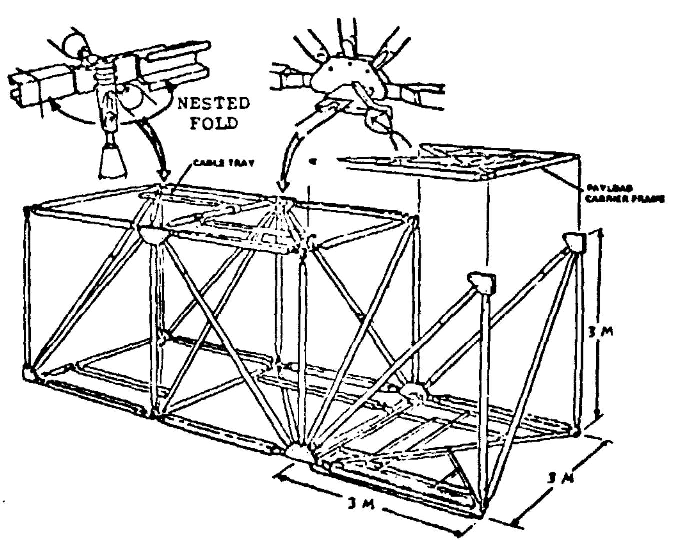


FIGURE 38 CONCEPT 2: BIAXIAL SCISSORS FOLD GEOMETRY



PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
4 LONG	8
2 DIAG(TELB/LOCK)	8
2 DIAG(SURF)	4
1 BULKHEAD (2 LAT,2 VERT, DIAG)	0
9 TOTAL	20

13.6 Kg WT

FIGURE 39 CONCEPT 3: NESTED SINGLE FOLD CONFIGURATION

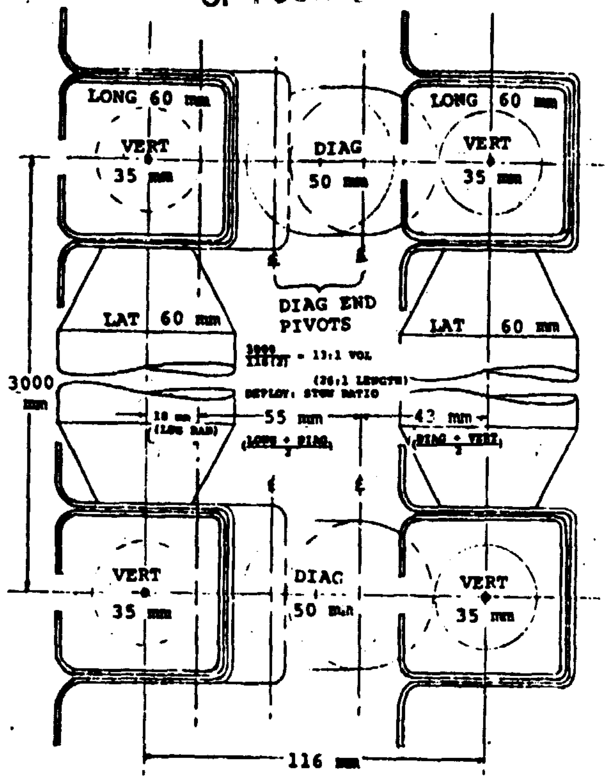
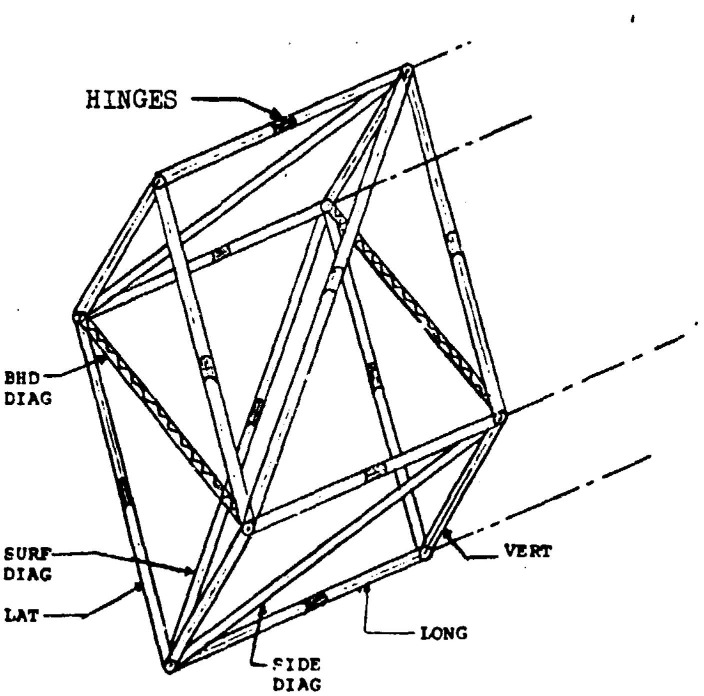
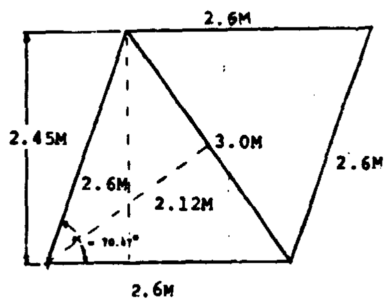


FIGURE 40. CONCEPT 3: NESTED SINGLE FOLD FOLDED GEOMETRY



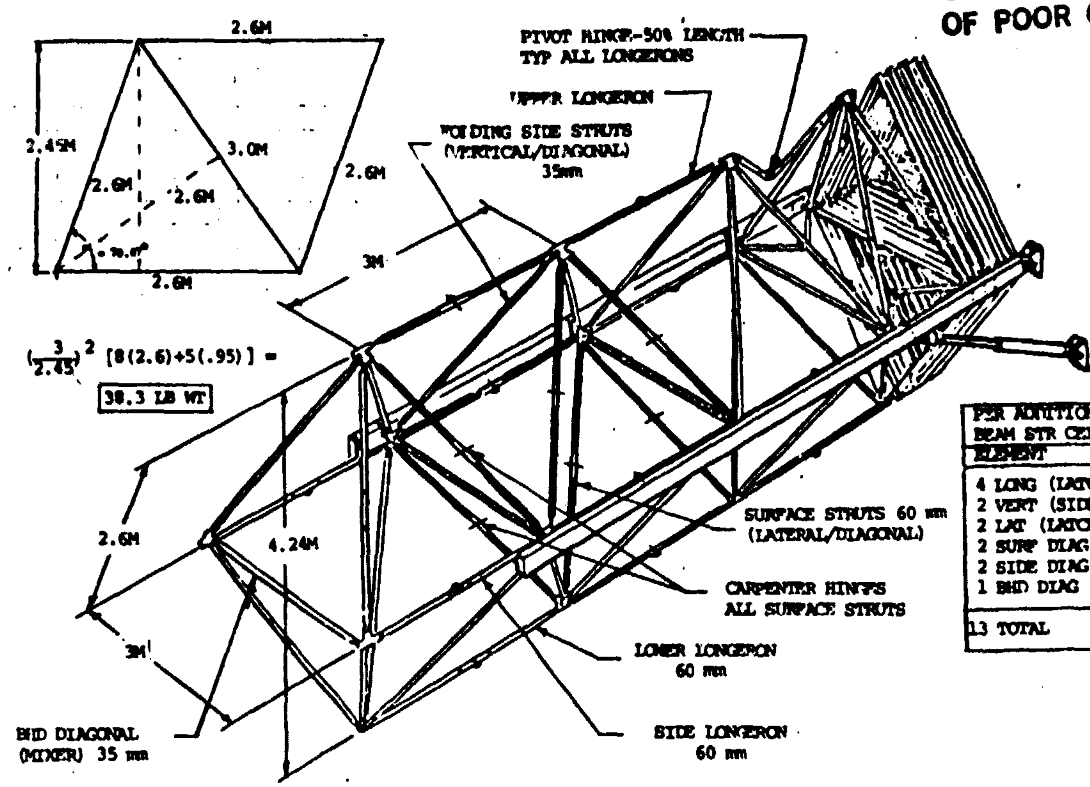


17.4 Kg WT

PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
4 LONG (LATCH)	16
2 LAT (LATCH)	8
2 VERT	2
2 SIDE DIAG	4
2 SURF DIAG (LATCH)	8
1 BHD DIAG	0
13 TOTAL	38

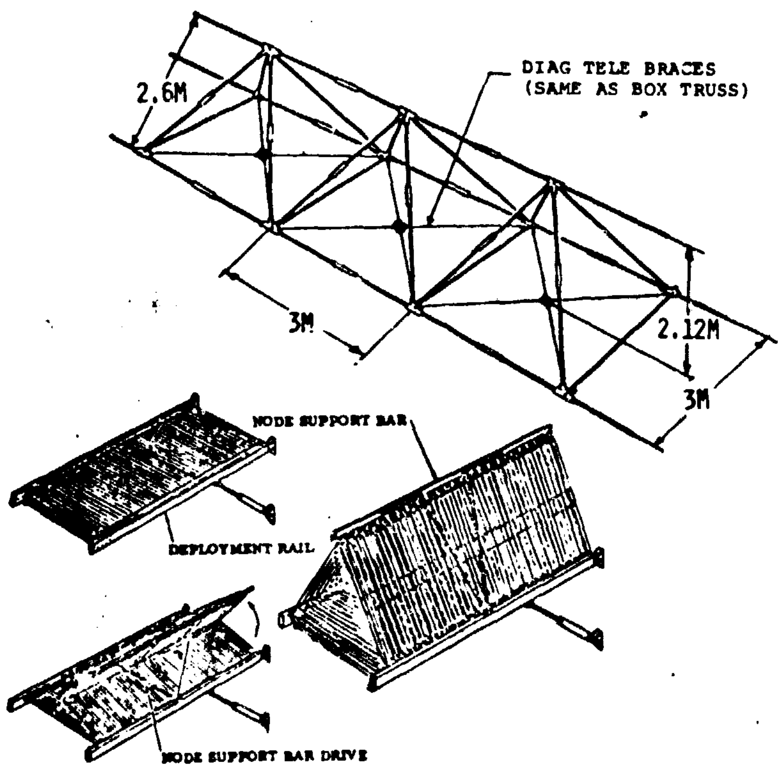
FIGURE 41 CONCEPT 4: PETA CONFIGURATION

as a beam is illustrated. The carpenter tape hinges, on the structure which folds, can be seen in the illustration. Also noted in the corner of the figure are the dimensions assumed for this shape which are slightly different, because it is not completely square. The estimated weight is 17.4 Kg. and there are 38 joints and 13 separate type elements per structural cell. In Figure 42 the Diamond Truss Beam evolution of the PETA is shown with the externally actuated deployment mechanism. The weight is approximately the same, 17.4 Kg and the number of joints now has been increased to 56 per cell with 13 different structural elements. Figure 43 illustrates the Half Diamond Beam. The added tension diagonals of the type on the Box Truss can be seen on the square lower surface. A cell of this structure is estimated to weigh 24.4 Kg and has 44 joints and 12 type elements. Figure 44 shows the folding configuration of the PETA, Diamond Beam, and Half Diamond Beam all shown on the same figure because of their similarity. The compaction ratios are also illustrated. The volume ratio is 114:1 and the length ratio is 15.8:1. In Figure 45 the Martin Marietta Box Truss is illustrated showing some of the details of the node and hinge fittings. Also shown are the telescoping surface diagonals added to the upper and lower surfaces, as opposed to the tension tapes, in order to obtain equivalent stiffness to the other trusses. There are 28 elements per cell and 100 joints in this design. The estimated weight per cell is 13.6 Kg. Figure 46 shows the Box Truss retracted configuration having a very compact 293:1 volume ratio. Figure 47 illustrates the Inflatable Double Fold showing its deployed configuration, its folded configuration and showing that there are 28 joints and 13 elements per cell. The estimated weight of a cell is 40.9 Kg. The volume compaction ratio is estimated to be 306:1. The inflatable struts are tubes constructed of multiple plies of laminated aluminum and Mylar. Each ply consists of two layers of 0.05 mm aluminum foil sandwiching a single 0.025 mm layer of Mylar film. The plies are loosely wound to permit sequential yielding of the aluminum during inflation. The number of plies required was determined as that which is necessary to provide an axial strut stiffness equal to the stiffness which would be obtained with graphite/epoxy construction. For graphite/epoxy with a representative modulus of 130 GPa (19 x 10^6 psi), the equivalent strut wall thickness for a 60 mm strut diameter is about 3 mm (including Mylar), and approximately 24 plies are required. The inflatable strut is about four times as heavy as graphite/epoxy. Comparing to a



PER ADDITIONAL BEAM STR CELL:	
ELEMENT	JOINTS
4 LONG (LATCH)	16
2 VERT (SIDE)	8
2 LAT (LATCH)	12
2 SURF DIAG (LATCH)	12
2 SIDE DIAG	8
1 BHD DIAG	0
13 TOTAL	56

FIGURE 42 CONCEPT 5: DIAMOND BEAM CONFIGURATION



PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
3 LONG (LATCH)	12
1 SIDE VERT	4
1 SIDE DIAG	4
1 LAT (LATCH)	6
1 SURF DIAG (LATCH)	6
1 BHD DIAG	0
4 TELE DIAG	12
12 TOTAL	44

24.2 Kg WT

FIGURE 43 CONCEPT 11: HALF-DIAMOND BEAM CONFIGURATION

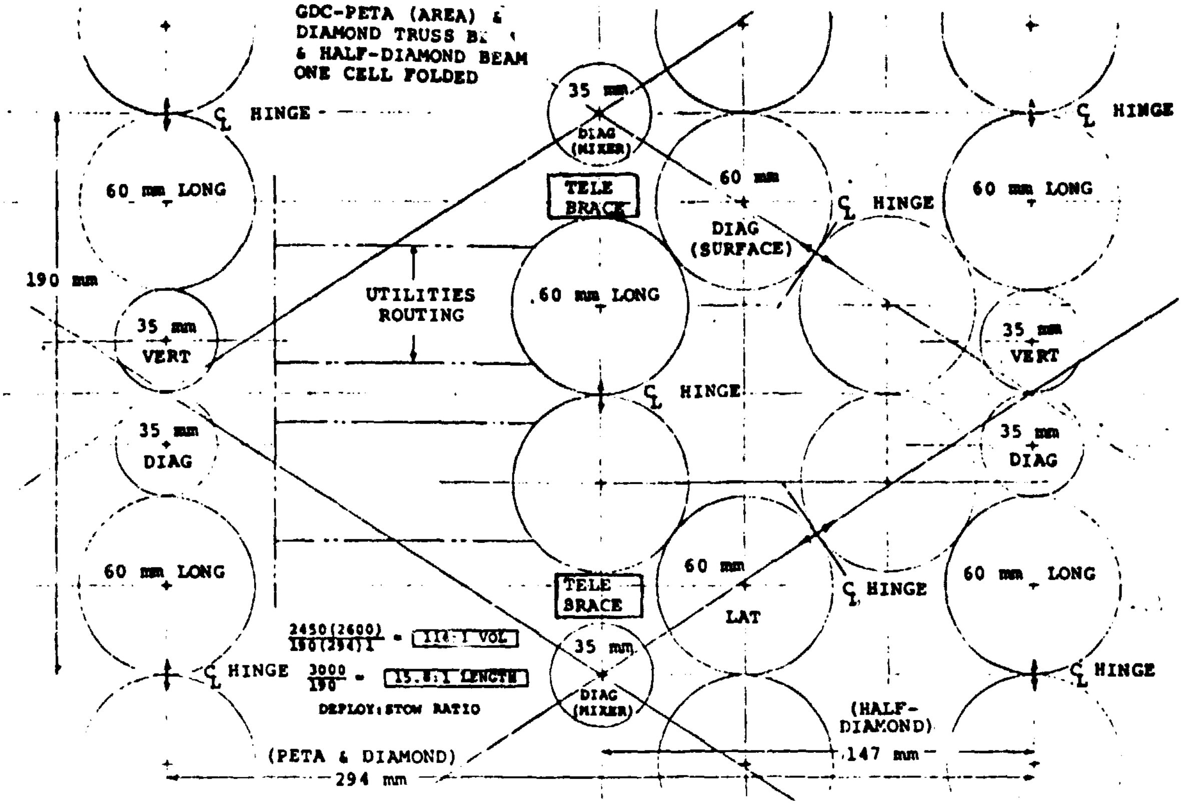
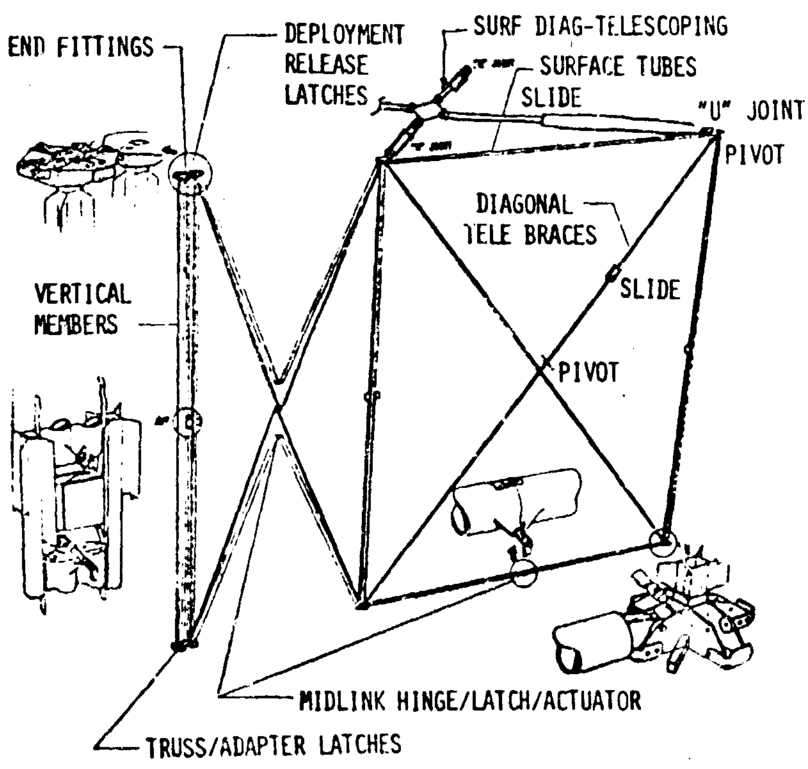


FIGURE 44
CONCEPT 4: PETA; 5: DIAMOND BEAM; 11: HALF-DIAMOND BEAM FOLDED GEOMETRY



PER ADD. CELL OF BEAM STR:	
ELEMENTS	JOINTS
4 LONG(LATCH)	16
2 LAT(LATCH)	8
2 VERT	0
8 SIDE DIAG "X"	24
8 UPR&LWR DIAG "X"	40
4 BHD DIAG "X"	12
28 TOTAL	100

13.6 Kg WT

FIGURE 45 CONCEPT 6: BOX TRUSS CONFIGURATION

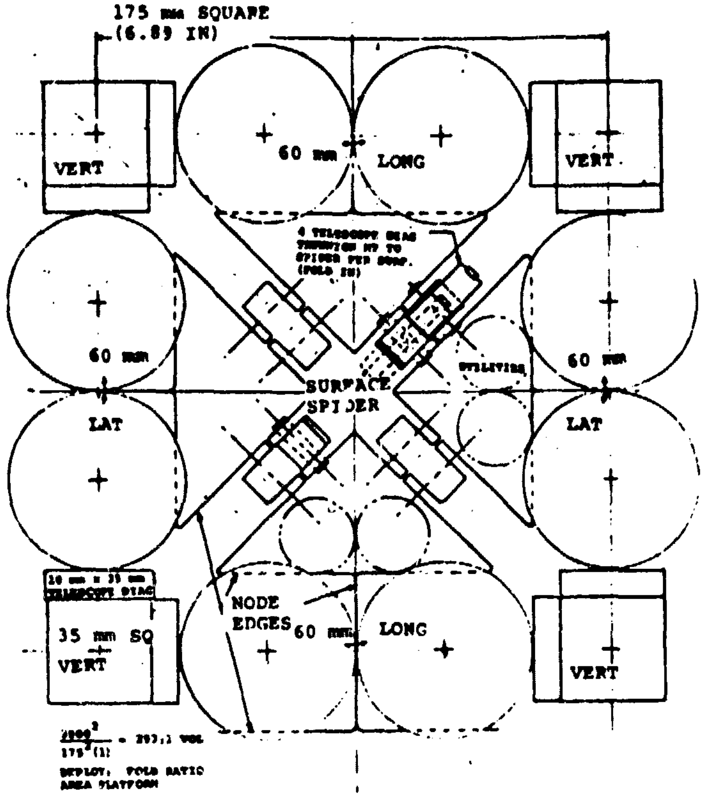
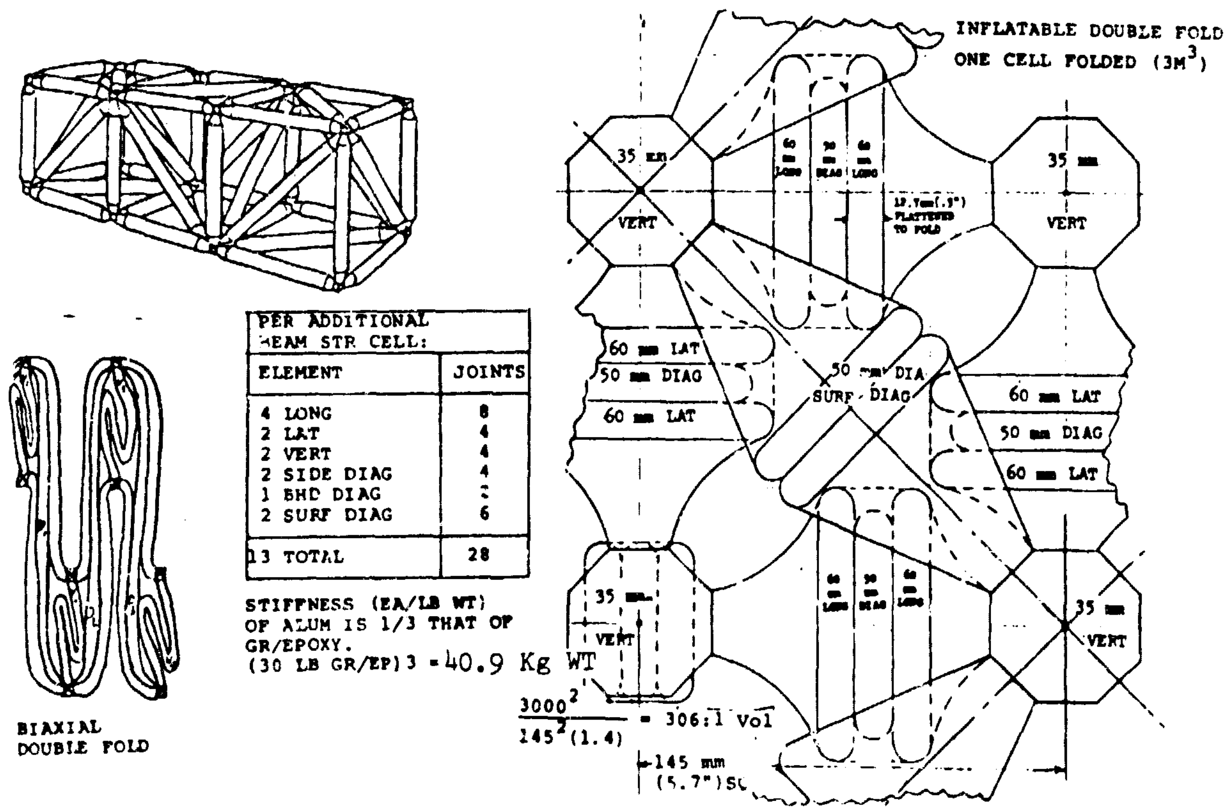


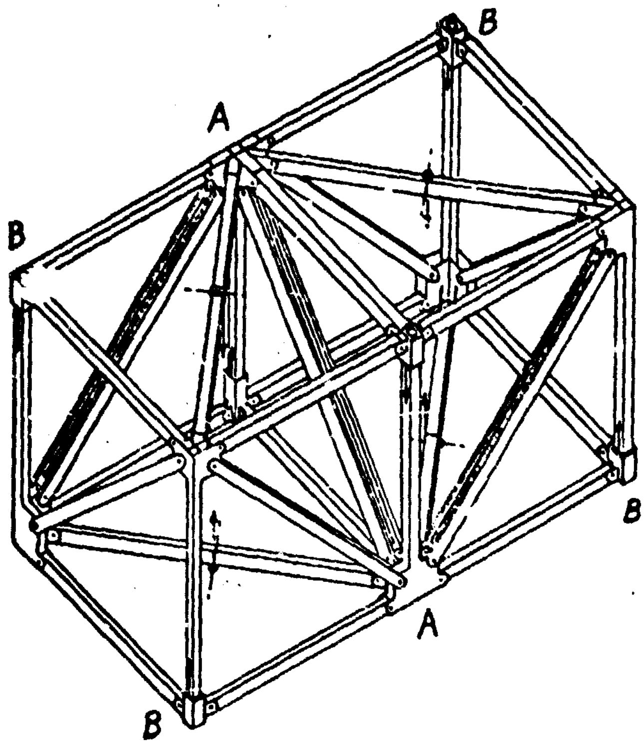
FIGURE 46 CONCEPT 6: BOX TRUSS FOLDED GEOMETRY



PER ADDITIONAL BEAM STR CELL: ELEMENT	JOINTS
4 LONG	8
2 LAT	4
2 VERT	4
2 SIDE DIAG	4
1 BHD DIAG	2
2 SURF DIAG	6
13 TOTAL	28

FIGURE 47 CONCEPT 7: INFLATABLE DOUBLE FOLD CONFIGURATION

graphite/epoxy strut of the same diameter, the inflatable strut will withstand about the same compressive load prior to buckling. Depending on the final selection of diameter and construction details, failure could occur in crippling (which would be evaluated in any subsequent inflatable truss studies). It is seen that the advantage of an extremely compact stowage volume is offset by the weight of the Inflatable Double Fold concept. Figure 48 shows the Biaxial Double Fold. In this early version of the BADF the upper and lower surface diagonals are rigid struts with knee joints. (The final version has crossed tensioned diagonals on the upper and lower surfaces.) As shown in the figure the estimated weight is 13.6 Kg. There are 30 joints and 13 elements involved. Figure 49 shows the folding arrangement and the stowed configuration crossection. The BADF folds very compactly, with a volume ratio between stowed and deployed of 293:1. As also shown in this figure the folding arrangement is such that the diagonals are not telescoped but pivoted about the node. This results in a folded length of 1.4 times the height of the cell in the deployed configuration. Figure 50 illustrates the Pivoted Double Fold, showing its estimated weight also at 13.6 Kg with 38 joints and 13 elements. Its folding arrangement is shown in Figure 51. The longitudinals and laterals have knee joints at their 30% lengths. The volume ratio is also good, at 153:1. The McDonnell Douglas Telefold configuration is shown in Figure 52. Its estimated weight is about 13.6 Kg. It has 48 joints per cell with 13 elements. Also illustrated in the figure is its cable actuated deploy and retract system. Its stowed configuration is shown in Figure 53. This is an axially deploying single fold structure. The length and volume ratio are both shown as 19.3:1. It should also be pointed out that many of the stowage ratios in the previous figures are different from those cited in the literature for the various concepts. This results because all the concepts were sized to have the same stiffness and to be the same basic truss size with the same strut slenderness ratios. The results of the above design studies provided inputs into the screening matrix which will be discussed in the following section.



PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
4 LONG	8
2 LAT	4
2 VERT(LATCH)	4
2 SIDE DIAG	4
2 UPR&LWR DIAG LATCH	8
1 BHD DIAG	2
13 TOTAL	30

13.6 Kg WT

FIGURE 48 CONCEPT 8: BIAXIAL DOUBLE FOLD CONFIGURATION

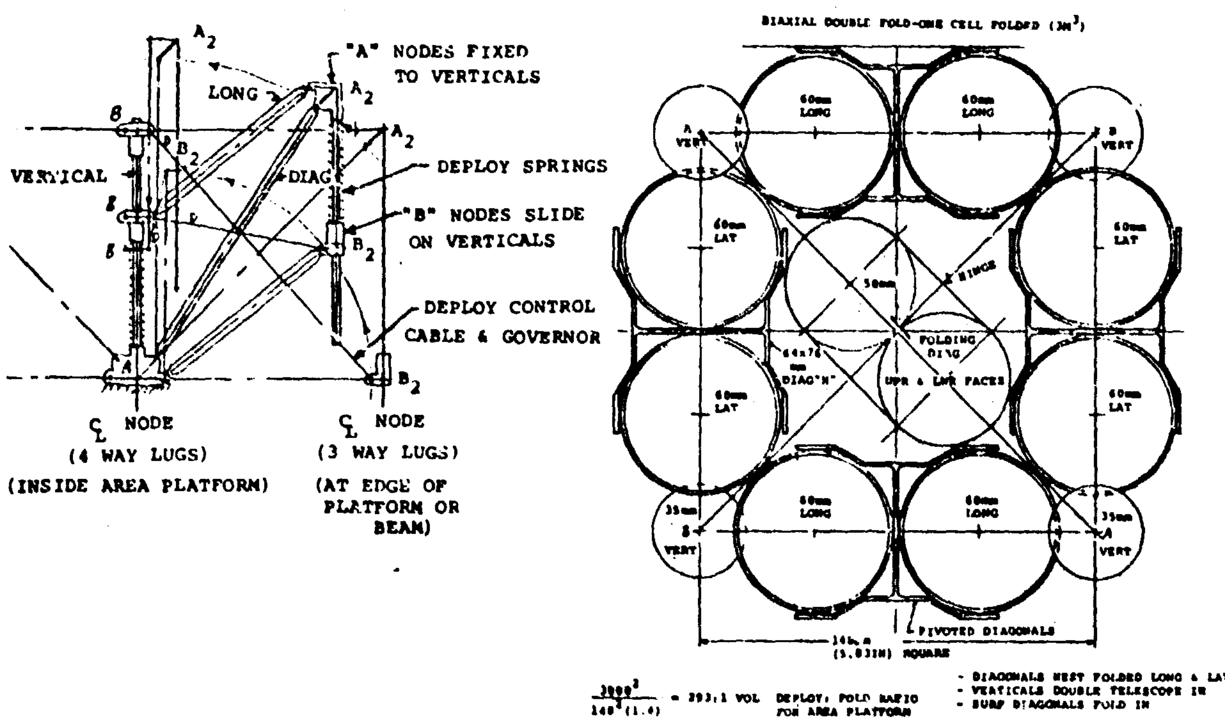
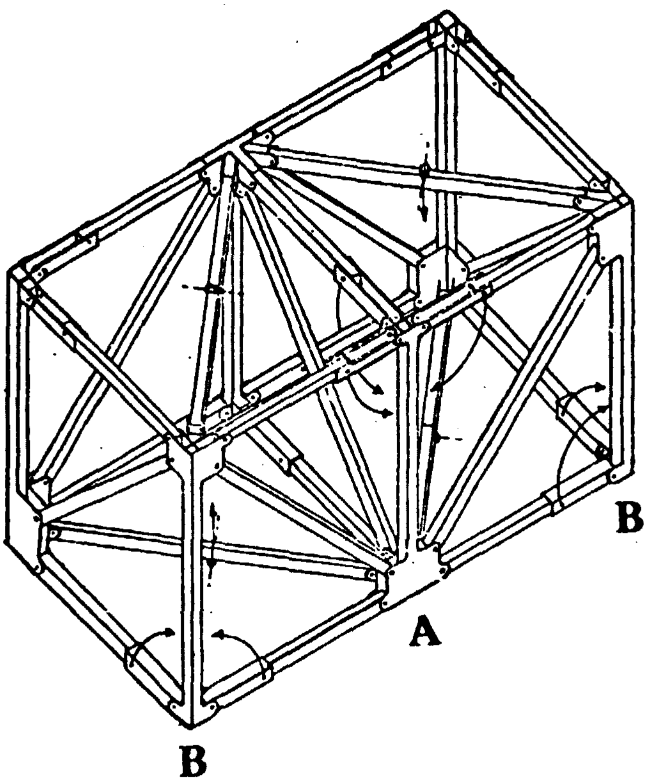


FIGURE 49 CONCEPT 8: BIAXIAL DOUBLE FOLD FOLDING GEOMETRY



PER ADDITIONAL BEAM STR CELL:	
ELEMENTS	JOINTS
4 LONG (LATCH)	16
2 LAT (LATCH)	8
2 VERT	0
2 SIDE DIAG	4
2 SURF. DIAG (LATCH)	8
1 BHD DIAG	2
13 TOTAL	38

13.6 Kg WT

FIGURE 50 CONCEPT 9: PIVOTED DOUBLE FOLD CONFIGURATION

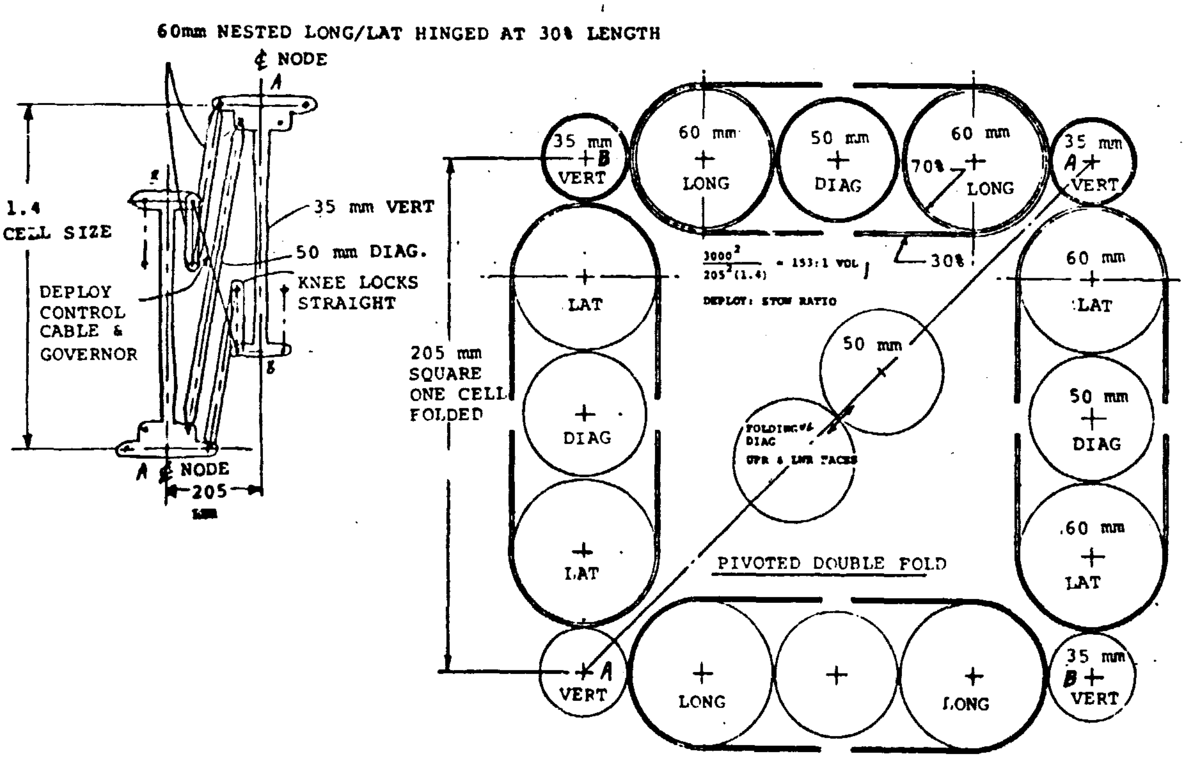
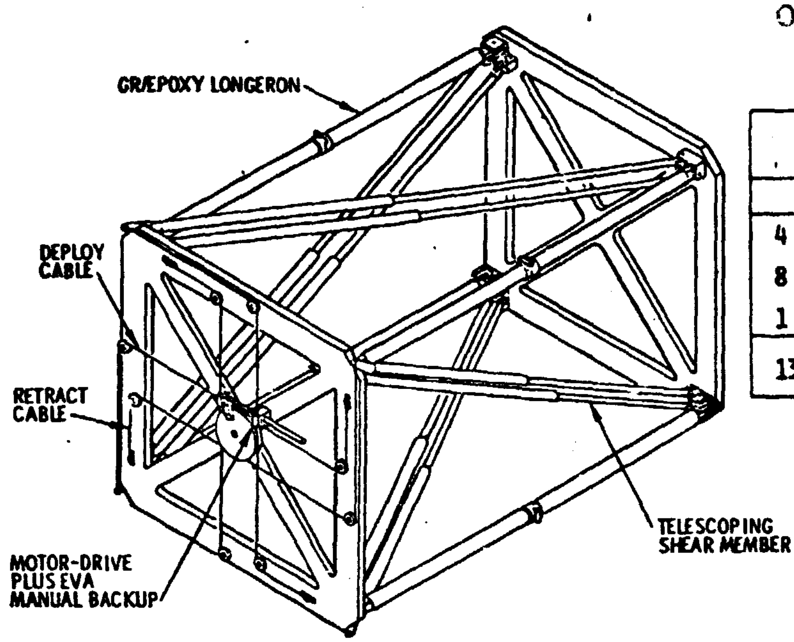


FIGURE 51 CONCEPT 9: PIVOTED DOUBLE FOLD FOLDING GEOMETRY



PER ADDITIONAL BEAM STR CELL: ELEMENTS	JOINTS
4 LONG(LATCH)	16
8 DIAL(LATCH)	32
1 BULKHEAD	0
13 TOTAL	48

13.6 Kg WT

FIGURE 52 CONCEPT 10: TELEFOLD CONFIGURATION

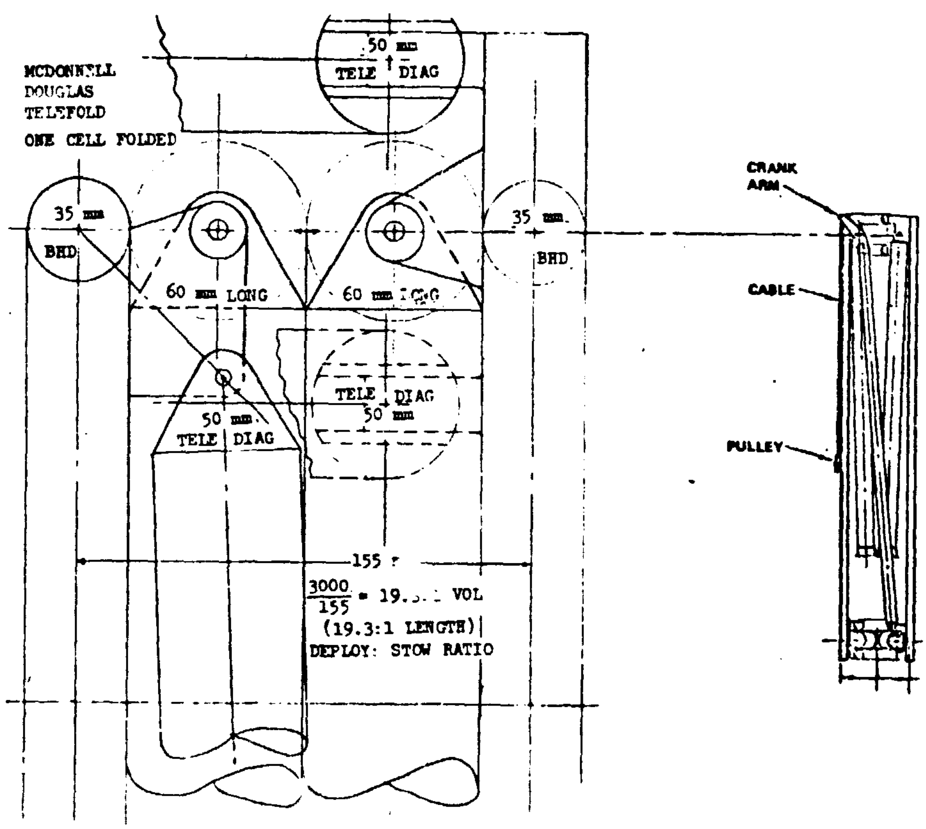


FIGURE 53 CONCEPT 10: TELEFOLD FOLDING GEOMETRY

2.4 SCREENING EVALUATION AND SELECTION

Table 5 shows each of the 22 screening critiera and summarizes the procedure used in their evaluation. The individual criteria are grouped under 5 categories which are considered as the driving factors in rating a deployable structure candidate. As indicated in Table 5, each of the individual criteria can be scored in the range of 0 to 10. The detailed definition of the rating criteria is given under the remarks column. One of these tables was filled out for each of the 11 concepts. They were then entered into a matrix that grouped the results of the scores for each of the 11 concepts on one sheet. Normalized weighting factors were applied. These factors were normalized such that under each of the major categories a total score in the range 0-10 could be obtained. Thus, for all 5 categories, the maximum points a concept could score is 50. To illustrate the application of the worksheet the evaluation of the Double Fold concept scores for deploy/stow volume ratio, the reliability factor number of joints per cell, and deployability index are given in Figures 54, 55, and 56. In Figure 54 the evaluation of the deploy/stow ratio is illustrated. The calculations show the volume ratio is 78:1 and, as indicated on the worksheet, the score is 3% of that, or 2.4. Figure 55 illustrates the procedure in calculating the reliability factor based on the number of joints per cell. For the Double Fold it shows the 36 joints involved divided into the factor of 200 which results in a score of 5.6. Figure 56 illustrates the evaluation of the deployability index figure-of-merit. The calculation of the deployability index was based on the work of H. W. Stoll (Ref. 21). This index depends on the deployable structure geometry, the length dimensions, and which element is driven to effect deployment. The index itself is the determinent of the coefficients of the simultaneous equations relating the dependent velocities of the mechanism. When this determinent becomes small, the mechanical advantage also becomes small and the deployability of the structure is reduced. Also, if this index is small the deployment mechanism will function poorly in all respects; force transmission, motion transformation, sensitivity to manufacturing errors, etc. Stoll has derived the deployability index for 7 basic linkage types. It was possible to evaluate the 11 structural concepts by using different combinations of these 7 basic types. According to Stoll, the overall deployability index of merit for a structure is equal to the product of all the individual linkages indicies calculated for each loop

TABLE 5

WORKSHEET AND DEFINITIONS OF
PRELIMINARY SCREENING CRITERIA

CRITERIA			SCORE (0-10)	REMARKS
PLATFORM CAPABILITY	DEPLOY STOW VOLUME RATIO			RATIO OF VOLUME OF A DEPLOYED CELL TO A FOLDED CELL OF STRUCTURE. BASED ON ℄ TO ℄ NODE DIMENSIONS. 3M x 3M CELL FACES. L/D OF 150 GIVES 60 MM LONG. & LAT. L/D OF 250 GIVES 50 MM DIAG AND 35 MM VERT. SCORE = 3X VOL RATIO.
	LINEAR & AREA DEPLOY			RATES A CONCEPT ON ITS ABILITY FOR USE AS EITHER A BEAM, MAST, OR AREA STRUCTURE. SCORE WAS LESS THAN 10 IF NOT DEPLOYABLE AS ALL THREE STRUCTURES.
DEPLOYABILITY	AUTO DEPLOY			RATES A STRUCTURE CONCEPT ON ITS ABILITY TO FULLY DEPLOY AND LATCH AUTOMATICALLY, ONCE POSITIONED TO ASSURE DEPLOY CLEARANCE BY RMS OR EVA. EXTERNAL POWER OR STORED ENERGY SYSTEM MAY BE USED.
	AUTO RETRACT			RATES A CONCEPT RELATIVE TO COMPLEXITY, COST, SPACE AND WEIGHT REQUIRED TO BUILD IN THE CAPABILITY TO AUTOMATICALLY RETRACT AND RESTOW IT IN ITS TRANSPORT SUPPORTS.
	CONTROL	DYNAMIC		PRIMARILY DEPLOY RATE CONTROL TO LIMIT DEPLOY STOP IMPACT TO SAFE STRESS LEVEL. CLOSE CONTROL BY GOVERNORS OR DAMPERS PERMIT HIGHER ENERGY MARGINS TO OVERCOME FRICTION THAN CONTROL USING STORED ENERGY AND CELL DEPLOY SEQUENCING TO LIMIT RATES.
		DIRECTIONAL		BECOMES LESS ACCURATE AS THE NUMBER-OF-DEGREES-OF-FREEDOM OR MOBILITY OF STRUCTURE DURING DEPLOYMENT INCREASES. MOBILITY OF TWO OR MORE REQUIRE MULTIPLE INPUTS WITH KNOWN RELATIONSHIP TO CONSTRAIN DEPLOYMENT WITH A KNOWN DIRECTION.
	DEPLOYABILITY INDEX			DETERMINANT OF THE COEFFICIENTS OF THE SIMULTANEOUS EQUATIONS RELATING THE DEPENDENT VELOCITIES OF A MECHANISM. CALCULATED FROM 0 TO 100% DEPLOYMENT. SCORES DETERMINED AT 60% DEPLOYMENT - HIGHEST CONCEPT 10 POINTS, LOWEST 1 POINT, OTHERS LINEAR DISTR.
	UTILITIES IMPACT			BENDING FORCES MAY AID OR HINDER AT DIFFERENT POINTS OF DEPLOYMENT. MAY REQUIRE REDESIGN FOR DEPLOY ENERGY DISTRIBUTION AND CONTROL. INTERNAL ROUTING THRU PIVOTS AND LATCHES MAY REQUIRE REDESIGN.
VERSATILITY	SCALING EASE SIZE-STR-STIFF			A HIGH SCORE REQUIRED THAT CELL SIZE, STRENGTH AND STIFFNESS COULD BE INDEPENDENTLY SCALED UP OR DOWN.
	MODULE ASSY	LINEAR		RATES A CONCEPT IN EASE OF ASSEMBLING DEPLOYED MODULES INTO LARGER PLATFORMS. SMALL AUTOMATIC COUPLERS AT INTERFACE HARD POINTS SCORED HIGH. SPECIAL FITTINGS OR EXTRA STRUCTURAL ELEMENTS SCORED LOW.
		AREA		SAME AS LINEAR.
	DISHED SURFACE AREA CAPAB			RATES A CONCEPT ON THE EASE WITH WHICH ITS CELL SURFACE AND DIAGONAL ELEMENTS CAN BE VARIED IN LENGTH AND STILL FOLD EASILY AND COMPACTLY.
SUBSYSTEM INTEGRATION	LOCAL HARD POINTS			RATES A CONCEPT ON THE EXISTANCE, OR THE ABILITY TO INCORPORATE, LOCAL HARD POINTS WHICH WILL ACCEPT INTERFACE LOADS FOR SUBSYSTEM INTEGRATION.
	LOCAL STRUCTURE			RATES A CONCEPT ON THE ABILITY TO DISTRIBUTE LOADS FROM HARD POINTS INTO LOCAL STRUCTURE. STRONGER LOCAL STRUCTURAL ELEMENTS SCORED HIGHER THAN IF ADDITIONAL ELEMENTS WERE REQUIRED.
	UTILITIES	INTERNAL		RATES A CONCEPT RELATIVE TO ROUTING SPACE INSIDE STRUTS THRU END PIVOTS AND KNEE JOINTS. MANY BENDS OR PIVOTS WERE SCORED LOWER DUE TO LARGE NUMBER OF FLEXIBLE SECTIONS, WHICH INCREASE WEIGHT, COST AND DEPLOY ENERGY.
		EXTERNAL		RATES A CONCEPT RELATIVE TO ROUTING SPACE BETWEEN FOLDED STRUCTURAL ELEMENTS. MANY BENDS OR PIVOTS SCORED LOWER AS ABOVE.
		STOW VOL		RATES A CONCEPT ON ITS ABILITY TO PROVIDE LARGE ROUTING SPACE, INTERNALLY AND EXTERNAL COMBINED, WITHOUT SEPARATING FOLDED ELEMENTS AND INCREASING STOW VOLUME.
PERFORMANCE & MATURITY	RELIABILITY	# JOINTS/CELL		COUNTED EVERY PIVOT SLIDE, AND LATCH ACTION ON ELEMENTS REQUIRED FOR ADDITIONAL 3M BEAM STRUCTURE CELL. SCORE = 200 ÷ NUMBER OF JOINTS/CELL.
		REDUNDANT LOAD PATHS		BEAM STRUCTURE OF TWO OR MORE 3M CELLS HAD REDUNDANT LOAD PATHS IF STABLE UNDER AXIAL COMPRESSION AND ALSO BENDING AND TORSION MOMENTS WITH ONE ELEMENT OMITTED.
	WEIGHT WT PER CELL			SAME ELEMENT SIZES AS IN DEPLOY/STOW VOL RATIO, ASSUMING B/t = 50 FOR GR/EP MATERIAL ON ALL SQUARE CELLS. FOR DIAMOND OR TRIANGULAR CELLS t WAS INCREASED TO GIVE SAME BENDING STIFFNESS. SCORE = 200 ÷ WEIGHT/CELL.
	MATURITY			BASED ON HOW MANY STAGES OF DEVELOPMENT GONE THROUGH. BASIC FOLDING STRUCTURE DESIGN, AUTO DEPLOY, FABRICATION, TESTING, UTILITIES DESIGN OR TESTING.
	MIN TECH DEVELOPMENT			A MINIMUM AMOUNT OF NEW TECHNOLOGY DEVELOPMENT REQUIRED TO MATURE A CONCEPT TO A PRODUCTION DESIGN SCORED HIGH.

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TABLE 5 (CONT'D)

CRITERIA			SCORE (0-10)	REMARKS
PLATFORM CAPABILITY	DEPLOY/STOW VOLUME RATIO			RATIO OF VOLUME OF A DEPLOYED CELL TO A FOLDED CELL OF STRUCTURE. BASED ON 6 TO 6 NODE DIMENSIONS. 3M x 3M CELL FACES. L/ρ OF 150 GIVES 60 MM LONG, & LAT. L/ρ OF 250 GIVES 50 MM DIAG AND 35 MM VERT. SCORE = 3% VOL RATIO.
	LINEAR & AREA DEPLOY			RATES A CONCEPT ON ITS ABILITY FOR USE AS EITHER A BEAM, MAST, OR AREA STRUCTURE. SCORE WAS LESS THAN 10 IF NOT DEPLOYABLE AS ALL THREE STRUCTURES.
DEPLOYABILITY	AUTO DEPLOY			RATES A STRUCTURE CONCEPT ON ITS ABILITY TO FULLY DEPLOY AND LATCH AUTOMATICALLY, ONCE POSITIONED TO ASSURE DEPLOY CLEARANCE BY RMS OR EVA. EXTERNAL POWER OR STORED ENERGY SYSTEM MAY BE USED.
	AUTO RETRACT			RATES A CONCEPT RELATIVE TO COMPLEXITY, COST, SPACE AND WEIGHT REQUIRED TO BUILD IN THE CAPABILITY TO AUTOMATICALLY RETRACT AND RESTOW IT IN ITS TRANSPORT SUPPORTS.
	CONTROL	DYNAMIC		PRIMARILY DEPLOY RATE CONTROL TO LIMIT DEPLOY STOP IMPACT TO SAFE STRESS LEVEL. CLOSE CONTROL BY GOVERNORS OR DAMPERS PERMIT HIGHER ENERGY MARGINS TO OVERCOME FRICTION THAN CONTROL USING STORED ENERGY AND CELL DEPLOY SEQUENCING TO LIMIT RATES.
		DIRECTIONAL		BECOMES LESS ACCURATE AS THE NUMBER-OF-DEGREES-OF-FREEDOM OR MOBILITY OF STRUCTURE DURING DEPLOYMENT INCREASES. MOBILITY OF TWO OR MORE REQUIRE MULTIPLE INPUTS WITH KNOWN RELATIONSHIP TO CONSTRAIN DEPLOYMENT WITH A KNOWN DIRECTION.
	DEPLOYABILITY INDEX			DETERMINANT OF THE COEFFICIENTS OF THE SIMULTANEOUS EQUATIONS RELATING THE DEPENDENT VELOCITIES OF A MECHANISM. CALCULATED FROM 0 TO 100% DEPLOYMENT. SCORES DETERMINED AT 60% DEPLOYMENT - HIGHEST CONCEPT 10 POINTS, LOWEST 1 POINT, OTHERS LINEAR DISTR.
	UTILITIES IMPACT			BENDING FORCES MAY AID OR HINDER AT DIFFERENT POINTS OF DEPLOYMENT. MAY REQUIRE REDESIGN FOR DEPLOY ENERGY DISTRIBUTION AND CONTROL. INTERNAL ROUTING THRU PIVOTS AND LATCHES MAY REQUIRE REDESIGN.
VERSATILITY	SCALING EASE SIZE-STR-STIFF			A HIGH SCORE REQUIRED THAT CELL SIZE, STRENGTH AND STIFFNESS COULD BE INDEPENDENTLY SCALED UP OR DOWN.
	MODULE ASSY	LINEAR		RATES A CONCEPT IN EASE OF ASSEMBLING DEPLOYED MODULES INTO LARGER PLATFORMS. SMALL AUTOMATIC COUPLERS AT INTERFACE HARD POINTS SCORED HIGH. SPECIAL FITTINGS OR EXTRA STRUCTURAL ELEMENTS SCORED LOW.
		AREA		SAME AS LINEAR.
	DISHED SURFACE AREA CAPAB			RATES A CONCEPT ON THE EASE WITH WHICH ITS CELL SURFACE AND DIAGONAL ELEMENTS CAN BE VARIED IN LENGTH AND STILL FOLD EASILY AND COMPACTLY.
SUBSYSTEM INTEGRATION	LOCAL HARD POINTS			RATES A CONCEPT ON THE EXISTANCE, OR THE ABILITY TO INCORPORATE, LOCAL HARD POINTS WHICH WILL ACCEPT INTERFACE LOADS FOR SUBSYSTEM INTEGRATION.
	LOCAL STRUCTURE			RATES A CONCEPT ON THE ABILITY TO DISTRIBUTE LOADS FROM HARD POINTS INTO LOCAL STRUCTURE. STRONGER LOCAL STRUCTURAL ELEMENTS SCORED HIGHER THAN IF ADDITIONAL ELEMENTS WERE REQUIRED.
	UTILITIES	INTERNAL		RATES A CONCEPT RELATIVE TO ROUTING SPACE INSIDE STRUTS THRU END PIVOTS AND KNEE JOINTS. MANY BENDS OR PIVOTS WERE SCORED LOWER DUE TO LARGE NUMBER OF FLEXIBLE SECTIONS, WHICH INCREASE WEIGHT, COST AND DEPLOY ENERGY.
		EXTERNAL		RATES A CONCEPT RELATIVE TO ROUTING SPACE BETWEEN FOLDED STRUCTURAL ELEMENTS. MANY BENDS OR PIVOTS SCORED LOWER AS ABOVE.
		STOW VOL		RATES A CONCEPT ON ITS ABILITY TO PROVIDE LARGE ROUTING SPACE, INTERNALLY AND EXTERNAL COMBINED, WITHOUT SEPARATING FOLDED ELEMENTS AND INCREASING STOW VOLUME.
PERFORMANCE & MATURITY	RELIABILITY	# JOINTS/CELL		COUNTED EVERY PIVOT SLIDE, AND LATCH ACTION ON ELEMENTS REQUIRED FOR ADDITIONAL 3M BEAM STRUCTURE CELL. SCORE = 200 ÷ NUMBER OF JOINTS/CELL.
		REDUNDANT LOAD PATHS		BEAM STRUCTURE OF TWO OR MORE 3M CELLS HAD REDUNDANT LOAD PATHS IF STABLE UNDER AXIAL COMPRESSION AND ALSO BENDING AND TORSION MOMENTS WITH ONE ELEMENT OMITTED.
	WEIGHT WT PER CELL			SAME ELEMENT SIZES AS IN DEPLOY/STOW VOL RATIO, ASSUMING D/t = 50 FOR GR/EP MATERIAL ON ALL SQUARE CELLS. FOR DIAMOND OR TRIANGULAR CELLS t WAS INCREASED TO GIVE SAME BENDING STIFFNESS. SCORE = 200 ÷ WEIGHT/CELL.
	MATURITY			BASED ON HOW MANY STAGES OF DEVELOPMENT GONE THROUGH. BASIC FOLDING STRUCTURE DESIGN, AUTO DEPLOY, FABRICATION, TESTING, UTILITIES DESIGN OR TESTING.
	MIN TECH DEVELOPMENT			A MINIMUM AMOUNT OF KEY TECHNOLOGY DEVELOPMENT REQUIRED TO MATURE A CONCEPT TO A PRODUCTION DESIGN SCORED HIGH.

DEFINITION:

- RATIO OF VOLUME OF A DEPLOYED CELL TO A FOLDED CELL OF STRUCTURE

METHOD/ASSUMPTIONS:

- BASED ON ℄ TO ℄ NODE DIMENSIONS
- 3M X 3M CELL FACES
- L/ρ OF 150 RESULTS IN 60mm DIA LONG. & LAT.
- L/ρ OF 250 RESULTS IN 50mm DIA & 35 mm VERT.
- SCORE = 3% VOLUME RATIO

EVALUATION:

(FROM CONCEPT DESCRIPTION)

- DEPLOYED CELL = 3M CUBE

  VOLUME = $\underline{3000mm^3 \text{ DEPLOYED}}$
- FOLDED CELL = 9M LONG & $196mm^2$

  VOLUME = $\underline{9000(196)^2 \text{ FOLDED}}$
- $\frac{3000^3 \text{ DEPLOYED}}{9000(196)^2 \text{ FOLDED}} = \frac{3000^2}{3(196)^2} = \boxed{78{:}1 \text{ VOL}}$ DEPLOY: STOW RATIO

$\boxed{\text{SCORE} = 3\%(78) = 2.4}$

FIGURE 54
EVALUATION OF SCORE FOR DEPLOY: STOW VOLUME RATIO
CONCEPT 1: DOUBLE FOLD

DEFINITION:

- THE NUMBER OF JOINTS PER CELL OF STRUCTURE IS A MEASURE OF THE CONCEPTS COMPLEXITY AND THEREFORE RELIABILITY OF FULLY DEPLOYING AND LOCKING.

