Electron Beam Curing - A Cost Analysis

by

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ABSTRACT AND SUMMARY

Forming composites requires a material application phase, a cure phase, and a post fitting or assembly phase. Electron Beam (EB) curing can contribute to the cure phase directly, and to the material application phase indirectly. The three elements of the material application and cure phase that contribute to different costs of alternative methods of forming are the direct labor, capital costs, and utilities or consumables costs.

Labor Comparisons

EB curing was compared to autoclave curing using both Northrop and ABARIS developed cost models of the cure process. Based on the size of the part, EB curing demonstrated considerable man-hour cost savings. Using Northrop Formula the following savings were determined:

Part	Autoclave Cure	EB Cure	Savings
32 sq. ft, 0.032" thick	13	5.4	7.6 Man-Hrs
70’ by 4' by 3" thick	191	175	16 Man-Hrs
70' by 4' by 0.5" thick	53.8	38.7	15 Man-Hrs

Using the ABARIS model for a graphite cover, 24" by 24" with 6 plies of graphite, total weight of 2.4 pounds:

Part	Autoclave Cure	EB Cure	Savings
One at a time (Continuous for EB cure)	11.9	3.45	8.45 Man-Hrs
Six at a time (Continuous for EB cure)	6.9	3.45	3.45 Man-Hrs

Utilities and Nitrogen

Cost of utilities for heating, and nitrogen as an inert gas, to cure a composite structure was examined. The heating cycle is assumed to be only four hours: two to heat up and two additional ones holding at elevated temperature. Thus the heating costs for thicker parts, i.e., longer cure cycles, will be greater, although the nitrogen costs will be about the same. Based on two different size autoclaves, the following data was developed:

AUTOCLAVE	MAX #/RUN	UTILITIES/RUN	NITROGEN/RUN	TOTAL
65’ by 25’	6000	613	3272	3885
40’ by 8’	600	38	228	266

Capital Equipment Costs per Pound, Based on through-put

The capital equipment cost of a large autoclave or an EB cure facility is high. The exact cost of a given installation is difficult to determine, but based on discussions with several persons, the estimated cost of the 65 by 25 feet autoclave at Beech Aircraft is estimated to be about $8 million dollars. An EB facility was assumed to cost $ 6 million. Based on this the range of allocated costs of the capital, not discounted but based on a ten year life of the equipment is as follows:

LARGE AUTOCLAVE:

Utilization	Lbs/cycle	Cycles/day	Days/yr	Total Lbs	Capital/Lb
MAXIMUM	6000	2	360	4,320,000	$0.19
70%	2000	2	360	1,008,000	$0.79
60%	1500	2	360	648,000	$1.23
60%	1500	2	250	450,000	$1.78
100%	400	1	250	100,000	$8.00

EB FACILITY:

Utilization	Lbs/hour	Operating Hrs	Days/yr	Total Lbs	Capital/Lb
Maximum	3968	24	360	34,293,520	$0.018
70%	2000	24	360	12,096,000	$0.050
60%	1500	24	360	7,776,000	$0.077
60%	1500	12	250	2,700,000	$0.22
100%	400	8	250	900,000	$0.75

Overall Cost Comparison

Autoclave Cure

Using the 32 square foot and the 70 foot long part described in the preceding sections, an overall parts cost analysis was conducted. A thick (3”) and a thin (0.5”) product, each 70 feet long, were analyzed. The elements include the direct materials, direct labor, labor burden at 40% of direct labor, and general and administrative expenses and fee. In addition, a per part cost for capital equipment, tooling, and utilities are provided to illustrate how these costs contribute.

This analysis indicates a cost savings for the small part cured by EB compared to curing in a small autoclave, would represent about a 12 percent savings. A 25 % savings was indicated in the curing of a very large part, assuming that it could actually be done in an autoclave. It indicates the relative advantages of EB curing for mass production of small parts, as well as considerable savings on very large parts.

Filament Wound Structure

An analysis of simultaneous EB curing (insitu curing) of a filament wound structure was conducted. Focusing on the difference in the capital, labor, and utilities costs, assuming overhead, general and administrative, and fee are the same, the saving in winding a 26,000 pound part would be about $15,000.

Summary

By any measure of comparison of the common items in EB curing vs alternative methods, EB curing can be very cost effective. In addition to its technical benefits, the potential for continuous processing and curing at ambient temperature are potential further cost savings.

DISCUSSION OF COSTS OF CURING ADVANCED COMPOSITES

1.0 Background

ABARIS conducted the following cost analysis of curing composites by the use of Electron Beam (EB) Cure to determine the variables that are involved in defining the final parts cost. The alternative cure concepts are the use of room temperature cure for filament winding post cure, and oven or autoclave cure of vacuum bagged, prepreg parts. The advantages of EB curing, as well as some of the technical aspects, are discussed in References 1 and 2.

1.1 Fabrication Steps

Fabricating a composite part requires a materials application step, a cure operation, and a trim drill, and assembly step. EB curing can make major contribution to the cost of curing, and the technical performance of composite parts. EB curing can be combined with a material application activity to reduce the time required to form and cure parts.

1.2 Similarity Between Autoclave and Oven Cure

There is a strong similarity between the use of autoclaves and ovens. Both are methods of curing composites. Both use heat and pressure. An oven generally uses only vacuum pressure, but can use mechanical means of providing pressure to consolidate a laminate. An autoclave uses high pressure gas against a vacuum bagged part to apply pressure. The two elements being achieved are compaction and thermal curing.

Much of the analysis will discuss the comparison of these EB curing with these two techniques as if they were the same. The significant differences is in the degree of compaction by autoclave cure, which is greater than can be achieved by oven cure. Autoclaves are much more expensive to build and to operate than ovens. The capital and operating costs will be discussed in other sections.

1.3 Filament Winding as a Means of Material Application

Filament winding is a means of material application, and thus must be considered in a different light than alternative methods of curing parts. In a filament or tape wound part, the materials are applied to a mandrel, and then post cured. This can consist of simply letting the resin room temperature cure, or by the application of an external heated tool and an internal expandable mandrel for pressure. In some cases, the winding is simply a method of material application compared to cutting and laying plies of prepreg material. The wound material can be removed from the mandrel and secondarily formed and cured in another tool.

The relationship to EB curing is the possibility of insitu curing of thick composites on a mandrel as the material is being applied. This has the potential of reducing fiber waviness or marcelling, and minimizing thermal stresses. An additional option is the use of EB curing to reduce the time to post cure filament wound structures. This is further discussed in Reference 3.

2.0 INTRODUCTION

2.1 Content of Analysis

This analysis will discuss autoclave cure and the differences between oven cure, and compare them to EB curing. Cost elements of using EB curing in conjunction with filament winding will discussed. Several different size components and quantities will be considered. There are sizes and quantities where each of several methods of fabrication have advantages, and others where they are not cost effective.

There are three basic areas where the costs of curing composites by alternate means are different. One of these is the direct labor content of the process. The second is in the capital equipment costs amortized over the production life of the equipment. The third element is in- the utilities and support costs. These include the cost of electricity or gas to provided energy, costs of consumables such as bagging film, and inert gasses such as nitrogen.

There does not seem to be any significant difference in the engineering or process development time, nor in the general and administrative expenses. It may be that the potential consistency of EB curing could result in reduced manufacturing variability allowances, which would reduce material costs and product weight. It is also possible that the consistency could reduce the inspection costs, which are now a significant part of the overhead of composite companies. The preparation of materials and process specification for thermal or EB cure is expected to take about the same amount of time. The EB processes will require dosage calculations and power/energy requirements. The very rapid processing time for EB cure could mean significant savings in tooling, in that far fewer tools would be required to achieve a specified high rate of production compared to the very long cycle time required for autoclave or oven curing. This subject is not addressed in this paper.

2.2 Selection of Parts for Comparison

For the purpose of this cost analysis, it was necessary to select composite parts that could be compared. The overall cost will vary depending on which material system is selected, e.g., whether a prepreg or a dry fiber and liquid resin. The cost of graphite is very much higher than glass, and in addition, different weaves, tows, and performance graphite will have different costs. The two issues in this comparison is either the cost of curing when comparing EB to autoclaves or ovens, or the cost of the combined material application and curing process in the case of using EB to cure filament wound parts.

2.3 Parts

For comparing EB curing to oven (or autoclave) cure, different size parts have been analyzed. These are:

- 32 square foot, 4 ft by 8 ft, 24 ply .0055 thick graphite fiber
  (Note size part is discussed in Reference 5, which will allow further comparisons of automation in additional analysis.)

