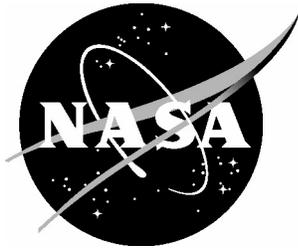


NASA/CR-2004-213016



A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports

Kevin R. Bradley
George Washington University
Joint Institute for the Advancement of Flight Sciences
Langley Research Center, Hampton, Virginia

September 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

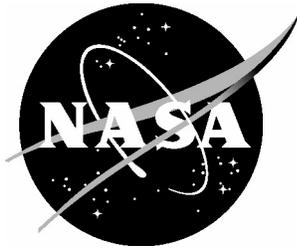
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at (301) 621-0134
- Phone the NASA STI Help Desk at (301) 621-0390
- Write to:
NASA STI Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

NASA/CR-2004-213016



A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports

Kevin R. Bradley
George Washington University
Joint Institute for the Advancement of Flight Sciences
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Cooperative Agreement NCC1-03006

September 2004

This work was performed by the author while serving as a 2nd Lt. in the United States Air Force. The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports

Kevin R. Bradley
Joint Institute for Advancement of Flight Sciences
George Washington University

1.0 Abstract

This paper describes the development of a methodology for sizing Blended-Wing-Body (BWB) transports and how the capabilities of the Flight Optimization System (FLOPS) have been expanded using that methodology. In this approach, BWB transports are sized based on the number of passengers in each class that must fit inside the centerbody or pressurized vessel. Weight estimation equations for this centerbody structure were developed using Finite Element Analysis (FEA).

This paper shows how the sizing methodology has been incorporated into FLOPS to enable the design and analysis of BWB transports. Previous versions of FLOPS did not have the ability to accurately represent or analyze BWB configurations in any reliable, logical way. The expanded capabilities allow the design and analysis of a 200 to 450-passenger BWB transport or the analysis of a BWB transport for which the geometry is already known. The modifications to FLOPS resulted in differences of less than 4 percent for the ramp weight of a BWB transport in this range when compared to previous studies performed by NASA and Boeing.

2.0 Introduction

2.1 Importance of BWB

Interest in Blended-Wing-Body (BWB) began in the late 1980s as industry and researchers looked for ways in which to improve the performance of transport aircraft. Comparison of the aerodynamic figure of merit, ML/D , of transport aircraft from 1960 to the late 1980s showed that no significant increase had occurred (see figure 1). The appeal of BWB aircraft is the promise of improved performance because of a higher L/D than can be obtained with a conventional “tube and wing” aircraft. Using the fuselage structure as both a passenger compartment and part of the wing has the potential to decrease the wetted area, and improve L/D .

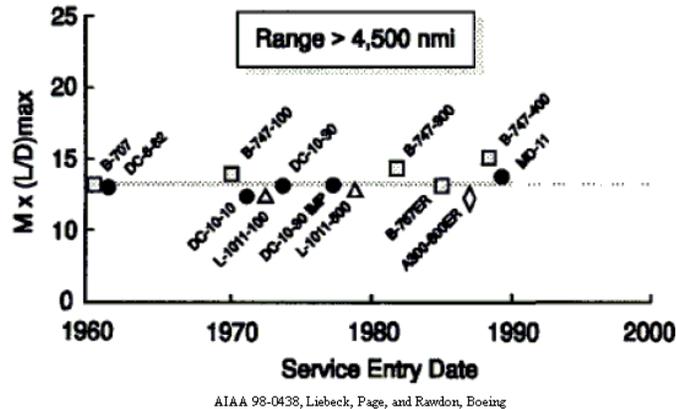


Figure 1. Progress in Aerodynamic Efficiency

The performance potential of the BWB configuration led to a NASA-sponsored study of the technical and commercial feasibility. The results of that study led to a Boeing preliminary design study. NASA has also continued to study the BWB for its potential as a more efficient, quieter transport, as well as in studies of distributed propulsion and advanced technology engines.

2.2 Current FLOPS Capability

The current interest in analyzing transports with a BWB configuration has led to a need for a method to rapidly size and analyze conceptual BWB designs. The Flight Optimization System (FLOPS) is widely used at NASA for evaluating a variety of configurations. FLOPS is a multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. The modular nature of FLOPS allows the user to incorporate new equations and data tables that enable the program to analyze a wide variety of concepts.

The current version of FLOPS does not have the ability to accurately represent a BWB configuration. The calculations are based on empirical equations derived from data for conventional transport aircraft. FLOPS assumes that all fuselages are cylindrical and calculates the weight of those tubes based on equations for circular fuselages. Eliminating the fuselage and modeling the BWB as only a wing results in poor weight estimates since it does not account for the added structure required to hold the internal pressure of a fuselage within part of the wing. FLOPS has been used to analyze the impact of advanced engines and distributed propulsion on a BWB configuration, as well as the noise and emissions generated by a BWB. These studies used BWB configurations from more detailed analyses and matched FLOPS results of the weights and performance for the baseline condition by altering input values and overriding internal calculations. While this is sufficient for analyzing the impact of changes to a BWB configuration that has accompanying detailed analysis, its usefulness is limited to a particular mission and aircraft size. It is not possible to estimate the size, weight, or performance of a given configuration, to obtain performance results for a different mission, or to design and size a BWB.

This paper will discuss a methodology that sizes the pressurized cabin, or centerbody, of BWB transports using the number and class of passengers as the independent design variables. It will discuss the development of weight estimates for the sized cabin compartment. It will show how FLOPS has been expanded to allow the design and analysis of BWB transports, and the quality of results obtained by the improved program.

3.0 Sizing Methodology

3.1 Sizing the Pressurized Cabin

The design study conducted by Boeing^[1] showed that for a BWB configuration the centerbody could be treated as a ruled surface in the spanwise direction. The centerbody is composed of a pressurized cabin section and an aft centerbody section, which is non-pressurized. As the number of passengers increases, the centerbody is expanded laterally by adding passenger bays as shown in figure 2. This lateral expansion automatically increases or decreases wing span and planform area with passenger capacity. The study determined that it was possible to design a family of aircraft with identical outer wing panels and the aircraft sized entirely by the centerbody.

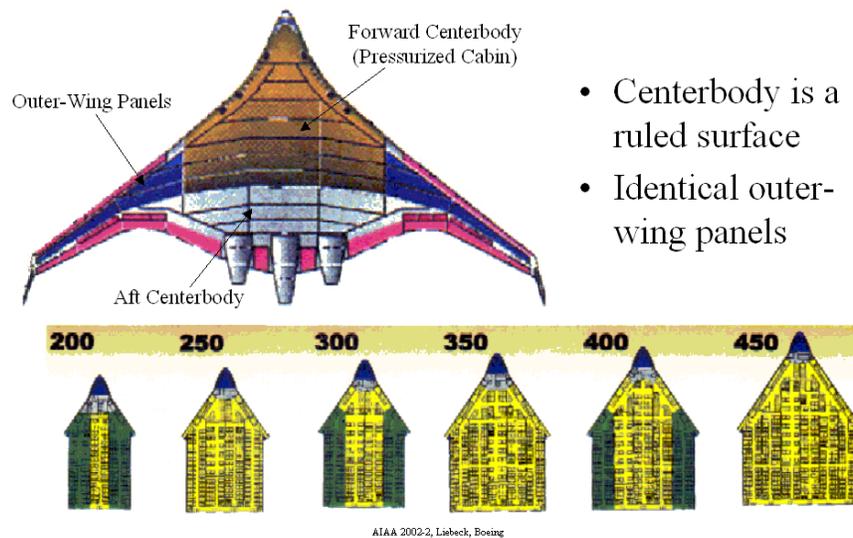


Figure 2. General BWB Configuration and Spanwise Expansion

A generalized BWB configuration is important in developing a sizing methodology since the centerbody is part of the wing, and the cabin has to fit inside the wing. It was possible to determine what shape the generic configuration should take by looking at the configurations developed in the NASA and Boeing studies. Figure 3 shows a planform view of the simplified generic BWB geometry and the pressurized cabin. The aft spar, assumed to be at 70% chord, serves as the rear pressure bulkhead for the pressurized compartment as well as taking bending and shear loads from the wing. The passenger cabin extends forward to the leading edge (also the front spar), which must also take the internal pressure load in addition to bending and shear loads. Passenger bays are located between ribs, which serve as the walls of each bay, and the outer ribs of the centerbody have to be designed to take the internal pressure load of the cabin. A

leading edge sweep angle of 45 degrees for the centerbody has been chosen as a good general representation.

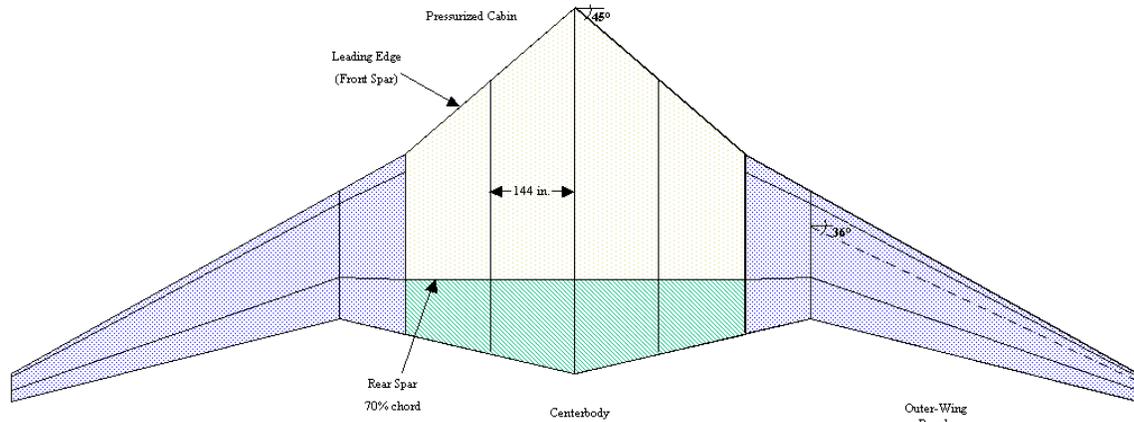
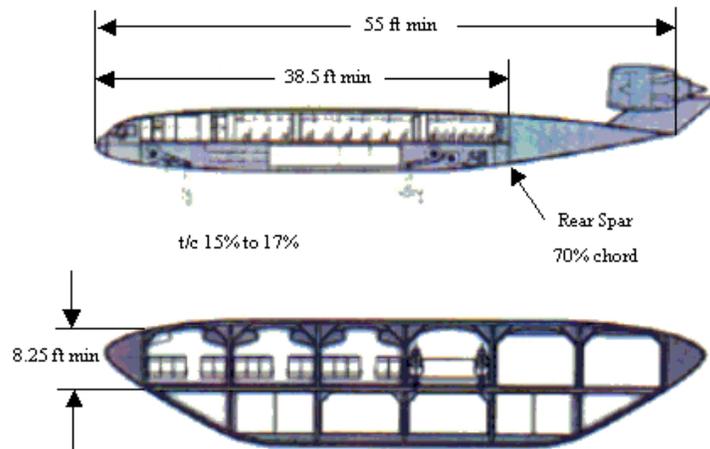


Figure 3. Planform View of Simplified BWB Geometry

Rib placement in the centerbody is determined by the necessary width of each passenger bay. The best configuration to maximize the number of passengers abreast with the minimum width is a 3-by-3 since this requires only one aisle. Current seat width in commercial transports is only about 18 inches, with an aisle width around 20 inches. Allowing some room for wider seats or aisles, as well as furnishings on the walls and the width of the rib, the width for each bay was set at 144 inches. In a 3-class configuration, this width would allow 4-abreast seating in first class, 5-abreast in business class, and 6-abreast in tourist class. The minimum length for the outer rib of the centerbody is determined by the minimum height of the passenger compartment and airfoil thickness to chord ratio. The thickness to chord ratio, t/c , of the centerbody airfoils for a BWB will likely be in the range of 15-17% to provide sufficient cabin height with reasonable transonic airfoil performance. Assuming that the t/c for the centerbody airfoils is 15%, a minimum chord length of 55 ft. has been chosen (see figure 4). This results in a depth of 8.25 ft., which should be enough for the depth of the upper and lower skin surfaces, passenger deck, internal furnishings, and the standing height of a passenger. Since the passenger bay extends forward from the aft spar, which is at $0.7c$, the minimum length of a bay is fixed at 38.5 ft.