METHOD/ASSUMPTIONS:

- ALL ADDITIONAL STRUCTURE ELEMENTS REQUIRED TO CONSTRUCT ONE ADDITIONAL CELL OF BEAM STRUCTURE WERE COUNTED AND LISTED.
- EACH PIVOT, SLIDE, AND LATCH OPERATION WAS COUNTED AS A POINT AND LISTED.
- ALL POINTS WERE ADDED AND THE TOTAL LISTED.
- SCORE = 200 ÷ TOTAL NUMBER OF POINTS PER CELL

EVALUATION:

(FROM CONCEPT DESCRIPTION)

- 13 ELEMENTS HAD 36 JOINTS TOTAL PER ADDITIONAL BEAM STRUCTURE CELL.
- TO CHECK ANOTHER WAY, 26 PIVOT
  26 PIVOT + 5 SLIDE + 5 LATCH = $\boxed{\text{36 TOTAL}}$

$\boxed{\text{SCORE} = 200 \div 36 = 5.6}$

FIGURE 55
EVALUATION OF SCORE FOR NUMBER OF JOINTS
PER ADDITIONAL BEAM STRUCTURE CELL
CONCEPT 1: DOUBLE FOLD

DEFINITION:

- THE DEPLOYABILITY INDEX OF MERIT IS THE DETERMINANT OF THE COEFFICIENTS OF THE SIMULTANEOUS EQUATIONS RELATING THE DEPENDENT VELOCITIES OF A MECHANISM. IT DEPENDS ON STRUCTURE GEOMETRY, LINK DIMENSIONS, AND WHICH LINK IS DRIVEN TO EFFECT DEPLOYMENT.

METHOD/ASSUMPTIONS:

- DEPLOYABILITY INDEX CALCULATIONS WERE BASED ON WORK OF H. W. STOLL USING THE SAME EQUATIONS.
- THE ELEVEN CONCEPTS WERE EVALUATED USING COMBINATIONS OF FOUR BASIC LINKAGE TYPES.
- CALCULATION RESULTS AS A FUNCTION OF % DEPLOYMENT WERE PRESENTED AS CURVES ON A GRAPH.
- AT 60% DEPLOYMENT THE HIGHEST INDEX WAS RATED 10 POINTS AND THE LOWEST WAS RATED 1 POINT.
- ALL OTHER INDEXES WERE RATED POINTS BASED ON THEIR LINEAR DISTRIBUTION BETWEEN 1 AND 10 AT 60%.

EVALUATION:

CONCEPT 1 SCORES 7 POINTS A. 60%, ON THE GRAPH.

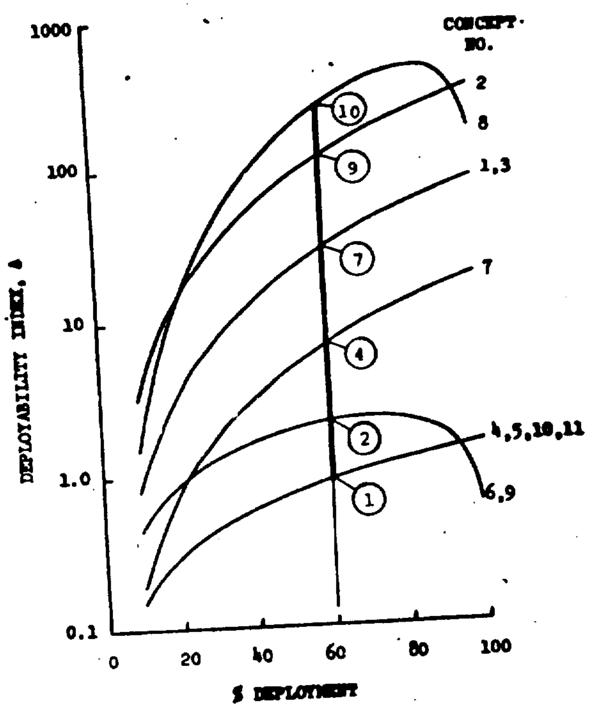

FIGURE 56 EVALUATION OF SCORE FOR DEPLOYABILITY INDEX OF MERIT CONCEPT 1: DOUBLE FOLD

closure equation associated with a particular link motion. The deployability index was calculated for each concept assuming a 3 m truss. The results of these calculations are presented in the plot in Figure 56 as a function of the percentage of deployment. All of those curves go to zero at zero percent deployment. In addition the curve for Concepts 6 and 9 go to zero with 100% deployment. The concepts were all evaluated at the 60% deployment point, and assigned a score between 1 point (Concepts 4, 5, 10, 11) and 10 points (Concept 8). Other scores were linearly interpolated. Using this procedure the Double Fold (No. 7) scored 7 points.

Table 6 shows the evaluation results for the 11 concepts assembled onto the screening matrix. In Table 6 the unweighted scores from the worksheets were transcribed directly onto the table. Table 7 includes the application of the normalized weighting factors. In the far right column the total score for each concept is given and in the right column under each of the five categories the subtotal in that category for each concept is given. Table 8 lists the results of the ranking. The total points are given for each concept, and the concepts are listed in the order of their rank. It can be noticed that four of the top five concepts are Vought designs, and that all five of the concepts are box type trusses, deployable in two axes. In order to obtain a broader perspective and more distinct concepts for detail system studies, Vought Concepts No. 2 and No. 9 were omitted. The sixth-ranking Concept, the MSFC Single Fold, was omitted because it is being evaluated inhouse at NASA. The Diamond Beam ranking was very close to that of the PETA area platform from which it was derived. Because of the guideline that area platforms would be constructed from linear platforms, and because the Diamond Beam offered more maturity and better adaptability to linear platforms, it was chosen as the fourth selection in preference to the PETA. The final selection of four concepts for additional study, as indicated on the table, are the Vought Biaxial Double Fold, the Vought Double Fold, the Martin Box Truss and the General Dynamics Diamond Beam.

TABLE 6

EVALUATION OF SCREENING MATRIX (UNWEIGHTED)

CRITERIA	I. PLATFORM CAPABILITY (0-10)			II. DEPLOYABILITY (0-10)							III. VERSATILITY (0-10)					IV. SUBSYS INTEGRATION (0-10)						V. PERFORMANCE & MATURITY (0-10)						TOTAL POINTS (0-50)
						CONTROL						MODULE ASSY						UTILITIES				RELIABILITY						
NORMALIZED WEIGHTS / CONCEPTS	DEPLOY/STOW VOL RATIO	LINEAR & AREA DEPLOY	SUB TOTAL	AUTO DEPLOY	AUTO RETR	DYN	DIR	DEPLOY INDEX	UTILITY IMPACT	SUB TOTAL	SCALING EASE SIZE STR-STIFF	LIN	AREA	DISHED SURF AREA CAPAB	SUB TOTAL	LOCAL HARD POINTS	LOCAL STR	INT	EXT	STOW VOL	SUB TOTAL	JOINTS PER CELL	REDUN LOAD PATHS	WT PER CELL	MATUR	MIN DEV TECH	SUB TOTAL	
1. VOUGHT DOUBLE FOLD	2.4	10	12.4	10	7	10	8	7	9	51	10	10	10	10	40	10	10	10	10	10	50	5.6	10	6.7	8	8	38.3	191.7
2. VOUGHT SCISSOR FOLD	6.7	10	16.7	10	9	10	8	9	7	53	10	6	8	6	30	7	10	6	7	7	37	10	0	9.2	5	7	31.2	167.9
3. MSFC SINGLE FOLD	0.4	7	7.4	10	5	10	8	7	9	49	10	8	8	1	27	10	10	0	8	9	37	10	10	6.7	8	8	42.7	163.1
4. GEN DYN PETA	3.4	10	13.4	10	1	3	9	1	6	30	8	10	10	10	38	9	8	6	8	7	38	5.3	10	5.2	8	7	35.5	154.9
5. GEN DYN DIAMOND BEAM	3.4	7	10.4	8	7	10	10	1	8	44	9	6	8	10	32	7	8	6	7	8	36	3.6	10	5.2	9	8	35.8	159.2
6. MARTIN BOX TRUSS	8.8	10	18.8	7	3	7	3	2	5	27	9	10	10	10	39	10	10	5	4	6	35	2.0	10	6.7	7	5	30.7	150.5
7. INFLATABLE DOUBLE FOLD	9.2	10	19.2	10	0	5	3	4	3	25	3	10	10	10	33	8	4	5	5	7	29	7.1	8	2.2	3	3	23.3	129.5
8. BIAXIAL DOUBLE FOLD	8.8	10	18.8	10	7	10	8	10	10	55	10	10	10	6	36	10	10	10	10	9	49	6.7	10	6.7	4	8	35.4	204.2
9. PIVOTED DOUBLE FOLD	4.6	10	14.6	9	3	9	7	2	6	36	8	10	10	6	34	10	8	0	8	10	36	5.3	10	6.7	3	6	31	151.6
10. MDAC TELEFOLD	0.6	7	7.6	7	7	10	10	1	10	45	9	10	10	1	30	10	8	7	8	10	43	4.2	10	6.7	6	6	32.9	156.5
11. GEN DYN HALF-DIAM. BEAM	3.4	7	10.4	8	7	10	10	1	6	42	8	6	8	1	23	7	8	5	5	6	31	4.5	0	3.8	7	6	[illegible]	139.7

TABLE 7

EVALUATION OF SCREENING MATRIX (WEIGHTED)

CRITERIA	I. PLATFORM CAPABILITY (0-10)			II. DEPLOYABILITY (0-10)							III. VERSATILITY (0-10)					IV. SUBSYS INTEGRATION (0-10)						V. PERFORMANCE & MATURITY (0-10)						TOTAL POINTS (0-50)
NORMALIZED WEIGHTS	DEPLOY/ STOW VOL RATIO	LINEAR & AREA DEPLOY	SUB TOTAL	AUTO DEPLOY	AUTO RETR	CONTROL DYN	CONTROL ON	DEPLOY INDEX	UTILITY IMPACT	SUB TOTAL	SCALING EASE; SIZE STR-STIFF	MODULE ASSY		DISHED SURF AREA CAPAB	SUB TOTAL	LOCAL HARD POINTS	LOCAL STR	UTILITIES INT	UTILITIES EXT	STOW VOL	SUB TOTAL	RELIABILITY JOINTS PER CELL	RELIABILITY REDUN LOAD PATHS	WT PER CELL	MATUR	MIN DEV TECH	SUB TOTAL	
CONCEPTS	.60	.40		.20	.10	.25	.10	.15	.20		.30	.30	.20	.20		.20	.20	.10	.20	.30		.30	.20	.30	.10	.10		
1. VOUGHT DOUBLE FOLD	1.44	4.0	5.44	2.0	0.7	2.5	0.8	1.05	1.8	8.85	3.0	3.0	2.0	2.0	10.0	2.0	2.0	1.0	2.0	3.0	10.0	1.68	2.0	2.01	0.8	0.8	10.0	41.58
2. VOUGHT SCISSOR FOLD	4.02	4.0	8.02	2.0	0.9	2.5	0.8	1.35	1.4	8.95	3.0	1.8	1.6	1.2	7.6	1.4	2.0	0.6	1.4	2.1	7.5	3.0	0	2.76	0.5	0.7	6.96	39.03
3. MSFC SINGLE FOLD	0.24	2.8	3.04	2.0	0.5	2.5	0.5	1.05	1.8	8.65	3.0	2.4	1.6	0.2	7.2	2.0	2.0	0	1.6	2.7	8.3	3.0	2.0	2.01	0.8	0.8	8.61	35.80
4. GEN DYN PETA	2.04	4.0	6.04	2.0	0.1	0.7	0.9	0.15	1.2	5.05	2.4	3.0	2.0	2.0	9.4	1.8	1.6	0.6	1.6	2.1	7.7	1.59	2.0	1.56	0.8	0.7	6.65	34.84
5. GEN DYN DIAMOND BEAM	2.04	2.8	4.84	1.6	0.7	2.5	1.0	0.15	1.6	7.55	2.7	1.8	1.6	2.0	8.1	1.4	1.6	0.6	1.4	2.4	7.4	1.08	2.0	1.56	0.9	0.8	6.14	34.23
6. MARTIN BOX TRUSS	5.28	4.0	9.28	1.4	0.3	1.7	0.3	0.30	1.0	5.00	2.7	3.0	2.0	2.0	9.7	2.0	2.0	0.5	0.8	1.8	7.1	0.6	2.0	2.01	0.7	0.5	5.81	36.89
7. INFLATABLE DOUBLE FOLD	5.52	4.0	9.52	2.0	0	1.2	0.3	0.60	0.6	4.70	0.9	3.0	2.0	2.0	7.9	1.6	0.8	0.5	1.0	2.1	6.0	2.13	1.6	0.66	0.3	0.3	4.99	33.11
8. BIAXIAL DOUBLE FOLD	5.28	4.0	9.28	2.0	0.7	2.5	0.8	1.50	2.0	9.50	3.0	3.0	2.0	1.2	9.2	2.0	2.0	1.0	2.0	2.7	9.7	2.01	2.0	2.01	0.4	0.8	7.22	44.90
9. PIVOTED DOUBLE FOLD	2.76	4.0	6.76	1.8	0.3	2.2	0.7	0.30	1.2	6.50	2.4	3.0	2.0	1.2	8.6	2.0	1.6	0	1.6	3.0	0.2	1.59	2.0	2.01	0.3	0.6	6.50	36.56
10. MDAC TELEFOLD	0.36	2.8	3.16	1.4	0.7	2.5	1.0	0.15	2.0	7.75	2.7	3.0	2.0	0.2	7.9	2.0	1.6	0.7	1.6	3.0	8.9	1.26	2.0	2.01	0.6	0.6	6.47	34.18
11. GEN DYN HALF-[illegible]IAN BEAM	2.04	2.8	4.84	1.6	0.7	2.5	1.0	0.15	1.2	7.15	2.4	1.8	1.6	0.2	6.0	1.4	1.6	0.5	1.0	1.8	6.3	1.35	0	1.14	0.7	0.6	3.79	28.08

TABLE 8

SELECTION OF 4 CONCEPTS FOR ADDITIONAL STUDY

CONCEPTS STACKED BY WEIGHTED TOTAL POINTS:

CONCEPT	TOTAL POINTS	RANK	SELECTED
8. VOUGHT BIAXIAL DOUBLE FOLD	44.90	1	✓
1. VOUGHT DOUBLE FOLD	41.58	2	✓
2. VOUGHT BIAXIAL SCISSORS FOLD	39.03	3	--
6. MARTIN BOX TRUSS	36.89	4	✓
9. VOUGHT PIVOTED DOUBLE FOLD	36.56	5	--
3. MSFC NESTED SINGLE FOLD	35.80	6	--
4. GEN DYN PETA	34.84	7	--
5. GEN DYN DIAMOND BEAM	34.23	8	✓
10.MDAC TELEFOLD	34.18	9	
7. INFLATABLE DOUBLE FOLD	33.11	10	
11.GEN DYN HALF-DIAMOND BEAM	28.08	11	

2.5 DEVELOPMENT OF STRUCTURAL AND DEPLOYMENT CONCEPTS

This section of the report discusses the design related studies to definite the structural and deployment related characteristics of the four concepts that were traded. The results of these analyses were then input into the concept trade matrix. Several key issues in the structural and deployment concept design were identified and are listed in Table 9.

TABLE 9
KEY ISSUES IN STRUCTURAL & DEPLOYMENT CONCEPT DESIGN

- ARRANGEMENT AND FOLDING GEOMETRY OF TRUSS MEMBERS
- SINGLE FOLD OR DOUBLE FOLD
- STOWAGE VOLUME AND SHAPE
- NUMBER OF PARTS AND JOINTS
- STRUCTURAL PERFORMANCE AND WEIGHT
- THERMAL DISTORTION AND STRESS
- EXTERNAL OR SELF-CONTAINED DEPLOYMENT/RETRACTION
- SEQUENTIAL OR COLLECTIVE DEPLOYMENT
- SINGLE AXIS OR BIAXIAL DEPLOYMENT
- DIRECTIONAL STABILITY AND CONTROL DURING DEPLOYMENT
- FORCES, VELOCITIES, AND ACCELERATIONS DURING DEPLOYMENT
- RELIABILITY OF MECHANISMS PLUS COMPATIBILITY FOR MANUAL BACKUP
- COMPATIBILITY WITH UTILITIES AND INTERFACES
- SUITABLE FOR EVA PAYLOAD OPERATIONS

The approach for conducting the deployment and structural concept studies included first defining a 3m truss width configuration in order to evaluate the impact of utility bending moments and strut node configuration (carried out under the Utilities Integration Task, Section 2.7). Then a baseline deployment/retraction concept was developed for the Biaxial Double Fold configuration. For the GDC Diamond Beam and the Martin Marietta Box Truss the design of the deployment system was already at least partially accomplished and only had to be evolved. A similar situation existed with the Double Fold concept, where the prior concept established under Ref. (7) only had to be evolved. Alternate deployment options available to each structure were also identified as part of the approach. Concept definitions and comparisons were based on graphite/epoxy for the struts, nodes, fittings and hinges. Properties used are typical of GY70/934 or GY70/X30 high modulous graphite/epoxy layups.

2.5.1 Biaxial Double Fold

Figure 57 illustrates the basic unit of the Biaxial Double Fold which is a 2 cell unit and shows the refold/deploy control cable system. Figure 58 shows the BADF folding arrangement. The truss folds simultaneously in two directions by telescoping the verticals and pivoting the bulkhead and side diagonals. All cells in the truss fold at the same time. Only two types of nodes are involved in the BADF concept. As illustrated in Figure 57, the "A" nodes are those to which all diagonals struts are attached and the other nodes are labeled the "B" nodes. The tension surface diagonals are solid rigid small diameter diagonals that provide additional space in the folded truss for routing of utilities. The method used to energize the deployment and retraction is also illustrated in Figure 57. Deployment is by a combination of energy stored in linear springs located in the vertical struts, and torque springs at the end of each longitudinal and lateral. Tension on a cable system provides an opposing force for controlled deployment and retraction. A single reversible cable drive motor actuates the entire deployable truss section. The cable system consists of two trunk lines: one running through the face diagonals on either side of the truss, and a triad of branch lines at each vertical. Application of motion to the trunk lines actuates each of the branch triads. All cables operate in parallel to fold or deploy all cell faces in parallel. The initial cable stroke releases all vertical telescope locks. Additional cable stroke compresses the verticals and then folds them toward the diagonals with the longitudinals and laterals nested between. The location of the branch line tie-in on the diagonals is such that moment is applied to the strut to assist folding. Figure 59 shows the fold geometry drawn to scale, which is the same on all sides of all cells. The tension diagonals on the upper and lower surfaces are self folding as the A nodes and B nodes move together at different levels. This can be seen in Figure 58, and further detail is given in Figure 60. Figure 60 shows some details of the surface diagonals as viewed in the plane of two verticals connected by two diagonals. During the initial movement of A nodes together a fold-initiate cam at each end of the A surface diagonal rotates each end inward 10°. The diagonal is thus buckled 20° at its midpoint link A and will continue to fold inward as the A nodes come together. The same fold procedure occurs at the B surface diagonal, except it buckles and folds outward. The solid tension diagonals are used in place of the original hollow compression

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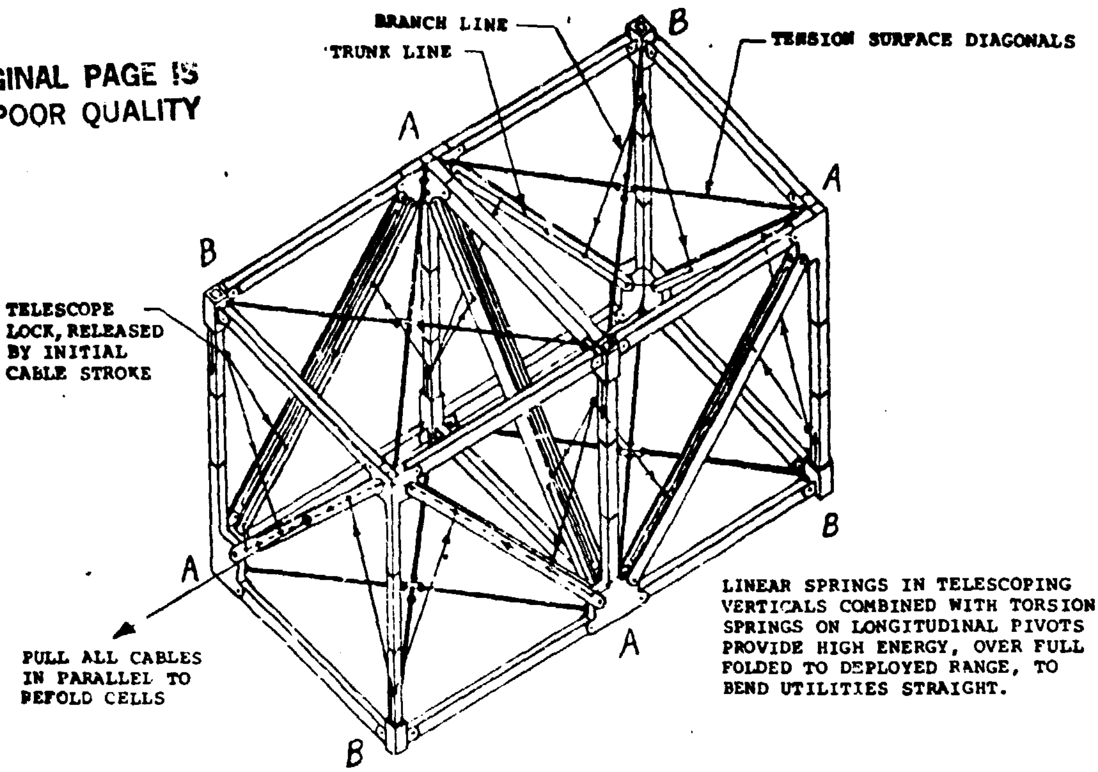

FIGURE 57 BIAXIAL DOUBLE FOLD REFOLD-DEPLOY CONTROL CABLE SYSTEM

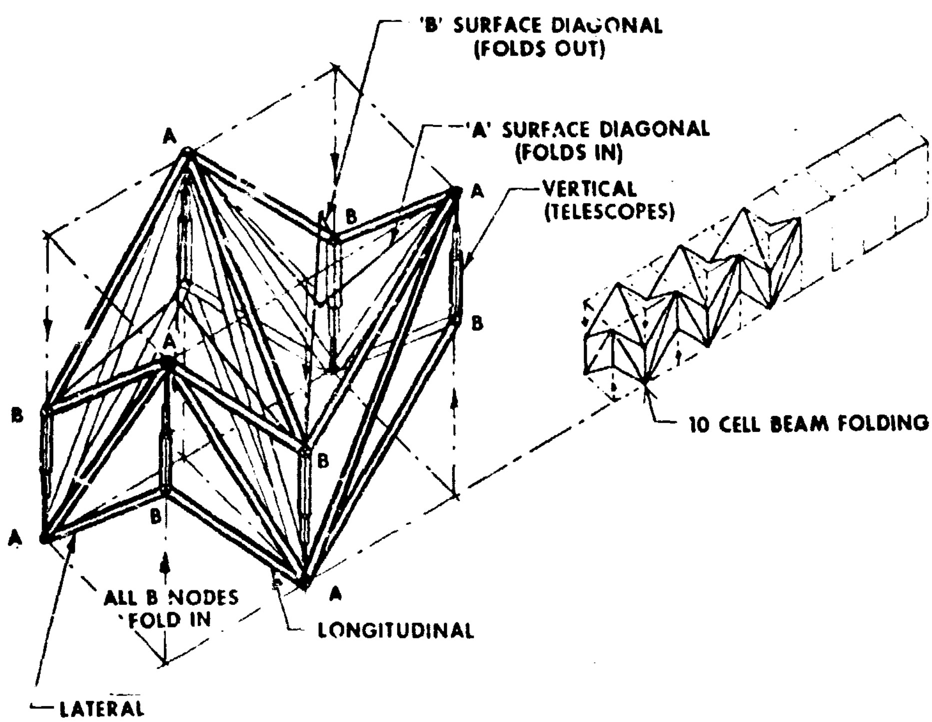

FIGURE 58 BADF STRUCTURE FOLDING

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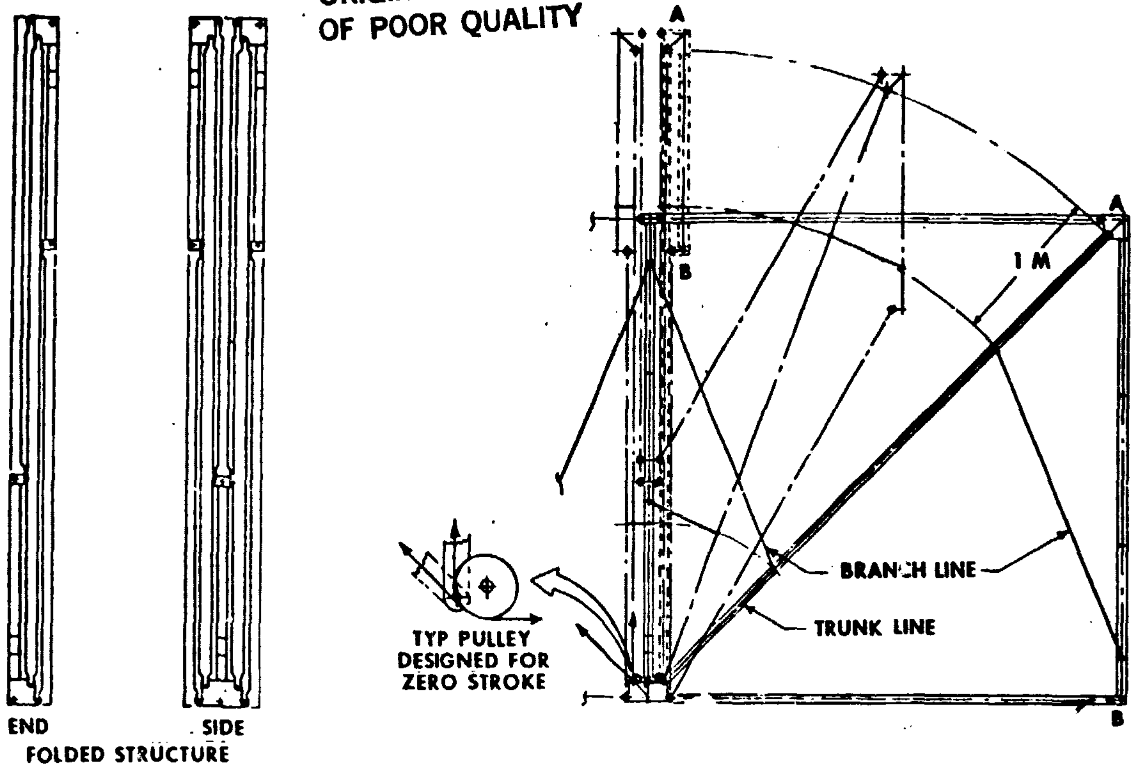

FIGURE 59 BADF FOLD GEOMETRY

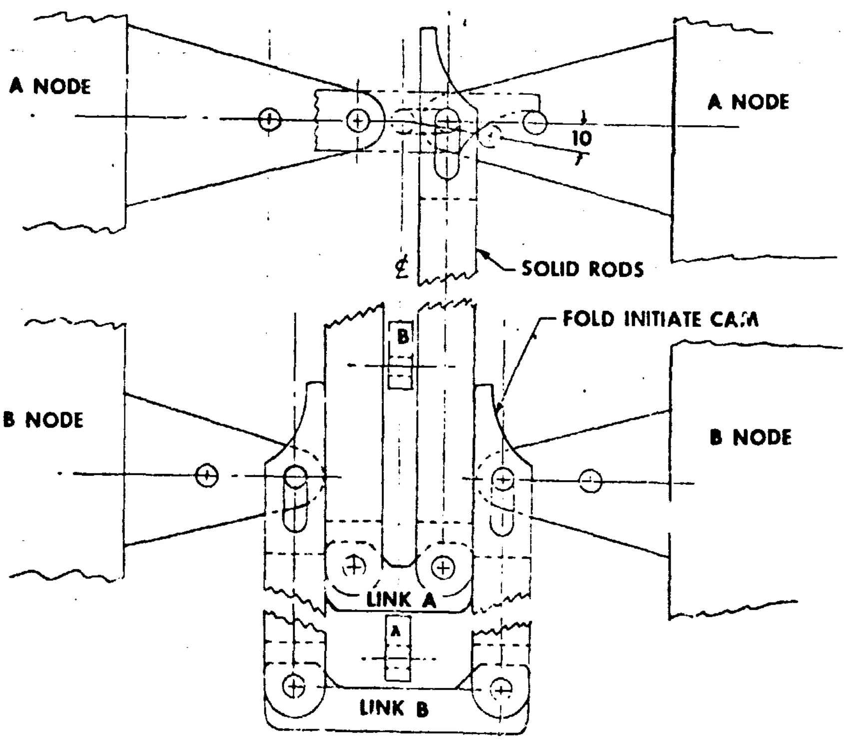

FIGURE 60 BIAXIAL DOUBLE FOLD SURFACE DIAGONALS DETAIL

diagonals with knee joint locks for two reasons. One, they are simpler to deploy and refold since they do not lock and unlock; and two, they fold compactly in the center of a cell leaving space around them for external utilities routing. A top view of a folded BADF cell is illustrated in Figure 61. This top view illustrates the octagonal crossection of the longitudinal and lateral struts, which provides space for the internal utilities routing and enhances the nesting characteristics. The "H" section diagonals can be seen nested around the octagonal struts, allowing optimum packaging. Also pointed out on the figure is the space available inside the folded formation for external utilities routing. In order to size the deploy springs it was necessary to estimate bending torques induced by the utilities. The result of this analysis is shown in Figure 62. Bending moments were taken from the test data and correlation established as presented in Section 2.7 on Utilities Integration. Figure 62 shows a combination of both linear and torque springs used to accomplish the deployment. Torque springs are provided at each node and linear springs are provided in the vertical struts, as illustrated in Figures 63 and 64. There are six small torque springs on A nodes and four on B nodes. Only one is shown in Figure 63, but there is one on either side of each pivot. Since each spring provides 6.2 N-m torque, a total of 12.4 N-m is provided then at each pivot in the fully folded position. The additive properties of the linear springs, shown in Figure 64, and the torque springs always exceeds the requirement of 12.4 N-m as shown in Figure 62. A summary of structural and deployment system characteristics, determined in the design studies for the BADF, is given in Table 10. These same criteria are also used in subsequent tables to evaluate the other concepts.

2.5.2 Martin Marietta Box Truss

The folding characteristics of the Martin Marietta Box Truss as a linear beam, are illustrated in Figure 65. The particular beam geometry depicted in that figure is not sized for utilities but rather is included as information transmitted to this study from Martin Marietta Corporation. In this figure a sequential folding scheme is shown which would require a separate cable reel, motor and control for each cell. Collective folding is also possible with the Martin Box Truss and would require one cable reel and one motor and control for all cells in a beam. Figure 66 illustrates the Martin Marietta Box Truss and a refold/deploy control cable system to provide collective deployment. Because the Box Truss concept has knee joints in the

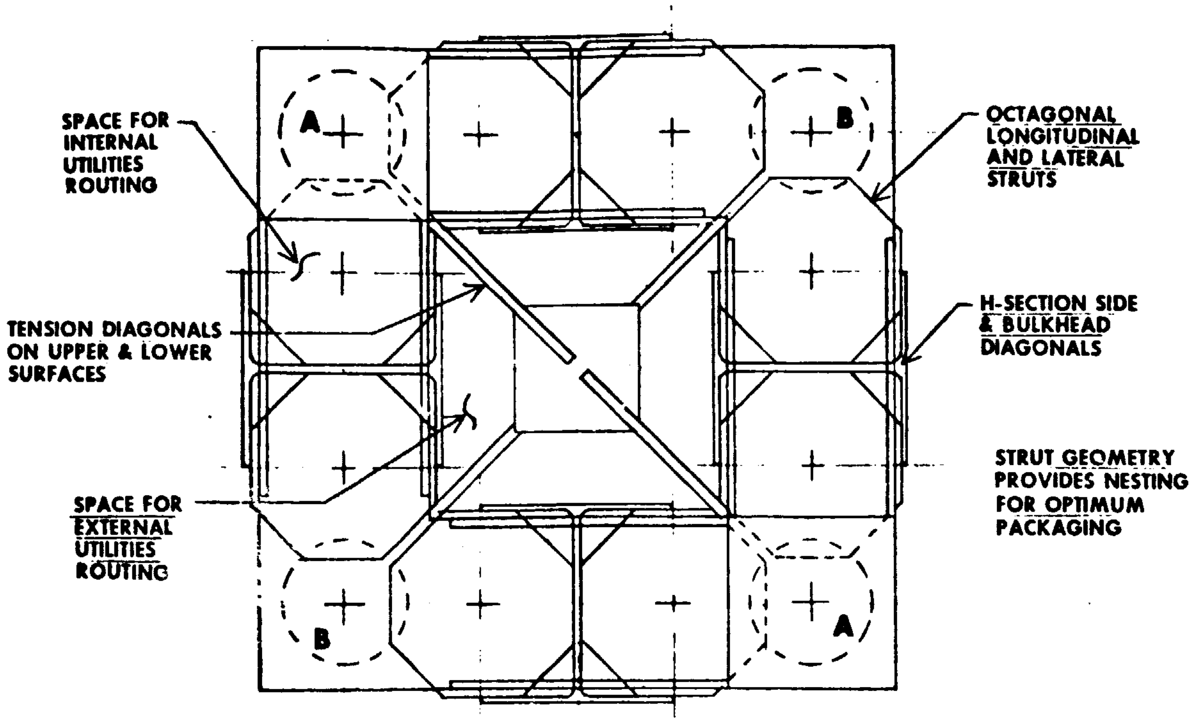

FIGURE 61 TOP VIEW OF BADF FOLDED CELL

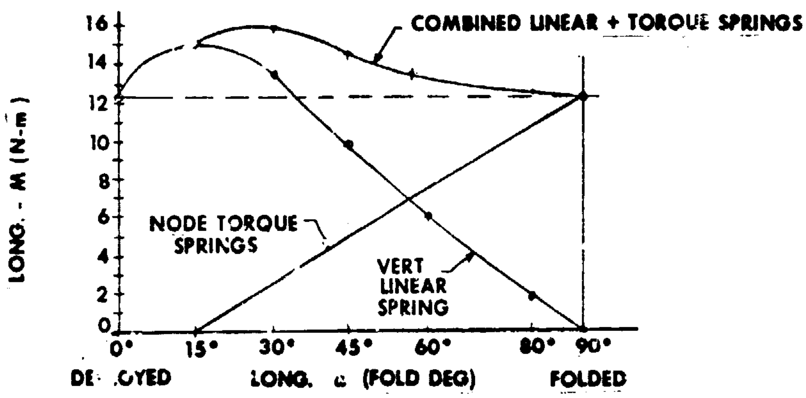

FIGURE 62 DEPLOY SPRING TORQUES FOR BIAXIAL DOUBLE FOLD

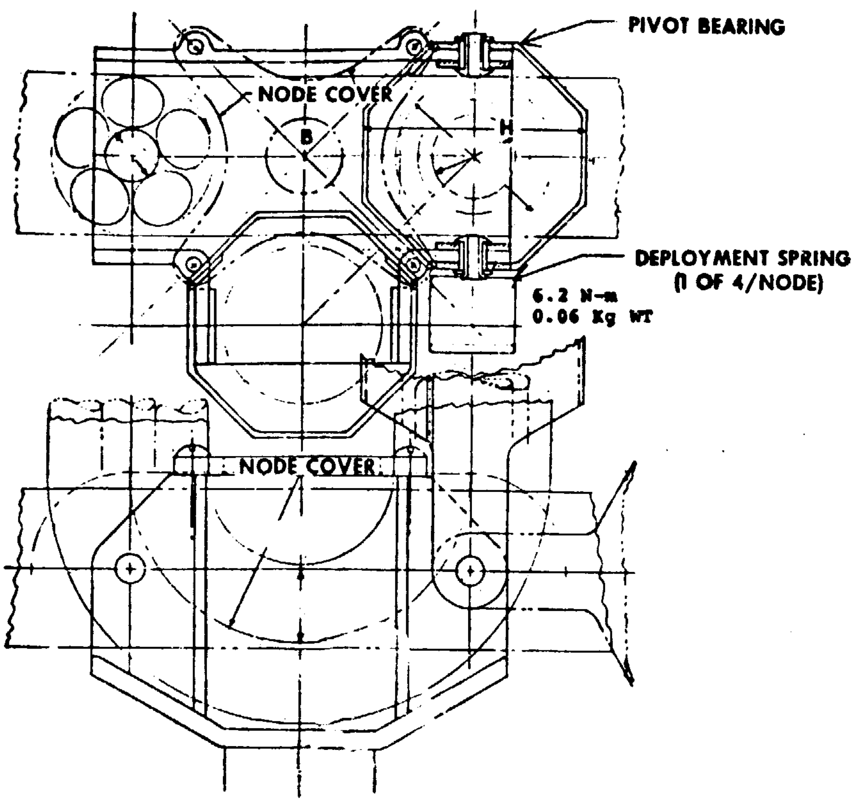

FIGURE 63 BADF B NODE DETAILS SHOWING DEPLOYMENT SPRING

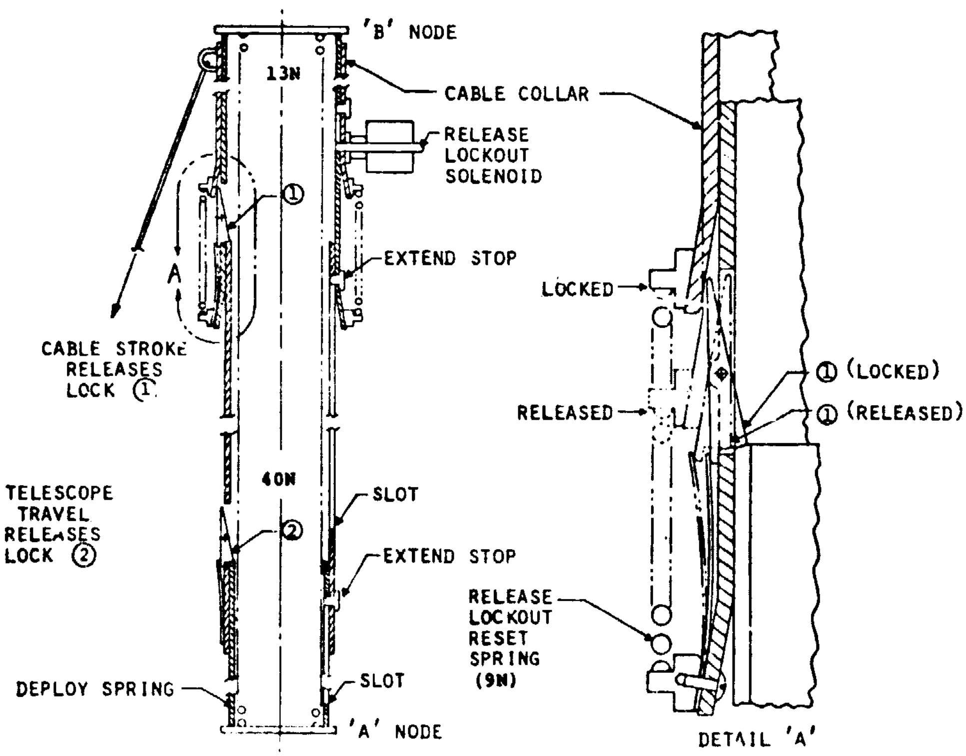

FIGURE 64 BADF DOUBLE TELESCOPE VERTICAL STRUT

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TABLE 10 SUMMARY OF BADF CHARACTERISTICS

COMPLEXITY
- 38 JOINTS PER CELL
- 15 ELEMENTS PER CELL

VOLUME RATIO
- 172 FOR 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

WEIGHT
- 21.6 KG (47.5 LBS) PER 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

UTILITIES IMPACT
- TWO 90° BENDS PER CELL

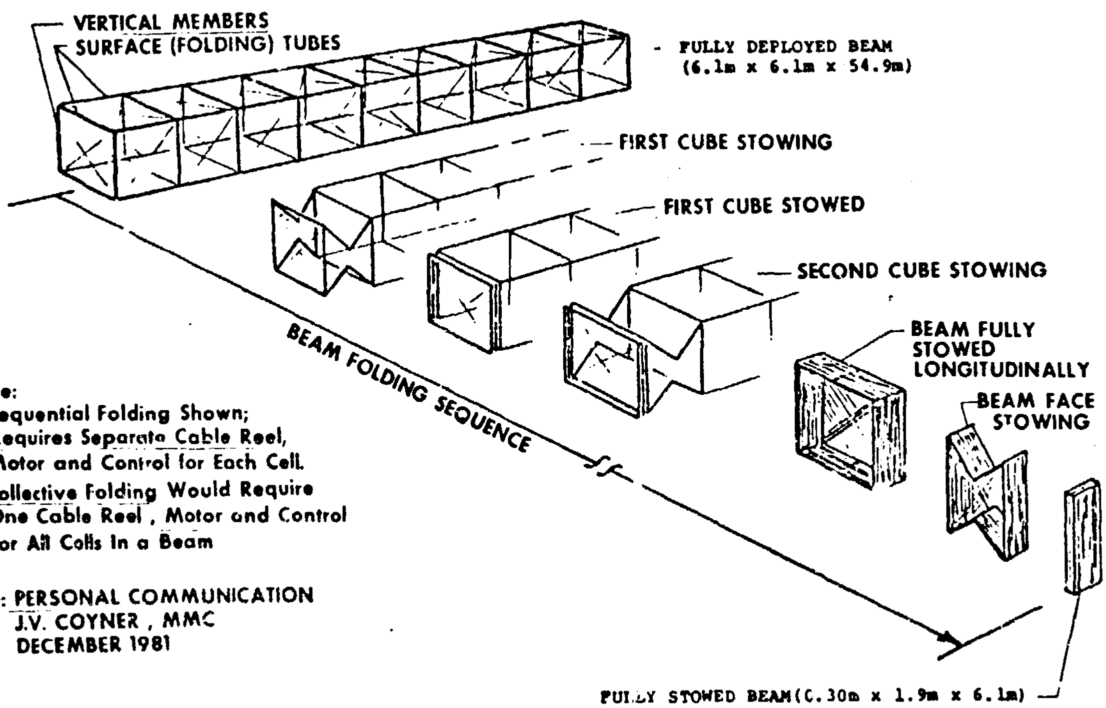
FOLD CONFIGURATION
- DOUBLE FOLD ONLY
- PACKAGE HEIGHT 1.4 TIMES CELL HEIGHT

DEPLOYABILITY
- STOLL INDEX VALUE OF 250

DYNAMIC AND DIRECTIONAL CONTROL
- PROVIDED BY RESTRAINT/RETRACT CABLE SYSTEM

DEPLOYMENT RELIABILITY
- PARALLEL, REDUNDANT, REVERSIBLE CABLE CONTROL SYSTEM
- EVA BACKUP

DEPLOYMENT TYPE
- SELF-CONTAINED ACTUATION ONLY
- COLLECTIVE, BIAXIAL DEPLOYMENT



Note:
- Sequential Folding Shown; Requires Separate Cable Reel, Motor and Control for Each Cell.
- Collective Folding Would Require One Cable Reel, Motor and Control for All Cells In a Beam

REF: PERSONAL COMMUNICATION
J.V. COYNER, MMC
DECEMBER 1981

FIGURE 65 MMC BOX TRUSS FOLDING SEQUENCE longitudinals, it would require greater torque for deployment. The required torque would be 12.4 x 2 = 24.8 N-m per 1/2 longitudinal. Also the Box Truss has no telescoping struts capable of housing linear springs to aid deployment. Therefore, all deploy energy must be in node pivot torque springs with a little aid from the knee joint lock spring at full deployment. These node torque springs would be at least 4 times the size required for the BADF concept. Figure 67 illustrates the top view of a Box Truss Folded Cell. In the figure there is indicated space for internal utilities routing and also space for external utilities routing. The telescoping diagonals are also shown. The square knee joints provide room for internal utilities routing. The lateral and longitudinal struts themselves are round. A summary evaluation of the Box Truss characteristics is given in Table 11. Examination of that Table shows that the Box Truss is much more complex than the BADF because of its many joints per cell, where, on the other hand, its deployment versatility (as indicated under Deployment Type) is better because it can deploy either sequentially or collectively, and biaxially or single-axis.

2.5.3 General Dynamics Diamond Truss Beam

Figure 68 illustrates a Square Diamond version of the General Dynamics Diamond Truss Beam concept. This concept is well documented in the literature and is distinctly different from other concepts evaluated because of its externally actuated deployment mechanism. Similar to the Box Truss, the Diamond Beam also has knee joints and will require additional torque to overcome the utilities bending moment. The torque will be approximately 49.7 N-m per strut. The deployment concept derived by General Dynamics is illustrated in Figure 69, and can also provide retraction. The Diamond Beam longitudinals cannot be pulled straight during deployment and the knee joint lock spring cannot provide the 49.7 N-m required. However, a shuttle arm which unlocks and breaks the knees during refold can be modified to also straighten and lock the knees during deployment. All the deploy and refold mechanisms will need to be made stronger to bend the integrated utilities. In Figure 70 a side view of a Diamond Beam folded cell is shown. As indicated there is space for either internal or external utilities routing. Flat sided knee joints are provided to allow routing of internal utilities. The longitudinal and diagonal struts are round for this concept. Table 12 summarizes the characteristics of the GD Diamond Beam. The Diamond Beam is seen to suffer somewhat from complexity but it does have advantages of being suitable for sequential or collective and biaxial or single axis deployment. It depends on the external deploy/retract mechanism and guide rails for

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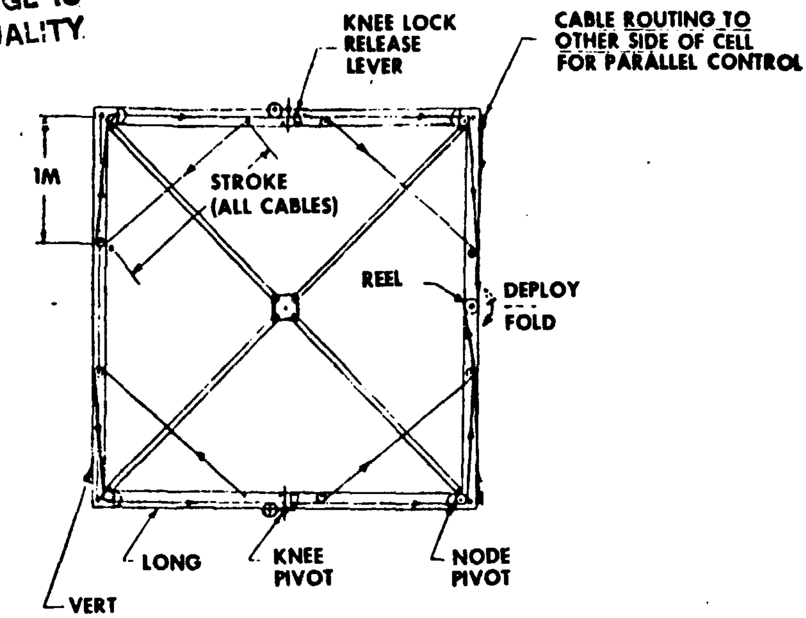

ALL KNEE JOINTS HAVE TORSION SPRINGS FOR DEPLOY ENERGY & LOCKING.
ALL NODE PIVOTS WITH UTILITIES THROUGH THEM ALSO HAVE TORSION SPRINGS FOR ADDITIONAL UTILITY DEPLOY ENERGY.

FIGURE 66 MMC BOX TRUSS REFOLD-DEPLOY CONTROL CABLE SYSTEM

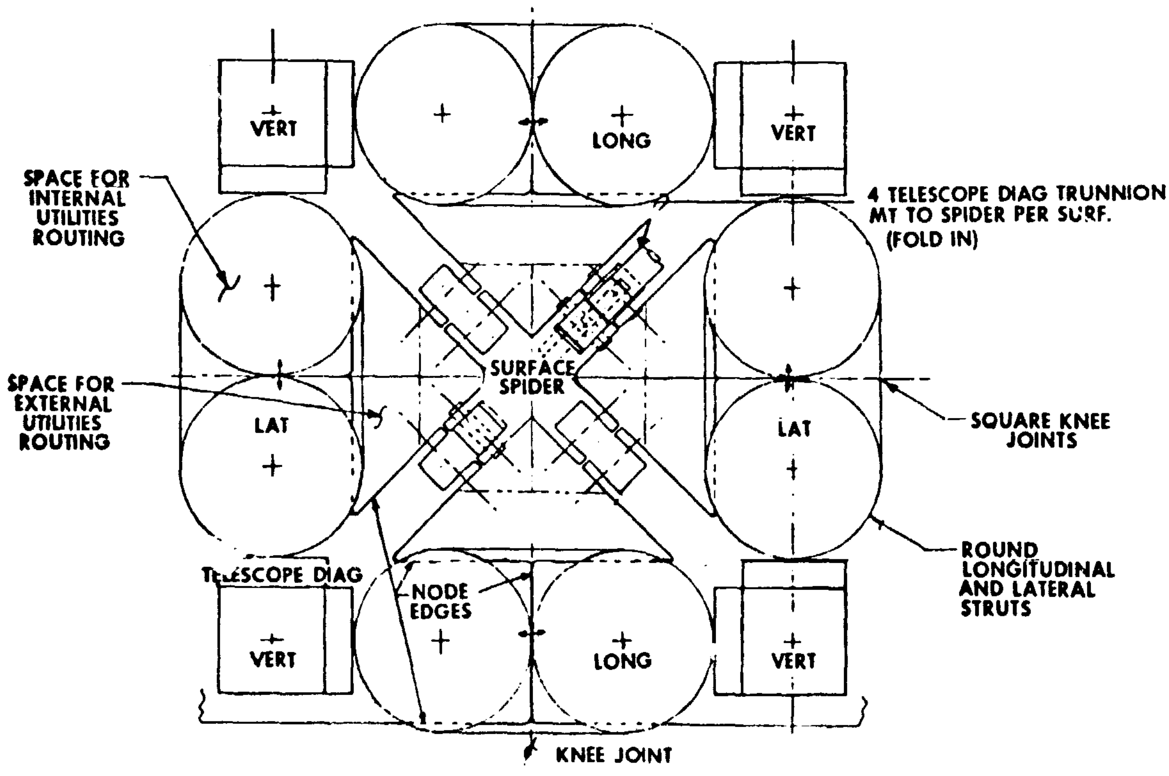

FIGURE 67 TOP VIEW OF BOX TRUSS FOLDED CELL

TABLE 11 SUMMARY OF MMC BOX TRUSS CHARACTERISTICS

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COMPLEXITY

- 100 JOINTS PER CELL
- 28 ELEMENTS PER CELL

VOLUME RATIO

- 120 FOR 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

WEIGHT

- 36.4 KG (80.0 LBS) PER 3m CELL SIZED FOR REPRESENTATIVE BUNDLES

UTILITIES IMPACT

- ONE 180° AND TWO 90° BENDS PER CELL

FOLD CONFIGURATION

- DOUBLE FOLD OR SINGLE FOLD
- PACKAGE HEIGHT 1.[illegible] TIMES CELL HEIGHT

DEPLOYABILITY

- STOLL INDEX VALUE OF 2

DYNAMIC AND DIRECTIONAL CONTROL

- PROVIDED BY RESTRAINT/RETRACT CABLE SYSTEM

DEPLOYMENT RELIABILITY

- PARALLEL, REDUNDANT, REVERSIBLE CABLE CONTROL SYSTEM
- EVA BACKUP

DEPLOYMENT TYPE

- SELF-CONTAINED OR EXTERNAL ACTUATION
- SEQUENTIAL OR COLLECTIVE AND BIAXIAL OR SINGLE AXIS DEPLOYMENT

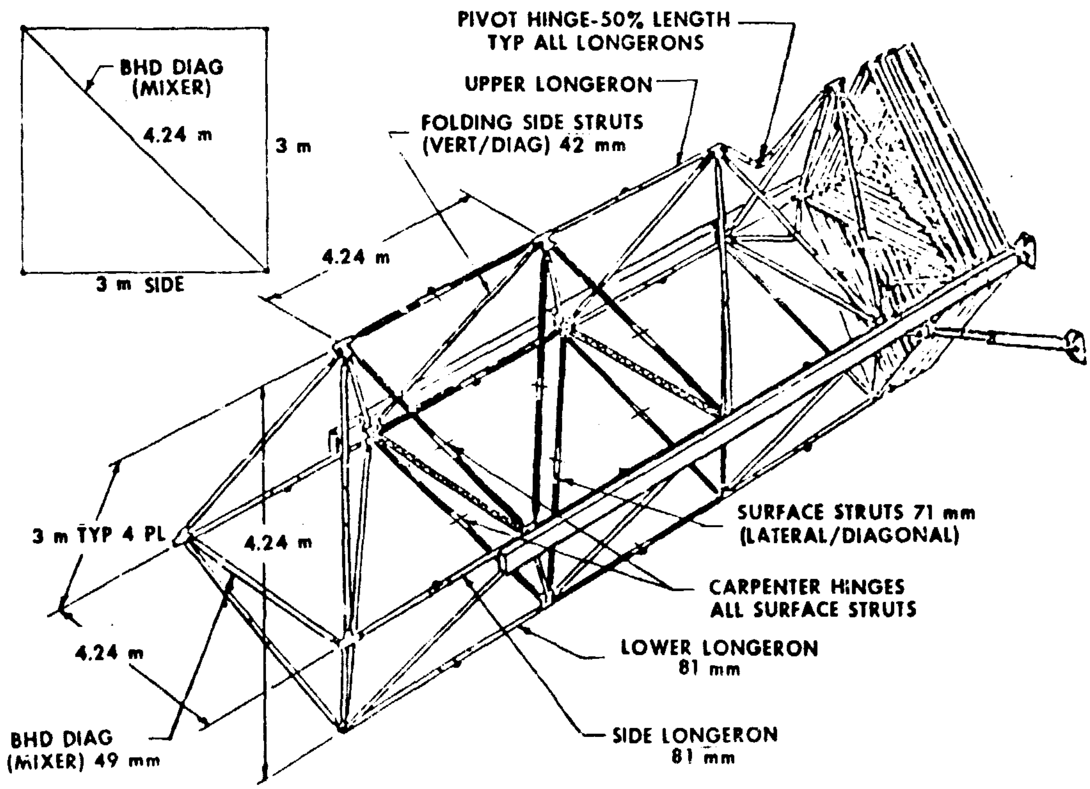

FIGURE 68 SQUARE DIAMOND BEAM DEPLOYMENT

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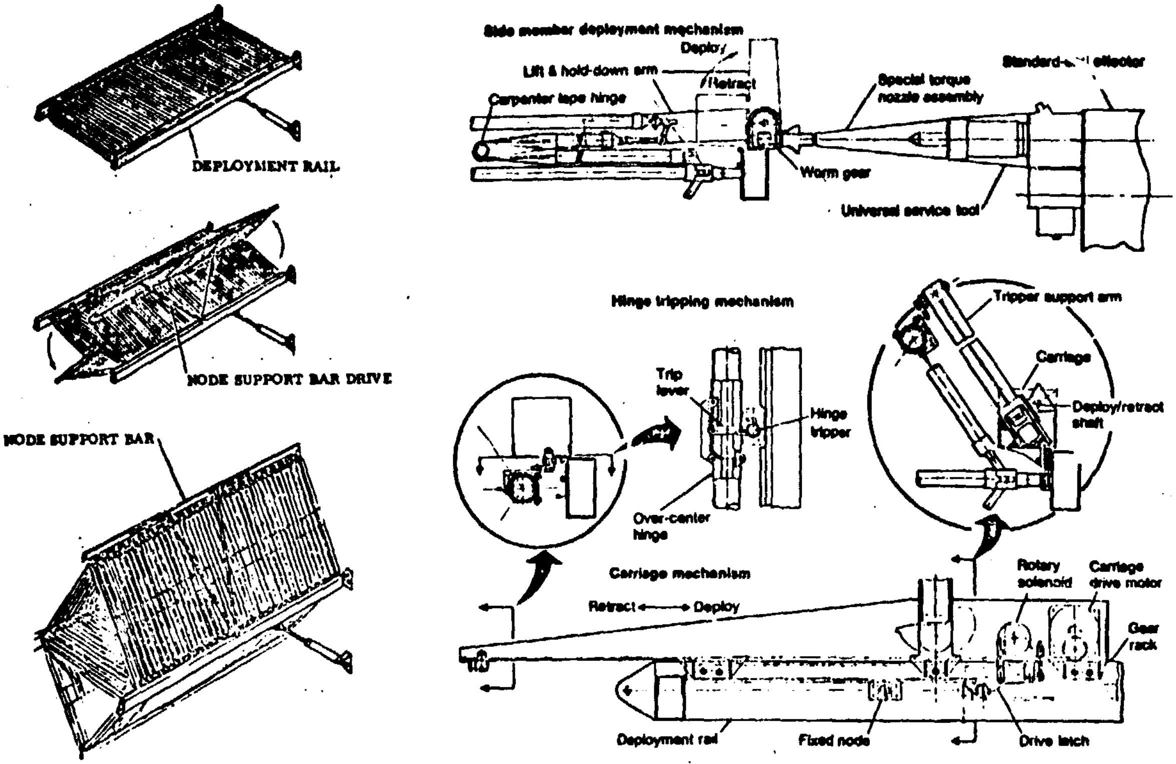

FIGURE 69 GDC DIAMOND BEAM DEPLOYMENT

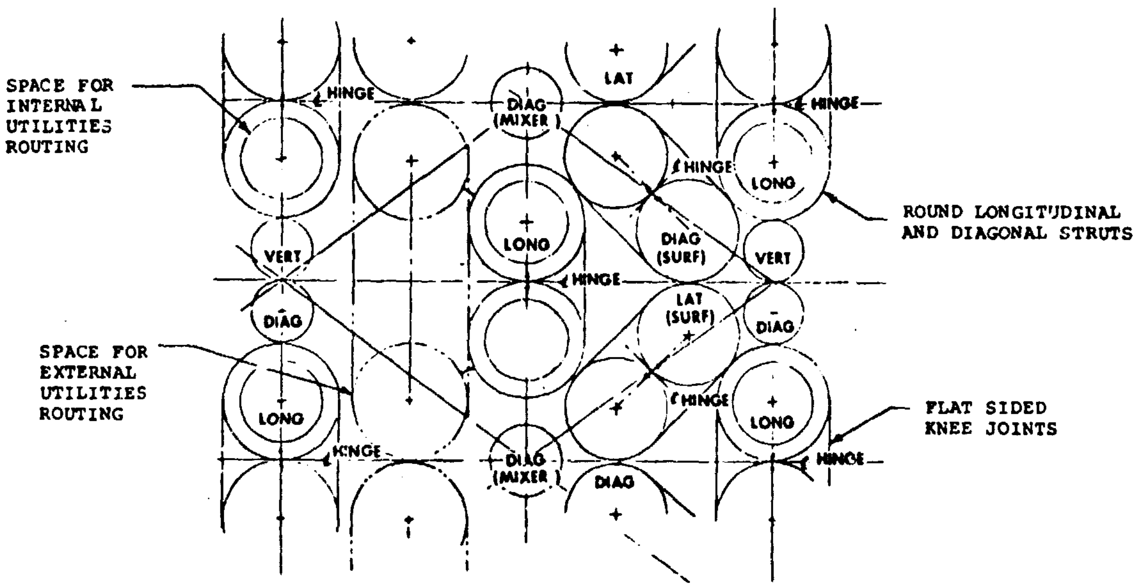

FIGURE 70 SIDE VIEW OF DIAMOND BEAM FOLDED CELL

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TABLE 12 SUMMARY OF GD DIAMOND BEAM CHARACTERISTICS

COMPLEXITY

- 56 JOINTS PER CELL
- 13 ELEMENTS PER CELL

VOLUME RATIO

- 120 FOR 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

WEIGHT

- 15.1 KG (33.2 LBS) PER 3m BEAM SIZED FOR REPRESENTATIVE UTILITY BUNDLES

UTILITIES IMPACT

- ONE 180° AND TWO 90° BENDS PER CELL

FOLD CONFIGURATION

- DOUBLE FOLD OR SINGLE FOLD
- PACKAGE HEIGHT 1.4 TIMES CELL HEIGHT

DEPLOYABILITY

- STOLL INDEX VALUE OF 1

DYNAMIC AND DIRECTIONAL CONTROL

- PROVIDED BY EXTERNAL DEPLOY/RETRACT MECHANISM ON GUIDE RAILS

DEPLOYMENT RELIABILITY

- ONE CELL AT A TIME DEPLOYMENT MONITORED BY EVA
- EVA BACKUP

DEPLOYMENT TYPE

- EXTERNAL OR SELF-CONTAINED ACTUATION
- SEQUENTIAL OR COLLECTIVE AND BIAXIAL OR SINGLE AXIS DEPLOYMENT

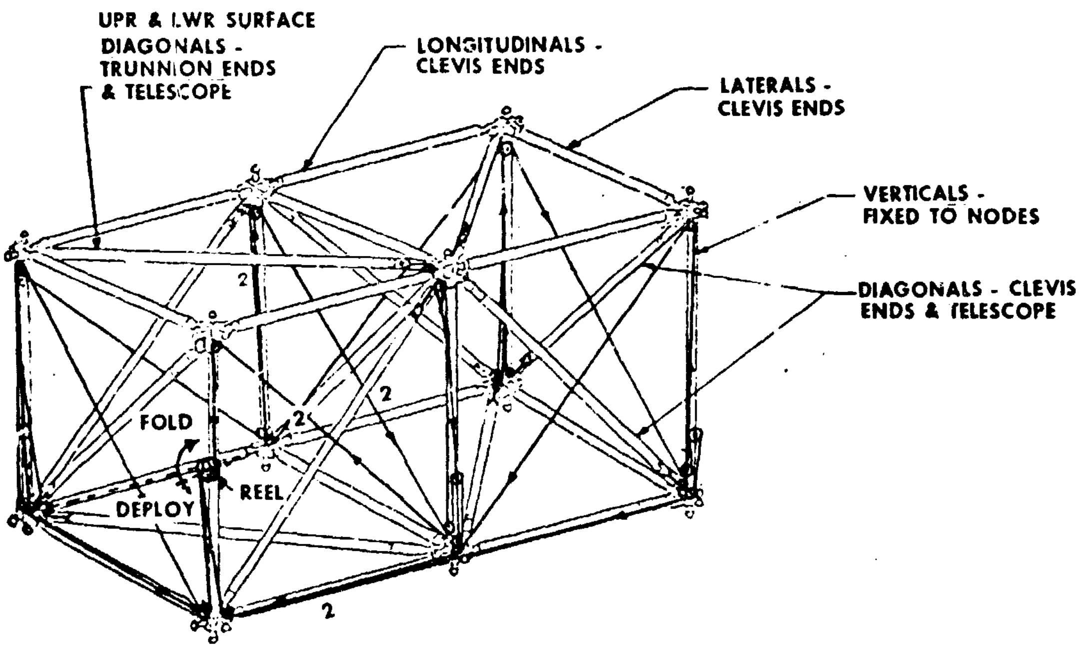


FIGURE 71 DOUBLE FOLD REFOLD-DEPLOY CONTROL CABLE SYSTEM

dynamic and directional control during deployment.