- 4 square foot, 2 ft by 2 ft, 6 ply, .012 thick graphite cloth.

- Very large part, 70 feet long, 4 feet wide, 3 inch thick, total weight 6894 lbs.

- Large part, 70 feet long, 4 feet wide, 0.5 inches thick, total weight 1158 lbs.
  (Note this part thickness was selected as representing a relatively thick graphite part, yet thinner than an optimal thickness for single sided EB cure, which is about 0.8”)

For comparing EB curing of filament wound parts, the part examined is:

- 26,000 pound wind generator blade, similar to that formed by Hamilton Standard. It is 170 feet long.

Large cylinders of revolution, such as submarine or autonomous undersea vessel pressure hulls are not specifically analyzed, but the concept of insitu cure of materials as they are being placed on a mandrel is now worth considering. This type structure requires that the material be applied without fiber waviness and with minimum thermal stresses in order to achieve optimal hydrostatic pressure resistance.

2.4 Direct Labor Analysis

Two methods were used to analyze the costs of autoclave/oven curing vs EB curing. One of these is the use of the Northrop developed formula in Reference 4. Two of the parts described in the preceding paragraph are analyzed, and the difference in man-hours to complete a lay-up and cure is noted. The second method was to develop a simple model, using our own experience in the time required to fabricate composite parts.

3.0 FORMING ADVANCED COMPOSITE PARTS

3.1 General

Advanced composite parts are formed of fibers and resins that are compacted and cured at elevated temperatures. There are presently two basic types of resins: thermosets and thermoplastics. The methods of compaction are typically vacuum bag or high pressure autoclaves. The methods of material application can be by automated or hand lay-up in mold form tools or by filament or tape application to a mandrel. A critical element of advanced composites is the precise placement of fibers on the tool or mandrel; usually within a few degrees. Mandrels are generally cylindrical in shape, but the material can be removed from the mandrel and post processed to a variety of shapes.

3.2 Electron Beam Curing as an Alternative

Electron Beam (EB) curing is a candidate for curing composites. The technique requires a specially formulated resin that provides free radicals that crosslink when exposed to electrons. EB curing still requires some method of material application, and a means of compaction. EB curing has a significant advantage over alternative methods of curing composites in that it has the ability to cure at ambient or near desired operating temperature, ability to cure very thick composites, and the ability to cure very long composite structures. Technical details of EB curing are contained in Reference 2, which discusses power, energy, and through-put. There are many subtleties to EB curing , such as the angle at which the energy strikes the part, the use of x-ray mode for thick parts and the ability to switch back-and-forth between modes on a single curing pass.

3.3 Curing Thick Composites

If a thick thermoset laminate is cured in an oven or autoclave, the temperature must be increased slowly to allow the inside of the part to heat up at a rate that allows the volatiles and trapped water to move out of the laminate. If the temperature of the oven or autoclave is raised too rapidly, then the outside of the part will cure before the inside, trapping gasses an moisture in the laminate. EB curing operates under a different set of principals, and the energy to cross link can be inserted into the center of the laminate. By partial curing per pass, the temperature of an EB cure process can be controlled to result in almost ambient temperature cure parts.

3.4 Oxygen Free Environment

Autoclave cure of composites is frequently done in a pressurized nitrogen environment to reduce the possibility of fire. Some operations do not use nitrogen, instead attempt to control the materials in the autoclave to reduce flammability.

There are concerns in EB curing with the need to provide an inert atmosphere, i.e., remove oxygen at the surfaces being consolidated or cured. Oxygen is an inhibitor of the free radical cross linking, and steps must be taken to minimize its effects. Gaseous nitrogen could be used to provide the inert atmosphere using very low flow rates. As References 1 and 2 indicate that high power cure can minimize the effects of oxygen, nitrogen costs are not considered for EB cure. In the case of a vacuum bagged EB cure part, oxygen at the surface of the part is minimized also.

3.5 Advantages of EB Curing of Composites

3.5.1 General

The advantages of EB curing of composites are discussed in detail in Reference 2. The significant advantages of radiation curing that are of interest are the potential for low per part costs for thick laminates, and the ability to process large quantities of materials in an almost continuous process instead of a batch process. One of the disadvantages that observers have commented on has to do with the necessity to provide contraction or consolidation forces during radiation cross linking. This is no different than using an oven cure, with vacuum bagging to provide compaction. If the additional compaction of an autoclave is necessary, say to achieve the desired strength-to-weight ratio, than an autoclave with a titanium window for the EB to pass through has been considered.

3.5.2 Part Thickness

The EB system can operate in two modes: EB and x-ray. The basic EB mode can cure unit density parts that are about 1.6 inches (4 cm) thick in single-sided operation, and 3.5 inches (8 cm) in two sided operation, at the maximum rate based on the power output of the magnetron. This means that when curing a graphite part, the distance must be divided by the density. This results in a part about 2 cm or 0.8 to 0.9 inches thick that can be cured by a single sided radiation source in one pass. By using the X-Ray mode of operation, the thickness can increase twenty fold, with a compensating reduction in throughput.

3.5.3 Minimum Thermal Stresses

The potential of radiation curing to achieve thick laminates with minimal thermal stresses should be of interest to a range of government and civilian organizations.

By making multiple passes with partial power, a part can be fractionally cured, with a minimum build-up in temperature. This means that a part can be fabricated at a temperature closer to the desired operating temperature. This capability obviously has an economic value, but is not quantified in this analysis.

3.5.4 Below Ambient Cure

An EB cross linked part could be cured at cryogenic temperature, with the temperature increase being controlled as discussed above. Thus the part can be consolidated/cross linked, at the desired operating temperature. This has significant application to space structures.

4.0 CURE DISCUSSION

4.1 Thermal Cure

The process of curing parts thermally in an autoclave or oven; or by cross linking by electron beam, has many of the same activities associated with them. Forming a part by applying materials by filament or tape winding, and then post curing by either heating or electron beam curing also has many of the same elements. Table A-1 is a sequential illustration of the steps that must be gone through to develop a composite part starting with "Requirements" and ending with "Production Start". Item 14 on the list is titled "Parts Fabrication." The detailed steps of this activity will vary depending upon the process selected. Table A-2 is a sequential listing of the steps required to form a part by hand or automated ply cutting, manual lay-up of plies, and either autoclave or oven cure and is typical of development or production.

4.2 Differences in Autoclave and Electron Beam Cure Processes

The possible differences in the total cost structure of an autoclave or oven cured part, vs EB curing, led to the development of the ABARIS Cost Model for comparing processes. This table lists costs that are associated with operating a factory that designs, analyzes, tools, and fabricates composite parts. The differences between an autoclave based cure concept, a filament winding concept, and an EB operation are noted.

This listing indicates that the overall operation of these activities would be similar. The materials for autoclave, oven, or EB curing would be about the same. It is assumed that they would be prepreg materials with the resin infused in the cloth or tape prior to its application to the tool There will undoubtedly be a difference in the strength-to-weight ratio of autoclave cured parts to either oven or EB cured parts. The significant difference is the cost of curing the composites.

TABLE A-1: Sequence to Develop Composite Components (EB Cure)

	Schedule (months)											
Task/Description	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1. Establish requirements	S=	=>										
2. Select material system		<=	=>									
3. Select structural concept		<=	=>									
4. Select manufacturing method		<=	=>									
5. Prep mat & process specs			<--	- ->								
6. Establish inspect criteria				<- -	-->	…	…	…>				
7. Define design allowables			<=	=>								
8. Conduct material qual tests				<=	=>							
9. Preliminary design				<=	=>							
10. Stress & load analysis					<=	=>						
11. Detailed design						<=	=>					
12. Establish tooling concept							<=	=>				
13. Detailed tool design								<=	=>			
14. Parts fabrication									<=	=>		
15. Validate/structural tests										<=	=>	
16. Detailed fixtures design								<=	=>			
17. Fixtures fabrication									<=	=>		
18. Assembly fit/function tests										<=	=>	
19. Redesign for results											<=	=>
20. Production start												*

==: Critical task ---: Non-critical task ….: Float time *: Project milestone <: Task has dependencies
>: Task has successors S: Task has no dependencies X: Task has no successors

TABLE A-2: Sequence to Develop Composite Components (Autoclave Cure)

	Schedule (months)											
Task/Description	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1. Obtain materials/templates	S=	=>										
2. Prep layup mold	S --	- ->	….>									
3. Cut pattern (no. plys)		<=	=>									
4. Apply to tool (no. of plys)			<=	=>								

5. Debulk after 3 to 4 plys				<=	=>							
6. Bag part					<=	=>						
7. Autoclave cure						<=	=>					
8. Debag							<=	=>				
9. Inspect part								<=	=>			
10. Trim to net									<=	=>		
11. Join as assembly										<=	=X	

==: Critical task ---: Non-critical task ….: Float time *: Project milestone <: Task has dependencies
>: Task has successors S: Task has no dependencies X: Task has no successors

EB curing is essentially a continuous process, not a batch process as are autoclaves and ovens. Some of the factors on the side of EB curing as mentioned earlier are the ability to:

- cure at ambient or near desired operating temperature.
- cure very thick composites.
- cure very long composite structures.
- cure large quantities (high through-put).