AIAA 2002-2, Liebeck, Boeing

Figure 4. Cutaway Views of Centerbody Interior

With the basic “homeplate” shape and the sizing constraints determined, the next step is to determine the minimum planform area of the pressurized compartment. It is assumed in this methodology, which is used for 250 to 450-passenger pressurized cabins, that one deck is sufficient to fit all the passengers. It is also assumed that no more than five bays will be used, since it might be better to use a second deck rather than introduce a sixth bay. To load passengers from the front and have access to all bays from a single door, a “horseshoe” aisle extends along the entire length of the leading edge (see figure 5). This aisle must be far enough behind the leading edge that a person walking along the aisle will be able to stand comfortably. The generic configuration assumes that an airfoil can be selected so that the aisle would only have to extend 5 ft. back from the leading edge. It is also likely that a cross aisle will be needed somewhere in the middle of the cabin to allow access between bays. Both aisles require rib cutouts in the interior ribs of the centerbody. Since the passenger compartment expands laterally with increasing passengers, the maximum length of the passenger compartment will be short enough that only one cross aisle is needed. The remaining area must be sized to hold the necessary number of passengers in their specified class, as well as the proper number of lavatories, galleys, and closets.

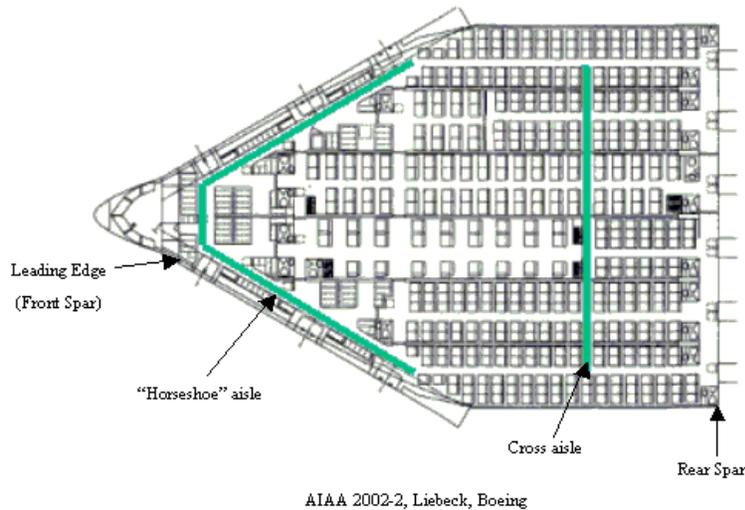


Figure 5. Interior Arrangement of Pressurized Cabin

The easiest way to size the cabin is to calculate a total required length, as if to fit everything into one long bay, and then determine the proper number of bays (see figure 6). The number of galleys, lavatories, and closets is calculated similar to a conventional fuselage design. The total length of these items is added to the length of all the rows of passengers to give a minimum required length, L_{req} . It is also necessary to define a “maximum length” for the outer rib of the centerbody. Spanwise expansion of the centerbody is preferable to longitudinal expansion because it maximizes the passenger carrying capacity with the minimum increase in root chord length. It follows that the maximum length of the outer rib should be defined as the point at which another minimum length bay can be added. Since t/c , leading edge sweep angle, and location of the $0.7c$ rear spar are fixed for the generic configuration, if we assume that the “homeplate” shape of the centerbody expands linearly, the maximum length of the outermost bay can be determined. This will allow us to treat the centerbody as a ruled surface, while keeping the outer wing panels fixed.

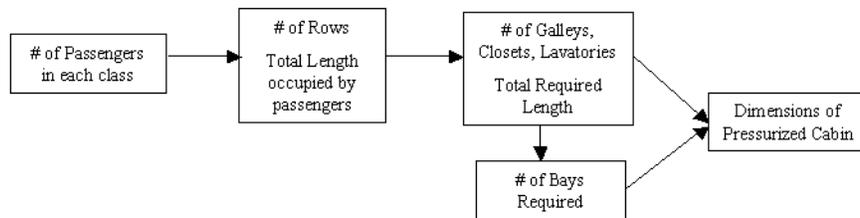


Figure 6. Cabin Sizing Process

Since the centerbody must blend into the outer wing panels, a good assumption for a fixed-geometry wing is that the root chord of the outer wing is 55 ft., the same as the minimum length of the outer ribs of the passenger compartment, which was already determined. A rib length of 55 ft. corresponds to a 38.5 ft. wall inside the passenger bay (70% chord length). Treating the centerbody as a linearly ruled surface, for every 6 ft.

increase in length of the passenger bays, the span increases 12 ft., which is enough to fit another bay (see figure 7). The maximum length of the outer wall of the pressurized cabin is then 44.5 ft. This lateral expansion could be continued indefinitely, but is limited to five bays as discussed previously.

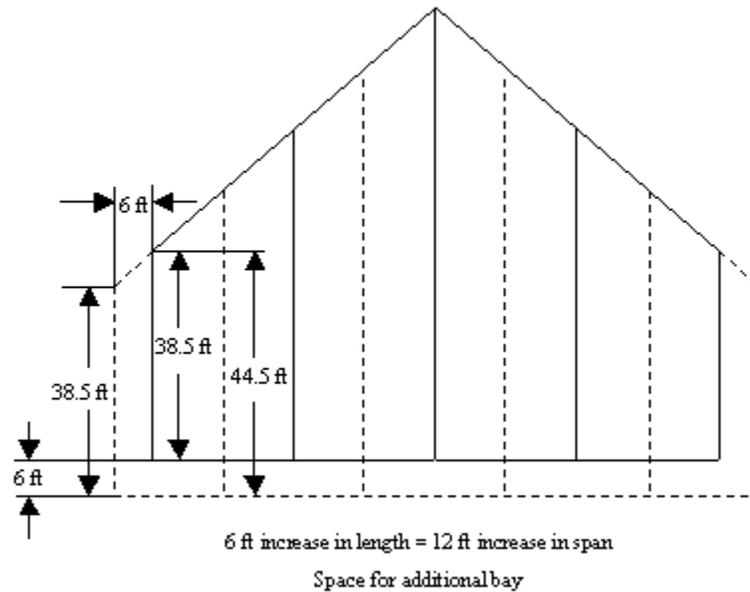


Figure 7. Centerbody as a Ruled Surface

The next step is to define the length of each bay that can be used to place rows of seats, galleys, lavatories, etc. Since the walls of each bay are usually different lengths, more seats can be placed along the inboard wall than along the outboard wall. A wall is that portion of the rib extending forward from the rear spar to the leading edge of the centerbody. To simplify the process, each bay can be broken down into two columns of seats, galleys, etc., with part of the aisle in each column. The length of each column is the length of the outboard wall of the bay, or the length of the centerline of the bay. By symmetry, there are always two columns of the same length, which can be recombined into an equivalent bay (see figure 8).

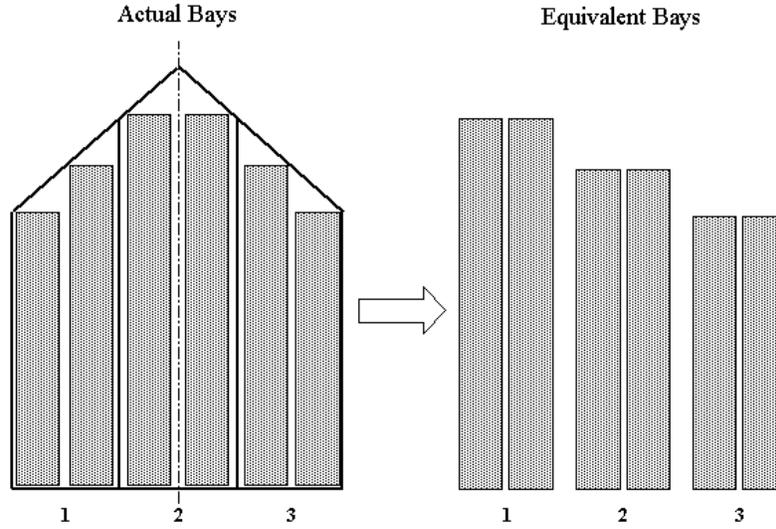


Figure 8. Conversion of Seating Area to Equivalent Bays

The useful lengths of the equivalent bays can be summed to calculate the total useful length of the centerbody, which will be sized by L_{req} . The following equation is used to calculate the total useful length, L_{total} .

$$L_{total} = \sum_{i=1}^n \left[l_w + \frac{w}{2} \tan \Lambda_{LE} (i-1) \right] = n l_w + \frac{w}{2} \tan \Lambda_{LE} \sum_{i=1}^n (i-1),$$

where: i = number of bays, l_w = length of outermost wall, w = width of each bay, and Λ_{LE} = sweep angle of centerbody leading edge.

The maximum L_{total} for a certain number of bays is constrained by the maximum length of the outermost wall, which is 44.5 ft. Table 1 lists the maximum useful lengths for the generic “homeplate” design, where the sweep of the leading edge is 45 degrees, and the width of each bay is 12 ft.

# bays	Maximum L_{total} (ft)
1	44.5
2	95.0
3	151.5
4	214.0
5	282.5

Table 1. Maximum Useful Lengths for Specified Number of Bays

The values in Table 1 are used to determine the necessary number of bays. The next step is to calculate the length of the outermost wall of the pressurized compartment. Setting $L_{total} = L_{req}$ and solving for l_w yields the following equation.

$$l_w = \frac{L_{req} - \frac{w}{2} \tan \Lambda_{LE} \sum_{i=1}^n (i-1)}{n}$$

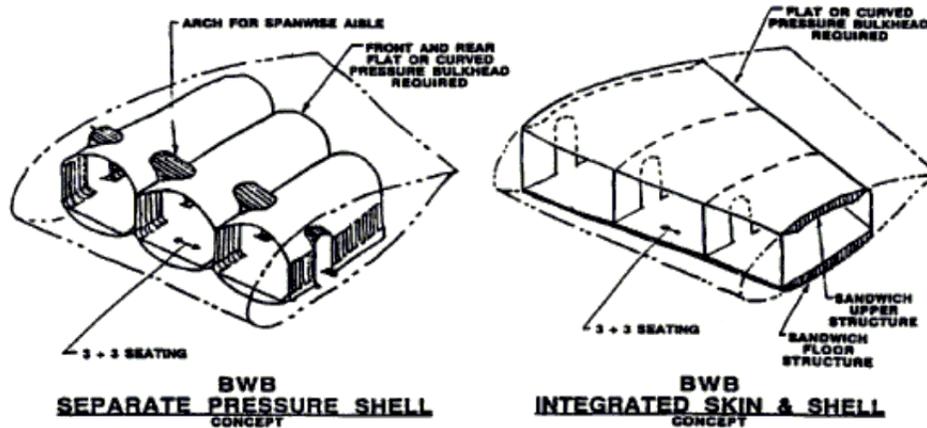
With the length of the outermost wall and the number of bays known, the geometry of the centerbody is defined.