2.5.4 Double Fold

Figure 71 illustrates the basic two cell module of the Double Fold truss with a refold/deploy control cable system sketched on it. Additional detail is given in Figures 72 and 73. Energy for deployment is provided by springs located in the longitudinal and lateral struts. These springs act through a cable passing over sheaves on levers to initiate deployment. Then the cables act in parallel to both the face and bulkhead diagonals, to exert a compressive force on these telescoping diagonals and insure full compression to the locked position. The reel and cable system illustrated in Figure 71 provides control during deployment as well as the force to retract the truss. The figure shows a numbered cable, No. 2, to illustrate the concept. The path of the cable from the reel is down the vertical to the node, then along the longitudinal to the next node, then diagonally across the bulkhead of the truss upward to the opposite node, from that point down the opposite vertical and then up the bulkhead diagonal strut a short distance to the latch. The arrows on the cable indicate the direction of force to retract. The initial motion, approximately 38 mm, applied to the cable unlatches the bulkhead diagonal in this case. This motion is imparted by turning the reel a small distance. As the reel turning is continued, the unlatching of the diagonal locks is completed and a stop is encountered by the cable. This now allows a force to be exerted across the truss between opposing nodes which tends to lengthen the telescoping diagonal and fold the nodes together. The routing of the cable system is such that this force is exerted to complete the folding of the truss unit. The fold cables are all in parallel and additional cells would also be keyed in parallel to provide one motion to deploy or retract the entire structure. A top view of the double folded cell is shown in Figure 74. Space is indicated for internal and external utilities routing. In the case of the Double Fold, all the struts are round. Table 13 summarizes the characteristics of the double fold truss. Because it has no knee joints it is relatively non-complex. It is also suitable for sequential or collective, biaxial or single axis deployment. It has the disadvantage of having a relatively low volume storage ratio. In addition, the folded package height is 2.8 times cell height which could result in inefficient use of the Shuttle cargo bay.

All the characteristics of the four concepts developed and summarized in this section were used in the trade studies and concept selection trade matrix given in Section 5.0.

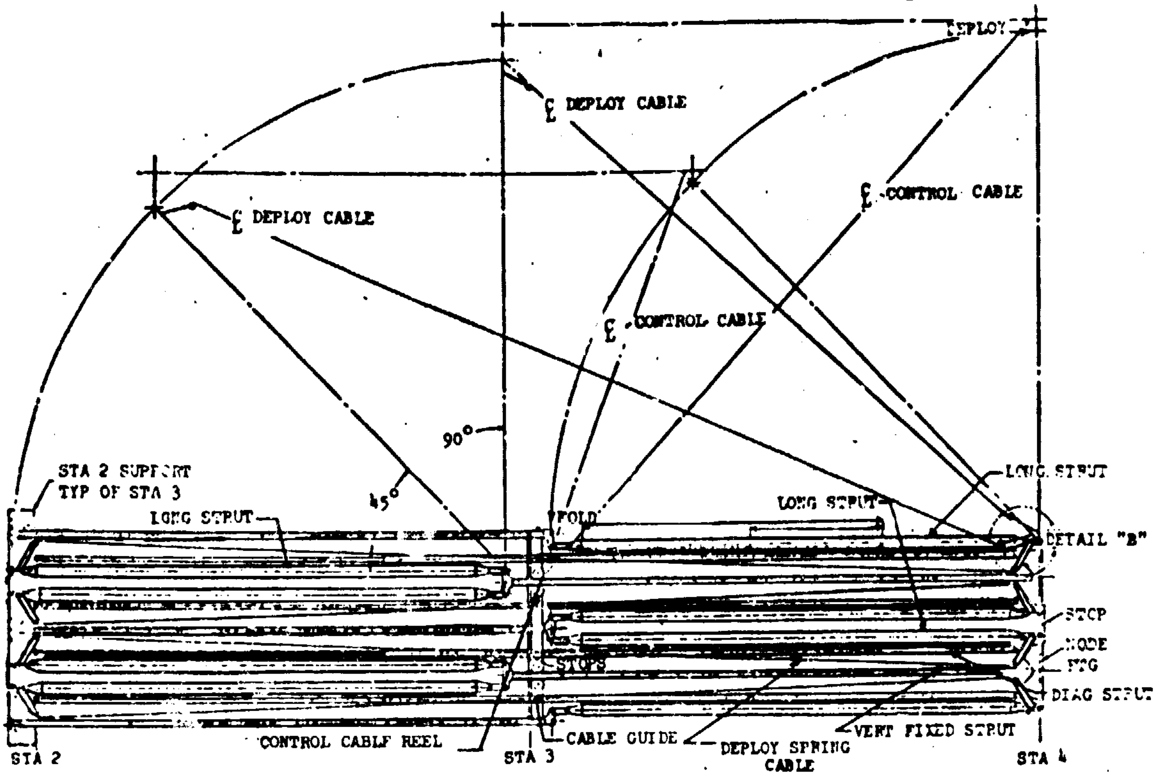


FIGURE 72 DOUBLE FOLD REFOLD-DEPLOY GEOMETRY

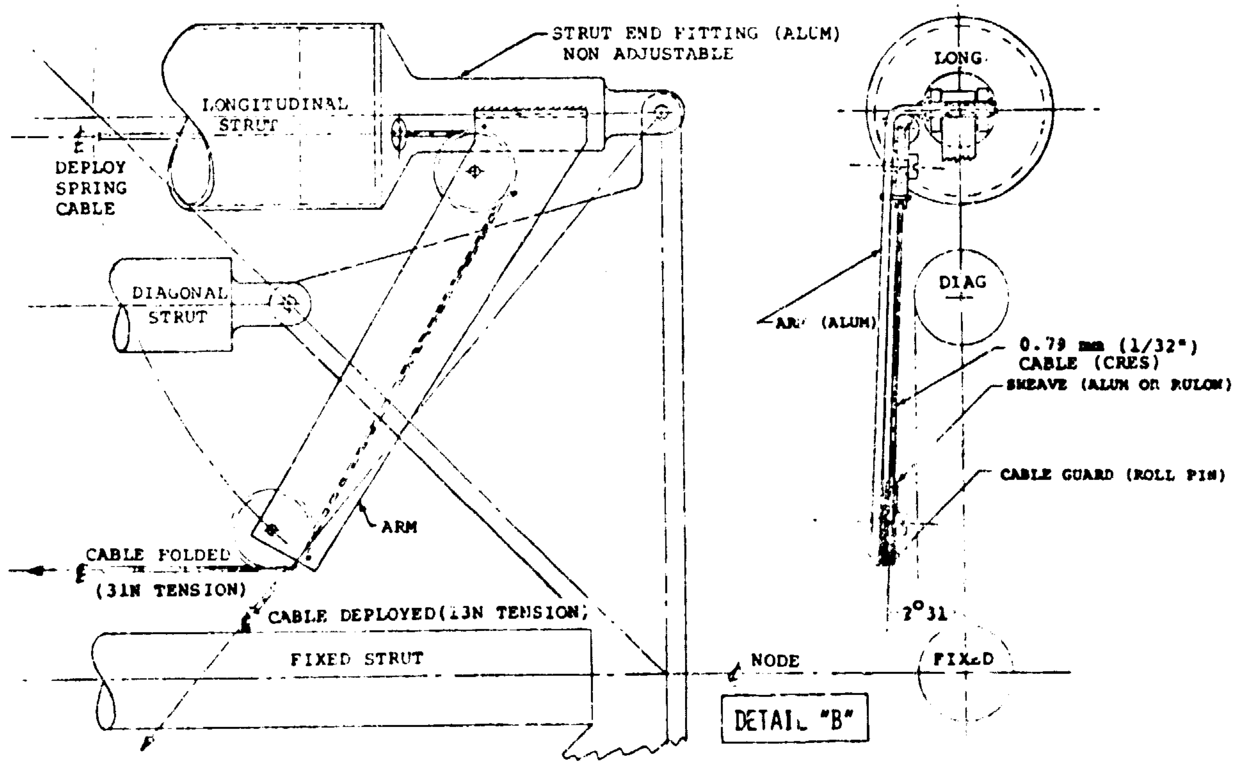


FIGURE 73 DEPLOY CABLE AND LEVER ARRANGEMENT FOR DOUBLE FOLD

TABLE 13 SUMMARY OF DOUBLE FOLD CHARACTERISTICS

COMPLEXITY

- 36 JOINTS PER CELL
- 13 ELEMENTS PER CELL

VOLUME RATIO

- 49 FOR 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

WEIGHT

- 22.5 KG (49.4 LBS) PER 3m CELL SIZED FOR REPRESENTATIVE UTILITY BUNDLES

UTILITIES IMPACT

- TWO 90° BENDS PER CELL

FOLD CONFIGURATION

- DOUBLE FOLD OR SINGLE FOLD
- PACKAGE HEIGHT 2.8 TIMES CELL HEIGHT

DEPLOYABILITY

- STOLL INDEX VALUE OF 30

DYNAMIC AND DIRECTIONAL CONTROL

- PROVIDED BY RESTRAINT/RETRACT CABLE SYSTEM.

DEPLOYMENT RELIABILITY

- PARALLEL, REDUNDANT, REVERSIBLE CABLE CONTROL SYSTEM
- EVA BACKUP

DEPLOYMENT TYPE

- SELF-CONTAINED OR EXTERNAL ACTUATION
- SEQUENTIAL OR COLLECTIVE AND BIAXIAL OR SINGLE AXIS DEPLOYMENT

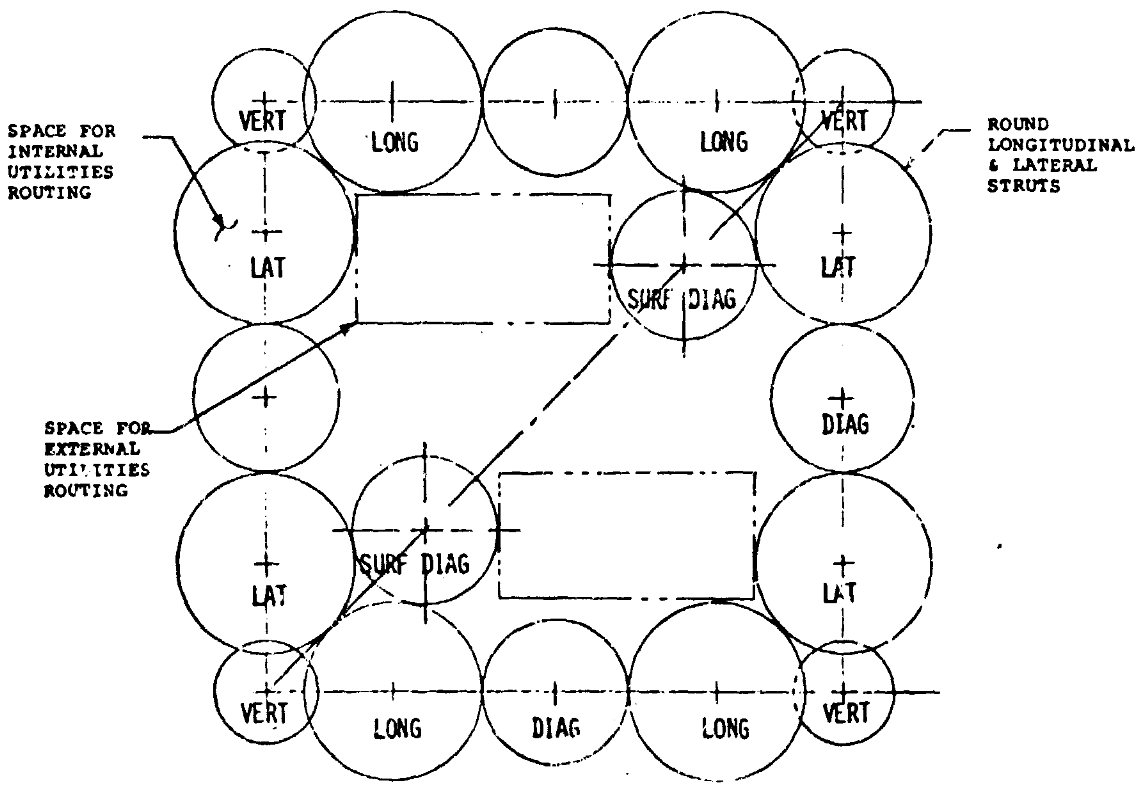
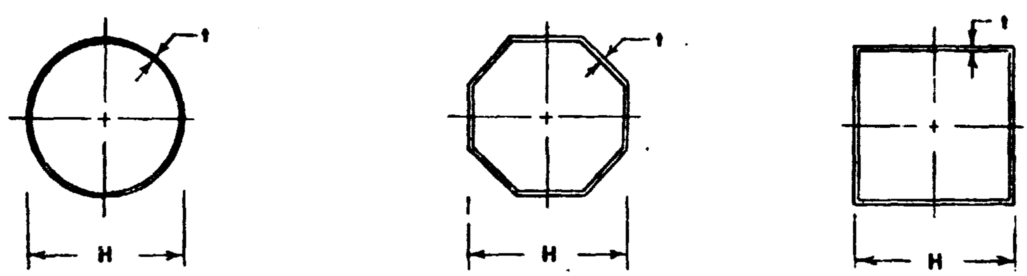


FIGURE 74 TOP VIEW OF DOUBLE FOLD FOLDED CELL

2.6 STRUCTURAL CHARACTERISTICS

This section provides parametric information comparing the structural concepts and establishing the characteristics of the structures and their range of applicability. In addition it contains supporting structural analysis to the design studies.

Three different geometric cross sections are involved in the design of the struts. The Biaxial Double Fold uses an octagonal strut cross section, the Double Fold uses a circular strut cross section, and the Martin Box Truss as well as the General Dynamics Square Diamond Beam uses circular cross sections combined with square areas in the knee joint portion of the strut to permit utilities passage. It was necessary, therefore, in the present structural analysis to consider the effect of strut cross section on structural characteristics. Figure 75 shows the three cross sections and indicates the formulas expressing their area, radius of gyration, and moment of



$A = \pi t H$	$A = 3.31\, t H$	$A = 4\, t H$
$\rho = 0.354\, H$	$\rho = 0.364\, H$	$\rho = 0.409\, H$
$I = \frac{\pi}{8}\, t H^3$	$I = 0.438\, t H^3$	$I = 0.667\, t H^3$

WHERE:

A = STRUT CROSS SECTIONAL AREA
t = STRUT WALL THICKNESS
ρ = RADIUS OF GYRATION
I = MOMENT OF INERTIA

FIGURE 75 GEOMETRIC PROPERTIES OF STRUT CROSS SECTIONS

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inertia. In order to compare the four truss concepts on the same basis, considering the three different strut cross sectional geometries, an equivalent circular diameter was defined. This equivalent diameter is such that when the struts are compared at equal ratios of equivalent diameter-to-wall thickness, and equal ratios of strut length-to-radius of gyration, their cross sectional areas are also equal. The result of these conditions is that the strut stiffness, weight, and buckling strength are all equal regardless of cross sectional geometry for a given point of comparison. The width and wall thickness of an octagonal strut are both about 97% that of an equivalent circular strut. The respective width and thickness of a square strut are about 87% and 91% that of an equivalent circular strut. Figure 76 shows the simplified expressions developed for comparing bending stiffness and axial, bending and shear deflection for the case of the early version of the

BENDING STIFFNESS

BADF, DF, MMC

$$EI_B = \frac{8\pi E\ell^4}{(D/t)(\ell/\rho)^2}$$

GDC

$$EI_B = \frac{4\pi E\ell^4}{(D/T)(\ell/\rho)^2}$$

SHEAR STIFFNESS

BADF, DF

$$EI_S = \frac{16\pi\ell^4 E}{3(D/t)(\ell/\rho)^2}\left\{\frac{N^3}{N^2 + 2\sum_{i=1}^{N-1} i^2 + 3.927N}\right\}$$

GDC

$$EI_S = \frac{16\pi\ell^4 E}{3(D/t)(\ell/\rho)^2}\left\{\frac{N^3}{4.84 + 9.69\,(2N-1) + 0.504\sum_{i=1}^{2N}(2i-1)i}\right\}$$

DEFLECTIONS

AXIAL: $\delta_a = \frac{PaL}{4AE}$ BENDING: $\delta_B = \frac{ML^2}{2EI_B}$ SHEAR: $\delta_s = \frac{PsL^3}{3EI_S}$

WHERE:

ℓ	=	LONGERON LENGTH	N	=	NUMBER OF CELLS
D	=	LONGERON DIAMETER	L	=	TRUSS LENGTH
t	=	LONGERON THICKNESS	P	=	LINEAR LOAD
ρ	=	LONGERON RADIUS OF GYRATION	M	=	BENDING MOMENT
A	=	LONGERON CROSSECTIONAL AREA	δ	=	DEFLECTION

$$\frac{\ell/\rho\ (\text{DIAGONAL})}{\ell/\rho\ (\text{LONGITUDINAL})} = 5/3$$

FIGURE 76 SIMPLIFIED PARAMETRIC FORMULATIONS

Biaxial Double Fold, the Double Fold and the General Dynamics Truss Beam. The early Biaxial Double Fold has top and bottom surface diagonals consisting of folding struts as opposed to crossed tension diagonals. It was not possible within the scope of this program to develop closed expressions for the more complicated situat.on of crossed tension diagonals which exist on the final versions of the Biaxial Double Fold and the Martin Box Truss. Figure 77 illustrates the models utilized in a NASTRAN analysis conducted to provide

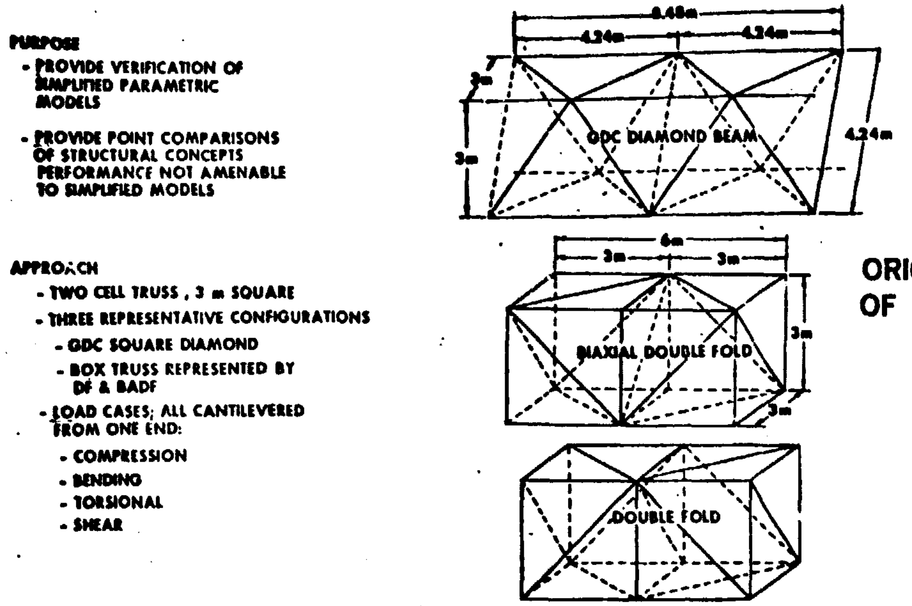

FIGURE 77 NASTRAN ANALYSIS

verification of the simplified parametric models and point comparisons of performance items which were not amenable to simplified models. The approach was to define models based on 3 m square trusses using 2 cell models. Three representative configurations were modeled: the GDC Square Diamond Beam, a box truss as represented by the Double Fold, and the early version of the Biaxial Double Fold. Four load cases were considered: compression, bending, torsional, and shear. In Table 14 the results of the NASTRAN analysis are given. The tabulated information shows the results predicted by the simplified expression compared to the results predicted by NASTRAN. In almost all cases close agreement is obtain in axial compression, vertical shear, and pure bending. It was concluded from the good correlation shown in this table that the simplified models are sufficient for parametric conceptual trades. A point comparison taken from the NASTRAN results also shows the torsional stiffness of the three different trusses. The torsional stiffness is considerably higher for the GDC Diamond Beam than for the two box truss configurations.

Figure 78 is a parametric bending stiffness comparison of the different truss concepts. Truss cube width is plotted against pure bending

TABLE 14 NASTRAN RESULTS

VERIFICATION OF BEAM THEORY MODELS:

LOAD CASE	BIAXIAL DOUBLE FOLD		DOUBLE FOLD		DIAMOND	
	BEAM THEORY	NASTRAN	BEAM THEORY	NASTRAN	BEAM THEORY	NASTRAN
AXIAL COMP δ_a ~ mm	0.0227	0.0198	0.0227	0.0227	0.0161	0.0161
VERTICAL SHEAR δ_s ~ mm	0.315	0.330	0.315	0.328	0.414	0.414
PURE BENDING δ_b ~ mm	0.0455	0.0455	0.0455	0.0450	0.0455	0.0455

TORSIONAL STIFFNESS (D/t = 50, ℓ/ρ = 100)

TRUSS	GJ (in^2-lbs)	$N.m^2$
GDC	15.3×10^{10}	4.39×10^{8}
BADF	8.42×10^{10}	2.42×10^{8}
DF	7.52×10^{10}	2.16×10^{8}

CONCLUSION:

SIMPLIFIED MODELS ARE SUFFICIENT FOR PARAMETRIC CONCEPTUAL TRADES

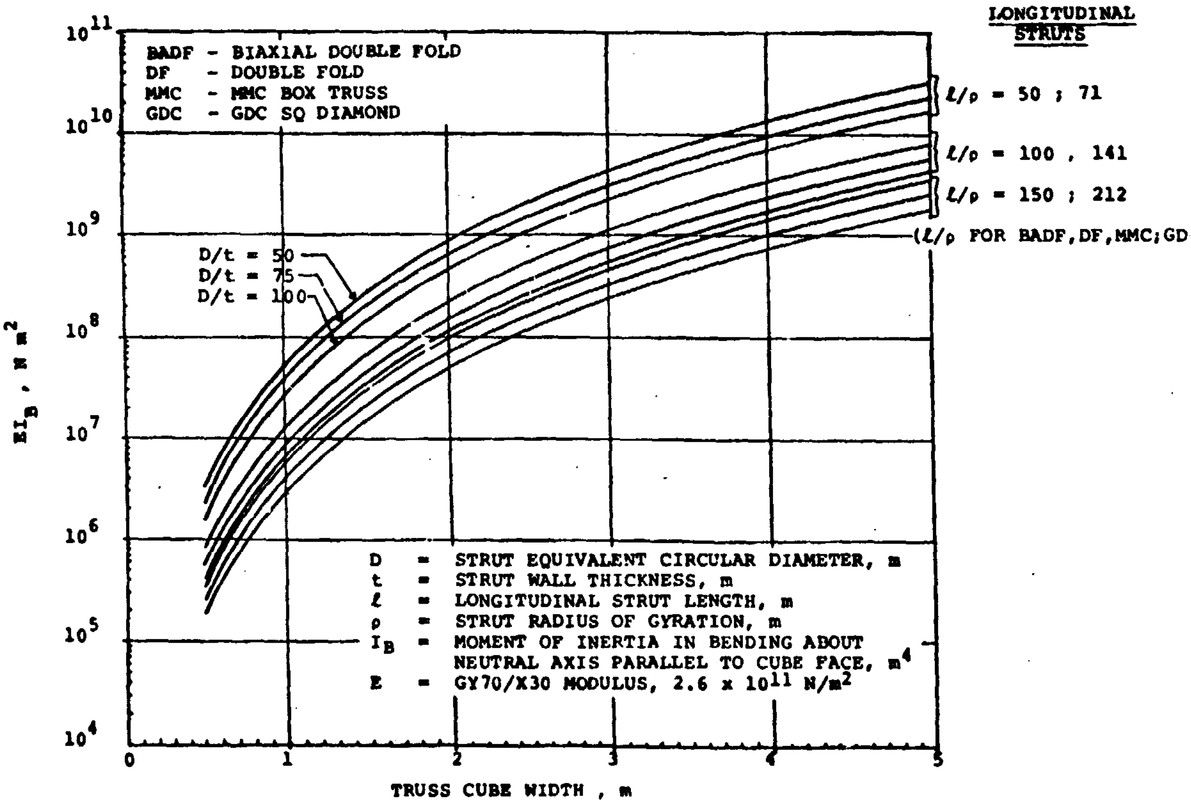

FIGURE 78 BENDING STIFFNESS COMPARISON

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stiffness. The curve is parametric in strut equivalent diameter to thickness ratio and also parametric in strut length-to-radius of gyration ratio. Values of longitudinal strut length-to-radius of gyration ratio of 50, 100 and 150 were evaluated for the cubic truss configurations and values of 71, 141 and 212 were evaluated for the Diamond Beam. These differences in strut length-to-radius of gyration were necessary in order to compare the trusses on the basis of equal strut cross sectional area and equal truss stiffness for a given truss cube width. This resulted from the difference in the truss geometry of the Diamond Beam. Results show that stiffnesses in excess of 10^{10} Nm^2 are easy achievable with all the truss configurations at a truss cube width of 5m. On the small end of the scale it is seen that bending stiffnesses in the range of 10^5 to 10^6 Nm^2 for a truss cube width of about 0.5m is obtained. All of these analyses were conducted for a material with properties typical of GY70/X30 graphite/epoxy. The particular modulus of 2.6×10^{11} Nm^2 shown on the figure is that which was obtained from analysis of the properties of a minimum gage balanced symmetric four ply layup as will be described in the Materials Section (3.0) of this report. Figure 79 shows the parametric bending strength comparison. In all cases mapped by this parametric plot the struts failed in crippling and not buckling. It is also evident from examination of the figure that the bending strength of the GDC beam is lower than that of the cubic cell beams (because of its higher strut length-to-radius of gyration ratio). Figure 80 presents the method used for parametric weight estimates. This work was done in two steps. First, the weight per unit length was computed using a generalized formula for the basic truss configurations indicated. Second, a correction was added for the specific trusses based on the estimated weight of joints, springs and cables for the individual designs. The latter estimates were based on analysis of the 3m truss design which had been sized for representative internal utilities. Since it is rather specific the percentages indicated are expected to be applicable only over the limited range of about 1 to 5m truss width. As shown on the figure, the joints added about 1% weight per joint. The spring and cable weights were estimated specific to each concept based on the designs described in Section 2.5. Because of the large number of joints in the Box Truss design, considerable additional weight is added to the basic truss weight calculated by the parametric formula. The Diamond Beam also has a considerable weight addition due to its large number of joints. Its weight is

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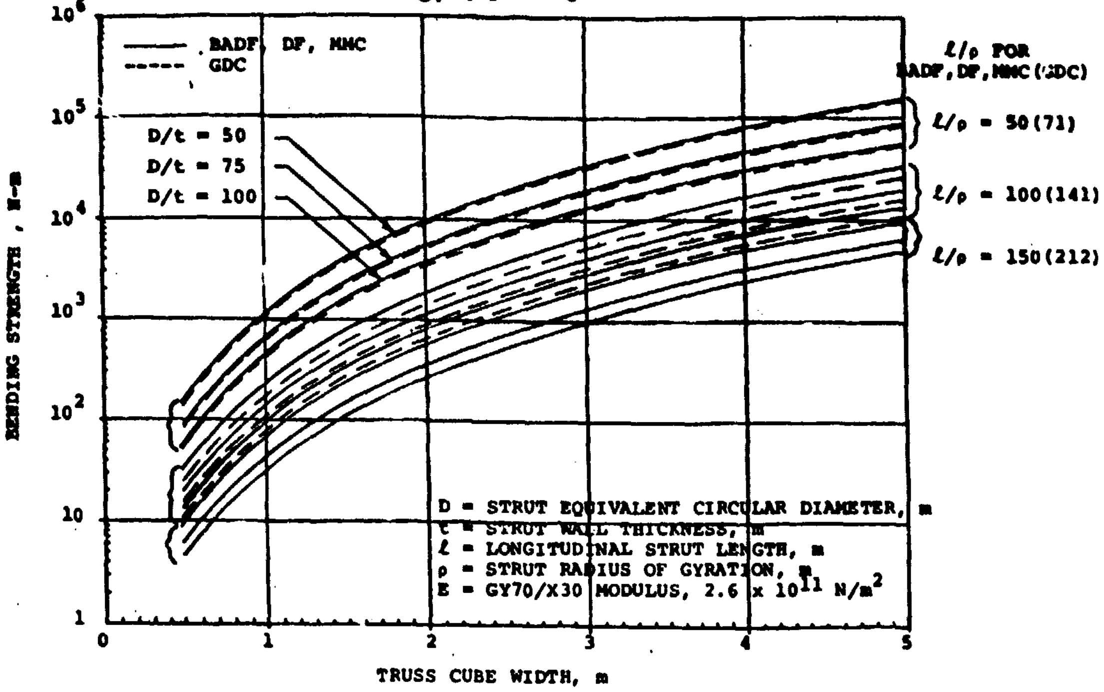

FIGURE 79 BENDING STRENGTH COMPARISON

APPROACH

- GENERAL FORMULA DERIVED EXCLUSIVE OF FITTINGS, SPRINGS, AND CABLES

$$\frac{W}{L} = \frac{84\,\pi\,\beta\,w^2}{(D/t)\,(\ell/\rho)^2} \quad \text{(BADF, DF, MMC)}$$

$$\frac{W}{L} = \frac{100\,\pi\,\beta\,w^2}{(D/t)\,(\ell/\rho)^2} \quad \text{(GDC)}$$

WHERE:

W = BEAM MASS, KG
L = BEAM LENGTH, m
w = BEAM WIDTH, m
D = STRUT EQUIVALENT DIAMETER, m
β = GY70/934 DENSITY, 1770 KG/m^3
t = STRUT THICKNESS, m
ℓ = LONGITUDINAL STRUT LENGTH, m
ρ = STRUT RADIUS OF GYRATION, m

- ESTIMATE MADE FOR WEIGHT OF JOINTS, SPRINGS, AND CABLES FOR EACH INDIVIDUAL DESIGN, BASED ON 3m TRUSS WIDTH SIZED FOR REPRESENTATIVE INTERNAL UTILITIES.
  - JOINTS ADD 1% WEIGHT PER JOINT
  - SPRING AND CABLE WEIGHTS ESTIMATED SPECIFIC TO EACH CONCEPT
  - PERCENTAGE WEIGHT INCREASE RESULTS ADDED TO GENERAL FORMULA:

    BADF - 53% GDC - 79% (NO DEPLOYMENT WEIGHT)
    MMC - 158% DF - 59%

  - ESTIMATE THESE PERCENTAGES ARE APPLICABLE OVER 1-5 m TRUSS WIDTH RANGE

FIGURE 80 PARAMETRIC WEIGHT ESTIMATES

somewhat on the low side because the external deployment mechanism weight is not included. It would be necessary to include the mechanism weight in an analyses of absolute launch capability with the Space Shuttle. Figures 81, 82, and 83 present the parametric weight comparisons at strut diameter-to-thickness ratios of 50, 75 and 100. As can be surmised from Figure 80, it is evident here that the Martin Box Truss is the heaviest and the Diamond Beam is the lightest structure. Specific bending stiffness is plotted in Figure 84, where the bending stiffness values were divided by the weight per unit length to obtain bending stiffness per unit weight and length.

Figure 85 is a presentation of an approximate calculation of thermal distortion characteristics of a beam. The plot is parametric in coefficient of thermal expansion (CTE) and in temperature gradient from one side of the beam to the other. Beam length is plotted against the resulting tip thermal distortion. The two temperature gradients evaluated are a gradient of $10^{\circ}C$ across the beam and a gradient of $100^{\circ}C$ across the beam. The beam itself was modeled as a 3m square truss. (Coefficient of thermal expansion values of 0.1×10^{-6}, 2×10^{-6} and 10×10^{-6} cm/cm-$^{\circ}$C were analyzed. The lowest value of CTE corresponds to a well tailored graphite/epoxy composite. A value of 2×10^{-6} is representative of materials such as Invar or an isotropic layup of graphite/epoxy. The value of 10×10^{-6} is representative of titanium or an isotropic metal matrix composite. Aluminum would have a tip distortion value of about 2-1/2 times that shown for the CTE of 10×10^{-6}. (Its CTE is about 25×10^{-6}). If a tip thermal distortion of 1° were allowed, it is seen that an aluminum structure with the maximum thermal gradient would not be acceptable for a long beam. A graphite/epoxy structure with average properties in the range of 2×10^{-6} cc/cm-$^{\circ}$C would be suitable for use up to the $100^{\circ}C$ gradient.

In addition to the parametric analyses, several point analyses were conducted to support the design effort. An analysis was carried out to determine the influence of the octagonal cable tray concept strut cross section on strut load bearing capability. The analysis compared the octagonal strut cross section to a round cross section. A GY70/X30 strut of 6m length was evaluated with a wall thickness of 1.7mm and a circular diameter of 85mm. The octagon size was that which would just fit inside the 85mm diameter. Results showed the octagonal strut will bear a greater compressive load

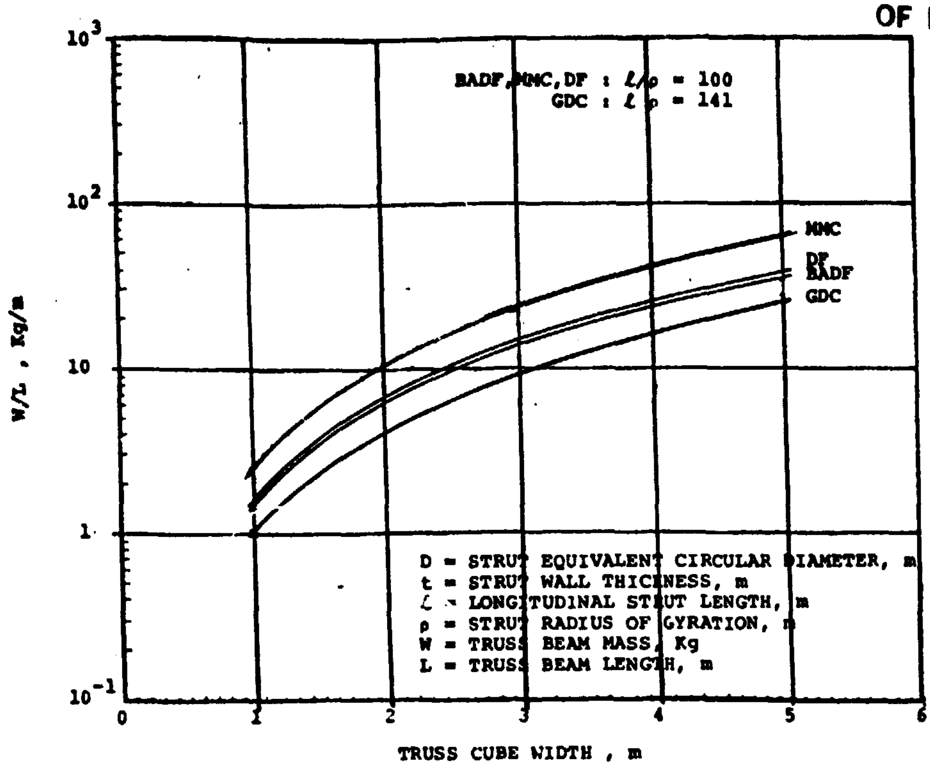

FIGURE 81 PARAMETRIC COMPARISON OF TRUSS WEIGHT PER UNIT LENGTH D/t = 50

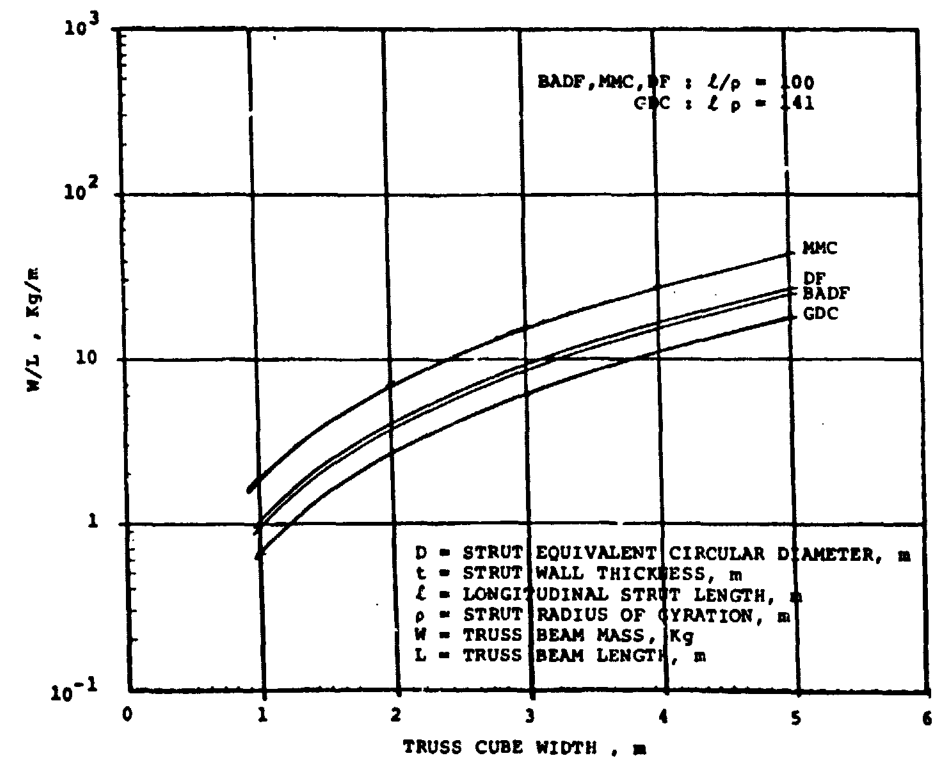

FIGURE 82 PARAMETRIC COMPARISON OF TRUSS WEIGHT PER UNIT LENGTH D/t = 75

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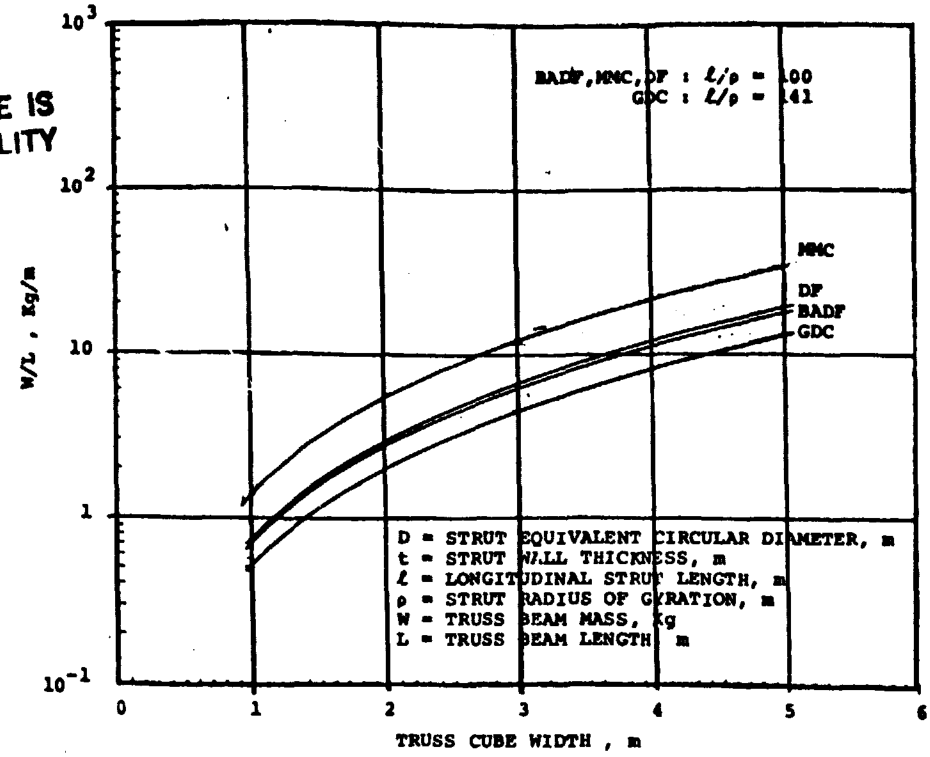

FIGURE 83 PARAMETRIC COMPARISON OF TRUSS WEIGHT PER UNIT LENGTH D/t = 100

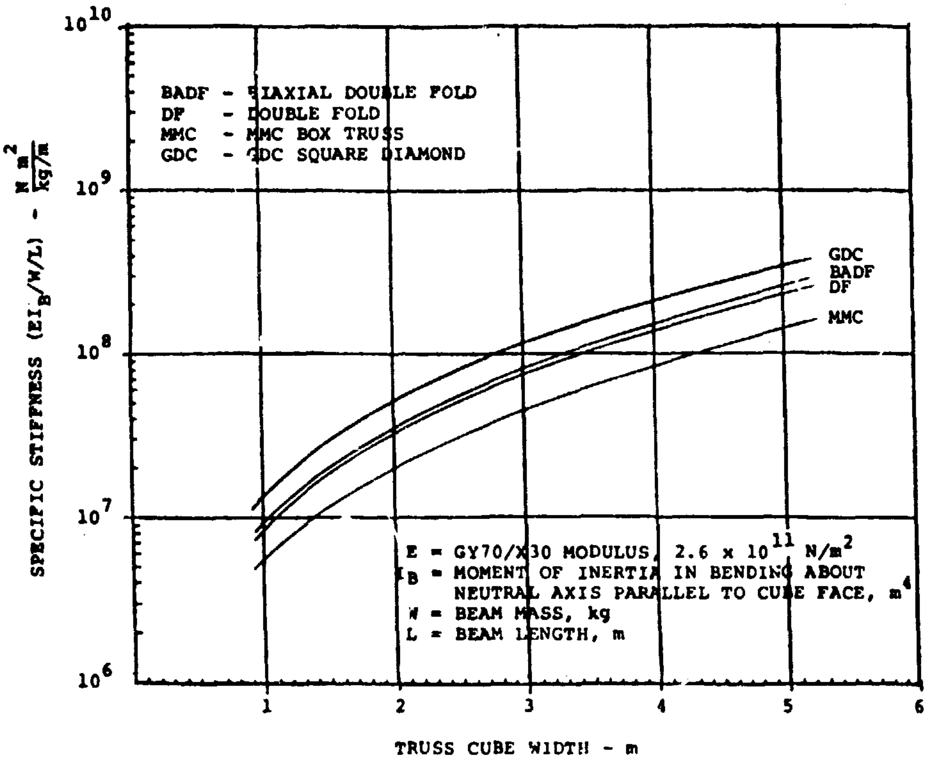

FIGURE 84 SPECIFIC BENDING STIFFNESS COMPARISON OF TRUSS CONCEPTS

(25,580 N vs 20,840 N), as it fails in Euler buckling, while the circular tube fails in Johnson crippling. In addition, the octagonal strut is about 3% lighter. Another abbreviated analysis was conducted to examine the effect of manufacturing or thermal eccentricities on strut load bearing capability. A 6m long GY70/X30 tubular strut with an 85mm diameter and a 1.7mm wall thickness was evaluated. Results show a 10% decrease in compressive strength due to a 10mm eccentricity.

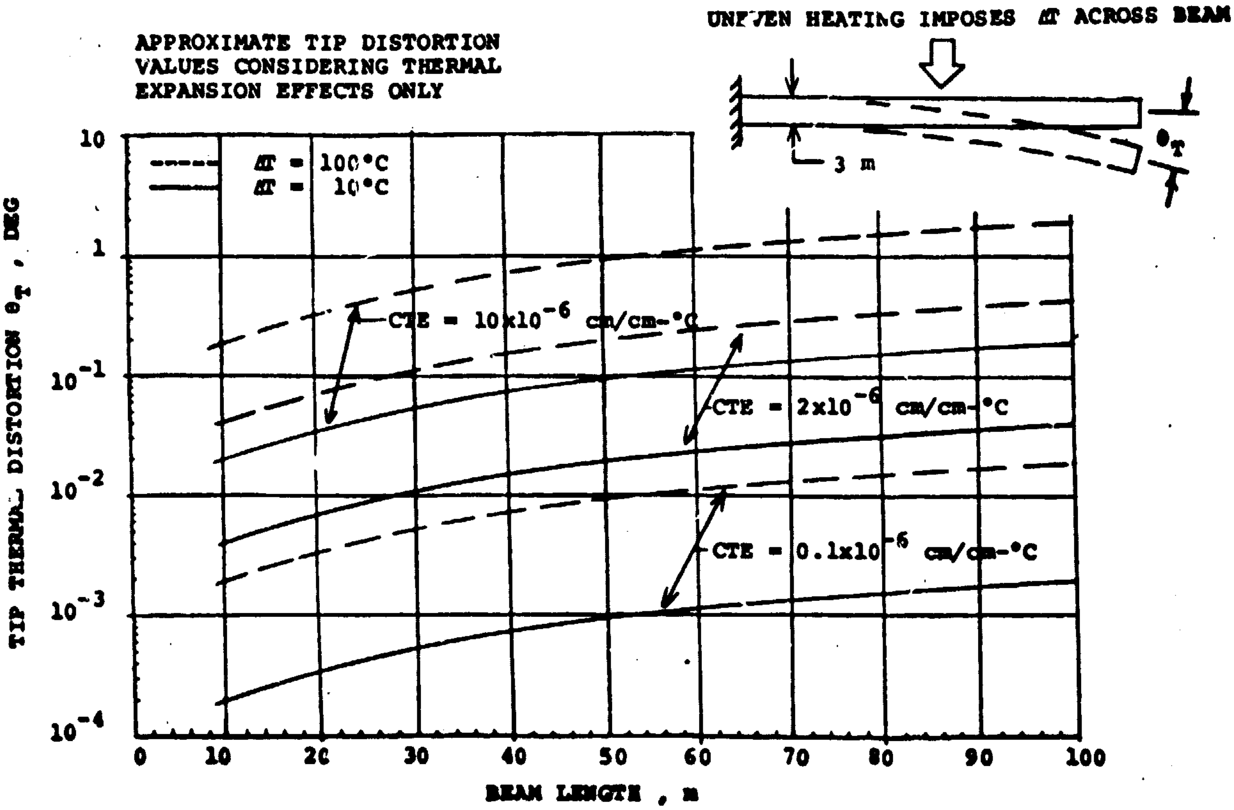

FIGURE 85 THERMAL DISTORTION CHARACTERISTICS OF BEAM

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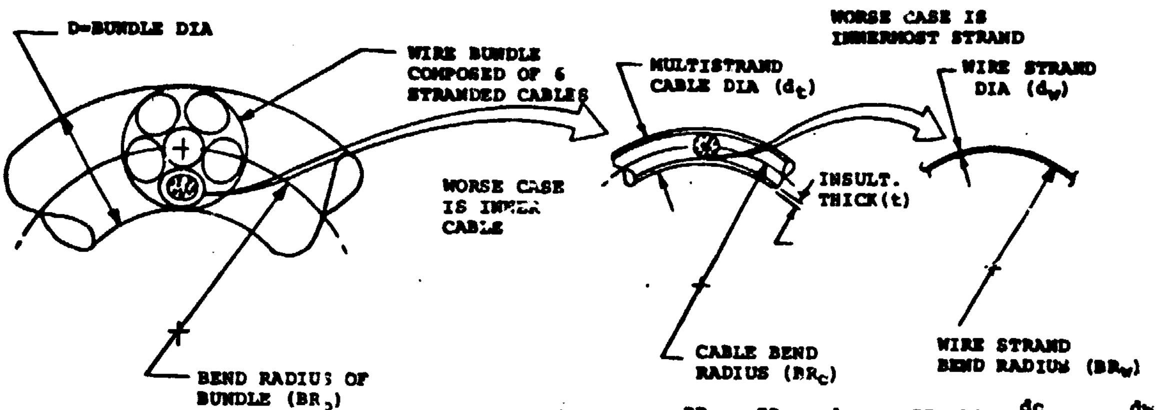
2.7 UTILITIES INTEGRATION CONCEPTS

This section provides information relative to utilities bend radius, fatigue life, and bending moments, followed by a description of the utilities integration concepts for the various truss designs for both internal and external routing of the utilities. The section closes with parametric comparisons of the impact of utilities routing on stowage volume.

Figure 86 presents a summary of the evaluation of the minimum bend radius experienced by wire strands as the bundle is bent to a bend radius-to-diameter ratio of unity, which is the minimum value used. The left



$BR_c = BR_b - d_c$ $\qquad BR_w = BR_c - \frac{d_c}{2} + t + \frac{d_w}{2}$

MIN $BR_b/D = 1$
DESIGN GUIDELINE

$$\frac{BR_w}{d_w} = \frac{BR_b}{d_w} - \frac{3}{2}\frac{d_c}{d_w} + \frac{t}{d_w} + \frac{1}{2}$$

RESULTS:

CABLE SIZE	CABLE DIA. d_c (mm)	STRAND DIA. d_w (mm)	INSUL. THK. t(mm)	BUNDLE DIA. D(mm)	BR_w/dw @ $BR_B/D = 1$
0	13.1	0.254	1.35	39.4	84
4	9.02	0.455	1.22	27.2	33
14	3.51	0.361	0.89	10.4	17

REF: MIL-W-22759D/1E

FIGURE 86 MINIMUM BEND RADIUS OF WIRE STRANDS

side of the figure shows a wire bundle composed of 6 stranded cables. The worst case cable is the inner cable. As shown on the figure, a multistranded inner cable will have a bend radius indicated by BR_c. The most critical wire in the cable will be the inner wire. For an inner wire diameter of d_w and for a minimum radius of that wire of BR_w the most critical design will then be for the minimum value of the ratio of BR_w/d_w (for the case of a bundle bend radius to diameter ratio of unity). The table at the bottom of the figure shows a comparison for three cables, Sizes 0, 4 & 14. Using cable diameters, insulation thicknesses, and wire strand diameters from the reference specification, it is seen that the small cable size of 14 results in the most critical bend radius to diameter ratio of 17 for the wire strand. For the utilities considered in the current study this is the most critical case that will be involved.

Figure 87 shows an experimental evaluation conducted to determine the bend life on several copper wire sizes. The plot shows the number of cycles to failure for an oscillating 90° bend. The left of the figure shows a

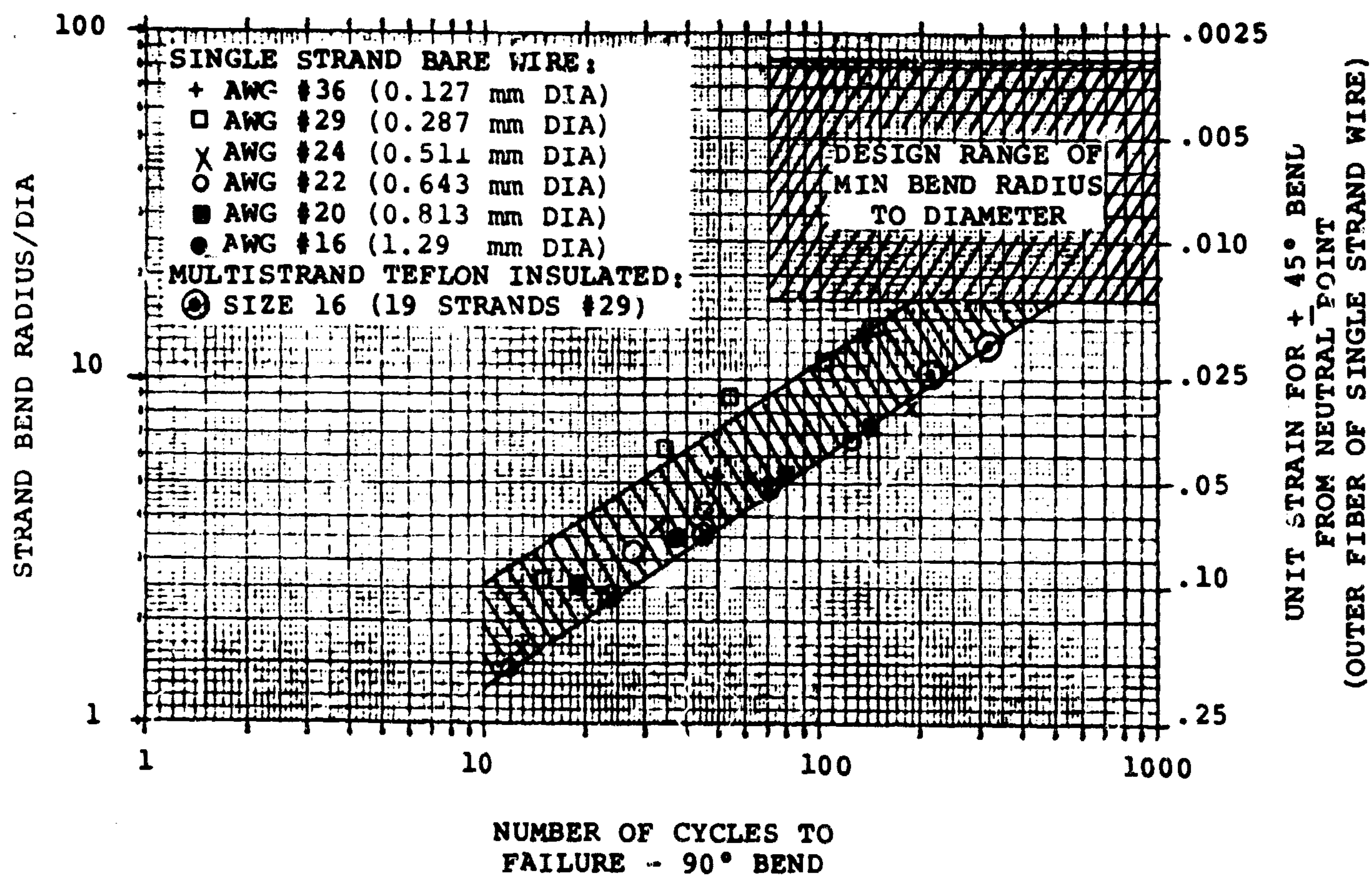


FIGURE 87 BEND LIFE TEST DATA ON COPPER WIRE

ratio of strand bend radius-to-diameter. The right side of the figure plots unit strain for $\pm 45^{\circ}$ from the neutral point. The various wires evaluated, both single and multistrand, are tabulated in the legend of the figure. Also the design minimum bend radius range is indicated. The data on this figure show that an expected life of 200 or greater cycles is likely for the most severe case of bend radius-to-diameter ratio of 17. It is expected that this will be in excess of the number of cycles needed for a deployable platform.

