# Pilot Production of Superplastically Formed/Diffusion Bonded T-38 Main Landing Gear Doors

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**This paper discusses the engineering development effort, the preliminary and final airworthiness qualification of a test door, and the manufacture of 30 titanium main landing gear strut doors for the T-38 aircraft using superplastic forming and concurrent diffusion bonding (SPF/DB) as the principal fabrication method. The structural concept of the new door is a variable thickness sandwich panel having an internal core structure with rectangular cells. The tooling concept and fabrication steps, from sheet preparation to final assembly and nondestructive testing, are described, with particular emphasis on those elements that contribute most to the process reliability. Cost analyses indicated that fabrication costs are sensitive to the cost and utilization of the titanium material. Although acquisition costs for the SPF/DB doors are higher than those for the currently used aluminum honeycomb doors, significant life-cycle cost savings can be achieved. The discussion on costs deviates from the standard and highlights the implications from the time lag between front-end investments and later benefit accrual as a potential barrier for technology implementation. Since 1983, the titanium doors have been used on U.S. Air Force aircraft.**

## Introduction

ON an earlier Air Force-sponsored manufacturing program, it was demonstrated that the T-38 main landing gear (MLG) strut door could be produced competitively with the superplastic forming/diffusion bonding process in lieu of the present adhesive bonding aluminum honeycomb method.[1] However, only six doors were produced and the data needed to estimate production costs were limited. The need for additional production experience prompted a follow-on pilot production program for 30 doors to establish a more credible basis for cost projections. Since the MLG door is representative of many other aircraft components, the additional production experience was expected to provide a much needed generic base for evaluating the cost and performance benefits of titanium parts fabricated by the superplastic forming and diffusion bonding (SPF/DB) method.

The doors were fabricated with the proprietary McDonnell Douglas SPF/DB four-sheet expanded sandwich process using a rather simple pressure/temperature/time SPF/DB processing schedule. The successful fabrication of all 30 doors without a single failure was attributed to the combination of conservatism in the design and the inherent reliability of the process itself.

Cost analysis indicated that the labor part of the fabrication progressed along a 91% learning curve. The sensitivity of the door costs to the material costs was clearly indicated. Although acquisition costs for the SPF/DB doors were shown to be higher than those for the current aluminum honeycomb doors, fleet life-cycle cost savings of $5-10 million, depending upon specific pricing and procurement conditions, could be realized.

Airworthiness of the SPF/DB titanium door was demonstrated through flight testing by the Air Force Logistics Command at Kelly AFB, San Antonio, Texas. Flight airworthiness was granted in May 1980.

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## Structural Configuration of SPF/DB Door

Design requirements imposed upon the new design were interchangeability with the current aluminum doors and compatibility with the installation and rigging procedures defined in the U.S. Air Force maintenance manuals. These requirements demanded geometrical equivalence and near-identical stiffness properties.

The interchangeability requirement was readily satisfied by duplicating the external geometrical configuration of the aluminum door. The only deviation from the aluminum door was the incorporation of the trailing-edge tab into the basic door construction as shown in Fig. 1. On the current door for the T-38 aircraft, the tab is permanently locked in the faired position and has no function. This design was initially derived from commonality considerations with the F-5 door that has an operable trailing edge tab.

Design tradeoff studies were performed to identify the most efficient sandwich core geometry for this application. Straight and sine wave truss and vertical web core configurations were investigated. The best compromise between the fabrication and structural parameters was found to be rectangular core cells having dimensions of 1×2 in., as illustrated in Fig. 2. The cross webs provided additional stiffness in the fore and aft direction when the door was installed in the aircraft.