3.2 Structural Weight Estimate

The centerbody is composed of a pressurized passenger compartment and an aft non-pressurized section, which is used to support the engines. The aft centerbody can be treated much like a horizontal tail since it will be largely composed of moving control surfaces, but a factor must be included for the additional weight associated with supporting the engines. The current version of FLOPS has equations to estimate the weight of a horizontal tail, and there are factors in the current fuselage weight equations to estimate the impact of mounting engines on the fuselage. A simple way of estimating the weight of the aft centerbody section is to treat it like a horizontal tail using the equations that already exist, modified to include the factor for engine placement. The outer wing panels of a BWB are just like the wings of a conventional aircraft, but carry only a portion of the total aerodynamic load. The wing weight equations in FLOPS should accurately predict the weight of the outer wing panels of a BWB just as they would for a conventional transport design. This means that the only structure for which a weight estimate must be developed is the pressurized section.

3.2.1 Development of the Centerbody Structural Concept

The pressurized cabin has to be designed to take internal pressure loads in addition to bending, shear, and torsion from aerodynamic loads. Previous research at NASA^[4,5] studied possible structural concepts that could be used in a BWB configuration. As explained in those papers, in a conventional circular fuselage section internal pressures are carried efficiently in hoop stress by a thin skin. Internal pressure in a non-circular section induces large bending stresses, which requires the structure to be heavier than a conventional fuselage. Two concepts for addressing the structural problems with a non-circular pressurized cabin are shown in figure 9. The NASA studies concluded that the optimum structural concept was to use inner cylindrical shells for the internal pressure, and the outer skin for bending. The Boeing design study^[2] argued that for this “multi-bubble” fuselage structure, the outer skin would have to be designed to take the internal pressure loads if there were a leak in the inner shell. Since the outer skin has to be designed to take the internal pressure anyway, there is no need to build the inner cylindrical shells. Based on this logic, the best solution is to design a single shell that will be strong enough for the additional stresses due to a non-circular shape.



AIAA 2002-2, Liebeck, Boeing

Figure 9. Centerbody Structural Concepts

The first BWB design study^[1] was for an 800-passenger transport and used a 5 in. thick sandwich structural shell. The study also mentions that a deep skin/stringer concept was competitive and had manufacturing benefits. The second Boeing design study was for a smaller BWB that carries approximately 450 passengers. The optimum design, based on cost and weight, was to use the skin/stringer concept with 5 to 6 in. deep stringers.^[2] The internal ribs had Y-braces to reduce the bending moment on the skin from internal pressure. It is assumed that for a 200 to 450-passenger BWB transport, a skin and stringer arrangement will be the optimum solution. Since the internal pressure has to be the same for all configurations, it follows that the depth of the stringers will be a function of the size of the cabin and the maximum aerodynamic loads (a function of takeoff gross weight, TOGW). A weight estimate for the entire pressurized cabin is of the following form:

$$W_{cabin} = a(TOGW)^b (S_{cabin})^c \quad \text{where } a, b, c \text{ are constants.}$$

3.2.2 Finite Element Analysis

Model Development and Meshing

Finite Element Analysis (FEA) was used in developing a weight estimation equation for the BWB centerbody structure. The purpose for the analysis was not to predict the actual weight of a working centerbody structure, but to find the relationship between TOGW, cabin planform area, and cabin weight. The relationship determined through finite element analysis was then calibrated to match the results of the more detailed structural analysis performed by Boeing. The same generic BWB centerbody geometry developed for the sizing equation (see section 3.1) was used to create a family of five transports, sized for approximately 250 to 450-passengers, at 50-passenger increments. The t/c of the entire centerbody structure is set at 17%, since this is a practical limit for transonic airfoils and is the same ratio used by Boeing. The outer wing panels are identical for all five geometries, and a small “mid-wing” section is used to blend the wing smoothly into the centerbody (see figure 10). The quarter chord sweep angle of the outer wing panels is fixed at 36 degrees, with a span of 78 ft., based on Boeing and NASA designs. The mid-wing section is defined so that the leading edge has

the same sweep as the outer wing panel, while the trailing edge has the same sweep as the centerbody. These basic geometries were reduced to the major load-bearing structures of the BWB for the finite element models.

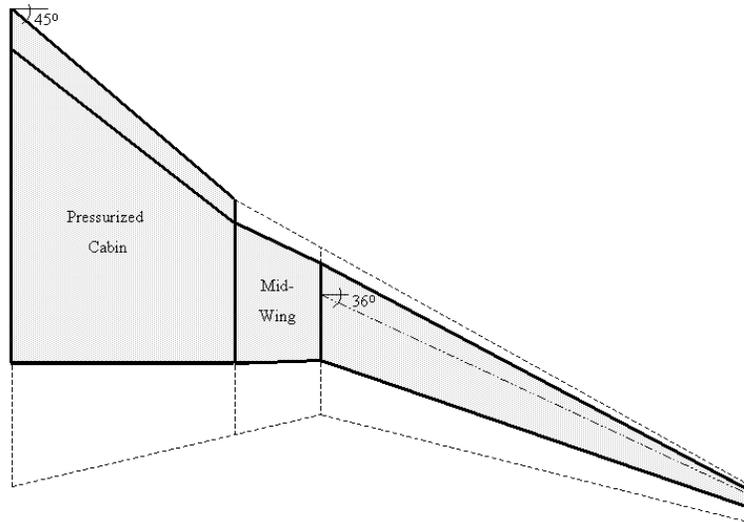


Figure 10. Finite Element Model of Simplified Geometry

The finite element model included two main spars that extend from the centerline out to the wing tips. A front spar was located at 10% chord for the finite element models and the rear spar was located at 70% chord. Rib locations in the centerbody were determined by the locations of the passenger bay walls as previously discussed. Ribs were placed at regular intervals in the outer-wing panels. A skin was modeled between the front and rear spars, and extends to an elliptical leading edge for the centerbody. This rounded leading edge was included for the centerbody to more accurately model the effect of internal pressure loads. Two additional spars were modeled in the centerbody that extend laterally from the centerline to the outer-wing, and from the bottom of the centerbody to the passenger deck. The two spars help to support the passenger deck, and stiffen the centerbody in bending.

The finite element model geometries were created and meshed in COSMOS/M™, a desktop computer based finite element analysis program used in previous NASA studies.^[4,5] Each surface was meshed with 4-node flat plate shell elements, with 6 degrees of freedom per node. The number of elements to mesh each model varied from 10553 for the 250-passenger model to 16747 for the 450-passenger model. Figure 11 shows the meshed outer-surfaces of the 450-passenger model, and is representative of the way in which all five models were created and meshed in COSMOS.

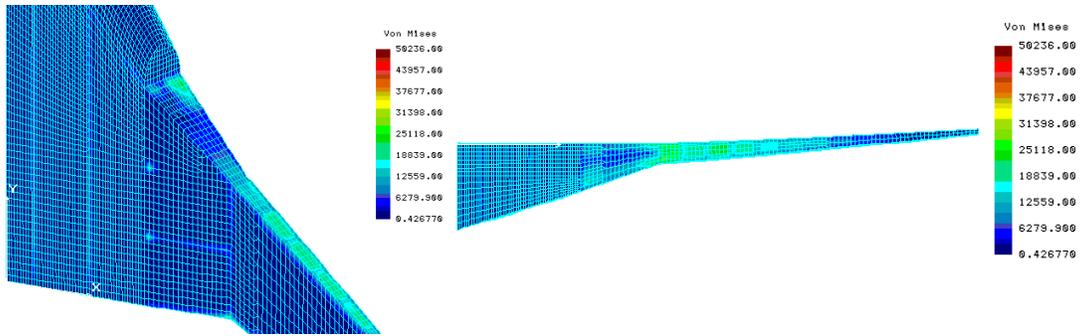


Figure 11. Finite Element Model With Exaggerated Deflections

Element Material Properties

The materials used in the wing and centerbody structure, excluding the passenger deck, are assumed to be composed of carbon-fiber reinforced plastic (CFRP) laminates. These laminates are assumed to have isotropic material properties, with a Young's modulus of $E=10 \times 10^6$ psi, Poisson's ratio $\nu=0.4$, 0.056 lb/in.^3 density, and allowable tensile stress of approximately 50,000 psi.^[4] The shear modulus is found using the equation: $G = \frac{E}{2(1 + \nu)}$.

These material properties were applied to ribs and spars that did not have internal pressure loads applied to them. The skin of the centerbody and outer-wing panels, as well as the rear spar and outermost rib in the centerbody, require stiffeners to take the internal pressure and aerodynamic loads. Since each of these structures was modeled as a surface meshed with flat-plate elements, a method of converting the skin/stringer arrangement into a flat plate of the same width and length was necessary.

The method used to determine the thickness and modulus of elasticity for an equivalent flat plate is similar to finding an equivalent beam.^[6] Using the definitions of bending and extensional stiffness, a mechanically equivalent flat plate can be found.

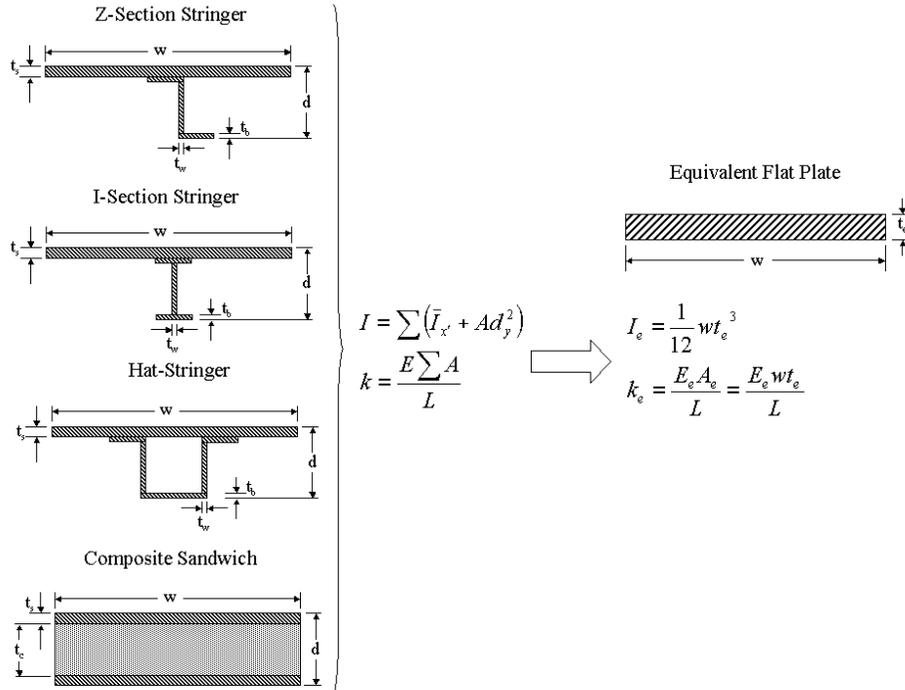


Figure 12. Conversion to Equivalent Flat Plate

The extensional stiffness, k , and bending stiffness, E^*I , must be the same for the skin/stringer arrangement and the equivalent flat plate. The following equations were used to determine the thickness and modulus of elasticity of the equivalent flat plate.

$$k = \frac{EA}{L} = \frac{E_e wt_e}{L} \Rightarrow E_e = \frac{EA}{wt_e}$$

$$\frac{EI}{k} = \frac{E_e I_e}{k_e} \Rightarrow t_e = \sqrt{\frac{12I}{A}}$$

The moment of inertia, stringer spacing, and cross-sectional area of the skin/stringer arrangement determine the thickness and modulus of elasticity of the equivalent flat plate. The most likely structural concepts for the skin of the pressurized vessel are a composite sandwich, or thin skin with hat, z-, or I-section stringers (see figure 12). A thin skin with z-section stringers was chosen for the centerbody and the outer-wing panels from a comparison of the equivalent material properties and weight per unit area of each arrangement. Using fixed thickness for the skin and stringer, the depth and spacing were varied to obtain a variety of weights and material properties for the equivalent flat plate. In other words, by varying the material properties of the shell elements a skin with z-section stringers of 5 to 6 inch depth, and spacing between stringers from 6 to 9 inches, can be quickly modeled and modified for the pressurized cabin.