A set of representative utilities bundles was defined based on the requirements for the ASASP Arm A Interface C, which is one of the most extensive requirements of the missions evaluated. Table 15 tabulates the requirements and also tabulates the four representative bundles. These representative utilities bundles pictured in Figure 88 were used in all utilities integration studies. The utilities routing was studied on a 3m truss in the designs shown later in this section. To obtain information required in estimating the bending moments for the utilities study, wire

TABLE 15 REPRESENTATIVE UTILITIES EXCEED ASASP REQUIREMENTS

ASASP ARM "A" INTERFACE "C"			4 REPRESENTATIVE BUNDLES	
QUANTITY	SIZE UTILITIES	USE	QUANTITY OF UTILITIES IN BUNDLE NO.	SIZE UTILITIES
6	AWG 1/0 (12 MM)	124-164 VDC 20KW PWP	6 IN 1	1/0 (12 MM DIA)
28	AWG 2 (9 MM)	16/30-12/164 VDC 50 KW PWP	16 IN 2 18 IN 3 } EQ TO 12 18 IN 4 } AWG 2	AWG 2 (9 MM DIA) AWG 6 (7 MM DIA) AWG 6 (7 MM DIA)
4	AWG 14 (2 MM)	30 VDC 4 KW PWP	10 IN 2	AWG 14 (2 MM DIA)
2	19 MM I.D. 30 MM O.D.	METAL HOSE (2070 kPA FREON)	1 IN 3 1 IN 4	25 MM I.D., 38 MM O.D. METAL HOSE
35	5 MM DIA F.O.	DATA (FIBER OPTICS)	35 IN 1	3 MM DIA F.O.

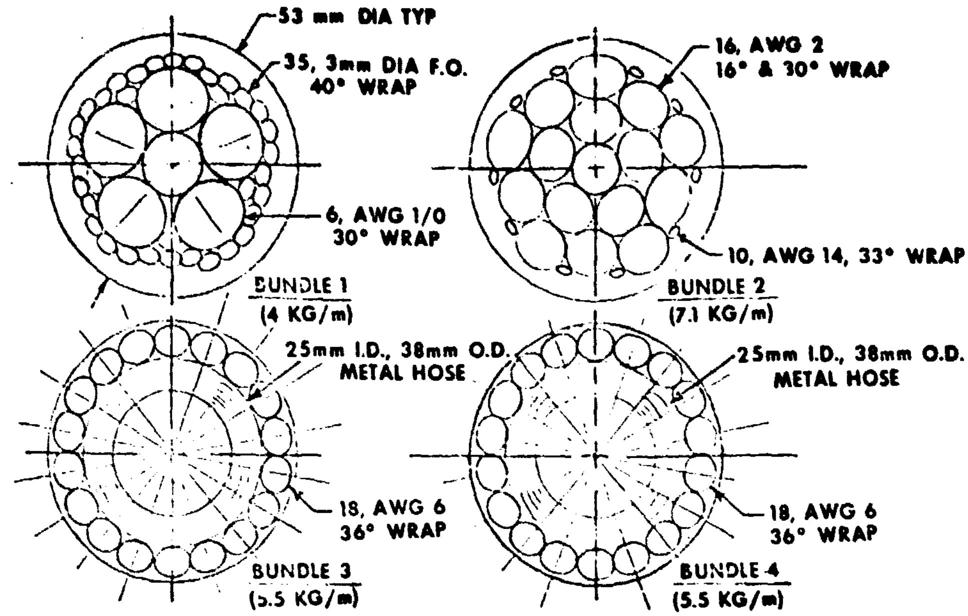


FIGURE 88 REPRESENTATIVE UTILITIES BUNDLES

cables and metal hoses were evaluated in torque tests. Figures 89 and 90 show these evaluations. It is apparent that much less bending energy is required to straighten the utilities during deployment than to bend them during folding of the structure. The 25 mm I.D. metal hose can be bent to a 51 mm bend radius according to both suppliers, Metal Bellows and Anaconda. A bend radius of 57 mm was used for the 25 mm metal hose in design studies. In order to estimate the bending moment of the utilities bundles the test data was correlated, with the following results:

Bending Moment of cable:

$$M_b = 0.1655 \times D_w^3 \times N \text{ , N-m}$$

Straightening Moment of cable:

$$M_s = 0.0552 \times D_w^3 \times N \text{ , N-m}$$

where:

N = number of strands in cable

D_w = wire diameter in mm

These correlations are for specification MIL-W-22759/1 cable with Teflon tape and braided fiberglass covers. It is correlated at a ratio of bend radius to cable O.D. of 3.

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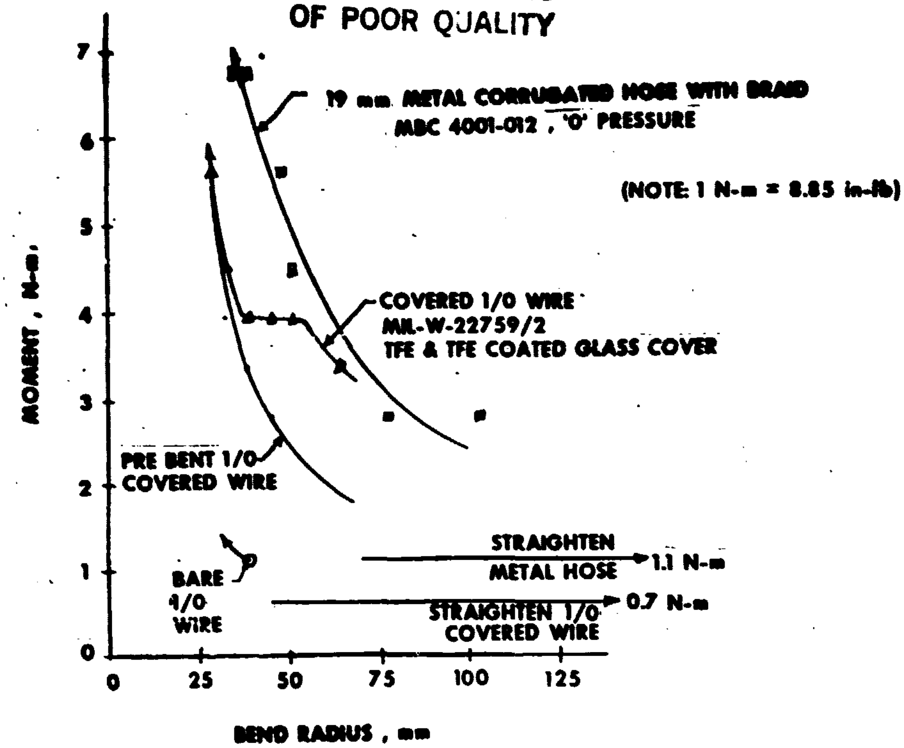

FIGURE 89 TORQUE WRENCH TEST WIRE & METAL HOSE

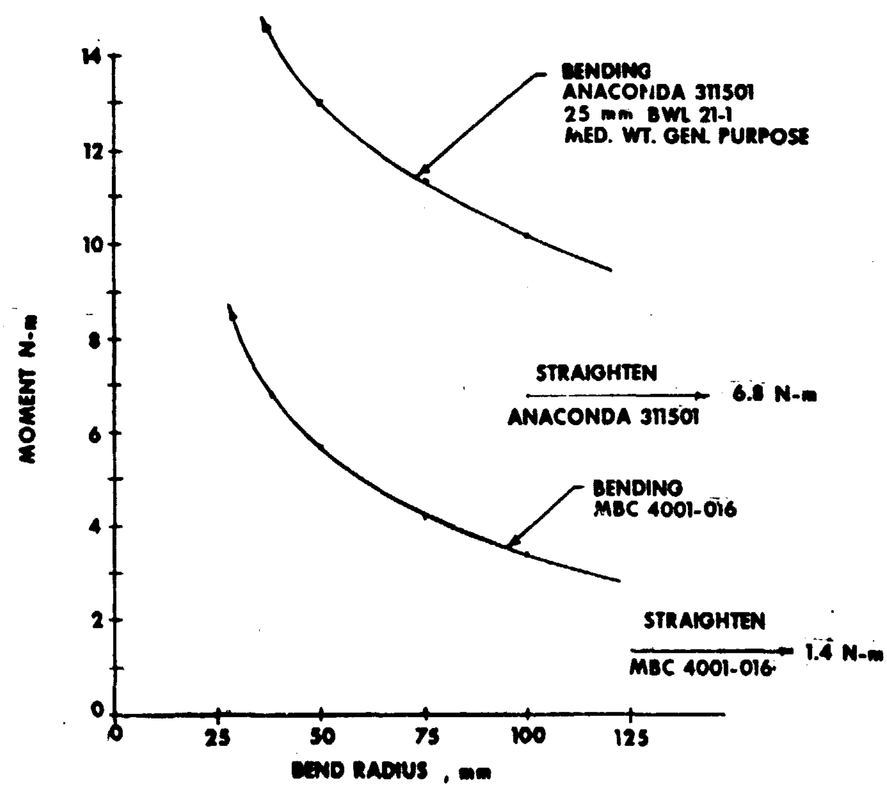

FIGURE 90
TORQUE WRENCH TEST AT O-PSI 1 IN. I.D.
METAL CORRUGATED HOSE WITH BRAID

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Table 16 presents the bending moment estimates for the representative bundles based on the preceding correlations data and the MBC 4001-016 metal hose test. It shows the design moment for each of the four representative bundles for both bending and straightening.

TABLE 16
BENDING MOMENT ESTIMATES FOR REPRESENTATIVE BUNDLES

	DESIGN N-m FOR REPRESENTATIVE UTILITY BUNDLE NUMBER			
	1	2	3	4
TO BEND BUNDLE DURING FOLDING	17.9	30.5	23.7	23.7
TO STRAIGHTEN BUNDLE DURING DEPLOYMENT	6.0	10.2	7.9	7.9

The following utility design bending moments were calculated by averaging bundles 2 and 3. Calculating the required deploy spring moment in N-m, the average straightening moment for bundles 2 and 3 is the average of 10.2 and 7.9 which is 9.1 N-m. Adding a 25% tolerance of 2.2 N-m in the moment determination and 10% tolerance in spring rate of 1.1 N-m, the resulting total design deploy spring moment is 12.4 N-m. A similar calculation of the folding moment in N-m was made. Averaging the folding moment of bundles 2 and 3 and adding the spring moment of 12.4 N-m results in a 39.5 N-m fold moment. In addition, a deploy rate control moment was estimated by subtracting the straightening moment of 9.1 N-m from the spring moment of 12.4 N-m to result in a value of 3.3 N-m.

Figure 91 illustrates the cable tray structure concept. It shows that the cable tray strut is fabricated in two pieces. The strut cover is left off until after assembly of the utility harness into the cable tray and attachment to the connectors. It is then bonded. Analysis shows that either a room temperature adhesive (HYSOL EA934) or a 300°F cure adhesive (NARMCO Metalbond 329-7) will be acceptable in providing adequate lap strength to proportionately distribute strut loads. Figure 92 illustrates the utilities routing for both internally and externally routed bundles in a folded configuration of the BADF. Figure 93 shows the details of the BADF A-node utility routing using the cable tray concept. It is seen that a bend radius equal to the width of the octagonal strut results. It is also seen that the maximum diameter bundle that can be fit through the node is approximately 0.7

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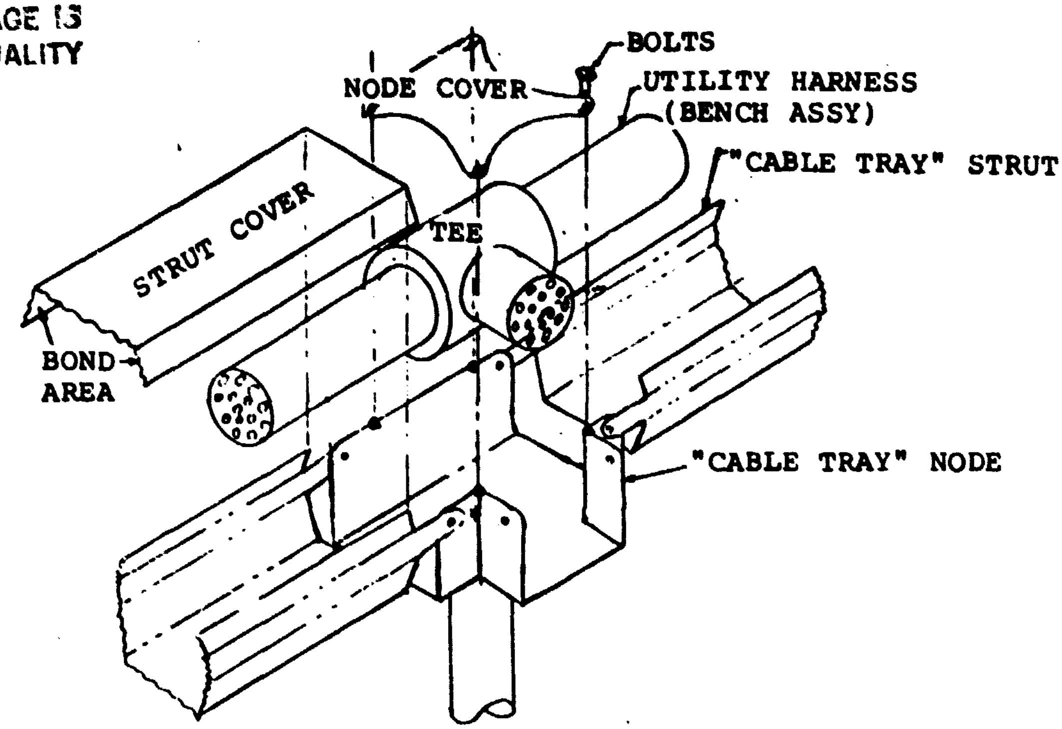

FIGURE 91 CABLE TRAY STRUCTURE CONCEPT

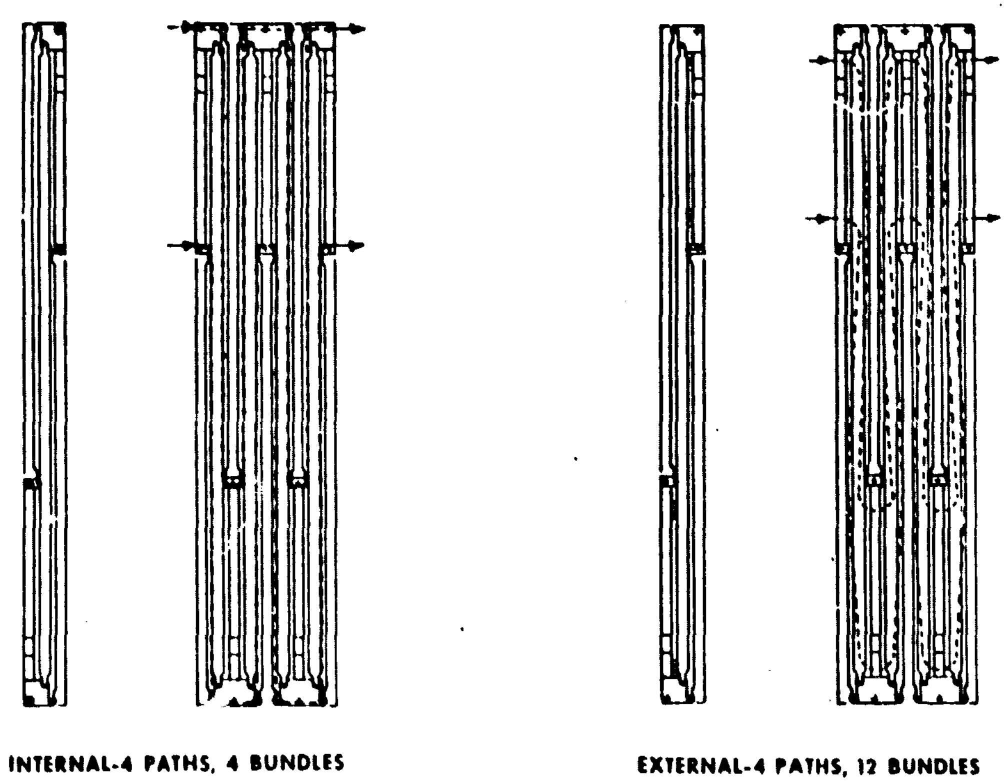

FIGURE 92 BADF UTILITIES ROUTING

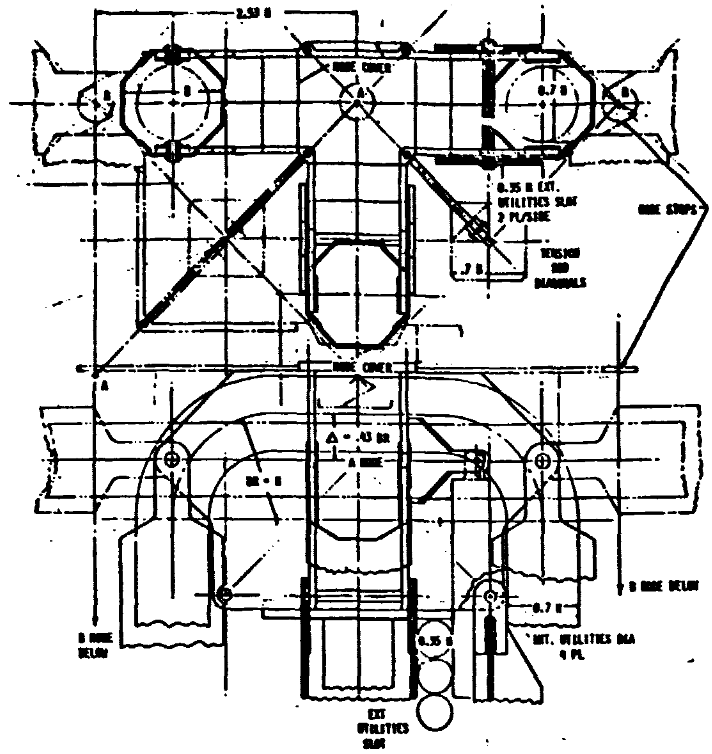

FIGURE 93 BADF "A" NODE DETAILS

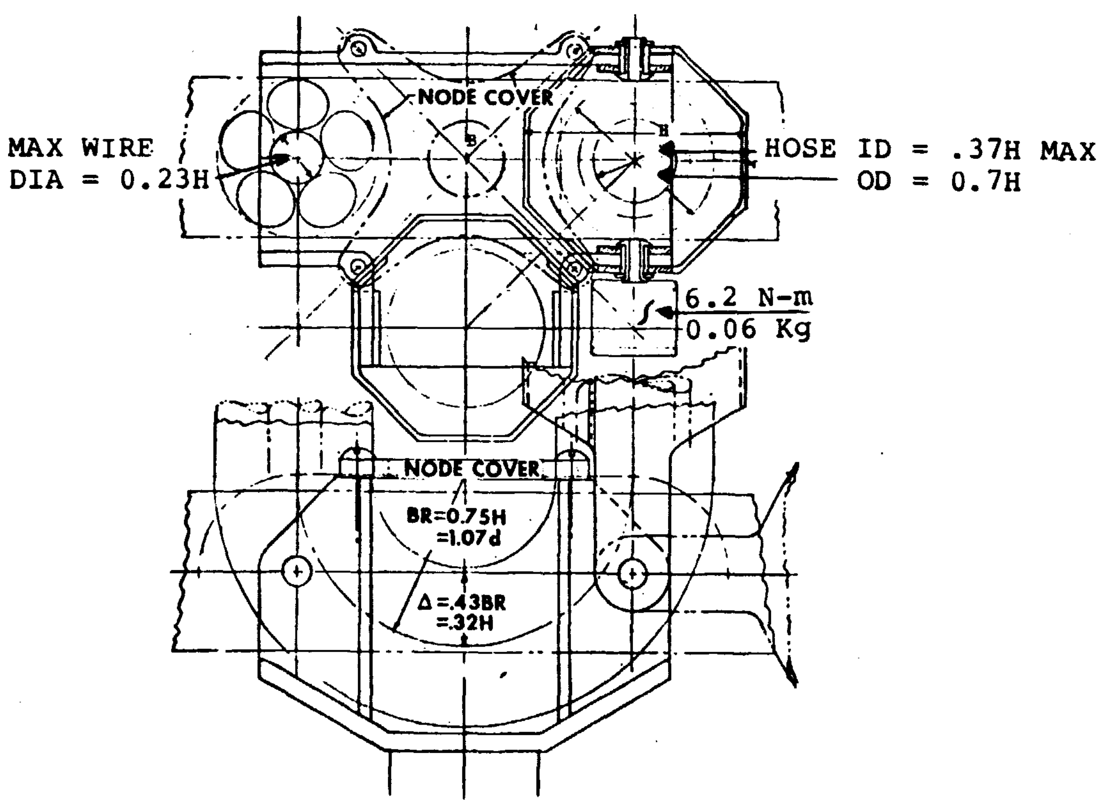

FIGURE 94 BADF "B" NODE DETAILS

the width of the strut. The figure also indicates that for external utilities routing the cable is subdivided into three smaller diameter areas that have equal cross section to the one larger cable routed through the nodes internally. The bend radius-to-diameter ratio for the A-node is seen to be approximately 1.4. Figure 94 shows the BADF utility routing through B-node. In this case a sharper bend radius of slightly over 1 diameter is required. While the details for the utilities routing through the nodes were worked out only for the BADF the internal routing of utilities through the nodes of other concepts would be similar. Figure 95 shows the knee joint design on the Martin Marietta Box Truss and the General Dynamics Diamond Truss Beam. It is seen that the original design of the Box Truss provides no space for internal utilities. A small amount of space is provided in the General Dynamics design. Current studies evolved the knee joint designs on both of these for larger utilities routing space.

Figure 96 shows the results of studies for the Box Truss knee joint. As seen in this figure, it is possible, using this design concept, to route a utilities bundle diameter of 0.58 strut width through the knee joint. The cross section of the strut is seen to be square. It would be possible to transition from this cross section into a round cross section for the portion of the strut remote from the knee if desired, as indicated in the Section 2.5 Design Description.

Figures 97 and 98 illustrate the external utilities routing concept evolved for the Box Truss. It is seen that the utilities bundles are subdivided into three smaller utilities bundles, resulting in a total of 12 bundles for four paths. In order to provide the necessary space for the external routing it can be seen in Figure 98 that a portion of the lateral strut had to be cut away.

Figure 99 shows the General Dynamics Diamond Beam in the folded configuration and shows space for the external utilities routing as well as indicating the upper limit of the space for internal utilities routing. The internal utilities routing through the hinged areas would be an evolution of the General Dynamics design indicated in Figure 95, where the strut would be slotted to enable a diameter of something between 0.6 and 0.7 strut diameter to be routed through the hinged area without exceeding the guideline of a bend radius to diameter ratio of unity. It was possible to get a slightly larger external utility through the General Dynamics Diamond Beam than through the

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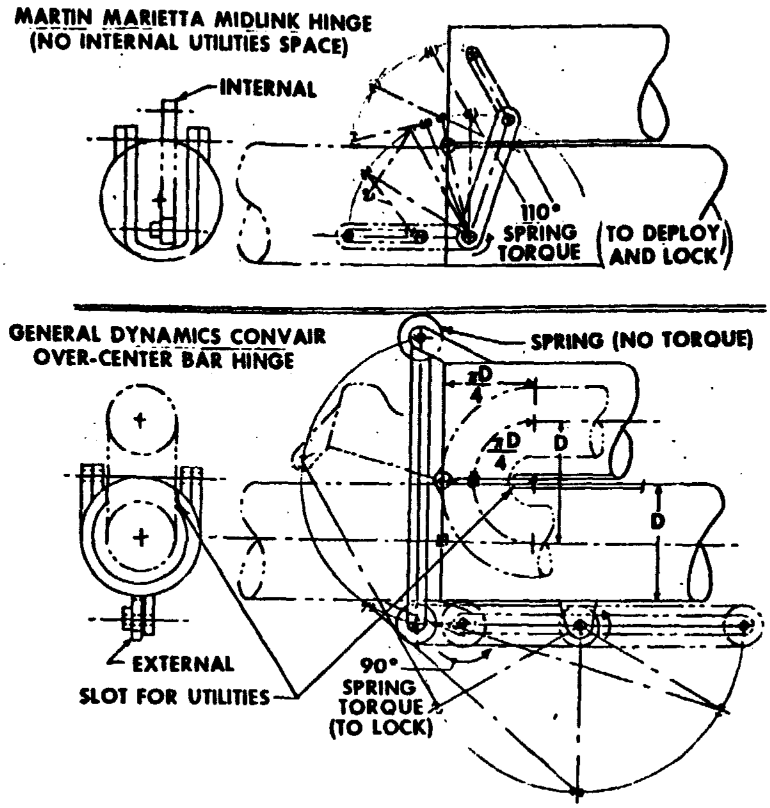

FIGURE 95 INTERNAL UTILITIES SPACE THROUGH ORIGINAL KNEE JOINTS

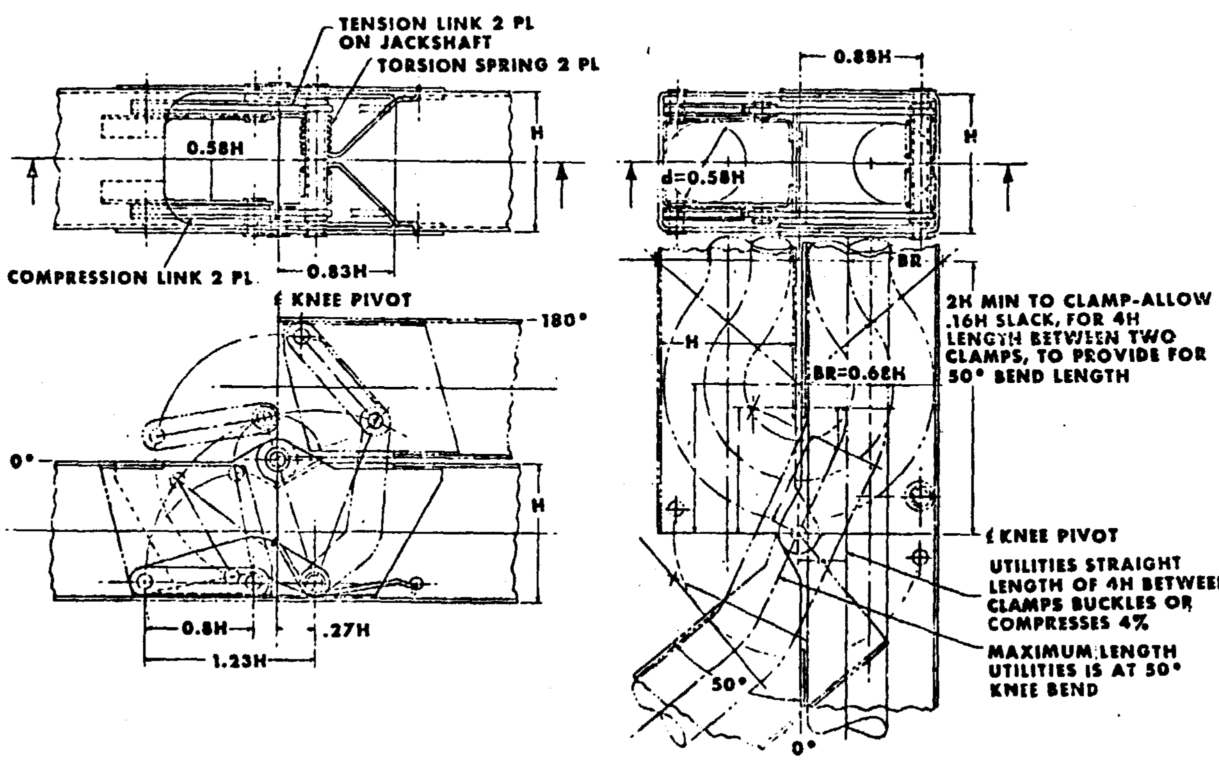

FIGURE 96 BOX TRUSS KNEE JOINT CONCEPT FOR INTERNAL UTILITIES ROUTING

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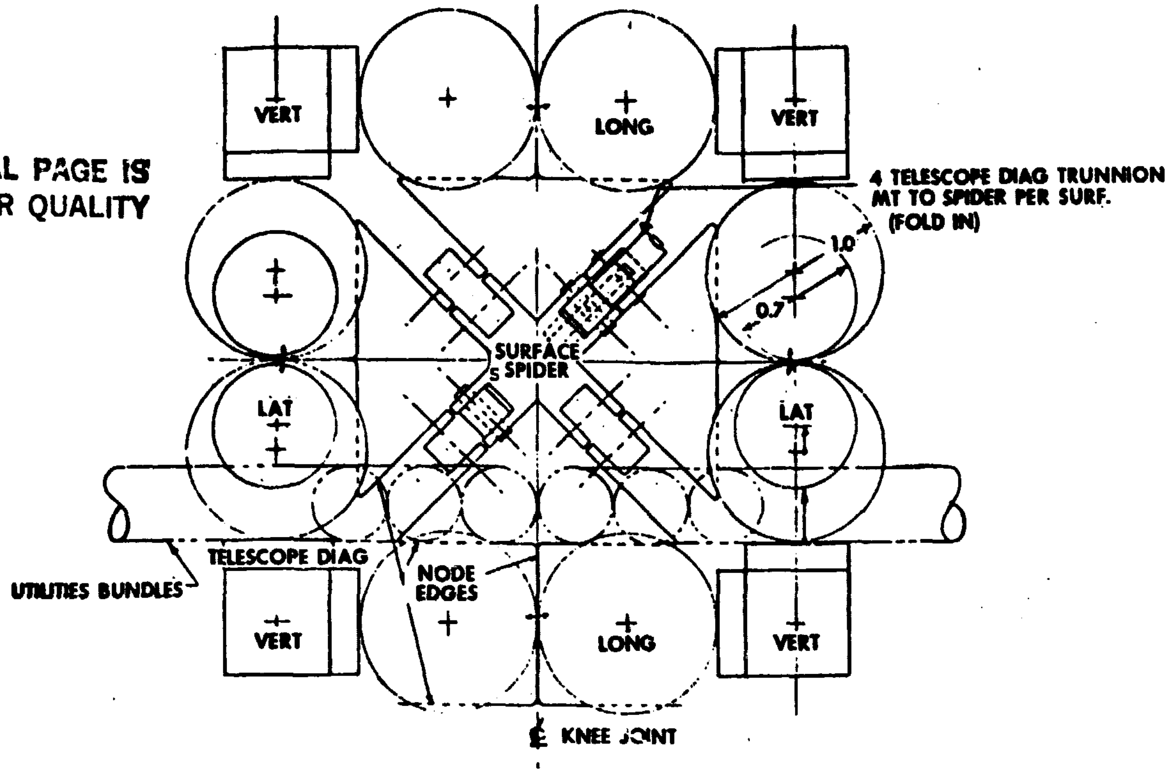

FIGURE 97 BOX TRUSS EXTERNAL UTILITIES ROUTING

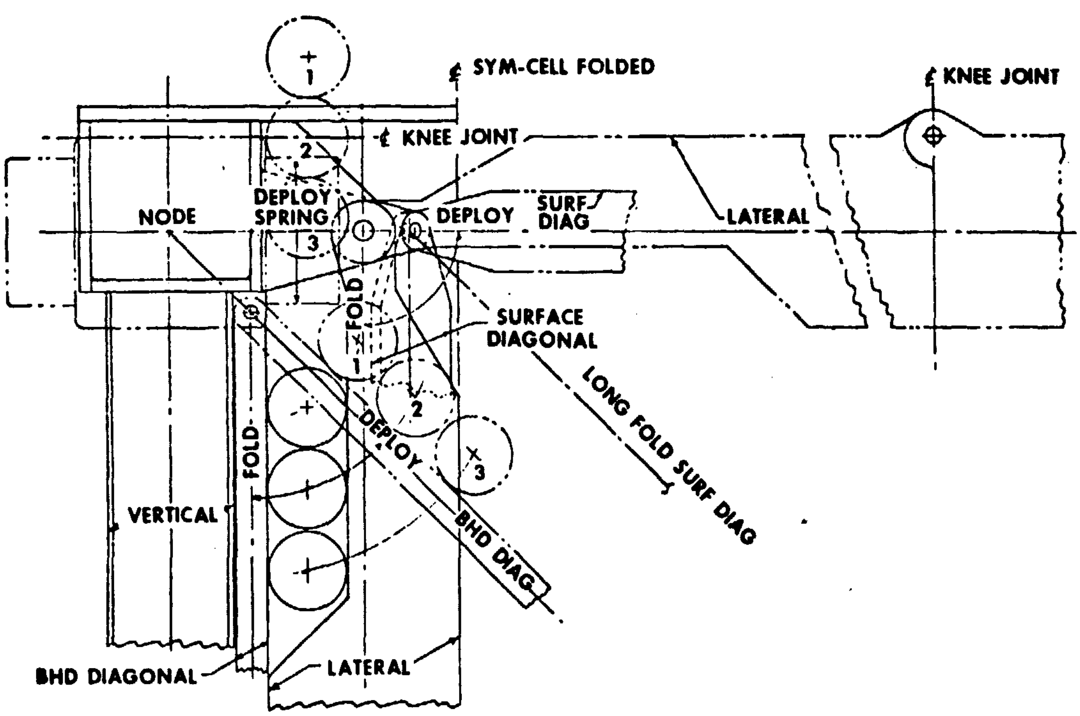

FIGURE 98

BOX TRUSS EXTERNAL UTILITIES ROUTING
4 PATHS, 12 BUNDLES

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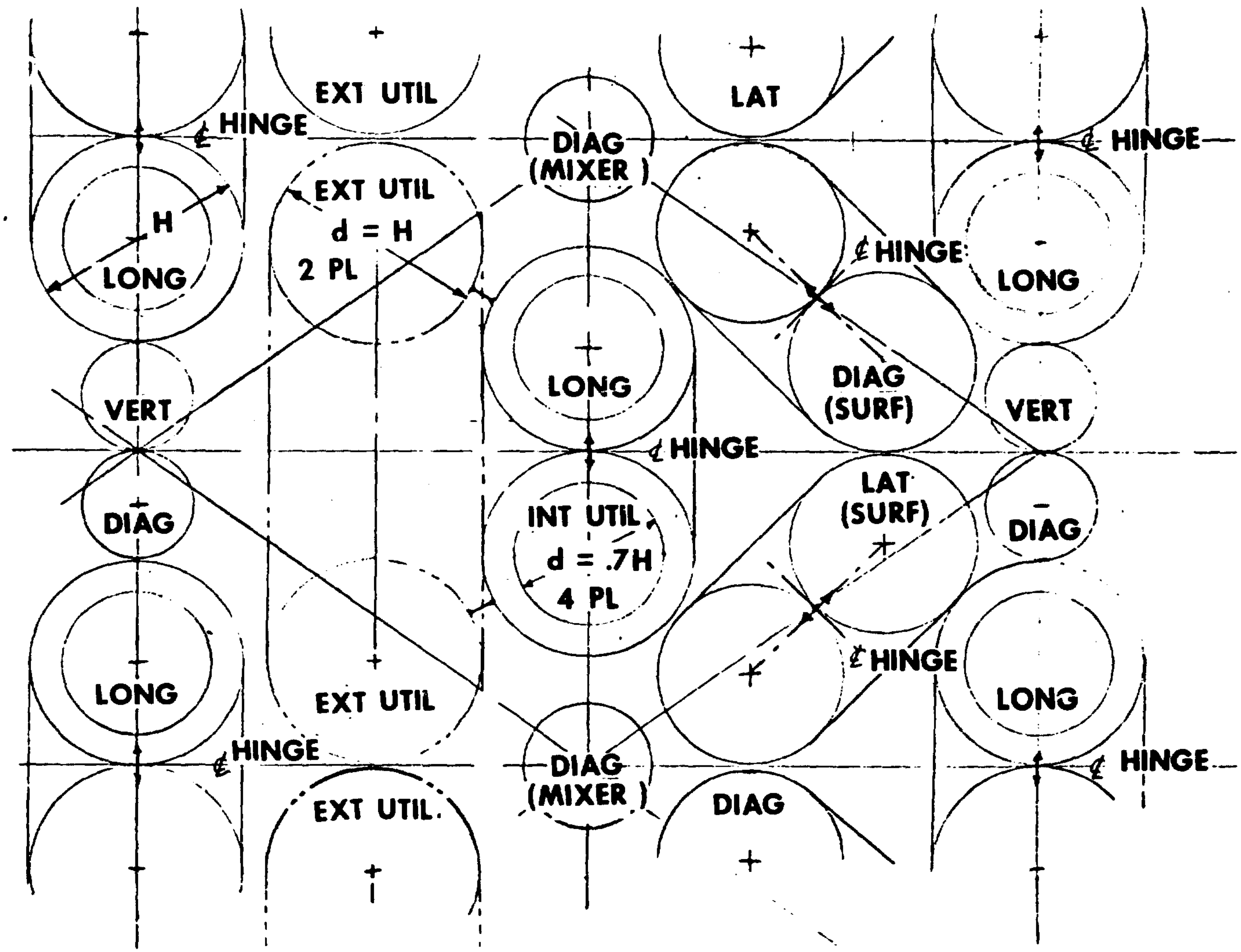

FIGURE 99 UTILITIES IN FOLDED DIAMOND BEAM

Box Truss because of the additional space available in its folded configuration for hinge components outside the strut knee joints.

Figure 100 is a photograph taken of some tests conducted at General Dynamics to demonstrate the external utilities routing. The routing space used in this test is that illustrated in our Figure 99. To route the full utilities complement externally, the diameter of the bundle that can be routed is equal to the strut diameter which allows the use of only two bundles in place of the four possible internally.

Figure 101 is a plot derived to illustrate the permissible utilities bundle diameter for internal routing. The truss cube width is plotted vs permissible bundle diameter in centimeters (per longeron). The solid lines on the figure are for the Biaxial Double Fold, Double Fold, or the Square Diamond Truss where the limitation is in the node space for utility routing. The Box Truss with its greater limitation in the knee joint area is plotted with the dotted line. The curve is parametric in strut length-to-radius of gyration ratio, where again the General Dynamics Diamond Beam strut length-to-radius of gyration ratio is 1.4 times that for the other trusses because of its longer strut length per unit cell. This approach bases the comparison on equal bending stiffnesses of the trusses. The requirements for a few of the potential missions are also spotted on the curve, showing that it is feasible to route internal utilities in all the concepts for strut length-to-radius of gyration ratios of 100 or less.

Figure 102 compares the utilities routing characteristics of the four trusses for both internal and external utilities. The utilities bundle diameter in centimeters is plotted vs the deployed/stowed volume ratio. It is seen that for internal utilities routing the Biaxial Double Fold has the superior volume ratio. The Box Truss and Diamond Beam are second and the Double Fold is the poorest volume ratio. For external utilities the order is slightly modified. The Box Truss and Biaxial Double Fold both have approximately the same volume ratio for the 5.3 cm equivalent bundle diameter plotted. The Diamond Beam has approximately the same utilities capability internal and external as does the Double Fold. All of these comparisons were done for a 3m truss cell width. In Figure 103 the internal utilities routing capabilities of the four concepts are compared as a function of truss cell width. Again the dependent variable is the deployed/stowed volume ratio. A fixed wire bundle diameter of 5 cm was used for this parametric plot. Figure

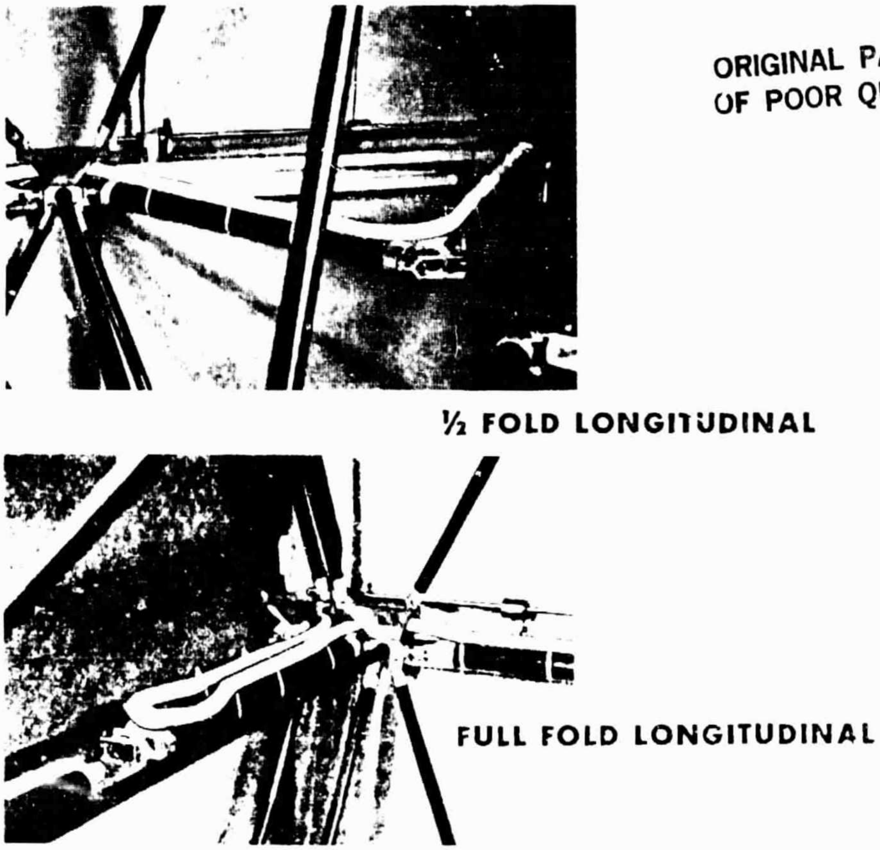

FIGURE 100 DIAMOND BEAM EXTERNAL UTILITIES

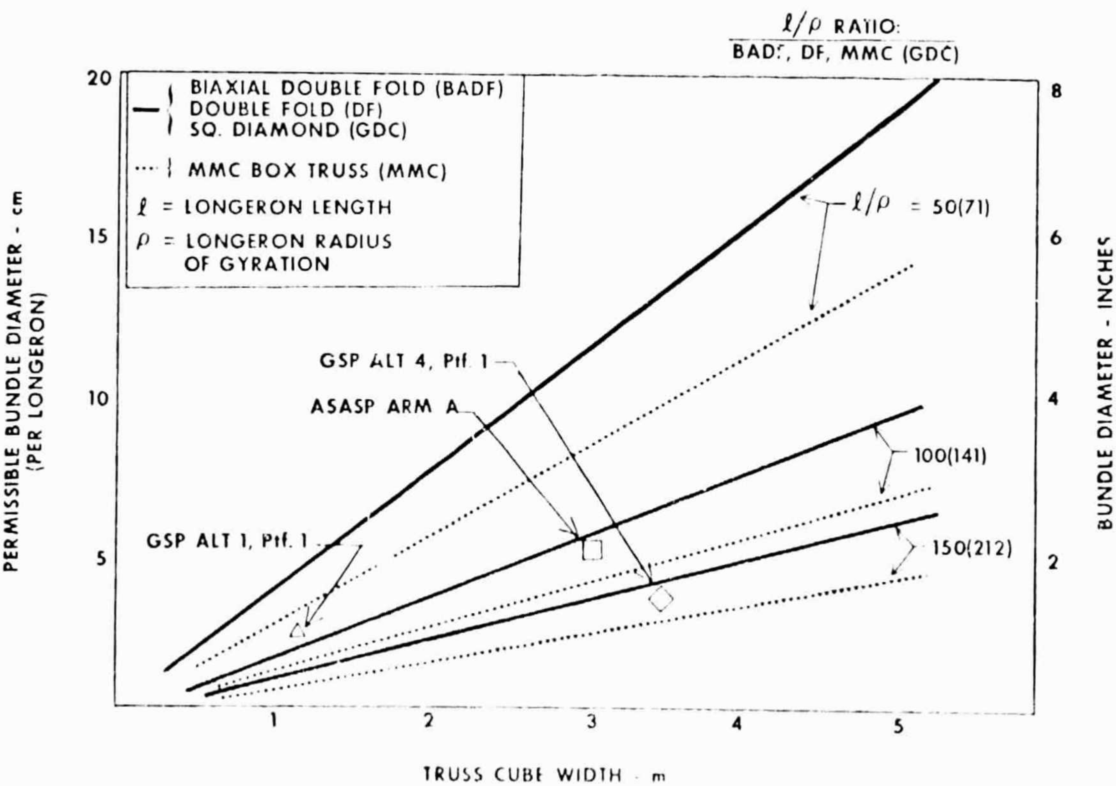

FIGURE 101 PERMISSIBLE UTILITY BUNDLE DIAMETER FOR INTERNAL ROUTING

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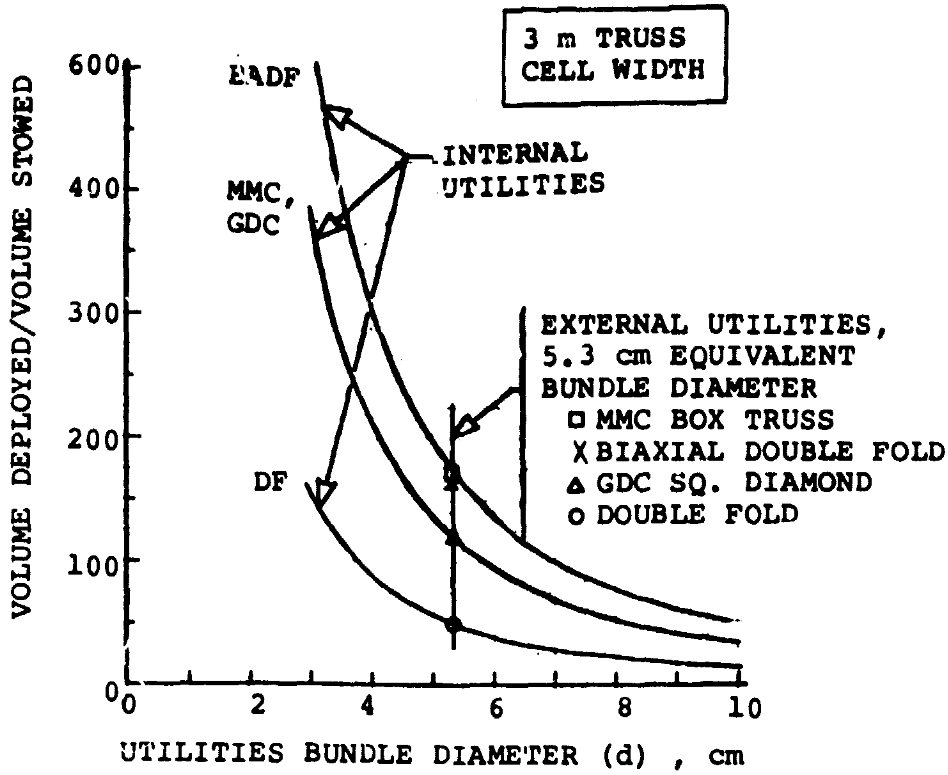


FIGURE 102 POINT COMPARISON BETWEEN EXTERNAL AND INTERNAL UTILITIES ROUTING

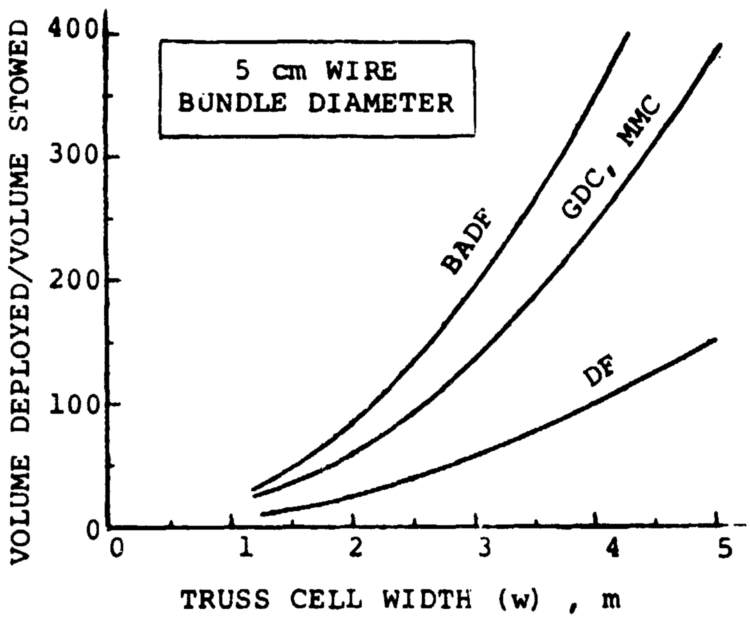


FIGURE 103 COMPARISON OF STOWAGE VOLUME RATIO FOR TYPICAL INTERNAL UTILITIES BUNDLE

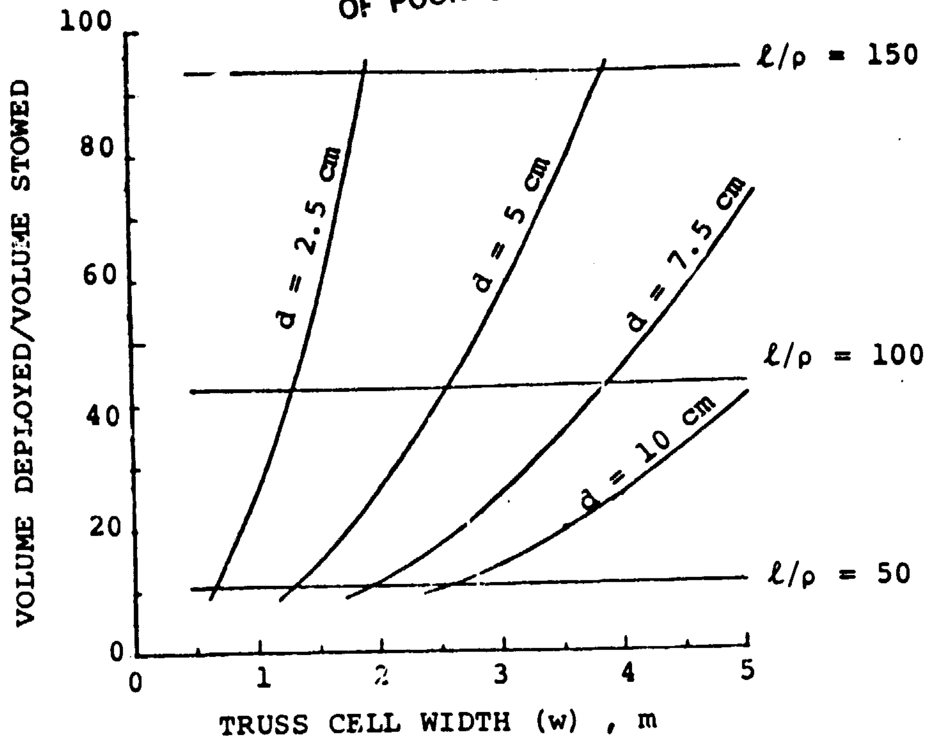


FIGURE 104
EFFECT OF INTERNAL UTILITIES BUNDLE DIAMETER ON
STOWAGE VOLUME RATIO FOR DOUBLE FOLD

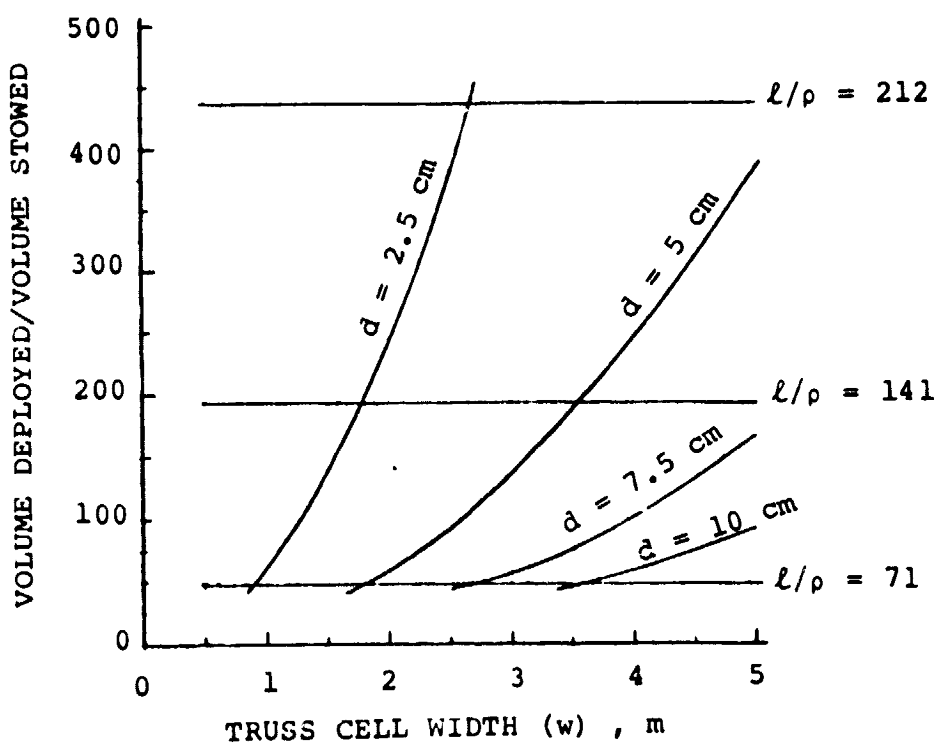


FIGURE 105
EFFECT OF INTERNAL UTILITIES BUNDLE DIAMETER ON
STOWAGE VOLUME RATIO FOR GDC SQUARE DIAMOND TRUSS

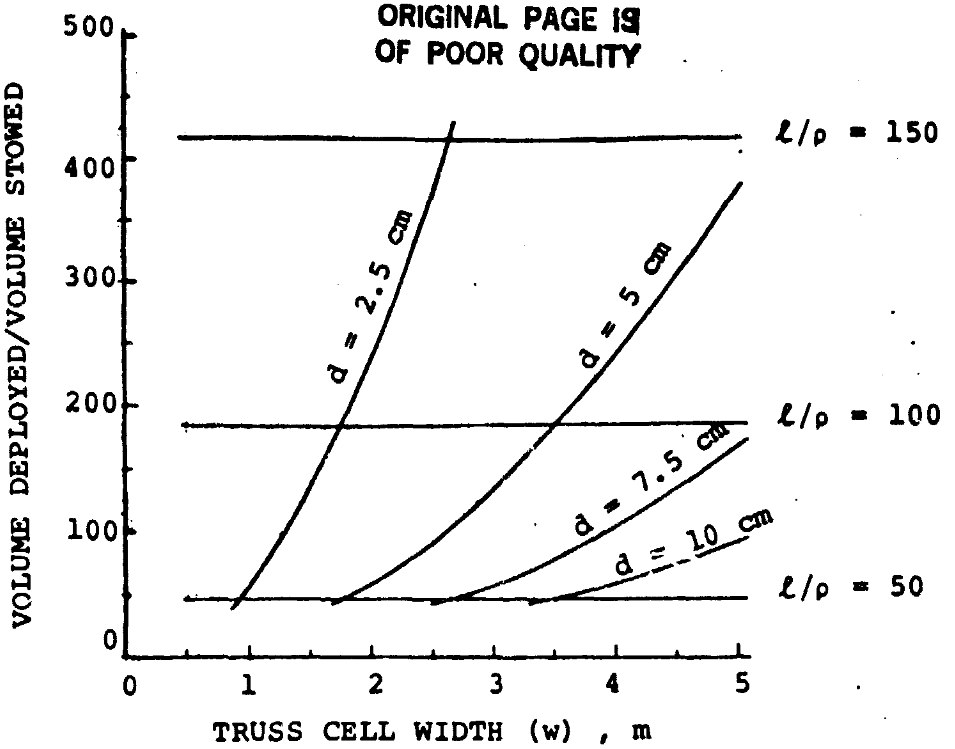


FIGURE 106
EFFECT OF INTERNAL UTILITIES BUNDLE DIAMETER ON
STOWAGE VOLUME RATIO FOR MMC BOX TRUSS

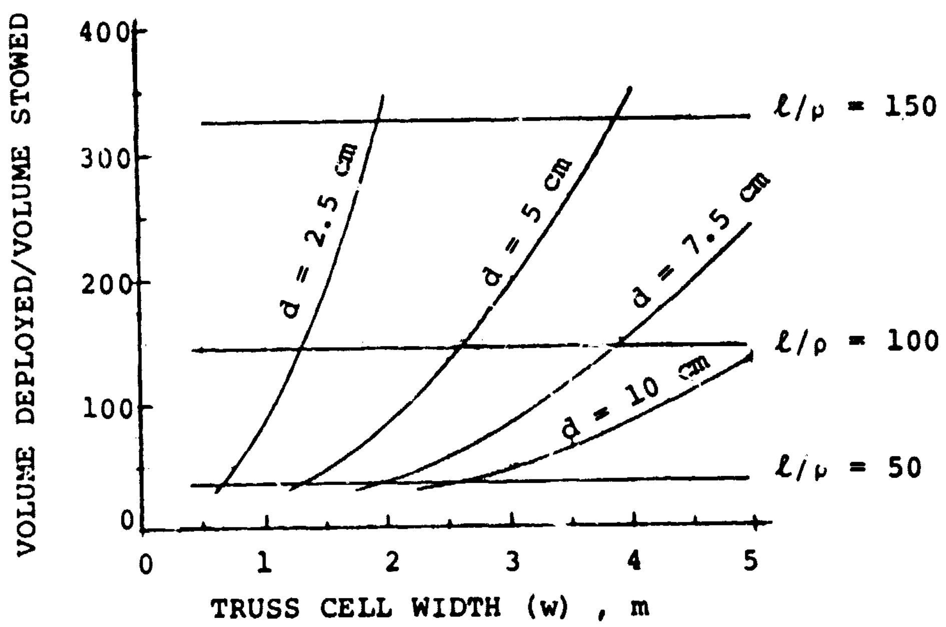


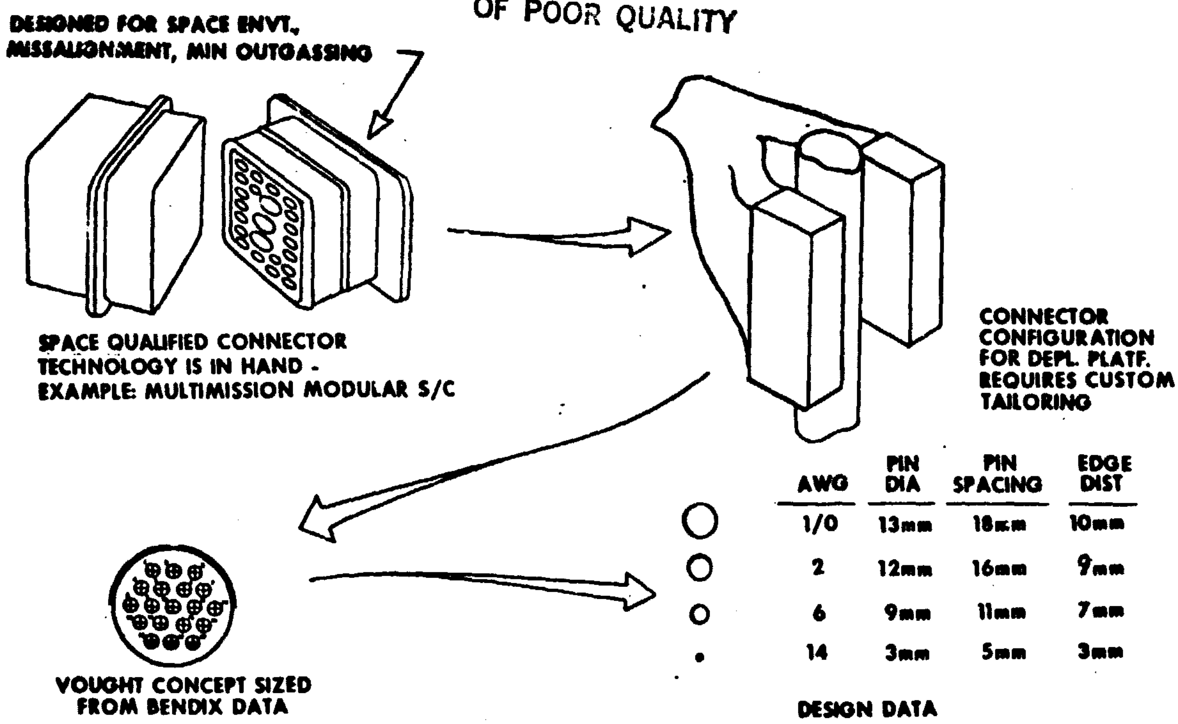
FIGURE 107
EFFECT OF INTERNAL UTILITIES BUNDLE DIAMETER ON
STOWAGE VOLUME RATIO FOR BADF

2.8 INTERFACE CONCEPTS FOR UTILITIES AND STRUCTURE

While section 2.7 showed the feasibility of external and internal routing of utilities for each of the four concepts, it is also important to be able to route the utilities out of the structure through connectors and interfaces for branching of services to payload or to subsystems or to branch into other truss structures. This section presents utilities interface concepts for each of the four truss designs. The key issues involved in deriving the concepts are that the utility connector location, the harness routing, and the mechanical compatibility must be taken into account. Another issue to be addressed is how the brancning and crossover of the utility lines can be accomplished. Also, the actual making of the utility connection is important. Provision for mechanical mating on truss-to-truss, truss-to-adapter, and truss-to-equipment interfaces is likewise a necessary issue. Installation or deployment of interface hardware is another important consideration in examining the interface design.