While an oven can be built to almost any length, at present the largest autoclave is 90 feet long. Thus it would not presently be possible to built parts longer than 90 feet if autoclave cure was desired.

4.3 Process Steps

In general, the work of fabricating a part, after tooling is proofed, and processes developed, can be organized into three steps. The first is material application: cutting the material and applying it to the lay-up mold. The second step is the preparation for curing by bagging, curing, then removing bagging material and demolding. The third step is the trimming and drilling and preparation for assembly. The first activity, of cutting and placing materials, and the third activity of trim and drilling and preparation for assembly, appear to be almost independent of the curing process.

4.4 Autoclave Cure

An autoclave is a pressurized oven, capable of monitoring temperature and pressure. It is usually provided with an inert environment, such as nitrogen gas, to avoid fires. Autoclaves can be as small as a few inches in diameter and length, to 90 feet long and 25 feet in diameter. The typical temperature for curing is about 350^{o}F for thermosets, with some thermoplastics requiring up to 800°F. Pressures of up to 200 psi are obtainable.

5.0 ESTIMATED LABOR TO CURE IN AN AUTOCLAVE

5.1 Reference

The time for each of the individual specific steps required to perform an Autoclave cure, see step 7 of Table A-2, has been analyzed by Northrop Corporation in 1976 and reported in Reference 4, USAF Number AFFDL-TR-76-87. ABARIS has some detailed disagreements with the equations developed by Northrop, and believe that they tend to underestimate the time required to accomplish a task. However, for purpose of comparison we have used these formula.

5.2 Northrop Formula

A printout of the formulas used in the analysis is given in Reference 4. In most cases the formulas are a constant, such as 0.00175 times a value, such as number of debulk cycles, to a power, such as 0.6911.

5.3 Assumptions in Comparison, Small Part

The assumption of this analysis is that a part, 4 ft. by 8 ft, consisting of 24 plies of 0.0055” thick tape is formed by the same technique of ply cutting and placing on a tool. After the second debulk cycle, the part is prepared for the autoclave or EB cure. The differences are in that no bleeder, separator, etc., are required, just a breather to allow for good vacuum compaction. After cure, the EB cured part has its vacuum bag and breather removed, and the autoclave cured part has its consumables removed.

5.4 Results of Northrop Formula, Small Part

Table A-3 is a result of using the Northrop formula to analyze 31 detailed steps. The Northrop analysis results in hours, which have been converted to minutes for better analysis. The part used for analysis is a 4 foot by 8 foot (32 Square Feet), 24 ply, 0.132 inch thick graphite/epoxy part. This part weighs 34.7 pounds, and is of the same size and materials as one analyzed in the study conducted at MIT and reported in Reference 5, which concerns with the cost of automation of various methods of manufacture of composites. Additional analysis may be able to examine the overall impact of EB on the automation of composites.

Debulking takes place twice, and the cure is shown as taking 6 hours. Those items which are common to autoclave and electron beam curing, such as tool preparation, are shown to take the same amount of time. Those that are not required for a specific process are shown as 0 time. The EB cure is shown as requiring a number of minutes equal to a throughput of 1800 kilograms per hour at 50% efficiency, based on the weight of the part. Some of the numbers resulting from Northrop’s analysis seem low, such as Step 16, "Load Autoclave" at 0.389060 minutes. However, it is assumed that the time to load the part to be cured in the autoclave is the same as to load it in the EB curing fixture.

This analysis indicates that if the EB cure requires about 1 minutes, that the total elapsed time for the autoclave cure is about 13 hours and for EB Curing, the elapsed time is about 5.4 hours, for a savings of about 7.6 hours of direct labor by the use of EB cure.

5.5 Results, Northrop Formula, Very Large Part

A similar analysis was conducted on a very large part, 70 feet by 4 feet by 3.0 inches thick, which would be difficult to form in an autoclave. The difficulty comes in achieving the proper cure temperature inside a thick laminate, by applying heat to the outside of the part. The part must be heated slowly in order for the water, volatiles, air, etc, to escape. The analysis assumes that the part would have to be heated very slowly to achieve this, resulting in possibly tripling the time to cure the part. The results of this analysis is shown in Table A-4.

This analysis indicates that for a part of the maximum length that could be cured in an autoclave, about 70 feet, that the time to conduct the 31 steps, including extensive debulking, is about 190 hours which includes an autoclave cycle of 12 hours. The equivalent time for an EB cured part is 174 hours, with the same amount of time spent in cutting and laying plies, and in debulking. Undoubtedly automation would reduce some of these times. The savings in man-hours is about 16 hours using the Northrop formula.

TABLE A-3: Results Using Northrop Formula; Small Part

		NORTHROP FORMULA		EB CURE
		AUTOCLAVE CURE	BEST	ESTIMATE
STEP	ACTIVITY	(HRS)	MINUTES	MINUTES
1	PREP TOOL	0.10368	6.2208	6.2208

2	CUT & LAYUP	3.647810	218.8686	218.8686
3	DEBULK	1.191026	71.46160	71.46160
4	APPLY SEPARATOR	0.041472	2.48832	0
5	APPLY BLEEDER	0.09216	5.5296	0
6	APPLY SEPARATOR	0.041472	2.48832	0
7	APPLY BREATHER	0.09216	5.5296	5.5296
8	INSTALL VAC PORTS	0.0248	1.488	1.488
9	INSTALL THERMOC	0.0648	3.888	0
10	APPLY SEAL TAPE	0.04608	2.7648	2.7648
11	APPLY SAG	0.027648	1.65888	1.65888
12	SEAL EDGES	0.15552	9.3312	9.3312
13	APPLY VACUUM	0.0061	0.366	0.366
14	SMOOTH DOWN	0.027648	1.65888	1.65888
15	LEAK CHECK	0.004896	0.29376	0.29376
16	LOAD AUTOCLAVE	0.006484	0.389060	0.389060 LOAD EB
17	CONNECT T.C.	0.0368	2.208	0
18	CONNECT VAC LINES	0.0244	1.464	0
19	CHECK BAG.SEALS	0.995968	59.75808	0
20	MISC. PREP.	0.1394	8.364	0
21	CONDUCT CURE	6	360	1.048717 EB CURE
22	OPEN CLAVE	0.09684	5.8104	0
23	DISC T.C.	0.014	0.84	0
24	DISC VAC	0.0124	0.744	0.744
25	ROLL OLJT	0.012	0.72	0.72
26	REMOVE LAYUP	0.006484	0.389060	0.389060
27	REL. CLAMPS	0.02016	1.2096	1.2096
28	REMOVE SAG	0.002304	0.13824	0.13824
29	REMOVE T.C.	0.038	2.28	0
30	REMOVE VAC FITE	0.0116	0.696	0.696
31	REMOVE CONSUM	0.014112	0.84672	0
	SUBTOTAL:	**12.99822 HRS**	**779.8935 MIN**	**324.9768 MIN**
		PER POUND:	**22.49438 MIN/LB**	**9.373270 MIN/LB**
DECREASE DUE TO EB CURE:		**7.581945 HRS**	**(NOTE: NO THERMOCOUPLES)**	

* Based on Technical Report: AFFDL-TR-76-87 Northrop Corporation, Aircraft Division, Hawthorne, CA Wright-Patterson AFB, volume 1, 1976

MODEL PART:	4’ x 8’ x 0.132”	GRAPHITE/EB-curable resin	FABRIC:	0.0055 in./ply
	Area	32 SQ FT	PLYS:	24
	Area	4608 SQ IN	DEBULKS	2 cycles
	Perimeter	288 Inches	VAC PRTS	4
	Weight	34.67059 lb.	T.C.	4
	Density	0.057 lb./cu.in	EB cure:	188 kg/hr max; 33.06 lbs.min; 50% eff.