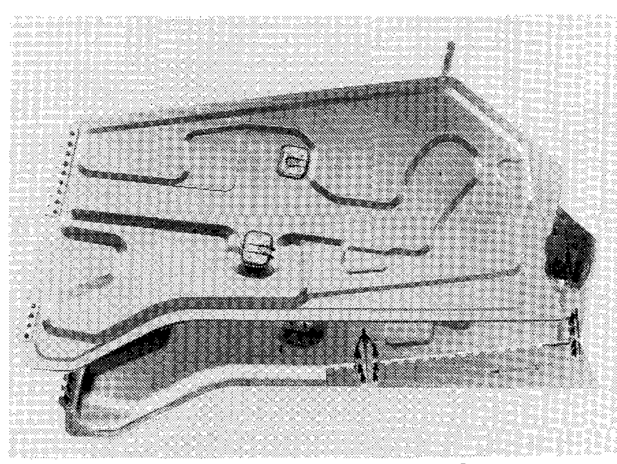

**Fig. 1 T-38 main landing gear strut doors.**

Titanium sheets 0.025 in. thick were chosen with conservatism for the internal core structure to prevent the possibility of rupturing the sheets due to excessive thinning during superplastic forming. The minimum thickness after forming the deepest cells translated to a maximum engineering strain of only 300% in the cell corners.

The determination of the face sheet thickness was governed by the maximum weight goal of 18 lb, the weight of the aluminum door. From that, the skin thickness of the final door must not have exceeded 0.043 in. Allowing for chemical milling, which is a standard post-SPF/DB fabrication operation, 0.050 in. thick sheets were selected. All titanium material was Ti-6Al-4V.

Structural analysis verified that the titanium door satisfied the stiffness requirements. Although deflections were of primary concern, stresses were surveyed and found to be very low; the maximum skin stresses were below 20,000 psi and the maximum shear stresses in the vertical core webs were in the order of 30,000 psi.

## Test Door

One door was fabricated for structural testing and flight qualification prior to the production of 30 doors.

### Structural Testing

The door was installed and tested in a support fixture previously used for static testing of other T-38 and F-5 MLG strut doors. The support fixture simulated the main landing gear wheel well in the aircraft with the door attach links in the proper location. The links were strain gaged and calibrated for measuring the loads. Deflections were measured around the perimeter of the door at several locations.

The first of two critical loading conditions represented flight maneuvers including turns with the doors open. This condition generated the maximum torque loading and, in general, verified the strength adequacy of the attach structure for the hinges and brackets. The second loading condition represented the critical deflection case during high-speed flight at sea level with the doors closed. This static test, performed at Northrop Corporation, verified the stiffness properties and the structural integrity of the door.

### Door Installation and Rigging

The test door was installed and rigged on a T-38 aircraft at SA-ALC to established procedures defined in the Air Force Technical Orders. After adjusting the strut links to generate the required preload, it was not possible to fully retract the gear. This was diagnosed as excessive stiffness of the door. The door was successfully installed and rigged after the stiffness was reduced by chemical etching to be near that of the aluminum door.

### Stiffness Verification

The major portion of the door including the critical leading-edge area was approximated by a two-dimensional bending system. Disregarding local effects near the hinges and the inboard support, the deflection $\delta$ of the door as a function of the applied uniform pressure loads $p$ can be expressed as

$$\delta = \frac{5_p l^4}{384\,EI} - \frac{Pl^3}{48\,EI}$$

where $P$ was an elastic reaction provided by the links, $EI$ the bending stiffness, and $l$ the distance between the edge supports. The first term of the equation expresses the part of the deflection caused by the pressure loads $p$ and the second term the deflections related to the link loads. The above equation was modified to

$$\mathrm{d}p/\mathrm{d}\delta \propto EI$$

and means that the slope of the load/deflection line is proportional to the stiffness.

Measured deflections were plotted as a function of load in Fig. 3 to derive relative stiffness measures. From the slope of the load/deflection line, the stiffness of the aluminum door was estimated to be 82% of that of the titanium door. The nonlinear characteristics at low load levels is related to the preload of the links.

The door stiffness was reduced by chemically milling both surfaces of the door. Material removal during the chemical milling process progresses at a relatively slow and constant rate, in this case 0.024 in./h and was, therefore, readily controllable. Considering practical chemical milling tolerances, the panel stiffness was adjusted to the desired stiffness within ±1.5%.