The approach in the interface concepts study was to mount the utilities connectors on the structure for automated mating to the interfacing connectors with no planned EVA. It was desired to provide both pre-installed mechanical utilities connectors at selected nodes and also the compatibility for orbital add-on of supplementary utilities interfaces. Another element of the approach was to utilize prior interface hardware designs wherever possible. These would be reconfigured for current needs as required and, if necessary, new concepts would be evolved. It was important to avoid utilities interface designs which impose high electrical, fluid, or fiber optic losses. The interface concepts study was conducted using the same 3m wide truss and the same representative utilities bundles used in the basic utilities routing task of Section 2.7.

Figure 108 shows some electrical connector design considerations. As indicated in the figure, space qualified connector technology already exists. An example is the Multimission Modular Spacecraft connector, which was designed for the space environment, for misalignment, and for minimum outgassing. The availability of this technology allowed us to configure connectors for the deployable platform considerations by just tailoring existing designs. In order to provide the information for this tailoring, Vought obtained pin locations and sizes and connector spacing considerations from existing data, such as the Bendix connector data illustrated.



AWG	PIN DIA	PIN SPACING	EDGE DIST
1/0	13mm	18mm	10mm
2	12mm	16mm	9mm
6	9mm	11mm	7mm
14	3mm	5mm	3mm

DESIGN DATA

FIGURE 108 ELECTRICAL CONNECTOR DESIGN CONSIDERATIONS

Figure 109 shows the results of electrical connector sizing studies. It shows that the typical configuration of a connector pair must be slender in order to accommodate the interface needs of the deployable trusses. Also shown are the sizes of the insulator blocks and the male and female shells.

Figure 110 shows design considerations for fiber optic connectors and electrical tees. As indicated in the figure, fiber optic connector technology is also available and provides the dimensional requirements to permit the preliminary sizing of connectors for interface studies. Also indicated on the figure, compact fiber optic tees result in prohibitively large optical losses. Low loss tees, however, are themselves prohibitively large for the current utilities branching. That resulted in the approach for the current study of eliminating tees in fiber optics in favor of splitting out a predetermined number of cables at each interface location. The number of cables branched could be up to the total number. A compact, low loss fiber optic tee was identified as a technology development item. The current electrical tee design illustrated on the figure is also bulky. While the dimensions of this tee were compatible for the current branching studies, improvements could be made with a more compact tee. A concept was devised for a more compact electrical branch tee, as indicated in the figure.

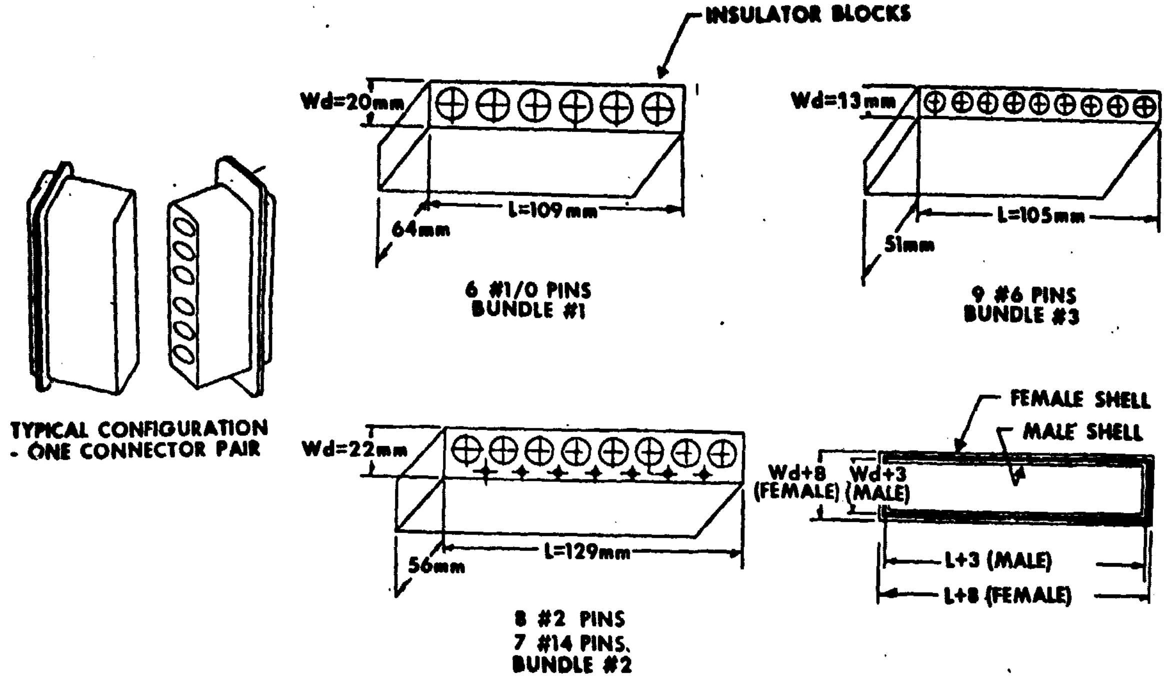


FIGURE 109 ELECTRICAL CONNECTOR SIZING

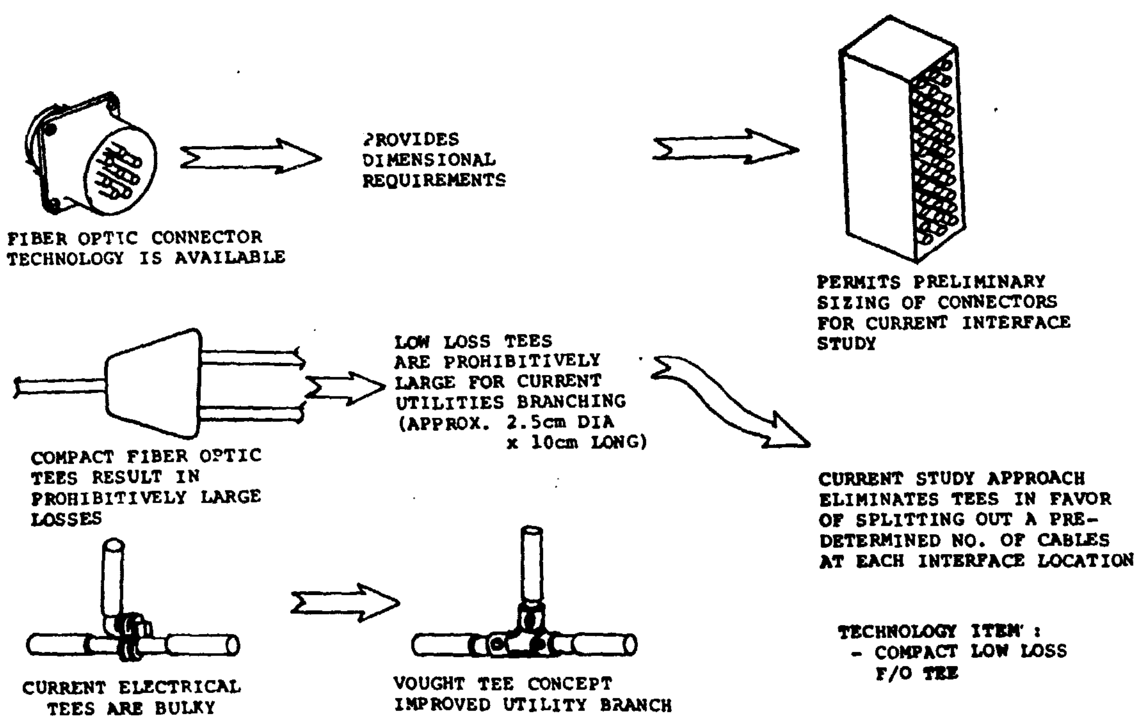


FIGURE 110
DESIGN CONSIDERATIONS FOR FIBER OPTIC
CONNECTORS & TEES AND ELECTRICAL TEES

Figure 111 illustrates a fluid connector concept. Current fluid connector designs are too large to fit in well with the utilities interfacing concepts being evaluated. In addition, their internal structure is too small and restrictive to adequately handle typical flowrates of the 2.5 cm fluid transport lines. By enlarging the internal flow area and making the design more compact, as indicated in the figure, the design of an existing prototype NASA-MSFC/Fairchild connector can likely be evolved to provide the needed performance. This was defined as a technology development item.

Figure 112 illustrates several mechanical interface hardware items which were cataloged for use in the current study and were considered to be acceptable concepts without modification. The McDonnell Douglas Advanced Technology Docking Adapter illustrated on this figure was derived in conjunction with the SASP and related studies (Refs. 6, 22). This interface system was designed to capture and attach two bodies, one which would be maneuvered by the RMS and the other which might be fixed to the Orbiter. Significant loads and velocities would be involved. Forward and lateral closing velocities of 0.3 m per second with 1 deg/sec pitch, roll, or yaw rate were imposed as design requirements. The adapter allows for a lateral mismatch of 30.5 cm and a misalignment in pitch, roll or yaw of 15^{0}. It provides a clear access opening in the port of 1m. The McDonnell Douglas concept is designed for a truss load of 9080 Kg and moments in pitch, roll and yaw of 21,690 N-m. It consists of an upper passive half and a lower active half. The lower active half has capture guides, a capture and structural latch, and alignment keys. It is mounted by support struts which may be damped to take up the shock loads or locked to provide rigid structural support. Provisions are also included for coolant and electrical umbilical connections. The figure also shows a three socket ball castor and socket berthing adapter which would be lighter construction and more suitable for payload interfaces. It would provide self aligning and automatic latching and could be designed for automatic thermal compensation. Two additional joining devices are illustrated for joining nodes to struts or small structure, or joining nodes to nodes. The Autolock Coupler is for axial insertion of a probe into a drogue where the sidelatch coupler allows latching from axial or side directions (Ref. 7). Both of these have been verified in neutral bouyancy testing. Also schematically indicated in the figure is a rotary joint derived for the SASP study, which provides for 360^{0} joint rotation and

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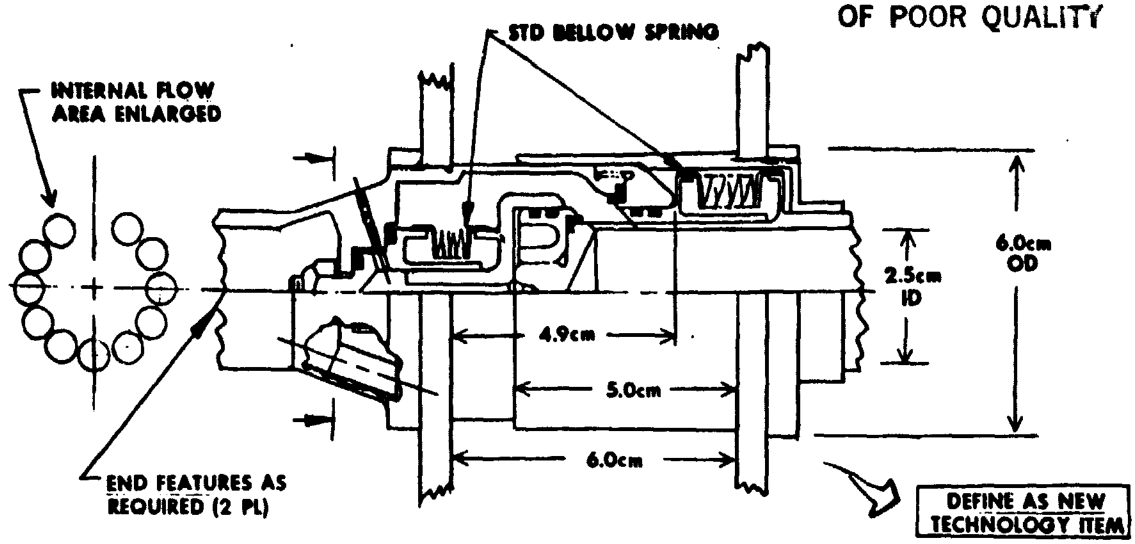
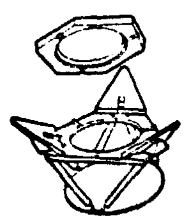
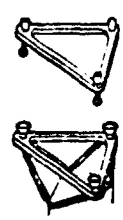


MODIFIED FROM NASA-MSFC/FAIRCHILD CONNECTOR TO REDUCE PRESSURE DROP, INTERFACE 2.5 cm LINE, AND MINIMIZE LENGTH

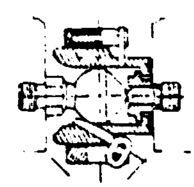
FIGURE 111 FLUID CONNECTOR CONCEPT



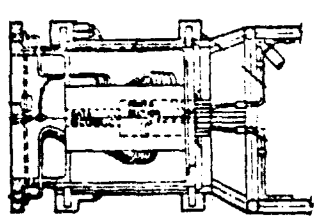
MDAC ADVANCED TECHNOLOGY DOCKING ADAPTER



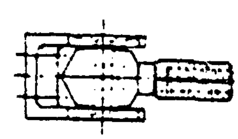
3-SOCKET BERTHING ADAPTER FOR PAYLOADS



AUTOLOCK COUPLER FOR TRUSS JOINING AND LOCAL EQUIPMENT MOUNTING



MDAC ROTARY JOINT



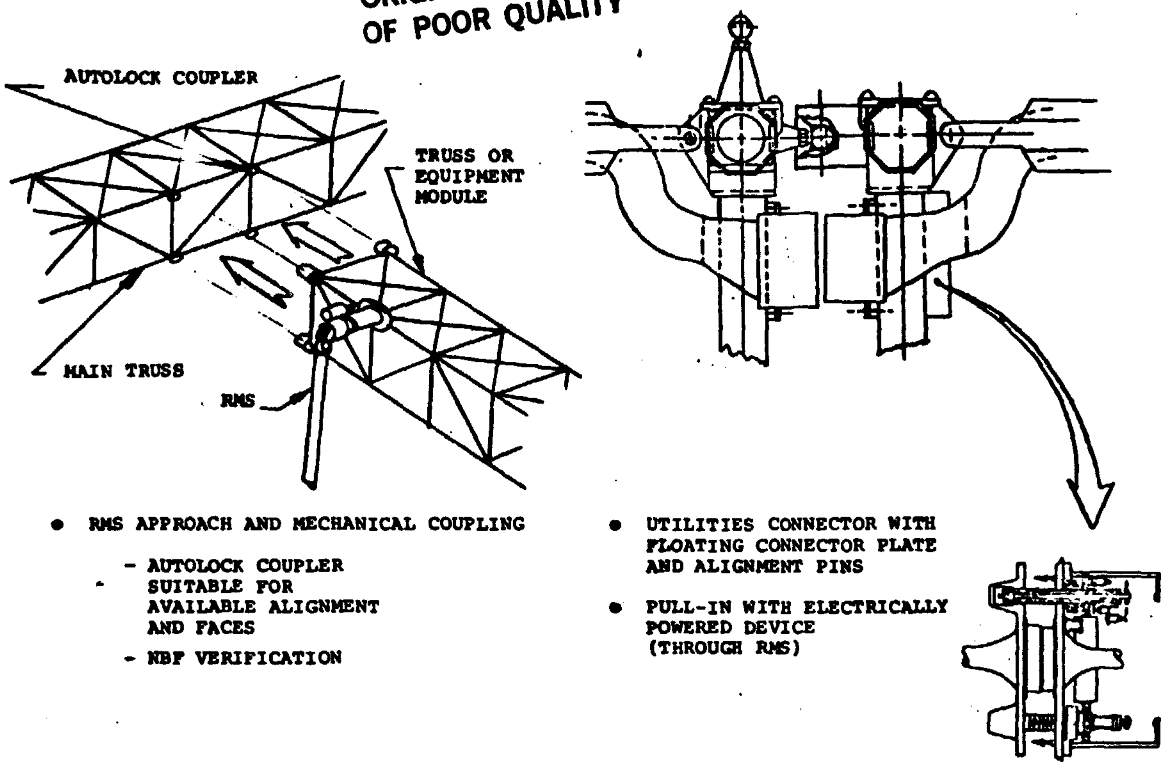
SIDELATCH COUPLER FOR ASSEMBLED INTERFACE STRUCTURE

FIGURE 112 CATALOG OF REPRESENTATIVE MECHANICAL INTERFACE DESIGNS for transmission of data and power. This design could also be made to transfer fluid. On the left side of the device are provisions for a passive docking port. The design is intended to be capable of transmitting 25 kW of power and 120 MBPS of data. It is intended that it can be EVA replaceable.

Figure 113 further illustrates the interface mating approach. Two trusses are shown being joined with the aid of the RMS. The truss that is being butted into the main truss has Autolock Coupler drogues positioned on the four node positions. The RMS provides the force necessary to bring the two trusses together and to couple them. This type of joining with the Autolock Coupler has been demonstrated in neutral bouyancy testing. On the right hand side of the figure, additional detail is shown for both the mechanical latch portion of a node as well as the scheme for bringing the utilities connector plates together. The utilities connector plate has a floating plate on it with alignment pins. Once the mechanical connection is made an electrical drive device using power supplied through the RMS pulls in and completes the connection. The device for pulling in and completing the utilities connection was derived during the present study, and is illustrated in more detail in Figure 114. The plug and receptacle are shown with the two actuators in the extended and locked position. The motor drive mechanism is shut off by the retract load switch after the actuators pull the connectors together and compress the load springs.

Figure 115 illustrates the nodes selected for utility interfaces on the Biaxial Double Fold. This is necessary because space inside the nodes for utilities crossovers is different on the different nodes. The A nodes provide more space and are used for fluid connectors and all utility tees. The B nodes are used at utility crossovers.

Figure 116 is an illustration showing the internal utility routing, where a tie in utility bundle No. 3 is terminated at connectors adjacent to an A node. The utilities which are routed through the longitudinal struts have a branched harness which is routed behind the struts and exits through the connector immediately below the node fitting. The illustration shows how both the fluid connector in the base of the node and the two electrical connectors on either side of the vertical strut can be located at the interface. It also illustrates the connector pull-in plate alignment pin. A phantomed outline in the illustration shows the motion of the utilities bundle, especially in the tee area, as the lateral strut is folded or deployed. Also shown is a small cutaway in the lateral and diagonal struts to clear the branched harness.



- RMS APPROACH AND MECHANICAL COUPLING
  - AUTOLOCK COUPLER SUITABLE FOR AVAILABLE ALIGNMENT AND FACES
  - NBF VERIFICATION
- UTILITIES CONNECTOR WITH FLOATING CONNECTOR PLATE AND ALIGNMENT PINS
- PULL-IN WITH ELECTRICALLY POWERED DEVICE (THROUGH RMS)

FIGURE 113 INTERFACE MATING APPROACH

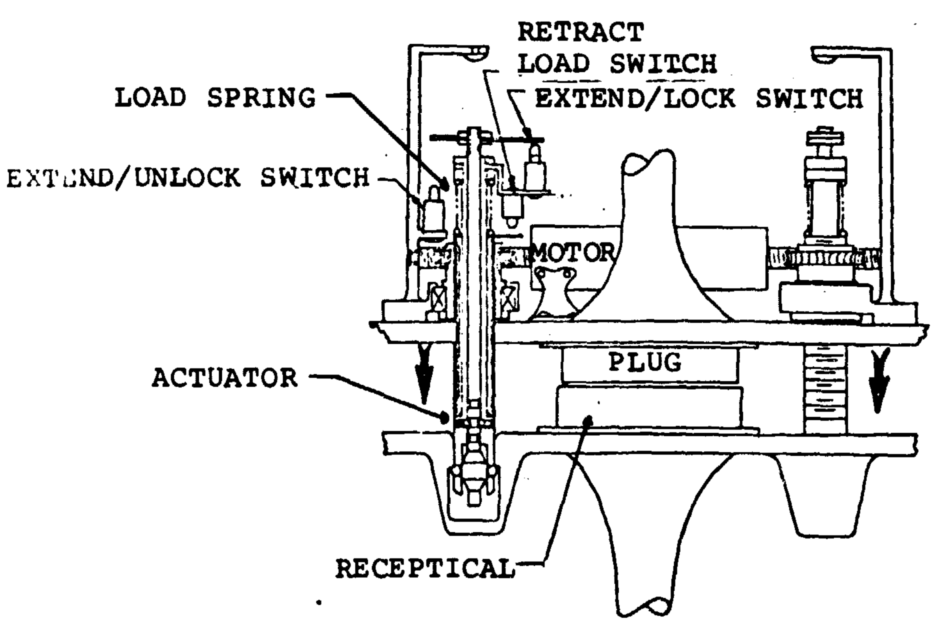


FIGURE 114 UTILITY PANEL PULL-IN

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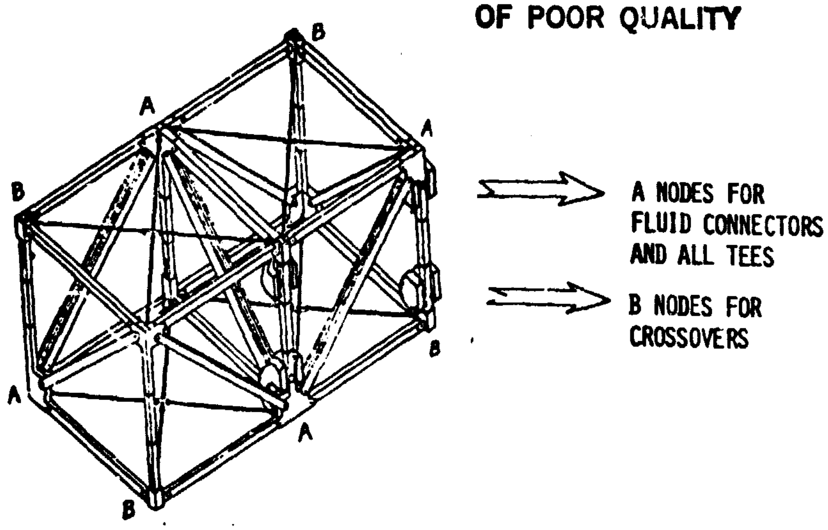

FIGURE 115 NODE SELECTION FOR BADF UTILITIES INTERFACES

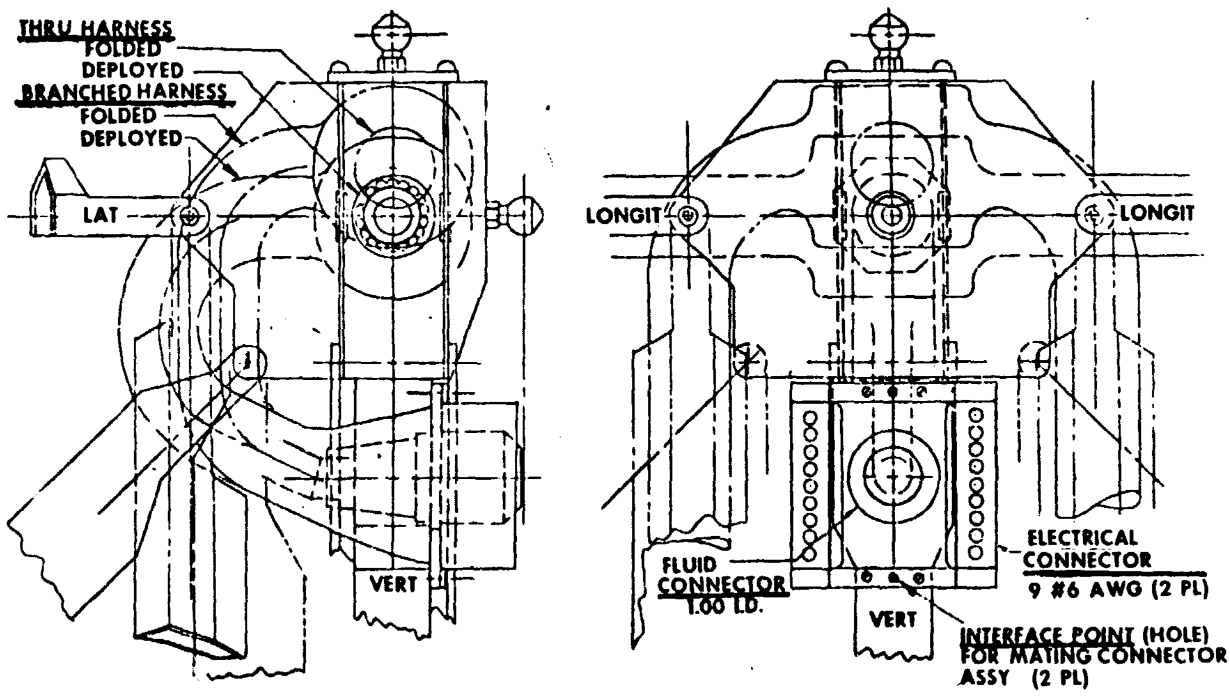

FIGURE 116 "A" NODE UTILITIES - BADF INTERNAL ROUTING - BUNDLE #3

Figure 117 shows a tee in an A node for routing through a lateral strut across the truss to a crossover at a B node. Figure 118 shows a crossover at a B node where bundle No. 1 utilities are illustrated. The utility bundle passing through the B node along the longitudinal is undisturbed. The crossover takes place by routing through the lateral strut and then down below the B node to the connectors located immediately below the B node. Figure 119, also for the Biaxial Double Fold is similar to Figure 118 except that the No. 2 utilities bundle shown is slightly different.

In Figure 120 the utilities interfaces for the Double Fold are illustrated. Node selections are shown, where tees and crossovers are best located at nodes 1 and 2. Connectors at nodes 3 and 4 are routed from a tee located up or down a vertical strut from nodes 1 and 2, respectively. The actual design of the connector installation is very similar to the Biaxial Double Fold illustrated on this figure for reference.

Figure 121 illustrates the utilities interfaces for the Martin Box Truss. In this case the selection of nodes for tees and crossovers is not critical. Also shown on this figure is an enlarged view of a longitudinal strut with a tee and connector at an interface node. The connector must be geometrically positioned with its long dimension oriented vertically in order to fit into the narrow space available on the vertical struts. Figure 122 shows additional cross routing detail for the Box Truss at a crossover, vertical tee, and lateral tee.

Figure 123 shows the utilities interface concept for the GDC Diamond Truss Beam. The external utility routing is shown where utilities bundles are on only 2 of the longitudinals beams. The routing indicated would be similar for internal utilities except smaller bundles would be inside all 4 longitudinals. The larger fluid connectors require a clearance cut in the bulkhead diagonal for fold clearance.

Figure 124 summarizes some of the most important considerations for utilities branching with external utilities. For the Biaxial Double Fold widening the B nodes would probably be required. The Double Fold probably will not require any changes in routing or widening of nodes. The Martin Box Truss will have to be modified to make the verticals larger to gain room where penetration is necessary to get out of this truss. The Diamond Beam has approximately the same routing complexity internal or external to the truss. Connector space is not available for branching a full complement of both internally and externally routed utilities at the same truss location in any of the truss concepts.

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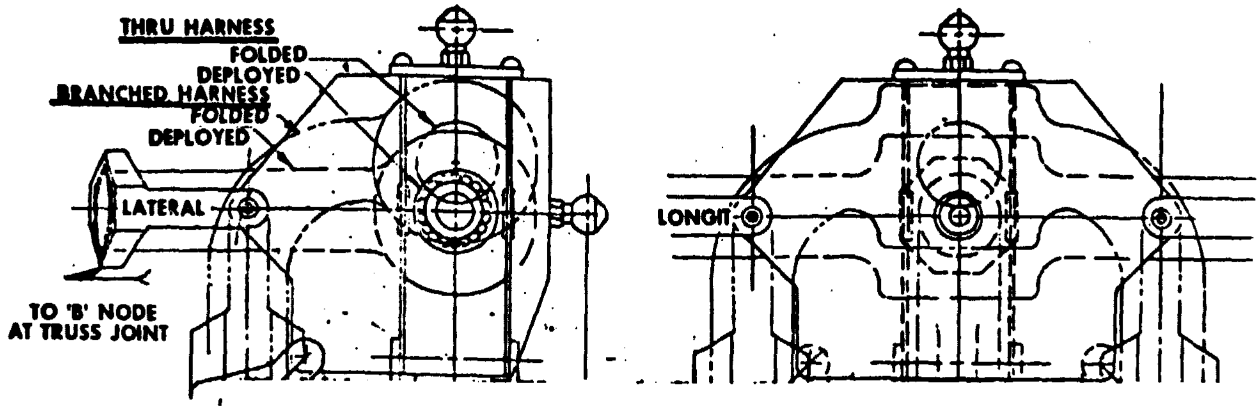

FIGURE 117 "A" NODE UTILITY "T" FOR ROUTING BUNDLE TO "B" NODE AT TRUSS JOINT

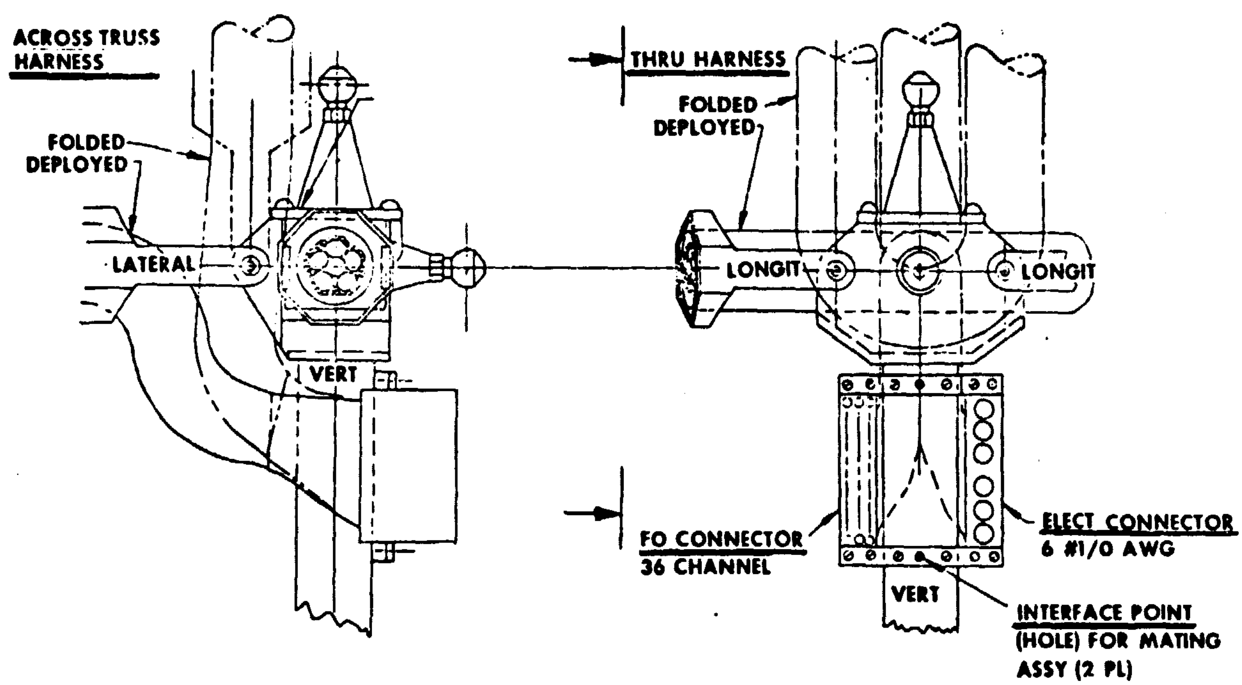

FIGURE 118 "B" NODE UTILITIES - BADF INTERNAL ROUTING-BUNDLE #1

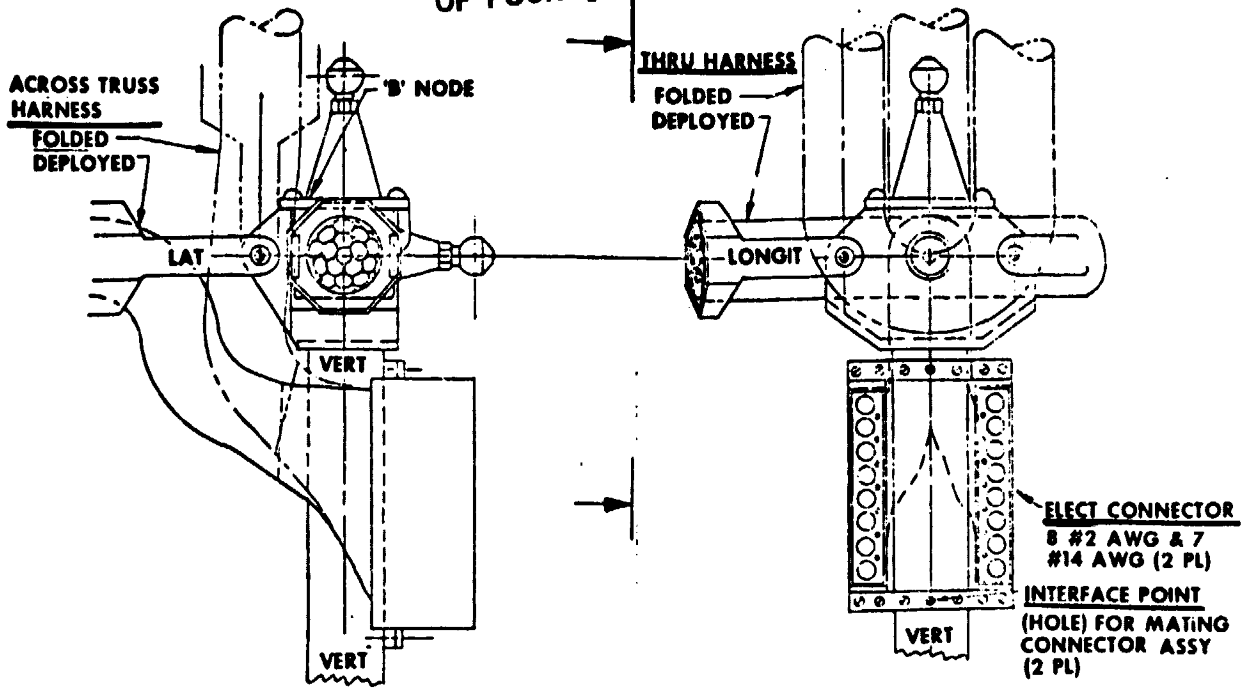

FIGURE 119 BADF INTERNAL ROUTING-BUNDLE #2

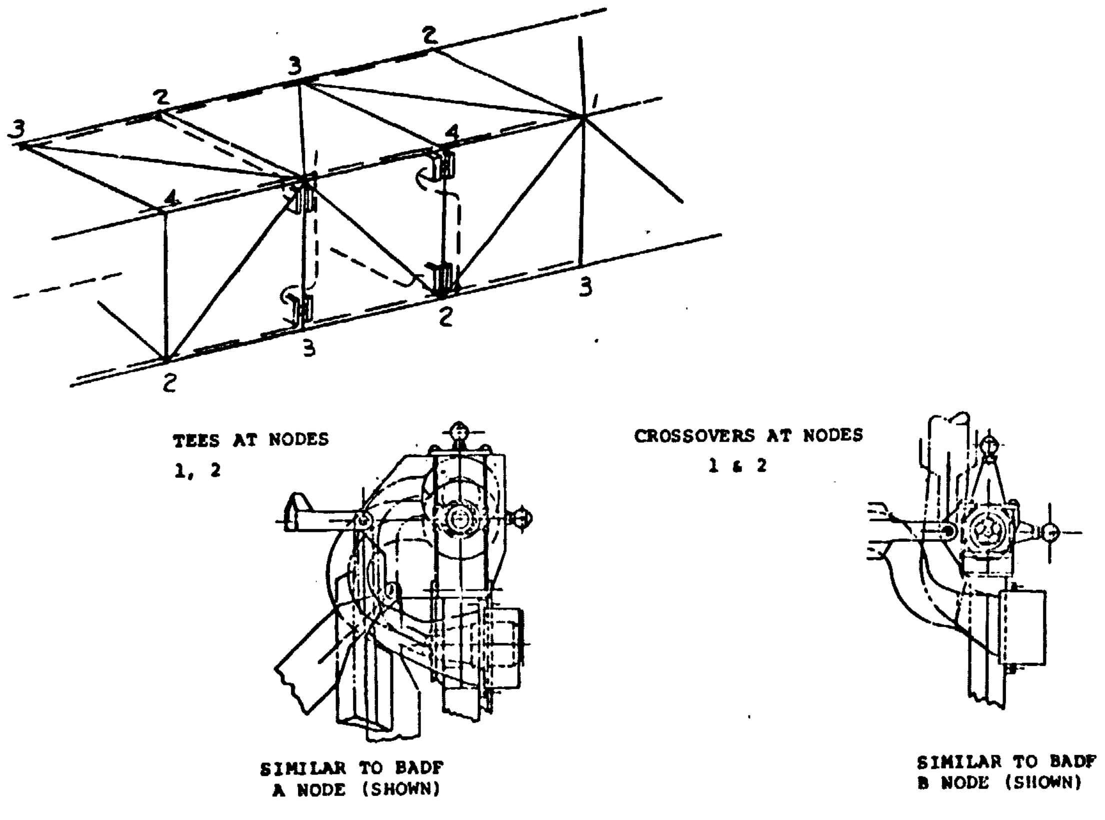

FIGURE 120 UTILITIES INTERFACES FOR DOUBLE FOLD

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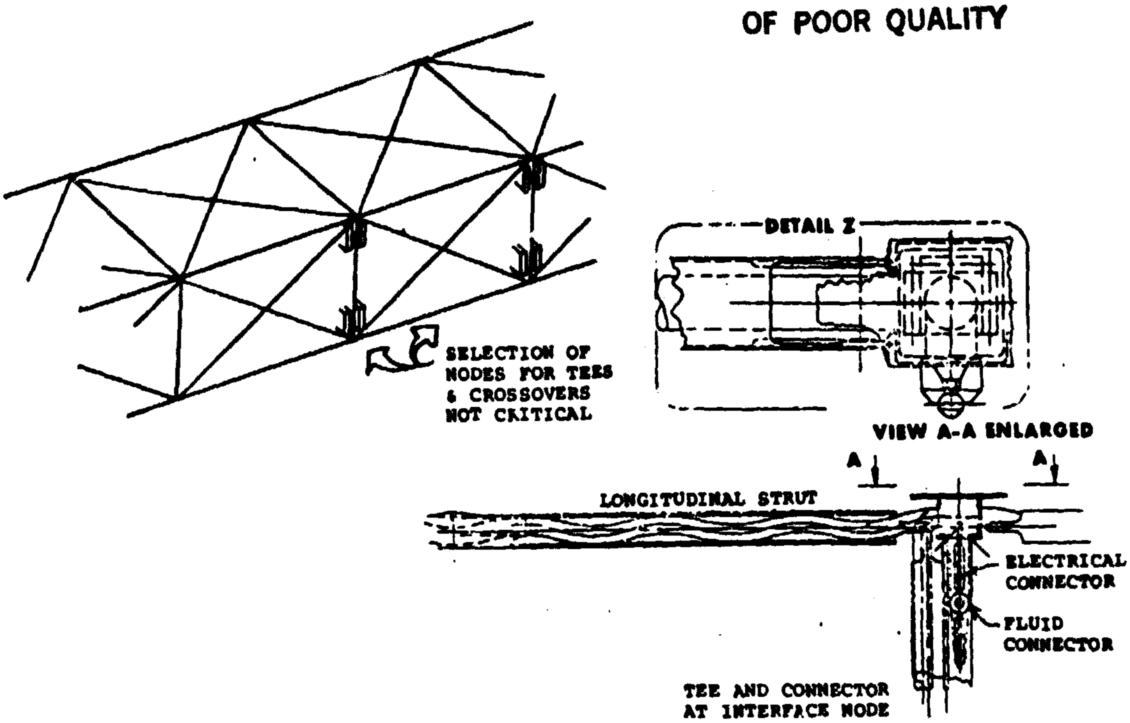

FIGURE 121 UTILITIES INTERFACES FOR MARTIN BOX TRUSS

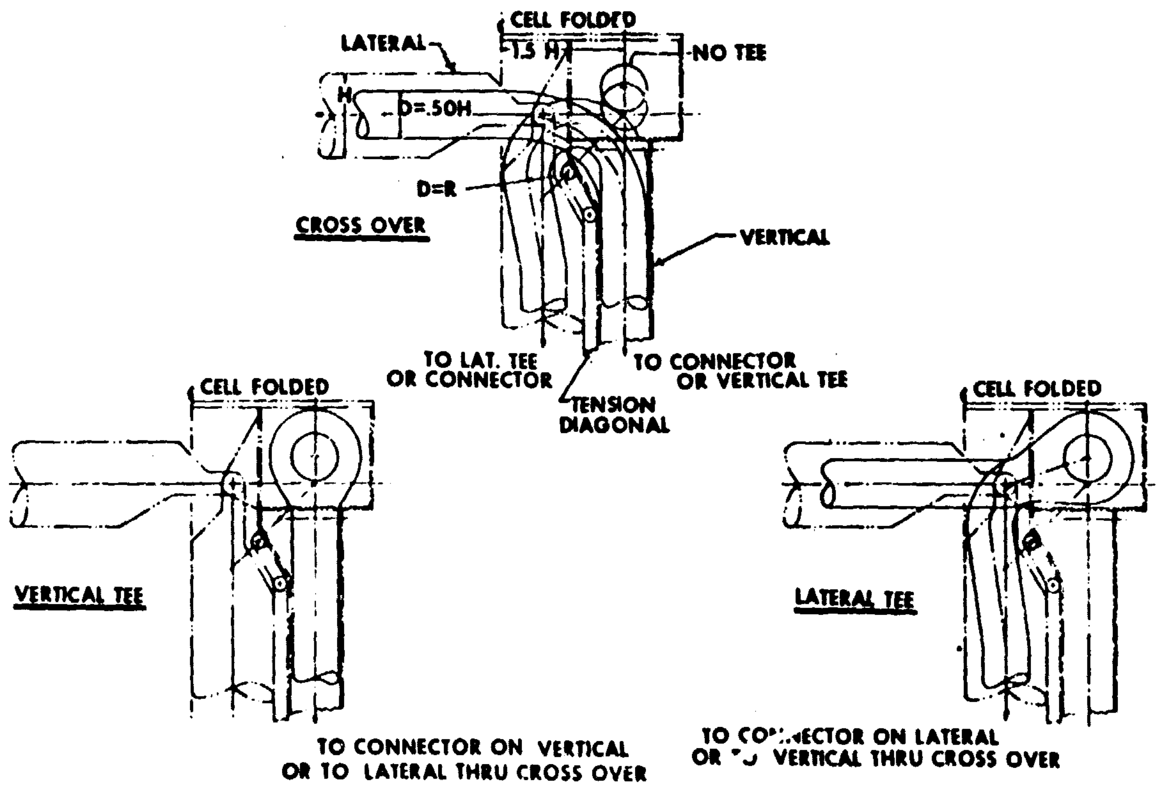

FIGURE 122 BOX TRUSS INTERNAL UTILITIES CROSS ROUTING

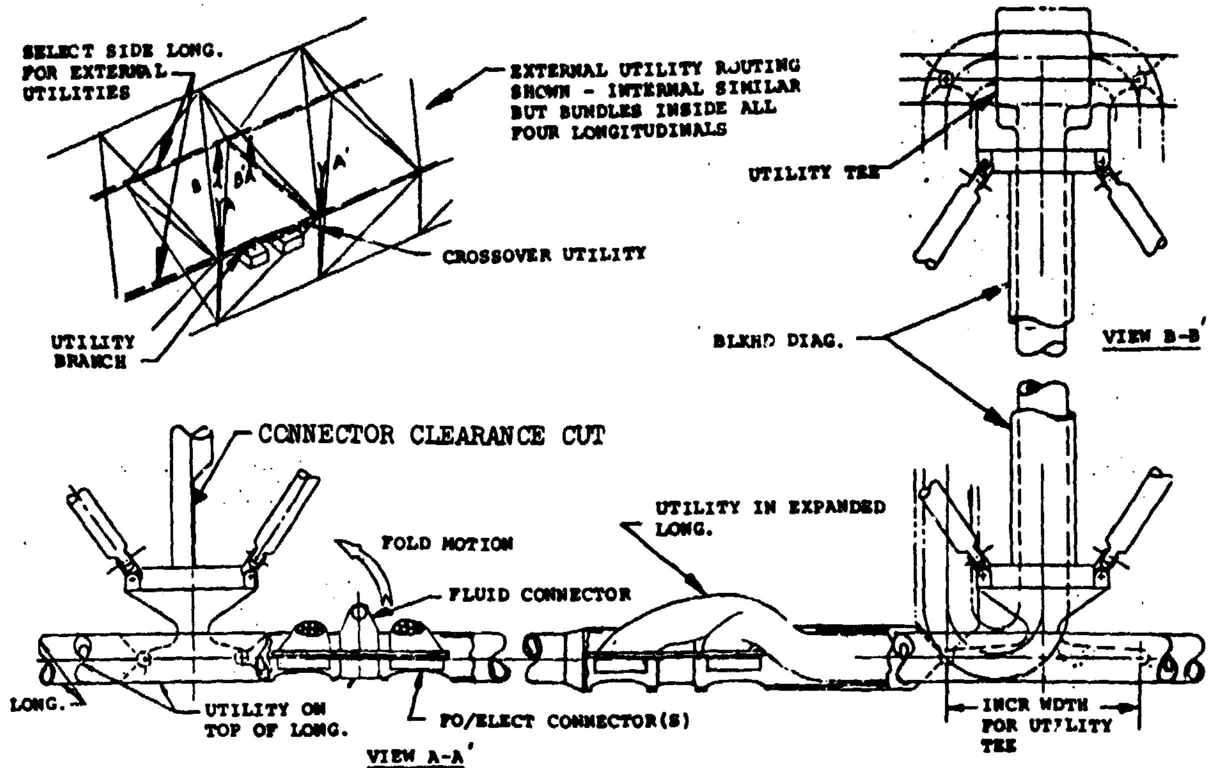

FIGURE 123 UTILITIES INTERFACE FOR GDC DIAMOND BEAM

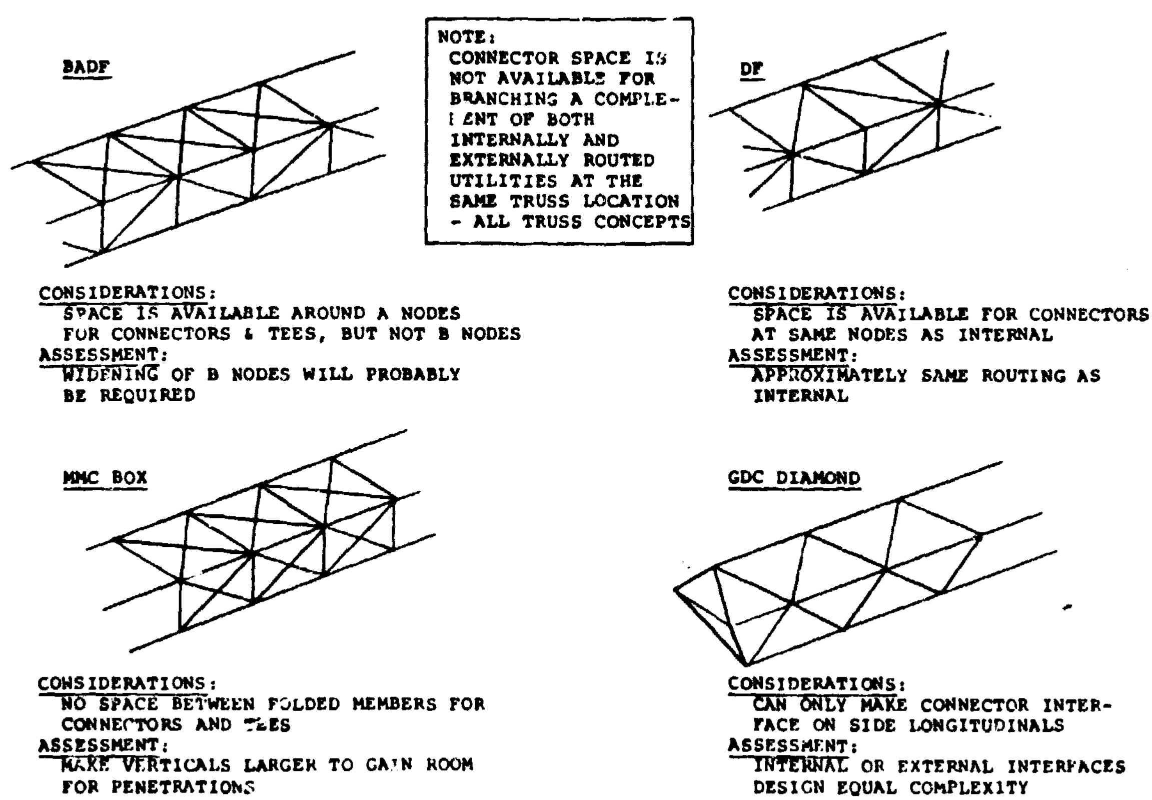

FIGURE 124 CONSIDERATIONS FOR UTILITY BRANCHING WITH EXTERNAL UTILITIES

The summary of interface results show the following important findings:

1. Tee, crossovers and connectors can be provided at nodes to accommodate branching of up to a full complement of utilities for all concepts.

2. For internal utilities routing the impact of utility branching and interface connectors is to expand node size and increase cell stowage volume in all concepts except the Biaxial Double Fold and Double Fold. For the Box Truss the approximate increase is 40% in node thickness with no increase in stowage volume. For internal utilities branching on the Diamond Beam the node thickness will need to be increased 90% and stowage volume increased about 67%.

3. There are some limitations in node selection for fluid connectors and there are preferable nodes for tees. These limitations are not overly restrictive.

4. Branch truss mechanical and utility interface connections can be accomplished by use of the RMS without EVA assistance.

5. While most of the interface studies have been with internally routed utilities, branching of externally mounted utilities at interfaces has also been shown to be feasible. Preliminary results indicate that the impact will be somewhat greater than with internal utilities.

2.9 CONCEPTS FOR INTERFACE WITH PAYLOADS AND EQUIPMENT

From studies of interfaces with equipment and payloads, it was determined that small equipment and hardware items such as sensors and RMS probe can be attached at intermediate local points on the structure and deployed or stowed directly with the truss structure on the Biaxial Double Fold, Double Fold, and Martin Marietta Box Truss concepts. The GDC Diamond Beam is limited to mounting such items on the end of the truss structure. Figure 125 illustrates the standard RMS grapple fixture installed on a B node of the Biaxial Double Fold. Equipment items such as flat panel radiators can also be directly mounted to the truss at nodes, using couplers and utility connectors. An additional option available with large equipment items that require a significant amount of utilities is the external routing of add on utilities as part of the installation procedure. Large equipment items and interface items such as a docking ring can also be attached at intermediate points or on the ends of the structure and deployed with the Biaxial Double Fold, the Martin Marietta Box Truss, or the Double Fold trusses.

Figure 126 illustrates the deployment of the Biaxial Double Fold truss with end mounted and intermediately mounted equipment. It shows a transition structure on the end of the truss connecting a docking or berthing device with the main truss. It also illustrates a docking adapter, equipment item, or payload item at an intermediate location on the side of the truss. On the Biaxial Double Fold it would be necessary to make these equipment interfaces on the side rather than the top of the truss because the side diagonals pivot at the ends while the top diagonals fold in. The attachment of a payload or equipment item, if no transition structure were included, would be at the two ends of the side/end diagonal near the nodes. As the structure deploys the rigidizing third point would engage a ball and socket joint at one of the other face nodes as the deployment is completed. If a transition truss were used, as illustrated in Figure 126, the equipment would be attached in a similar manner, but to the end diagonal of the transition structure. Figure 126 also shows the relative volumes of the folded main and transition truss with a rigid docking device or other equipment item on the side and end. As a further example of a hardware interface, Figure 127 shows a rotary joint attached at the ends of two segments of a truss and deployed with the truss. Again this could be either the Double Fold, the Martin Marietta Box Truss, or Biaxial Double Fold.

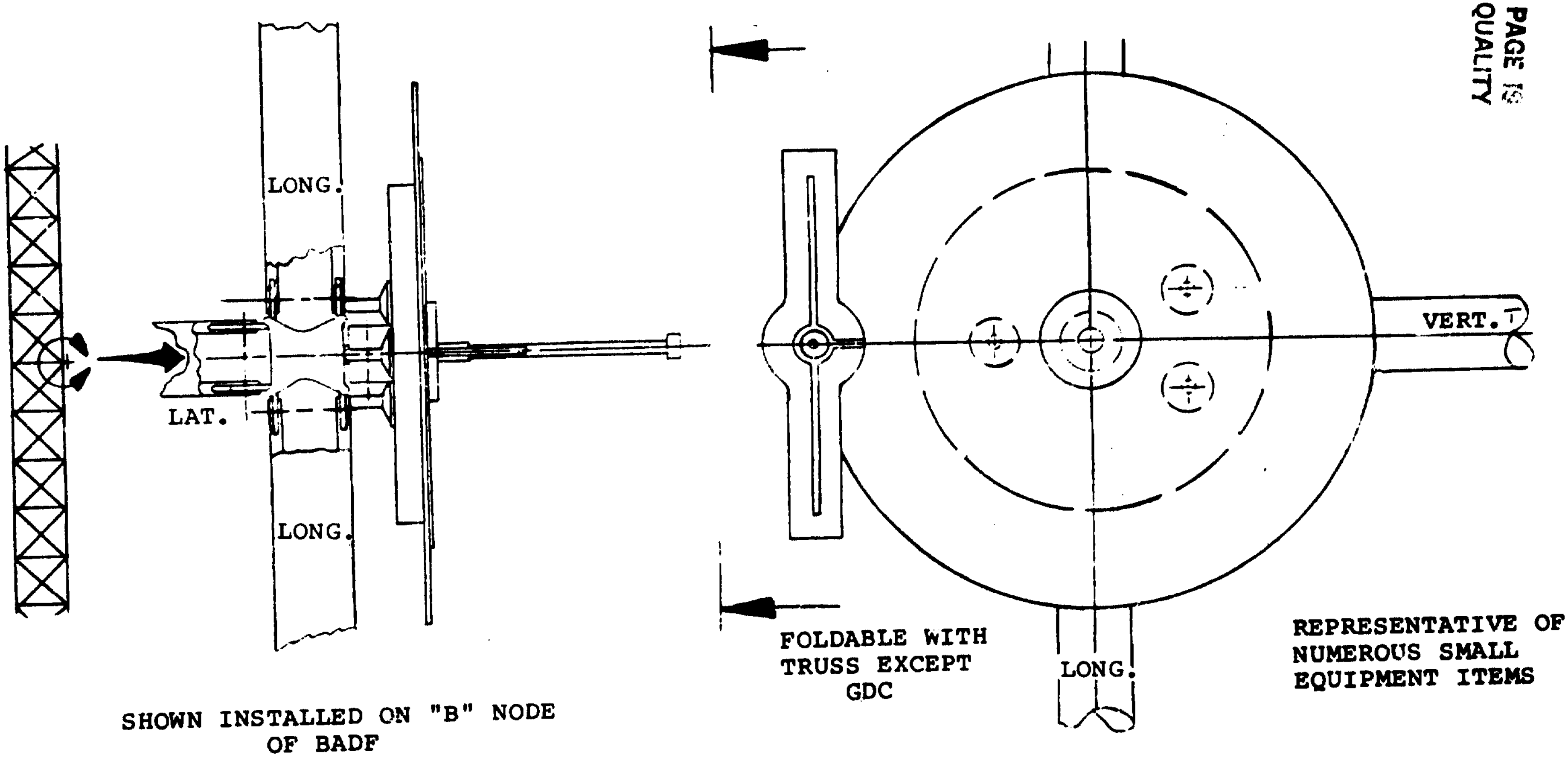

FIGURE 125 RMS STANDARD GRAPPLE FIXTURE INSTALLED AT NODE

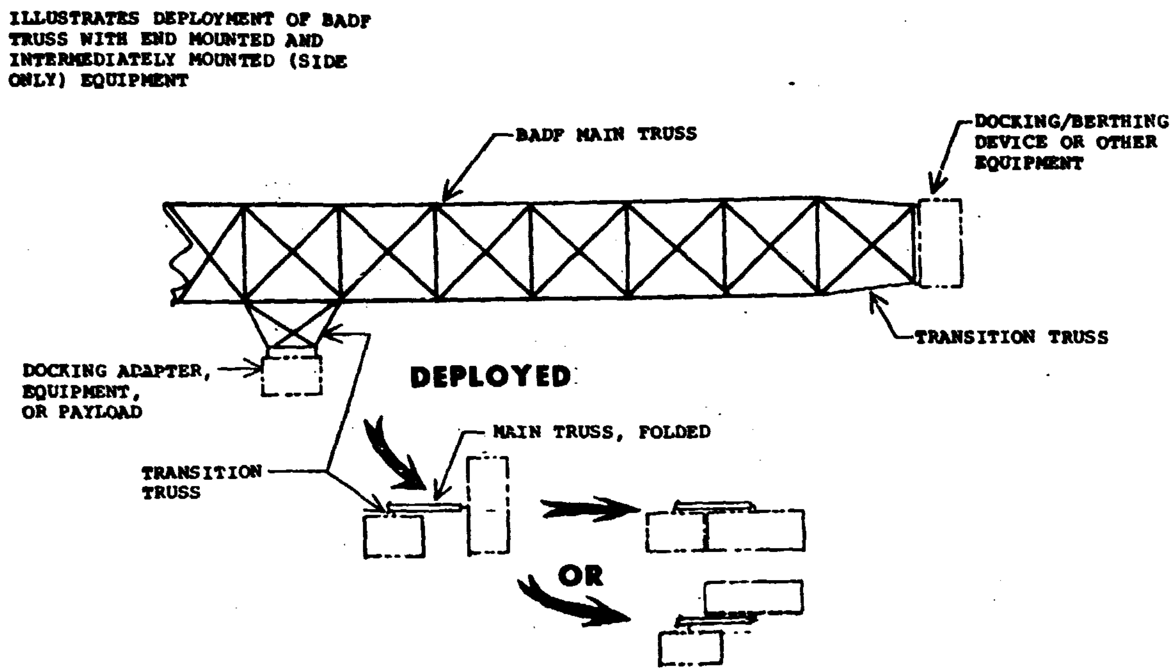

FIGURE 126 BADF SUBSYSTEM AND PAYLOAD INTERFACE

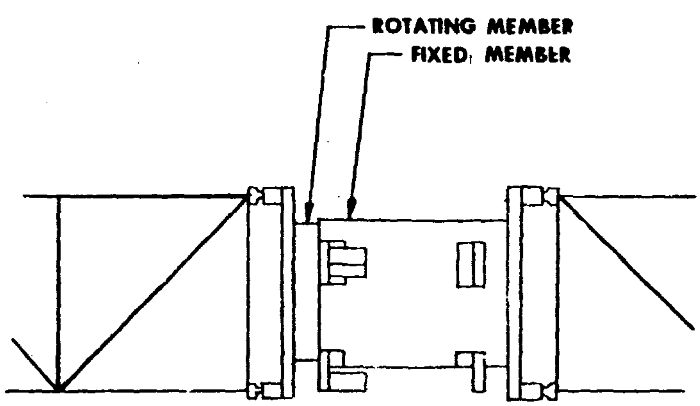

FIGURE 127 ROTATING JOINT INTERFACE

In conclusion, small equipment hardware items such as sensors and RMS probe can be attached at intermediate local points and deployed or stowed directly with the truss structure on all concepts except the GDC Diamond Beam. The Diamond Beam does not permit this because of the external deployment mechanism. Larger equipment and interface items such as a docking ring can be attached at intermediate points and deployed with the Biaxial Double Fold, the Martin Marietta Box Truss, or the Double Fold. It can be rigidly attached at two points in the stowed configuration and then engage one or more additional points as it is deployed. All the concepts provide the versatility for add-on equipment after deployment.

