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AUTOMATED BEAM BUILDER

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SUMMARY

With an eye on the future, NASA has been funding study and development contracts to determine the feasibility of constructing large volume, light weight structures in space. This would include deployable, erectable and fabricatable space structures, depending upon the size of the structure to be constructed and its ultimate utilization. One such approach, space fabrication of large space structures, has been under study by several aerospace companies. Early in 1977, Grumman Aerospace Corporation was awarded a contract (Ref. 1) to design, develop, manufacture and test a machine which would automatically produce a basic building block aluminum beam (Fig. 1). This paper discusses the results of that effort and the work which still continues today, including:

- Aluminum Beam Builder, which was completed and delivered to NASA-MSFC in October, 1978

- Composite Beam Builder, for which technology development is still underway.

INTRODUCTION

In-house study efforts at Grumman during the early 1970's indicated that a machine which could automatically produce beams in space would be a likely candidate requirement for construction of large space structures, such as a solar power satellite. Further study under a seven month contract with NASA (Ref. 2) indicated that near-term feasibility demonstration of such a machine which would produce aluminum beams was possible. Next, a competition was held to build such a machine, and Grumman was named the winner. The work performed, including designing, developing, manufacturing and testing of the first ground demonstration aluminum "beam builder", is discussed in some detail below.

When the effort associated with this aluminum beam builder was well underway, recognition of the need for a machine which would produce composite beams encouraged us to start investigating the technological development necessary to do this. Grumman has been conducting various significant critical process development tests from mid-1977 to the present time. These are also discussed below.

ALUMINUM BEAM BUILDER

The approach to providing a ground demonstration machine entailed two significant steps, i.e.:

- Design and Development - several approaches to solving problems associated with various subsystems were investigated, including:
  - Beam cap forming
  - Brace storage, dispensing and transporting
  - Beam component fastening
  - Beam cut-off
- Manufacture and Test - problems, encountered and solved, were also associated with several subsystems, including:
  - Beam cap roll forming machinery
  - Brace dispensing mechanisms
  - Control devices.

DESIGN AND DEVELOPMENT

Basic to the design of the beam builder was the idea that the machine must be capable of transforming high density, low volume material brought into space into lightweight, high volume structural beams in space. Ideally, this would apply to the production of all the structural members to be formed and assembled to fabricate a beam. Therefore, initial design concepts included six machine components to fabricate the beam components, three to continuously form the beam caps and three with appropriate cut-off and handling devices to form the braces and bring them into assembly position. Cost restraints and the desire to have the demonstration machine fit within the Orbiter payload bay accounted for the present configuration of the beam builder: three cap forming machines and preformed brace storage, dispensing and handling devices (Fig. 2).

Beam Cap Forming

Two approaches to forming the open beam cap shown in Fig. 1 were considered: roll forming and step pressing. Development tests were conducted utilizing available production equipment (Figs. 3 and 4). Both approaches formed acceptable caps. However, it became clear that while the roll forming required more tooling, the length within which the beam cap could be formed was considerably less than that of the step press, with its finite forming station lengths and required step to step transition zone.

Brace Storage, Dispensing and Transporting

The initial approach was to have the brace storage, dispensing and transporting all performed in one package (Fig. 5). The concept had the entire package moving to the brace fastening position, picking off one brace and camming it into position on the beam cap for the clamp and fastening mechanism to hold it while the entire package retracted to its clear position. At the PDR (preliminary design review), it was decided that it would be undesirable to have these packages (three vertical and three diagonal brace cannisters) moving due to their mass. Therefore, a separate pivoting, pick-up and transporting device was developed (Fig. 6). The figure only shows two arms on the development cannister, although the plan was to have four arms in order to assure positive brace gripping and transportation.

Mechanization of the concept as it developed and the desirability to either reload or replace empty cannisters led us to consider another approach (Fig. 7). This final approach divorced the transportation function from storage and dispensing. Transportation is now accomplished by a separate brace gripping and carriage mechanism (Fig. 8) which has simplified overall mechanization of all brace storage and dispensing functions.

Fastening Beam Components

A number of approaches to fastening the braces to the caps to construct the 1 m beam were explored, some simply on paper and others by development testing. Concepts which required pre-finished holes and insertion of rivets, screws or other similar fastening devices were eliminated due to inherent alignment problems which could exist, depending upon the size of the parts being assembled. Concepts which would result in metal vaporization, such as electron beam or laser welding, were also eliminated. Concepts which involved punching or punch and bending were attempted and eliminated for one of two reasons: (1) they produced debris (self-piercing rivets or screws) or (2) the fastening technique produced cracking in either the brace or cap material at the fastening points (punch and upset in a fashion similar to a grommet or tab and bend). Ultrasonic welding (Fig. 9) and resistance spot welding (Fig. 10) seemed to be the only readily available approaches which satisfied all design conditions. Ultrasonic welding yielded inconsistent results and was therefore abandoned.

Development tests of series resistance spot welding (Fig. 11) gave consistent, predictable results, which led to the clamp and weld mechanisms utilized in the machine (Fig. 12) and shown conceptually in Fig. 13. Each pair of electrodes is actuated individually by a separately driven cam within each weld block. To minimize peak power, each pair of welds is made sequentially after a set of braces has been clamped in place, first the verticals and then the diagonals, to complete each beam bay.

Because the peak power required for resistance welding exceeds the peak power capability of the Orbiter, a separate power supply will be required, unless another less demanding fastening approach is developed. This possibility is presently being explored.

Beam Cut-off

The first approach attempted to provide beam cut-off once the desired length had been fabricated was a simple single shear device (Fig. 14). This proved to be unacceptable, since it produced severe rippling of the beam end away from the cutting edge. (This rippling would impair the installation of a beam end tripod used to attach one beam to another, as well as providing a possible safety hazard to the astroworker assembling the beams or installing equipment on them.)

The solution, although it did produce debris, was a double shear mechanism which not only sliced cleanly through the cap but also caught the debris in a self-contained storage box (Fig. 15).

MANUFACTURE AND TEST

Considering the complexity of the machine, the actual manufacture of the detail parts and assembly of the beam builder, as well as its preacceptance debugging and testing, went very well. There were, however, several areas in which problems did occur, as discussed in the following paragraphs.

Beam Cap Roll Forming Machinery

The lower right rolling mill (when looking at the machine from the material feed end) produced beam caps with pronounced flange waviness. Although structural compressive load tests demonstrated that this waviness was not detrimental to the strength of the part, it was still considered unacceptable since the other two machines were producing beam caps without waviness. No amount of adjustment of the roll tooling or subsequent weld block shunt bars which guide the beam caps through the brace fastening section of the beam builder eliminated the problem. Finally, all the roll form tooling from the three rolling mills were removed and shipped back to the manufacturer for comparative measurements on a forming station by forming station basis. It was found that the roll tooling from the lower right rolling mill was slightly different from that of the other two rolling mills, although it was still within the manufacturer's tolerances. The tooling was reworked to match precisely, and since its reinstallation in the beam builder, it has given no further problems.

Brace Dispensing Mechanisms

In the original brace storage and dispensing device (Fig. 5) there was a tendency to pick off more than one brace from time to time. This was solved by careful design and placement of brace spacers which maintain brace flange alignment and also transmit the stacking spring load through the stack of braces to the retaining/pick-off surface of the present helical brace dispenser (Fig. 7).

Presently, there are occasions when a brace fails to dispense. It has been determined that this has been caused by improper installation of the braces when loading the cannister. Care must be taken to assure that all braces are properly stacked and aligned, and free within the cannister, i.e., clear of the dispensing helix drive rod and not bound against any of the brace guide surfaces within the cannister.