Composite sandwich structures are commonly used for aircraft passenger decks because of their strength and durability. A sandwich composed of CFRP face skins and aluminum-honeycomb core was used to model the passenger deck in the finite element models. It was assumed that the core material does not contribute to axial or

bending stiffness, it simply keeps the face skins a constant distance apart. The core material does contribute to the weight, which made it undesirable for the pressurized shell of the centerbody or the outer-wing panels. The thickness of the sandwich was determined by the maximum deflections of the passenger deck. A 0.75 in. thick sandwich with 0.0625 in. thick face skins and a core density of 2 lb/ft³ was used for all five models.

Loads and Boundary Conditions

Four types of loading, the same as those used in previous studies,^[4] were included in the finite element analysis (internal pressure, 2.5g inertial load, lift load, and passenger deck loading). Since the objective was to find trends to determine the relationships between variables rather than to attempt to predict the actual weight of the structure, no factor of safety was included in the loads. The ultimate cabin pressure differential was modeled as an internal pressure of 18.6 psi applied to the skin, rear spar, and outermost rib of the centerbody. The critical flight condition is a +2.5g maneuver at maximum TOGW. Aerodynamic loading due to lift was modeled as pressure on the upper skin surface. A triangular lift distribution was used based on a discussion with Liebeck.^[7] The magnitude of the load was varied to find the maximum TOGW for each model and skin/stringer arrangement. The passenger deck loading at 2.5g was assumed to be 0.625 psi. Since only the right half of each BWB was modeled and meshed, symmetric boundary conditions were applied along the aircraft plane of symmetry.

Cabin Weight Data

The data of interest in this analysis is the weight of the pressurized cabin section of the BWB for various values of TOGW. The thickness of the ribs and spars of the centerbody were determined by adjusting the aerodynamic load (TOGW) and element thickness until the maximum deflection of the cabin skin was nominally 4.0 in. and the maximum stress occurred in one of the ribs of the centerbody (see figure 13). Four inches was chosen as the maximum allowable deflection based on a presentation given by Liebeck at NASA.^[8] The centerbody ribs carry the internal pressure loads in tension and are assumed to have the greatest stresses.

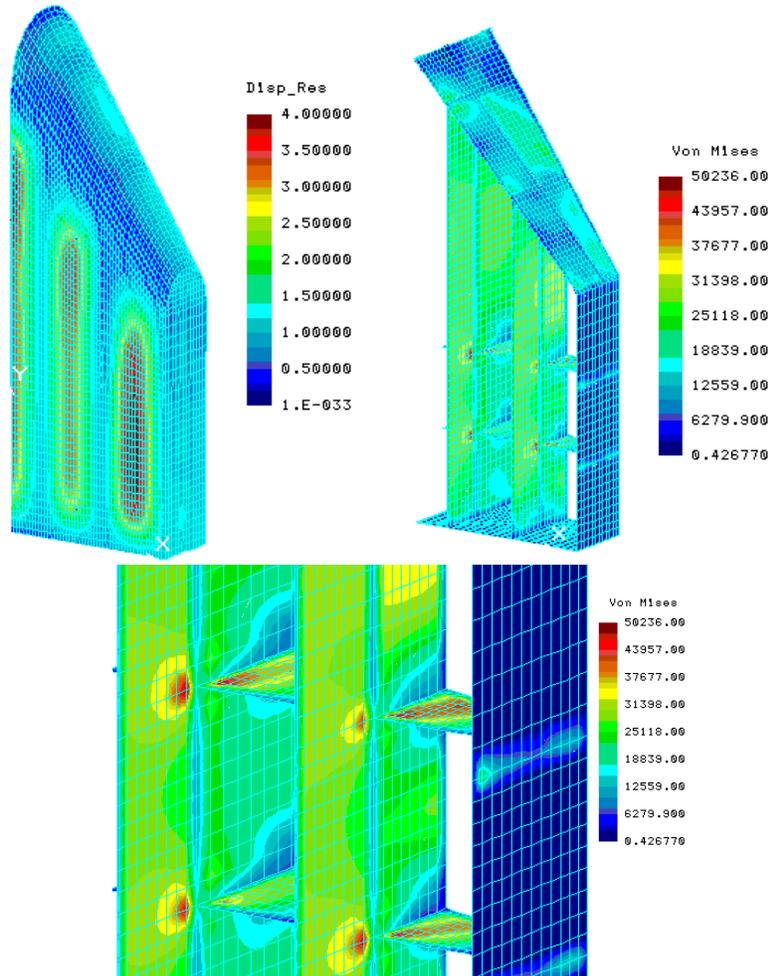


Figure 13. Cabin Skin Deflections and Centerbody Stresses

For each finite element model, the first run used the material properties for the heaviest centerbody structure, that is, the one with the deepest stringers (6 in.) spaced the minimum distance apart (6 in.). The thicknesses of the ribs and spars in the centerbody were varied along with TOGW until both the conditions for maximum deflection and stress occurred. After the thicknesses for spars and ribs were determined for the heaviest skin/stringer arrangement, those thicknesses remained fixed for the other skin/stringer arrangements. The material properties of the shell were then changed to represent a wider spacing of the stringers, or a shorter stringer depth. As the material properties of the shell changed to represent various skin/stringer arrangements, the same maximum stresses occurred when the skin deflected the maximum 4.0 in. The stresses in the ribs are a result of the deflections in the centerbody shell, and once the proper thickness for the ribs and spars was determined for the first case, those properties were good for all other cases. The cabin weight was found using COSMOS by summing the masses of all the elements in the centerbody. Since the material properties of all but the outer skin of the centerbody remained constant, the weight of the centerbody was a function of the material properties of the outer skin. A heavier cabin represented a skin arrangement with deeper or more closely spaced stringers than a lighter cabin. For each skin/stringer arrangement, a new TOGW was found to match the maximum deflection and stress

requirements, so that a relationship between TOGW and cabin weight could be established. The material properties used for one BWB model were then used as an initial guess for the next size BWB, and the same process was repeated until data for all five cabin sizes was collected.

This process was used to consistently define the thickness of the element groups for each model and find the maximum TOGW for each cabin weight. With the data collected from all five models, regression analysis can be used to obtain a relationship between cabin weight, size, and TOGW.

3.2.3 Regression Analysis

The data obtained from finite element analysis have been used to find the coefficients of the weight estimate equation,

$$W_{cabin} = a(TOGW)^b (S_{cabin})^c .$$

The equation can be linearized to the form

$$\ln(W_{cabin}) = \ln(a) + b \ln(TOGW) + c \ln(S_{cabin}) .$$

Using the method of least squares fitting,

$$\Pi = \sum_{i=1}^n [\ln(W_{cabin}) - (\ln(a) + b \ln(TOGW) + c \ln(S_{cabin}))]^2 = \min$$

results in the three equations,

$$\frac{\partial \Pi}{\partial a} = 0, \quad \frac{\partial \Pi}{\partial b} = 0, \quad \frac{\partial \Pi}{\partial c} = 0,$$

which are solved simultaneously to obtain the coefficients. The equation obtained from regression analysis is then

$$W_{cabin} = 0.316422(TOGW)^{0.166552} (S_{cabin})^{1.061158}$$

Lines of constant cabin area are plotted against the data from finite element analysis in figure 14. The correlation coefficient for this surface fit to the data is $R^2 = 0.99873$. The weights obtained through finite element analysis are generally lower than the weight of a fabricated structure. The weight of the centerbody has been scaled to match data supplied by Boeing to reach an estimate for the actual weight of a BWB pressurized cabin. With a scale factor of $K_s=5.698865$, the final equation for cabin weight is then

$$W_{cabin} = K_s * 0.316422(TOGW)^{0.166552} (S_{cabin})^{1.061158}$$

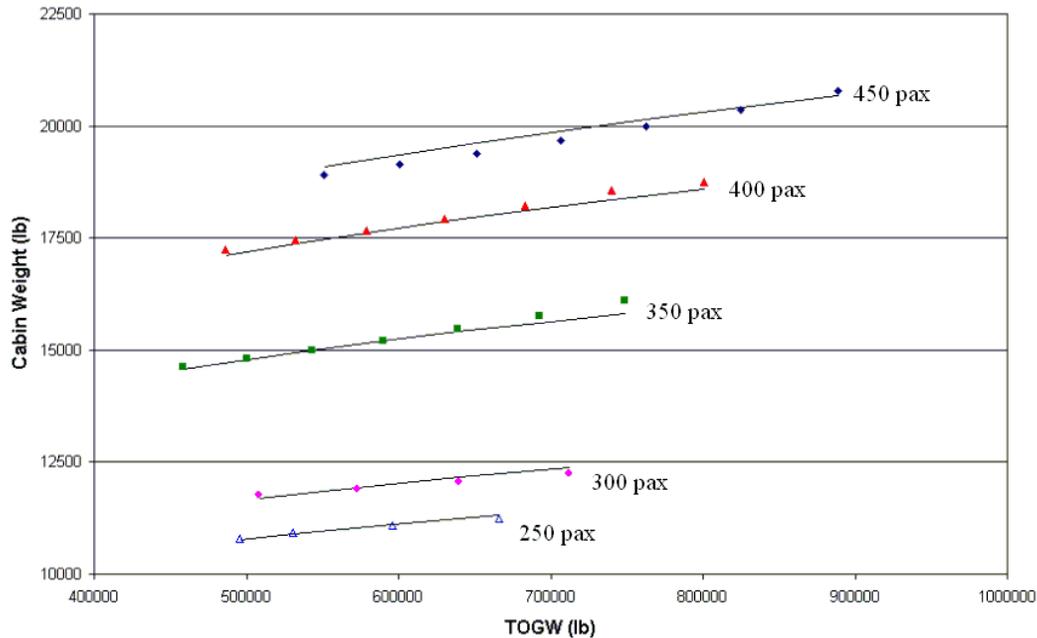


Figure 14. Regression Analysis Surface Fit to FEA Data

4.0 Flops Implementation

4.1 Passenger Compartment Design

FLOPS 6.03 has been modified to more accurately represent a BWB transport using the sizing methodology discussed above. Appendices A and B contain the sections of the weights and aerodynamics modules (sfwate.f and sfaero.f) that were modified. The variable IFITE indicates what type of aircraft is being analyzed and which equations are to be used. A value of IFITE = 3 now indicates that the methodology and equations for a BWB transport will be used.