3.0 MATERIALS SELECTION IMPACTS

This part of the report discusses the effort performed under the task Materials Selection Impacts and includes consideration of materials selection issues, candidate materials and their properties, and other materials characteristics important in deployable truss design. Additional data is developed on the graphite/epoxy material selected for use in concept evaluation studies.

3.1 ISSUES

Some material selection issues such as basic structural material properties have a major impact on deployable platform designs to meet mission needs. Others, such as degradation characteristics, life and operational considerations also have a significant impact. Material selection issues, impacts, and solution approaches are identified in Table 17. It can be concluded from reviewing the table that density, stiffness and coefficient of thermal expansion of candidate materials are of particular importance for deployable space structure. Other properties shown to be important include strength, thermal conductivity, specific heat, space radiation effects, outgassing in vacuum, vibration damping characteristics, and cost.

3.2 CANDIDATE MATERIALS AND MECHANICAL PROPERTIES

The materials surveyed included lightweight metal alloys and high modulus continuous fiber reinforced organic and metal matrix composites. A listing of the materials surveyed and rationale for why they were selected or not selected for further study is given in Tables 18, 19 and 20. As shown in those tables, this list was reduced to four metal alloys, five fiber reinforced epoxy matrix composites, and three high modulus graphite fiber reinforced metal matrix composites. A summary showing typical significant properties for these selected materials is given in Tables 21 and 22. These materials fall in the three categories of metal alloys, fiber reinforced epoxy matrix composites and fiber reinforced metal matrix composites. The four metals shown in the list of Table 18 are typical of the metal alloys which are candidates either for low cost structures or for fittings used in conjunction with graphite/epoxy struts. In addition, the aluminum and magnesium alloys selected are presently being evaluated as a metal matrix material in a graphite fiber reinforced metal matrix composite. The organic matrix materials selected for evaluation are limited to the epoxy resins most commonly used in the Aerospace industry today. Polyimide and thermoplastic

TABLE 17 MATERIALS ISSUES

ISSUE	MATERIAL SELECTION IMPACTS	POTENTIAL SOLUTIONS/APPROACHES
Structural Performance	• Structural member size and min. gage limits • Truss dimensions and configuration • Secondary structure requirements • Damping of vibrations • Natural frequency • Packaging volume; weight • Bearing Loads	• High modulus graphite composites • Metal matrix composite fittings • Aluminum & magnesium tubing/fittings • Passive damping/Viscoelastic materials
Thermal Stability	• Out of plane platform distortion • Structural member bowing	• Tailored CTE composites • Thermal coatings • Insulations
CTE Mismatch (Composites end fittings)	• Structural integrity • Tailored CTE limitations • Thermal fatigue • Manufacturing Costs	• Invar or Titanium end fittings for graphite composites • Composite end fitting development • Transition sections
Radiation Effects	• Degradation of composites reduces strength • Degradation of coatings increases distortion and temperature cycles • Utilities insulation degradation	• Radiation resistant composites and coatings • Coating protection of composites • Shielding of utilities/insulation • Detection and replacement of degraded elements
Cost	• Primary structure and manufacturing costs • Launch costs • Maintenance and replacement costs	• Initial cost vs maintenance/replacement • Technology development for low cost • Simplified designs for manufacturing and operations
Life	• Structural material fatigue resistance • Space environment degradation	• Tailored CTE composites • Thermal coating • High endurance life materials/min microcracking
Contamination	• Payload and thermal control degradation • High voltage corona discharge	• Selection of space stable, low outgassing structural materials, coatings, lubricants

TABLE 18
SELECTION OF CANDIDATE STRUCTURAL MATERIALS - METAL ALLOYS

MATERIAL	SELECTION	RATIONALE
6061 AL	✓	• TYPICAL CHOICE LOW COST STRUCTURE & FITTINGS • PRESENT CANDIDATE IN METAL MATRIX
6 AL-4V TI	✓	• CANDIDATE TUBE ENDS, FITTINGS ON COMPOSITES • BETTER CTE MATCH THAN AL OR MG
AZ-31 MG	✓	• LOWEST DENSITY STRUCTURAL ALLOY • POSSIBLE USE LOW COST STRUCTURE & FITTINGS • PRESENT METAL MATRIX CANDIDATE
INVAR	✓	• LOWEST CTE STRUCTURAL METAL • MINIMIZES THERMAL DISTORTION • CANDIDATE FOR COMPOSITE TUBE FITTINGS • LIMITED BY LOW STIFFNESS/DENSITY RATIO

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TABLE 19

SELECTION OF CANDIDATE STRUCTURAL MATERIALS
ORGANIC MATRIX COMPOSITES

MATERIAL	SELECTION	RATIONALE
T-300/934 Gr/Ep	✓	. TYPICAL OF INTERMEDIATE MODULUS, LOW CTE, LOW COST
GY-70/X-30 & P-75/CE339 Gr/Ep	✓	. ULTRA HIGH MODULUS, LOW CTE, HIGH COST
P-50/Epoxy Gr/Ep	NO	. POOR COMPROMISE BETWEEN GY-70 MODULUS & T-300 COST
P-100/934 Gr/Ep	✓	. P-100 FIBER 30% STIFFER THAN GY-70 . FUTURE CANDIDATE AS PROCESSES ARE DEVELOPED
BORON/EPOXY	NO	. NO STIFFNERS ADVANTAGE; HIGHER COSTS; HIGHER CTE
KEVLAR/934	✓	. LOWEST DENSITY STRUCTURAL MATERIAL, LOW COST, LOW CTE . LIMITED BY RELATIVELY LOW MODULUS (COMPARABLE Al)
GRAPHITE/LaRC-160 BORON/LaRC-160 CERAMIC/LaRC-160 FIBER/POLYIMIDE	NO	. NO IMPROVEMENT OVER EPOXY IN CTE, STIFFNESS, DENSITY; HIGH COST . POTENTIAL HIGH TEMPERATURE USE
GRAPHITE/P-1700 BORON/P-1700 CERAMIC/P-1700 (POLYSULFONE & OTHER THERMOPLASTICS)	NO	. NO IMPROVEMENT OVER EPOXY IN CTE, STIFFNESS, DENSITY; HIGH COST

TABLE 20

SELECTION OF CANDIDATE METAL MATRIX COMPOSITES

MATERIAL	SELECTION	RATIONALE
P-100/6061 Gr/Al	✓	. CANDIDATE FOR FITTINGS: MODERATE CTE AND GOOD LOAD BEARING
P-100/Az-31 Gr/Mg	✓	. POTENTIALLY BEST COMBINATION OF PROPERTIES CANDIDATE FOR FITTINGS
BORON/METAL MATRIX	NO	. HIGHER CTE AND DENSITY THAN GRAPHITE FIBERS
SiC/M.M. Ceramic/M.M.	NO	. HIGHER CTE AND DENSITY THAN GRAPHITE FIBERS

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TABLE 21
TYPICAL PROPERTIES OF CANDIDATE METAL AND METAL MATRIX MATERIALS

MATERIAL	DENSITY Kg/m^3	0° TENSILE STRENGTH MPa	0° TENSILE MODULUS GPa	0° COMPRESSION STRENGTH MPa	0° COMPRESSION MODULUS GPa	SHEAR STRENGTH MPa	SHEAR MODULUS GPa	COEFF. OF Th. EXPANSION $M/M/°K \times 10^{-6}$ ISOTROPIC	COEFF. OF Th. EXPANSION $M/M/°K \times 10^{-6}$ UNDIRECTIONAL	MAX SERVICE TEMP °K
ALUMINUM ALLOY 6061-T6	2770	310	68	276	69	207	26	25	25	475
TITANIUM ALLOY 6Al-4V	4430	1100	110	N/A	113	N/A	43	8.6	8.6	800
MAGNESIUM ALLOY AZ-31B-H24	1770	220	44	180	44	158	16	26	26	435
INVAR Fe-36%Ni	8000	345	147	N/A	147	N/A	N/A	1.4	1.4	450
GRAPHITE/ALUMINUM P-100/Al, 30 F. V.	2464	482	207	482	207	48	27	11	4.5	N/A
GRAPHITE/MAGNESIUM P-100/Mg, 30 F.V.	1799	482	186	482	138	69	21	13	3.2	N/A
GRAPHITE/MAGNESIUM P-100/Mg, 43 F.V. (Future goals)	1882	572	317	N/A	N/A	28	17	9	.4	N/A

N/A - NOT AVAILABLE

TABLE 22
TYPICAL PROPERTIES OF CANDIDATE FIBER/ORGANIC MATRIX MATERIALS

MATERIAL	DENSITY Kg/m^3	0° TENSILE STRENGTH MPa	0° TENSILE MODULUS GPa	0° COMPRESSION STRENGTH MPa	0° COMPRESSION MODULUS GPa	SHEAR STRENGTH MPa	SHEAR MODULUS GPa	COEFF. OF Th. EXPANSION $M/M/°K \times 10^{-6}$ ISOTROPIC	COEFF. OF Th. EXPANSION $M/M/°K \times 10^{-6}$ UNDIRECTIONAL	MAX SERVICE TEMP °K
GRAPHITE/EPOXY T-300/934 60 FIBER VOLUME	1605	1440	132	1502	145	57	3.7	3.1	-.05	390
GRAPHITE/EPOXY GY-70/X-30 60 FIBER VOLUME	1772	792	330	792	330	N/A	5.0	.04	-.87	350
GRAPHITE/EPOXY P-100/934 60 FIBER VOLUME	1772	792	413	792	413	N/A	6.9	.04	-.9	390
GRAPHITE/EPOXY P-755/339 60 FIBER VOLUME	1774	N/A	316	N/A	206	N/A	3.6	.9	-.8	350
KEVLAR/EPOXY K-49/934 60 FIBER VOLUME	1356	1440	74	263	72	N/A	1.8	[illegible].4	0	390

N/A - NOT AVAILABLE

resins for matrix materials are more expensive, much more difficult to process, and offer no advantages in materials properties for the temperature range of interest in this study. As indicated in Table 20 the metal matrix composites selected for study are limited to graphite fiber reinforcement because boron and inorganic fibers offer no advantage in density, stiffness or cost for space structure applications. In addition, telephone conversations with personnel at NASA-LaRC and NASA-MSFC indicate that their efforts will be directed primarily toward development of aluminum and magnesium matrix composites reinforced with ultra high modulus graphite fibers.

3.3 OTHER MATERIALS CHARACTERISTICS

The effects of space radiation on composite materials are important. Tests on graphite/epoxy GY70/X904 at GDC (Ref. 23) for 756 hours with vacuum and four equivalent suns ultraviolet plus 10 minutes of a radiation with 1 MeV electrons/protrons indicate no loss in strength of the composite. Personal communication with NASA-LaRC personnel (Ref. 24) indicates that all graphite/epoxy composites cured at 177°C (350°F) or greater are stable under combined space environments. A comparison of test data to the accumulated 10 year protron and electron dose calculated for the SASP mission indicates that GY70/X934 graphite/epoxy is not degraded (Ref. 6). Another important characteristic of a material is its outgassing. Table 23 lists the outgassing characteristics of some of the materials important to large structures taken from Reference 25. The outgassing range is acceptable compared to NASA document SP-2-0022A (Sept. 1974) on outgassing limits, which are 1% Total Mass Loss (TML) and 0.1% Collected Volatile Condensible Material (CVCM). Figure 128 presents information on the damping characteristics of materials, taken from References 25 and 26. It shows that the damping loss factor for graphite/epoxy is approximately 2 orders of magnitude greater than metals. Other characteristics of matrix and reinforcing fiber materials for composites are listed in Tables 24 and 25, giving key characteristics and also listing competing materials to those listed as typical materials.

3.4 SELECTED MATERIALS

Tables 26 and 27 provide recommendations for selection of metals and composite materials for further use in the current study. The particular materials or composites listed are subject to consideration of substitution of the competing materials listed in Tables 24 and 25. For the remaining structural and trade studies of Part 1 a graphite/epoxy typical of GY70/X30

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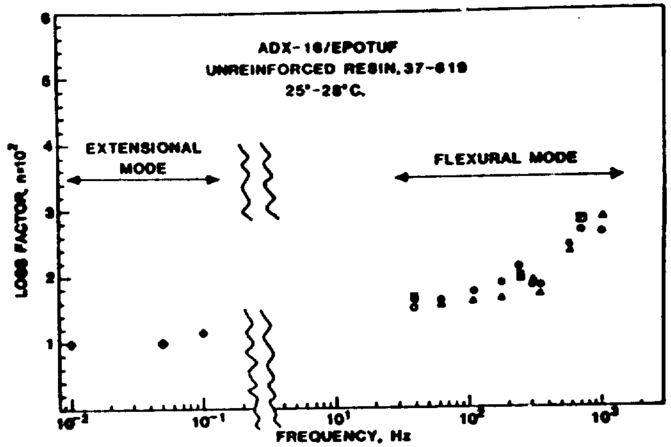
TABLE 23

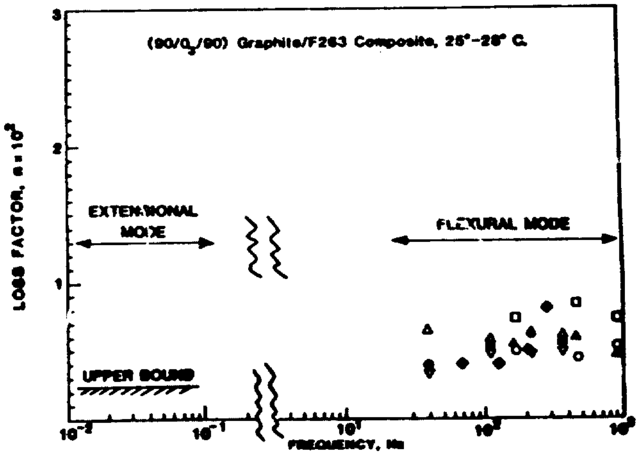
OUTGASSING CHARACTERISTICS OF SELECTED MATERIALS

Material	% TML	% CVCM
Adhesives:		
EA 9309 Epoxy	2.18	0.00
EA 934 Epoxy	0.49	0.01
EA 956 Epoxy	0.69	0.02
SR 529 Silicone	2.48	0.75
RTV 630 Silicone	1.30	0.81
Composites:		
Convair Graphite/Epoxy	0.63	0.03
Hercules 2002M Graphite Fiber Reinforced Polymer	0.48	0.01
GY 70/X-30 Graphite Epoxy	0.46	0.01
GY 70/5208 Graphite Epoxy	0.53	0.01
GY 70/5209 Graphite Epoxy	0.40	0.01
P1700 Polysulfone	0.09	0.02
Goodyear Graphite Fiber Epoxy Composite/FM 100	0.82	0.15
Elastomers and dampers:		
3M 467 Visoelastic Film	3.46	0.50
Rigidamp Silicone	2.01	0.04
BTR Rubber Vibration Isolator HT2-100	1.34	0.45
BTR Rubber HD222-22-2	1.39	0.13
BTR Rubber HD222-22-2 in Aluminum Sandwich	0.28	0.01

Material	Loss Factor
S glass/epoxy, unidirectional plies, 0°	0.003-0.008
Fiberglass/epoxy, undirectional plies, 90°	0.017-0.023
Graphite (Type 1)/epoxy, unidirectional plies, 0°	0.006
Graphite (Type 2)/epoxy, unidirectional plies, 0°	0.007
Graphite (Type 2)/epoxy, unidirectional plies, 90°	0.014
Boron aluminum	
Polyurethane elastomer	0.036
Nitrile rubber	0.22
Epoxy resin	
Aluminum	0.0001
Steel	0.0001-0.0006
Magnesium	0.0001

REF: MCDONNELL DOUGLAS, AIAA PAPER 80-0677





REF: UNIVERSITY IDAHO, 1981 LSST CONFERENCE

FIGURE 128 DAMPING CHARACTERISTICS OF SOME SELECTED MATERIALS

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TABLE 24

CHARACTERISTICS OF MATRIX MATERIALS
FOR FIBER REINFORCED COMPOSITES

MATERIAL	CHARACTERISTICS	COMPETING MATERIAL
FIBERITE 934 EPOXY (ORGANIC MATRIX)	450°K CURING THERMOSET EPOXY RESIN 395°K MAX SERVICE TEMPERATURE (MOISTURE EFFECTS LIMITS MAX. TEMP.) LOW DENSITY (1150 Kg/M^3) EASY TO CURE BY AUTOCLAVE PROCESSING TYPICAL OF MOST WIDELY USED ORGANIC MATRIX LOW COST (<$11/Kg)	NARMCO 5208 HERCULES 3501-6, 3502 FIBERITE 976 HEXEL F-263 AMERICAN CYANAMID 907
FIBERITE X-30 EPOXY (ORGANIC MATRIX)	395°K CURING THERMOSET EPOXY RESIN 355°K MAX SERVICE TEMPERATURE (MOISTURE EFFECTS LIMITS MAX. TEMP.) LOW DENSITY (1150 Kg/M^3) EASY TO CURE BY AUTOCLAVE PROCESSING NOT WIDELY USED FOR AEROSPACE COMPOSITES BECAUSE OF LOW MAX. SERVICE TEMPERATURE LIMIT LOW COST (<$11/Kg)	NARMCO 5209, 5213 HEXCEL F-155 FIBERITE 530, 948 FERRO CE 339
UNION CARBIDE P-1700 POLYSULFONE (ORGANIC MATRIX)	HEAT FORMABLE THERMOPLASTIC RESIN LOW DENSITY (1200 Kg/M3) 500 TO 580°K FORMING AND COMPACTION TEMPERATURE DIFFICULT TO FORM TO COMPLEX CONTOUR WITH CONTINUOUS REINFORCING FIBER EASY TO FORM OR INJECTION MOLD WITH CHOPPED REINFORCING FIBER NOT WIDELY USED FOR AEROSPACE COMPOSITES HIGH COST IN FORM OF CONTINUOUS FIBER REINFORCED SHEET (~$200/Kg)	POLYARYLSULFONE POLYPHENYLSULFONE
LARC-160 POLYIMIDE	590°K CURING ADDITION TYPE POLYIMIDE 503°K MAX. SERVICE TEMPERATURE LOW DENSITY (1430 Kg/M^3) DIFFICULT TO FABRICATE BECAUSE OF HIGH CURE TEMPERATURE AND PRESSURE REQUIREMENTS NO ADVANTAGE OVER EPOXIES EXCEPT IN HIGH TEMPERATURE APPLICATIONS	PMR-15
ALUMINUM ALLOYS (METAL MATRIX)	LAMINATES FORMED BY DIFFUSION BONDING (~ 800°K) MODERATE DENSITY (2770 Kg/M^3) DIFFICULT TO FORM TO COMPLEX CONTOURS WITH CONTINUOUS REINFORCING FIBER STILL IN EXPERIMENTAL STAGE OF DEVELOPMENT HIGH COST IN FORM OF CONTINUOUS FIBER REINFORCED SHEET (~$1100/Kg)	MAGNESIUM, EXCEPT FOR LOW DENSITY (1770 Kg/M^3) TITANIUM, EXCEPT FOR HIGH DENSITY (4430 Kg/M^3)

TABLE 25 REINFORCING FIBER MATERIALS

MATERIAL	KEY CHARACTERISTICS	COMPETING MATERIALS WITH SIMILAR CHARACTERISTICS
UNION CARBIDE T-300 GRAPHITE FIBER	. INTERMEDIATE MODULUS (234 GPa) . LOW CTE (-.05 μm/m/°K) . LOW FIBER DENSITY (1760 Kg/m^3) . GOOD DATA BASE-MOST WIDELY USED FIBER . LOW COST FIBER (~$66/KG)	HERCULES AS, AS-4 FIBERS CELANESE CELION FIBER HITCO HITEX FIBER
UNION CARBIDE P-50 GRAPHITE FIBER	. HIGH MODULUS (344 GPa) . NEGATIVE CTE (-.07 μm/m/°K) . LOW DENSITY (2100 KG/m^3) . MODERATE COST (~$220/KG)	CELANESE GY-50 FIBER HERCULES HMs FIBER
CELANESE GY-70	. HIGHEST MODULUS OF COMMERCIALLY AVAILABLE FIBERS (481 GPa) . NEGATIVE CTE (-1.1 μm/m/°K) . LOW DENSITY (2200 KG/m^3) . VERY HIGH COST (~$1100-$1600/kg)	UNION CARBIDE P-75
UNION CARBIDE P-100	. ULTRA HIGH MODULUS (689 GPa) . MOST NEGATIVE CTE (-1.4 μm/m/°K) . LOW DENSITY (2200 KG/m^3) . PILOT PLANT QUANTITIES AVAILABLE USED IN METAL MATRIX EVALUATIONS . VERY HIGH COST (~$1600/KG)	NONE
AVCO BORON FIBER	. HIGH MODULUS (350GPa) . MODERATE CTE (7 μm/m/°K) . LOW DENSITY (2550 KG/m^3) . MOST WIDELY EVALUATED REINFORCEMENT FOR METAL MATRIX . HIGH COST (~ $440/KG)	NONE
3M CO. NEXTEL 312 CERAMIC FIBER	. INTERMEDIATE MODULUS (152 GPa) . MODERATE CTE (6.3 μm/m/°K) . MODERATE DENSITY (2700 KG/m^3) . NO DATA AVAILABLE AS COMPOSITE REINFORCEMENT . MODERATE COST (~ $220/KG)	NONE
AVCO SILICON CARBODE FIBERS	. HIGH MODULUS (~420 GPa) . MODERATE CTE (4.3 μm/m/°K) . MODERATE DENSITY (3500 KG/m^3) . EXPERIMENTAL FIBER USED IN METAL MATRIX . HIGH COST (~$880/KG)	NONE
DUPONT KEVLAR 49	. LOW MODULUS (124 GPa) . LOW CTE (0.0 μm/m/°K) . LOWEST DENSITY OF ALL REINFORCING FIBERS (1380 KG/m^3) . READILY AVAILABLE WITH GOOD DATA BASE . LOW COST (~$40/KG)	NONE

TABLE 26 RECOMMENDATIONS FOR SELECTION OF METAL ALLOYS

MATERIAL	APPLICATION	TECHNOLOGY PERIOD	RATIONALE AND COMMENT
ALUMINUM ALLOYS	STRUTS AND FITTINGS	CURRENT & ADVANCED	LOWEST COST WHEN WEIGHT AND THERMAL DISTORTION AND CTE MISMATCH WITH STRUT ARE NOT MAJOR CONSIDERATIONS.
MAGNESIUM ALLOYS	STRUTS AND FITTINGS	CURRENT & ADVANCED	LOW COST AND WEIGHT WHEN THERMAL DISTORTION, CTE MISMATCH WITH STRUT, AND CORROSION ARE NOT MAJOR CONSIDERATIONS
TITANIUM ALLOYS	STRUT ENDS AND FITTINGS	CURRENT & ADVANCED	COMPATIBLE WITH GRAPHITE/EPOXY FOR CORROSION AND IMPROVED CTE MATCH. MODERATE COST AND GOOD COMBINATION OF PROPERTIES. SUITABLE WHERE WEIGHT IS NOT A MAJOR CONSIDERATION.
INVAR	FITTINGS	CURRENT	MAY BE REQUIRED FOR LOW THERMAL DISTORTION WHEN WEIGHT IS NOT A MAJOR CONSIDERATION OR CTE MISMATCH WITH STRUT IS PROBLEM.

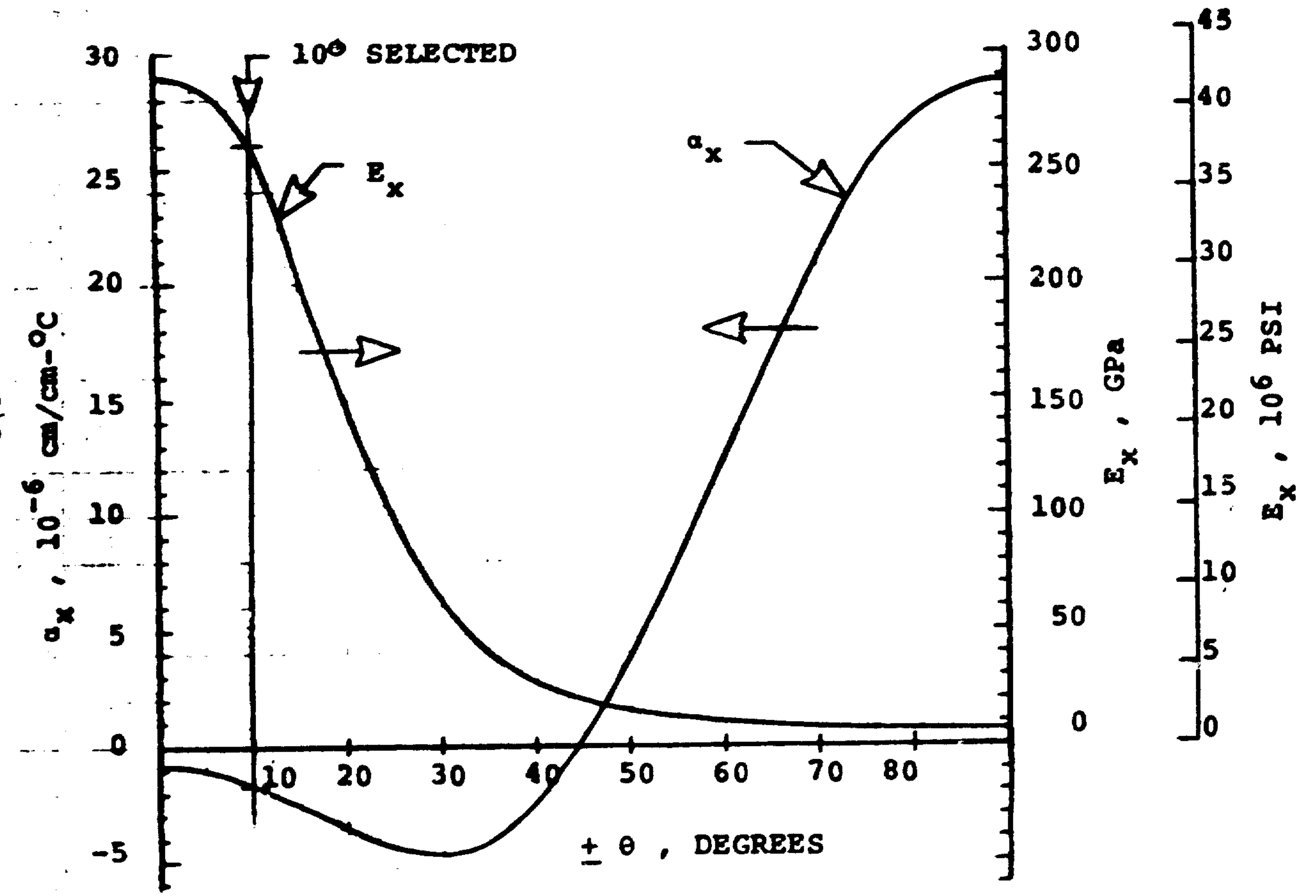
TABLE 27 RECOMMENDATIONS FOR SELECTION OF COMPOSITE MATERIALS

MATERIAL	APPLICATION	TECHNOLOGY PERIOD	RATIONALE AND COMMENT
GRAPHITE/EPOXY T-300/934	STRUTS AND FITTINGS	CURRENT	BEST AVAILABLE COMBINATION OF MATERIAL PROPERTIES AND COST. MODERATE BEARING LOADS.
KEVLAR/EPOXY K-49/934	TENSION MEMBERS	CURRENT & ADVANCED	LOW COST WITH LIGHTEST WEIGHT FOR MINIMUM GAGE TENSION APPLICATIONS
GRAPHITE/EPOXY GY-70/X-30 P-100/934	STRUTS AND FITTINGS	CURRENT & ADVANCED	BEST COMBINATION OF MATERIAL PROPERTIES IF HIGH FIBER COST IS JUSTIFIED OR REDUCED. MODERATE BEARING LOADS.
GRAPHITE/ALUMINUM P-100/Al	STRUTS AND FITTINGS	ADVANCED	GOOD COMBINATION OF MATERIAL PROPERTIES. SUITABLE IF MATERIAL AND FABRICATION COSTS ARE REDUCED AND WEIGHT AND MODERATE THERMAL DISTORTIONS ARE NOT MAJOR CONSIDERATIONS.
GRAPHITE/MAGNESIUM P-100/Mg	STRUTS AND FITTINGS	ADVANCED	GOOD COMBINATION OF MATERIAL PROPERTIES. SUITABLE IF MATERIAL AND FABRICATION COSTS ARE REDUCED AND MODERATE THERMAL DISTORTION IS NOT A MAJOR CONSIDERATION.

(or GY70/X934 which has a slightly higher use temperature of about 120°C) was selected as the basic structural material. Using a Vought computer routine the properties of the minimum gage of the graphite/epoxy was calculated. The results are shown in Figure 129. A balanced symmetric four ply laminate representative of those composites was evaluated. A ± 10° ply orientation at $+\theta/-\theta/-\theta/+\theta$ was selected for use in studies. For handleability considerations, an angle ply laminate is more desirable than a unidirectional laminate for the gages being considered. A ± 10° laminate yields a high longitudinal stiffness and a low expansion coefficient. And finally a ± 10° strut may be easily fabricated. For applications requiring a thicker gage it would be possible to design a multi-ply laminate with more optimum CTE and modulus characteristics.

An estimate of the load bearing capabilities of composite node fittings or pivots was made based on prior Vought experience and literature data. A value of 275 MPa (40,000 psi) was selected for GY70/X30 with a provision that the joint is thickened with ± 45° plies until at least 40% of the resulting total bearing plies are at ± 45°. From Reference 27, the ultimate compressive strength of GY70/X30 increases from 26 MPa (3800 psi) at -180°K to 195 MPa (28,300 psi) at +120°K for a quasi-isotropic layup $(0/45/90/135)_{2s}$. In Reference 28 an assessment of compressive bearing strength is given for 3 graphite/epoxys. The ratio of bearing strength to compressive strength for T300/5208 tape, AS3501 tape, HMS330C/34 fabric ranges from 2.12 to 2.39. If this data can be extended the quasi-isotropic GY70/X30, its bearing strength would be upwards of 400 MPa (58,000 psi). Thus the estimated 275 MPa allowable should be conservative.

BALANCED SYMMETRIC FOUR PLY LAMINATE REPRESENTATIVE OF GY70/X30 OR GY70/934



AT ± 10°

E_x = 260 GPa (37.7x10^6 PSI)

E_y = 6.8 GPa (0.99x10^6 PSI)

G_{xy} = 13.1 GPa (1.90x10^6 PSI)

α_x = -1.7x10^{-6} cm/cm-°C (-0.93x10^{-6} in/in-°F)

F_{cu} = 330 MPa (48,350 PSI)

F_{tu} = 620 MPa (90,500 PSI)

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FIGURE 129 CALCULATED PROPERTIES OF MINIMUM GAGE HIGH MODULUS GRAPHITE/EPOXY

4.0 SPECIAL TECHNOLOGY NEEDS

As a result of our concept development and trade studies six technology development items have been identified which would benefit the deployable truss configurations. The problem statement and the technology development needed for each of the items identified are shown in Figures 130 through 135. A candidate solution is also illustrated (where a concept has been generated), and an approximate estimate of the technology development schedule, milestones, and cost required to implement are given.

A compact, no leak fluid connector was identified as a technology development item to support the interface concepts. The design quick disconnect concept shown in Figure 130 is an evolution of an existing prototype design (Ref. 29) to provide more compact packaging and reduced pressure drop. As indicated in Figure 131, the development of low coefficient of thermal expansion strut members based on two possible solutions: 1) development of very low CTE tapes or possibly very thin tapes to permit more control during the layup process; and 2) development of node fitting design and manufacturing methods to permit better control of node properties. In addition to this there is a basic need to develop the node and strut components to flight qualification status.

Any concept involving integration of electrical cables into the struts will benefit by reducing the stiffness of the cables. Figure 132 gives a plan for developing high flexibility cables. Since much of the stiffness is in the insulator, the utilization of new insulation materials could improve the bending moments. One new material which has been examined during the current study is an expanded Teflon (Ref. 30), which appears to greatly reduce the stiffness of cables. This material, as well as other candidates should be investigated, as should high ductility long endurance life copper conductor materials (or possibly other conductor materials), to further reduce bend moments and to increase life of the electrical cables. As indicated in Figure 133 the benefits of increasing the flexibilty of fluid hoses would be similar to those of increasing the flexibility of cables. This design life for small bend radius multiple flexures is another area of investigation and improvement that is needed.

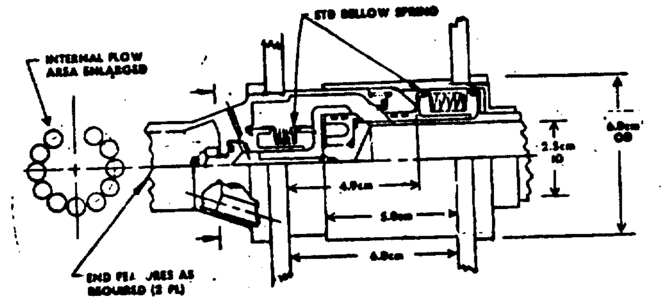
Efficient fiber optics tees would enhance the utility design by reducing the penalty to the system for branching and thus allowing the large

PROBLEM : EXISTING PROTOTYPE CONNECTOR DESIGNS ARE TOO LARGE, AND HAVE EXCESSIVE PRESSURE DROP FOR DEPLOYABLE PLATFORM NEEDS

TECHNOLOGY NEEDED : REDUCED LENGTH, ZERO LEAK, LOW PRESSURE DROP CONNECTOR

- RESULTS IN SMALLER, LOWER WEIGHT INTERFACE

CANDIDATE SOLUTION :: SHORTEN DESIGN AND OPEN UP FLOW PASSAGES. VOUGHT EVOLUTION OF NASA/FAIRCHILD CONCEPT FOR 2.54 cm LINE SHOWN.



TECHNOLOGY SCHEDULE :

YEARS FROM START

1 | 2 | 3

DESIGN COMPLETE

TEST COMPONENT FABRICATION COMPL

TESTING COMPLETE

SECOND DESIGN RECD

DOCUMENTATION

FINAL TESTING COMPLETE

ESTIMATED COSTS : $200K - $250K (1982-$)

FIGURE 130 SPECIAL TECHNOLOGY ITEM: SMALL, NO LEAK, LOW PRESSURE DROP FLUID CONNECTOR

PROBLEM : (1) OBTAINING VERY LOW COEFFICIENT OF THERMAL EXPANSION (CTE) FOR STRUTS WHILE MAINTAINING GAUGE THICKNESS IS DIFFICULT BECAUSE OF MINIMUM TAPE THICKNESS LIMITATIONS.

(2) THE HIGH CTE FOR CURRENT NODE FITTING DESIGN APPROACHES (BOTH METAL AND GRAPHITE EPOXY) CAUSE POTENTIALLY SIGNIFICANT DISTORTION IN STRUCTURE EVEN IF STRUTS HAVE ZERO CTE.

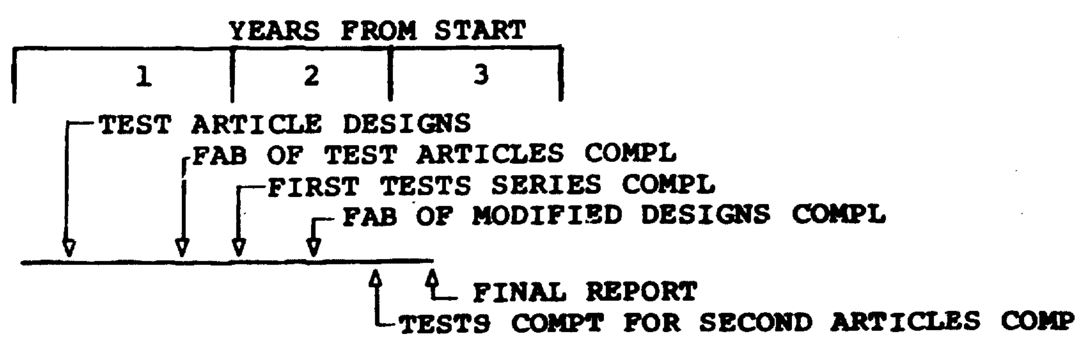
TECHNOLOGY NEED : (1) DEVELOP TECHNOLOGY FOR LOW CTE AT MINIMUM GAUGE THICKNESS.

(2) DEVELOP THE TECHNOLOGY AND DESIGN APPROACHES FOR LOW CTE NODE FITTINGS.

CANDIDATE SOLUTION : (1) DEVELOP MANUFACTURING TECHNIQUES FOR THINNER GRAPHITE EPOXY TAPE OR LOW CTE SINGLE LAYERS.

(2) DEVELOP GRAPHITE EPOXY NODE FITTING DESIGN AND MANUFACTURING METHODS TO PERMIT CONTROL OF NODE PROPERTIES.

TECHNOLOGY SCHEDULE :



ESTIMATED COST : $1300K (1982-$)

FIGURE 131 SPECIAL TECHNOLOGY ITEM: LOW CTE STRUT AND NODE MEMBERS

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PROBLEM : CURRENTLY AVAILABLE WIRE BUNDLES REQUIRE HIGH BENDING MOMENTS FOR SMALL BEND RADII.

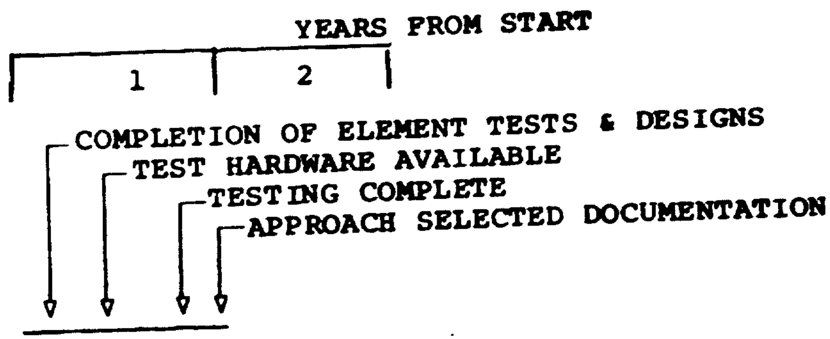
TECHNOLOGY NEED : HIGHLY FLEXIBLE ELECTRICAL CABLE WITH HIGH CYCLE LIFE

- REDUCE DEPLOYMENT AND FOLDING ENERGY
- REDUCE PLATFORM WEIGHT AND DESIGN COMPLEXITY
- INCREASE CYCLE LIFE

CANDIDATE SOLUTION : (1) HIGHLY FLEXIBLE INSULATOR DESIGN AND MATERIALS INCLUDING EXPANDED TEFLON AND NON-METALLIC BELLOWS

(2) ADVANCED CONDUCTOR MATERIAL INCLUDING HIGH ENDURANCE LIFE, HIGH DUCTILITY COPPER-SILVER ALLOYS

TECHNOLOGY SCHEDULE :



ESTIMATED COSTS : $150K (1982-$)

FIGURE 132 SPECIAL TECHNOLOGY ITEM: HIGH FLEXIBILITY ELECTRICAL CABLES

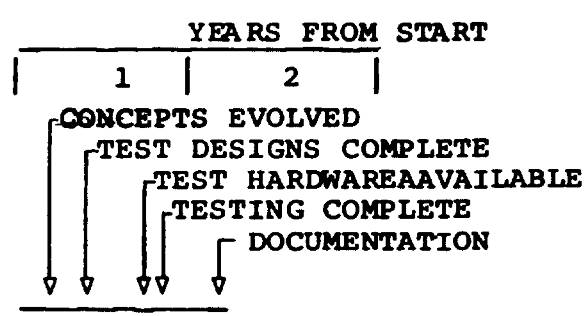
PROBLEM : CURRENTLY AVAILABLE FLEXIBLE METAL HOSES ARE VERY STIFF AND ACTUALLY YIELD FOR SMALL BEND RADII OF INTEREST IN DEPLOYABLE PLATFORM

TECHNOLOGY NEED : HIGHLY FLEXIBLE FLUID HOSE WITH HIGH CYCLE LIFE

- REDUCED DEPLOYMENT AND FOLDING ENERGY
- REDUCED PLATFORM WEIGHT AND DESIGN COMPLEXITY
- INCREASED CYCLE LIFE

CANDIDATE SOLUTION : EVOLVE DESIGN CONCEPTS WHICH REDUCE BENDING LOADS AND WITH NEGLIGIBLE YIELDING. CONSIDER BOTH ADVANCED METAL CONVOLUTE DESIGNS AND METAL/PLASTIC COMPOSITES.

TECHNOLOGY SCHEDULE :



ESTIMATED COST : $300K (1982-$)

FIGURE 133 SPECIAL TECHNOLOGY ITEM: SUPER FLEXIBLE FLUID HOSE

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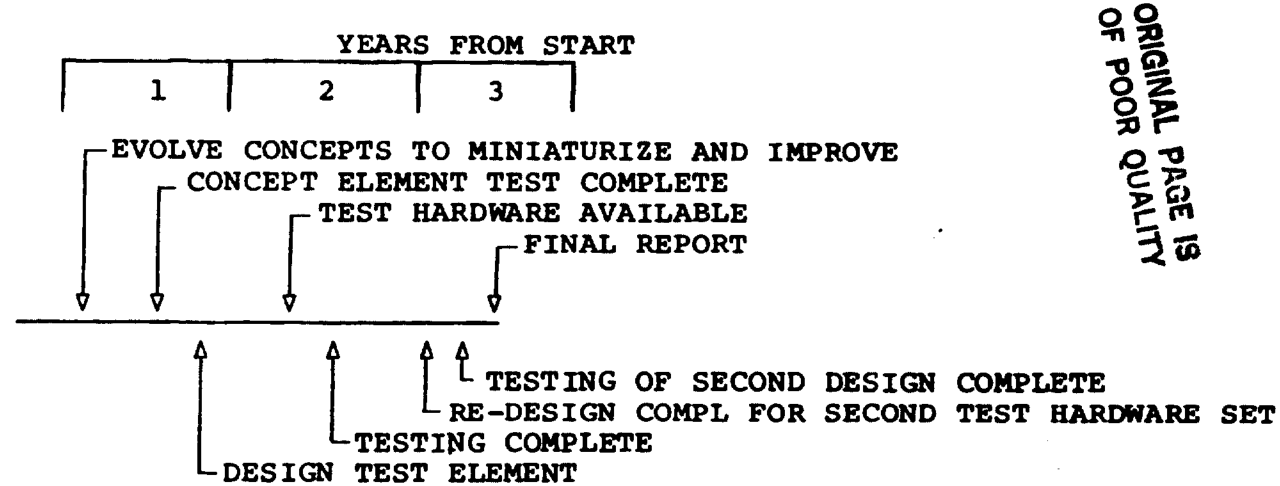
structure to more effectively accommodate utilities branching requirements. The program outlined in Figure 134 is aimed in this direction. The problem of thermal distortions in large structures is magnified by the orbital variation of temperature. This can be controlled to some extent by controlling properties of the thermal coating. In Figure 135 a low solar absorptance and emittance thermal coating is listed as a technology development objective. Also listed are some concepts which should be considered, and which would likely be required as integral considerations in developing the graphite/epoxy substrates. The program outlined is modest and would be contingent on early identification of techniques with good promise.

PROBLEM : CURRENT COMPACT FIBER OPTICS TEE DESIGNS HAVE LOW TRANSMISSION CHARACTERISTICS AND LIMIT BRANCHING IN DEPLOYABLE PLATFORMS

TECHNOLOGY NEED : DEVELOP MORE COMPACT AND EFFICIENT FIBER OPTICS TEES

CANDIDATE SOLUTIONS : EVOLVE METHODS TO MINIATURIZE LARGE TEE CONCEPTS WHICH CURRENTLY HAVE LOW LOSSES

TECHNOLOGY SCHEDULE :



ESTIMATED COST : $525K (1982-$)

FIGURE 134 SPECIAL TECHNOLOGY ITEM: EFFICIENT FIBER OPTICS TEES

PROBLEM : VARIATION IN SOLAR HEAT INPUT IN ORBIT CAN CAUSE WIDE TEMPERATURE SWINGS IN THE TEMPERATURE OF SOME STRUCTURAL ELEMENTS, CAUSING POTENTIAL STRUCTURAL DISTORTION PROBLEMS.

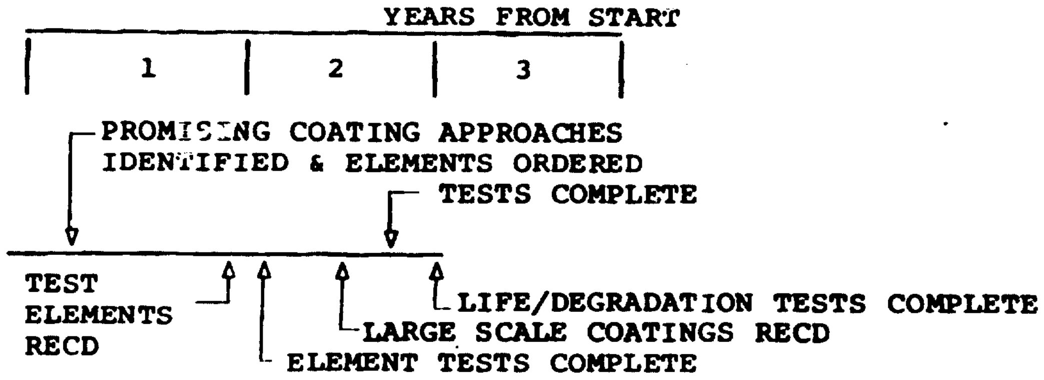
TECHNOLOGY NEED : A THERMAL COATING WITH $\epsilon^* < 0.1$ AND $\alpha/\epsilon^* < 1.0$ WHICH IS STABLE IN SPACE FOR LONG PERIODS OF TIME (10 YEAR TYPICAL)

CANDIDATE SOLUTIONS :

(a) TAPES HAVING VAPOR DEPOISTED METAL FILM WITH SILICON MONOXIDE OVERCOAT

(b) DIRECT DEPOSIT OF METAL FILM PLUS INORGANIC OR SUPER THIN ORGANIC OVERCOAT

TECHNOLOGY SCHEDULE :



ESTIMATED COSTS : $350K (1982-$)

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* ϵ = EMISSIVITY
α = SOLAR ABSORPTION

FIGURE 135 SPECIAL TECHNOLOGY ITEM - LOW ABSORPTION/EMITTANCE THERMAL COATING

5.0 CONCEPT SELECTION

This part of the report describes the evaluation, trade and selection of concepts developed and described in Section 2.0. Four topics are discussed. First, the configuration variability of the four structural concepts is described to assess their usefulness for future versatile space missions. Second, a set of cost trades is presented which examines differences in costs of the concepts including development and fabrication, as well as the launch costs. Third, a detailed evaluation of the trade matrix using the information developed in the previous sections of the report is presented. Finally, weighting factors are applied and a selection is made.

5.1 EVALUATION OF CONFIGURATION VARIABILITY

All four candidate trusses were evaluated for truss-to-truss joining for beam extension and branching butt joints, and lap joint interfaces. Figures 136 thru 140 illustrate the arrangements examined. These joints were evaluated at both square and oblique intersecting angles. Node-to-node couplers such as the Side Latching or Autolock Coupler (Ref. 7) were assumed.

Results with the Biaxial Double Fold show this truss lends itself to all angles of butt joining and does not require a separate transition cell. The transition members may be folded and deployed directly on the branch truss even if the connection is oblique. This can be accomplished whether the branch truss is of equal size, smaller or larger than the main truss. Figures 136, 137, 138, and 139 illustrate the Biaxial Double Fold butt joints and transition structure. The utilities routing at the butt joint is also indicated. Lap joints were also evaluated and determined to be feasible for a 90° intersection as indicated in Figure 140. Utilities would be routed in a way similar to that for the butt joints. For an oblique lap joint intersection a separately folded standoff transition cell would be required, which is undesirable. A butt joint would be preferrable both for packaging/assembly and for better structural efficiency.

Evaluation of the Double Fold concept shows that square and straight extension joints may be accomplished. For an oblique joint a separate foldable cell is required since the transition cell will not double fold. It is possible with the Martin Marietta Box Truss to biaxially fold the transition cell together with the truss if it is also biaxially folded. With the GDC Diamond Beam, square and straight extension joints may be achieved by the addition of an integral foldable structure. Oblique joints will require

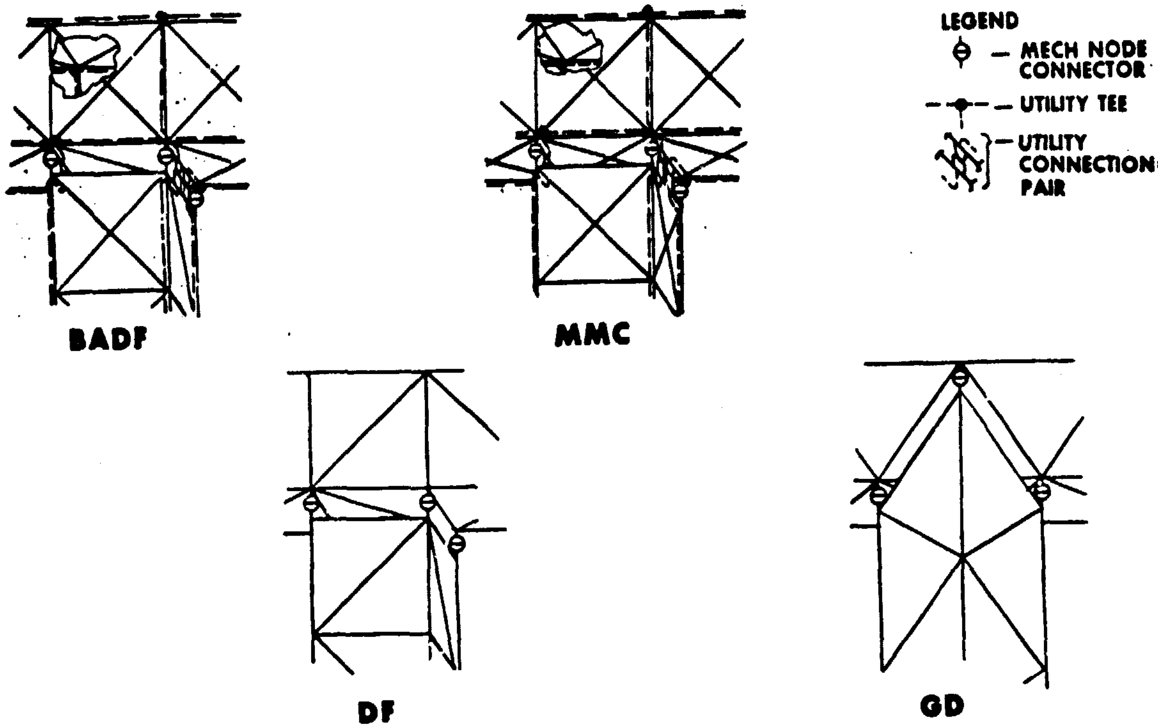

FIGURE 136 TRUSS SQUARE BUTT JOINTS

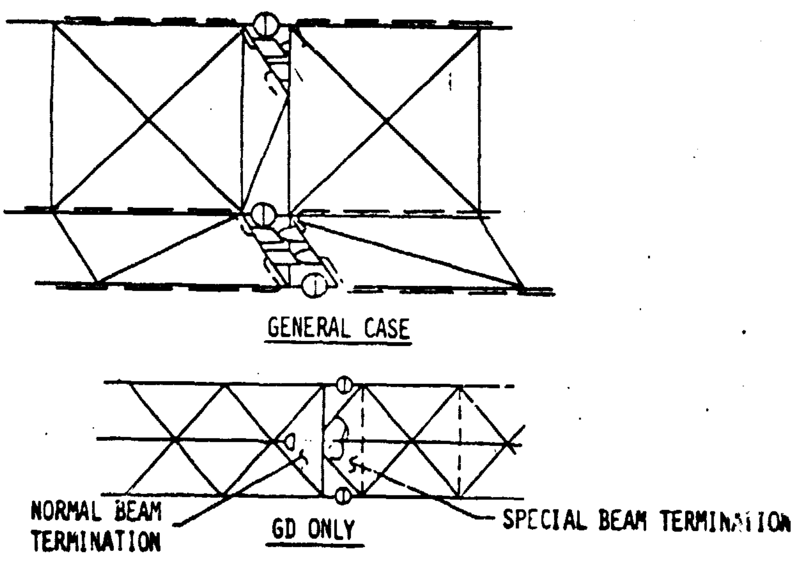

FIGURE 137 EXTENSION BUTT JOINT

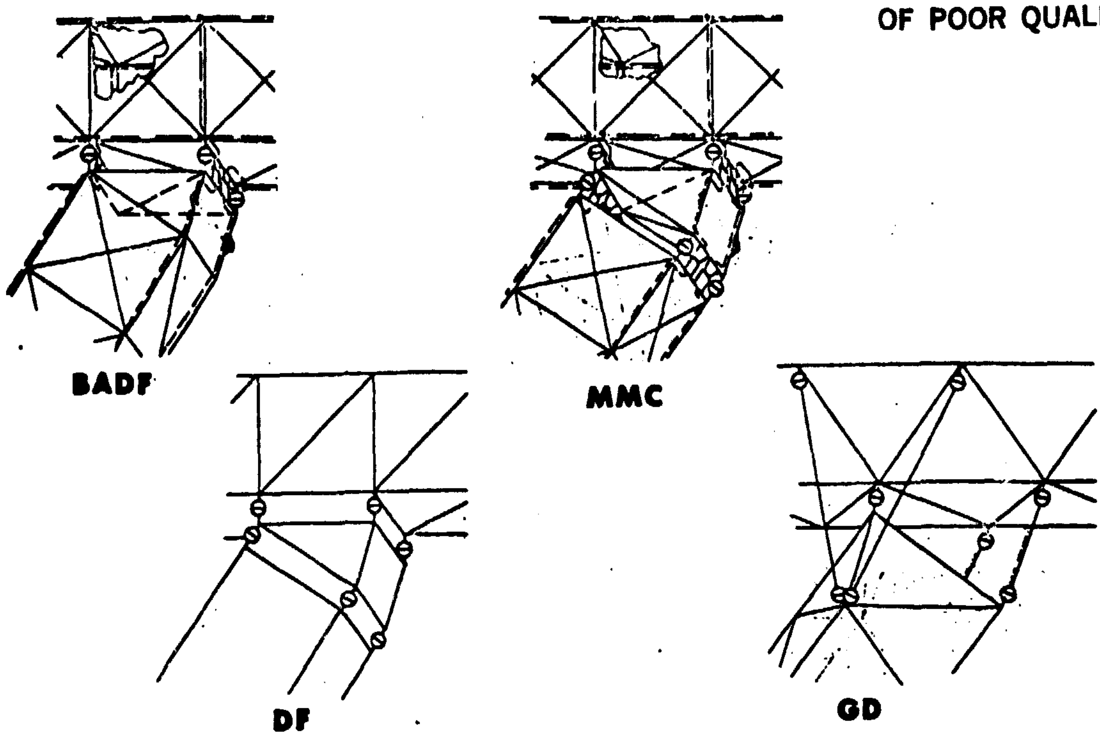

FIGURE 138 OBLIQUE TRUSS BUTT JOINTS

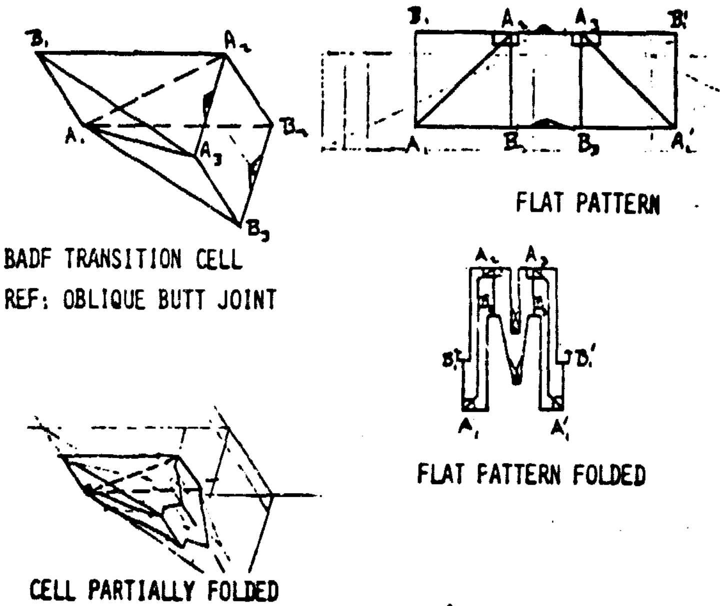

FIGURE 139 BADF FOLDABLE TRANSITION CELL

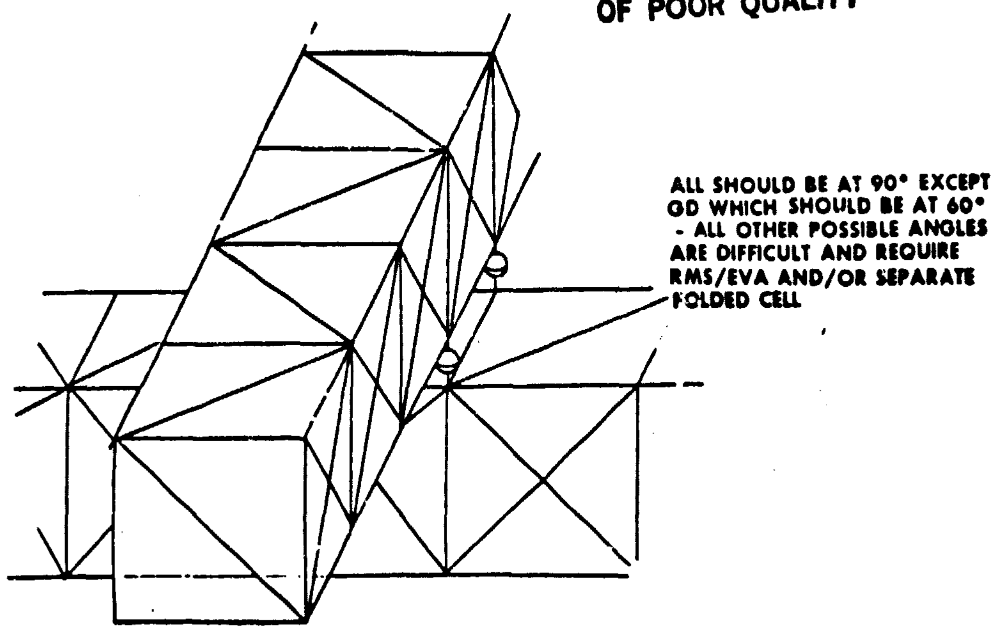

FIGURE 140 TRUSS-TO-TRUSS LAP JOINT INTERFACE

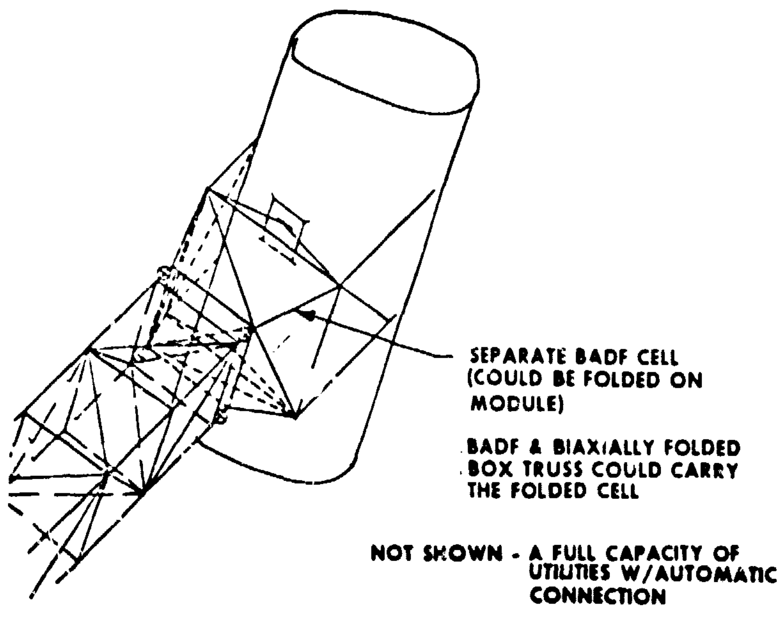

FIGURE 141 MODULE-TO-TRUSS INTERFACE

loose transition pieces and consequent EVA or RMS operations. Lap joints at 90° are suitable for the Double Fold and Martin Marietta Box Truss, while the GDC Diamond Beam may be lapped at 60°. Other lap angles on any of these trusses would require a standoff transition cell similar to that required for the Biaxial Double Fold.

