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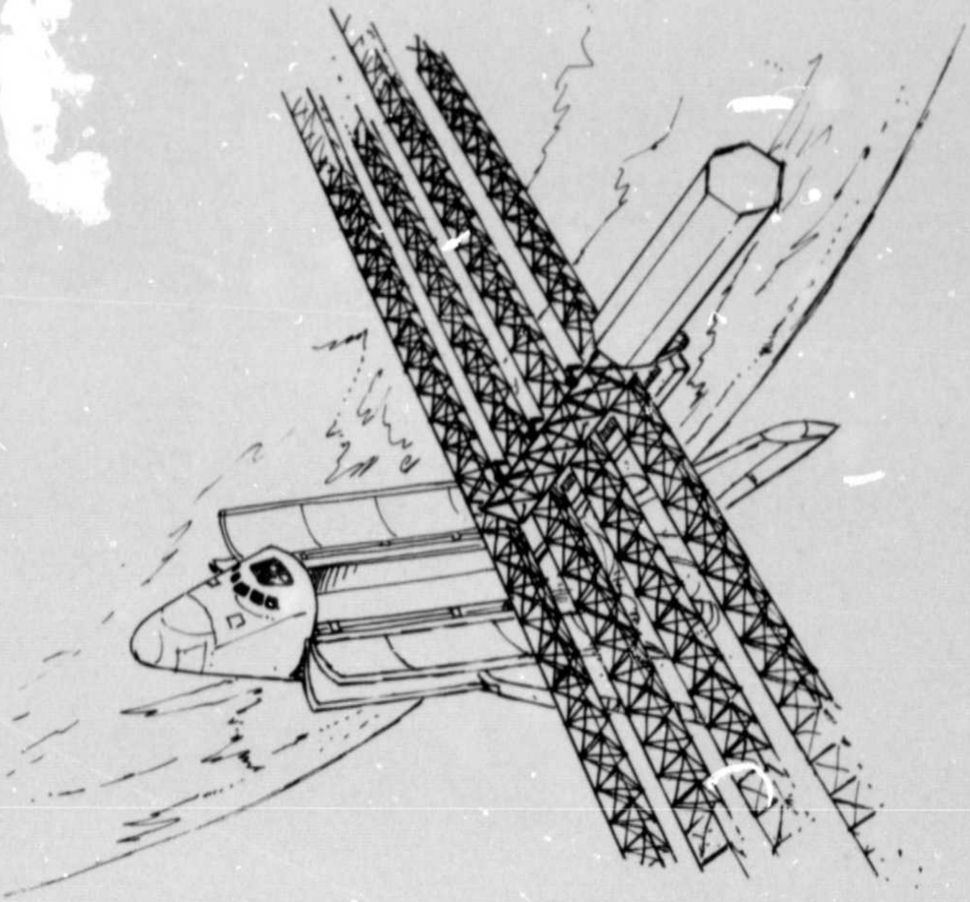

SPACE CONSTRUCTION AUTOMATED FABRICATION EXPERIMENT DEFINITION STUDY (SCAFEDS)

FINAL REPORT
VOLUME I ◆ EXECUTIVE SUMMARY

CONTRACT NO. NAS9-15310
DRL NO. T-1346
DRD NO. MA-664T
LINE ITEM NO. 3

GENERAL DYNAMICS
Convair Division

Kearny Mesa Plant, P.O. Box 80847
San Diego, California 92138
Advanced Space Programs

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12 May 1978

Submitted to
National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas 77058

Prepared by
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San Diego, California 92138

FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA/JSC in accordance with Contract NAS9-15310, DRL No. T-1346, DRD No. MA-664T, Line Item No. 3. It consists of three volumes: (I) A brief Executive Summary; (II) a comprehensive set of Study Results; and (III) a compilation of Requirements suitable for use as a preliminary system specification for subsequent Phase B studies.

The principal study results were developed from April 1977 through January 1978, followed by a beam fabrication task and final documentation. Reviews were presented at JSC on 19 July 1977, 1 September 1977, 9 November 1977, and 3 February 1978 and at NASA Headquarters on 10 February 1978.

Due to the broad scope of this study, many individuals were involved in providing technical assistance. General Dynamics Convair personnel who significantly contributed to the study include:

Study Manager	-	Lee Browning
Mechanical Design	-	John Bodle, Des Kozmary, Bob Trussell, Maurice Butler, A. D. McFarlan
Avionics & Controls	-	Jack Fisher, Dave Sears, Ron Newby
Requirements & Operations	-	Charlie Hyde, Jim Peterson, John Maloney, Tad Winiecki
EVA/IVA	-	Kent Geyer, Mike Byrd
Structural Design	-	Lee Browning, Des Vaughan
Structural Analysis	-	Denny Laue, Jack Dyer
Structural Dynamics	-	Des Pengelley, Mike Shafir, Jack Weber
Stability & Control	-	Bill Stubblefield
Thermodynamics	-	Bruce Kaser
Mass Properties	-	Dave Johnston, John Kessler, Marv French, Julie Richardson
Materials & Processes	-	Jules Hertz, Chuck May, Herb Urbach, Joe Villa, Carlos Portugal
Manufacturing R&D	-	Jerry Peddie
Economic Analysis	-	Bob Bradley
Test Integration	-	Phil Gardner

The study was conducted in Convair's Advanced Space Programs department, directed by J. B. (Jack) Hurt. The NASA-JSC COR is Lyle Jenkins of the Spacecraft Design Division, under Allen J. Louviere, Chief.

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1

INTRODUCTION

1.1 SCOPE

This Executive Summary is the first of three volumes comprising the SCAFED Study Final Report. Other volumes provide the detailed results of all study tasks and a comprehensive Requirements Document.

1.2 STUDY OVERVIEW

The top-level objectives of this definition study are:

a. Define the techniques, processes, and equipment required for automatic fabrication and assembly of structural elements in space using Shuttle as a launch vehicle and construction base.

b. Identify and define additional construction/systems/operational techniques, processes, and equipment which can be developed/demonstrated in the same program to provide further risk reduction benefits to future large space systems.

The corresponding objectives for downstream program phases consist of the development and flight demonstration of the above.

Study activities were divided into two parts, depicted in Figures 1-1 and 1-2. Convair proposal concepts for the platform structure and beam builder served as reference configurations for the Part I design trade tasks.

1.3 SCAFE SYSTEM CONCEPT

The SCAFE system concept is shown in Figure 1-3. Following boost to orbit and system deployment from the stowed position, a beam-builder, moving to successive positions along a Shuttle-attached assembly jig, automatically fabricates four triangular beams, each 200 meters long. Retention of the completed beams is provided by the assembly jig.

The beam-builder then moves to the position shown and fabricates the first of nine shorter, but otherwise identical, cross-beams. After cross-beam attachment, the partially completed assembly is automatically transported across the face of the assembly jig to the next cross-beam location, where another cross-beam is fabricated and installed. This process repeats until the "ladder" platform assembly is complete. During this process an opportunity to develop/evaluate EVA is provided by the difficult-to-automate task of sensor/equipment attachment, as shown.

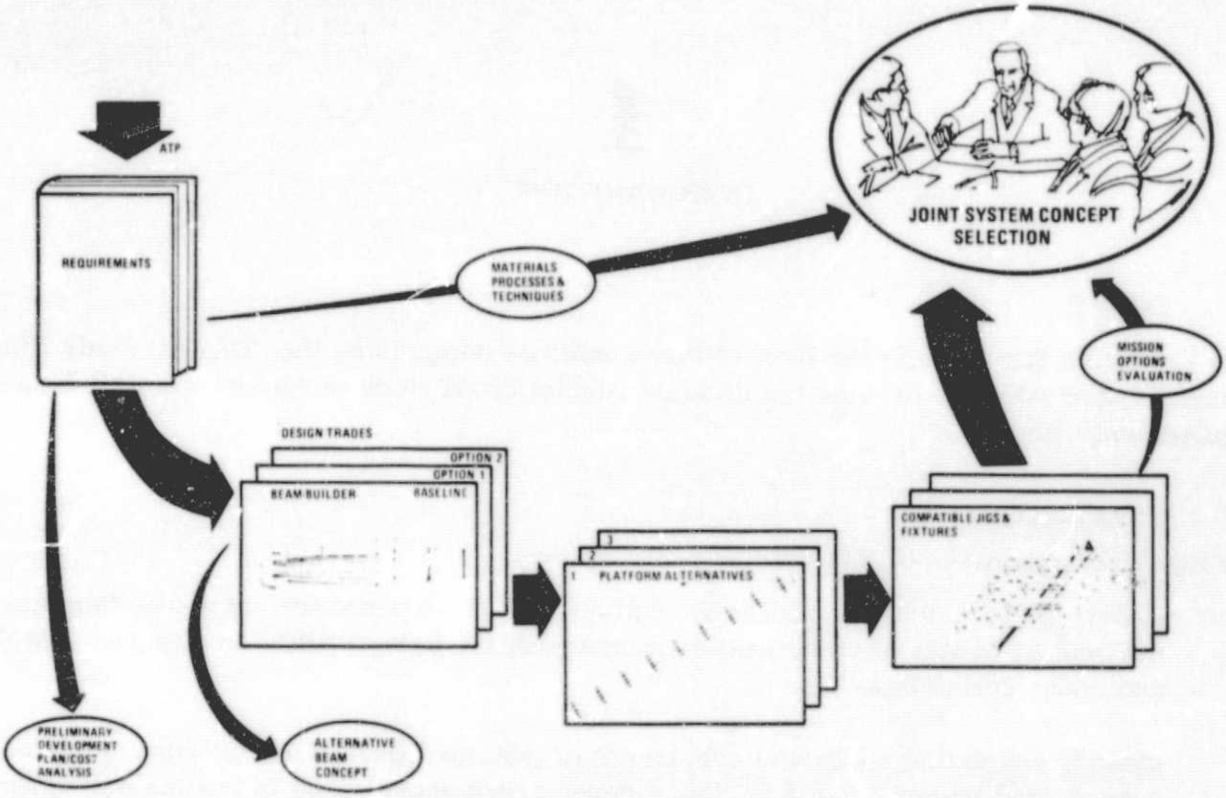


Figure 1-1. Study approach, Part I.

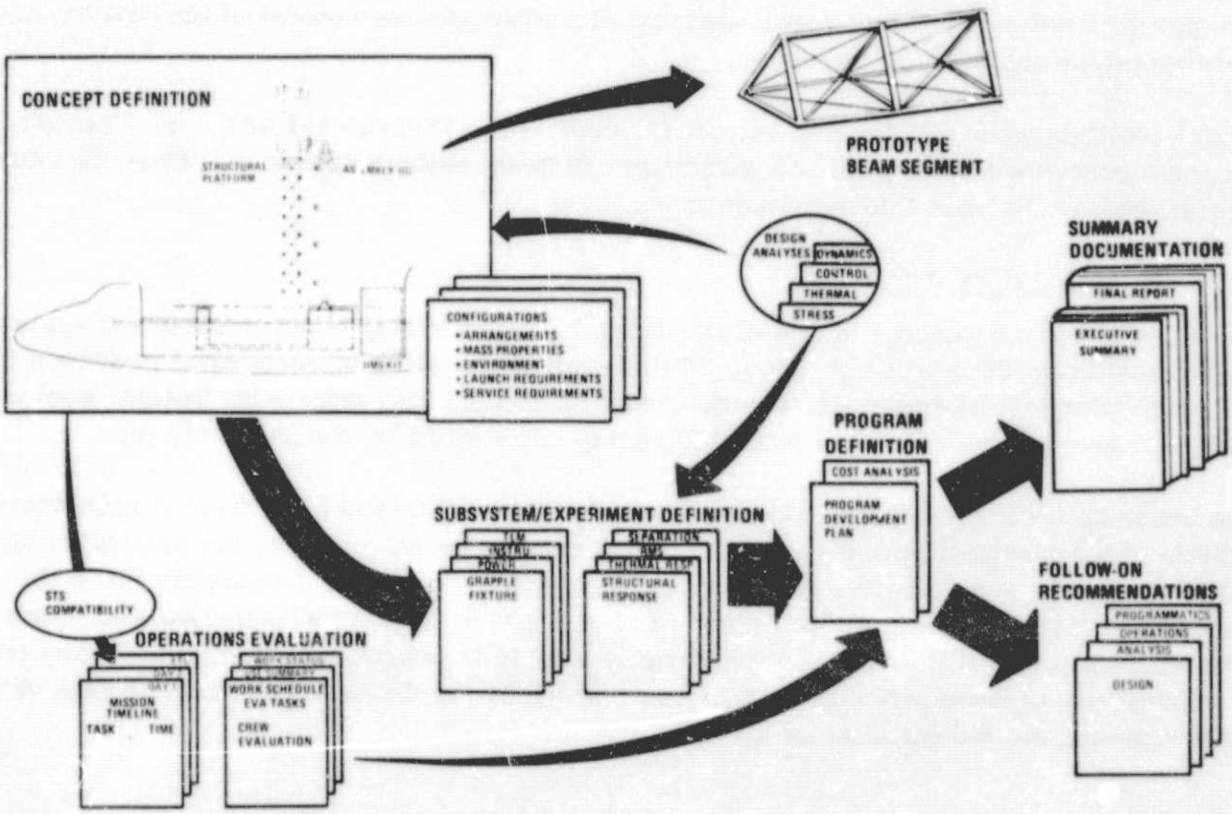


Figure 1-2. Study approach, Part II.