A new fuselage design subroutine, BWBFUS, has been added which uses the equations developed above to determine the size of the BWB centerbody. The centerbody dimensions can be entered in the input file to analyze a BWB of known geometry, or the dimensions can be calculated based on the number of passengers. For either case the routine calculates the number of galleys, lavatories, and closets, as well as the required number of bays. BWBFUS then determines the internal arrangement of each bay using the subroutine FILBAY and prints number of passengers in each class, galleys, closets, and lavatories for each bay. It also determines how efficiently the available space in the bay has been used (the percentage of the available space that is used). Table 2 gives an example of the input and output of the BWB fuselage design subroutines for a 350-passenger class BWB. When BWBFUS has completed the design of the centerbody, subroutine DEFINE modifies the input for detailed wing data so that the first wing station is at the same location spanwise and has the same length as the outermost rib of the centerbody. The wing loading is then adjusted to model a triangular lift distribution. The use of detailed wing input allows the user to define a number of wing stations for the wing root, break points, and wing tip with the corresponding chord length, t/c, and sweep at each station. It also allows the user to enter the fraction of the load carried by the

wing, and the type of pressure distribution. FLOPS detailed wing data was originally used only for wing weight calculation. Also, the use of this detailed wing data has been expanded for use in calculating a more accurate wetted area for a BWB configuration. Although it is an optional input for other configurations, detailed wing input is necessary for reasonable confidence in calculations of wetted area and wing weight for a BWB configuration.

FILBAY attempts to fill each bay with a logical arrangement. FILBAY is passed information about the length of the bay that needs to be filled, the number of passengers and other items that still need to be placed, and information to determine if there is a cross aisle or if one wall is longer than the other. The routine places first class passengers first along with the galleys, lavatories, and closets required for those passengers. If there is any remaining space in the bay after placing all first class passengers and other items, business class seats are placed in a similar manner and then tourist class.

INPUT

CLASS	PASSENGERS	ABREAST	PITCH (IN)
FIRST	22	4	61
BUSINESS	70	4	39
TOURIST	273	6	32

OUTPUT

PRESSURIZED CABIN DIMENSIONS	
LENGTH OF CENTERLINE	73.5 FT
LENGTH OF SIDE WALL	43.5 FT
NUMBER OF BAYS	5
WIDTH OF CABIN	60 FT
CABIN AREA	3512 SQFT

FUSELAGE DIMENSIONS	
FUSELAGE LENGTH	105 FT
FUSELAGE MAX DEPTH	15.8 FT

INTERIOR FUSELAGE LAYOUT

BAY #	LENGTH (FT)	GALLEYS	LAVS	CLOSETS	PASSENGERS BY CLASS			EFF. (%)
					FIRST	BUS	TOUR	
1	67.5	1	1	1	24	36	0	98.8
2	55.5	1	1	1	0	36	42	97.5
3	55.5	1	1	3	0	0	102	97.1
4	43.5	1	1	1	0	0	78	98.2
5	43.5	0	1	0	0	0	54	60.2

Table 2. Example Input/Output of Fuselage Design Subroutine

4.2 Weight Estimates

The most significant change to the FLOPS weight module is the fuselage weight equation. To better match the way Boeing bookkeeps structural weights, the weight of the aft centerbody and wing are lumped together, and the weight of the fuselage is the weight of the pressurized cabin. The fuselage weight is then

$$W_{fuse} = 5.698865 * 0.316422(TOGW)^{0.166552} (S_{cabin})^{1.061158}.$$

The weight of the aft centerbody was estimated by treating it as a horizontal tail, and modifying the horizontal tail weight equation to include a factor for the number of engines supported by the centerbody. The weight of the aft centerbody is then

$$W_{aft} = (1 + 0.05 * NEng) * 0.53 * S_{aft} * TOGW^{0.2} * (\lambda_{aft} + 0.5),$$

where NEng is the number of engines support by the centerbody, S_{aft} is the planform area of the aft centerbody, and λ_{aft} is the taper ratio.

Most of the other weight estimates are obtained by modifying the existing equations to more accurately represent a BWB configuration. In many of the weight equations there is a term, NFUSE*XL*WF, which is the number of fuselages times the length times the width. This is the total planform area of the fuselages, which for a BWB is the planform area of the cabin. FLOPS has also been expanded to account for business class passengers in addition to first and tourist class, which were already addressed.

4.3 Aerodynamics

The FLOPS aerodynamics module has been modified to calculate the wetted surface area using detailed wing station data and to use a different method for estimating skin friction. The new wetted surface area calculation uses a surface area correction factor, K_t , from a curve fit to a plot by G. Corning.^[9] This correction factor is based on the t/c of the wing section and the wetted area is calculated as

$$A_{wet} = \sum K_t A_{exposed} / \cos(\Gamma).$$

For the BWB calculation, the effect of dihedral angle, Γ , has been neglected to simplify integration of the new calculation into the existing FLOPS module. The wetted areas of the centerbody and outer-wing panels are included in the wing wetted area, and the fuselage wetted area is set to zero.

A comparison of the L/D and drag polars at cruise conditions between the original FLOPS results and the Boeing detailed analysis showed that FLOPS was predicting a much higher skin friction drag coefficient (see figure 16). The original FLOPS estimations were based on empirical data for calculating an average friction coefficient, or equivalent flat plate drag coefficient, and a form factor for the surface. The average friction coefficient used by FLOPS to calculate skin friction has been modified using an interpolation between curve fits of average friction vs. Reynolds number.^[10] The equivalent flat plate drag coefficient, C_f , obtained from this interpolation is then used to determine the skin friction component of the drag coefficient,

$$C_{Df} = C_f \frac{A_{wet}}{S_{ref}}.$$

5.0 Results

The modified FLOPS was tested for a 468-passenger and a 571-passenger BWB transport, which were compared to the Boeing BWB-450^[2] and BWB-600 baseline^[3] respectively. Appendix C contains the input files for the FLOPS test cases. The 468-passenger model has been tested using a fixed geometry based on the dimensions of the Boeing design as well as a free geometry, where FLOPS calculates the size of the centerbody. All FLOPS cases were run with the same engine deck, scaled to match the sea-level static thrust of the Boeing designs. Both fixed and free BWB-450 cases were iterated to find the ramp weight based on a 7,750 nmi design range and other constraints identical to the Boeing BWB-450. The weights breakdown and cruise drag polars for the Boeing BWB-450 were compared to the FLOPS results (see figures 15, 16). Both FLOPS cases resulted in differences of less than 3.0% in empty weight, and less than 4.0% in TOGW.

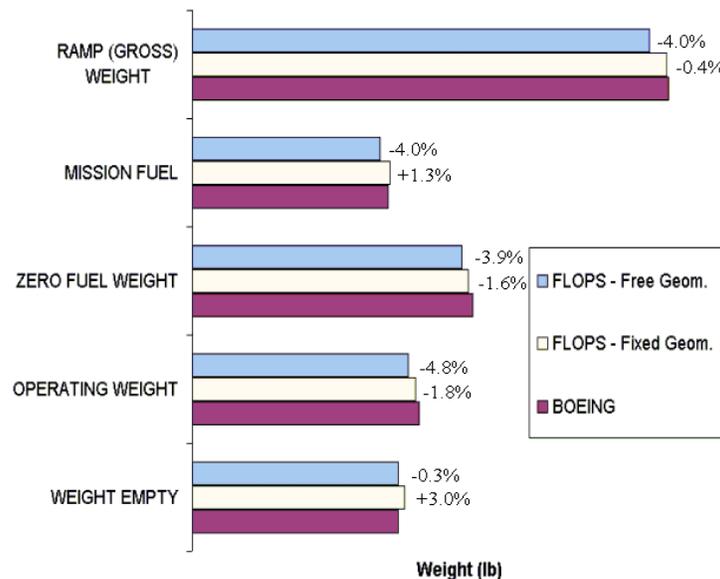


Figure 15. Comparison of FLOPS to Boeing Predicted Weights

Note that the difference between operating weight and empty weight is greater for the Boeing analysis than is predicted by FLOPS. This may be due to accounting differences, where some items that are included in the empty weight by FLOPS are considered operating items by Boeing.

The new equations for wetted area and equivalent flat plate drag coefficient also show a significant improvement in matching the Boeing predicted drag polars as shown in figure 16.

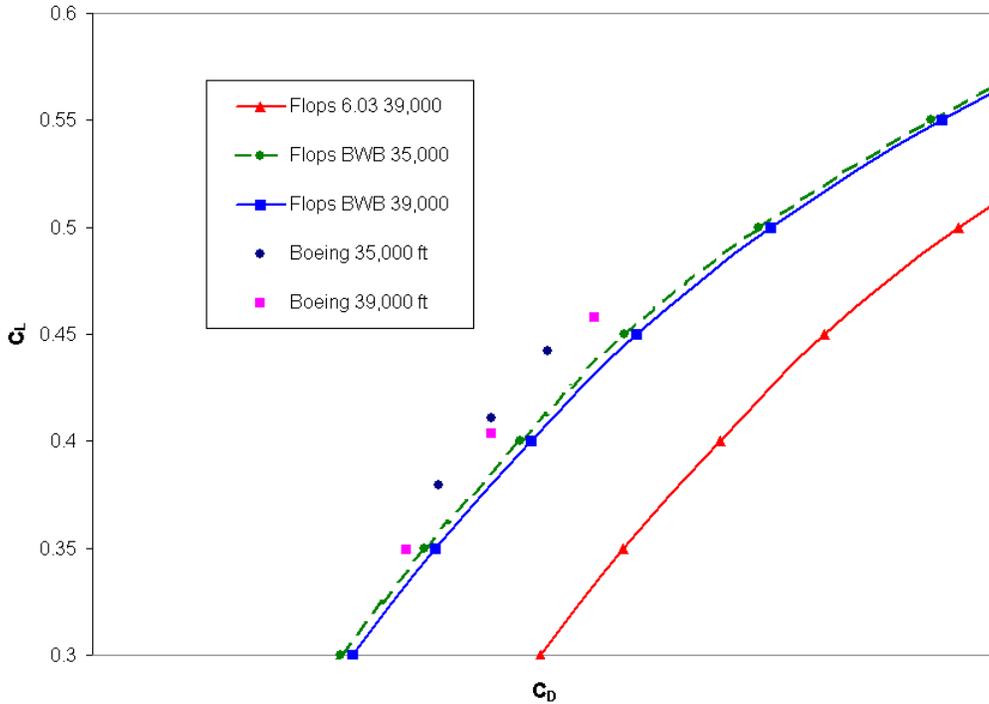


Figure 16. Improvement in Drag Polar Match

The FLOPS BWB-600 input used the same detailed wing data as the BWB-450, scaled to match the span of the Boeing BWB-600. FLOPS was allowed to size the centerbody, and iterated on TOGW for a design mission range of 7,100 nmi. This resulted in a TOGW about 5.3% lower than the Boeing BWB-600. One possible reason for the larger difference is that the sizing methodology assumes only one passenger deck will be used. It is likely that the Boeing model uses more than one deck. There is not enough available data from the Boeing analysis to make a more detailed comparison.