### Flight Testing

The modified, reduced stiffness door was successfully rigged on the T-38 aircraft. Flight airworthiness was established after flight testing the door at Kelly Air Force Base, Texas. Seven flights were made for a total of 7.3 fight hours. Ten in-flight gear cycles were accomplished including maximum side slip maneuvers. Sorties of the flight test program were symmetrical pullups to 6.6 $g$, 27 min of speed soak at 600 knots indicated airspeed, and maximum dynamic pressure flight with 4 $g$ pullups. Flight airworthiness was granted in May 1980.

## Production of Doors

### Tooling

The SPF/DB tool was a two-piece assembly machined from hot-rolled 22Cr-4Ni-9Mn stainless steel plates. The lower half was roughly 1.5 in. thick and contained the sculpturing of the inner door surface as shown in Fig. 4. Grooves along the sides were provided to accommodate the gas tubes. A continuous shallow groove at the perimeter of the tool was provided to accept a wire seal between the upper and lower tooling parts. The upper tool was only approximately 0.75 in. thick and had

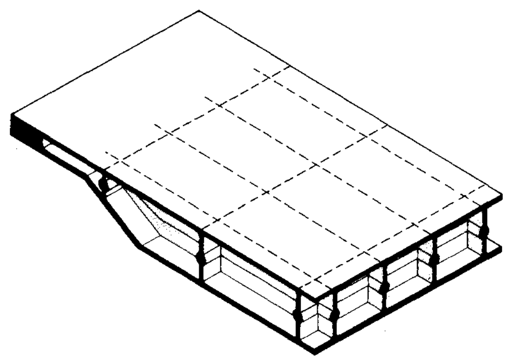

Fig. 2 Structural configuration of SPF/DB door.

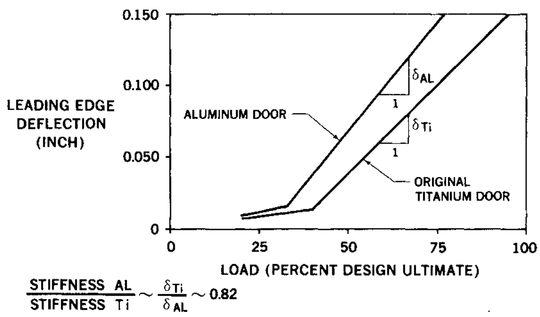


Fig. 3 Door stiffness.

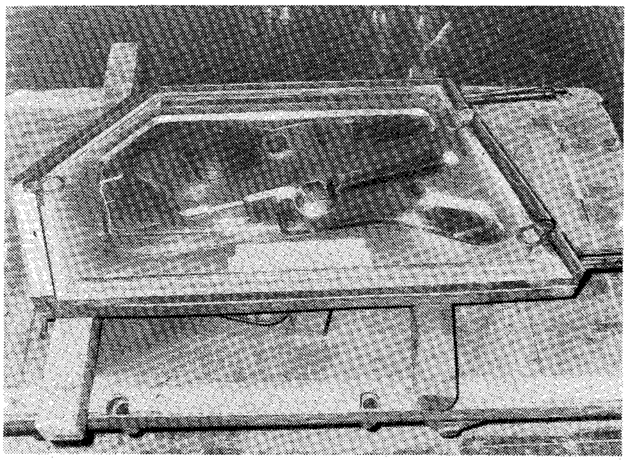

Fig. 4 Lower half of SPF/DB tool.

edge profiles welded around the perimeter corresponding with the grooves in the lower tool. The groove and tongue arrangement with a titanium wire seal prevented atmospheric contaminates from entering the tool and also aligned the upper and lower tooling halves. Early into the production, it was found that the wire seal was not necessary if a small argon gas flow purged the tool continuously.