As x-ray mode can cure parts several times thicker than is now done by autoclave, there is no reason to attempt to compare costs. If a very thick part is needed, it now must be made by secondarily bonding thinner laminates. Work is being done in laminating thick thermoplastics, but it is still in the laboratory stage. EB curing may be a solution to the fabrication of very thick laminates.

Note that in Table A-4 a factor for the size of the part was considered. As the total weight, not counting tools and consumables, will be about 6900 pounds, it was not believed that the Northrop formula could be extrapolated linearly. The 3 inch thickness was selected to represent a thick part, for example for shipboard application, that could be cured in multiple passes; or possibly by the use of x-ray mode.

5.6 Results, Northrop Formula, Large Part

The maximum thickness that a graphite laminate can be cured in one pass by a 10 kW EB system is about 2 cm or 0.8 inches. This part was selected as 0.5 inches, representing 42 ply of 0.012 inch thick cloth. This analysis indicates that if the autoclave cured part required 8 hours to cure, and the EB part required 35 minutes, that the overall savings in lay-up and cure is about 15 man-hours. This analysis is shown in Table A-5.

5.7 ABARIS Analysis

No attempt has been made to generate a learning curve or a change in cost vs quantity. The times shown are the estimated time of an experienced composite technician. The part that was selected for analysis is a cover that is typical of a part that would be cured in large quantities.

5.7.1 Autoclave Cure

Materials: Typical materials would be a 5 harness satin graphite cloth, woven of 3K tow of AS-4 fibers. A typical resin would be Hercules 9508-2 or Fiberite 934 epoxy.

Process: The parts will be cured in an autoclave at 350 °F per the process specifications. The parts will be laid up on a mold form tool, bagged, and cured. The parts will then be debagged, inspected, trimmed, labeled, and shipped.

The following discussion is based on forming a relatively small part by EB cure. The part is a cover that has 6 plies, nominally 19 inches by 17 inches, with an actual ply size of nominally 24 by 24 inches. The part as laid up would weigh about 2.4 pounds. Assume that a balanced and symmetrical laminate is used, most of the plies will be 0/90 which are relatively easy to cut and place. There will be two 45s, which are slightly more difficult to cut and lay-up.

TABLE A-4: Results Using Northrop Formula; Large Part

STEP	ACTIVITY	NORTHROP FORMULA (H)	FACTOR SIZE	OVEN/AUTOCLAVE CURE (MIN)	EB ESTIMATE (MIN)	
1	PREP TOOL	0.6048	3	108.864	108.864	
2	CUT & LAYUP	148.8521	0.7	6251.790	6251.790	AUTOMATE
3	DESULK	55.54846	1	3332.907	3332.907	AUTOMATE
4	APPLY SEPARATOR	0.36288	2	43.5456	0	
5	APPLY RLEEDER	0.8064	2	96.768	0	
6	APPLY SEPARATOR	0.36288	2	43.5456	0	
7	APPLY BREATHER	0.8064	2	96.768	96.768	
8	INSTALL VAC PORTS	0.1736	2	20.832	20.832	
9	INSTALL THERMOC	0.4536	2	54.432	27.216	
10	APPLY SEAL TAPE	0.28416	2	34.0992	34.0992	
11	APPLY SAG	0.24192	2	29.0304	29.0304	
12	SEAL EDGES	0.95904	2	115.0848	115.0848	
13	APPLY VACUL;M	0.0061	4	1.464	1.464	
14	SMOOTH DOWN	0.24192	4	58.0608	58.0608	
15	LEAK CHECK	0.030192	4	7.24608	7.24608	
16	LOAD AUTOCLAVE/OVEN	0.021982	10	13.18925	13.18925	LOAD EB
17	CONNECT T.C.	0.2576	1	15.456	0	
18	CONNECT VAC LINES	0.1708	1	10.248	0	
19	CHECK BAG.SEALS	0.360073	2	43.20884	0	
20	MISC. PREP	0.1394	4	33.456	0	
21	CONDUCT CURE	12	1	720	208.4949	EB CURE
22	OPENING CLAVE	0.09684	1	5.8104	0	
23	DISC T.C.	0.098	1	5.88	0	
24	DISC VAC	0.0868	1	5.208	5.208	
25	ROLL OLJT	0.012	3	2.16	2.16	
26	REMOVE LAYUP	0.178703	1	10.72220	10.72220	
27	REL. CLAMPS	0.12432	1	7.4592	7.4592	
28	REMOVE SAG	0.32256	1	19.3536	19.3536	
29	REMOVE T.C.	0.266	1	15.96	0	
30	REMOVE VAC FIT.	0.0812	1	4.872	4.872	
31	REMOVE CONSUM	1.97568	2	237.0816	118.5408	
	SUBTOTAL:	**225.9264**		**11444.50 MIN** **190.7417 HRS**	**10473.36 MINUTES** **174.5560 HRS**	
	PER POUND:			**1.659893 MIN/LB** **0.027664 HRS/LB**	**1.519041 MIN/LB**	

DECREASE DUE TO EB CURE: 16.18567 HRS NOTE: NOT THERMOCOUPLES IN EB CURE

* Based on Technical Report: AFFDL-TR-76-87 Northrop Corporation, Aircraft Division, Hawthorne, CA Wright-Patterson AFB, volume 1, 1976

MODEL PART: 4' x 70' x 3" GRAPHITE/EB-curable resin FABRIC: 0.012 in./ply
Area 280 SQ FT PLYS: 250
Area 40320 SQ IN DEBULKS 20.833 cycles
Perimeter 1776 Inches VAC PRTS 28
Weight 6894.72 lb T.C. 28
Density 0.057 lb/in^3 EB cure: 1800 kg/hr; 33.069 lb/min; 50% eff.

TABLE A-5: Results Using Northrop Formula, Large Part

STEP	ACTIVITY	NORTHROP FORMULA (H)	FACTOR SIZE	OVEN/AUTOCLAVE CURE (MIN)	EB ESTIMATE (MIN)	
1	PREP TOOL	0.6048	3	108.864	108.864	
2	CUT & LAYUP	25.00716	0.7	1050.300	1050.300	AUTOMATE
3	DEBULK	9.332141	1	559.9285	559.9285	AUTOMATE
4	APPLY SEPARATOR	0.36288	2	43.5456	0	
5	APPLY BLEEDER	0.8064	2	96.768	0	
6	APPLY SEPARATOR	0.36288	2	43.5456	0	
7	APPLY BREATHER	0.8064	2	96.768	96.768	
8	INSTALL VAC PORTS	0.1736	2	20.832	20.832	
9	INSTALL THERMOC	0.4536	2	54.432	27.216	
10	APPLY SEAL TAPE	0.28416	2	34.0992	34.0992	
11	APPLY SAG	0.24192	2	29.0304	29.0304	
12	SEAL EDGES	0.95904	2	115.0848	115.0848	
13	APPLY VACUUM	0.0061	4	1.464	1.464	
14	SMOOTH DOWN	0.24192	4	58.0608	58.0608	
15	LEAK CHECK	0.030192	4	7.24608	7.24608	
16	LOAD AUTOCLAVE/OVEN	0.021982	10	13.18925	13.18925	LOAD EB
17	CONNECT T.C.	0.2576	1	15.456	0	
18	CONNECT VAC LINES	0.1708	1	10.248	0	
19	CHECK SAG.SEALS	0.360073	2	43.20884	0	
20	MISC. PREP.	0.1394	4	33.456	0	
21	CONDUCT CURE	8	1	480	35.02715	EB CURE
22	OPENING CLAVE	0.09684	1	5.8104	0	
23	DISC T.C.	0.098	1	5.88	0	
24	DISC VAC	0.0868	1	5.208	5.208	
25	ROLL OLJT	0.012	3	2.16	2.16	
26	REMOVE LAYUP	0.178703	1	10.72220	10.72220	
27	REL. CLAMPS	0.12432	1	7.4592	7.4592	
28	REMOVE BAG	0.32256	1	19.3536	19.3536	
29	REMOVE T.C.	0.266	1	15.96	0	
30	REMOVE VAC FIT.	0.0812	1	4.872	4.872	
31	REMOVE CONSUM	1.97568	2	237.0816	118.5408	
	SUBTOTAL:	**51.86515**		**3230.034 MIN.**	**2325.426 MIN.**	
				53.83391 HRS	**38.75711 HRS**	
	PER POUND:			**2.788568 MIN/LB**	**2.007597 MIN/LB**	

DECREASE DUE TO EB CURE: 15.07680 HRS NOTE: NO THERMOCOUPLES IN ES CURE

* Based on Technical Report: AFFDL-TR-76-87 Northrop Corporation, Aircraft Division, Hawthorne, CA Wright-Patterson AFB, volume 1, 1976

MODEL PART: 4' x 70' x 0.504" GRAPHITE/EB-curable resin FABRIC: 0.012 in./ply
Area 280 SQ FT PLYS: 42
Area 40320 SQ IN DEBULKS 3.5 cycles
Perimeter 1776 Inches VAC PRTS 28
Weight 1158.312 lb T.C. 28
Density 0.057 lb/in^3 EB cure: 1800 kg/hr; 33.069 lb/min; 50% eff.