Control Devices

There are 173 operational detection devices located throughout the machine to monitor every function of the machine. They provide start and operation complete signals to the machine as the beam cap is rolled for one bay length of 1.5 m and stopped, braces are dispensed and transported into place, clamped and welded (first the verticals and then the diagonals), with each sequence repeated until the preprogrammed length of beam is produced, cut-off and the next beam started. Of these devices, 162 are limit switches, with the remainder being encoders, tachometers, photo-optical detectors and electrical pulse sensors. The limit switches are all alike. With regard to size, they are small enough to fit within the limited space available in a mechanism, such as the brace clamp and weld device. They provide no difficulty where protected within the particular mechanism with which they are associated, but where they are exposed and subject to accidental damage by technicians servicing the beam builder, they have been a source of beam builder malfunction. Although one can override a malfunction indicated by the control computer during operation, it is still a source of concern. Where possible, shielding has been provided to protect the most vulnerable limit switches. This has minimized the problem but has not eliminated it. Under consideration is the possible replacement of those limit switches which are still subject to damage by larger units, either photo-optical or magnetic proximity switches, where possible, to eliminate this troublesome problem altogether.

COMPOSITE BEAM BUILDER

As the development efforts associated with the aluminum beam builder were nearing completion, attention was focused on what it would take to modify the design of the primary machine subsystems in order to produce composite beams. This new development effort focused on three items, as noted in Fig. 16, while the remaining subsystems were considered to be usable as is or with slight modification to handle the new material.

Beam Cap Processing Development

In mid-1977, work began with a brute force approach of trying to roll form a graphite/polyethersulfone laminate using the aluminum beam cap development tooling with heaters added to soften the thermoplastic composite to forming temperature (Fig. 17a). Figure 17d shows the result of these efforts. Disastrous, burnt toast aptly describe the product, but at the same time, much was learned; such things as temperature control (polyethersulfone softens at about 260°C and has a forming range before it begins to sublimate of about 10°C), bend zone heating (heating the whole part resulted in severe rippling and deformation) and speed control between stations (the part must be kept in tension as it passes through the mill to prevent any rippling or folding in the bend area).

Following a thorough evaluation of the results, we decided to work with a lower forming temperature material that also had a broader working range. The material selected was graphite/acrylic which forms at 140°C with a 30°C range. The selection process and criteria are discussed further below (see Material Evaluation). Still recognizing the need for higher working temperature material, our intent was "to crawl before we walk and walk before we run". Using the same machine previously used but now modified to provide some temperature control, heating along the bend zone only and with a uniform drive (Fig. 17b), encouraging results were obtained (Fig. 17d). Although there was notable flange rippling and some twist, as well as skewing of the finished part, we were encouraged enough to ask corporate management for funding to design and build a composite structural component forming process development tool, since we had been tying up a piece of production machinery with our experiments (Fig. 17a and b).

Having received a go-ahead, the machine was designed and built (Fig. 17c). Figure 17d shows the results. After having successfully formed a good graphite/acrylic cap we tried graphite/polethersulfone once again. An acceptable product resulted (Fig. 18). With the composite industry supplying continuous strip stock (not available at the time of writing this paper) we hope to report on successful graphite/polyethersulfone beam cap production at the symposium.

Fastening of Composite Beam Components

As work on beam cap processing began to progress satisfactorily, development effort on fastening braces to beam caps began. Many approaches were considered; those listed in Fig. 19 were subjected to limited development testing and evaluation. Briefly:

- Ultrasonic Weld - Joint was acceptable but the ultrasonic vibrating horn tended to bore a hole in the part. Packaging presented a problem due to the horn size. Power consumption was higher than the other processes investigated.

- RF Welding - Joint appeared to be good. Arcing of the laminate to the test fixture away from the joint being made indicated a potentially difficult material quality control problem.

- Stapling (Cold) - Joint produced was excellent. However, uncontrollable debris was produced.

- Stapling (Hot) - Heating the parts at the fastening location eliminated the debris problem and still produced an excellent joint. Size and shape of the staple cartridge presents a packaging problem.

- Adhesive - Joint produced was good. Outgassing may be a problem (no measurements were attempted at this time).

- Induction Weld - Excellent joint was produced. Induction currents heat the part at the joint interface until the resin melts and fuses together. Packaging presents no problem and power consumption is extremely low. RFI may be a problem, although this is still to be investigated.

Material Evaluation

As discussed earlier, our first composite processing development efforts met with somewhat disastrous results. After reviewing our goals, we decided to try some alternate approaches. The material to be investigated had to satisfy the following simple requirements:

- Structurally sound in a space environment, including vacuum, thermal and radiation exposure

- No outgassing during forming in space or during its operational lifetime

- Simple to preprocess into the required strip stock laminate

- Long ground storage life

- Easy to handle.

Thermoplastics seemed to satisfy these general requirements (Ref. 3). (Thermosets present strip laminate processing, storage and handling problems since they have to remain in their uncured state until formed.) Figure 20 shows the thermoplastic composite materials which were evaluated. Acrylic was selected because it not only met our structural baseline (strength and modulus of elasticity to be as close to or better than that of aluminum) but also because it is a resin system which lends itself to continuous preprocessing of graphite and strip laminate production, including:

- Monomer/polymer blend liquid at room temperature

- Excellent fiber wetting characteristics

- Monomer and polymer are readily available in tank car quantities, if required

- Monomer and polymer are relatively low in cost - a factor which makes them attractive for research, development, and production.

The other materials tested did not, in general, meet the performance requirements. For example:

- Structural - much lower strength and modulus of elasticity than desired

- Preprocessing - poor fiber wetting. Press forming of strip stock required, thus limiting length available.

Woven graphite was chosen as the fiber medium because it is readily available and easy to handle. When processed as a graphite/acrylic composite, it gives good strength and stiffness properties and also forms easily.

The thermal performance of this particular composite is also quite good for passive structure in low earth orbit (Fig. 21). Through testing, we have demonstrated that though the strength of the material begins to fall off somewhat at the elevated temperature, compressive load testing at room temperature indicated a load carrying capability 180% greater than aluminum at room temperature and 120% at the elevated temperature. The coefficient of thermal expansion of this woven graphite/acrylic is 10% of that of aluminum. Recent electron bombardment testing in Grumman's Van de Graff facility has indicated that the material would have about a forty year life in low earth orbit (LEO). Ultraviolet exposure testing is still to be conducted.

While the graphite/acrylic satisfies the structural requirements for a passive structure (one which carries non-heat generating or radiating components or experiments), there still exists a need for a composite which could operate in a higher temperature regime. Work has therefore been continued with determining the forming process parameters associated with graphite/polyethersulfone laminates. The preliminary results have been encouraging (Fig. 18), although further study is required.

CONCLUSION

The automatic fabrication of basic building block aluminum beams has been ground demonstrated with the aluminum beam builder now operating at NASA-MSFC.

The automatic fabrication of basic building block composite beams still is to be demonstrated. Machine elements, composite beam cap forming and brace to cap fastening have been ground demonstrated. A composite beam builder still needs to be constructed.

To date, composite efforts have demonstrated the need for real improvements in basic thermoplastic composite processing in order to obtain better fiber wetting and continuous laminate strip stock. Short (1 to 3 m), press formed strips have been used for process development and demonstration purposes, but the real need is for a continuous strip up to 300 m long (the beam builder storage reel capacity). Material suppliers have been given this challenge.