The heating and press system used in the pilot production required cooling the part in the tool to near ambient temperature. Therefore, it was necessary to consider the different thermal expansion behavior between the titanium and the tooling material. An analytically and empirically determined reduction factor of 0.995 for the tool was carried implicitly in the computer program for the numerically controlled machining. This 0.5% reduction of all tooling dimensions appears to be valid when the part is released from the tooling constraints below 1000°F.

#### Fabrication

The sequence of operations from the material stock to the final product was: 1) inspection of Ti-6Al-4V titanium sheet material; 2) layout, cutting, deburring, and cleaning all details; 3) spotwelding of core sheets to prescribed pattern; 4) laying up face sheets, doublers, and core assembly; 5) attaching gas fittings and lines and seal welding perimeter; 6) testing weld assembly for leaks; 7) boron-nitride coating of tool and titanium assembly; 8) assembly of tool and loading into press; 9) execution of the SPF/DB processing cycle; 10) nondestructive evaluation; 11) chemical milling of total assembly; 12) panel trimming to size; 13) installation of hinges and brackets; and 14) painting and identification. The following discussion neglects the conventional fabrication tasks and addresses only those that relate to the SPF/DB process.

Figure 5 shows the core sheet assembly with prescribed spotweld pattern. Weld nugget size and spacing are primarily a function of the sheet thickness. Forming-relating considerations require sufficient area between the welds for gas migration. Yet the weld must provide enough strength to react to the flow stresses during straining. Spot weld spacing was approximately twice the longitudinal nugget dimension of 0.10 in.; the transverse dimension of the nugget was approximately 0.06 in. The assembled titanium pack consisting of the core sheets, edge doublers, face sheets, gas ports, and tubes are shown in Fig. 6. The assembly was tested for leaks in this condition. The forming gas inlets/outlets, two on each side for redundancy, were made of Type 321 CRES tubes swaged over commercially pure titanium tubes welded to titanium fittings, which, in turn, were welded to the titanium pack. Selective gas inlet between the core sheets and between the face sheets and core assembly, required for the sandwich panel SPF/DB process, necessitated special preparation of the local gas port areas.

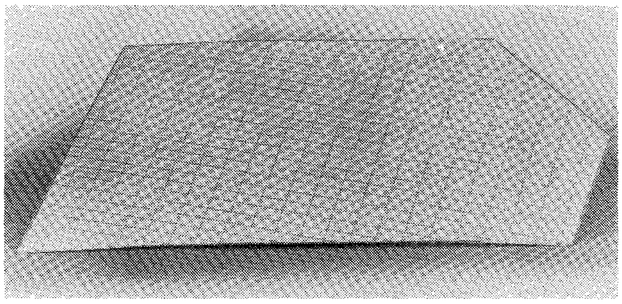

Fig. 5 Spot-welded core sheets.

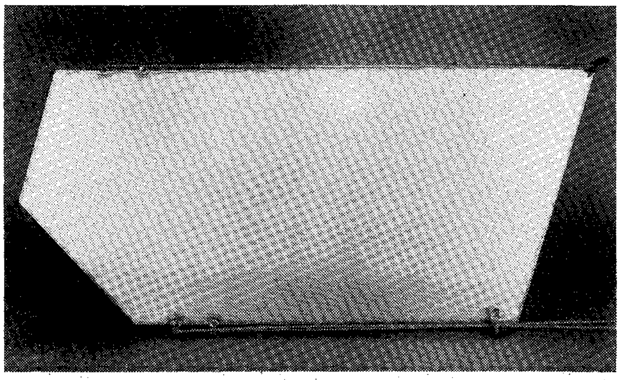

Fig. 6 Welded door assembly before SPF/DB.

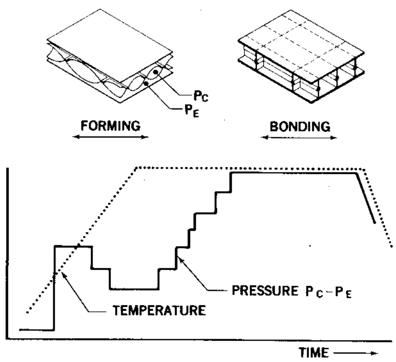


Fig. 7 SPF/DB processing schedule.