The results of Autoclave Cure Analysis are as follows:

TABLE A-6: Results of Autoclave Cure Analysis

TASK	MINUTES
MATERIAL PREPARATION	60
TOOL PREPARATION	40
THERMOCOUPLE INSTALLATION	5
BAGGING	60
AUTOCLAVE CURE	360
DEBAGGING/PRELIMINARY INSPECTION	30
ULTRASONIC INSPECTION	80
TRIM	40
LABEL AND FINAL INSPECTION	20
PACKING AND SHIPPING	20
TOTAL DIRECT TIME	715
LESS AUTOCLAVE TIME:	-360
NON-AUTOCLAVE TIME:	355
ASSUME SIX PARTS PER AUTOCLAVE RUN 360/6	60
AVERAGE TIME PER PART	415

HOURS: 11.9 OR 12 MAN-HOURS PER COVER ONE AT A TIME
HOURS: 6.9 OR 7 MAN-HOURS PER COVER 6 AT A TIME

A maximum of three autoclave runs could be conducted every day, for a total of 18 parts per day. On a 5 day week, three shifts, 4.33 weeks per month average, this is 390 parts per month.

5.7.2 EB Curing

Materials: Typical materials would be a 5 harness satin graphite cloth, woven of 3K tow of AS-4 fibers. The resin would be formulated for electron beam curing.

Process: The parts will be laid up on a mold form tool, vacuum bagged, and then cured using an EB system with a through put of about 3000 pounds per hour maximum, per the process specifications. The parts will be laid up on a mold form tool, bagged, and cured. The parts will then be debagged, inspected, trimmed, labeled, and shipped.

The following discussion is based on forming a relatively, small part by EB cure. The part is a cover that has 6 plies, nominally 19 inches by 17 inches, with an actual ply size of nominally 24 by 24 inches. The part as laid up would weigh about 2.4 pounds. Assume that a balanced and symmetrical laminate is used, most of the plies will be 0/90 which are relatively easy to cut and place. There will be two 45s which are slightly more difficult to cut and lay-up.

Results of Analysis, EB curing

The process of curing by EB is a continuous process, not a batch process.

TABLE A-7: Results of EB Cure Analysis

TASK	MINUTES
MATERIAL PREPARATION	36
TOOL PREPARATION	30
THERMOCOUPLE INSTALLATION	0
BAGGING	10
EB CURE	1
DEBAGGING/PRELIMINARY INSPECTION	10
ULTRASONIC INSPECTION	40
TRIM	40
LABELING AND FINAL INSPECTION	20
PACKING AND SHIPPING	20
TOTAL DIRECT TIME:	**207 MIN**
HOURS: 3.45 HOURS PER PART.	

This is a reduction from about 12 hours per part in an autoclave one at a time, or 6.9 hours per part based on 6 parts per run. The savings therefore would be either 12 minutes 3.45 to 12 hours for one part, or if multiple parts were formed in the autoclave, it would be 6.9 minus 3.45 or 3.45 direct labor hours per part.

6.0 OVEN CURING

6.1 Sequence

The sequence of event to cure a part by oven cure and vacuum bag pressure only, are nominally the same as for an autoclave. The tool must be prepare with a release agent, the materials cut to the proper shape, and then applied to the tool. The part must be bagged with bleeder, breather, separator cloths, and bagging film. Thermocouples must be installed, as well as vacuum ports. The part must be transported to the curing fixture, and leads attached. The difference in time to cure by oven and autoclave may not be significant. The autoclave is more expensive to acquire, and more expensive to operate. The labor to program the temperatures and monitor the cure will be nominally the same.

Once the part is cured, the time to remove the part from the fixture (oven or autoclave) will be about the same. The time to remove the leads and then the bagging film will be nominally the same.

6.2 Differences

Thus, the difference in cost between autoclave and oven cure is in the capital equipment and utilities to pressurize the chamber; not in the labor content.

As autoclave cure normally provides better compaction, more materials may be required to achieve the same strength when oven cured. Thus there is a slight increase in materials costs, and perhaps lay-up costs, for oven cure vs autoclave cure.

7.0 AUTOCLAVE THROUGH-PUT

7.1 General

A major part of the costs of composite parts is the amortized capital equipment costs. To study this element, it was necessary to develop an understanding of the maximum potential capability for curing composites, by the two methods being analyzed. The following two sections discuss the potential through-put of a very large autoclave and an EB system.

7.2 Autoclave Through-Put Analysis

One of the largest autoclaves presently in operation is at Beech Aircraft. It is 25 feet in diameter and 65 feet long. It is capable of nominally 350 °F and 100 psi pressure. The estimated cost of operation includes about 15 man-hours per cycle to load, cure and unload. Two cure cycles per day are possible. A typical cure consisting of 6 to 9 hours for up to about 6000 pounds maximum of several medium to small parts. A more typical cure run is for a wing of about 300 pounds. Any part which is longer than this distance cannot be cured in this autoclave. Boeing in Seattle, Washington, has a 90 foot long autoclave, 24 feet in diameter, and Rockwell, Tulsa, Oklahoma, has a 70 foot autoclave that is 21 feet in diameter. These are supposedly the largest three in the nation. Beech has cured parts up to about 1.5 inches thick, but they are generally thinner than that. An oven can be formed of any length with less cost than an autoclave. The cycle time in an autoclave or oven is usually 4 to 6 hours which indicates that the number of components that can be cured annually is limited. The operating cost of an autoclave of this size includes the operator, the utilities for heating, the nitrogen gas for inerting, recording media, and any wear and tear on the vacuum lines and thermocouple leads. A further discussion of operating costs in contained in a subsequent section.

If two autoclave cycles were conducted per day, 6000 pounds per cycle, 360 days per year, the maximum total number of pounds that could be cured would be 6000 times 2 times 360, (6000*2*360) or 4,320,000 pounds. It is highly unlikely that 6000 pounds could be loaded, cured, and unloaded in less than 12 hours. Assume that there is some routine maintenance, and down time, then 60 % to 70% utilization would be very high. If 2000 pounds were considered to be a normal load, this would result in 864,000 to 1,008,000 pounds as the maximum annual output. It is unlikely that 2000 pounds would be loaded on every cycle. If the average was reduced to 1500 pounds, which is still a great deal of composites, the annual 360 day output would be 648,000 pounds.

A five-day a week, 50 week operation, two shifts, 70 % utilization, 1500 pounds per cure cycle, would result in a more normal maximum of 525,000 pounds. Realistically, the autoclave would operate one shift per day, with perhaps 300 to 400 pounds, five days per week. Thus the unit would cure about 100,000-per year. This is the equivalent to about 50 Beech Starships per year. As can be seen, the cost analysis of an item of capital equipment such as an autoclave, oven, or EB installation is very sensitive to the assumptions. The actual costs will be a function of the actual utilization.

Assume that an autoclave such as the Beech 65 by 25 foot machine had a capital equipment cost of $8,000,000, with a 10 year life, then the amortized per pound cost would be from as low as $0.185 per pound for 4.32 million pounds per year, up to $8.00 per pound if only 100,000 per year were cured. The operating costs include the labor for loading and unloading, as well as the operation and monitoring of the cure cycle. In addition, there is a considerable cost for nitrogen to reduce the risk of fire, and the cost of electricity or gas for heating. The results of this analysis are shown in Table A-7.