The modified FLOPS code was also used to size three different BWB transports that have the same passenger capacity, maximum payload, and range with the maximum payload as the Boeing 757-300, 777-300ER, and 747-400. Payload vs. range plots for the BWB and conventional designs are shown in figure 17. The difference in the slopes of the payload vs. range curves is as expected because of the higher L/D of a BWB configuration. FLOPS calculates the maximum fuel capacity based on the size of the wing, which for a BWB configuration is quite large. As a result there is no break in the curves for a BWB since the amount of fuel needed for the mission was always less than the predicted maximum fuel capacity of the wing. In reality the fuel tanks would probably be designed for a lower capacity, which would place additional limits on the maximum range.

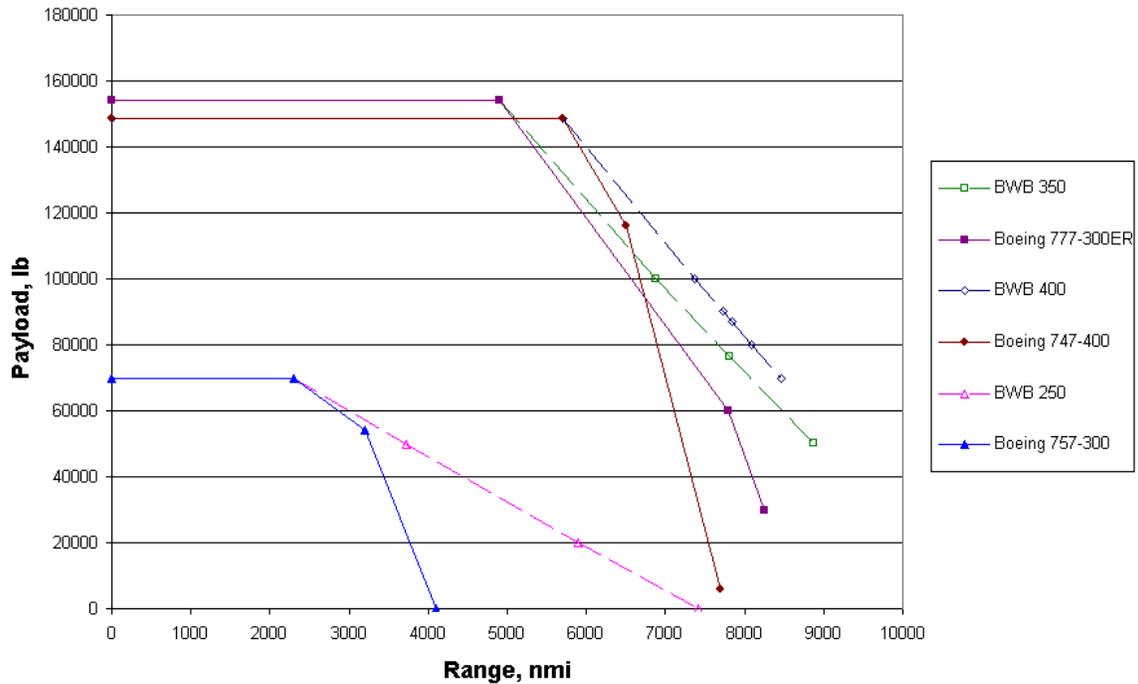


Figure 17. Payload vs. Range Comparison to Conventional Aircraft

The weight trends among the BWB configurations show a similar pattern to the conventional transports (see figure 18). While a direct comparison between BWB and conventional configurations is not possible without more detailed analysis, the trends in both performance and weight predicted by the sizing methodology follow logical expectations.

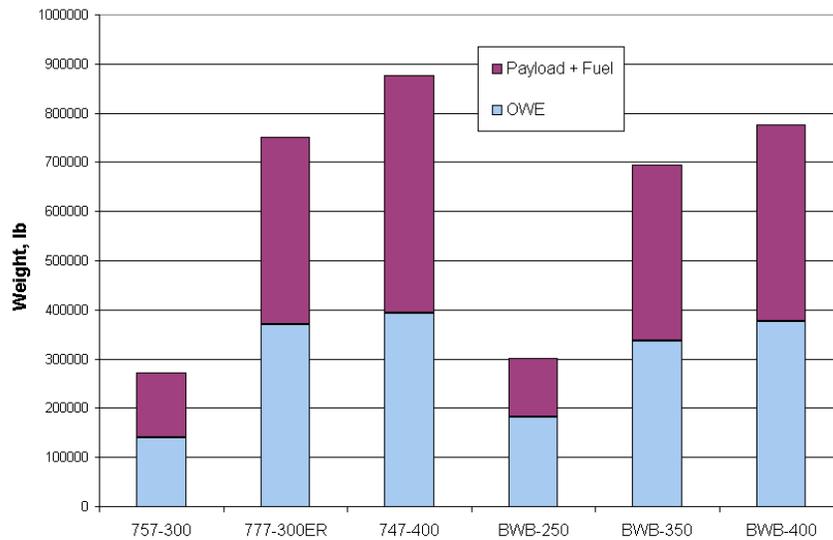


Figure 18. Comparison of Weight Growth Trends

6.0 Conclusions

The current capabilities of FLOPS have been expanded to better represent the geometry, weight, and aerodynamics of a BWB transport. The sizing methodology described in this paper, coupled with the weight estimate based on finite element analysis facilitates the creation of a conceptual design. The addition of a sizing module for a BWB to FLOPS, along with changes to the weight estimates and improved skin friction drag prediction, resulted in differences of less than 3.0% in empty weight, and less than 4.0% in TOGW for 450-passenger designs. The difference for the TOGW of a 600-passenger design was about 5.3%, but is considered reasonable since the sizing methodology was based on a 200- to 450-passenger class BWB. More validation with detailed analysis of various size BWB designs is needed, but based on the comparisons made to date, the TOGW difference for a 200- to 450-passenger design is expected to be less than 5%.

7.0 References

1. Liebeck, R. H., Page, M. A., and Rawdon, B. K., "Blended-Wing-Body Subsonic Commercial Transport", AIAA Paper 98-0438, January 1998.
2. Liebeck, R. H., "Design of the Blended-Wing-Body Subsonic Transport", AIAA Paper 2002-0002, January 2002.
3. Daggett, D. L., "Ultra Efficient Engine Technology Systems Integration and Environmental Assessment", NASA Report CR-2002-211754, July 2002.
4. Mukhopadhyay, V., "Structural Concepts Study of Non-circular Fuselage Configurations", AIAA Paper SAE WAC-67, October 1996.
5. Mukhopadhyay, V., Sobieszczanski-Sobieski, J., Kosaka, I., Quinn, G., and Charpentier, C., "Analysis, Design and Optimization of Non-cylindrical Fuselage for Blended-Wing-Body (BWB) Vehicle", AIAA Paper 2002-5664, September 2002.
6. Wong, M., "Sandwich Composite – 3-point Bending Test for Composites With Rohacell & Fuzzy Carbon Cores", Fermilab, BTeV Sandwich Composite, April 2002.
7. Liebeck, R. H., The Boeing Company, phone conversation, 28 January 2003.
8. Liebeck, R. H., AIAA sponsored lecture, NASA LaRC, June 2003.
9. Corning, G., "Airplane Design", Boeing D6-8195, C6
10. "Turbulent Flow Over an Insulated Smooth Flat Plate", Boeing D6-7161