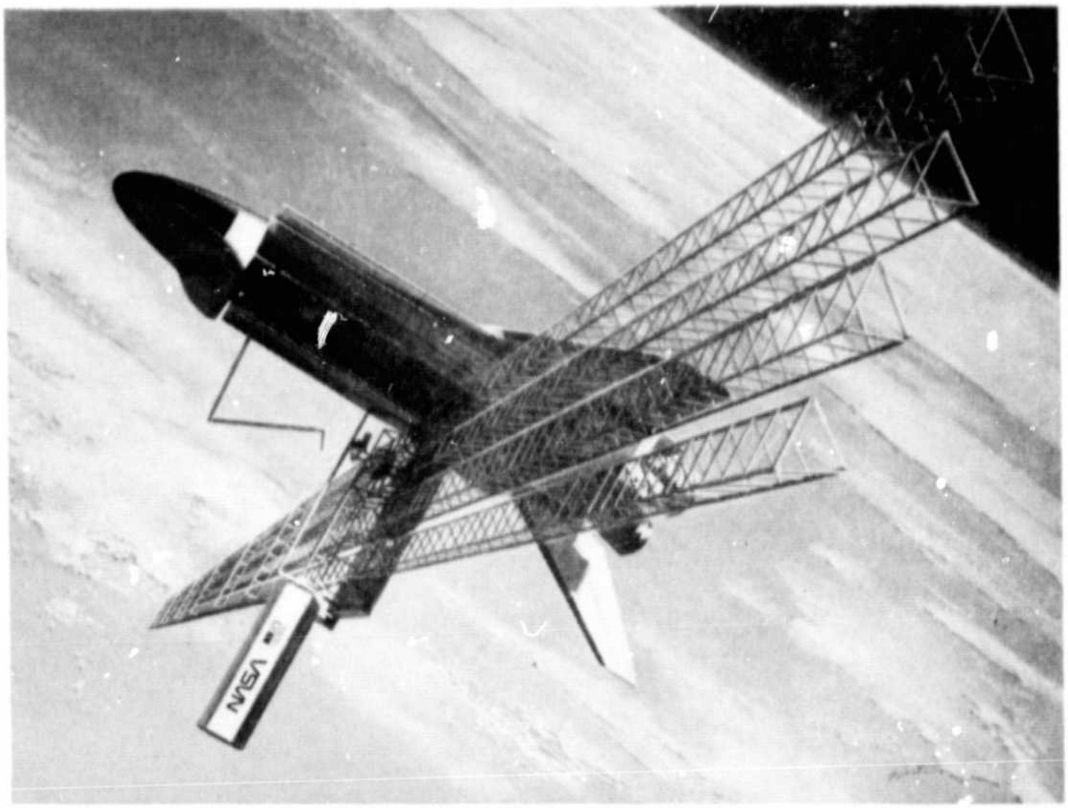


Figure 1-3. Baseline system concept.

Upon platform assembly completion, both structural and thermal response tests are conducted and RMS/platform release/recapture techniques are developed. The seven-day mission cycle concludes with EVA demonstration of unscheduled maintenance and repair activities followed by platform separation and Shuttle return.

NASA-provided guidelines used in developing the SCAFE system are summarized in Table 1-1.

Table 1-1. Study guidelines.

- FLIGHT MISSION
  - 28.5°; 556 km circular orbit
  - Mid-1982 ETR launch
  - Single flight, seven-day duration to:
    - Fabricate, assemble structural platform
    - Install instrumentation, scientific equipment
    - Conduct dynamic, thermal response tests
    - Separate platform
    - Perform reference scientific experiments (geodynamics, atmospheric composition)
- PLATFORM SPACECRAFT
  - NASA baseline configuration: 4 at 200m x 9 at 10.6m
  - Beams: triangular; >1m deep; continuous caps
  - Material: graphite/thermoplastic; ground pre-consolidated
- FABRICATION SYSTEM
  - STS compatible: wt/cg; loads; power; heat rejection; 1 OMS kit
  - Automatic in-situ beam fabrication
  - Compact raw material packaging
  - Rolltrusion forming process
  - Concept compatible with beam size scale-up

2

STUDY RESULTS

Study results in the areas of Structure/Materials, Fabrication Systems (Beam Builder, Assembly Jig, and Avionics/Controls), Mission Integration, and Programmatics are summarized in the following subsections.

2.1 STRUCTURE/MATERIALS

2.1.1 PLATFORM STRUCTURE

Characteristics of the "ladder" platform, its component beams, and individual beam elements are shown in Figure 2-1. Each longitudinal beam comprises 139 identical bays plus an allowance at each end for cutoff by the beam builder. Each cross-beam comprises 7 bays plus end cutoff allowances. Bay spacing, beam size, and element details are identical for both longitudinal and cross beams. Each beam assembly consists of three continuous cap members, equally-spaced flared-channel cross-members, and continuous diagonal cord cross-bracing. This structural concept, and its associated beam builder concept (Section 2.2.1) were selected in a combined machine/structure trade study which considered the four options illustrated in Figure 2-2.

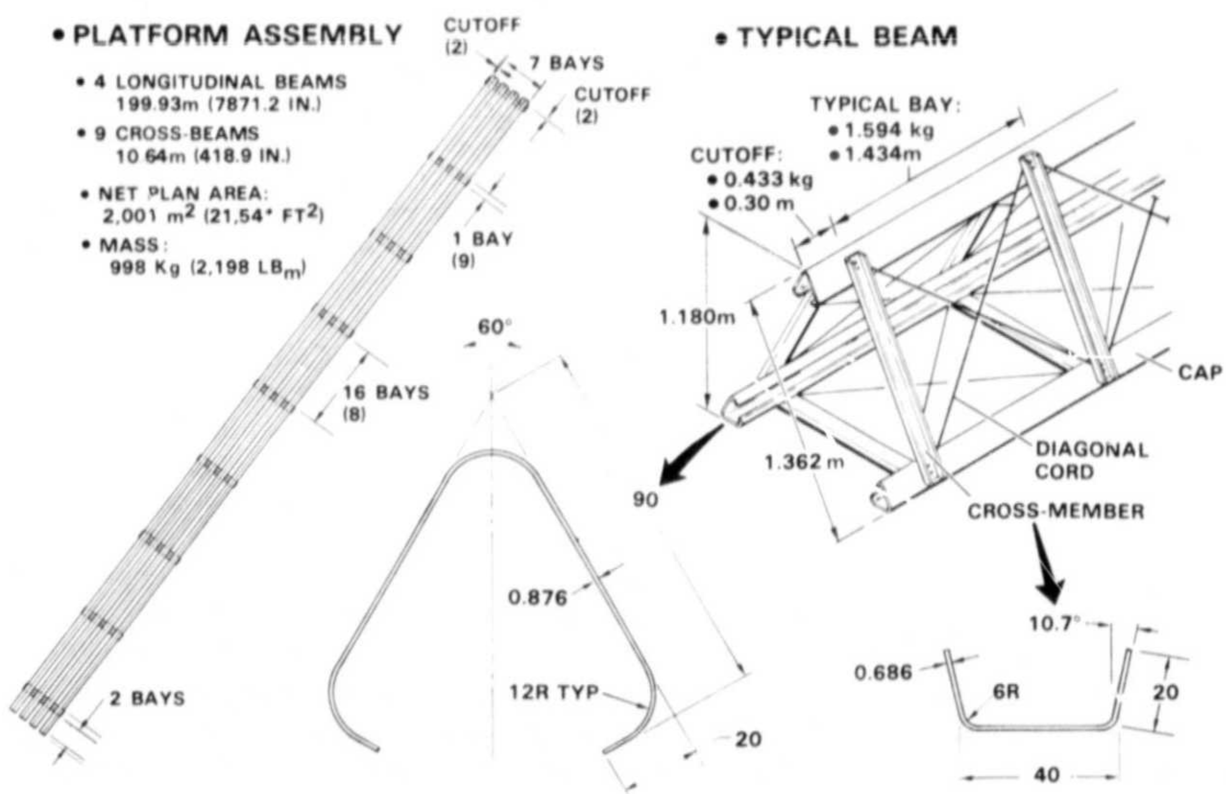


Figure 2-1. Platform characteristics.

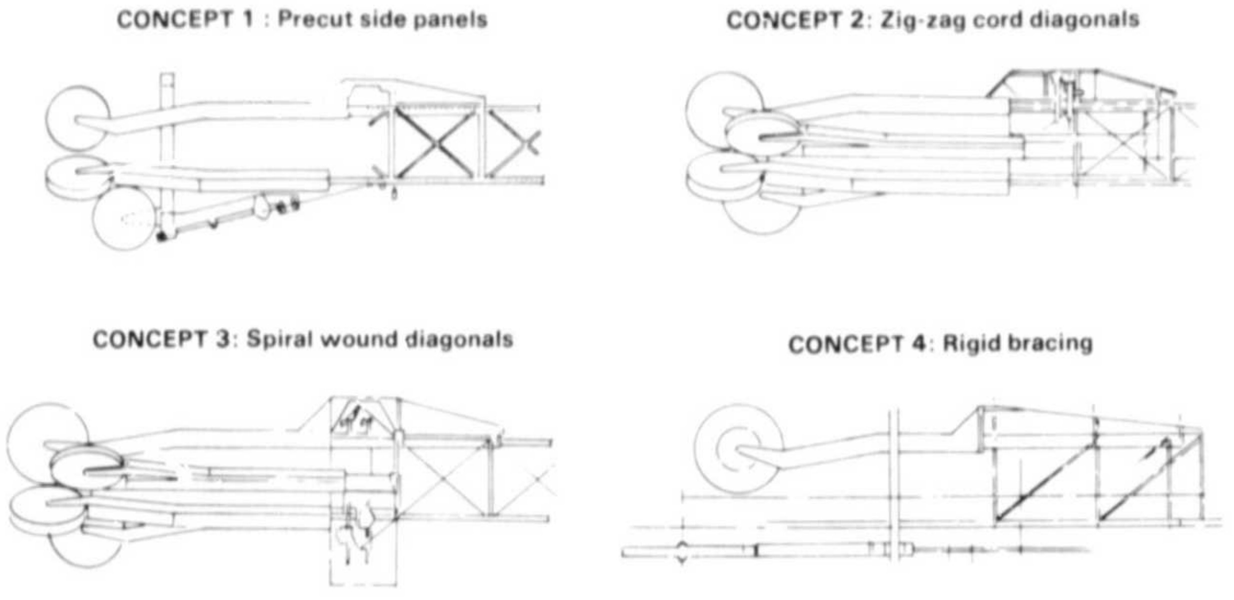


Figure 2-2. Machine/structure trade study options.

Specific beam dimensions were developed by considering assembly jig/Orbiter bay compatibility, beam cutoff, assembly jig retention/translation of longitudinal beams, and element clearances at beam-to-beam assembly joints.

The basic beam uses ground preconsolidated laminated composite strip material for both caps and cross-members. The cord diagonals are resin-impregnated to assure preload retention as well as providing improved packaging efficiency, and reduced beam weight and beam-builder power requirements. Diagonals are preloaded to prevent loss of shear stiffness due to differential cap-diagonal thermal deflection during sun/shadow transit. Beam element and platform assembly joints employ an ultrasonic spotweld technique which precludes use of secondary adhesives and produces no debris.

Integrated Mass Properties/Stability and Control/Structural Dynamics/Thermodynamics/Stress analyses were conducted to evaluate structure loads and distortion. Calculated disturbance torques due to gravitational, gyroscopic, drag, solar, and magnetic forces were applied to the orbiting system during successive phases of fabrication. Using current Orbiter VRCS firing logic, impulse time histories were computed for two values of maximum error in all three axes. Figure 2-3 illustrates the roll axis/platform complete case, showing that thruster firing frequencies are very low and widely adjustable by attitude error selection. Transient analyses were then conducted to determine the beam tip elastic responses due to firing of the VRCS thrusters. Resulting maximum beam bending moments were half as large as originally assumed and small clearance loss occurred between tips of adjacent beams. Thermal analyses indicated little cap-to-cap temperature variation with time (Figure 2-4), small distortion, and negligible loads.

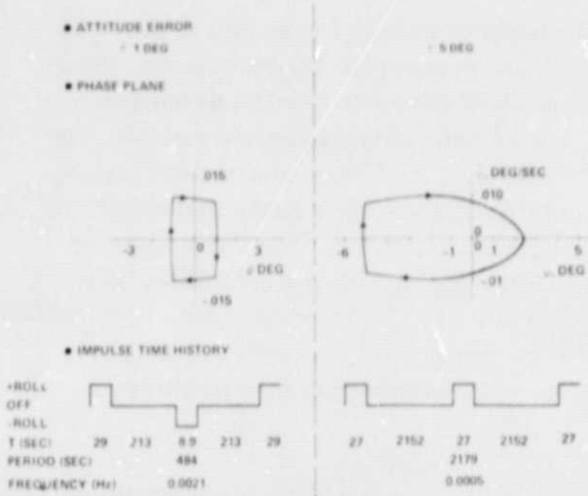


Figure 2-3. Orbiter VRCS duty cycles.

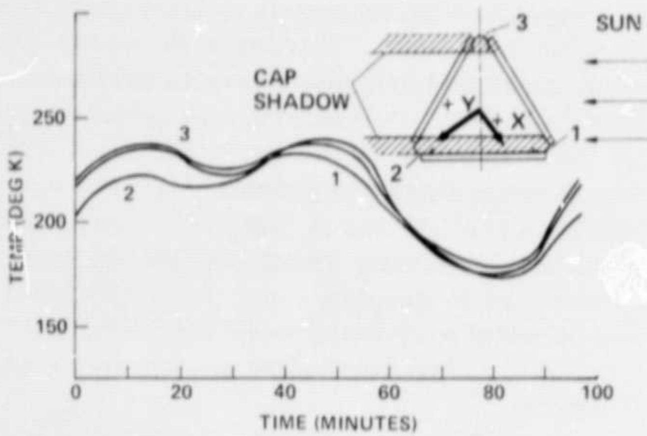


Figure 2-4. Beam cap temperatures vs. time.