TABLE A-7: Results of Autoclave Cure Analysis for Beech Starship

UTILIZATION	**LB/CYCLE**	**CYCLES/DAY**	**DAYS/YEAR**	**TOTAL LB**	**CAPITAL/LB**
MAXIMUM	6000	2	360	4,320,000	$0.185
70%	2000	2	360	1,008,000	$0.794
60%	1500	2	360	648,000	$1.23
60%	1500	2	250	450,000	$1.78
100%	400	1	250	100,000	$8.00

8.0 EB CURE THROUGH-PUT

8.1 EB Facility

An EB curing facility, with a capital cost of about $6 million, it reported to have a through-put capability of about 1800 kilograms per hour. This is about 3968 pounds. The method of calculation of the theoretical maximum through-put is as follows:

Mass (Kg/hr) = 360*e*P(KW) / D(MRads)

Where: e = beam utilization efficiency
P = accelerator Power
D = Dose

Assume: e = 60%, P = 50KW, D = 5 MRads

for an optimal part the part width is equal to the scan width, the thickness is 3.5 gm/cm^2
Therefore: **Mass = (360 * .6 * 50) / 5 = 2160 Kg/h or 4752 pounds per hour**
For the purposes of this analysis, the maximum through-put has assumed to be 1800 kg/hr or about 3968 pounds/hr. This is about a 17% reduction from theoretical maximum.

Under extreme circumstances, such as a very thin part of graphite, the through-put analysis indicates that the maximum capability might be as low as 400 pounds per hour. When examined as a number of parts per hour, however, the part used in this analysis of 2.4 pounds could be cured at the rate of 166 parts per hour. One part is cured in 22 sec.

8.2 Capability

On the same basis of 360 days and twenty four hours per day, with no down time for repair or upkeep, an EB facility could theoretically cure the following:

24 hours/day for 360 days at 3968 lb/hr = 34,285,939 lb of composites. This is unrealistic in that it assumes that there is a continuous flow of product under the EB head to be cured. If only a 50% utilization was achieved, then about 17 million pounds per year could be cured. This compares with the 4.32 million that the 65 feet by 15 feet autoclave can achieve.

8.3 Curing Very Large Parts

If large parts, say a 100 foot spar or keel section, is to be cured, then it is obvious that either a new autoclave would have to be built, or an alternative method selected for curing. An EB facility with a 200 foot long track could be built at only a small additional cost for the extra shielding and track. This installation could cure a 100 foot long, say 4 foot wide, 12 inch thick composite laminate of graphite/epoxy, compacted by vacuum pressure. This part will weigh, using 0.057 lb per cubic inch, 39,398 pounds. At a through-put of 3970 pounds per hour maximum, but assuming losses and loading time, using only 1984 pounds per hour, the part, would require 19.8 hours, and would not be able to be cured in a present day autoclave.

8.4 EB Through-Put

An EB cure facility capable of large through-put would have results similar to the following:

TABLE A-8: Results of EB Cure Analysis for Large Product

UTILIZATION	LB/HOUR	OPERATING HRS	DAYS/YR	TOTAL LB	CAPITAL/LB
MAXIMUM	3968	24	360	34,283.520	$0.0175
70%	2000	24	360	12,096,000	$0.050
60%	1500	24	360	7,776,000	$0.077
60%	1500	12	250	2,700,000	$0.22
100%	400	8	250	800,000	$0.75

As can be seen the capital equipment costs of a large autoclave and a high capability EB curing installation-shown- significant variations with utilization To achieve equivalent costs per pound, an autoclave would have to be used about 65% to 70% of the time with about 1500 pounds per cycle, two shifts per day, 360 days of the year.

9.0 UTILITIES

9.1 Costs

Much of the utilities costs of manufacturing under government projects is included in the overhead of the company. In an autoclave or oven cured part, the utilities to heat the structure, the tool, and the part, can be significant. In addition, the consumables such as bleeder, breather, porous and non-porous films, bagging film etc., can be very expensive. Thus the process which reduces the utilities costs and the consumables costs can make a significant contribution to reduced costs.

Electrical power costs vary considerable over the country. The local power company states that their rates of $0.04 per kilowatt hour plus additional demand charges, or about $0.08 per kilowatt hour, are typical.

9.2 Mass to be Heated

The mass of the steel used in an autoclave is the most significant element that has to be heated. An analysis was conducted that calculated the energy needed to heat an autoclave. It is based on a 350^{o}F cure, assuming two hours to reach that temperature. The analysis assumes that there is 15% heat loss the first hour and 30 %

per hour for the remaining three. The analysis does not consider the utilities required for vacuum pumps or blowers. It does not consider the cost of any cool down system.

Note that EB curing using the X-ray mode, can cure very thick parts. A thick part would require a longer heat up time with attendant radiant losses. The example used in the analysis is typical of thin parts, and thicker parts would obviously cost more per cycle. In the absence of definitive information on cure cycle times for thick composites, the power cost for heating were assumed to be the same for all parts cured in a specific size autoclave.

Two different size autoclaves were examined. One is 40 feet long by 8 feet diameter. The other is 50 feet long, 25 feet diameter. In both cases, the ends were assumed to be half spheres.

9.3 Nitrogen Costs

The cost of nitrogen was estimated using the cost of $1.40 per 100 cubic feet. The results of this analysis is shown in Table A-9. This indicates that to charge a medium autoclave with nitrogen at 100 psi is about $228 and to charge a large autoclave is about $3272.

9.4 Summary

The hourly operating costs of an autoclave, for power and nitrogen, based on the previous analysis, is tabulated as follows:

TABLE A-9
Results of Autoclave Cure Analysis

AUTOCLAVE	POWER COSTS	NITROGEN COST	TOTAL*
50' BY 25'	613	3273	3886
40' BY 8'	38	228	266

*Autoclave material: Steel (0.286 lb/in^3)
Specific Heat: 0.11 BTU/^{o}F
Cost of energy: average is 7.5 to 8 cents per KW Hr
"Demand" charges. Basic cost is 4 cents/KWHr
Ambient Temperature: 70 ^{o}F
Cure Temperature: 350 ^{o}F
Nitrogen @ 100 psi ; Average cost per cu ft: 14 cents
Assume: No costs of aborted runs.
No costs for consumables/utilities for blowers, vacuum, or controls.
No cost for labor to load, operate, or unload autoclave.
No cost for heating Nitrogen, or compressing it.

The analysis indicates that the minimum cost of utilities to heat a medium sized autoclave is about $40.00. The estimated cost to heat a large autoclave is about $613.00. Based on the maximum potential through-put of 600 pounds per run for the medium sized autoclave and 6000 pounds per run for the large autoclave, the cost per pound for utilities is $0.07 per pound and $0.107 per pound respectively.

When only the cost of nitrogen and heating energy are used, the cost per pound of cure composites is about $0.44 per pound for 600 pound per run in a medium autoclave and $0.65 per pound, for 6000 pound per run in a very large autoclave. Thus the actual costs will undoubtedly be higher than is indicated by this comparative cost analysis.

10.0 FILAMENT WINDING

10.1 General

Filament winding is a means of material application. It requires a winding machine, sometimes a tensioning device, and is now generally computer controlled. After the material is applies, it must be cured. This can be accomplished by letting the winding mandrel remain on the winder, or removed and cured. The curing can be accelerated by the application of heat, or by EB cure.

10.2 Insitu Curing

An alternative that has not been examined is the possibility of insitu curing of the material as it is being applied to the mandrel. This has several potential advantages, and some disadvantages. The advantage is in the ability to apply the material and partially consolidate it so that subsequently applied materials do not cause the plies to wrinkle. ABARIS has been under contract with the U.S. Navy to demonstrate a method of curing thermoplastics by an insitu method to avoid microscopic wrinkles which are potential sources of buckling and crippling of the material when hydrostatically loaded.

10.3 Large Filament Wound Structures

The largest filament winding machine was designed to make wind blades for wind power turbines. The machine is approximately 170 feet long and can swing a maximum diameter of 26 feet. Finished part weight is approximately 26,000 pounds. The basic winding machine was made by En-Tec of Salt Lake City , Utah. There are two machines, one in Italy , and one now at USAF Astronautics Laboratory, Edwards AFB, California. When this machine was built in 1980 it cost about $700,000 for the winder and controller, about another $500,000 for the carriage, and probably about and additional $4 to $500,000 for the installation. Assuming 4% inflation for ten years, this would be the equivalent of $ 2,736,543 in 1990 dollars.

The large blades formed by Hamilton Standard on the machine were formed of epoxy and glass. The method was to apply material around the spar core and then cure overnight. At some point, other structural elements were added, and more material wound around the new structure. The total time to form one part was about three weeks. Only part of the time was spent in winding. Much of it was waiting for the material to cure. Some of it was applying the internal components.