8.0 Appendix A

Changes to SFWATE.F

The majority of changes are minor and simply modify a line of code so that for IFITE values of 0 (conventional transport) and 3 (BWB) the same equations are used. The following pieces of code show where the more significant modifications have been made, or new sections added. Lines of code that have been changed or added are noted in italics.

```
COMMON / WTS / ACABIN,ARFIN ,CARGF ,CARGOF,CARGOW,CGCF ,CGCW ,
1 CGEA ,CGEF ,CGFWF ,CGLGM ,CGLGN ,CGZWF ,
2 DF ,DGW ,DIH ,FAERT ,FCOMP ,FLAPR ,FRCAN ,
3 FRFIN ,FRFU ,FRHT ,FRLGM ,FRLGN ,FRNA ,FRSC ,
4 FRVT ,FRWI ,FSTRT ,FULFMX ,FULWMX ,HYDPR ,
5 SFIN ,SWPCAN ,SWPFIN ,SWPHT ,SWPVT ,TCFIN ,
6 TCR ,TCT ,TRCAN ,TRFIN ,ULF ,XLF ,
7 WF ,WLDG ,XL ,XLP ,XMLG ,XNLG ,
8 YEA ,YEF ,YFIN ,YFUSE ,YVERT ,ZAP ,ZBW ,
9 ZEA ,ZEF ,ZFIN ,ZHT ,ZRV ,ZVT ,
1 CGSP(40,2) ,WSP(40,2) ,NTANK ,INRTIA ,
2 NFIN ,NPF ,NPT ,NPB ,NSTU ,NGALC ,NFLCR
COMMON /FUSDTA/ FPITCH ,BPITCH ,TPITCH ,NFABR ,NBABR ,NTABR

NAMELIST/ WTIN /IFITE ,ULF ,DGW ,NWREF ,CGREFL ,CGREFX ,MYWTS ,
1 IALTWT ,HYDPR ,SPAN ,DIH ,FLAPR ,GLOV ,VARSWP ,FCOMP ,FAERT ,
2 FSTRT ,NETAW ,ETAW ,CHD ,TOC ,SWL ,ETAE ,PCTL ,ARREF ,TCREF ,
3 NSTD ,PDIST ,NETAP ,ETAP ,PVAL ,SHT ,SWPHT ,ARHT ,TRHT ,TCHT ,
4 HHT ,SVT ,SWPVT ,ARVT ,TRVT ,TCVT ,SFIN ,ARFIN ,TRFIN ,SWPFIN ,
5 TCFIN ,NFIN ,SCAN ,SWPCAN ,ARCAN ,TRCAN ,TCCAN ,XL ,WF ,FSWREF ,DF ,
6 XLP ,XMLG ,XNLG ,WLDG ,CARBAS ,NEW ,NEF ,THRSO ,WENG ,EEXP ,XNAC ,
7 DNAC ,FULWMX ,FULFMX ,NTANK ,WPMISC ,NPF ,FPITCH ,WFLCRB ,NFABR ,
8 NPB ,BPITCH ,NBABR ,NPT ,TPITCH ,NTABR ,NSTU ,NGALC ,NFLCR ,WPPASS ,
9 WSTUAB ,BPP ,CARGF ,CARGOW ,CARGOF ,FRWI ,FRHT ,FRVT ,FRFIN ,FRCAN ,
* FRFU ,FRLGN ,FRLGM ,FRNA ,WPMSC ,WFSYS ,FRSC ,WIN ,WHYD ,WELEC ,
1 WAVONC ,WARM ,WFURN ,WAC ,WAI ,WUF ,WOIL ,WSRV ,WAPU ,WCON ,WPAIN ,
2 WTHR ,CGW ,CGHT ,CGVT ,CGFIN ,CGCAN ,CGF ,CGLGN ,CGLGM ,CGEF ,
3 CGEA ,CGAP ,CGAV ,CGARM ,CGCR ,CGP ,CGCW ,CGCF ,CGZWF ,CGFWF ,
4 CGAIS ,CGACON ,CGAXG ,CGAXT ,CGAMMO ,CGMIS ,INRTIA ,ZHT ,ZVT ,
5 ZFIN ,YFIN ,ZEF ,YEF ,ZEA ,YEA ,ZBW ,ZAP ,ZRV ,YMLG ,EWMARG ,
6 YFUSE ,YVERT ,SWTFF ,ITANK ,NFCO ,TX ,TY ,TZ ,TL ,TW ,TD ,TF ,
7 IFUFU ,VMMO ,TCR ,TCT ,FULAUX ,WAUXT ,NFUSE ,NVERT ,WINL ,EINL ,
8 WNOZ ,ENOZ ,MLDWT ,ISPOWE ,FRWI1 ,FRWI2 ,FRWI3 ,SPWTH ,SPWSW ,
9 SPWGW ,SPWCON ,FUELRF ,FUSCLA ,FUSCLB ,NTOW ,NSWR ,NTHR ,
* WTFILE ,DLDWT ,ACABIN

SUBROUTINE DEFINE
C CALL THE FUSELAGE DESIGN ROUTINE

CLP = ' '
CXL = ' '
IF ( XL .LT. 1.0D0 .OR. XLP .LT. 1.0D0 ) .AND. IFITE .EQ. 0 .AND.
1 NFUSE .GT. 0 ) CALL DESFUS ( CLP , CXL )
IF ( IFITE .EQ. 3 ) THEN
CALL BWBFUS ( CLP , CXL , XLW )
C PUT FIRST WING STATION AT SIDE OF PRESSURIZED CABIN FOR DETAILED
C WING DATA , AND ADJUST WING LOAD IF IT IS UNREASONABLE FOR BWB
IF ( NETAW .GE. 1 ) THEN
ETAW(1) = 0.5D0 * WF
CHD(1) = XLW/0.7D0
ENDIF
IF ( PCTL .GE. 1.D0 ) PCTL = ( 1.D0 - WF / SPAN ) ** 2
ENDIF

SUBROUTINE WEIGHT
C WEIGHT OF AUXILIARY POWER UNIT
WAPU = 54.0D0 * ( NFUSE * XL * WF ) ** 0.3D0 + 5.4D0 * NPASS ** 0.9D0
IF ( IFITE .EQ. 3 ) WAPU = 54.0D0 * ( ACABIN / 0.7D0 ) ** 0.3D0 +
1 5.4D0 * NPASS ** 0.9D0

CALL ORIDE ( WAPU , OAPU )

C WEIGHT OF INSTRUMENTS
IF ( IFITE .NE. 1 ) WIN = 0.48D0 * ( NFUSE * XL * WF ) ** 0.57D0 *
1 VMAX ** 0.5D0 * ( 10.D0 + 2.5D0 * NFLCR + FNEW + 1.5D0 * FNEF )
IF ( IFITE .EQ. 3 ) WIN = 0.48D0 * ( ACABIN / 0.7D0 ) ** 0.57D0 *
1 VMAX ** 0.5D0 * ( 10.D0 + 2.5D0 * NFLCR + FNEW + 1.5D0 * FNEF )
IF ( IFITE .EQ. 1 ) WIN = 0.09D0 * NFUSE * XL * DF * ( 1.0D0 +
1 2.5D0 * NFLCR + 0.1D0 * FNEW + 0.15D0 * FNEF )
CALL ORIDE ( WIN , OIN )

C WEIGHT OF HYDRAULIC SYSTEM
IF ( IALTWT .EQ. 0 ) THEN
WHYD = ( NFUSE * XL * WF + 0.27D0 * SW ) * ( 1.D0 + 0.03D0 * FNEW
1 + 0.05D0 * FNEF ) * ( 3000.D0 / HYDPR ) ** 0.35D0
2 * ( 1.0D0 + 0.04D0 * VARSWP )
IF ( IFITE .EQ. 3 ) WHYD = ( ACABIN / 0.7 + 0.27D0 * SW ) * ( 1.D0 +
1 0.03D0 * FNEW + 0.05D0 * FNEF ) * ( 3000.D0 / HYDPR ) ** 0.35D0
2 * ( 1.0D0 + 0.04D0 * VARSWP )

IF ( IFITE .EQ. 1 ) THEN
WHYD = 0.55D0 * WHYD * VMAX ** 0.10D0
ELSE
WHYD = 0.57D0 * WHYD * VMAX ** 0.33D0
ENDIF
ELSE
WHYD = 0.6053D0
1 * ( SW + 1.44D0 * ( SWTHT / ( 2.D0 + 387D0 * TCHT ) + SVT ) )
ENDIF
CALL ORIDE ( WHYD , OHYD )

C WEIGHT OF AVIONICS
IF ( IFITE .NE. 1 ) WAVONC = 15.8D0 * DESRNG ** 0.1D0 * NFLCR ** 0.7D0
1 * ( NFUSE * XL * WF ) ** 0.43D0
IF ( IFITE .EQ. 3 ) WAVONC = 15.8D0 * DESRNG ** 0.1D0 * NFLCR ** 0.7D0
1 * ( ACABIN / 0.7D0 ) ** 0.43D0
IF ( IFITE .EQ. 1 ) WAVONC = 0.41D0 * ( NFUSE * XL * DF ) ** 1.3D0
1 * ( 1.D0 + 0.37D0 * CARBAS ) * VMAX
CALL ORIDE ( WAVONC , OAVONC )

C WEIGHT OF FURNISHINGS
IF ( IALTWT .EQ. 0 ) THEN
IF ( IFITE .EQ. 1 ) THEN
WFURN = 80.D0 * NFLCR * VMAX ** 0.38D0 * XL ** 0.25D0
ELSE IF ( IFITE .EQ. 3 ) THEN
WFURN = 127.D0 * NFLCR + 112.D0 * NPF + 44.D0 * NPT
1 + 78.D0 * NPB + 2.6D0 * XLF * ( WF / DFLOAT ( NFUSE ) + DF )
2 + 2.6D0 * ( WF * ( 1 + DCOS ( 45.D0 / 57.296D0 ) ) * DF )
ELSE
WFURN = 127.D0 * NFLCR + 112.D0 * NPF + 44.D0 * NPT
1 + 78.D0 * NPB + 2.6D0 * XLP * ( WF + DF ) * NFUSE
ENDIF
ELSE
WFURN = 72.6D0 * NPASS + 5.25D0 * NPASS + 600.D0 * 2.5D0
1 + 4.3D0 * NPASS + 1000.D0 + 1000.D0 + 100.D0
ENDIF
CALL ORIDE ( WFURN , OFURN )

C WEIGHT OF AIR CONDITIONING SYSTEM
IF ( IALTWT .EQ. 0 ) THEN
IF ( IFITE .EQ. 1 ) THEN
```

```

WAC = .075D0*WAVONC + .37D0*FNENG*FTHRST**0.6D0*VMAX**0.57D0
ELSEIF (IFITE.EQ.3) THEN
WAC = (3.2D0*(ACABIN/0.7D0*DF)**0.6D0
+ 9.0D0*NPASS**0.83D0)*VMAX + 0.075D0*WAVONC
ELSE
WAC = (3.2D0*(NFUSE*XL*WF*DF)**0.6D0
+ 9.0D0*NPASS**0.83D0)*VMAX + 0.075D0*WAVONC
ENDIF
ENDIF
WAC = 26.D0*NPASS
ENDIF
CALL ORIDE (WAC,OAC)

```

C WEIGHT OF STRUCTURAL COMPONENTS

C WEIGHT OF WING

```

WTNFA = WENG + WTHR + WSTART + 0.25D0*WEC + 0.11D0*WIN +
1 0.13D0*WELEC + 0.13D0*WHYD + 0.25D0*WFSYS
WPOD = WTNFA / NENG + WNAC / TNAC
CALL WWGHT (WWING, B, DG, ULF, TR, SW, TCA, FLAPR, SWEEP, AR,
1 FCOMP, FAERT, FSTRT, VARSWP, WPOD, NFUSE, NEW, IFITE, IPRNT)
IF (IFITE.EQ.3) THEN
SAFTB = ACABIN * 0.3D0 / 0.7D0
TRAFTB = 1.D0 - 6.D0 * DFLOAT(NFUSE) * DSIN(45.D0 / 57.296D0)
1 / (0.7D0*XL)
WWING = WWING + (1.D0 + 0.05D0 * FNEF) * 0.53D0 * SAFTB *
1 DG**0.2D0 * (TRAFTB + 0.5D0)
ENDIF
CALL ORIDE (WWING,FRWI)

```

C WEIGHT OF FUSELAGE

```

DAV = (WF + DF) / 2.D0
IF (IALTTW.EQ.0) THEN
IF (IFITE.EQ.0) THEN
WFUSE = 1.35D0 * (XL * DAV)**1.28D0 * (1.0D0 + 0.05D0*FNEF)
1 * (1.0D0 + 0.38D0 * CARGF) * NFUSE
ELSE IF (IFITE.EQ.1) THEN
WFUSE = .15D0 * XL**9D0 * DG**61D0 * (1.D0 + .3D0*FNEF)
1 * (1.D0 + .33D0*VARSWP) * NFUSE**0.3D0
ELSE IF (IFITE.EQ.3) THEN
WFUSE = 5.698865D0 * 0.316422D0 * DG**0.166552D0
1 * ACABIN**1.061158D0
ELSE
SWFUS = 3.14159D0 * (XL/DAV - 1.7D0) * DAV**2
CALL ORIDE (SWFUS, SWETF)
WFUSE = 0.052D0 * SWFUS**1.086D0 * (ULF*DG)**.177D0
1 * QCRUS**2.41D0
ENDIF
ELSE
SWFUS = 3.14159D0 * (XL/DAV - 1.7D0) * DAV**2
CALL ORIDE (SWFUS, SWETF)
WFUSE = 3.939D0 * SWFUS / (DF/WF)**.221D0
ENDIF
CALL ORIDE (WFUSE,FRFU)

```

SUBROUTINE BWBFUS (CLP, CXL, XLW)

C THIS SUBROUTINE CALCULATES THE PRESSURIZED CABIN DIMENSIONS
C FOR A BWB TRANSPORT, BASED ON THE NUMBER OF FIRST, BUSINESS,
C AND TOURIST CLASS PASSENGERS - WRITTEN BY KEVIN BRADLEY, SUMMER 2003

IMPLICIT DOUBLE PRECISION (A-H, O-Z)

```

COMMON /UNITS / IU5, IU6, IU7, IU8, IU9, IU16, IU17, IU18
COMMON /EDETIN/ CAM, SBASE, BL, XD, AITEK,
1 SHT, TCHT, ARHT, TRHT, HHT, SVT,
2 TCVT, ARVT, TRVT, XNAC, DNAC, GLOV,
3 NEW, NEF, NFUSE, NVERT, ARCAN, SCAN, TCCAN
COMMON /WTS / ACABIN, ARFIN, CARGF, CARGOF, CARGOW, CGCF, CGCW,
1 CGEA, CGEF, CGFWF, CGLGM, CGLGN, CGZWF,
2 DF, DGW, DIH, FAERT, FCOMP, FLAPR, FRCAN,
3 FRFIN, FRFU, FRHT, FRLGM, FRLGN, FRNA, FRSC,
4 FRVT, FRWI, FSTRT, FULFMX, FULWMX, HYDPR,
5 SFIN, SWPCAN, SWPFIN, SWPHT, SWPVT, TCFIN,
6 TCR, TCT, TRCAN, TRFIN, ULF, XLF,
7 WF, WLDG, XL, XLP, XMLG, XNLG,
8 YEA, YEF, YFIN, YFUSE, YVERT, ZAP, ZBW,
9 ZEA, ZEF, ZFIN, ZHT, ZRVT, ZVT,
1 CGSP(40,2), WSP(40,2), NTANK, INRTIA,
2 NFIN, NPF, NPT, NPB, NSTU, NGALC, NFLCR
COMMON /XFLOPC/ IXFL, IU19, IU20, IU22
COMMON /FUSDTA/ FPITCH, BPITCH, TPITCH, NFABR, NBABR, NTABR
COMMON /FUSINT/ WFAISL, WTAISL, NFR, NTR, NAISL, NGALLY, NCLSET,