Adequate beam tip clearance remains after conservatively superimposing maximum thermal and dynamic displacements, as shown in Figure 2-5.

Resulting beam internal loads are also low, per Figure 2-6. Consequently, the open section cap exhibits substantial margin against instability failure, as seen in Figure 2-7, by comparing the SCAFE limit load (316 N) with the pre-failure 6583 N load at which the analysis was terminated.

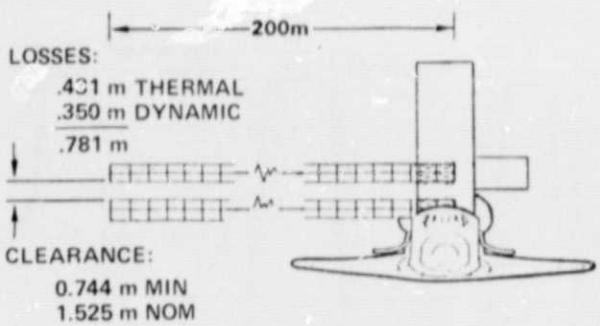


Figure 2-5. Beam tip clearance.

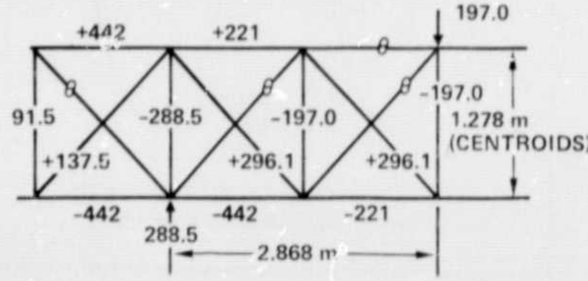


Figure 2-6. Ultimate internal bay loads.

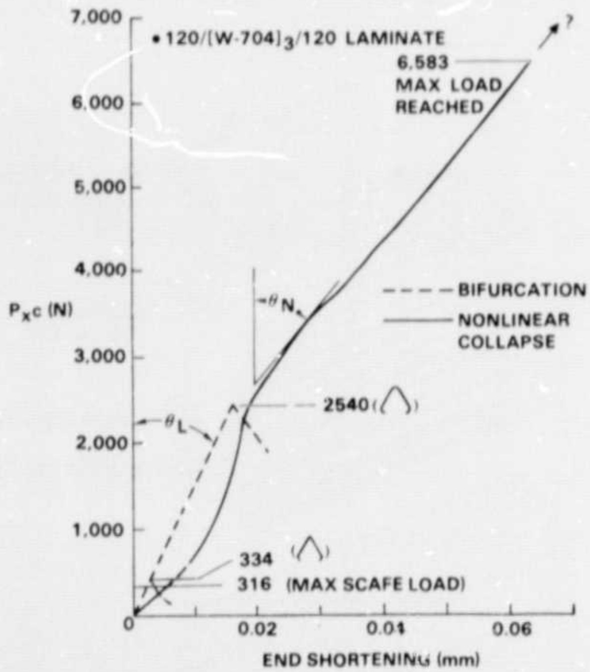


Figure 2-7. Open cap stability.

2.1.2 MATERIALS

A comprehensive materials evaluation process was used to select beam cap and cross-member laminates. Starting with the baseline advanced composite thermoplastic concept, glass and graphite fibers in various forms were selected for lamina properties determination. Polysulfone was selected from the candidate thermoplastic resins, for all lamina, based on its thermal characteristics, wide use, and best characterization. The various glass and graphite lamina were then combined into over sixty different laminate configurations designed to emphasize either high stiffness, high strength or low CTE. Laminate forms considered were (1) conventional multi-ply graphite, (2) sandwiched 0^{o} graphite, and (3) single-ply woven fabric. For each candidate, mechanical and physical properties were computed and these were compared, in addition to cost, availability, and fabrication energy requirements, to guide selection of a preferred laminate.

For near term development, the most flexible, least cost, and least risk approach is the system shown in Figure 2-8. In this hybrid laminate, conventional style 120 glass cloth sandwiches essentially unidirectional pitch (VSB 32T) graphite fabric, which provides the desired longitudinal strength and stiffness. The counteracting individual CTE's of glass (+) and graphite (-) also result in low net CTE.

Figure 2-9 shows a further significant advantage of the hybrid material. The temperature distribution across the total strip width is illustrated for two laminates after each has been locally heated in the three bend areas to a sufficient temperature to permit forming. The deeper valleys exhibited by the hybrid material indicate a lower transverse energy leakage from the heated regions. This is a direct consequence of its

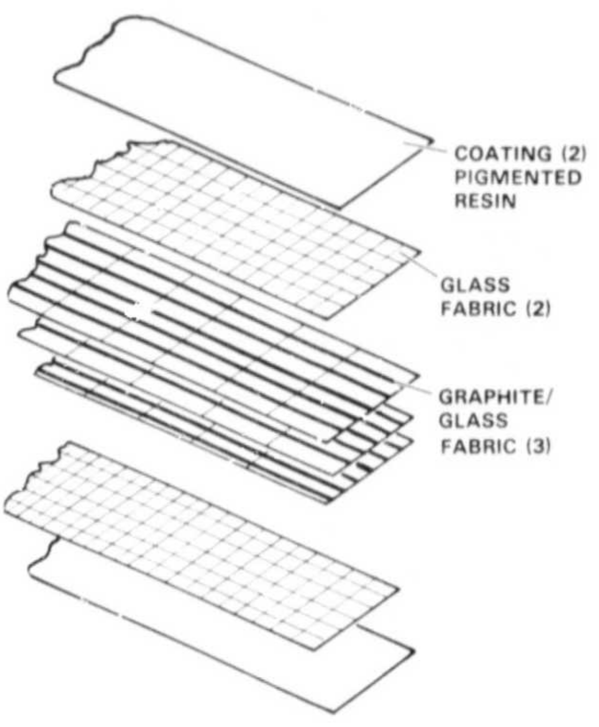


Figure 2-8. Selected hybrid laminate.

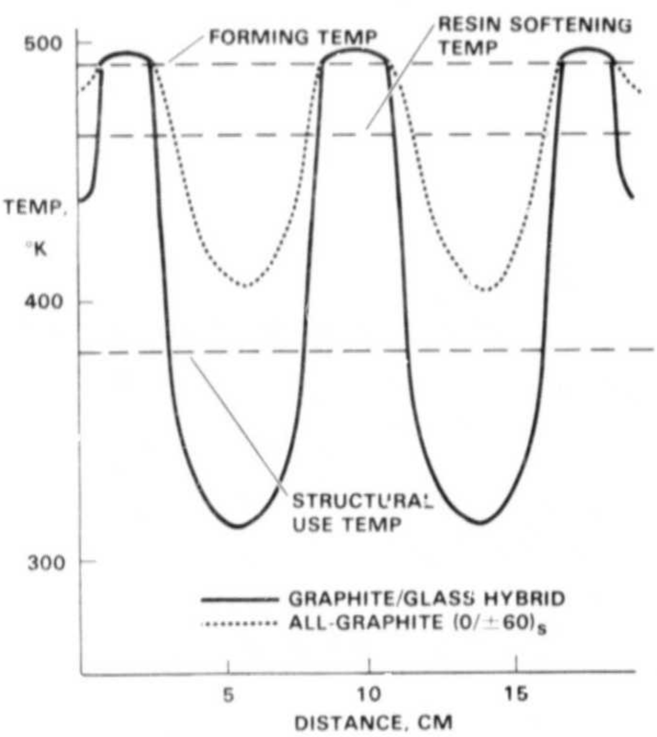


Figure 2-9. Laminate thermal characteristics.

greatly reduced transverse thermal conductivity, when compared with the all-graphite pseudo-isotopic laminate, and results in a 53% lower power requirement to heat the hybrid laminate to the desired forming temperature.

Application of a thermal control coating on the otherwise dark surface of a graphite/thermoplastic laminate reduces both maximum temperature and the temperature range experienced in a typical orbital cycle. If used, a coating must be compatible with both the processing and service environments. As shown in Figure 2-10, the baseline titanium dioxide coating satisfies these requirements but exhibits optical property degradation with time. This degradation arises from an increase in absorptance, α, with continued exposure to UV, electron, and proton radiation. Limited test data is available for long-term optical property degradation, but the trend can be seen in the curve shown. Values of α at 6 months (SCAFE mission duration) and 4 years are shown and their corresponding maximum temperatures found to be well within the maximum use temperature for the polysulfone resin system.

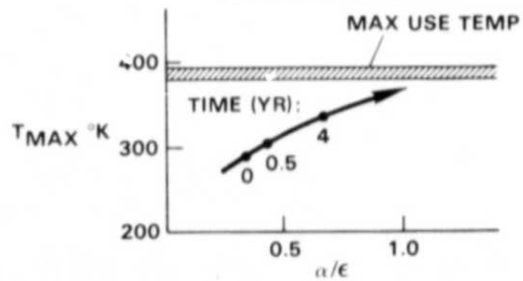
Cord material selection was based on satisfying the desired characteristics indicated in Figure 2-10. Among available candidates, Kevlar 29 provides the best mechanical/physical properties but is subject to degradation by UV radiation and possibly by heat generated during joining. Since analyses show that preload requirements are quite low, either of the glass candidates provides good ultimate strain with little increase in preload due to higher $E\alpha$. Of the two, impregnated/cured 20-end S-glass roving provides approximately the desired breaking strength, and has been selected.

• **COATING CONCEPT:** WHITE PIGMENT DISPERSED IN POLYSULFONE RESIN

• BASELINE PIGMENT: TiO_2
$\alpha = 0.33$; $\epsilon = 0.92$

• PROVIDES TEMPERATURE CONTROL
DIMENSIONAL STABILITY
LIMITS RESIN MAX TEMPERATURE
• COMPATIBLE WITH PROCESSING
READILY APPLIED
SPRAY-ON
LAMINATED FILM
FLEXIBLE
JOINABLE

• RADIATION EXPOSURE DEGRADES OPTICAL PROPERTIES



• **DIAGONAL CORD** POLYSULFONE-IMPREGNATED S-GLASS ROVING

DESIRED CHARACTERISTICS		FIBER CANDIDATES		
		KEVLAR 29	S-GLASS	OTHERS
SUSTAIN LOADS: APPLIED, PRELOAD, THERMAL	$P_{TU} = 574$ N*	✓	✓	• A-S GRAPHITE • KEVLAR 49 • E-GLASS • QUARTZ
LOW PRELOAD REQUIRED →	LOW $E\alpha$ (MN/m² · °K)	0.011	0.025	
COMPACT STORAGE →	HIGH ϵ_{TU} (m/m)	0.044	0.044	
PRELOAD RETENTION →	RESIN IMPREGNATE, CURE	✓	✓	
COMPATIBLE WITH WELDING →	THERMOPLASTIC RESIN	✓	✓	
→	WITHSTAND TEMPERATURE	?	OK	
COMPATIBLE WITH ENVIRONMENT →	RADIATION RESISTANT	?	OK	

*SCAFE PLATFORM: F.S. (ULT) = 2.0

Figure 2-10. Coating & diagonal cord materials.

2.2 FABRICATION SYSTEMS

2.2.1 BEAM BUILDER

Automated fabrication of the baseline beam is feasible using state-of-the-art electromechanical devices integrated into the beam builder concept of Figure 2-11. Its major features and subsystems are summarized in Table 2-1.

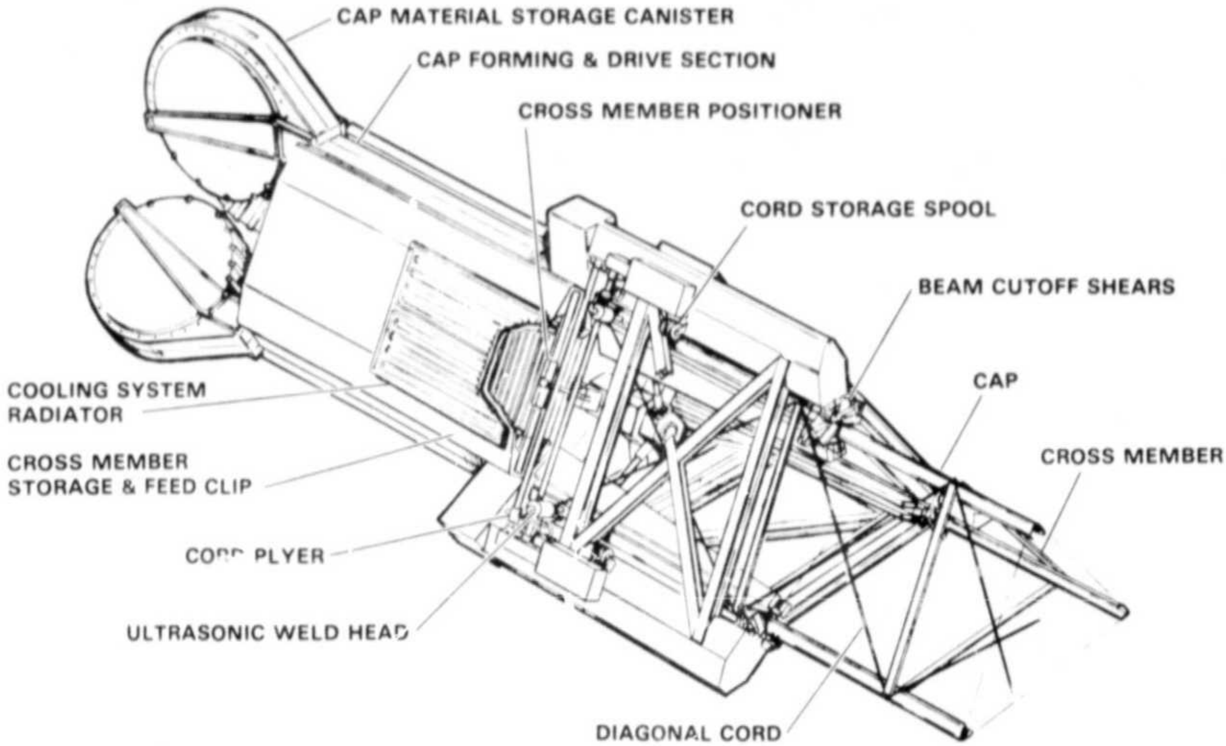


Figure 2-11. Beam builder concept.