Depending on the bandwidth being applied, it was possible to apply up to about 100 pounds per minute, or 6000 pounds per hour. This is based on winding about 14 to 16 inches per second, at about 6 to 8 rpm. Thus, if winding had been the only limitation, the 26,000 pound blade could have been wound in about 4 hours.

The operating cost of a winder would include the power to rotate it, the labor to operate the machine, and the labor to keep the creels and resin baths filled.

The capital cost of a machine that is about $3 million dollars, and has a life of 10 years, would be about $5,770 dollars per week. Thus, the three weeks that the machine was tied up during the lay-up and cure cost about $17,310.

10.4 Post Curing

In the Aerospatiale paper, Reference 3, the curing of rocket motor cases is discussed. The conclusion is that it is cost effective to wind the cases, transfer the uncured part to an EB cure facility for final cure.

10.5 Integrated Curing Concept

If integrated with an EB system, so that the cure at about 3000 pounds per hour maximum, and the application rate (6000 pounds per hour maximum), where coordinated, then the time to fabricate such a large part would be significantly reduced. Assume that 2000 pound per hour were applied, and the dosage set to cure at 2000 pounds per hour. Then the time to apply material and cure it for a 26,000 pound part would be 13 hours. Assume that it required three days to assemble additional components during the process. Thus the 26,000 pound blade could have been formed in about 4 days. The operating cost in terms of energy would have been the same, and the labor to keep the creels and resin filled would be the same. However, the operator costs would be reduced from 15 days to 4 days. The capital equipment cost would have been reduced from $17,310 to $4616.

The capital cost of the EB curing, based on a $6 million capital investment, 10-year life, for one full day of curing (assuming it was used for other items when not actually curing the blades) would be about $2300. The operator, at $40,000 per year, would cost about $300. The utilities required to cure 26,000 pounds of composites would be $70 based on a 50 Kilo Watt system operating for 17 hours. This is based on 26,000 pounds at 1500 pounds per hour. Thus, it can be seen that the combination of a winder for material application, and an EB curing system for curing, could be very cost effective.

10.5.1 Summary of Key Costs of Insitu EB Curing of Filament Winding

Reference 3, by Aerospatiale, discusses the winding of motor cases and the post curing using EB. Their analysis indicates that this is a cost effective method. There is a technical value in insitu curing of a wound structure to eliminate the possibility of fiber waviness as the outer plies tend to compact the inner plies, prior to cure. Assuming that the costs of materials are the same, the cost of winding a very large structure on a winding machine, allowing an ambient post cure, or simultaneously curing with an EB during winding. The concept would be a fractional or partial power cure to avoid heat build up, but resulting in the correct amount cross linking by the time the winding and cure is complete. The large 26,000 pound blade discussed above was used as the model. The results of this analysis is shown in Table A-10, which indicates that there are significant cost savings.

11.0 OTHER APPLICATIONS FOR EB CURE

11.1 General

During the course of this analysis, it became apparent that the obvious advantages of each of several alternatives for fabricating either large or small parts, in either large or small production quantities, needed to be highlighted. The following methods of curing were examined:

- electron beam curing
- autoclave cure
- vacuum bag cure, oven or room temperature
- resin transfer molding
- filament or tape winding
- press molding

Some of these methods are more flexible than others. For example, an oven can be made almost any size, and therefore can be used to cure a wide variety of sizes and production quantities. A large autoclave is expensive to make, and as the previous analysis indicates, can get very expensive to operate.

TABLE A-10: Comparison of Filament Winding Ambient Post Cure vs Insitu Curing using EB*

COSTS	**POST AMBIENT CURE**	**INSITU CURE (EB)**
DIRECT MATERIALS	SAME	SAME
CAPITAL COST OF EQUIPMENT		
WINDER	3 WEEKS	17310
WINDER	4 DAYS	4616
EB SYSTEM	4 DAYS	2300
DIRECT LABOR (FULLY BURDENE)		
WINDER: THREE PERSONS	6923	
THREE WEEKS		
$40K/PERS/YR		
WINDER: THREE PERSONS		1920
FOUR DAYS		
$40K/PERS/YR		
UTILITIES		
WINDER: 15 DAYS	SAME	
26,000 POUNDS		
WINDER: 4 DAYS		SAME
26,000 POUNDS		
EB SYSTEM: 17 HRS AT 50 KW		68
$0.08/KWHR		
OVERHEAD	SAME	SAME
GENERAL AND ADMINISTRATIVE	SAME	SAME
SUB-TOTAL	24233	8904

DIRECT SAVINGS DUE TO INSITU CURING: $15,329

* Mass of Part = 26,000 lb

Resin transfer molding is a method of using dry fibers and liquid resin, using two surface tools. Although not a focus of this study, it has the same attributes of filament winding, in that it is a method of material application, and requires a post cure. EB curing, of RTM parts could be very cost effective in that the tools could be recycles more often, thus reducing tooling costs. A resin with epoxy type performance and low shrinkage that was EB curable could allow for very cost effective production of medium size, medium quantity production runs.

Press molding is a method of curing parts that are laid up in a two-surface tool and cured under temperature and pressure. The tools are relatively more expensive but can be used for very large production runs. Presses to apply autoclave type pressure are expensive, and thus the size of the parts is somewhat restricted. For example, to apply 100 psi to the 32 square foot part discussed previously would require a press capable of over 230 tons of pressure. EB curing cannot provide the pressure, but could provide the cure mechanism, potentially reducing the capital equipment cost of the cure.

12.0 COST COMPARISON SUMMARY

12.1 General

Forming composites requires a material application phase, a cure phase, and a post fitting or assembly phase. EB curing can contribute to the cure phase directly, and to the material application phase indirectly.

The three elements of the forming phase that contribute to different costs of different methods of forming are the direct labor, capital costs, and utilities or consumables costs.

12.2 Labor Comparisons

EB curing was compared to autoclave curing using both Northrop and ABARIS developed cost models of the cure process. Based on the size of the part, EB curing demonstrated considerable man-hour cost savings. This is illustrated in Table A-11.

TABLE A-11: Comparing Cost Models

Using Northrop Formula:

Part	Autoclave Cure	EB Cure	Savings
32 sq ft, 0.032" thick	13	5.4	7.6 Man-Hrs
70' by 4' by 3" thick	191	175	16 Man-Hrs
70' by 4' by 0.5" thick	53.8	38.75	15 Man-Hrs

Using ABARIS Model*:

Rate	Autoclave Cure	EB Cure	Savings
One at a time	11.9	3.45	8.45 Man-Hrs
Six at a time	6.9	3.45	3.45 Man-Hrs

* Part: Graphite Cover, 24' by 24" 6 plies, Weight 2.4 lb.

12.3 Utilities and Nitrogen

Cost of utilities for heating, and nitrogen as an inert gas, to cure a composite structure was examined. This is based on a two hour heat-up cycle, and two hours at temperature. Thicker parts will undoubtedly require longer heat-up times and thus greater heat losses. Based on two different size autoclaves, the following data was developed:

TABLE A-12: Costs for Utilities and Nitrogen for Autoclaves

Autoclave	Max #/run	Utilities/run	Nitrogen/run	Total
50 feet by 25 ft	6000	613	3272	3885
40 feet by 8 ft	600	38	228	266

12.4 Capital Equipment Costs per Pound, Based on Through-put

The capital equipment cost of a large autoclave or an EB cure facility is high. The exact cost of a given installation is difficult to determine, but based on discussions with several persons, the estimated cost of the 65 by 25 feet autoclave at Beech Aircraft is estimated to be about $8 million. The EB facility is assumed to cost $6 million. Based on this the range of allocated costs of the capital, not discounted but based on a ten year life of the equipment, is given in Table A-13.

12.5 Overall Cost Comparison

An analysis of simultaneous EB curing (insitu curing) of a filament wound structure was conducted. Focusing on the difference in the capital, labor, and utilities costs, assuming overhead, general and administrative fee are the same, the saving in winding a 26,000 pound part would be about $15,000.

Using the 32 square foot and the 70 foot long part described in the two preceding sections, an overall parts cost analysis was conducted. The elements include the direct materials, direct labor, labor burden at 40% of direct labor, and general and administrative expenses and fee. In addition, a per part cost for capital equipment, tooling, and utilities are provided to illustrate how these costs contribute.