Further effort is required to improve the structural characteristics, ease of preprocessing and final forming of graphite reinforced thermoplastics. Other resin systems and graphite fiber orientations need to be examined. The performance of these materials in both vacuum and radiation environments also needs to be determined.

Finally, once all ground feasibility tests have been completed and the choice has been made between aluminum and composite for the first space flight demonstration, a flight beam builder will be built and integrated aboard the Orbiter and a still to be determined mission flown (Fig. 22).

REFERENCES

1. Space Fabrication Demonstration System. Rep. no. NSS-SFDS-RP013, Grumman Aerospace Corp., Mar. 15, 1979. (Available as NASA CR-161286.)

2. Space Fabrication Techniques. Rep. no. NSS-SF-RP004, Grumman Aerospace Corp., Dec. 15, 1976. (Available as NASA CR-150202.)

3. Lubin, G., Marx, W., Poveromo, L., "Reinforced Thermoplastic Composites for Space Beam Fabrication," SPI Reinforced Plastics/Composites Institute, <u>34th Annual Conference</u>, New Orleans, Louisiana, February 1979.

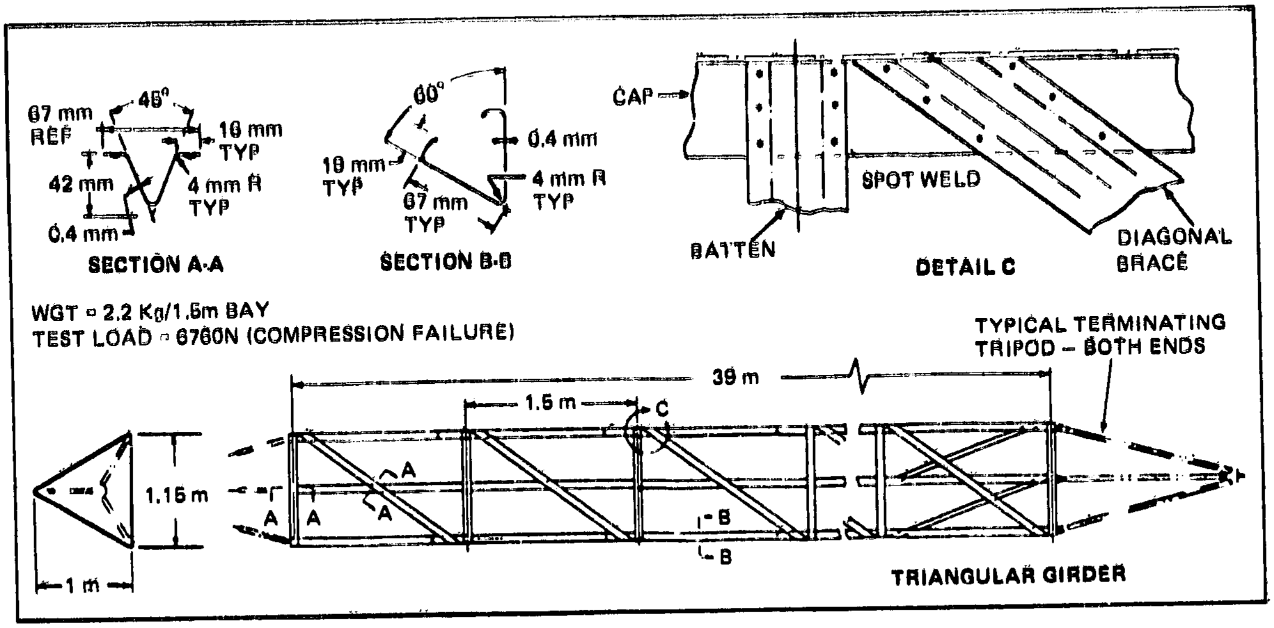

Figure 1.- Basic building block 1 m beam.

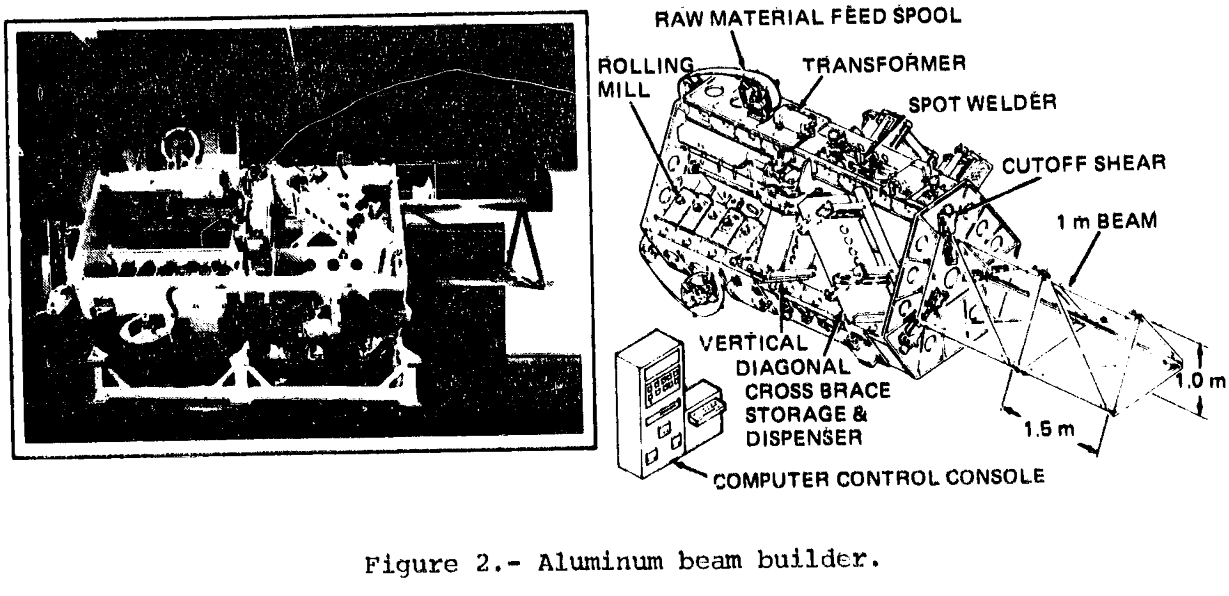

Figure 2.- Aluminum beam builder.

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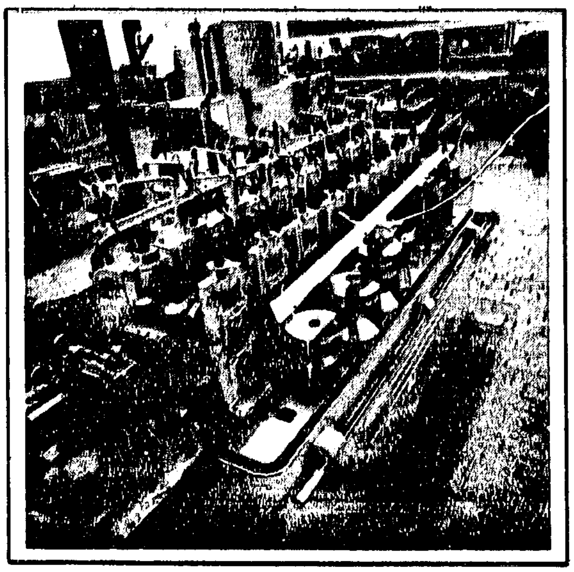


Figure 3.- Rolling mill with 1 m beam cap forming tools.