Table 2-1. Beam builder characteristics.

- Operating Mode - cyclic feed.
- Storage - Caps: continuous pre-consolidated flat strip, coiled in rolls
  Cord: continuous pre-cured, wound on spools
  Crossmembers: preformed, pre-cut, in clip feed mechanism
- Heating - Electrical resistance wire plus linear parabolic reflectors.
- Forming - Rolltrusion.
- Cooling - Fluid cooled platens.
- Heat Rejection - Integral radiator.
- Drive - Friction rollers.
- Crossmember Positioner - Translating swing-arm, single drive.
- Cord Positioning - Counter-reciprocating cord plyers on reversing screws.
- Cord Preloading - Constant-force tensioning mechanisms.
- Joining - Ultrasonic spot weld heads.
- Cutoff - Shears
- Structure - Welded aluminum.

The cyclic feed operating mode is functionally compared with the alternative constant run mode in Figure 2-12. The cyclic feed beam-builder rolltrudes cap section material at 2.2 meters per minute while simultaneously playing out diagonal cord material. After 1.434 meter beam extension (1 beam bay), a pause of 40 seconds is made for cross-member and diagonal cord attachment. During the pause period the cross-members are grasped by the positioner, extracted from the clip and placed against the caps. The diagonal cords are aligned between the cap and cross-member by the cord feed mechanisms and the cord and cross-member are ultrasonically welded to the cap. The beam-builder then repeats the operating cycle. Benefits of the cyclic feed operating mode are summarized in Table 2-2.

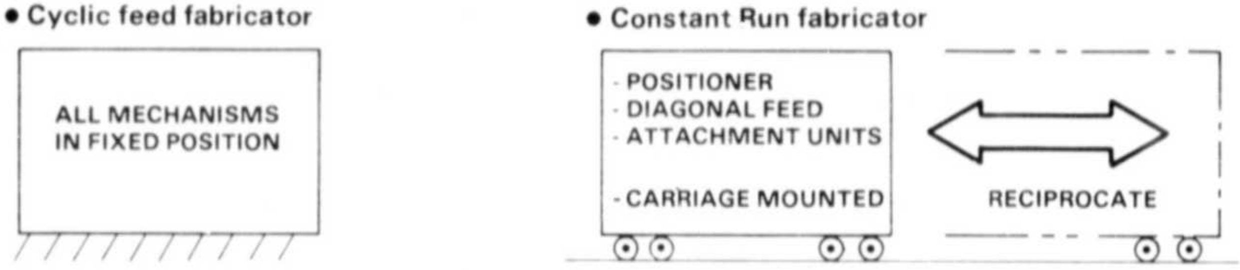


Figure 2-12. Operating mode functional comparison.

Rolltrusion forming was adopted at the start, by NASA guideline, but mechanisms for all other machine functions were selected through detailed trade studies of competitive process and technique options as illustrated in Figure 2-13.

Where possible, functions were integrated into subsystems as in the cap forming machine assembly of Figure 2-14.

This machine contains all elements necessary to continuously process the flat strip composite material into the baseline cap configuration. Approximately 918 m of material is coiled in a roll which is retained in the storage canister. The roll turns freely on bearing mounted rollers and unwinds uniformly as material is used. The canister is halved, with the outer half hinged to permit the material roll insertion. When the canister is closed and latched, an access panel in the hinged half is opened to allow the material to be routed over the heating section guide rollers into the forming section. The heating section is a continuous assembly with an internal passageway for the flat strip cap material. Continuous heating elements, each consisting of continuous wire helically wound on a concentric dielectric base located at the foci of parabolic reflectors, are positioned on the three centerlines about which the cap radii are subsequently formed.

Table 2-2. Cyclic feed benefits.

- Cyclic feed is compatible with SCAFE
  - Fabrication rate same as constant run
  - Dynamic impulse effects similar to constant run
- Cyclic feed fabricator has more advantages
  - Less complexity
  - Reduced size & weight
  - Lower cost
  - Better in-process quality control
- Cyclic feed permits use of platen cooling
  - Most efficient cooling
  - Precludes use of cyrogenic box for radiation cooling of material
- Further study required to identify scale-up constraints for cyclic feed

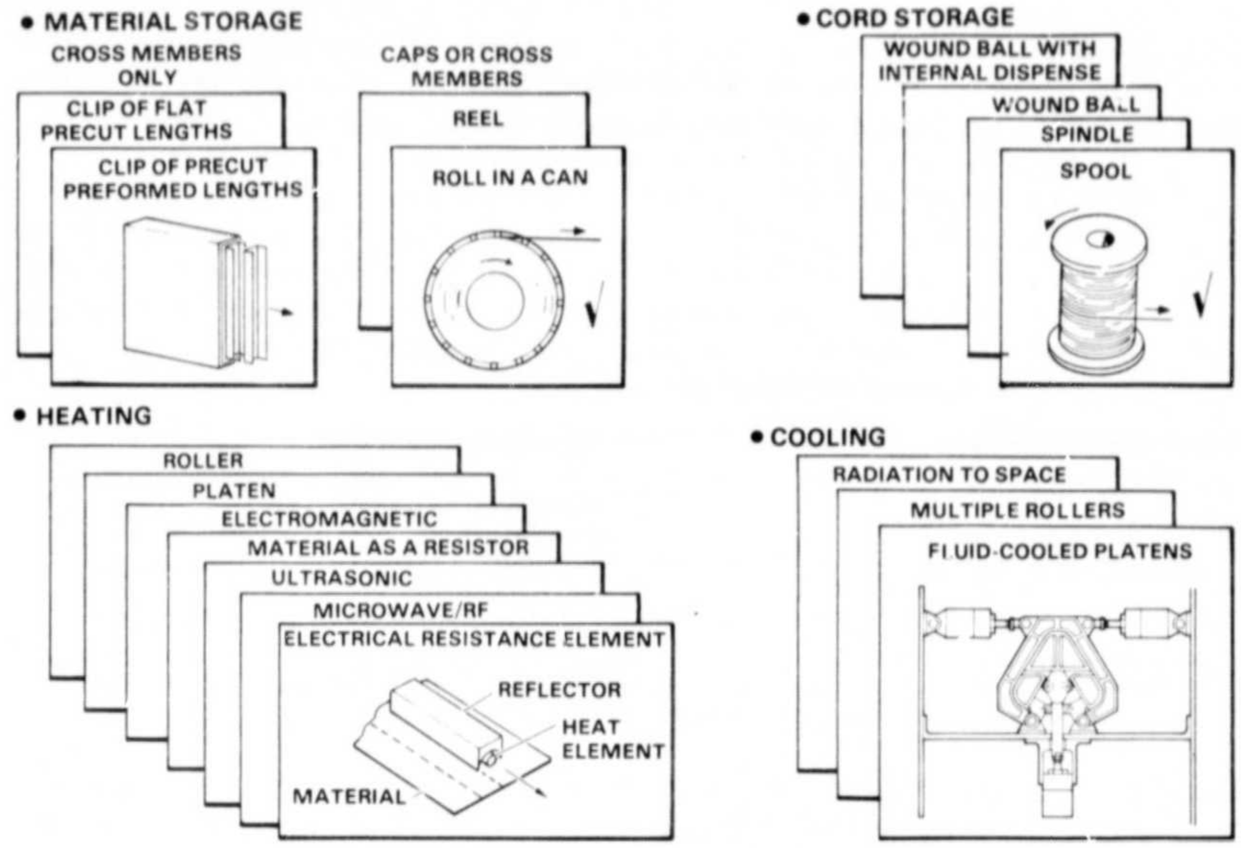


Figure 2-13. Beam builder processes & techniques.

The heating section is partially built into the storage canister with heaters and reflectors mounted on the access panel and extends from the access panel to the forming section entrance. The heated material then passes into the rolltrusion forming section, which is also equipped with strip heaters to preheat initially cool material during machine start-up.

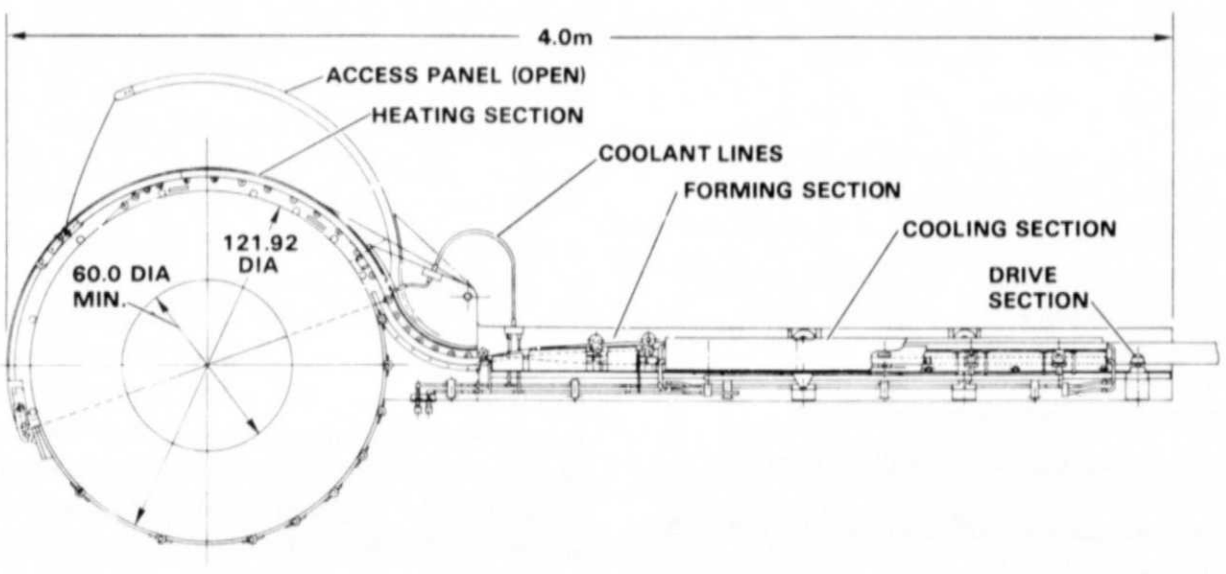


Figure 2-14. Cap forming machine assembly.

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After forming, the material passes into the cooling section where it is contact-cooled by aluminum platens which cool one complete bay length of cap section during the 40 second pause period.

The drive section has four friction rollers which provide the necessary force on the cap to pull the material from the storage roll through the heat/form/cool sections. Together, the three cap drive sections also provide the force to advance the beam out of the beam-builder.

The independent cooling system interfaces with the cap forming machine and provides a low energy, low weight alternative to using the Orbiter heat rejection system by eliminating long runs of flex line and the associated handling and reliability problems. It supplies coolant to the inside cooling platens and the reflector bodies and rejects the accumulated waste heat from a radiator mounted on one cross-member feed clip.

Each storage clip, Figure 2-15, supports a stack of 650 cross-members which it feeds to the beam assembly process on four serrated timing belts. Cross-member sides are flared (ref. Figure 2-1) to improve feed and packing density and reduce clip length and weight. With the handler in position to receive the next cross-member, Figure 2-16, retainers on each end of the next cross-member are retracted and the clip drive stepper motors are activated, advancing the stack until a sensor in the handler is triggered. The motors then stop, fingers on the handler close and grasp the cross-member, and the retainers re-engage to index the next cross-member. The cross-member positioner arm then rotates and translates to remove the cross-member from the clip and lay it in proper position for welding to the cap members.