Truss-to-module joining accomplished subsequent to deployment was also evaluated as illustrated in Figure 141. Results were similar to those obtained for the truss-to-truss butt joints for the situation where the interfacing structure provides coupler pickup points on a suitable plane as part of the module. Unequal truss/module sizes and oblique angles may also be accommodated as on the truss-to-truss intersections. As noted on Figure 141, a cell from the Biaxial Double Fold or Martin Box Truss could be attached to the rigid module as a separate foldable cell of transition structure. In the case of the Biaxial Double Fold, or the biaxially folded Martin Box Truss, the transition structure alternately could be carried with the truss to be joined to the module and folded with the truss.

Concepts for preattachment of deployable masts or beam trusses to a rigid module were also examined. In Figures 142 and 143 examples of mast type uses of the trusses are illustrated. The example shown is the GSP Alternate 1 core structure, where the two arms indicated are two masts extended to deploy antennas. As shown in Figure 143 for the Biaxial Double Fold, the Martin Box Truss, or the GD Diamond Beam, it is feasible to double fold the truss into a pancake package, which then may be pivoted 90° to lie parallel to the surface of the module to minimize stowage volume. Deployment would involve an actuator to pivot the pancake package out 90°. On the BADF and MMC Box Truss an interface with two side latch couplers completes the structural load paths into the four longerons of the deployed beam. This interface could be made automatically. The GDC Diamond Beam would not require the two couplers as its external deployment structure provides a cantilever support for the beam. A similar support guide load path for the BADF could be used to avoid the couplers if found to be advantageous. The support guide which might be used with the Biaxial Double Fold is illustrated in Figure 144. In each of these three truss configurations, utility interface routing could be accomplished through laterals or diagonals and not require connectors. Single folded configurations, illustrated in Figure 142, are not considered to be competitive in stowage volume.

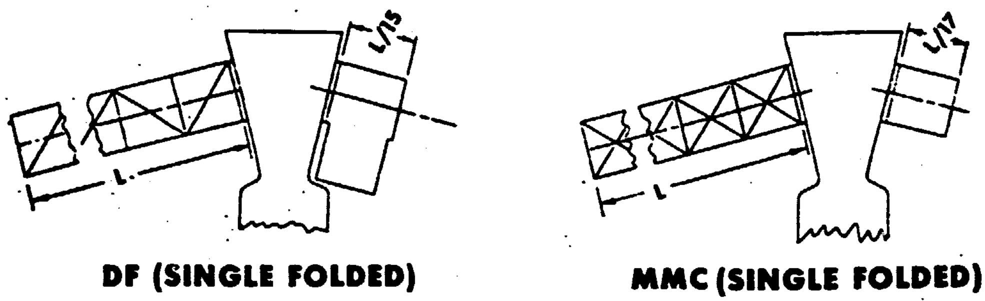

FIGURE 142 DEPLOYABLE MASTS (SINGLE FOLD)

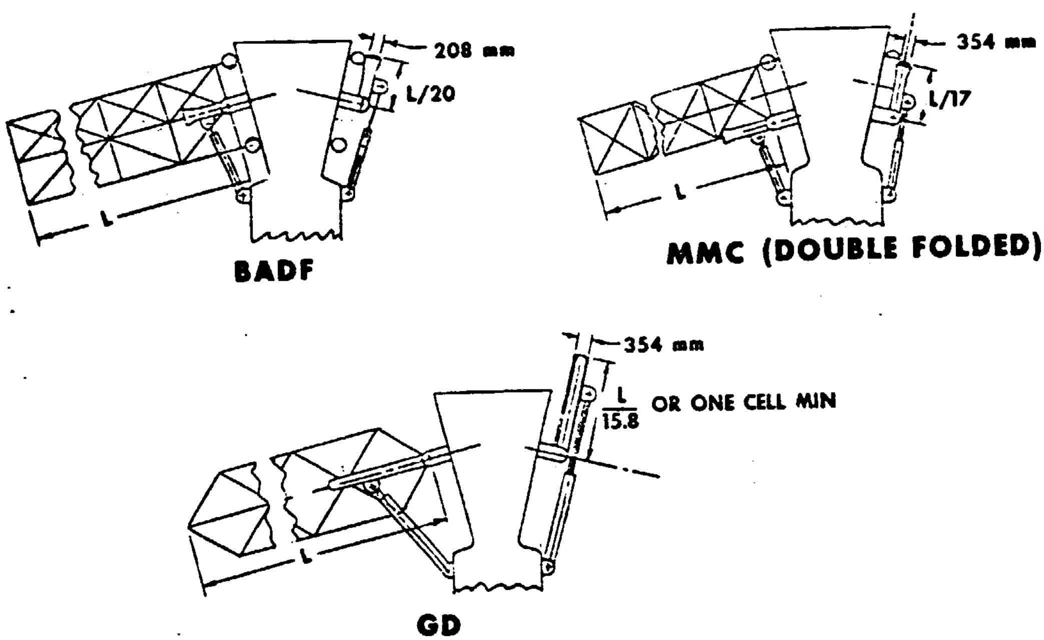

FIGURE 143 DEPLOYABLE MASTS (DOUBLE FOLDED)

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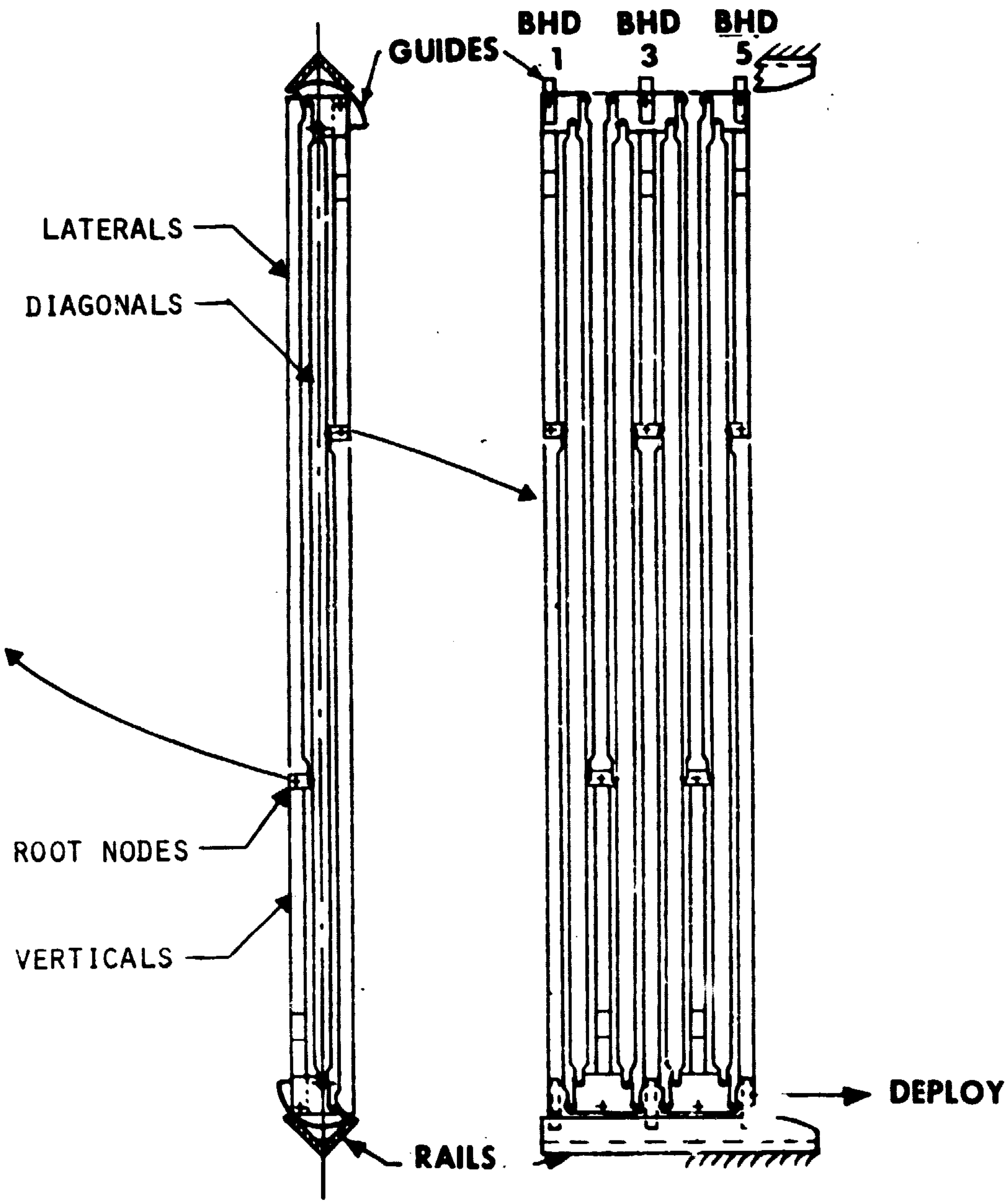

FIGURE 144 BADF REDEPLOYABLE MAST ON GUIDE RAILS SUPPORTS

As a derivative of studies on transition cells a potentially useful second result was obtained. Trusses that can be double folded biaxially can be designed with tapered sections, either locally or continuously as a tapered beam, and still be fully foldable. This capability applies to the Biaxial Double Fold and also to the Martin Marietta Box Truss if its fold sequence were to be biaxial. Figure 145 shows one possible construction that could be made to take advantage of this capability. The spoked hoop structure could be deployed from either the Biaxial Double Fold or a biaxially folded Box Truss.

5.2 COSTS TRADES

Comparative cost trades were initiated to assess the development, fabrication and launch cost differences for the four structural concepts. The basis for fabrication cost estimates was the labor expenditure record accrued in fabricating the (Ref. 7) 3m x 15m Double Fold truss which was tested in the NASA-MSFC Neutral Bouyancy Facility. This test article was fabricated by Vought using aluminum as the structural material. The labor base for this article was adjusted based on Vought experience with manufacturing costs of graphite/epoxy vs aluminum. It was estimated that the structures were fabricated from GY70/934 graphite/epoxy with a materials cost of $1100/kg. Estimates were then made of differences in complexity and number of parts for the Biaxial Double Fold, the current Double Fold version, the Martin Box Truss and the GDC Diamond Beam relative to the neutral bouyancy article to estimate labor costs for these designs. In considering large quantities the Modified Wright Learning Curve was used with a slope of 0.85. Design, development and qualification costs were included in addition to fabrication costs. While costs associated with utilities integration are inherent in the structural design, the cost for the actual fluid hoses, utilities cables, and connectors were not included because of the comparative nature of the study. The article size was based on a 3m x 3m square truss cell. Cost estimating was done in 1982-dollars. Representative 1982 Aerospace labor rates were assumed. A Shuttle transportation cost of $100M per launch was used. The Shuttle launch constraints applied were a maximum payload weight of 29,500 kg and a maximum payload volume of 250 cubic meters, with an assumed 75% utilization.

Figure 146 shows the approach for estimating non-recurring costs. Part numbers were based on experience with the neutral bouyancy article. Fabrication of four cells was assumed for development and qualification. In Figure 147 the manufacturing cost estimating approach is outlined. The

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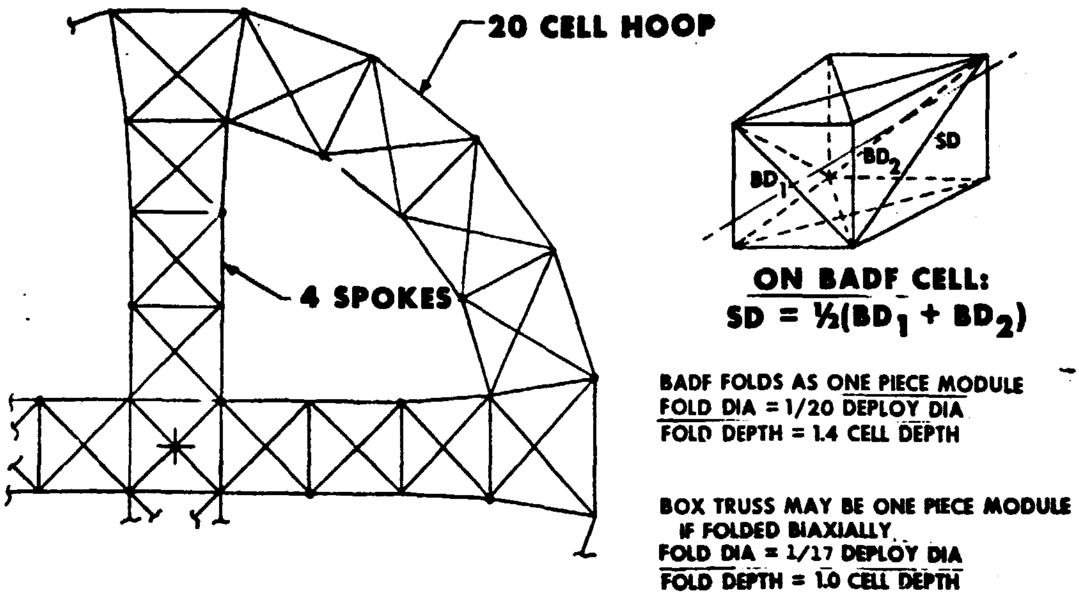

FIGURE 145 BADF & BOX TRUSS TAPERED CELLS IN SPOKED HOOP STRUCTURE

- **ESTIMATE DESIGN AND DEVELOPMENT COST FOR EACH PART NUMBER BASED ON NEUTRAL BOUYANCY ARTICLE EXPERIENCE WHERE AVAILABLE.**

. DESIGN ALLOWABLES	4400 HOURS
. DESIGN & ANALYSIS	340 HRS/PN
. ELEMENT TESTING	40 HRS/PN
. DEVELOPMENT TESTING	120 HRS/PN
. QUALIFICATION TESTING	120 HRS/PN
. DATA MANAGEMENT	60 HRS/PN

TOTAL DESIGN AND DEVELOPMENT 4400 HRS + 680 HRS/PN

- **CALCULATE COST OF FABRICATION OF FOUR CELLS FOR DEVELOPMENT AND QUALIFICATION USING RECURRING COST FORMULA.**

FIGURE 146 NON-RECURRING COST ESTIMATING APPROACH methodology was computerized for the parametric cost studies. Figure 148 lists the important formulas involved in that analysis. Figure 149 shows the launch cost estimating approach. Two cases, assuming either a Shuttle weight constraint or a volume constraint, were analyzed. Results for design, development and production cost are plotted over a wide range of sizes in Figure 150. It is seen that the cost of the hardware item is greatest for the Box Truss and least for the Biaxial Double Fold, which represents the difference in complexity of these designs. Figure 151 gives the launch cost comparison. A single line represents the weight constraint case. (The launch cost model did not include weight differences due to joints.) The results for the volume constraint case show that the Biaxial Double Fold is the lowest in cost and the Double Fold is the most expensive, which is proportional to their packaging ratios.

5.3 EVALUATION OF TRADE MATRIX

A trade matrix was constructed to evaluate the four structure concepts. Five major categories of criteria were defined for the matrix: Platform Capability, Deployability, Versatility of Application, Subsystem and Payload Integration, and System Performance. Each of these major criteria was assigned a maximum value of 10 points. The criteria for each major category were subdivided into detail subcriteria which were, in turn, assigned a normalized weighting factor between 0 and 1. There are a total of 26 subcriteria. The sum of the normalized weighting factors under each major criteria is unity resulting in a maximum possible multiplier of 1.0. The overall highest score possible is 50. Table 28 is the trade matrix. It shows the scores assigned to each of the subcriteria and (in parentheses) the weighting factors applied to each of these scores. The product of the two is the weighted score, and is also given in the table. For each major category the weighted total score is summed to show the relative ranking of the four concepts. Finally, at the end of the table the grand total weighted score is presented. By comparison with the preliminary screening matrix of Section 2.4 it can be seen that the subcriteria are somewhat expanded and slightly different. This is a result of the additional insight gained as the study progressed. A process of evaluation similar to that involved in the preliminary screening matrix was employed.

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- ESTIMATE THE MANHOURS REQUIRED TO BUILD EACH MAJOR SUBASSEMBLY (DEFINED AS A MEMBER, SUCH AS A STRUT, NODE FITTING, ETC.) BASED ON ACTUALS FROM THE NEUTRAL BOUYANCY ARTICLE. ADJUST TO GRAPHITE/EPOXY. ASSUME LABOR IS EQUAL FOR EACH MEMBER.

$$\text{LABOR/MEMBER}(MH_s) = 28 \text{ TO } 114 \text{ MAN HOURS}$$

- DETERMINE NUMBER OF DIFFERENT MEMBER DESIGNS (OR PART NUMBERS) AND NUMBER OF PIECES FOR EACH DESIGN FOR EACH STRUCTURES CONCEPT.

- APPLY THE MODIFIED WRIGHT LEARNING CURVE IN CUM AVERAGE FORM TO THE MAN HOURS FOR EACH PART NUMBER.

$$\frac{MH_{si}}{MH_{s1i}} = 1.307 \frac{NP_i^{.765} - 1}{NP_i - 1}$$

WHERE:
MH_{si} = SHOP MAN HOURS TO MAKE PART NO. i
MH_{s1i} = SHOP MAN HOURS FOR THE FIRST PART OF PART NO. i
NP_i = NUMBER OF PARTS FOR PART NUMBER i

- ADD 200 MAN HOURS FOR ACCEPTANCE TESTING, DOLLARIZE THE HOURS, AND ADD MATERIALS COST.

FIGURE 147 MANUFACTURING COST ESTIMATING APPROACH

FORMULAS WERE DEVELOPED FOR ESTIMATING NON-RECURRING & RECURRING COSTS:

$$C_R(NC) = \left\{ MH_{AT} + \sum_{i=1}^{NPN} MH_S \cdot \left[1.307 \left(\frac{NP_i^{.765} - 1}{NP_i - 1}\right)\right] \cdot NP_i \right\} \cdot R_S + \sum_{i=1}^{NPN} NP_i CM_i$$

$$C_{NR} = \left[MH_{DA} + MH_D\,(NPN)\right] \quad RE + C_R\,(4)$$

WHERE:
$C_R(NC)$ = RECURRING COST FOR NC CELLS
C_{NR} = NON-RECURRING COST
MH_{AT} = MANHOURS FOR ACCEPTANCE TEST
MH_S = SHOP MANHOURS FOR EACH MAJOR SUBASSEMBLY
NPN = NUMBER OF DIFFERENT SUBASSEMBLY DESIGNS
NP_i = NUMBER OF PARTS FOR PART NUMBER$_i$ = $NPC_i \cdot NC$
NPC_i = NUMBER OF PART NO. i PER CELL
NC = NUMBER OF CELLS
R_S = SHOP LABOR WRAP RATE
CM_i = COST OF MATERIALS FOR PART NO. i
MH_{DA} = MANHOURS FOR DESIGN ALLOWABLES
MH_D = DESIGN MANHOUR
R_E = ENGINEERING WRAPRATE
$C_R(4)$ = RECURRING COST FOR 4 CELLS

FIGURE 148 COST COMPARISON METHODOLOGY

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- ESTIMATED NUMBER OF LAUNCHES FOR EACH CONCEPT BASED ON WEIGHT CONSTRAINED AND VOLUME CONSTRAINED
- FORMULAS FOR ESTIMATION

$$NL_W = \frac{Wc \cdot Nc}{Wmax}$$

$$NL_V = \frac{Vc \cdot Nc}{Vmax}$$

WHERE:

NL_W	=	NUMBER OF SHUTTLE LAUNCHES BASED ON WEIGHT CONSTRAINT
NL_V	=	NUMBER OF SHUTTLE LAUNCHES BASED ON VOLUME CONSTRAINT
Nc	=	NUMBER OF CELLS
Wc	=	WEIGHT PER CELL = 82 KG (INCLUDING 68 KG UTILITIES)
Vc	=	VOLUME PER CELL (DF = .55 m^3, BT & DB = .225 m^3, BADF = .156 m^3)
Wmax	=	MAXIMUM ORBITER PAYLOAD WEIGHT = 29,500 KG
Vmax	=	MAXIMUM ORBITER PAYLOAD VOLUME = 215 m^3

FIGURE 149 LAUNCH COST ESTIMATING APPROACH

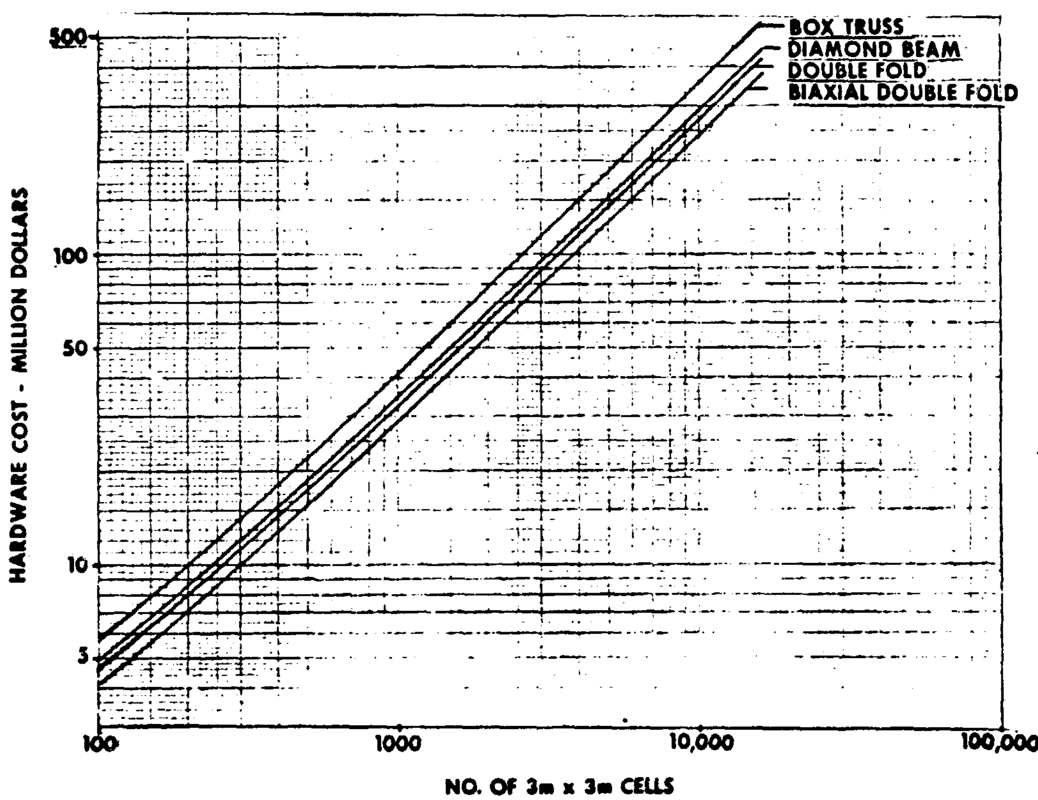

FIGURE 150 DESIGN, DEVELOPMENT & PRODUCTION COST COMPARISON

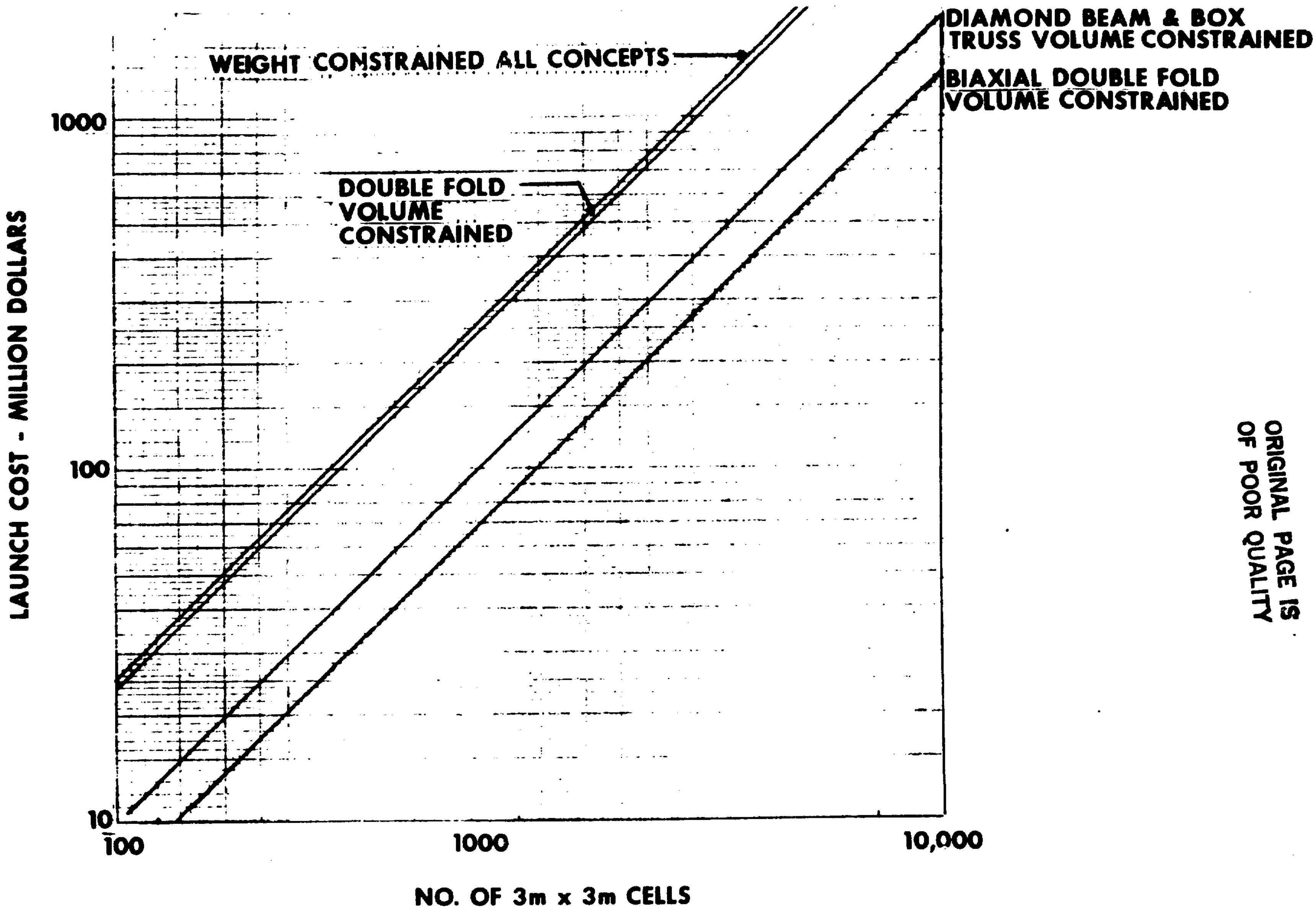

FIGURE 151 LAUNCH COST COMPARISON

TABLE 28 TRADE MATRIX

CRITERIA (WF) \ CONCEPT		VOUGHT DOUBLE FOLD	GDC DIAMOND BEAM	BIAXIAL DOUBLE FOLD	MMC BOX TRUSS
PLATFORM CAPABILITY					
. DEPLOY/STOW VOLUME RATIO	(.6)	2.4(.6) = 1.4	6.8(.6) = 4.1	8.8(.6) = 5.3	8.8(.6) = 5.3
. AREA PLATFORM ASSEMBLY	(.4)	9(.4) = 3.6	8(.4) = 3.2	10(.4) = 4.0	9(.4) = 3.6
SUBTOTAL		5.0	7.3	9.3	8.9
DEPLOYABILITY					
. AUTO DEPL./RETR.	(.2)	7(.2) = 1.4	8(.2) = 1.6	9(.2) = 1.8	6(.2) = 1.2
. COMPLEXITY	(.2)	6(.2) = 1.2	6(.2) = 1.2	10(.2) = 2.0	8(.2) = 1.6
. CONTROL - DYNAMIC - DIRECTIONAL - DEPL. INDEX - SEQUENTIAL	(.2)	6(.2) = 1.2	7.5(.2) = 1.5	7.5(.2) = 1.5	7.5(.2) = 1.5
. UTILITY IMPACT	(.2)	9(.2) = 1.8	7(.2) = 1.4	9(.2) = 1.8	6(.2) = 1.2
. ALTERNATE ACTUATION - SELF CONTAINED - EXTERNAL	(.2)	7(.2) = 1.4	7(.2) = 1.4	5(.2) = 1.0	8(.2) = 1.6
SUBTOTAL		7.0	7.1	8.1	7.1
VERSATILITY OF APPLICATION					
. SCALING CAPABILITY - SIZE - STRENGTH - STIFFNESS	(.2)	10(.2) = 2.0	9(.2) = 1.8	10(.2) = 2.0	9(.2) = 1.8
. MODULE ASSEMBLY	(.2)	10(.2) = 2.0	8(.2) = 1.6	10(.2) = 2.0	10(.2) = 2.0
. MAST	(.1)	5(.1) = 0.5	10(.1) = 1.0	10(.1) = 1.0	10(.1) = 1.0
. BRANCHING	(.1)	5(.1) = 0.5	5(.1) = 0.5	10(.1) = 1.0	10(.1) = 1.0
. TAPERED BEAMS	(.1)	0(.1) = 0	0(.1) = 0	10(.1) = 1.0	8(.1) = 0.8
. SPECIAL SHAPES	(.1)	6(.1) = 0.6	6(.1) = 0.6	10(.1) = 1.0	8(.1) = 0.8
. EVA/RMS	(.2)	4(.2) = 0.8	9(.2) = 1.8	9(.2) = 1.8	8(.2) = 1.6
SUBTOTAL		6.4	7.3	9.8	9.0

NOTES: 1. EACH MAJOR CRITERIA VALUED 0-10 POINTS
2. EACH SUBCRITERIA VALUED 0-10 POINTS x (WF)
3. (WF) = WEIGHTING FACTOR, SHOWN AS (.X)

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TABLE 28 (CONT'D)

CRITERIA (WF) \ CONCEPT		VOUGHT DOUBLE FOLD	GDC DIAMOND BEAM	BIAXIAL DOUBLE FOLD	MMC BOX TRUSS
SUBSYSTEM AND PAYLOAD INTEGRATION					
. LOCAL ATTACHMENTS	(.2)	10(.2) = 2.0	4(.2) = 0.8	10(.2) = 2.0	10(.2) = 2.0
- SUBSYSTEMS					
- PAYLOADS					
. INTERFACE HARDWARE	(.1)	9(.1) = 0.9	7(.1) = 0.7	9(.1) = 0.9	9(.1) = 0.9
- DOCKING					
- ROTARY JOINTS					
. UTILITIES INTERFACES	(.2)	9(.2) = 1.8	7(.2) = 1.4	9(.2) = 1.8	6(.2) = 1.2
- BRANCHING					
- CONNECTOR INTERFACE					
. INTERNAL UTILITIES	(.2)	8(.2) = 1.6	7(.2) = 1.4	9(.2) = 1.8	5(.2) = 1.0
- COMPLEXITY					
- PKG RATIO					
. EXTERNAL UTILITIES	(.2)	8(.2) = 1.6	7(.2) = 1.4	8(.2) = 1.6	6(.2) = 1.2
- COMPLEXITY					
- PKG RATIO					
. ADD-ON UTILITIES	(.1)	10(.1) = 1.0	10(.1) = 1.0	10(.1) = 1.0	7(.1) = 0.7
SUBTOTAL		8.9	6.7	9.1	7.0
SYSTEM PERFORMANCE					
. STRENGTH-TO-WT	(.1)	10(.2) = 2.0	7(.2) = 1.4	10(.2) = 2.0	6(.2) = 1.2
. STIFFNESS-TO-WT	(.2)	7(.2) = 1.4	10(.2) = 2.0	7(.2) = 1.4	4(.2) = 0.8
. COMPLEXITY	(.2)	5.6(.2) = 1.1	3.6(.2) = 0.7	6.7(.2) = 1.3	2(.2) = 0.4
- JOINTS PER CELL					
. MATURITY	(.1)	7(.1) = 0.7	9(.1) = 0.9	4(.1) = 0.4	7(.1) = 0.7
- BASIC STR					
- UTILITIES INTEG					
- DEPLOYMENT					
. COST	(.2)	3(.2) = 0.6	7(.2) = 1.4	10(.2) = 2.0	7(.2) = 1.4
- SPECIAL TECHNOLOGY					
- DESIGN & DEV					
- PRODUCTION					
- LAUNCH					
. SHUTTLE COMPATIBILITY	(.2)	6(.2) = 1.2	8(.2) = 1.6	9(.2) = 1.8	9(.2) = 1.8
- PACKAGING					
- EVA/RMS					
SUBTOTAL		7.0	8.0	8.9	6.3
TOTAL SCORE		29.3	29.5	35.9	29.4

5.4 SELECTION

Table 29 is a summary of the trade matrix showing the relative position of the concepts under each criteria area. Examining Table 29 in conjunction with Table 28 the Biaxial Double Fold is a clear winner in every major criteria category (by a substantial margin in most cases). The other three trusses are close to each other in total score and within the evaluation scatter. If weighting factors had been applied at the major category level first place would not have changed but second place could have been altered. For example, if Versatility of Application were weighted twice that of the other major categories the Martin Marietta Box Truss would have ranked a clear second place.

TABLE 29 CONCEPT TRADE SUMMARY

RELATIVE RANKING BY MAJOR CRITERIA CATEGORY

CLEAR WINNER

CRITERIA \ CONCEPT	VOUGHT DOUBLE FOLD	GDC DIAMOND BEAM	BIAXIAL DOUBLE FOLD	MMC BOX TRUSS	REMARKS
PLATFORM CAPABILITY	4	3	1	2	TOP DEPLOY/STOW VOL, MOST EFF. AREA PLATFORM ASSY.
DEPLOYABILITY	4	2	1	2	TOP RANKING IN FOUR OR FIVE SUB-CATEGORIES
VERSATILITY	4	3	1	2	DEPLOY AND/OR ASSEMBLE MORE SHAPES WITH LEAST EVA
INTEGRATION	2	4	1	3	CONCEPT CONCEIVED FOR EFF. UTILITIES, SUBYS. & P/L INTEG.
PERFORMANCE	3	2	1	4	FEWEST PIECES MINIMIZE WEIGHT, COST, COMPLEXITY

6.0 DEPLOYABLE VOLUMES

Future missions such as a manned space platform will require both pressurized and unpressurized volumes for use as crew quarters, manned laboratories, transfer tunnels and maintenance hangars. To minimize launch costs and/or enable use of volumes greater than those which can be transported by the Space Shuttle Orbiter, it is necessary to consider deployable volumes. The objective of the Deployable Volume task was to determine concepts which offer potential for deployable volumes. This section reviews effort in establishing guidelines and requirements, generating and studying concepts, and assessing technology development requirements, design drivers and expected major problem areas for promising concepts.

The concepts considered include deployable/erectable, flexible/inflatable/expandable, and hybrid approaches. Some of the major design related issues considered in evolving the concepts include:

a) What is the location and type of pressure shell (i.e., should the shell be rigid with folds and seals or should it have a bladder which either carries the pressure load or is supported by structure which in turn carries the pressure load).

b) What should be the split between deployment and assembly of the volume?

c) What is a proper assembly approach and sequence?

d) How should the equipment and facilities be installed?

e) How would hard points and feed-throughs be accommodated?

f) How would the door seal be installed for a pressurized hangar?

g) How would the deployable volume module be mated with the space station structure?

h) How would the Orbital Transfer Vehicle interface the hangar for ingress and egress?

Some of the major information sources utilized in defining requirements and evolving concepts included the Ref. (2) Science and Applications Manned Space Platform (SAMSP) study conducted by NASA-MSFC during 1981, the Ref. (31) Evolutionary Science and Applications Space Platform study conducted by McDonnell Douglas, Space Operations Center (Ref. 32) studies by the Boeing Company, and studies on inflatable/flexible space structure conducted by the Goodyear Aerospace Corporation (Ref. 3) in the mid 1960's.

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6.1 GUIDELINES AND REQUIREMENTS FOR DEPLOYABLE VOLUMES

Requirements were derived to be generic in nature and not to preclude the advantages inherent in inflatable or deployable/erectable concepts. Table 30 is a summary listing of the broad guidelines and requirements derived from a review of the documents previously mentioned and other related studies. One of the requirements that has a significant impact on evolution of concepts is that of a probability of 0.95 for no meteoroid penetration over a ten year mission, taken from Ref. (2). Related to this is the basic thermal protection requirement of passive cabin wall temperature control within the band below that of the pain threshold (about 45°C) and above that of the maximum cabin dewpoint (about 15°C). The approach chosen was to use an integral thermal/meteoroid blanket on the exterior of the structure in most of the concepts. The current Spacelab layup was used as a representative design for

TABLE 30 GUIDELINES AND REQUIREMENTS

(1) CONSIDER PRESSURISED MANNED HABITANTS AND INTERCONNECTING TUNNELS.

(2) CONSIDER PRESSURISED AND UNPRESSURISED OTV HANGER.

(3) DEPLOYED DIAMETERS OF HABITATS AND HANGERS UP TO AT LEAST 10m SHOULD BE CONSIDERED.

(4) STOW IN MINIMUM LENGTH OF CARGO BAY WITH 4.5 m MAX DIA. OR 3.1 m MAX SQUARE PACKAGE.

(5) PRESSURIZATION MAY BE FROM 55 kPa TO 101 kPa (8 to 14.7 PSI)

(6) ENVIRONMENT MAY BE IN LEO OR GEO.

(7) 10 YEARS OPERATIONAL LIFE WITH MAINTENANCE.

(8) ALLOW SPACE OUTSIDE PRESSURIZED VOLUMES FOR THERMAL/METEOROID BLANKET TO PROVIDE A PROBABILITY OF NO METEOROID PENETRATION (Po) OF 0.95 FOR A 10 YEAR MISSION.

(9) OTV HANGER SPACE REQUIRED FOR MAX OTV DIMENSIONS OF 15.3 m LONG x 4.5 m DIAMETER PLUS AT LEAST 2 m CLEARANCE FOR MAINTENANCE ACCESS.

(10) MINIMIZE EVA REQUIREMENTS FOR ASSEMBLY AND MAINTENANCE.

(11) ONE METER DIAMETER MINIMUM PASSAGEWAY FOR TUNNELS AND HATCHES.

(12) COMPATIBLE WITH SHUTTLE LAUNCH AND EVA OPERATIONS.

(13) NO RETRACTION REQUIRED (EXCEPT POSSIBLY TUNNELS).

(14) PROVIDE COMPATIBILITY FOR UTILITIES ROUTING AND PENETRATIONS AND HARDPOINT PENETRATIONS.

(15) DEPLOYED VOLUME TO BE OUTFITTED WITH FURNITURE, RACKS, ETC., AFTER DEPLOYMENT. THESE ARTICLES ARE NOT STOWED INSIDE RETRACTED VOLUME.

(16) PROVIDE THE CAPABILITY FOR VERSATILE STRUCTURAL INTERFACES BETWEEN THE DEPLOYABLE VOLUME AND SPACE STATION STRUCTURE, INTERNAL STRUCTURE, AND OTV DOCKING.

(17) INSULATE VOLUME SUFFICIENTLY TO AVOID PAIN THRESHOLD (45°C) AND CONDENSATION AT MAXIMUM CABIN DEWPOINT (ABOUT 15°C).

(18) PROVIDE ADEQUATE RADIATION SHIELDING FOR 90-180 DAY CREW MISSION.(<.5 to 1.3gm/cm²)

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purposes of this conceptual study. The concept is illustrated in Figure 152, also taken from Ref. (2). The approach was to require the same level of protection as the Manned Space Platform Phase III growth version. This is

REQUIREMENT:

- MAINTAIN MINIMAL HEAT GAIN/LOSS TO CONTENTS OF VOLUME
- MAINTAIN WALL TEMPERATURE BELOW PAIN THRESHOLD (45°C) AND ABOVE MAXIMUM CABIN DEW POINT (MDAC SAMSP IS 16°C, SPACELAB IS 11°C)

APPROACH:

- INTEGRAL THERMAL/METEOROID BLANKET ON EXTERIOR OF STRUCTURE
- USE CURRENT SPACELAB LAYUP AS REPRESENTATIVE DESIGN:

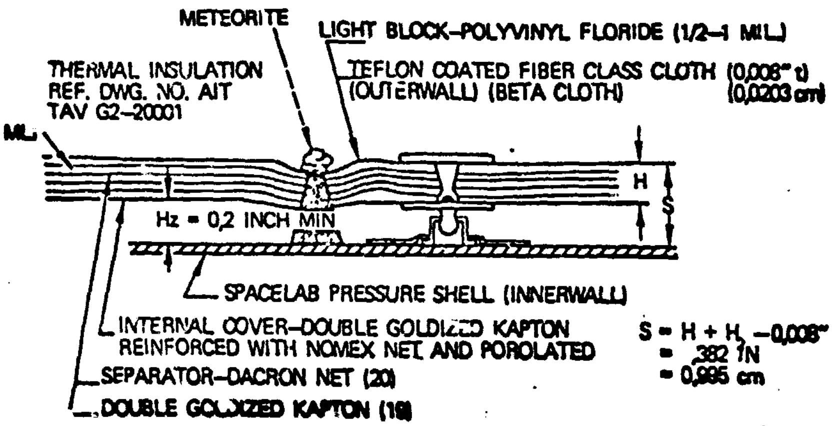

FIGURE 152 THERMAL PROTECTION APPROACH

somewhat optimistic or conservative, depending on differences in total pressurized area of the Manned Space Platform when deployable volumes are used. For the current study the Manned Space Platform protection design was modified consistent with differences in deployable volume materials and the thermal meteoroid blanket standoff distance, as indicated in Figure 153. Figure 154 illustrates the analytical relationship between the meteoroid protection and the material properties as the standoff distance of the blanket from the interior wall is varied. The analysis plotted in Figure 154 shows

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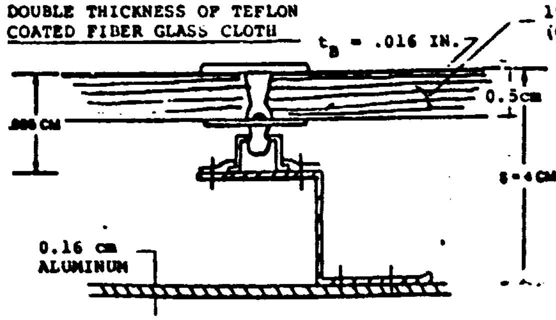
REQUIREMENT:

- PROBABILITY OF NO PENETRATION FOR OVERALL MANNED SPACE PLATFORM (MSP) OF 0.95 FOR 10 YEARS (SAME AS NASA-MSFC OCTOBER 1981 STUDY)

APPROACH:

- PROVIDE SAME LEVEL OF PROTECTION AS MSP PHASE III GROWTH VERSION. THIS MAY BE SOMEWHAT OPTIMISTIC OR CONSERVATIVE DEPENDING ON DIFFERENCES IN TOTAL PRESSURIZED AREA OF THE MSP WHEN DEPLOYABLE VOLUMES ARE USED.
- INTEGRAL THERMAL/METEOROID BLANKET ON EXTERIOR OF STRUCTURE, LIKE MSP.
- MODIFY MSP PROTECTION DESIGN CONSISTENT WITH DIFFERENCES IN DEPLOYABLE VOLUME MATERIALS AND BLANKET STANDOFF DISTANCE.

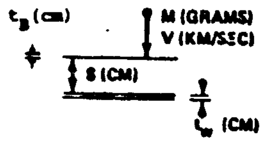
REVIEW OF MSP THERMAL/METEOROID DESIGN CONCEPT:



MODIFIED SPACELAB DESIGN PROVIDES 10 YEAR PROTECTION AT Po = .95 FOR FOUR 3-SEGMENT MANNED MODULES

FIGURE 153 METEOROID PROTECTION APPROACH

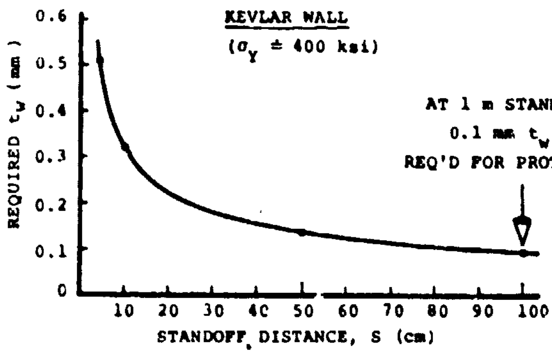
METEOROID PROTECTION RELATIONSHIP:



$$t_w = \frac{0.055\,(\rho_m \rho_B)^{1/6}\, M^{1/3}\, V}{(S)^{1/2}} \left(\frac{70000}{\sigma_Y}\right)^{1/2}$$

ρ_m = METEOROID DENSITY (g/CM^3) ≐ 0.5 gm/cm^3
ρ_B = BUMPER DENSITY (g/CM^3)
σ_Y = YIELD STRENGTH OF WALL (PSI)
t_B = BUMPER THICKNESS $\geq$.04 METEOROID DIAMETER
V = METEOROID VELOCITY ≐ 20 km/SEC
M = METEOROID MASS (gm)
S = STANDOFF DISTANCE (cm)

PROTECTION WITH SOFT PRESSURE CONTAINMENT WALL:



CONCLUSION:
PRESSURE CONTAINER IS SIZED BY STRUCTURAL CONSIDERATIONS

FIGURE 154 METEOROID PROTECTION

that for a bladder material made of Kevlar, which is a very high strength material, and with the large standoff distances which exist in concepts for most of the deployable volumes, a very minimal thickness of the pressure containment wall is required for meteoroid purposes (on the order of 0.1 to 0.5 mm, depending on the standoff distance). It was thus concluded that the pressure bladder thickness should be sized for pressure containment rather than for meteoroid protection.

Another requirement with potential substantial influence on deployable volume design is the provision of adequate Van Allen radiation shielding to prevent an excessive dose to the crew. The required shielding to avoid over-exposure has been the subject of a detailed evaluation during the 1977 and 1978 Space Construction Base (SCB) space station study conducted by McDonnell Douglas (Ref. 33). That study evaluated low earth orbit missions ranging from 28.5° to 55° inclination at orbital altitudes ranging from 400-500 km. This includes the range of orbital conditions considered by the NASA-MSFC inhouse study for the Manned Science and Applications Platform (Ref. 2) where a reference orbit of 390 Km and a reference inclination between 28 and 56° was considered. In defining shielding requirements for the SCB study McDonnell Douglas evaluated the radiation dose accumulated by the skin, eyes and bone marrow, and determined that the skin is most difficult to protect. Their studies looked at mission durations from 30 days to 90-180 days. The allowable dose was 105 REM over a period of 90 days or 210 REM for a 180 day mission. This is equal to a 1.16 REMs per day allowable dose for the skin. The SCB study considered module shielding in the range of 0.5 gm per sq. cm to about 1.4 gm per sq. cm, and determined that for an orbital inclination of 28.5° shielding of 0.5 gm per sq. cm is more than adequate for the 90-180 day mission (only 65% of the allowable dose). That margin allowed sufficient allocation for crew EVA operations, where the dose received is much higher. At the 55° orbital inclination and 500 km altitude the condition was much more severe. Their study showed that if no EVA were allowed the shielding requirement would be on the order of 0.8 gm per sq. cm. From an analysis of the influence of EVA on the module shielding, McDonnell Douglas concluded that for a 55° orbit at 450 km altitude about 1.1 gm per sq. cm module protection is desirable. This level of protection was in conjunction with a recommendation for additional protection for the EVA crewmen, and short and well scheduled shifts. It was estimated from their results that 1.3 gm per sq. cm would be required for a 500 km altitude at 55^{0} inclination. It was concluded for the current study that required protection against the Van Allen radiation is in the range of somewhat below 0.5 gm per sq. cm to a maximum of 1.3 gm per sq. cm. The approximate meteoroid thermal blanket weight is on the order of 0.05 gm per sq. cm to provide adequate meteoroid protection for the deployable volume concepts. The bladders sized from structural considerations are on the order of 0.35 gm per sq. cm, resulting in a total inherent shielding by the flexible material of approximately 0.4 gm per sq. cm. This should be adequate for missions at the lower inclinations and altitudes such as the reference mission for the Manned Space Platform (especially considering the extra shielding provided by the equipment and structure). For a more severe environment, extra layers of shielding materials, perhaps in the form of a blanket, could be added on the outer portion of the structure.

6.2 FLEXIBLE AND INFLATABLE CONCEPTS

Three distinct concepts have been considered relating to flexible materials, one involving telescoping tubes with rolling diaphragm seals, one involving flexible convoluted tubes, and a third involving flexible straight tubes. In Figure 155 the telescoping tube tunnel concept is illustrated. This concept would be applicable mainly for tunnels and is not considered a candidate for habitats or hangars. A cable system is used to adjust the length and to retract the telescoping tunnel. The concept is similar to the current Shuttle docking module, does not seem to offer any new technology, and was not pursued.