The SPF/DB processing cycle, the pressure/temperature/time relationship, is graphically illustrated in Fig. 7. Core pressures were analytically determined using classical membrane stress theories to hold the superplastic flow stresses and strain rates within a reasonable range for the various geometrical configurations of the core cells. The pressurization profile was controlled by the critical thick section strain rate/flow stress conditions to prevent sheet rupture from extensive thinning. Although the core pressure was always higher than the face sheet pressure, face sheet forming preceded core cell forming because of geometry reasons. Only the difference between the core pressure $P_C$ and the face sheet envelope pressure $P_E$ is acting upon the core sheets, promoting cell formation. The simple pressure profiles were easily controllable. Actual forming was initiated at a temperature at around 1500°F and was completed shortly after the maximum temperature of 1700°F was reached. The relatively short time exposure to high temperatures limited the microstructural grain growth and, thus, enhanced the diffusion bond quality. The actual SPF/DB cycle from forming initiation to cool down required approximately 4.5 h. A moderate internal pressure was maintained during cooling of the part in the tool.

All of the doors are radiographically inspected. As a standard procedure, x-ray pictures were taken looking normal to the surface, angle views only selectively. Fig. 8 is a typical x-ray picture showing the formation of the internal cell structure. The dark areas signify the vertical cell walls. Door thicknesses, transitional areas, spot welds, openings between spot welds, and edge doublers are clearly visible.

The x-ray picture not only showed the general panel area in the expanded sandwich area but also the door edges where skins, core sheets, and doublers were a solid diffusion bonded laminate. Differences in the darkness of the x-ray exposure indicated local and minor disbonds in some places along the door edges. Since it was difficult to interpret the darkness intensities reliably, the edges on all doors were ultrasonically C-scanned.

Chemical milling of the doors was performed in several steps with intermittent thickness checks to control the amount of material removal within close tolerances.

All 30 doors were fabricated without a single failure. Preparation of details, welding operations, the actual forming and bonding process, and the post-SPF/DB tasks proceeded routinely. The quality of the parts was excellent with only few and minor deficiencies observed. The process reliability was attributed to several key factors:

1) Conservative design of the core geometry limited the metal strain to only 300%, reducing the likelihood of rupturing the sheets during forming from excessive metal thinning.

2) Antibond maskant was not required, thus eliminating potential sources of internal surface contamination.

3) The SPF/DB cycle used a simple, easily controllable pressurization profile. Commercial-grade argon gas was used.

4) Proven, all-welded bimetallic steel/titanium tube assemblies were used as gas inlets/outlets.

5) Face sheet forming proceded core forming, thus eliminating the possibility of face sheet grooving.

6) More than 99% of the skin area is bonded to the core, providing more than adequate shear strength between bending material and core—an excellent feature of the four-sheet SPF/DB method.

7) The four-sheet sandwich structure is inherently tolerant to small flaws and deficiencies. Therefore, processing schedule, are inconsequential.

## Cost Analysis

The first part of the discussion summarizes the cost estimate results based on pilot production experience; the second part addresses the cost issue from the viewpoint of the customer's needs and actual conditions affecting the marketability of the new technology product.

### Manufacturing Costs

SPF/DB production of the doors contains generally standard fabrication elements and does not offer opportunities for large learning gains. Production labor progressed along a 91% learning curve. The relatively high material costs contributing to the total cost of the doors tend to make learning gains less significant than on conventional aluminum aircraft structures. The material utilization, commonly referred to as fly-to-buy ratio, for the pilot production was a low 37%, indicating that only slightly over one-third of the purchased material was present in the final product. The relatively powerful material utilization effects on the total cost suggest making a conscious effort to use material efficiently.

Fabrication costs for titanium doors, adjusted from the original 1980 estimates to fiscal 1984 dollars using escalation factors from the appropriate U.S. Bureau of Labor Statistics indexes, were approximately $5000 each based on a production quantity of 300 units. The costs for the baseline aluminum doors under the same conditions were estimated to be $5700.[2] These costs were developed using standard industrial engineering estimating methods.