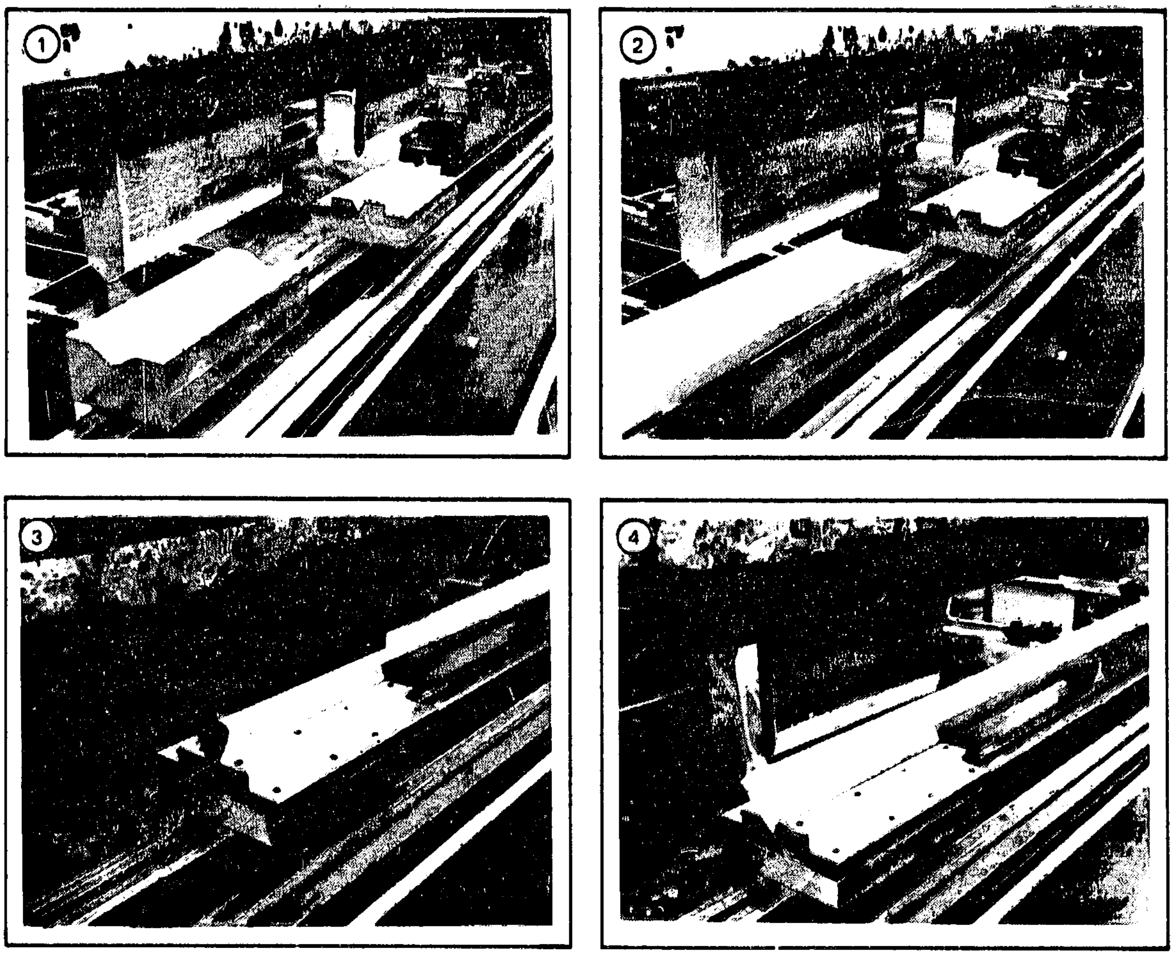


Figure 4.- Step press 1 m beam cap forming.

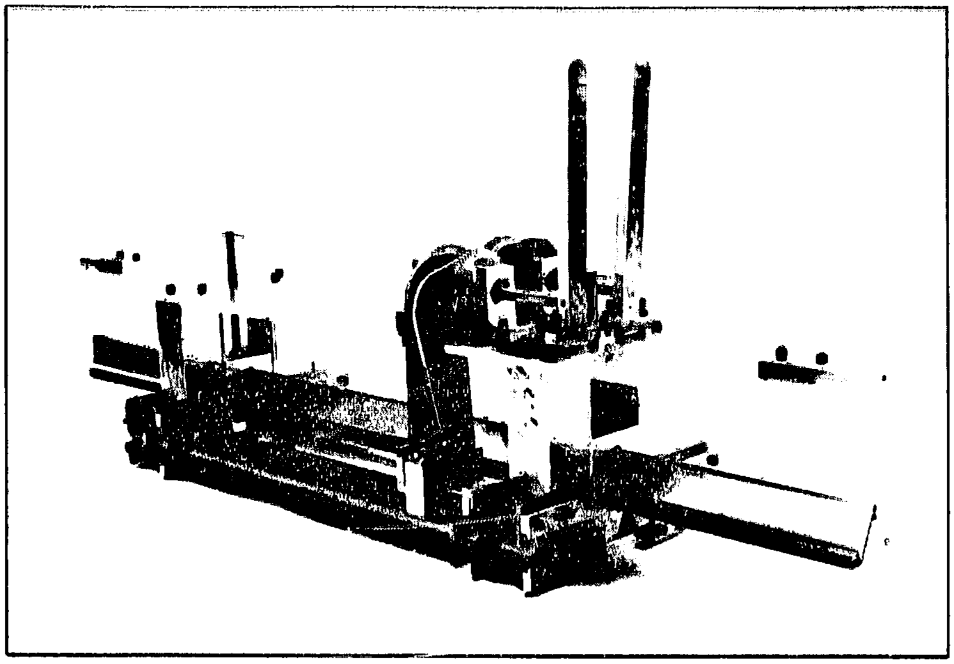


Figure 5.- Brace storage and dispensing device.

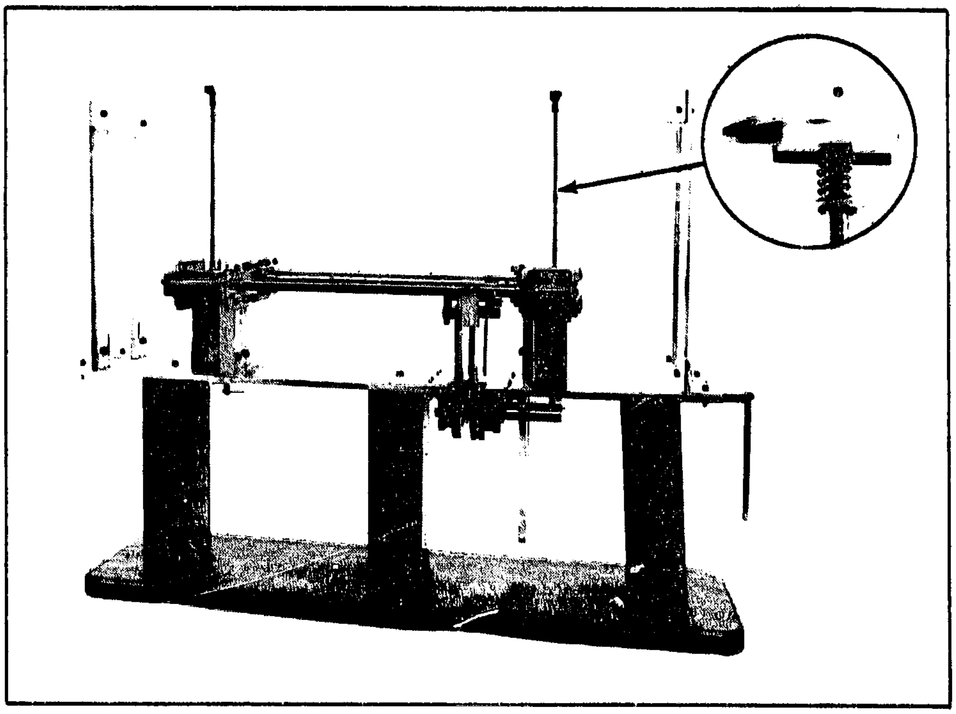
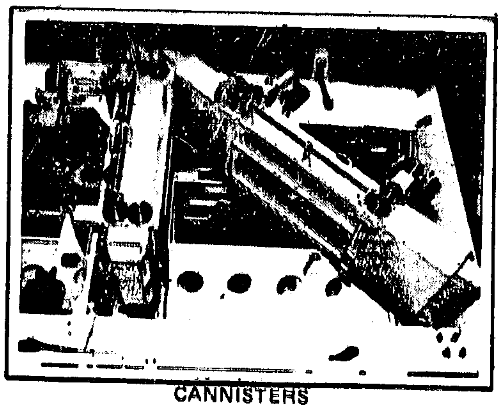
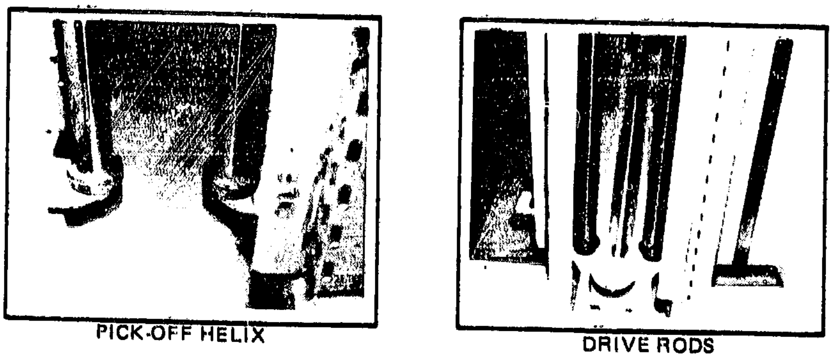