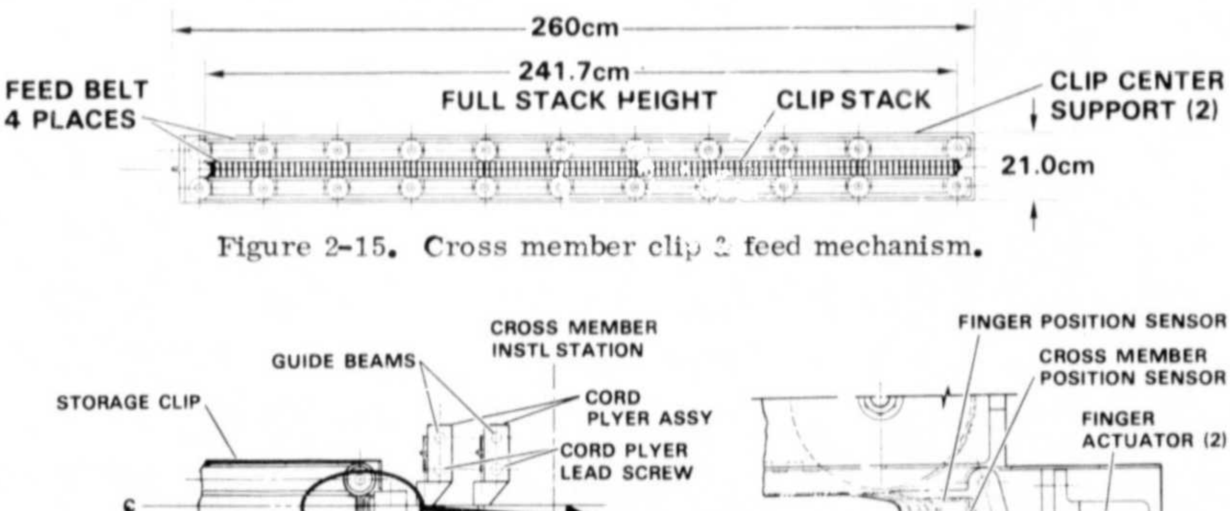


Figure 2-15. Cross member clip & feed mechanism.

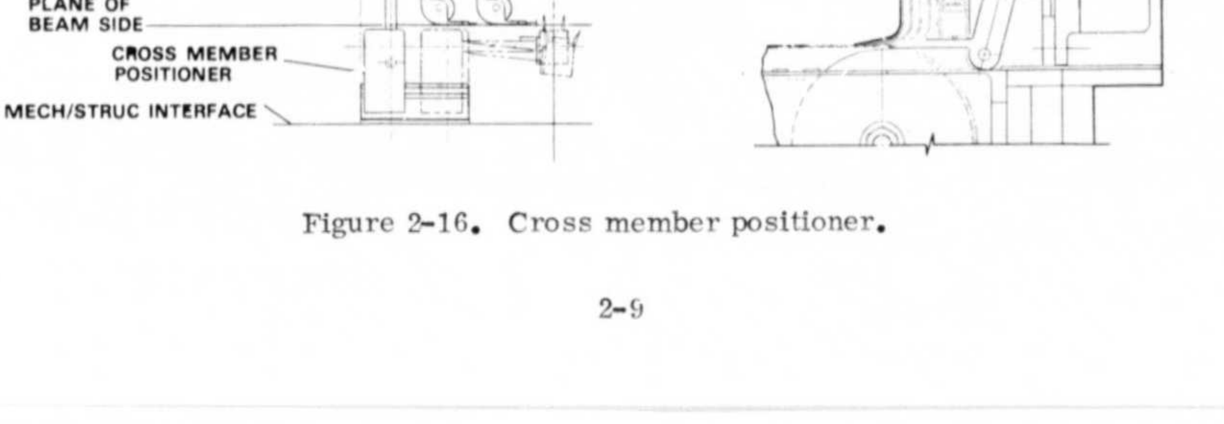


Figure 2-16. Cross member positioner.

During cross-member positioning the cord plyers are positioned at their extreme travel stops to provide clearance. Figure 2-17 illustrates the cord plyer mechanism which consists of six reciprocating cord plyer subassemblies, driven along a guide beam by a motor driven ball reverser lead screw. Cord is supplied to each plyer from a storage spool over a series of pulleys. Using dual (forward and aft) cord plyers permits the two cords on each side of the beam to be applied without interference between the moving plyers. The aft cord plyers, being further from the attachment station, require a longer stroke to achieve the required cord/cap angle.

A cord tension force of 10 $\pm$ 2 lb, measured by a force transducer attached to a guide pulley, is applied to each cord during assembly. This preloads the cords sufficiently to preclude any slackening or over tensioning due to thermal and deflection effects. The liberal $\pm$ 2 lb variation allows a twist and tip deflection of less than 1.2° and 0.5 cm, respectively, over the 200 m beam length.

With cord plyers and cross-members positioned as shown, the ultrasonic welding heads are advanced and activated momentarily to allow a pin on each weld head to pierce the cross-member and cap just below each cord. When piercing is completed, the cord plyers then move to the ready to weld position while cord tension is maintained by the cord tensioning mechanism.

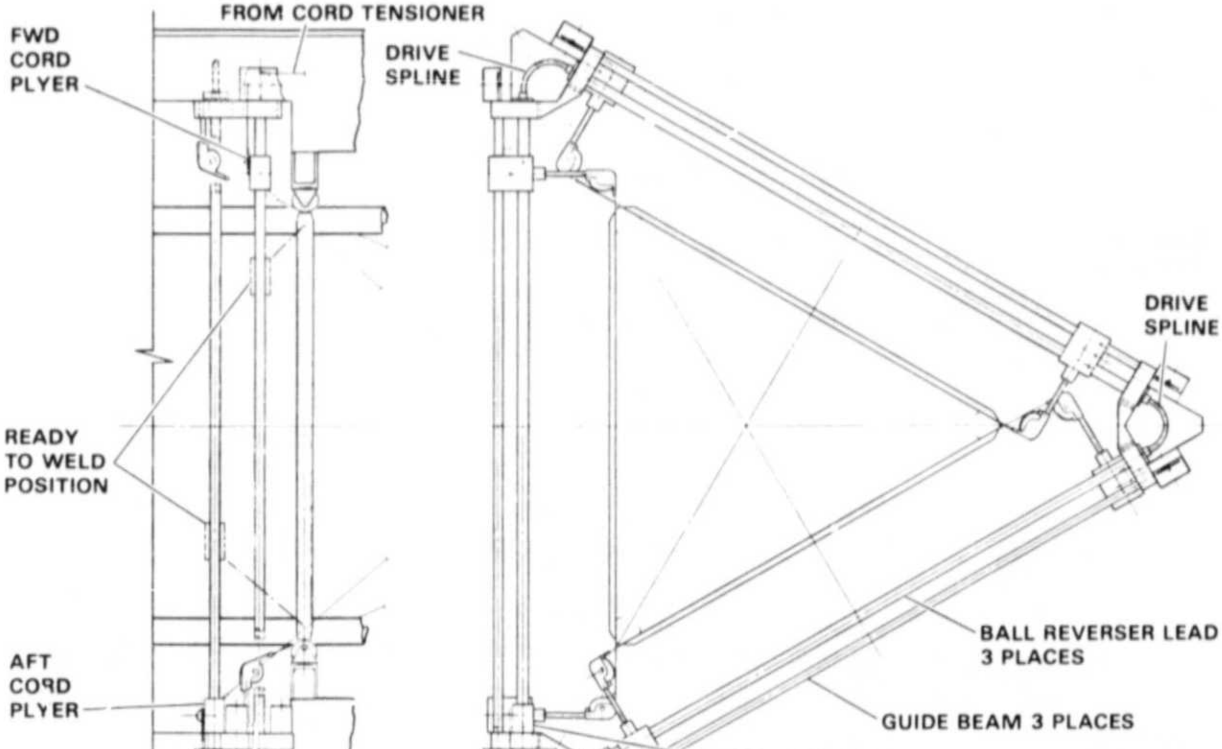


Figure 2-17. Cord plyer mechanism.

The beam-builder welding mechanism has six ultrasonic weld head assemblies, arranged in pairs at each cap as shown in Figure 2-18. Three weld head positions are required: (1) fully retracted (to allow cross-member positioning); (2) pierce (see above); and (3) weld (where the weld horn is engaged and properly loaded for welding). Each horn performs two circular spot welds and one special cord capturing weld simultaneously. The horns act against internal anvils which are extended against the inside surface of the caps by a centrally located drive mechanism. The ultrasonic spotweld technique was adopted for beam element joining for the reasons given in Table 2-3.

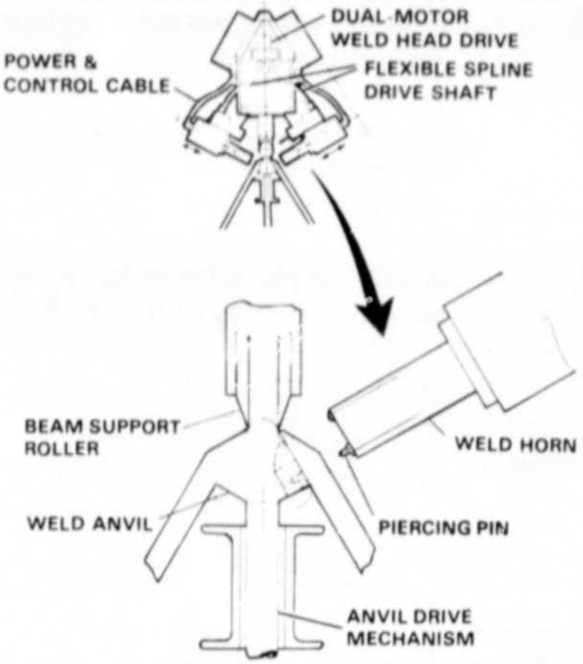


Figure 2-18. Beam welding subsystem.

The beam cutoff mechanism is a device which shears each cap and cord member to separate a completed beam from the beam builder. The cutoff device is normally retracted to allow the cross-members to travel past the outer clamps. In preparation for beam cutoff, a 60 cm cutoff bay is manufactured by the beam builder (ref. Figure 2-1). The cords are laid along the caps within this short bay rather than crossing (as they do in normal bay construction) to permit cutting by the cap cutoff mechanism.

Table 2-3. Ultrasonic weld benefits.

- RAPID, LOW ENERGY
- NO ADHESIVES/VOLATILES
- NO LOOSE PARTS, NO DEBRIS
- COMPACT EQUIPMENT
- AUTOMATED QA
- SPOT VARIETY

2.2.2 ASSEMBLY JIG

The function of the assembly jig is to automatically assemble the beams produced by the beam builder to form the baseline platform (ref. Figure 2-1). To accomplish this, it must perform the functions illustrated in Figure 2-19, in the following sequence:

1. Position and support the beam builder for fabrication of each of four longitudinal beams. This requires a carriage and a roll and turn mechanism, as well as a latching mechanism to secure the beam builder to the jig.
2. Grasp and retain each longitudinal beam in position after it is completed and cut off from the beam builder. This requires retractable retention and guide mechanisms at three locations for each beam.
3. Position and support the beam builder for fabrication of cross beams. This is accomplished with the carriage and roll/turn mechanism.
4. Advance all four longitudinal beams into proper position for joining to each cross beam. This is accomplished with a drive mechanism provided for each beam.

5. Grasp and place each cross beam into proper position after it is completed and cut off from the beam builder. This requires a cross beam positioner mechanism.

6. Join the cross beam to the four longitudinal beams using automatic welding mechanisms.

7. Permit EVA personnel to traverse the platform and perform equipment installation tasks. An EVA bridge and personnel carriage is required for this purpose.

8. Allow the platform to be quickly released for deployment to space. This is another function of the beam retention and guide mechanisms.

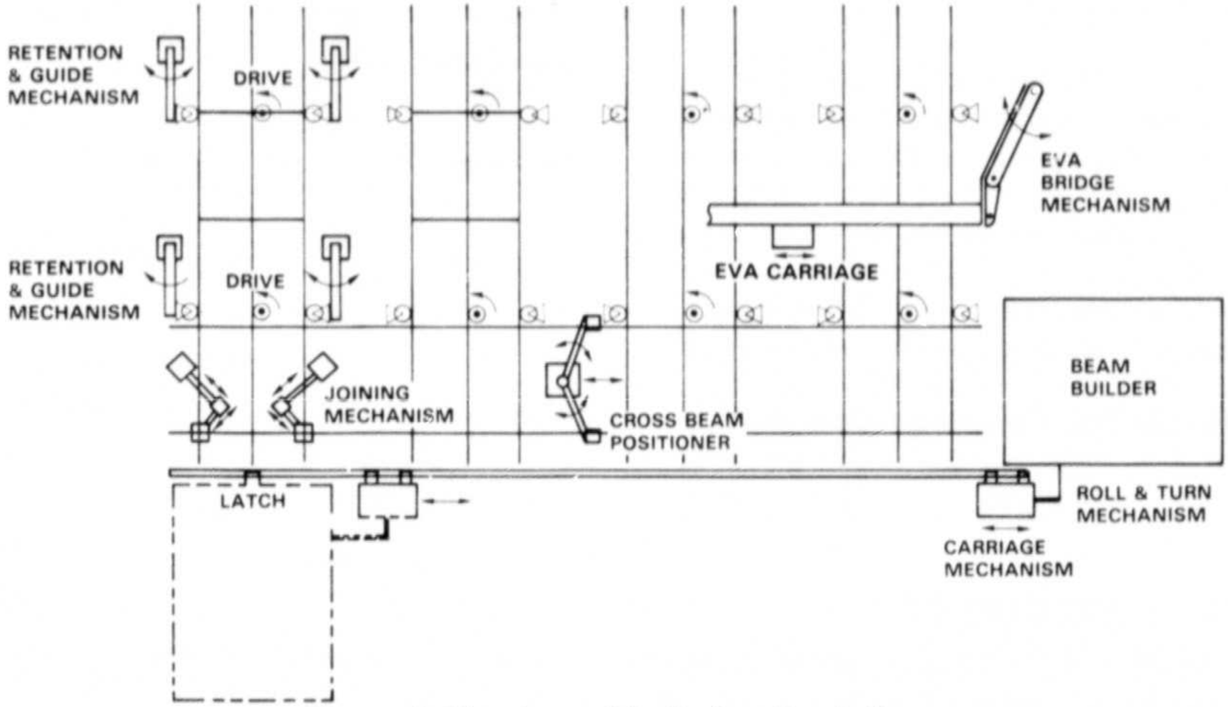


Figure 2-19. Assembly jig functional diagram.