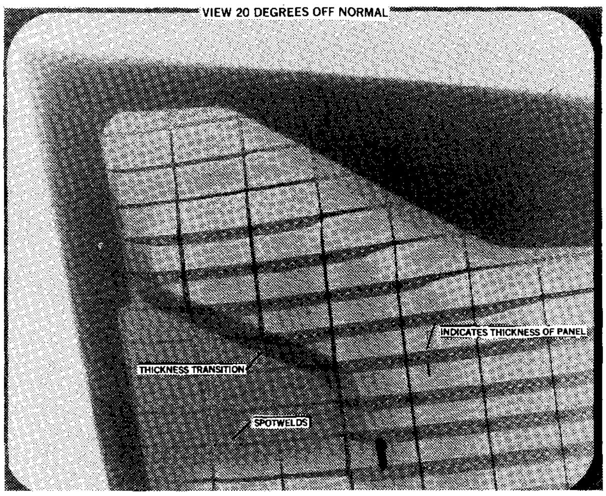


**Fig. 8 Local x-ray of SPF/DB door.**

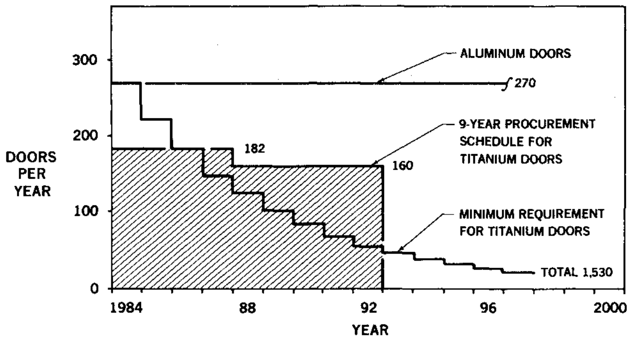


**Fig. 9 Procurement scenarios.**

In actuality, however, the most probable purchase price by the U.S. Government is only $2500 for aluminum doors, which was derived by escalating prices of previous purchases to 1984 conditions. The relatively low price can be explained by the fact that small business concerns fabricate the doors at much lower cost than large airframe manufactures.

Although the aircraft industry's cost analysis methods are generally accepted and accredited as authoritative for the economic appraisal of a new technology, in this case, they projected a far too optimistic picture in favor of the titanium door.

### Life-Cycle Cost Analysis

It was assumed that the initial operation life of the T-38 aircraft through 1990 was extended beyond 2000, probably 2010, though the use of new wings. The average life of current aluminum doors is approximately 5 years, requiring 270 doors as spares annually to satisfy the fleet support needs.

Further, it was assumed that the life expectancy of titanium doors, through their virtue of immunity to corrosion attack and foreign object damage, is the same as that of the aircraft itself. The requirements for replacement doors will be steadily reduced if titanium doors are being phased into the spares inventory and being used on the aircraft. As more and more aircraft will be equipped with titanium doors, fewer and fewer aircraft will have aluminum doors requiring replacement. From this hypothesis, the minimum requirement for titanium doors is indicated by the jagged line in Fig. 9. Eventual replacement of doors on all aircraft determines the total number of titanium doors, which is approximately 1530.

The theoretical procurement profile derived from the minimum requirement schedule is very impractical from an