Figure 6.- Brace pivoting pick-up transport arm.



CANNISTERS



PICK-OFF HELIX

DRIVE RODS

Figure 7.- Final brace storage and dispensing device.

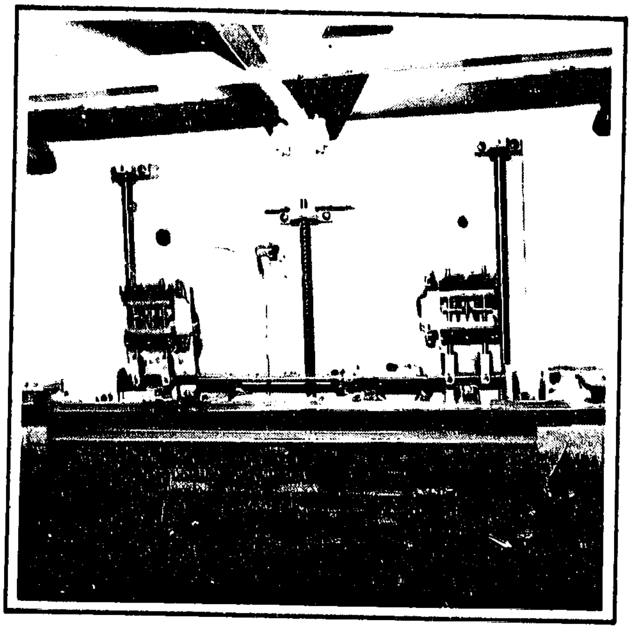
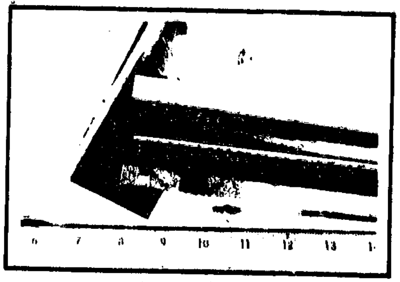
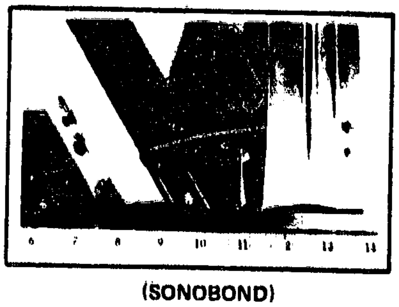


Figure 8.- Brace gripping and carriage mechanism.



(BRANSON)



(SONOBOND)

Figure 9.- Ultrasonic weld sample.

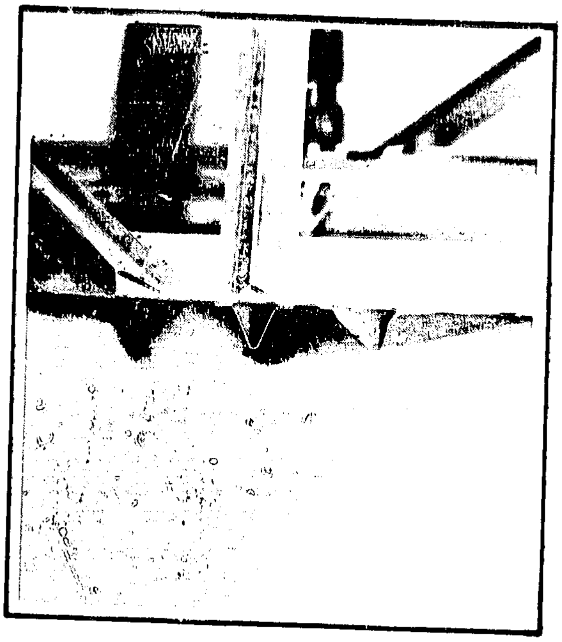


Figure 10.- Resistance spot welded brace to cap.

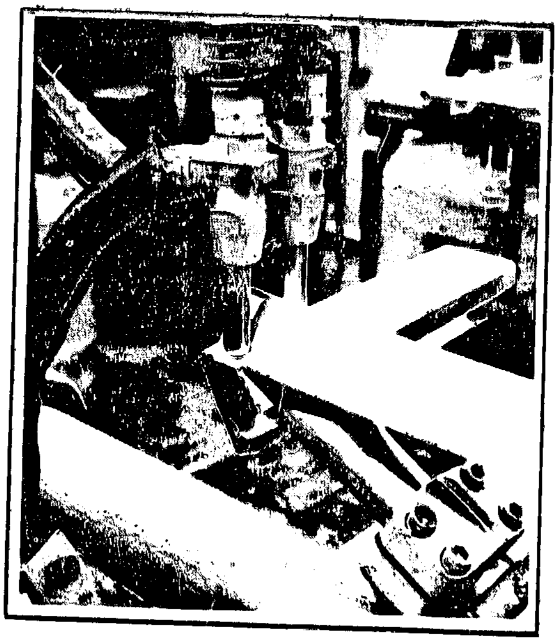
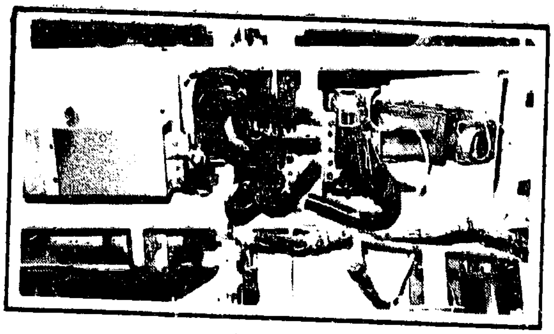
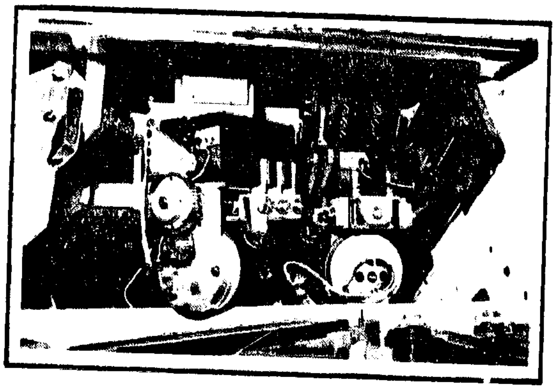


Figure 11.- Series resistance spot welding development set-up.