As for the beam builder, mechanisms for each assembly function were selected through individual trades of applicable process/technique options. Selected options were integrated into four assembly jig candidates which were evaluated in terms of mechanical and control/software complexity, risk, weight, and operational compatibility. The concept shown in Figure 2-20 was selected. Its primary advantage lies in the capability to retract the platform after all cross-beams have been attached. This is accomplished by orienting the longitudinal beams with their apexes towards the jig. This permits all assembly mechanisms to have a fixed position on the jig. Three rows of Retention and Guide Mechanisms (RGM) provide the capability to retract the platform. The cross-beams step through the RGMs as described below:

1. As a cross beam approaches the first row of RGMs, the entire row retracts to clear the cross beam leaving the platform supported by the second and third row of RGMs.

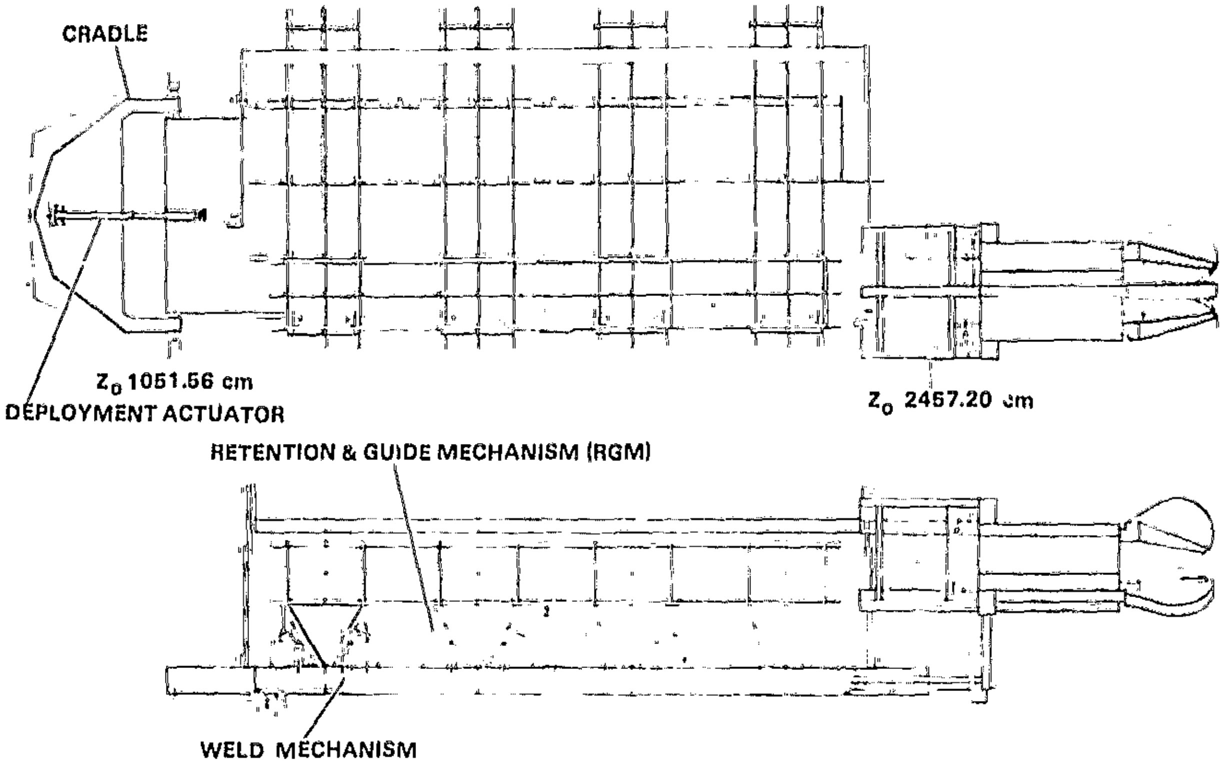


Figure 2-20. Assembly jig design concept.

2. The cross beam advances to the next row of RGMs and the platform pauses.
3. The first row of RGMs is engaged and the second row retracts leaving the platform supported by the first and third row. The platform is advanced.
4. As the cross beam approaches the third row of RGMs the platform pauses. The second row is engaged and the third row retracted leaving the platform supported by the first and second row. The platform is advanced.
5. The third row of RGMs engages after the cross beam passes and the platform continues to retract until the next cross beam is encountered, at which time the step through process is repeated.

2.2.3 AVIONICS

Similar control system concepts were developed for both the beam-builder and assembly jig. As an example, the baseline beam builder system is shown in Figure 2-21. It consists of four major subsystem categories: the Beam Control Unit (BCU); cap subsystems (3); cross-member subsystems (3); and assembly subsystem. The BCU performs overall control and monitoring of beam fabrication operations and contains a microprocessor with interval timer, approximately 4K of memory and the input/output interfaces shown.

The cap subsystem control concept of Figure 2-22 illustrates the next level of detail, identifying the sensors and control devices associated with the electromechanical functions discussed in Section 2.2-1. In the baseline concept, the drive system also performs the beam alignment (i.e. accuracy) control function.

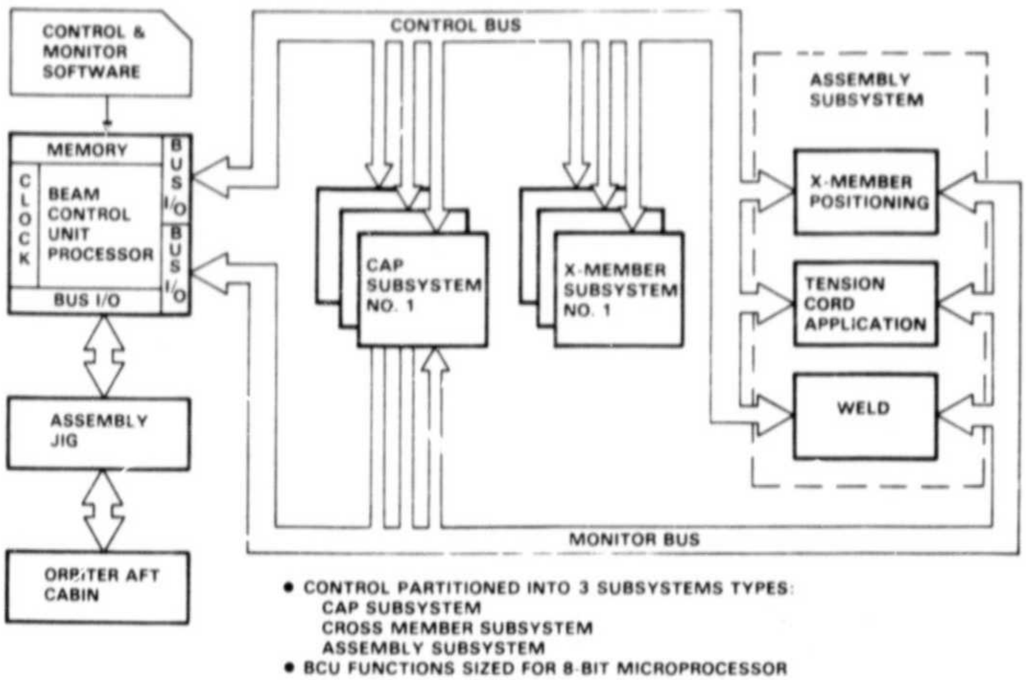


Figure 2-21. Beam builder control system.

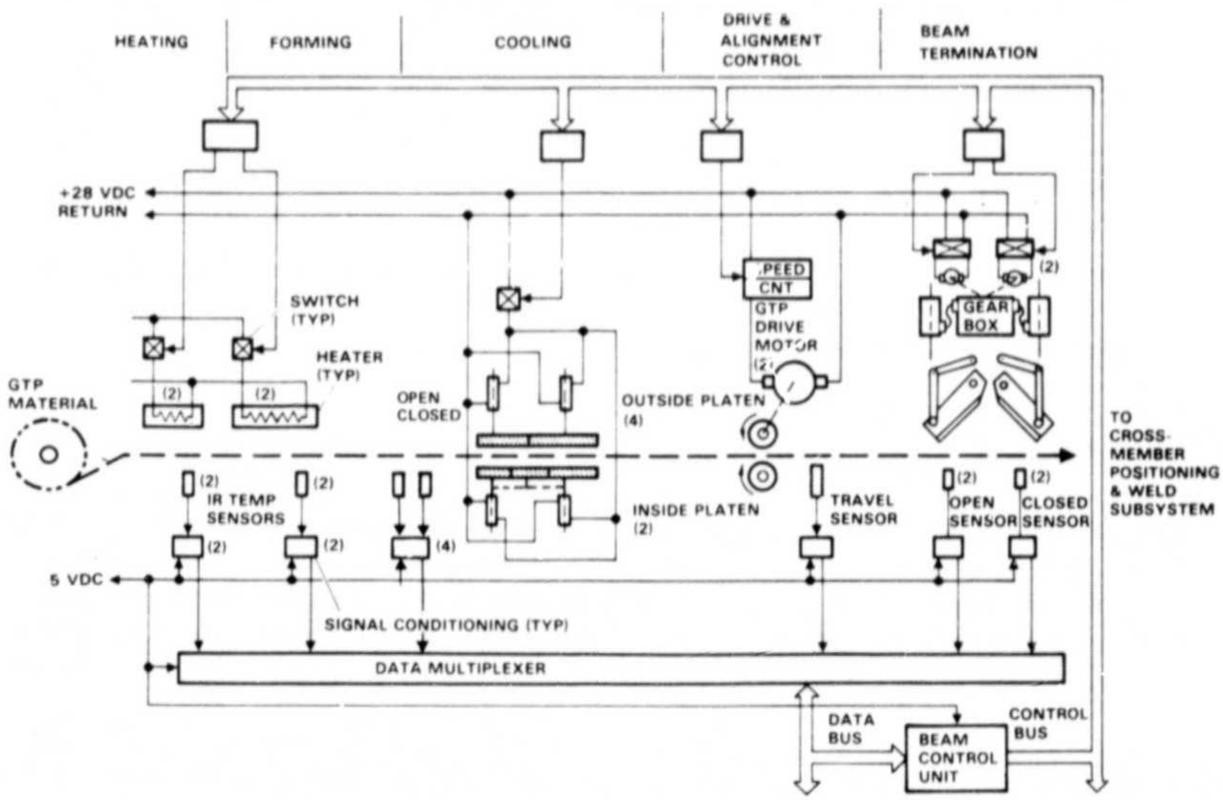


Figure 2-22. Cap member subsystem control diagram.

Small differences in the 3 cap lengths can result in large manufacturing-induced beam tip displacement. However, correction of manufacturing errors in real-time by observation of the "as-built" beam is complicated by continuously variable environmentally induced distortions which tend to mask the small manufacturing errors being monitored for correction purposes. Consequently an in-process bay "square-up" approach employing differential cap drive, schematically illustrated in Figure 2-23, was selected. In operation, a travel sensor system with a resolution of 0.1 mm provides length data for each cap to the BCU for comparison. Differential motor speed commands are generated to correct potential misalignment. Final positioning is accomplished during the last 3 seconds of the cap drive cycle while cap drive speed is progressively reduced as the desired position (length) is reached.

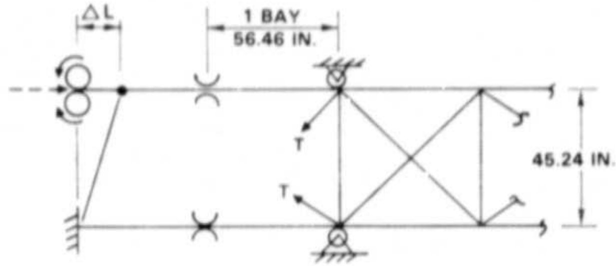


Figure 2-23. Differential cap drive.

The baseline sensor/feedback system uses a magnetically encoded strip applied to the beam cap material. Assuming standard computer magnetic tape character densities (800 characters/inch), length resolution to 0.032 mm (.00126 inch) is achievable. This technique also allows three strips of magnetic material to be vendor-applied to the composite cap material and coded simultaneously prior to slitting (into three cap tapes) to eliminate or average out errors in coding.

The BCU software control and monitor functions were identified and sized to determine capabilities required for the beam builder function. For the baseline, 2651 software instructions (approximately 3200 bytes of memory) and a speed capacity of 52 KOPS (thousands of operations per second) will be required. These results, shown in Table 2- 4 , indicate that beam-builder processor requirements fall well within the capability spectrum of current commercial microprocessors and microcomputers.

Table 2- 4 . BCU Software Sizing

Beam Control Unit Software	Program Size (Instructions)	Program Speed (KOPS)
Executive Software		
Process Control	800	22.1
Peripheral Control	490	3.4
Software Task Modules		
Cap Subsystem Control	759	7.1
Cross-Member Control	282	1.1
Assembly Control	320	18.4
Totals	2651	52.1
Memory: (1.2 × Instructions)	(3181 Bytes)	

The total estimated power requirement for heating/forming decreased significantly with system design maturity, as shown in Table 2- 5 . The most dramatic effects resulted

Table 2-5. Heating/forming power requirement history.