This analysis indicates a cost savings for the small part cured by EB compared to curing in a small autoclave, would represent about a 12 percent savings. A 25% savings was indicated in the curing of a very large part, assuming that it could actually be done in an autoclave. This analysis is provided as Table A-14 (A) for the 32 square foot 0.032 inch thick part and Table A-14 (B) the 4 foot by 76foot by 0.5 inch thick part. Table A-14 (C) is the analysis for the 3 inch thick 70 feet long part. It indicates the relative advantages of EB curing for mass production of small parts, as well as considerable savings on very large parts.

TABLE A-13: Capital Cost Comparison

Large Autoclave:

Utilization	**Lb/cycle**	**Cycles/day**	**Days/year**	**Total Lbs**	**Capital/Lb**
Maximum	6000	2	360	4,320,000	$0.185
70%	2000	2	360	1,008,000	$0.794
60%	1500	2	360	648,000	$1.23
60%	1500	2	250	450,000	$1.78
100%	400	1	250	100,000	$8.00

EB Facility:

Utilization	**Lbs/h**	**Hours/day**	**Days/year**	**Total Lbs**	**Capital/Lb**
Maximum	3968	24	360	34,283,520	$0.0175
70%	2000	24	360	12,096,000	$0.050
60%	1500	24	360	7,776,000	$0.077
60%	1500	12	250	2,700,000	$0.22
100%	400	8	250	800,000	$0.75

SUMMARY

By any measure of comparison of the items that are different and those that are common, in EB curing vs. alternative methods, EB curing can be very cost effective. Savings of between 15 % and 25 % are indicated. In addition to its technical benefits, the potential for continuous processing and curing at ambient temperature are potential further cost savings.

Table A-14 (A): Summary Cost Comparison; EB vs Autoclave for Thin Products*

Item	Cost Basis	Unit Cost	Autoclave	EB cure
DIRECT MATERIALS				
GRAPHITE/EPOXY	PER POUND	40	1735	
GRAPHITE/EB RESIN	PER POUND	40		1596.20
DIRECT LABOR				
AUTOCLAVE CURE HRS	13	15	195	
EB CURE HRS	5.4	15		81
LABOR BURDEN	40 % DIR. LABOR			
AUTOCLAVE CURE			78	
EB CURE				32.4
UTILITIES				
AUTOCLAVE			266	
EB CURE	50 K WATTS, ASSUME 5 MINUTES OF OPS. $0.08/KW HR			0.33
CAPITAL ALLOCATION				
AUTOCLAVE	$1 MIL @800#/DAY 250DAYS/YR-10 YRS 60% EFFICIENCY	0.416	18.07	
EB CURE	$6 MIL @1500#/HR 250DAYS/YR-10 YRS 60% EFFICIENCY	0.22		8.78
SUB-TOTAL			**2292.07**	**1718.71**
OTHER OVERHEAD	ESTIMATE: SUPERVISION QUALITY CONTROL FACTORY UP KEEP CONSUMABLES	30%	687.62	515.61
SUB-TOTAL			**2979.69**	**2234.32**
GENERAL AND ADMINISTRATIVE	ESTIMATE	15%	446.95	335.15
SUB-TOTAL			**3426.65**	**2569.47**
FEE	ESTIMATE	10%	342.66	256.95
		TOTAL COST:	**3769.31**	**2826.42**
		DOLLAR PER POUND:	**108.63**	**81.45**
		PERCENT SAVING:	**25.01%**	

* Small Part Description: 4' x 8'; 24 plies of .0055" thick prepreg
Final Thickness: 0.132
Final Weight, pounds: 34.7
Weight with scrap: 43.375 (Autoclave); 39.905 (EB, No bleed)

Table A-14 (B): Summary Cost Comparison; EB vs Autoclave for Large Products*

Item	Cost Basis	Unit Cost	Autoclave	EB cure
DIRECT MATERIALS				
GRAPHITE/EPOXY	PER POUND	40	344,700	
GRAPHITE/EB RESIN	PER POUND	40		317,124
DIRECT LABOR				
AUTOCLAVE CURE HRS	191	15	2865	
EB CURE HRS	174	15		2610
LABOR BURDEN	40 % DIR. LABOR			
AUTOCLAVE CURE			1146	
EB CURE				1044
UTILITIES				
AUTOCLAVE			3885	
EB CURE	50 K WATTS, ASSUME 209 MINUTES OF OPS. $0.08/KW HR			13.93
CAPITAL ALLOCATION				
AUTOCLAVE	$1 MIL @800#/DAY 250DAYS/YR-10 YRS 60% EFFICIENCY	1.78	15,339.15	
EB CURE	$6 MIL @1500#/HR 250DAYS/YR-10 YRS 60% EFFICIENCY	0.22		1744.18
SUB-TOTAL			**367,935**	**322,536**
OTHER OVERHEAD	ESTIMATE: SUPERVISION QUALITY CONTROL FACTORY UP KEEP CONSUMABLES	30%	110,380	96,760
SUB-TOTAL			**478,315**	**419,296**
GENERAL AND ADMINISTRATIVE				
	ESTIMATE	15%	71,747	62,894
SUB-TOTAL			**550,063**	**482,191**
FEE	ESTIMATE	10%	55,006	48,219
		TOTAL COST:	**605,069**	**530,410**
		DOLLAR PER POUND:	**87.77**	**76.94**
		PERCENT SAVING:	**12.3%**	

* Small Part Description: 4’ x 70’; 250 plies of .12” thick prepreg
Final Thickness: 3”
Final Weight, pounds: 6894
Weight with scrap: 8617.5 (Autoclave); 7928.1 (EB, No bleed)

Table A-14 (C): Summary Cost Comparison; EB vs Autoclave for Thick Products*

Item	Cost Basis	Unit Cost	Autoclave	EB cure
DIRECT MATERIALS				
GRAPHITE/EPOXY	PER POUND	40	57,900	
GRAPHITE/EB RESIN	PER POUND	40		53,268
DIRECT LABOR				
AUTOCLAVE CURE HRS	53.8	15	807	
EB CURE HRS	38.8	15		581.25
LABOR BURDEN	40 % DIR. LABOR			
AUTOCLAVE CURE			322.8	
EB CURE				232.5
UTILITIES				
AUTOCLAVE			3885	
EB CURE	50 K WATTS, ASSUME 35 MINUTES OF OPS. $0.08/KW HR			2.33
CAPITAL ALLOCATION				
AUTOCLAVE	$1 MIL @800#/DAY 250DAYS/YR-10 YRS 60% EFFICIENCY	1.78	2576.55	
EB CURE	$6 MIL @1500#/HR 250DAYS/YR-10 YRS 60% EFFICIENCY	0.22		292.97
SUB-TOTAL			65,491	54,377
OTHER OVERHEAD	ESTIMATE: SUPERVISION QUALITY CONTROL FACTORY UP KEEP CONSUMABLES	30%	19,647	16,313
SUB-TOTAL			**85,138**	**70,690**
GENERAL AND ADMINISTRATIVE	ESTIMATE	15%	12,770	10,603
SUB-TOTAL COSTS			**97,909**	**81,293**
FEE	ESTIMATE	10%	9,791	8,129
		TOTAL COST:	**107,700**	**89,423**
		DOLLAR PER POUND:	**93.01**	**81.29**
		PERCENT SAVING:	**17.0%**	

* Small Part Description: 4' x 8'; 42 plies of .12" thick prepreg
Final Thickness: 0.5"
Final Weight, pounds: 1158
Weight with scrap: 1447.5 (Autoclave); 1331.7 (EB, No bleed)

REFERENCES

1. The Advantages of Electron-Beam Curing of Fiber-Reinforced Composites." Saunders, C. B. and Singh, Ajit. AECL Radiation Application Research Branch Whiteshell Nuclear Research Establishment, Pinawa, Manitoba ROE 1LO. September 1989.

2. "Carbon Fiber-Acrylated Epoxy Composites: An Application for High Energy Electron Beam Curing." Saunders, C.B., November 1989. "A personal communication of the senior author."

3. "Composite Curing: A new Process." Beziers, D. and Denost J.P., Aerospatiale Space and Strategic Systems Division. Copyright 1989, Published by AIAA

4. Advanced Composite Cost Estimating Manual, USAF AFFDL-TR-76-87, Vol. I, August 1976, Northrop Corporation, Aircraft Division, Hawthorne, CA 90250

5. "Effect of the Automation of Advanced Composite Fabrication Processes on Part -Cost," Krolewski, S, and Gutowski, T. Laboratory of Manufacturing and Technology Massachusetts Institute of Technology, SAMPE Journal, May/June 1987, p 21-26