OUTBOARD



INBOARD

Figure 12.- Clamp and weld block mechanism.

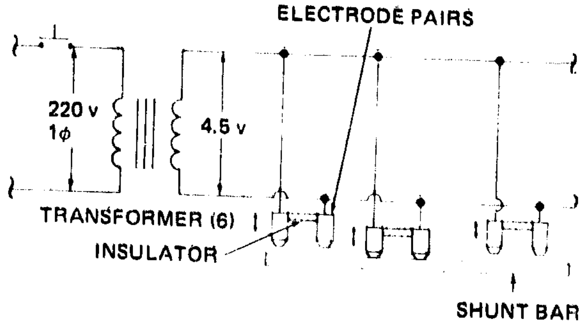


Figure 13.- Series resistance spot weld schematic.

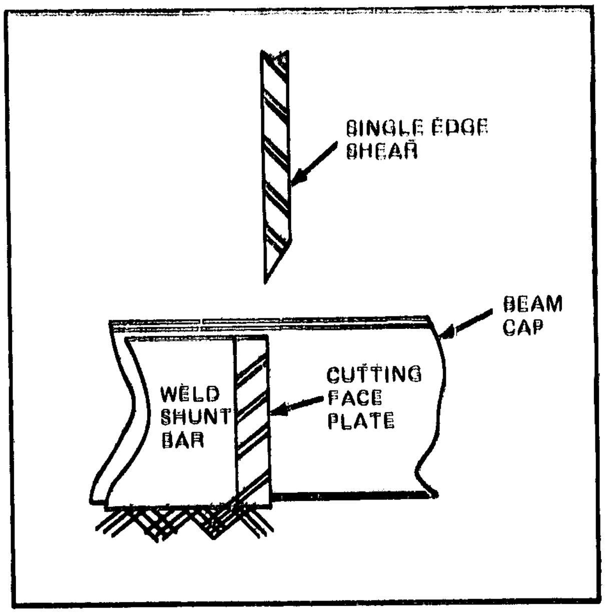


Figure 14.- Single edge shear cut-off schematic.

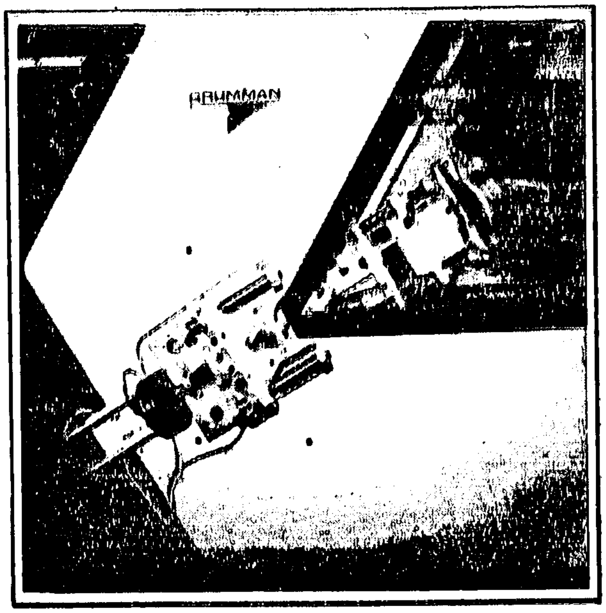


Figure 15.- Double edge shear cut-off mechanism.

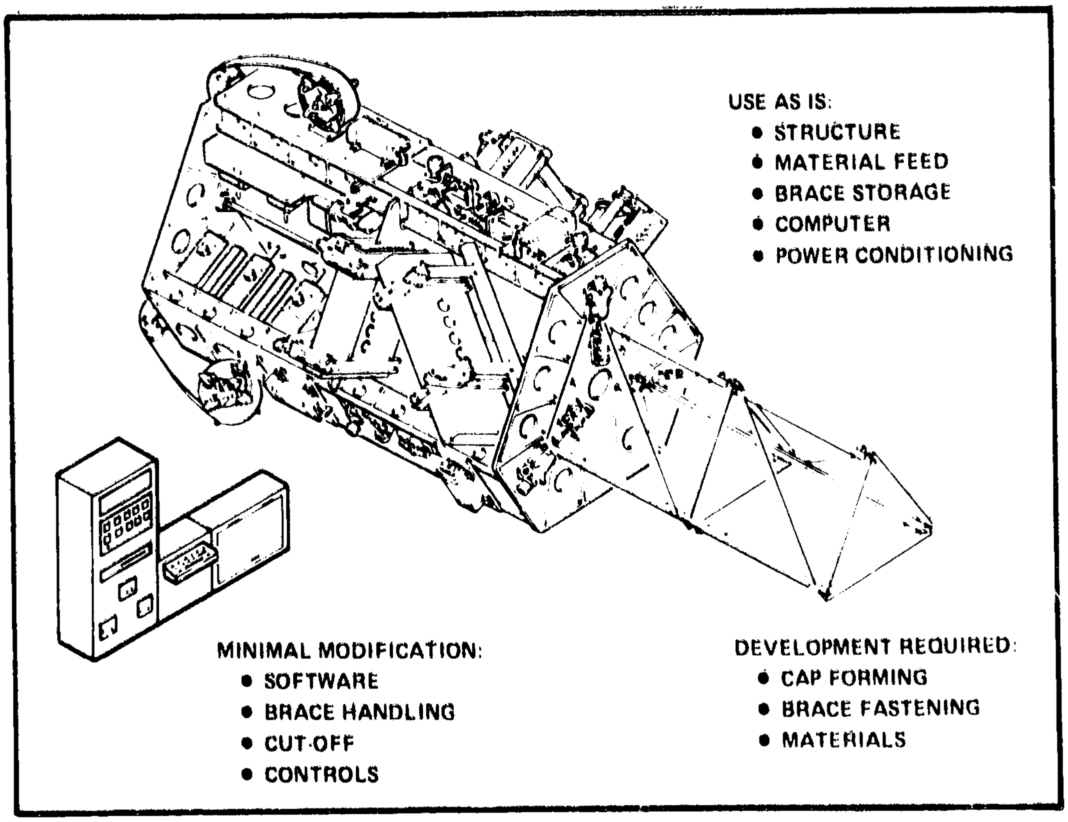
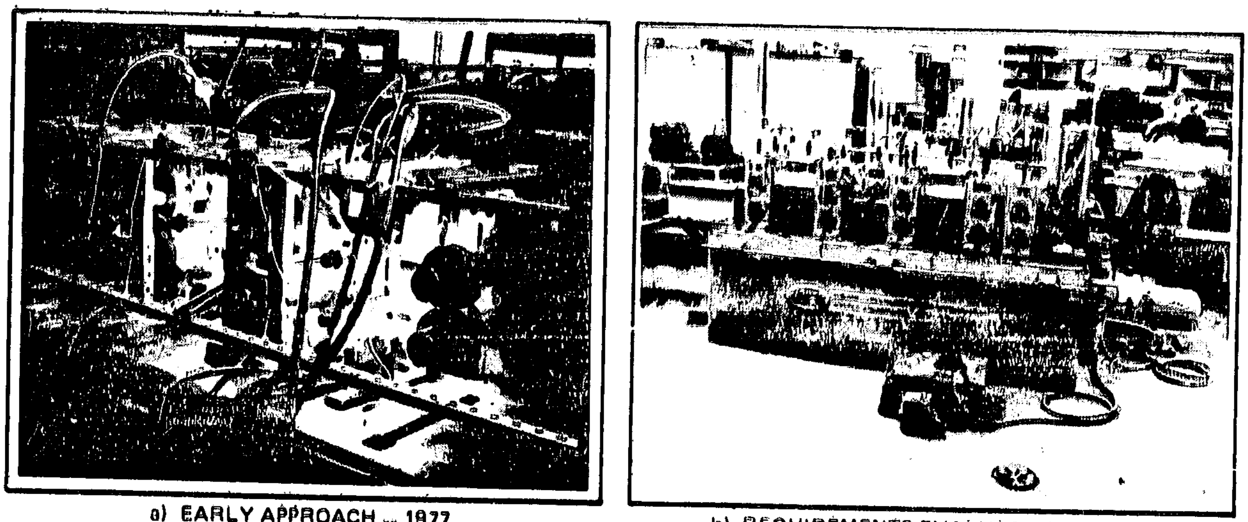
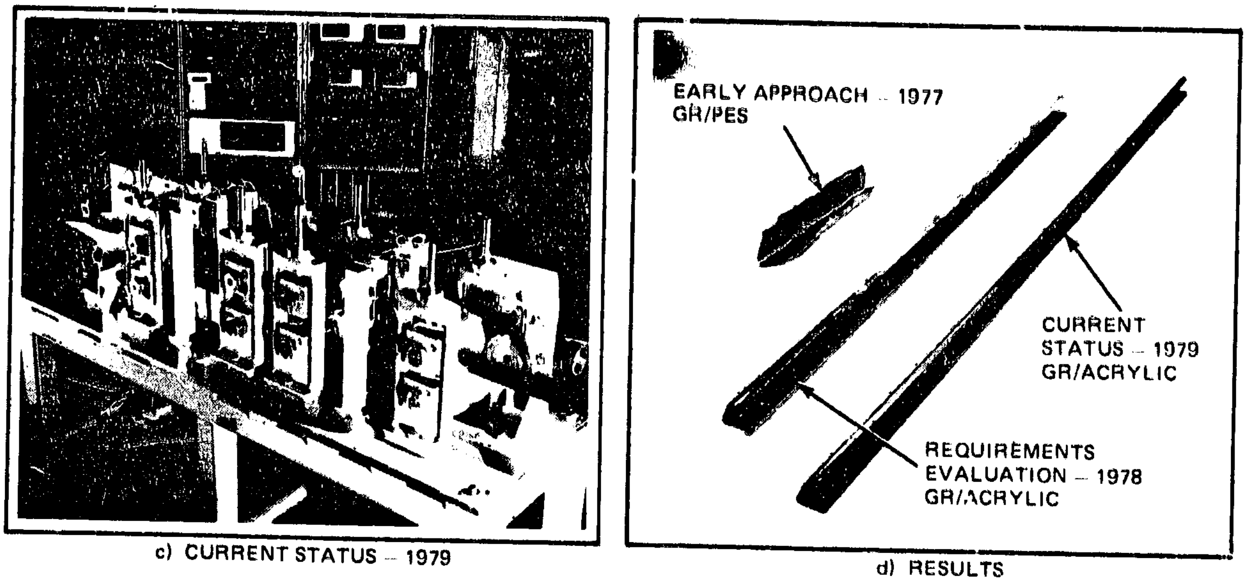