VARIABLE	MILESTONE					
	PROPOSAL	PART I — MID	PART I — FINAL	NOW		
LAMINATE •MATERIAL •LAYUP	GRAPHITE $(0 \pm 60)_s$	GRAPHITE $(0 \pm 60)_s$	GRAPHITE/GLASS $(0/90)_s$	GRAPHITE/GLASS $(0/90)_s$		
FORMING SECTION LENGTH, (cm)	45	33.5	33.5	33.5		
BEND RADIUS (mm)	15	15	15	12		
STRIP TEMP (K) •INITIAL	255.4	255.4	255.4	255.4	294.3	310.9
•FINAL	533.2	491.5	491.5	491.5	491.5	491.5
REQUIRED POWER (w) •CROSS-MEMBERS	2,030	1,016	0	0	0	0
•CAPS	4,620	4,023	1,903	1,577	1,318	1,206
•TOTAL	6,650	5,039	1,903	1,577	1,318	1,206

LEGEND: —— CHANGE — — SELECTED BASELINE

from: (1) selection of the glass-graphite material (Section 2.1.2) instead of the all-graphite pseudo-isotropic material initially baselined; and (2) ground prefabrication and clip storage/feed (Section 2.2.1) of the cross-members. In addition, the material initial temperature can be maintained at the selected 294.3°K (70F) level with minimal storage canister insulation and no make-up heat source. Total beam builder power and energy requirements include the needs of several functions in addition to heating/forming as summarized in Table 2-6. The resulting 2008 W average power requirement represents only 28% of the Shuttle's 7 kw capability.

Table 2-6. Beam builder power & energy requirements.

PROCESS/BAY	ENERGY (KJ/BAY)	AVE PWR (W)	PEAK POWER (W)	ENERGY
CAP HEATING/FORMING	105.4	1318	1215 205 1420	66%
COOLING	4.6	58	58	3%
WELDING	21.6	270	900	13%
SUBSYSTEM ASSEMBLY & CONTROL	28.9	362	861	18%
TOTALS/BAY	160.5	2008	3239	100%

2.3 MISSION INTEGRATION

All flight mission objectives can be met, within the guidelines of Table 1-1, on the single 7-day mission whose profile is shown in Figure 2-24.

The SCAFE equipment will be installed with the Orbiter in the horizontal position in the Processing Facility within the 14.5 hour on-line integration period. It will not require special environmental monitoring or control during any ground operations phase or time critical prelaunch access at the pad. Payload handling in the vertical position is not planned, but is not precluded by the design.

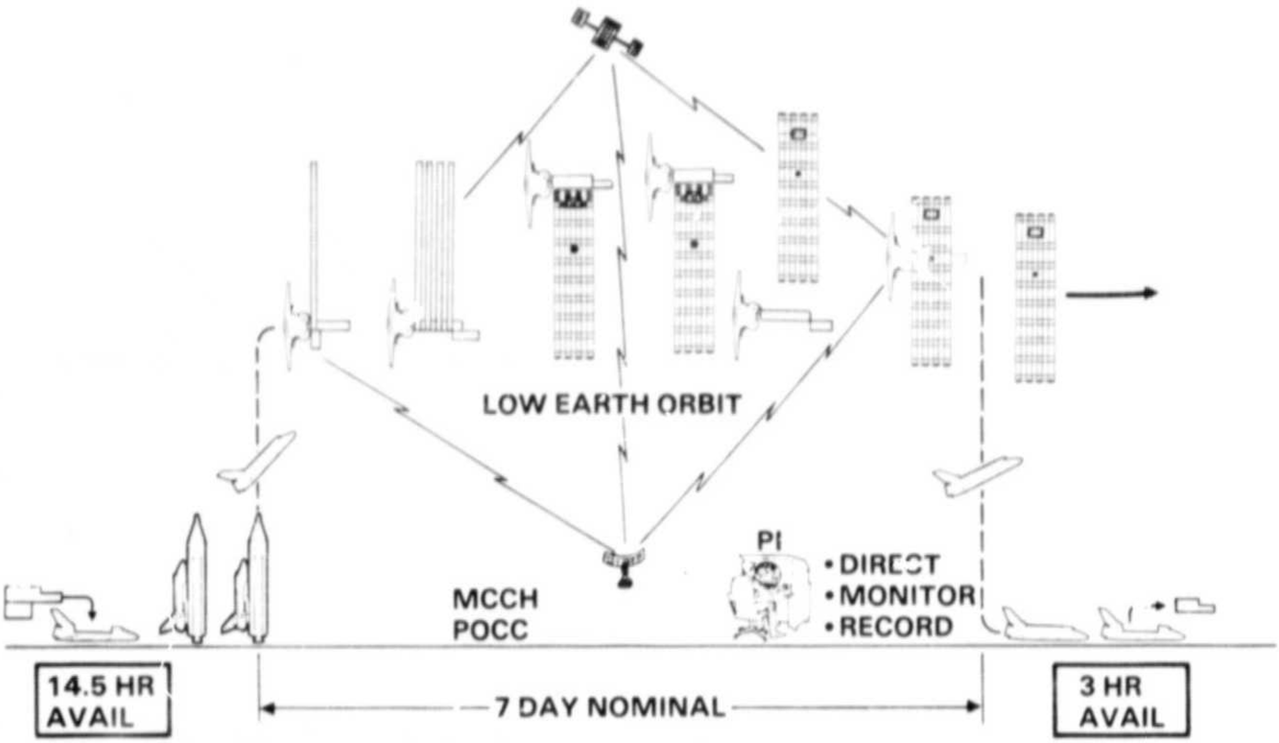


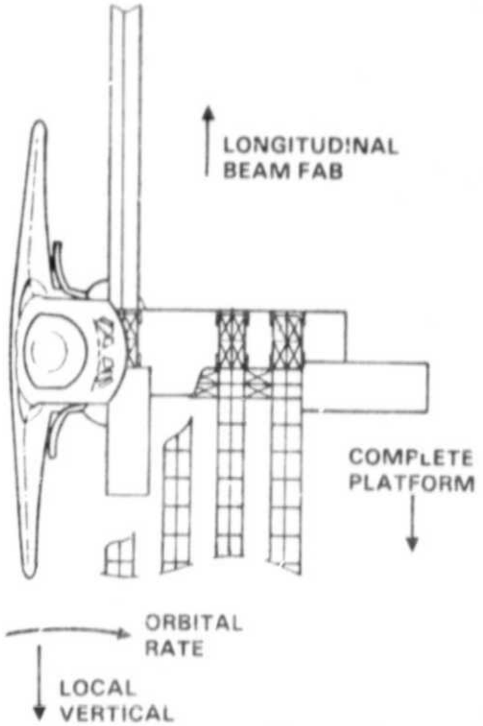
Figure 2-24. Flight profile.

During ascent/descent the SCAFE equipment is inactive - requiring only mechanical and caution/warning support from the orbiter. The orbiter crew initiates each operational or test phase and controls orbiter maneuvers and RMS operations as well as performing supporting EVA activities. Beam fabrication and platform assembly are fully automated. The sequence of on-orbit illustrations shows the major activities by mission day.

When the first beam is finished a dynamic response test will be conducted to determine beam characteristics, with data fed back to the ground to compare with predicted behavior to help predict the characteristics and behavior of the completed platform. The remainder of the platform will be completed by the middle of the third day. During this time the crew will monitor the operation at the aft flight deck and observe directly and with TV. During the afternoon of the third day, EVA is performed to install the test instrumentation, subsystems, and free flight experiment equipment. On the fourth day dynamic response and thermal deflection experiments will be performed. The morning of the fifth day the separation and recapture demonstration experiment will be conducted, with dynamic response and thermal deflection tests resuming that afternoon.

On the sixth day another EVA operation will be performed to demonstrate possible unscheduled maintenance and repair activities. The seventh day includes platform release, closeout activity and re-entry. Executive control and monitor of the beam fabrication on-orbit operation is provided via the orbiter RF command link ground controllers at the Payload Operations Control Center (POCC), co-located with Mission Control Center-Houston (MCC-H). MCC-H provides orbiter and overall mission control.

To select system on-orbit orientation, earth-fixed, inertially fixed, and time-varying options were considered. A constant earth fixed orientation, shown with its summary evaluation in Figure 2-25, was selected.



- **MASS PROPERTIES/STABILITY & CONTROL**
  - Platform built in stable release attitude
  - No attitude control maneuvers required
  - VRCS rate mode operation in yaw, roll
  - System oscillates within ± 10° limits
  - Low propellant consumption (11%)
  - Low VRCS impulse frequencies (.0008 Hz)
- **COMMUNICATIONS**
  - No specific communication requirements
  - 342° coverage via TDRSS
- **VIEWING/ILLUMINATION**
  - Minimizes sunward/earthward viewing component through aft cabin windows
- **THERMAL**
  - Platform insensitive: Distortion/load negligible
  - No orbiter constraint for i<55°

Figure 2-25. Fabrication orientation.

Figure 2-26 shows the general arrangement of platform-mounted equipment. Where possible, subsystems will be composed of standard spacecraft parts to minimize cost.

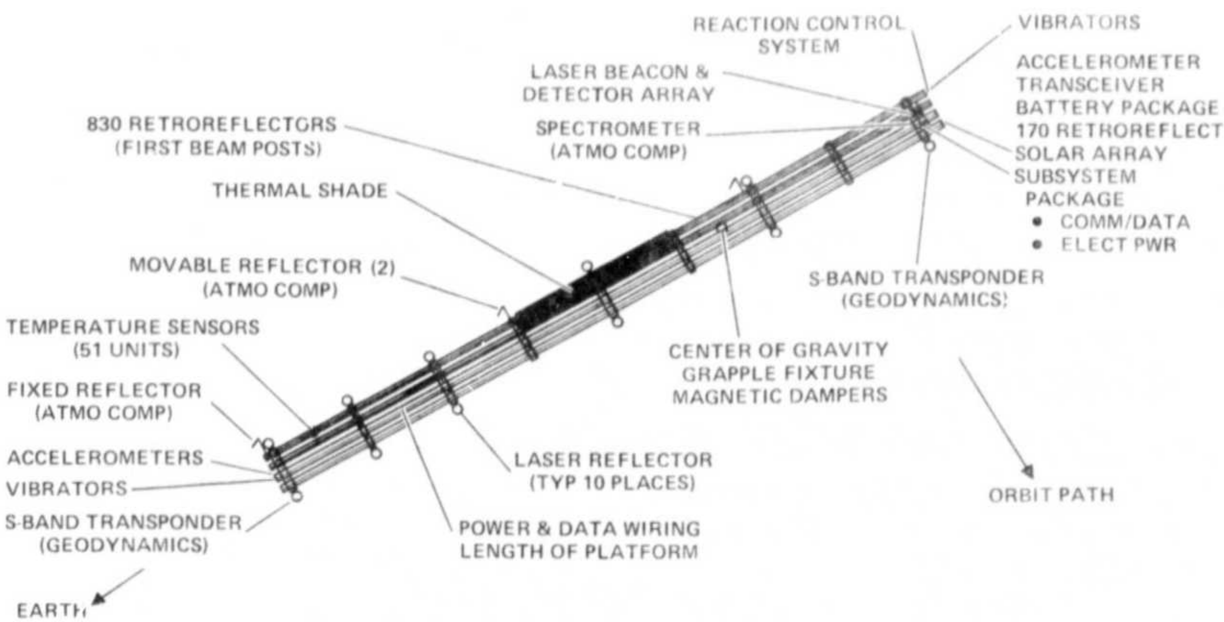


Figure 2-26. Platform equipment arrangement.

The 10 m^2 solar array is placed on the end of the platform for maximum exposure to the sun. The platform avionics equipment as well as batteries and other electrical power system components are contained within the subsystem equipment package. The baseline avionics concept is to use the multimission spacecraft communication and data handling module, which includes the transponders, data processor and data bus system for distribution of command and acquisition of data. Although its capability exceeds the current requirements it is a logical choice since it: (a) is standard NASA equipment, (b) can accommodate additional platform and experiment functions, and (c) will be developed, tested and in production during experiment time frame.

The cold gas reaction control system is placed in the end of one of the longitudinal beams and is used to spin up the platform near the end of its mission life for the atmospheric composition experiment.

The thermal shade is required by the thermal response experiment to cause an unsymmetrical temperature distribution in the platform to permit temperature pattern and platform distortion measurement. The laser beacon and detector array are used, in conjunction with the retroreflectors, to provide real-time structural distortion characteristics during the structural and thermal response tests. The grapple fixture is placed near the center of mass to enhance stability during RMS handling operations, accompanied by magnetic dampers which reduce oscillations due to both separation from the orbiter and cyclic environmental torques.

Equipment installation will be accomplished on the third day by EVA using the work station shown in Figure 2-27. Installation is accomplished by translating the platform to preselected positions under the astronaut (MS), who will be restrained in the EVA work station carriage. The carriage is equipped with a local control panel to permit the astronaut to manually control his position with respect to the platform. Safety position limit sensors prevent inadvertent collision with the platform.

All aspects of the experiment are compatible with the Shuttle. The stowed system lies wholly within the cargo bay envelope, with allowance for an OMS kit, and support reactions are low. System weight and cg are well within required boost and entry limits and are compatible with VRCS control throughout the on-orbit sequence in spite of significant inertia variation. RCS propellant consumption is low since the constant earth-fixed orientation precludes attitude changes, and the VRCS operates in a rate damping mode in two axes during the majority of the mission. In addition, a potential interface with the Orbiter heat rejection system was eliminated by adopting the self-contained beam builder cooling system.