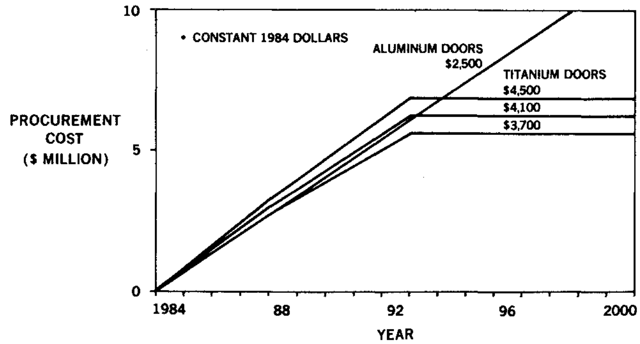


**Fig. 10 Cumulative procurement costs for aluminum and titanium doors.**

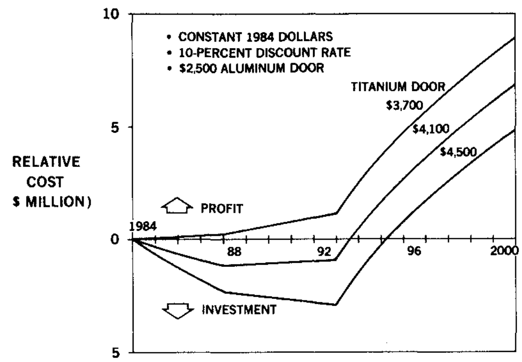


**Fig. 11 Relative procurement costs for aluminum and titanium doors.**

item management and producer's point of view. Therefore, a more useful 9 year procurement schedule, as outlined in Fig. 9, was used in the cost analysis.

Procurement costs for aluminum and titanium doors in constant 1984 dollars commensurate with the assumed procurement schedule are plotted in Fig. 10. Constant dollars analysis assumes that the buying value remains constant in future years and is often used to better relate the benefits to today's value of the dollar.

Annual and cumulative funding requirments for aluminum doors costing $2500 each are essentially the same as for titanium doors costing $3700 each during the 9 year procurement phase. After that, expenditures for titanium doors cease, yielding benefits of approximately $6 million by the year 2000, an arbitrary date for the purpose of cost measurement. Understandably, benefits are lower for the higher cost titanium doors by the amount of the additional front-end investment. This type of benefit analysis ignores the fiscal implications from the time lag between early investment and later return.

New U.S. Government regulations mandate to evaluate the effects of timing of cash flow and the time value of money by, for example, discounting and cost escalation if, as in the above procurement alternatives, costs occur in a particular and different pattern over the life cycle. Discounting is an analytical device that recognizes the present value of future cash flow. A 10% discount rate per DoD Instruction 7041.3, which implicitly reflects alternate benefit opportunities from the value of fiscal resources, was used.

The effects of discounting on costs and benefits are graphically illustrated in Fig. 11, showing only the cost differences between aluminum and titanium doors. When comparing these results with the undiscounted dollar analysis results in Fig. 10, it becomes very clear that the penalty for additional front-end investment is severely magnified. As an example, the required cumulative investment of approximately $800,000 by 1992 for $4500 titanium doors reflects a discounted dollar value of nearly $3 million. The increased sensitivity of door prices on the profit/investment behavior is noticeable throughout the life cycle.

In conclusion, the effects of dynamic, time-dependent money value distort the traditional conception of return-on-investment break-even points, etc., and make early investments with the expectation of later recovery and profit far less attractive. The author even believes that the rather low acceptance of new technology in new products programs originates in the unrealistic treatment of the fiscal parameters in cost analyses.

## Conclusions

The successful fabrication of 30 T-38 MLG strut doors demonstrated that the SPF/DB technology has matured to a state of production readiness. The SPF/DB method used on the pilot production was the McDonnell Douglas proprietary four-sheet sandwich process, which has proved reliable, easily controllable, and insensitive to fabrication tolerances.

Replacing current aluminum doors with SPF/DB titanium doors is economically viable by the virtue of much increased durability and consequently favorable effects on operation and support costs. Life-cycle cost analysis using traditional and accepted methods for appraising the worth of new technology indicates cost effectiveness for a wide range of conceivable cost ratio conditions. This optimism is severely dampened when considering the different value of fiscal resources over certain time periods. This concept of dollar discounting, or inversely escalating, to recognize the fiscal dynamics limits the marketable price of the titanium doors to approximately $4500, assuming that the aluminum doors cost $2500.

## Acknowledgments

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