Figure 16.- Composite beam builder technology development.



a) EARLY APPROACH – 1977

b) REQUIREMENTS EVALUATION – 1978



c) CURRENT STATUS – 1979

d) RESULTS

Figure 17.- Composite beam cap forming process development and results.

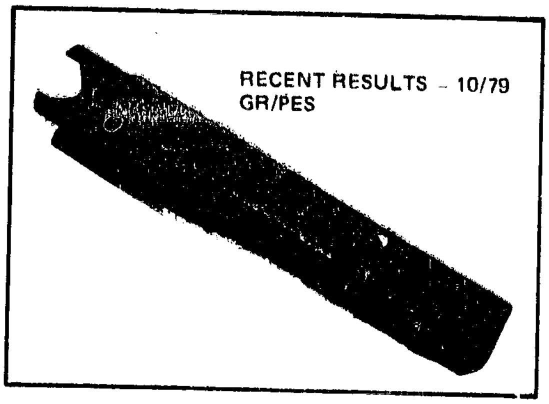


Figure 18.- Graphite/polyethersulfone beam cap sample.

METHOD	RESULT	PROBLEM	RECOMMENDATION	STATUS
ULTRASONIC WELD	ACCEPTABLE	POWER SIZE	DROP	—
RF WELDING	LIMITED SUCCESS	ARCING	DROP	—
STAPLING (COLD)	LIMITED SUCCESS	DEBRIS	DROP	—
STAPLING (HOT)	EXCELLENT	SIZE	MORE WORK (BACK-UP)	ON HOLD
ADHESIVE	GOOD	OUTGASSING	MORE WORK (BACK-UP)	ON HOLD
INDUCTION WELD	EXCELLENT	RFI	MORE WORK (PRIME)	NAS8-32472

Figure 19.- Composite fastening process development summary.

PHYSICAL/MECHANICAL PROPERTIES

LAMINATE IDENT	MFG	RESIN	CLOTH REINFORCEMENT	PROCESS PARAMETERS			LONG. TENS. STRESS (MPa)	LONG. TENS. MODULUS (GPa)	RESIN CONT	THICKNESS (mm)*
				TEMP	PRESS	TIME				
				(°K)	(KPa)	(min)			(%)	
201P	3M	Polycarbonate	Gr. 2423	533	690	30	333.7	43.2	–	1.0
102PH	Hexcel	Phenoxy	Gr. 1313	450	690	30	341.3	39.4	–	0.6
101A	GAC	Acrylic	Gr. 1212**	422	690	30	469.5	62.7	48.3	0.8 **
201A	GAC	Acrylic	Gr. 2423	422	690	30	444.7	58.3	35.4	0.8
301A	GAC	Acrylic	Gr. 2423/ Glass Scrim	422	690	30	427.5	42.8	–	1.1
302A	GAC	Acrylic	Gr. 2423	422	690	30	433.0	50.1	–	0.9
102PL	Hexcel	Polyester	Gr. 2424	–	–	–	281.3	30.1	–	1.5
303A	GAC	Acrylic	GR. 2423	422	690	30	284.1@ 350°K	36.1 @ 350°K	–	0.7
501A	Hexcel	Acrylic	Gr. 2423	477	1380	2	451.6	47.4	–	0.9
501A	Hexcel	Acrylic	Gr. 2423	477	1380	2	270.3 @ 350°K	39.9 @ 350°K	–	0.9

* LAMINATES – 2 PLIES THICK EXCEPT AS NOTED
** LAMINATES – 4 PLIES THICK

Figure 20.- Thermoplastic materials requirements evaluation.