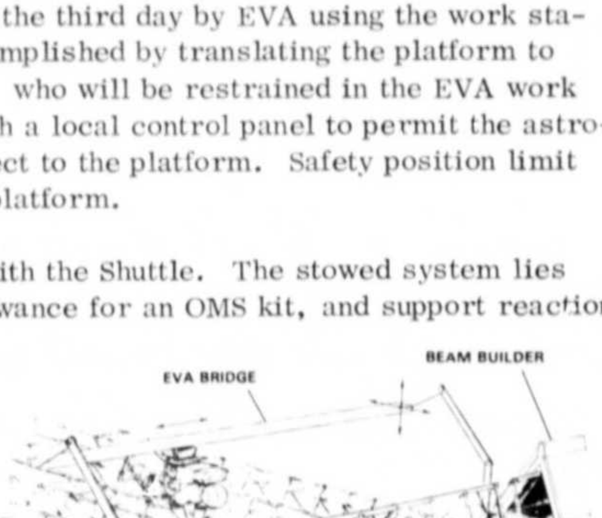
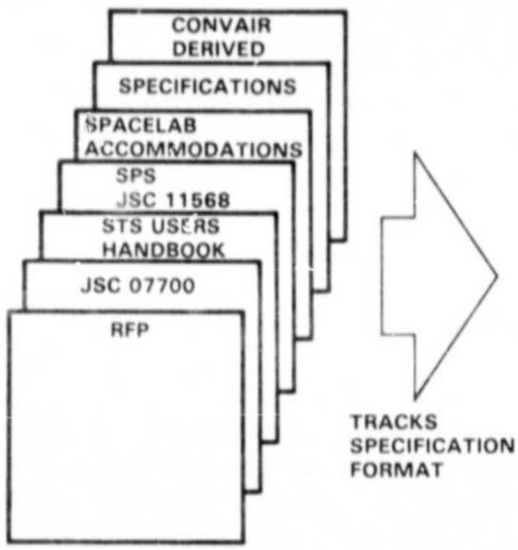


Figure 2-27. Assembly jig EVA work station.

2.4 PROGRAMMATICS

Early in the study a preliminary SCAFE Requirements Document was prepared as illustrated in Figure 2-28 to define qualitative and quantitative performance, design, and verification requirements for the SCAFE system and its elements. It was updated at study conclusion and now contains derived requirements based on study generated system performance characteristics as well as imposed requirements based on STS interface and safety considerations. A specification type format was selected to insure that its scope was adequate to capture requirements as they developed and, when completed, to serve as a preliminary Phase B system specification. The source of each requirement is also identified to provide traceability. The current version has been published as Volume III of the Final Report.



SECTION	CONTENTS	SOURCE
3.1	SCAFE PROGRAM DEFINITION	
3.2	CHARACTERISTICS: PERFORMANCE, RELIABILITY, SAFETY, ETC.	
3.3	DESIGN & CONSTRUCTION	
3.4	LOGISTICS	
3.5	PERSONNEL & TRAINING	
3.6	STS INTERFACES: FUNCTIONAL, PHYS, ENVIRONMENTAL, OPNS	
3.7	REQUIREMENTS OF PROGRAM ELEMENTS: FLIGHT HARDWARE, ASE, PLATFORM	
4.0	VERIFICATION	

Figure 2-28. Requirements document.

A master schedule, summarized in Figure 2-29 for both the total program and the beam builder, was generated assuming the guideline mid-1982 launch date. The program can be accomplished with a minimum of risk to meet the scheduled launch date, and is driven mainly by the Phase C/D Engineering Development and Qualification Test activity.

The overall schedule and detail task durations were based on several guidelines and assumptions:

- SCAFE contract follow-on ends 1 Oct 1978.
- The Phase B contractor is assumed to be selected to conduct Phase C/D without a further competitive bid.
- The follow-on contract produces, as a minimum:
  - Updated SCAFE conceptual design
  - Preliminary specification for beam builder and assembly jig subsystems
  - Plans and costs for Phase B

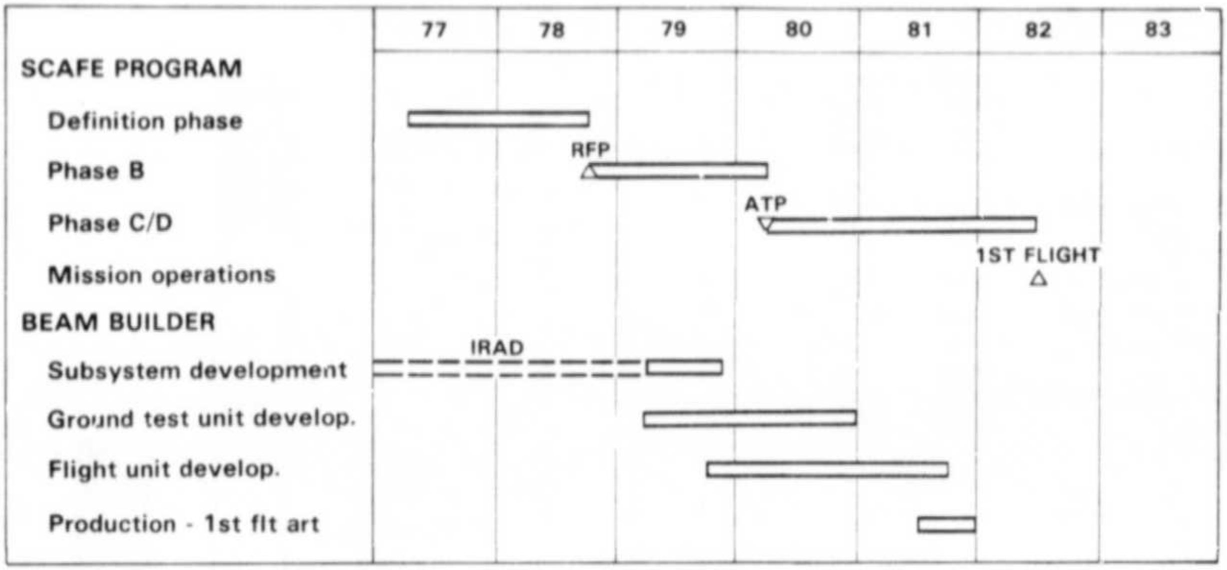


Figure 2-29. Preliminary program development schedule.

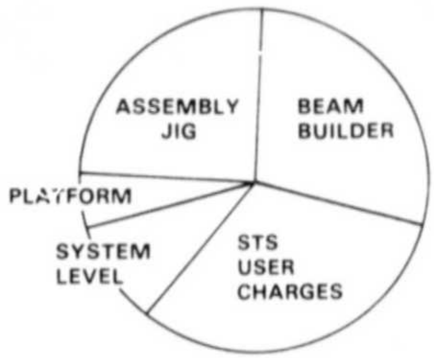
- The Phase B study produces, as a minimum:
  - Requirements in the form of specifications
  - Definition of flight experiments
  - A selected system predesign
  - Plans and costs for development
- Phase B includes a prototype development program to be carried out before the start of C/D on the key beam builder and assembly jig subsystems.
- Phase C/D system engineering and integration includes definition of the integrated payload system and compatibilities with the STS, mission and flight operations, verification, software integration, reliability and safety analyses, and configuration management.
- Phase C/D design and analysis task reflects maximum utilization of existing equipment listed in the NASA Low Cost Program Office CASH catalog, as well as multi-use mission spacecraft equipment.
- Phase C/D prototype development equipment will be as near to final design as practical including drives, controls, and sensors.

A cost analysis of the SCAFE Program was conducted and detailed data collected per a WBS containing all of the hardware and tasks associated with program development and test, the fabrication of the flight hardware, and the operations activities incurred during the first flight.

Summary data is shown in Figure 2-30, for both the total program and the beam builder element, and separately identifies pre-phase C/D prototype development effort in addition to Phase C/D costs and Shuttle user charges. It was assumed that the Shuttle user charge includes all Shuttle related activities such as on-line payload installation (OPF), MOC activities, flight crew costs and other common ground operations/mission operations and

COST SUMMARY ($M)

	SCAFE PROG	B.B. ONLY
PREPHASE C/D	2.30	1.50
PHASE C/D		
NONRECURRING	33.39	15.94
RECURRING		
PRODUCTION	4.71	2.13
OPERATIONS	1.50	—
SCAFE PAYLOAD	41.90	19.57
USER CHARGES		
SHUTTLE	18.89	—
TRACKING & DATA	(TBD)	—
TOTAL	61.79	19.57



SCAFE ANNUAL FUNDING

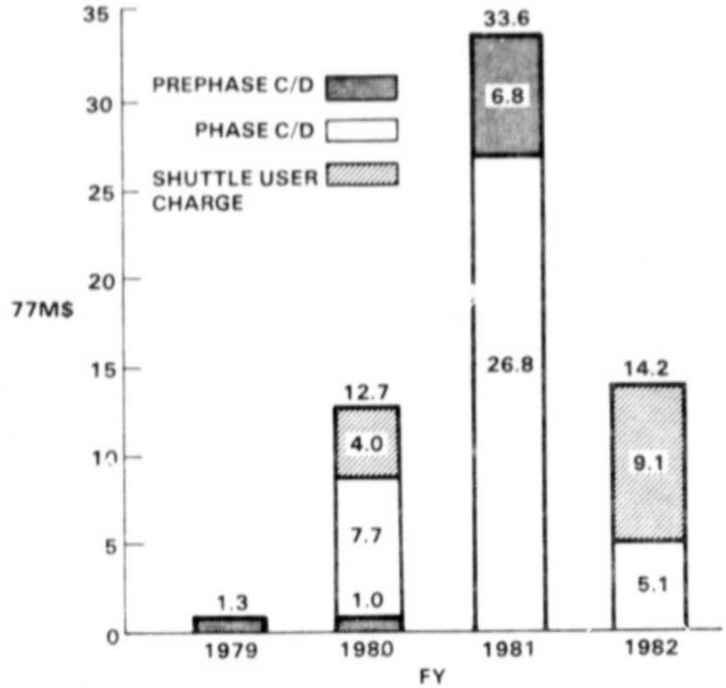


Figure 2-30. Program funding requirements.

activities. Other Shuttle related services such as OMS kits, RMS, and other optional services are added to the Shuttle user charge for the basic transportation. Potential user charges for tracking and data acquisition (TDRSS, etc.) are carried as separate program level items.

Phase C/D cost totals are presented for the nonrecurring (development), the recurring production (flight hardware), and recurring operations phases of the program. All costs are estimated in current constant FY 1977 dollars and prime contractor fee is not included. The estimate includes all payload incurred costs through the first launch (1982) of the fabrication experiment including three months of experiment orbital monitoring and data acquisition.

The nonrecurring development (DDT&E) phase includes all of the one-time tasks and hardware to design and test the SCAFE experiment. The production phase (unit cost estimate) includes all tasks and hardware necessary to fabricate one complete set of flight hardware equipment. The operations phase includes all preparation launch and on-orbit operations associated with the SCAFE experiment.

The annual funding requirements for the SCAFE program are also shown. This distribution was established by spreading individual cost elements in accordance with the program schedule shown previously. Shuttle funding was spread in accordance with the Space Transportation System User Handbook, dated June 1977.

3

CONCLUSIONS & RECOMMENDATIONS

3.1 CONCLUSIONS

Principal study conclusions are grouped by major category in Table 3-1.

Table 3-1. Study Conclusions

- SYSTEM DESIGN & ANALYSIS
  - Fabrication equipment
    - Automated fabrication & assembly feasible
    - Electromechanical devices state-of-the-art but continued development needed in selected areas
    - Control functions within memory & speed capability of current microcomputer systems
    - Power requirements well within orbiter capability
    - Control & monitor concepts compatible with orbiter crew & equipment
    - Orbiter software support functions generally acceptable
  - Platform
    - Dynamic response & resulting structural loads low
    - Peak temperatures low & orbital variation small
    - Thermal distortions & loads low
    - Open section cap easy to form, exhibits large margin of safety
    - Hybrid laminate material minimizes forming energy; has high E; low CTE; uses low-cost pitch fiber
- FLIGHT MISSION INTEGRATION
  - All objectives accomplished in single seven-day mission
  - Fabrication & assembly fully automated; EVA capability devoted to equipment installation & checkout, maintenance demo
  - System orbiter compatible: weight & cg; support reactions; VRCS control; low propellant consumption; low power demand; no radiator interface
  - Constant earth fixed orientation preferred: platform in release position; rate mode control in yaw & roll
- PROGRAMMATICS
  - Mid-1982 flight date achievable if:
    - Prototype fabrication equipment development parallels phase B
    - Phases C/D not re-competed
  - Total SCAFE payload cost \$41.9M; beam builder cost \$19.6M
  - Single mission accomplishment saves \$19.9M Flight 2 user charge

3.2 RECOMMENDATIONS

From effort to date, several areas of further activity were identified. The most significant of these are collected, by major category, in Table 3-2.

Table 3-2. Recommendations.

- DEFINE GROUND-BASED BEAM BUILDER DEVELOPMENT ARTICLE
  - Prepare detailed concept design
  - Define a development test plan
- MANUFACTURE & TEST
  - Develop & fabricate beam builder equipment prototypes; conduct sequenced tests with prototype controller
  - Continue materials characterization
  - Conduct component & assembled beam tests
- FURTHER DEFINE SCAFE SYSTEM CONCEPTS
  - Conduct selected analysis, design & Orbiter interface trades
  - Identify & define fab equipment cost reduction approaches
  - Update beam builder & assembly jig concept designs
  - Identify fab equipment elements suitable for individual "suitcase" experimentation; define experiments
- UPDATE PROGRAM DEFINITION
  - Define & integrate latest requirements
  - Conduct schedule & cost trades
  - Prepare development plan; conduct cost analysis