The flexible convoluted tube and flexible straight tube concepts drew heavily on the flexible structures work that was conducted by Goodyear Aerospace (Ref. 3) during the latter part of 1960 and early 1970's. The flexible convoluted tube concept illustrated in Figures 156 and 157 is most promising for tunnel applications. One reason for this is that it stows by compressing in length but does not compress in diameter. Thus no advantage in maximum diameter could be obtained if used in a habitat or a hangar. As evolved by Goodyear the convoluted tube tunnel uses a structural cloth for loop tension loads, with an inner layer to provide gas sealing and scuff protection, and an outer blanket to provide thermal/meteoroid protection. Tension cables are on the inside for longitudinal stiffness. Cable reels adjust the length or curvature of the tunnel. Rigid end flanges are used to

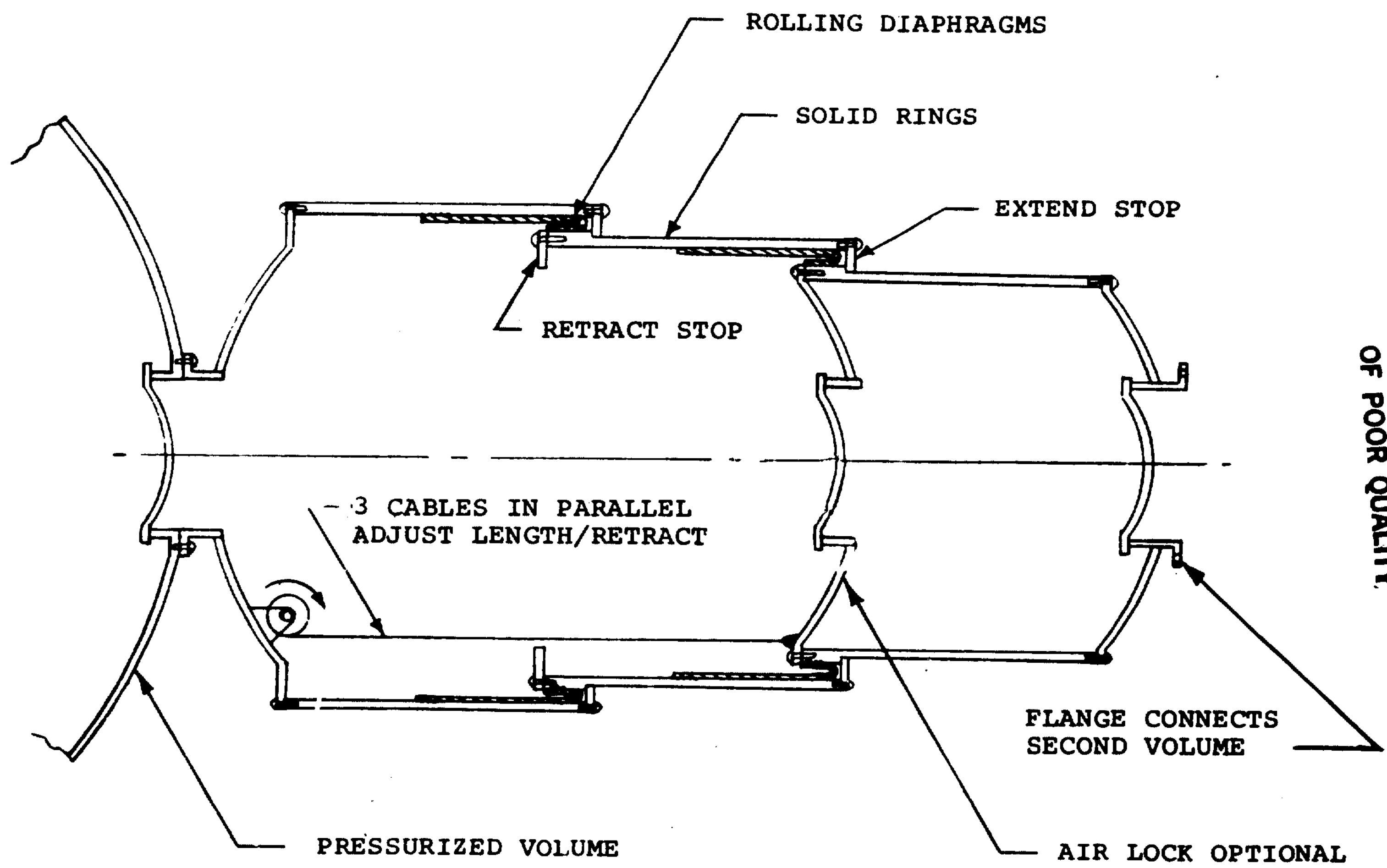


FIGURE 155 TELESCOPING TUBE TUNNEL

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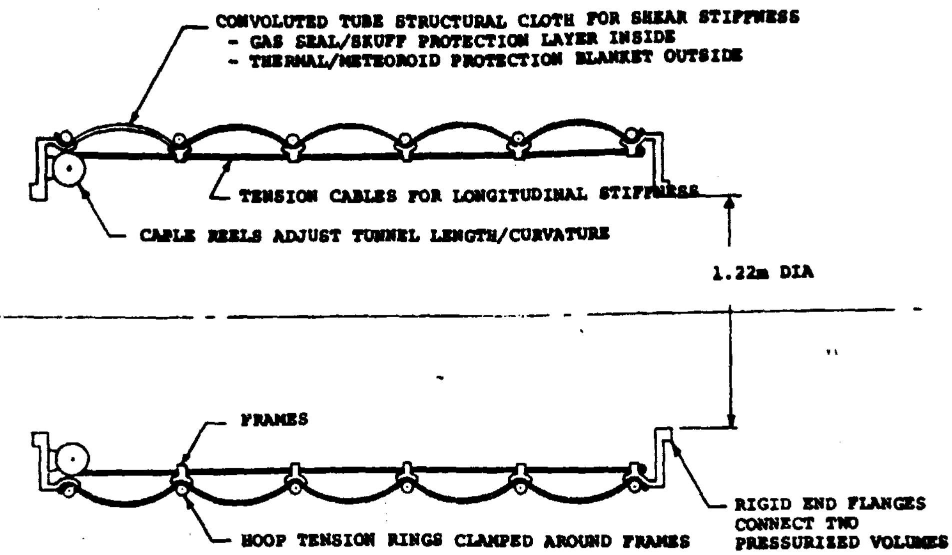


FIGURE 156 CONVOLUTED TUBE TUNNEL

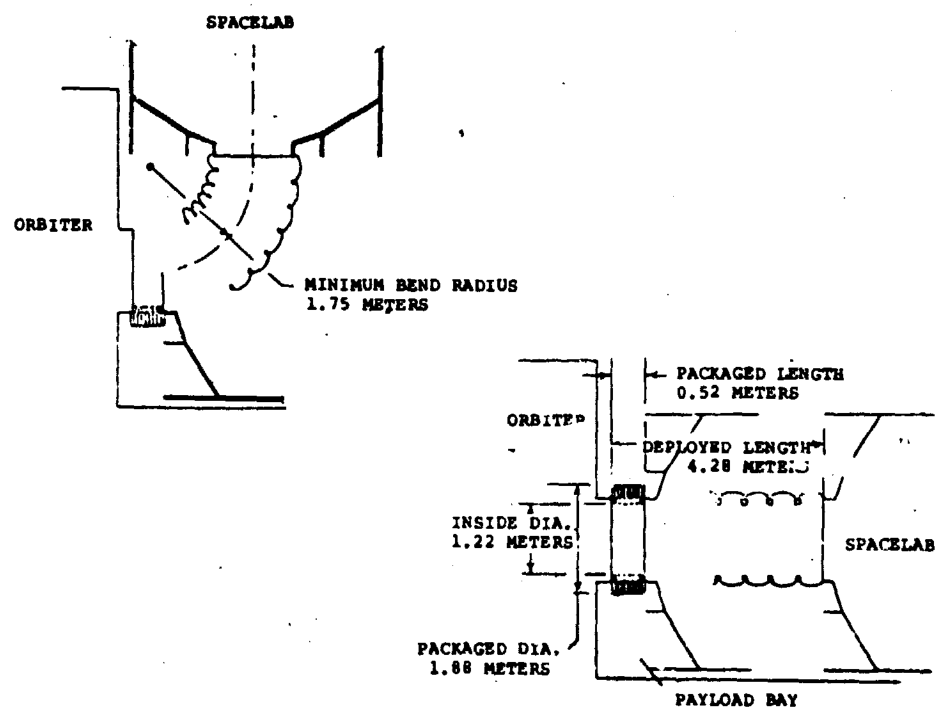
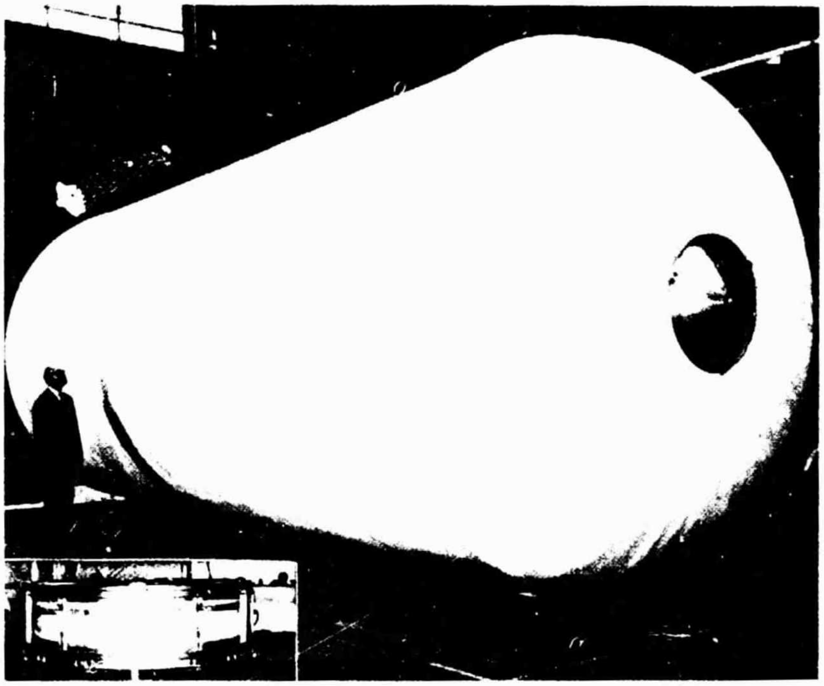


FIGURE 157 GOODYEAR CONVOLUTED TUBE MODEL DIMENSIONS

connect to pressurized volumes. Maximum dimensions deployed could be as great as 4-1/2 meters dia by 120 meters long to stow in a length of 15.3 meters for compatibility with the Shuttle Orbiter cargo bay. A minimum useful diameter of 1.9 meters is possible with this concept. The materials used in the Goodyear study included Kevlar as the structural layer, a laminate of Nylon fabric and film and EPT foam for a gas seal layer, and a laminate of Nylon film and fabric with polyurethane foam for thermal/meteoroid protection. Hoop tension rings were clamped around the frame over the flexible layers. Some variations have been identified in the present study that could enhance the usefulness of this concept. To improve the meteoroid protection for long life missions it would be possible to use a multilayer meteoroid blanket with a greater standoff distance from the convoluted tube. In addition, the tube could be placed inside an axially folding truss to provide structural stiffness, to enable utility integration and to provide a support for a thermal/meteoroid blanket with a substantial standoff distance.

Figure 158 shows the flexible straight tube concept as developed by Goodyear. The photograph shows that the cylinder is collapsed in an axial direction similar to that of the convoluted tube. However, it can also be folded and collapsed in the diameter direction. In current evaluations the straight tube concept was considered for a tunnel, a habitat module, or a hangar. For the hangar and the habitat module it was evaluated as a bladder, with no load carrying requirements other than itself. The capability to collapse the flexible straight tube into a flat configuration and roll it the long way provides the potential for compact stowage. It would be possible to stow a very long bladder up to 9.7 meters in diameter. Figure 159 illustrates some bladder materials that were selected by Goodyear. Also shown is an aramid (Kevlar) cable and its properties.

In order to successfully use flexible concepts, approaches must be available for attaching hardpoints. With the flexible convoluted tube, rigid end flanges could provide primary structural attachments. Rigid frames at each convolution could provide many points for equipment mounting. The addition of external axially folded trusses could be used to provide stiffness, utility, and blanket support. The flexible straight tube concept would require reinforced fabric for attachment at the ends or sides. Attach points in the fabric would be rigid in shear only, and rigid frames to take loads in any direction would have to attach at three or more shear points around 180° or more circumference.

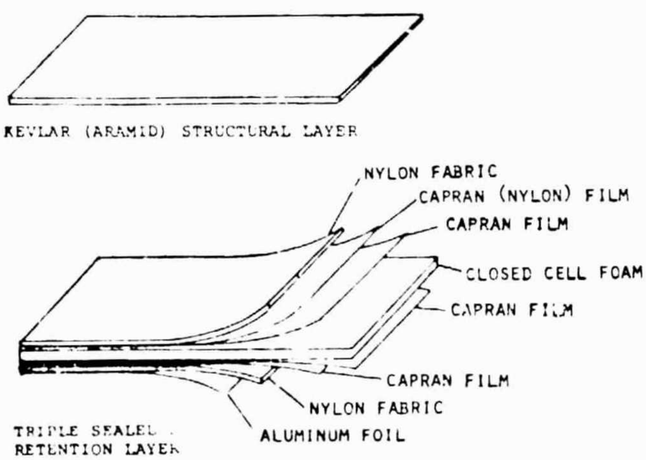


Packaged

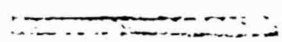
Deployed

FIGURE 158 GOODYEAR MOBY DICK FLEXIBLE TUNNEL

BLADDER CONCEPT (AFTER GOODYEAR)



FLEXIBLE HOOP



ARAMID CABLE

NOTE:
1 GPa = 0.145×10^{6} PSI

TYPICAL ARAMID PROPERTIES

MATERIAL	CTE ($\times 10^{-6}$ cm/cm$^{\circ}$-C)	DENSITY gm/cm^3	E GPa	F_{tu} GPa
KEVLAR 49	-4 TO -7	1.44	124	2.76
ARAMID CABLE	-4 TO -7	1.3	96.5	1.38

FIGURE 159 BLADDER MATERIALS

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6.3 DEPLOYABLE STRUCTURE CONCEPTS

The primary thrust of the current Deployable Volumes effort has been to evolve new concepts based on extention of deployable structure ideas previously generated by Vought and others. Four deployable structure concepts were considered in the Deployable Volume study. An initial look was carried out with a folding panel concept. This was followed by examination of a concept with a truss backbone and ribs that collapse and are covered with an exterior blanket. Then two versions of deployable truss concepts were evaluated. Both of these are versions that use bladders: one has a separate bladder and the other has an attached bladder. Figure 160 illustrates the Folding Doors deployable volume concept which will stow in a 3.1 meter square, if disconnects are used. It was determined that 8 panels, each 3.1 meters wide and hinged together will deploy into an octagonal structure which is 15.8 meters long with a 7.5 meters outside diameter, 6.7 meter inside diameter, and 0.4 meter thick walls. This dimension is not large enough for an OTV hangar but does fill the cargo bay. The Folding Door concept was not selected for more detail study because of its size limitation and the many seals required if used as a pressurized module. In addition, its small deployed-to-stowed volume ratio (about 4.5:1) and its lack of potential new benefits were not attractive.

Figure 161 illustrates the Covered Wagon deployable volume concept considered as a hangar. It has a deployable backbone beam, such as the Biaxial Double Fold or Martin Marietta Box Truss, with light folding ribs that form hoops centered around the OTV. A rolled meteoroid shield insulation is wraped around the ribs and attached by EVA using snaps or Velcro. Rolled end cap shield are also attached by EVA. This lightweight, compactly stored concept is not pressurizable and only has minimal rigidity. It was considered to be promising only for an unpressurized hangar, and was not selected to be pursued further.

Deployable truss options were considered next and were the main thrust of the Deployable Volume study. These concepts take advantage of the capabilities of some trusses, such as the Biaxial Double Fold and the Martin Marietta Box Truss, which deploy simultaneously in two directions and form the basis for a completely deployable volume structure. Figure 162 illustrates some of the capabilities of these two deployable trusses for volumes. The cylindrical volume, if deployed from a Biaxial Double Fold truss, would

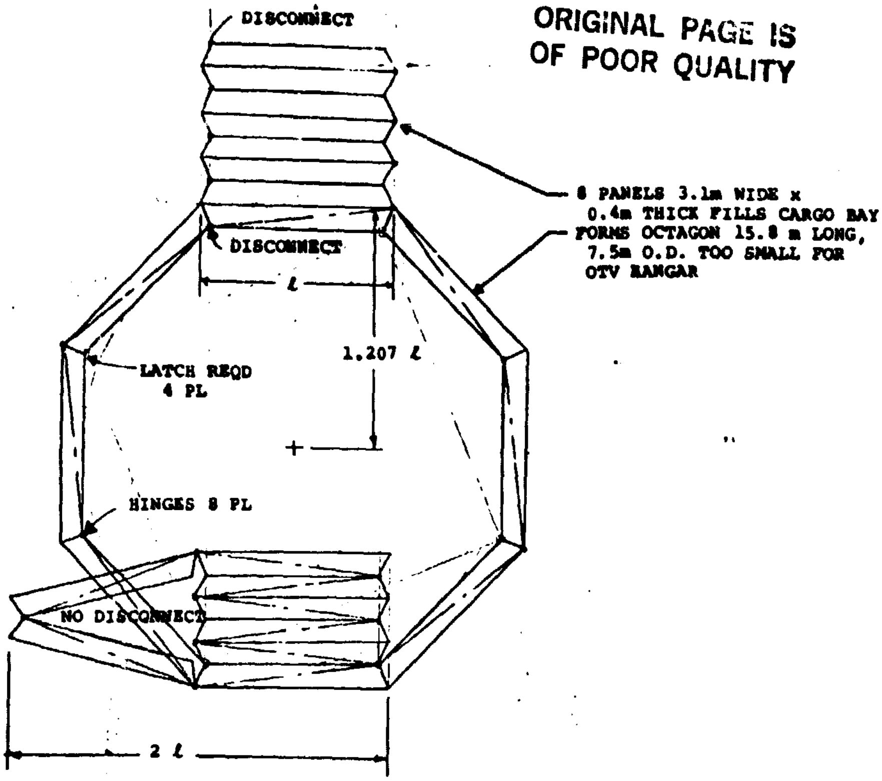

FIGURE 160 "FOLDING DOORS" DEPLOYABLE VOLUME

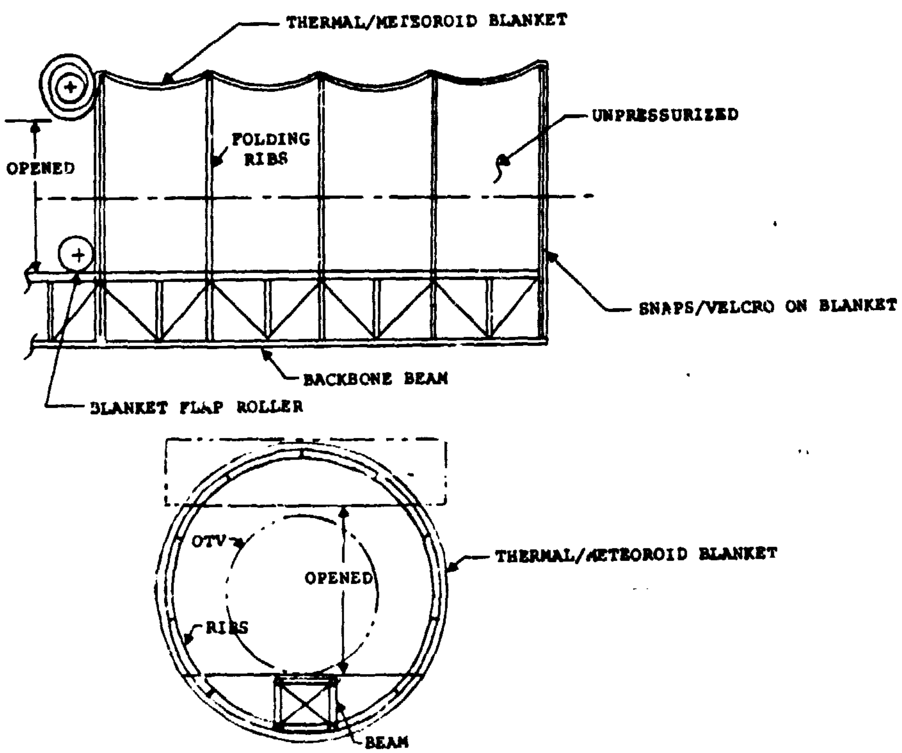

FIGURE 161 "COVERED WAGON" DEPLOYABLE VOLUME CONCEPT

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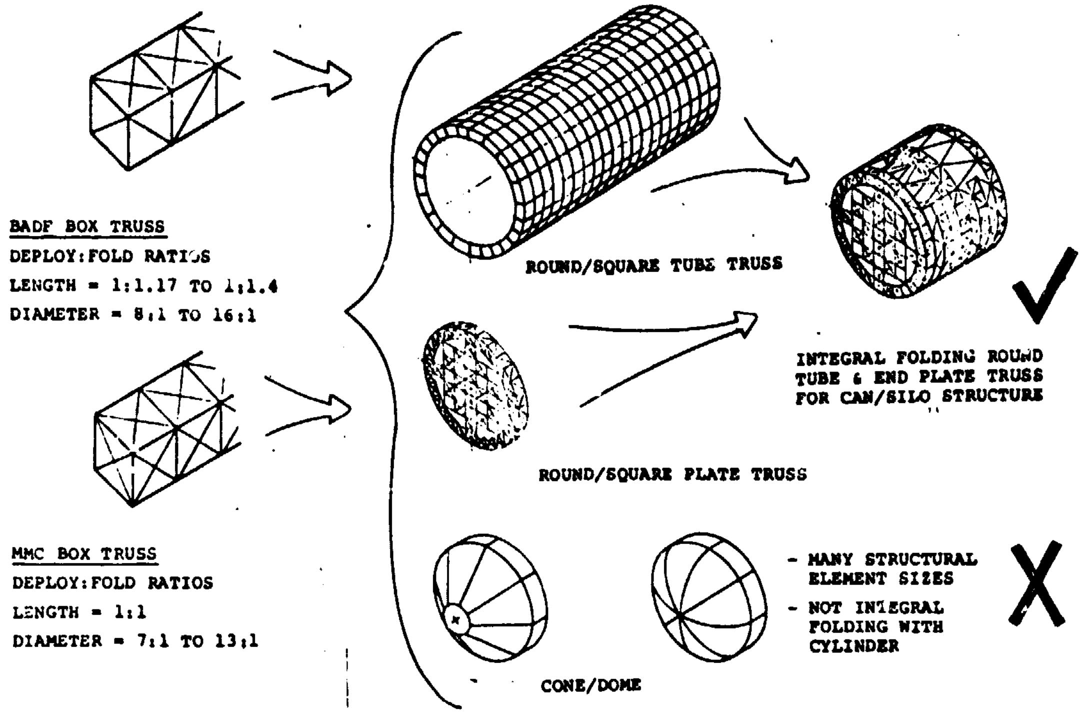

FIGURE 162 CAPABILITIES OF DEPLOYABLE TRUSS OPTIONS

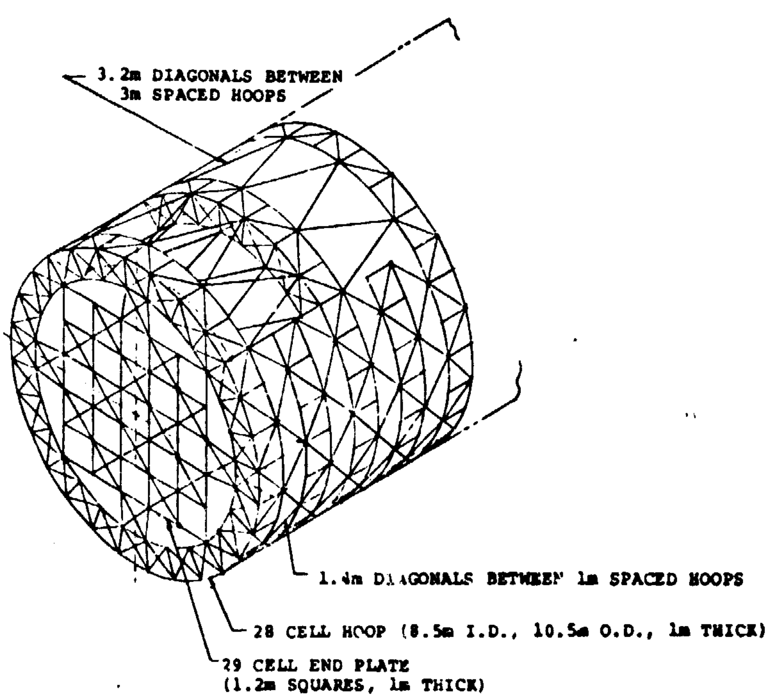

FIGURE 163 BADF SILO TRUSS CYLINDER

have a diameter ratio of 8:1 up to 16:1. Its stowed length, however, is about 1.17 to 1.4 times as great as its deployed length. Some of the optional shapes it can be deployed into are round or square tube trusses, round or square plate trusses, or a dome. The conical or curved dome were not selected to consider further primarily because they could not be folded intregally with a cylinder. In contrast, the plate truss can be intregally folded to form a more complete deployable structure. The fold ratios for the Martin Box Truss are also illustrated on the figure. The length of the cylinder formed by this truss is the same folded as deployed. The diameter ratio range is 7:1 to 13:1. Thus it is not as efficient in diameter ratio as the Biaxial Double Fold but is more efficient in length ratio. The volume ratio is slightly superior for the BADF.

Figure 163 illustrates the Silo Truss Cylinder deployable structure concept. The Biaxial Double Fold truss is illustrated on the figure. The illustration shows that the truss structure need not have uniform strut lengths and angles between struts. For current conceptual evaluation studies a 1 meter truss thickness was used. The hoop on the structure has 28 cells and the end plate has 29 cells. A habitat module using this structure would have 1 cylindrical section and 2 end caps, while a hangar would have 2 cylinder/end cap sections hinged together to provide for OTV entry. One hangar section would be longer than the other. The longer cylindrical section of the hangar attachs rigidly to the Space Station platform. While the short section is hinged to the longer one and is opened and closed using two linear actuators attached at the sides. The short cylinder end caps opens 90° when the two actuators are extended. The OTV would be inserted into the Silo hangar with an RMS and docked to the fixed end cap structure to provide access all a· ınd it over its entire length.

Figure 164 shows additional details of the Silo concept deployable OTV hangar. The one meter folded truss diameter expands to a 10.5 meter OTV hangar diameter. The deployed length is 17% shorter than the stowed length with the Biaxial Double Fold truss, which is illustrated. Rolled thermal/meteoroid shields would be attached by EVA to cover the cylinder and end cap structure. Alternately, it may be possible to preattach the thermal/meteoroid shield and fold it with the structure at the expense of a less favorable stowage volume ratio. The 2000 kg bladder weight estimate given on the figure is for a 14.7 psi pressurized atmosphere with an adequate

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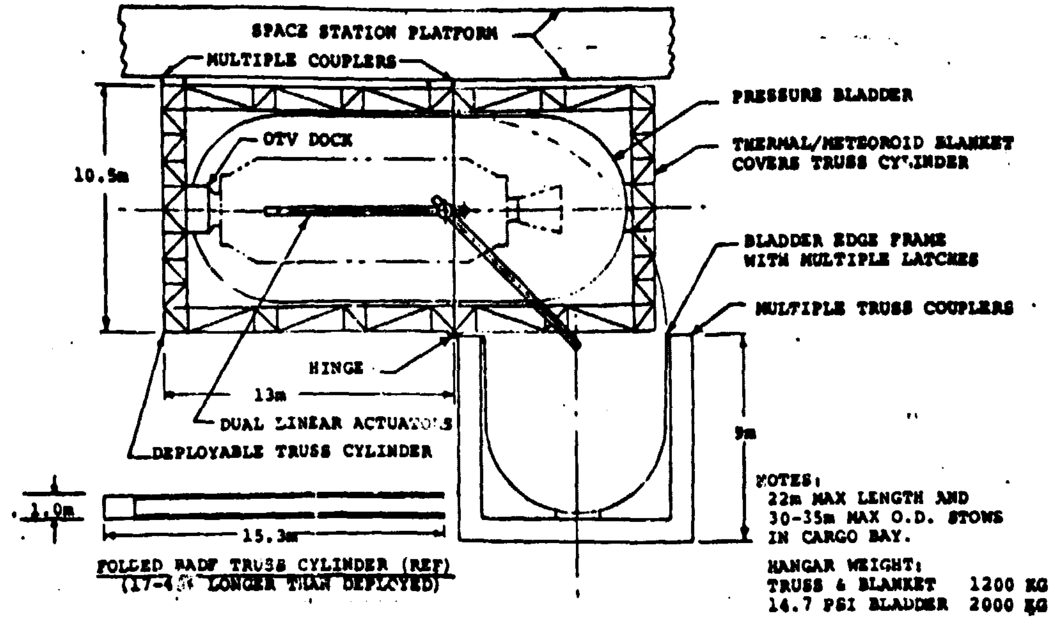

FIGURE 164 SILO CONCEPT-DEPLOYABLE OTV HANGAR

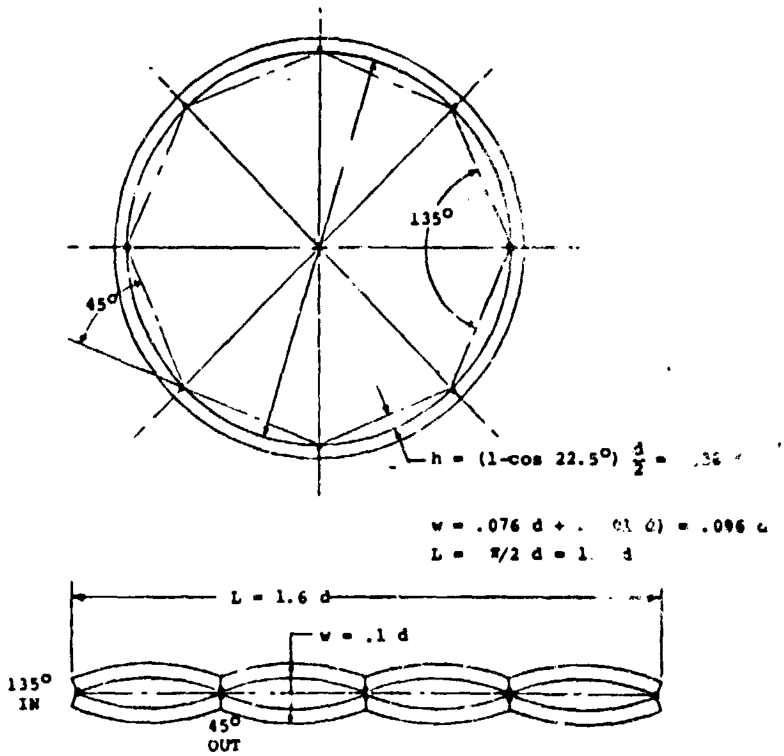

FIGURE 165 ATTACHED BLADDER EDGE FOLDING FRAME

safety factor, using Kevlar as the structural fabric. The truss and blanket structure are estimated to weigh approximately 1200 kg.

Figure 165 illustrates how the frame to which the bladder attaches might be folded so it could stow more conveniently in the cargo bay. It would be desirable to roll the bladder around this frame. With the intregal attachment of the bladder to the frame it was important to investigate the feasibility of folding the frame without stretching or crimping the bladder edge, which would interface with a pressure seal. Figures 166 and 167 show a concept for this. If it is not possible to preattach the bladder to the edge folding frame and maintain structural or sealing integrity, a concept such as that illustrated in Figure 168 could be used for a detachable bladder.

Figure 169 shows the two options considered in bladder pressure load retention. Option A shows the bladder resting against the truss structure, which supports the pressure force due to the internal pressurization of the bladder. The bladder primarily seals the gas inside. While this would provide a lighter bladder it complicates the design and loads the struss in an unfavorable bending mode. In Option B the bladder itself both restrains the pressure and contains the gas. It is loaded in hoop tension. The truss structure then provides a backbone for hard mounting internal equipment (through penetrations), external equipment, utilities, and the thermal/meteoroid blanket. The bladder then is much simpler, the truss structure is simplified and lighter and fit/function reliability is high. Option B was selected as the most desirable approach for use in the Deployable Volume concepts. In Figure 170 the concept for the hardpoint penetration of the bladder with a bellows seal is illustrated. It would be possible also to evolve this concept to allow utilities to pass through. A utility integration concept compatible with the deployable truss and bladder volumes is illustrated in Figure 171. A subsystem could be placed inside the external truss or located anywhere on it and be protected by the thermal/meteoroid blanket. Access is through blanket flaps. Subsystems could be installed with the aid of the RMS or EVA after deployment of the truss. The utilities paths are through the docking hatch directly to external subsystems or through the docking hatch and into the pressurized compartment. External subsystem utility interfaces to the pressurized compartment would be through the structural/utility bladder penetration.

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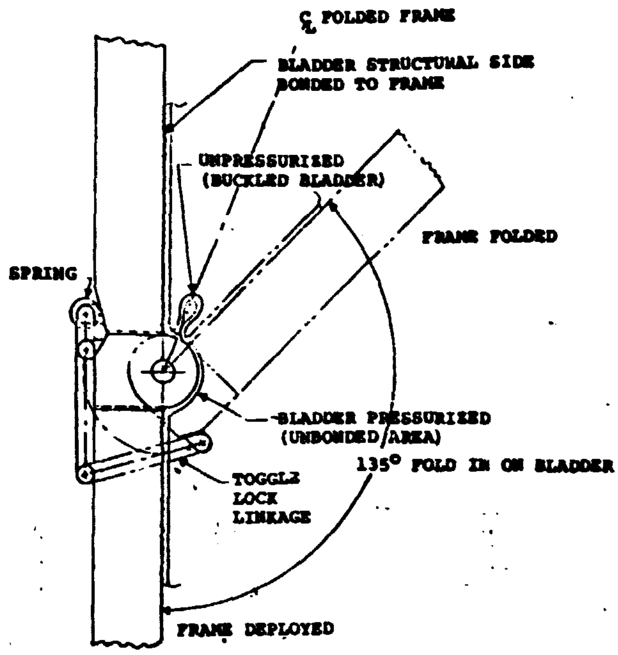

FIGURE 166 135° INSIDE BLADDER FRAME BEND

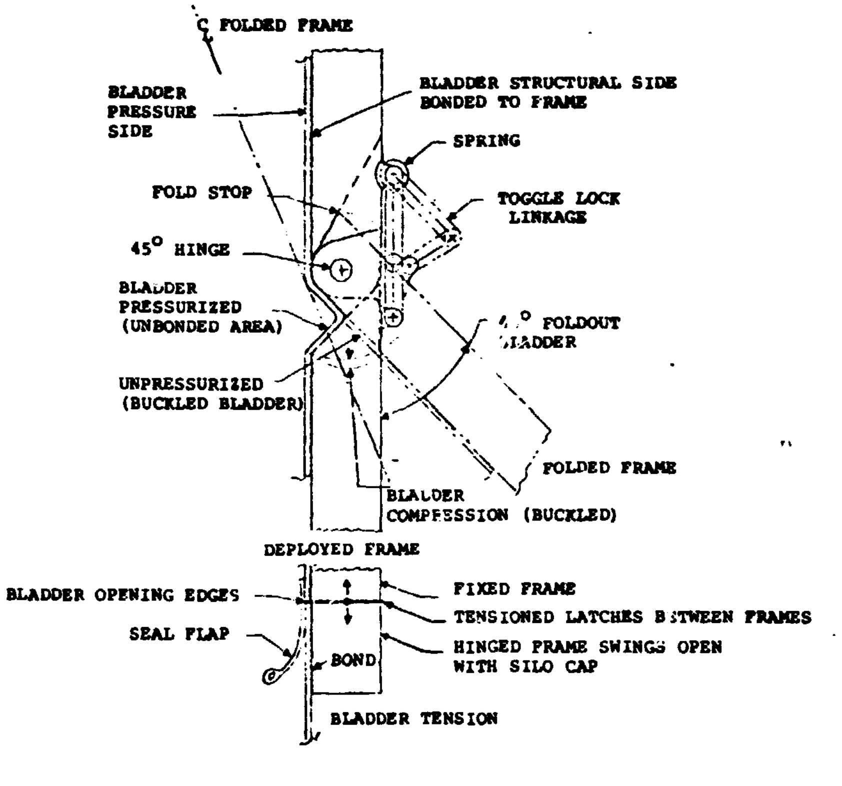

FIGURE 167 45° OUTSIDE BLADDER FRAME BEND-NO BLADDER STRETCH

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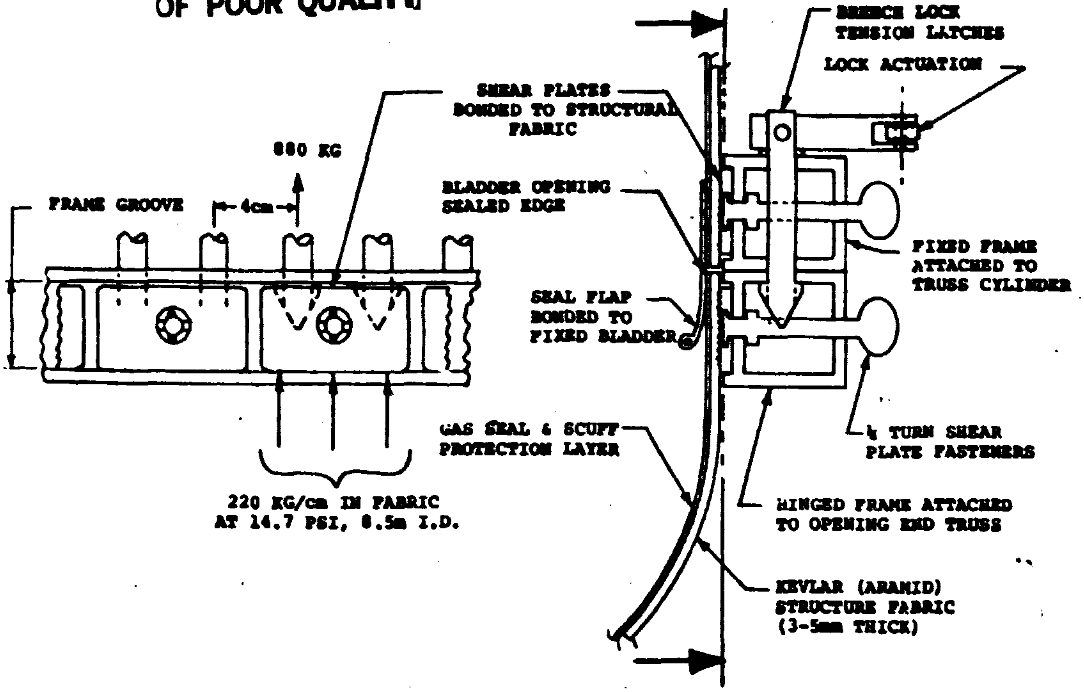


FIGURE 168 DETACHABLE BLADDER EDGE FOLDING FRAME

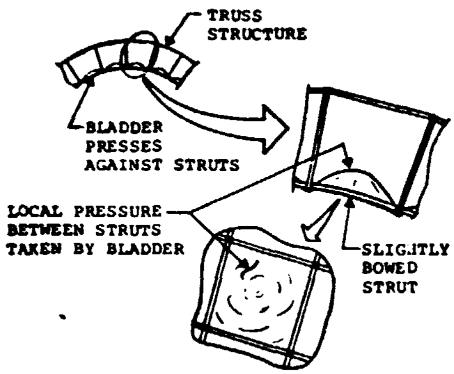
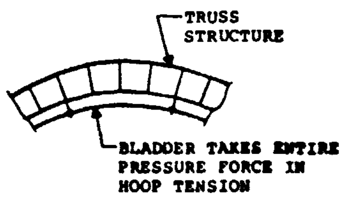
OPTIONS	ADVANTAGES	DISADVANTAGES
A. STRUCTURE RESTRAINS BLADDER  TRUSS STRUCTURE BLADDER PRESSES AGAINST STRUTS LOCAL PRESSURE BETWEEN STRUTS TAKEN BY BLADDER SLIGHTLY BOWED STRUT	. LIGHTER BLADDER	. REQUIRES PREFORMED BULGES IN BLADDER TO MATCH TRUSS . STRUT LOADING REQUIRES HEAVIER TRUSS STRUCTURE X
B. BLADDER RESTRAINS PRESSURE  TRUSS STRUCTURE BLADDER TAKES ENTIRE PRESSURE FORCE IN HOOP TENSION	. LIGHTER TRUSS STRUCTURE . SIMPLIFIES BLADDER CONSTRUCTION . SIMPLIFIES TRUSS STRUCTURE . MORE RELIABLE FIT/FUNCTION	. HEAVIER, LESS FLEXIBLE BLADDER √ SELECTED

FIGURE 169 BLADDER PRESSURE-LOAD RETENTION OPTIONS

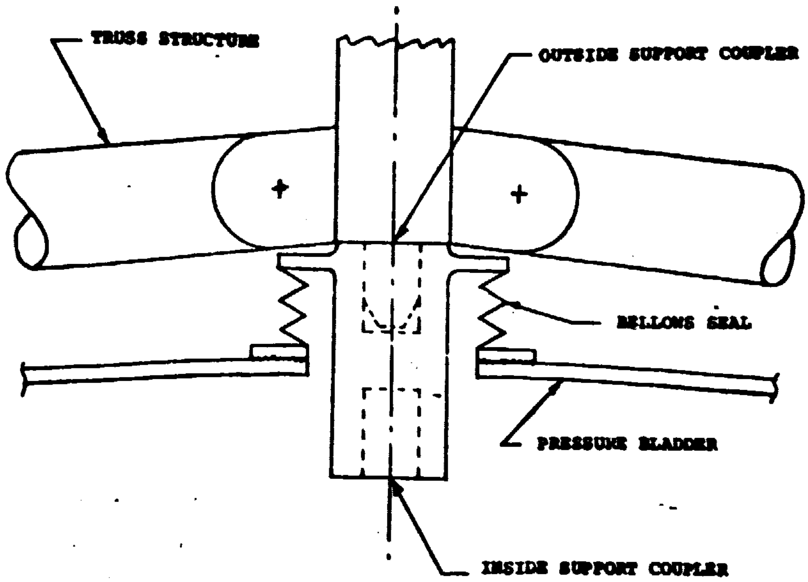


FIGURE 170 BELLOWS SEALED INSIDE SUPPORTS

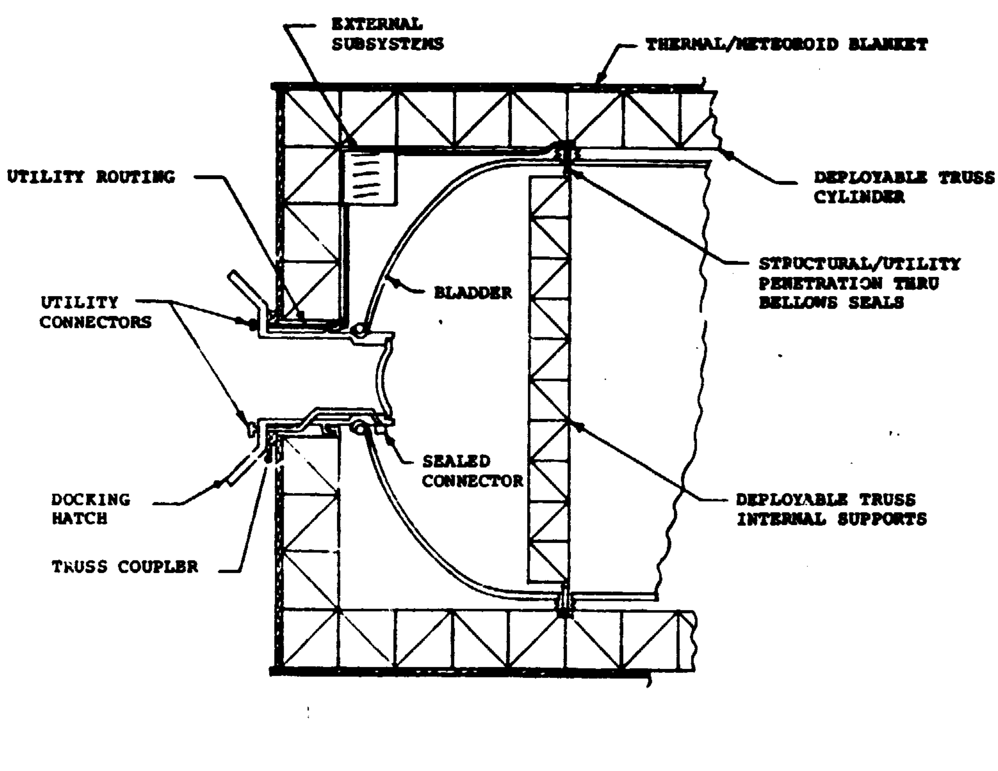


FIGURE 171 UTILITIES CONCEPT DETAILS

Figure 172 illustrates the stowage capability of the Silo OTV hangar. Stowage for 2 OTV hangars requires a space of only half the cargo bay. For each hangar two cylinders are shown. Inside one of the cylinders a thermal meteoroid shield is rolled. Stored under the truss cylinders are the pressure bladders which are wraped on their folded edge frames.

Figure 173 shows the Silo concept for a deployable habitat. In this case a seal frame is not necessary because the bladder would be continuous except for the openings at the hatch on each end. If it is possible to preattach the bladder and fold or roll it inside the stowed structure it will be necessary to use the Martin Marietta truss cylinder, which does not change length during deployment. Dimensions in the stowed and deployed configurations shown on this figure are for the Martin Marietta truss. The weight estimate for the truss and blanket is 800 kg and for the bladder is 1400 kg. Also indicated on the sketch is a truss deck located at several places across the inside of the module. Decks could similarly be located in other arrangements, picking up hard point penetrations through the bladder. The deployable truss decks could be inserted inside and deployed, subsequent to deployment of the habitat itself.

Figure 174 shows the stowage envelope for 2 habitat modules which are 10.8 meters in diameter and 15.3 meter long when deployed. Two complete modules can be stowed in half of the Shuttle cargo bay. The habitats shown have folded trusses with integral pressure bladders and rolled thermal/meteoroid shields. It is also indicated that folded internal supports and airlock structures could be included.

The concept for installation of equipment inside the pressurized volume of a habitat module is illustrated in Figure 175. The options are to install the equipment through the hatch tunnel into the pressurized area or install the equipment through a sectioned bladder and structure. Equipment installation through the hatch/tunnel into the pressurized area has the advantage that deployment or connection work is accomplished in a pressurized environment and no added seals are required. It has the disadvantage of requiring that the equipment and experiments be designed relatively small or be deployed or assembled in sequence after they are moved inside. The advantage of installing through the sectioned area is that large non-specialized equipment would be acceptable. However, considerable EVA would be required because of the unpressurized condition, and the habitat

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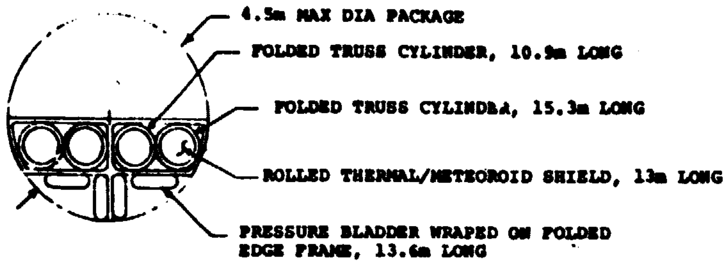

FIGURE 172

TWO SILO OTV HANGARS STOWED IN
ONE HALF CARGO BAY

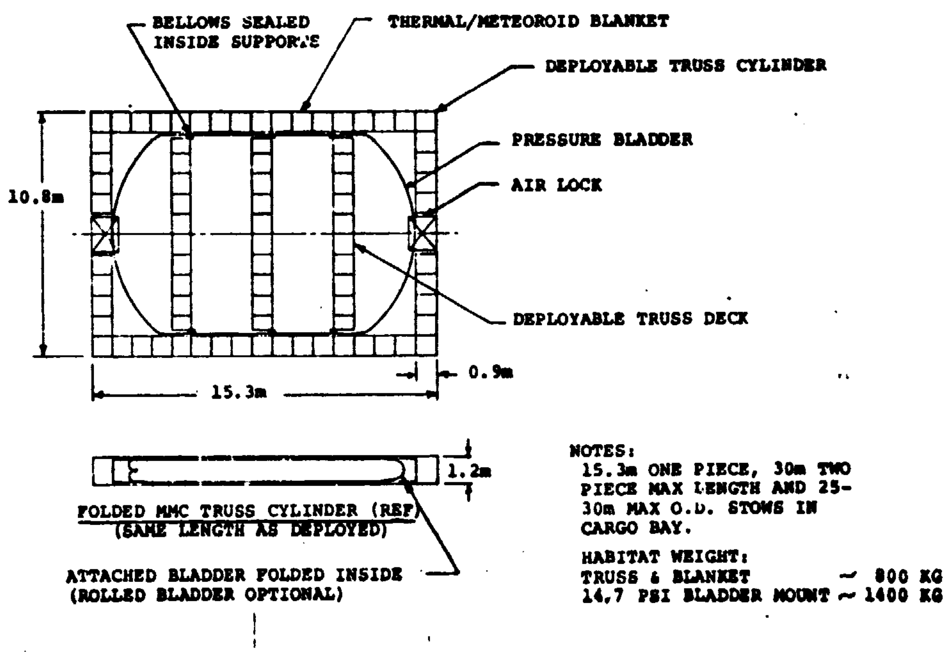

FIGURE 173 SILO CONCEPT-DEPLOYABLE HABITAT

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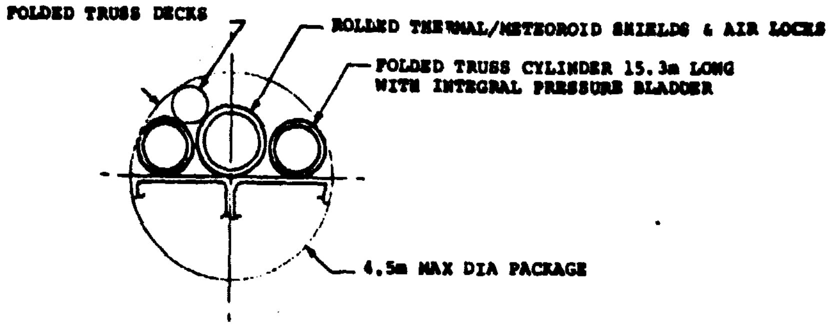

FIGURE 174 TWO SILO HABITATS STOWED IN ONE HALF CARGO BAY

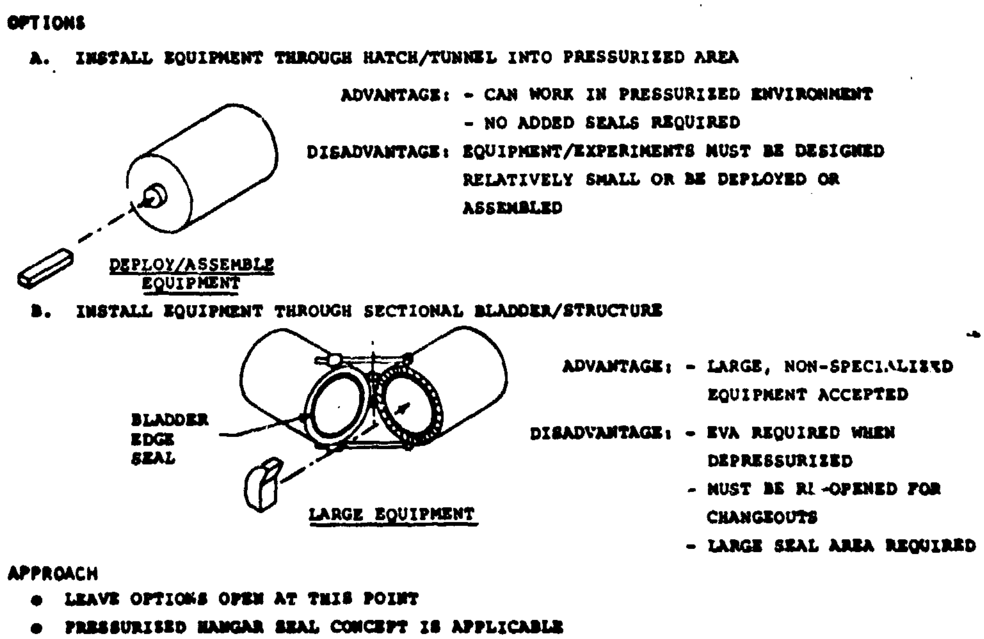

FIGURE 175
CONCEPTS FOR INSTALLATION OF EQUIPMENT IN PRESSURIZED HABITAT/STORAGE VOLUME

module would have to be reopened for changeouts. Either of these options could be used and are left open at this point. If the sealed, sectioned concept were to be used the pressurized hanger seal concept would be applicable.

6.4 RECOMMENDED CONCEPTS FOR FURTHER WORK

Figure 176 illustrates the three concepts recommended for further study. The flexible convoluted tube should be considered for tunnel applications. Variations should be evaluated that include external structure for providing more rigidity and standoff mounting of thermal/meteoroid shielding. The Silo type truss habitat is recommended for further design studies. It is recommended that both the Biaxial Double Fold and Martin Marietta Box Truss be evaluated and that the attached bladder and blanket be evaluated further. The Silo type truss hangar is recommended for further design studies, both pressurized and unpressurized.

6.5 TECHNOLOGIES DRIVERS

Emerging candidates for design drivers and technology development for deployable volumes include a reliable, long life bladder seal and bladder materials and construction techniques to provide flexibility for rolling and folding. Design concepts should be considered and evolved for EVA compatible assembly of rigid and flexible structures. Techniques for achieving adequate radiation shielding mass while retaining the benefits of flexible deployable structures will need to be considered for some orbits that have very high radiation fluxes. Subsequent definition of technology development requirements will be needed and will evolve in the recommended further studies.

FLEXIBLE CONVOLUTED TUBE

- RIGIDIZED BY FRAMES AND LONGITUDINAL CABLES
- CABLES ADJUST LENGTH/CURVATURE
- 4.5m MAX DIA, 120m MAX LENGTH

SILO TRUSS HABITAT

- ATTACHED BLADDER & BLANKET DEPLOY WITH TRUSS
- MMC TRUSS FOR CONSTANT LENGTH
- INTERNAL EQUIPMENT/SUPPORTS INSTALL THRU HATCHES

SILO TRUSS HANGAR

- TWO PIECE TRUSS & BLADDER
- BLADDER & BLANKET ATTACHED AFTER TRUSS DEPLOYS
- BADF OR MMC TRUSS USABLE
- INTERNAL EQUIPMENT/SUPPORTS INSTALL THRU OPEN SECTION

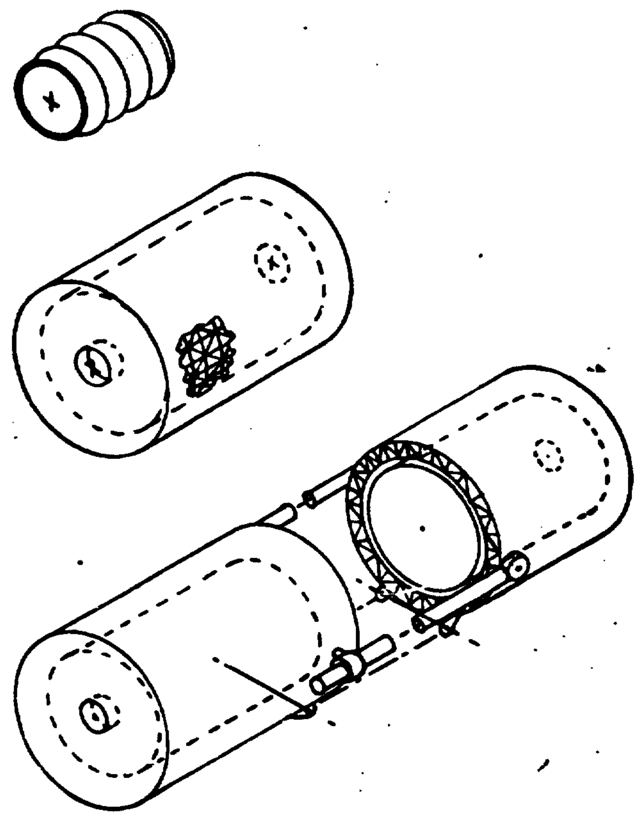

FIGURE 176 RECOMMENDED CONCEPTS FOR FURTHER WORK

7.0 CONCLUSIONS

7.1 LINEAR AND AREA PLATFORMS

1. All the design objectives of the deployable platform system can be achieved. It is possible to automatically deploy and retract large structures with fully integrated utilities and which possess a very high degree of configuration variability. These structures can provide versatile payload and subsystem interfaces. A high structural packaging efficiency is possible even with the integration of utilities. Technology readiness by 1986 can be accomplished with only a modest amount of technology development required. Minimum EVA and RMS support of the deployable structures will be necessary, and full compatibility with the Space Shuttle Orbiter is possible.

2. The Biaxial Double Fold is the clear choice as the best structure for a deployable platform system. It is a new concept evolved during the present study for the specific purposes of compact packaging and utilities integration. In detailed trade studies it was evaluated against three other leading concepts: the Vought Double Fold, the General Dynamics Square Diamond Truss Beam, and the Martin Marietta Box Truss. The Biaxial Double Fold scored top in each of the following five major criteria categories: Platform Capability, Deployability, Versatility, Integration, and Performance. When evaluated against the 26 sub-criteria comprising the major categories it scored highest or tied for highest score in 23 of the 26 entries. Consideration of the sensitivity of the choice to the weighting factors used showed that the Biaxial Double Fold selection is insensitive to the assignment of weighting factors.

3. The characteristics of the Biaxial Double Fold relative to each of the design objectives are as follows:

   a) Automatic Deployment and Retraction - The Biaxial Double can deploy and retract automatically and repeatedly with a full complement of utilities integrated into it. Dynamic and directional control is provided by a restraint/retract cable system. The truss collectively deploys all cells at the same time, and biaxially deploys in two directions at the same time. It is suitable for self contained actuation only. The deployment system consists of linear compression spring energy at vertical struts plus torsion spring energy at node pivots controlled by the cable restraint and retraction system.

Redundancy is provided for reliability by the parallel cable systems. When evaluated by the Stoll Deployability Index of Merit the Biaxial Double Fold scores a very high 250.

b) Utilities Integration - The Biaxial Double Fold is suitable for integrating full utilities requirements internal to the struts and through the nodes. For a representative example, the utilities requirements for the ASASP, consisting of four bundles of approximately 5cm in dia each, routed through the longitudinal struts of a 3m truss, can be accommodated. The Biaxial Double Fold is suitable for utilities branching to make interfaces with truss-to-truss and truss-to-module joints. Tests indicate that when utilities are routed through the struts the bend radius at the nodes is such that greater than 200 cycles of deployment and retraction are possible before fatigue limitations are reached. The Biaxial Double Fold can also accommodate utilities routed adjacent but external to the struts. An equal quantity of utilities external to the struts can be included at the same time the internal routing is integrated into the structure. However, sufficient connectors to terminate both internal and external utilities cannot be located at the same node.

c) Configuration Variability - The Biaxial Double Fold is suitable for deploying into a linear beam or for mast type operations. Its suitable for interfacing other trusses at various oblique angles and interfaces can be made with transition structure which biaxially folds with the main truss. It can deploy into tapered beams as well as straight beams. It can deploy into curved shapes, flat shapes such as area platforms, and round shapes. It can be built up into various other shapes simply by coupling linear or curved surfaces that are deployed.

d) Versatile Payload and Subsystem Interfaces - The Biaxial Double Fold is capable of integrating small equipment or payload items directly onto the truss in the folded stage and deploying it with the truss, without subsequent attachment required. Larger structures can also be integrated and preattached prior to deployment but involve an automatic latching of two nodes at the time deployment is completed. Likewise, intermediately mounted trusses, such as a branch arm with an antenna at the end, can be deployed with the Biaxial Double Fold. Subsystems may be directly mounted to the structure prior to or subsequent to deployment, or they may be mounted in a module attached to the structure.

e) Structural and Packaging Efficiency - For a representative 3m truss filled with utilities, the Biaxial Double Fold stowage ratio is 172:1. A representative 3m cubic cell of this truss would weigh about 21.6 kg. The truss packages in a double fold configuration only. The package height is 1.4 times the cell height. The structure is efficient in that it is very simple. There are only 38 joints required per cell and 2 types of nodes are involved. There are 15 elements per cell.

f) Technology Readiness - The Biaxial Double Fold does not require any substantial amount of technology development for 1986 readiness. Six items were identified and recommended for technology development. Only one, the development of the composite material for use in the structure and nodes can be considered as a potentially enabling technology, but is not specific to the BADF concept.

g) EVA/RMS Requirements - No EVA is required to deploy or retract the Biaxial Double Fold, but the truss is compatible with EVA for backup contingency operation. No RMS is required for basic deployment of the truss. The truss is compatible with the RMS for such operations as assembling the truss modules together.

h) Shuttle Operational Compatibility - Because of its light weight and excellent packaging ratio, the Biaxial Double Fold is highly compatible with the Space Shuttle for transportation and deployment. It would be possible to package a beam which is 3m square in cross section and 276 m long when deployed, in the Shuttle cargo bay as a single beam. Also 44 individual truss modules, each 15 cells long and 3 meters square, could be packaged in the Shuttle cargo bay leading to a total deployed and assembled length of 1980 meters. A maximum cross section beam of 12-1/2 meter square will fit in the cargo bay of the Shuttle.

4. Six special technology items were identified to enhance the effectiveness of the deployable platform system: 1) compact, low pressure drop, "zero" leak fluid quick disconnect, 2) materials and design concepts suitable for tailored low coefficient of thermal expansion graphite/epoxy materials in minimum gage struts and fittings, 3) high flexibility, high endurance life electrical cables suitable for small bend radius use, 4) super flexible fluid hose for high endurance life suitable for small bend radius use, 5) compact, low loss fiber optics tee, 6) low solar absorptance, low thermal emittance thermal coating. It is expected than none of these, with the possible exception of tailored low coefficient of thermal expansion graphite/epoxy minimum gage materials, is required to enable the platform design.

7.2 DEPLOYABLE VOLUME CONCLUSIONS

1. A highly compact deployable volume concept using trusses which deploy from a small diameter cylinder is feasible. Biaxially folding trusses such as the Martin Marietta Box Truss or the Biaxial Double Fold are suitable. This concept would be useful for large habitats or OTV hangars transported by the Space Shuttle. A separate pressure bladder supported by the structure would be contained and protected by the truss structure. The entire truss structure with the internal bladder would be passively controlled thermally and protected from micrometeoroids by an external blanket. The blanket and bladder materials provide sufficient Van Allen radiation shielding for near term Space Station missions.

2. A flexible convoluted tube which deploys in the axial direction is a good candidate for a transfer tunnel. This is an evolution of a concept developed in the late '60's and early '70's. It is an excellent candidate when combined with a deployable truss for structural rigidity, mounting space for utilities and equipment, and spacing for meteoroid and thermal blanket mounting.

3. Several technology development requirements are expected to evolve in such areas as strong foldable bladder materials, long life bladder seals, and concepts for assembly of rigid and flexible structures . It is recommended that additional work be done in the deployable volume areas which would entail identifying these technologies as well as evolving the concepts.

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