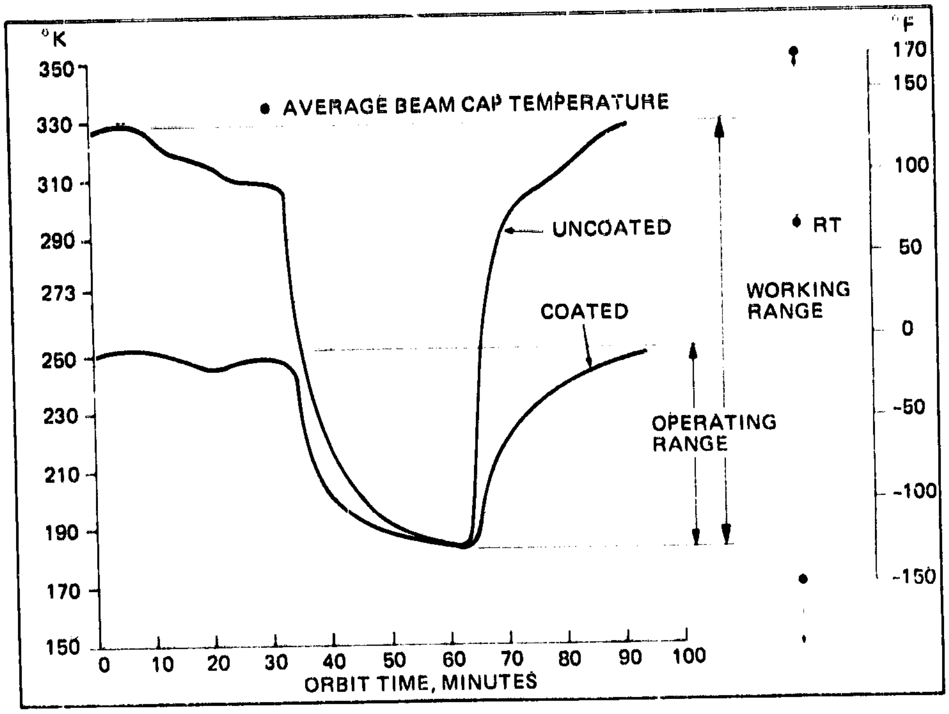
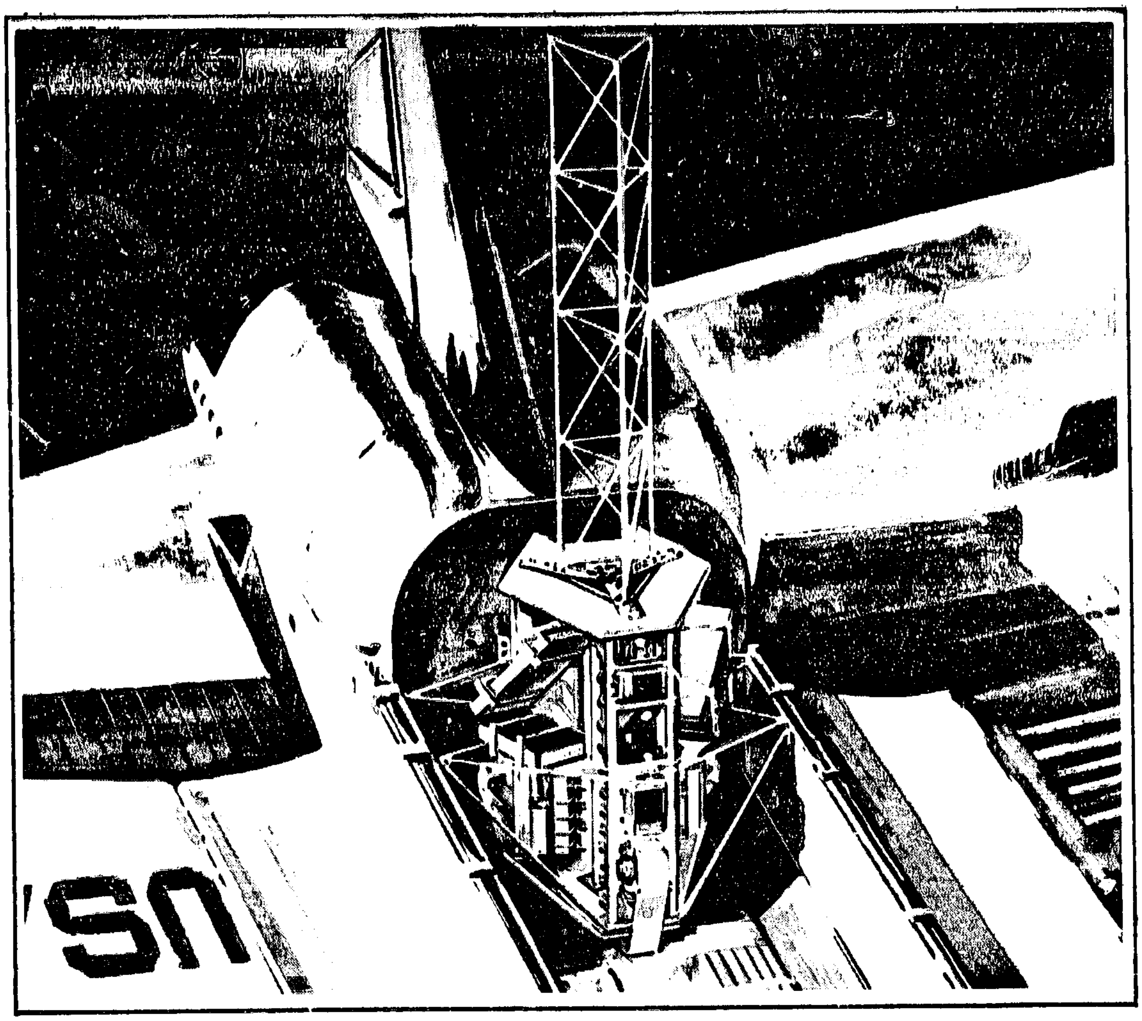
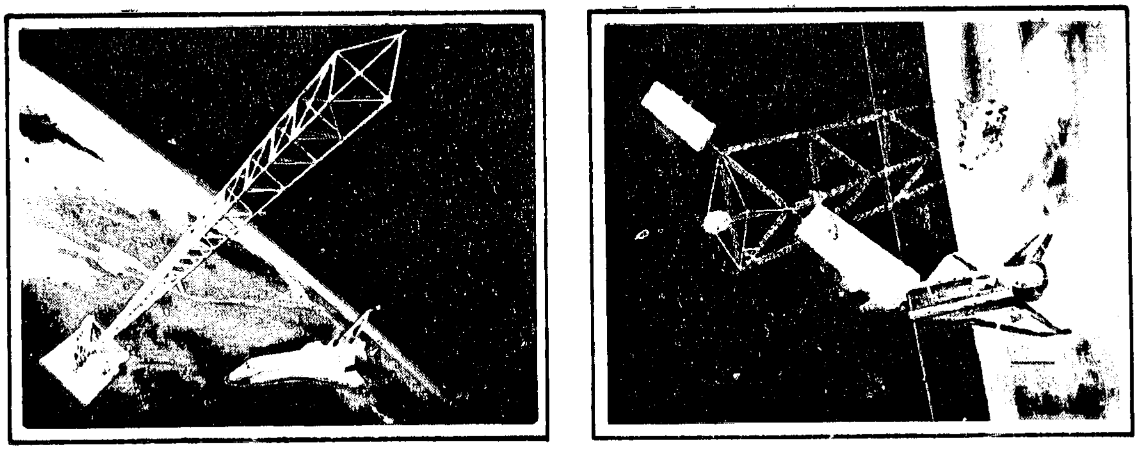


Figure 21.- Graphite/acrylic thermal gradient in low earth orbit.



BEAM BUILDER



GRAVITY GRADIENT RADIOMETER

TRIBEAM PLATFORM

Figure 22.- Early Orbiter beam builder mission possibilities.