```

```

1 NDOORS, NLAVA
COMMON /BWBINT/ NPPF, NPBP, NPPT, NPFR, NPBR, NPTR,
1 NGALP, NGALR, NLAVAP, NLAVAR, NCLSTP, NCLSTR

```

```

DATA XLREQ /0.D0/, XODD /0.D0/, XSHORT /0.D0/
DATA NBAY /0/

```

```
CLP = '(CALC)'
```

C THIS FIRST PART CALCULATES THE TOTAL LENGTH REQUIRED TO FIT ALL OF
C THE PASSENGERS, GALLEYS, LAVATORIES, AND CLOSETS AS THOUGH THE BAYS
C WERE ARRANGED END TO END

```

IF (NFABR.EQ.0) NFABR = 4
IF (NBABR.EQ.0) NBABR = 4
IF (NTABR.EQ.0) NTABR = 6
FROWS = DFLOAT(NPF / NFABR)
IF (MOD(NPF,NFABR).NE.0) FROWS = FROWS + 1.D0
BROWS = DFLOAT(NPB / NBABR)
IF (MOD(NPB,NBABR).NE.0) BROWS = BROWS + 1.D0
TROWS = DFLOAT(NPT / NTABR)
IF (MOD(NPT,NTABR).NE.0) TROWS = TROWS + 1.D0
XLREQ = (FROWS * FPITCH + BROWS * BPITCH + TROWS * TPITCH) / 12.D0

```

C GALLEYS, LAVS, AND CLOSETS ARE ASSUMED TO BE PLACE ON EITHER SIDE
C OF AN AISLE, SO THERE ARE ACTUALLY TWICE AS MANY

```

NGALLY = (1 + ((NPF + NPB + NPT) / 100))
NLAVA = (1 + (NPT / 100)) + (1 + ((NPF + NPB) / 60))
NCLSET = (1 + (NPF / 30) + (NPB / 45) + (NPT / 60))
XLREQ = XLREQ + DFLOAT((NGALLY + NLAVA) * 36 + NCLSET * 12) / 12.D0

```

C NOW WE WILL FIGURE OUT HOW MANY BAYS IT WILL TAKE TO FIT EVERYTHING
C INCLUDING THE HORSESHOE AISLE (5 FT.) AND ANY CROSS AISLES (2 FT.)

```

XLREQ = XLREQ + 5.D0
NFUSE = 1
IF (XLREQ.GT.44.5D0) THEN
XLREQ = XLREQ + 7.D0
NFUSE = 2
IF (XLREQ.GT.95.D0) THEN
XLREQ = XLREQ + 7.D0
NFUSE = 3
IF (XLREQ.GT.151.5D0) THEN
XLREQ = XLREQ + 7.D0
NFUSE = 4
IF (XLREQ.GT.214.D0) THEN
XLREQ = XLREQ + 7.D0
NFUSE = 5
ENDIF
ENDIF
ENDIF
ENDIF

```

C CALCULATE DIMENSIONS OF PRESSURIZED CABIN

```

NSUM = 0
DO 10 N = 1, NFUSE
NSUM = NSUM + (N - 1)
10 CONTINUE
XLW = (XLREQ - 6.D0 * DTAN(45.D0 / 57.296D0) *
1 DFLOAT(NSUM)) / DFLOAT(NFUSE)
IF (XLW.LT.38.5D0) XLW = 38.5D0
XLP = XLW + 6.D0 * DTAN(45.D0 / 57.296D0) * DFLOAT(NFUSE)
XLF = XLREQ
IF (XL.LT.1.D0) THEN
XL = XLP / 0.7D0
DF = 0.15D0 * XL
WF = DFLOAT(NFUSE) * 12.D0
ELSE IF (WF.EQ.0.D0 .OR. DF.EQ.0.D0) THEN
WRITE(IU6,190)
RETURN
ENDIF
ENDIF
IF (ACABIN.LT.5.D0) ACABIN = 0.5D0 * WF * (XLP + XLW)

```

C CALCULATE AND PRINT INFORMATION FOR INTERNAL ARRANGEMENT

```

NPFR = NPF
NPBR = NPB
NPTR = NPT
NLAVAR = NLAVA
NCLSTR = NCLSET
NGALR = NGALLY

```



```

NLAVAP = NLAVAP + 1
NLAVAR = NLAVAR - 1
XLNGTH = XLNGTH - 3.D0
ENDIF
IF (XLNGTH .GT. 3.D0) .AND.
1 (NGALP .LT. (1 + ((NFPF + NPBP + NPTP)/100))) .AND.
2 (NGALR .GT. 0)) THEN
  NGALP = NGALP + 1
  NGALR = NGALR - 1
  XLNGTH = XLNGTH - 3.D0
ENDIF
IF (XLNGTH .GT. 1.D0) .AND.
1 (NCLSTP .LT. (1 + (NFPF/30) + (NPBP/45) + (NPTP/60))) .AND.
2 (NCLSTR .GT. 0)) THEN
  NCLSTP = NCLSTP + 1
  NCLSTR = NCLSTR - 1
  XLNGTH = XLNGTH - 1.D0
ENDIF
IF (XLNGTH .GE. TPITCH/12.D0) .AND. (NPTR .GT. NPTP)) GO TO 50
NPTR = NPTR - NPTP

60 CONTINUE

C IF ONE SIDE OF THE BAY IS LONGER THAN THE OTHER (ALWAYS THE CASE
C EXCEPT FOR CENTER BAY WITH ODD NUMBER OF BAYS) THEN WE CAN FILL
C IN THE EXTRA SPACE ALONG THE LONGER WALL

XTRASP = XTRASP + XLNGTH

C FILL IN EXTRA SPACE WITH GALLEYS, LAVATORIES, AND
C CLOSETS FIRST SINCE THERE IS EASY ACCESS FROM
C MULTIPLE BAYS

IF ((XTRASP .GE. 6.D0) .AND. (NLAVAR .GT. 0)) THEN
  NLAVAP = NLAVAP + 1
  NLAVAR = NLAVAR - 1
  XTRASP = XTRASP - 6.D0
ENDIF

```

```

IF ((XTRASP .GE. 6.D0) .AND. (NGALR .GT. 0)) THEN
  NGALP = NGALP + 1
  NGALR = NGALR - 1
  XTRASP = XTRASP - 6.D0
ENDIF
IF ((XTRASP .GE. 2.D0) .AND. (NCLSTR .GT. 0)) THEN
  NCLSTP = NCLSTP + 1
  NCLSTR = NCLSTR - 1
  XTRASP = XTRASP - 2.D0
ENDIF
65 IF ((XTRASP .GE. FPITCH/12.D0) .AND. (NPFR .GT. 0)) THEN
  NPFP = NPFP + (NFABR/2)
  NPFR = NPFR - (NFABR/2)
  XTRASP = XTRASP - FPITCH/12.D0
  GO TO 65
ENDIF
70 IF ((XTRASP .GE. BPITCH/12.D0) .AND. (NPBR .GT. 0)) THEN
  NPBP = NPBP + (NBABR/2)
  NPBR = NPBR - (NBABR/2)
  XTRASP = XTRASP - BPITCH/12.D0
  GO TO 70
ENDIF
75 IF ((XTRASP .GE. TPITCH/12.D0) .AND. (NPTR .GT. 0)) THEN
  NPTP = NPTP + (NBATR/2)
  NPTR = NPTR - (NBATR/2)
  XTRASP = XTRASP - TPITCH/12.D0
  GO TO 75
ENDIF

C CALCULATE THE EFFICIENCY OF BAY (% OF LENGTH USED)

EFFBAY = (XLBAY - XTRASP) * 100.D0 / XLBAY

RETURN
END

```

9.0 Appendix B

Changes to SFAERO.F

Lines of code that have been changed or added are noted in italics.

```

SUBROUTINE DPREP
C DATA FROM FLOPS INPUT NAMELISTS ARE CONVERTED FOR USE IN EDET
IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
COMMON /AWETO / SWETW ,SWETH ,SWETV ,SWETF ,SWETN ,SWETC
COMMON /ACTWET/ SWTWG ,SWTHT ,SWTVT ,SWTFU ,SWTNA ,SWTCN
COMMON /CONFIG/ GW ,AR ,THRUST ,SW ,TR ,SWEEP ,TCA ,
1   VCMN ,CH ,ETIT ,EOPR ,EFPR ,EBPR ,ETTR ,
2   EALT ,VARTH ,ROTVEL ,PLR ,DESRNG ,NDV
COMMON /EDETIN/ CAM ,SBASE ,BL ,XD ,AITEK ,
1   SHT ,TCHT ,ARHT ,TRHT ,HHT ,SVT ,
2   TCVT ,ARVT ,TRVT ,XNAC ,DNAC ,GLOV ,
3   NEW ,NEF ,NFUSE ,NVERT ,ARCAN ,SCAN ,TCCAN
COMMON /CONPON/ NAME(4,100)
COMMON / XLAM /XLLAM ,TRUW ,TRLW ,TRUH ,TRLH ,TRUV ,TRLV ,
1   TRUB ,TRLB ,TRUN ,TRLN ,TRUC ,TRLC
COMMON /MISSA/ AITEKX ,ARX ,CAMX ,CHX ,DB ,BODYLD ,SBASEX ,
1   SPI ,SREF ,SW25 ,TAPER ,TC ,VCMIN ,
2   CDCTAB(20) ,CDF(102) ,CDFCRD(10) ,
3   CDFTAB(20) ,CDITAB(15) ,CDPTAB(20,15),
4   CDREF(20) ,CF(101) ,CL(15) ,
5   CLBUEF(20) ,FF(100) ,FR(100) ,
6   EM(20) ,RN(100) ,SWET(101) ,
7   TRU(100) ,TRL(100) ,EL(100) ,
8   ITAB ,LAM ,MNO ,N ,NCRUD
COMMON / MIMOD /FWID ,MIKE
COMMON / FORT /IFITE
COMMON / WDEF / ETAW(21) ,CHD(21) ,TOC(21) ,SWL(21) ,ETAP(51),
1   PVAL(51) ,ETAE(4) ,PDIST ,PCTL ,ARREF ,TCREF ,
2   NETAW ,NETAP ,NSTD
CHARACTER*4 NAME

C THE NAME ARRAY IS INPUT AND OUTPUT IN THIS SUBROUTINE -
C IT IS CHANGED IF THERE IS MORE THAN ONE FUSELAGE, ETC.
C IT CONTAINS NAMES OF THE AIRCRAFT PARTS

C SWITCH COMMON BLOCKS FOR CONFIGURATION VARIABLES

ARX = AR
SREF = SW
TAPER = TR
SW25 = SWEEP
TC = TCA
VCMIN = VCMN
CHX = CH
CAMX = CAM
SBASEX = SBASE
AITEKX = AITEK
XDX = XD
IF ( MIKE .EQ. 1 ) XDX = FWID

C CALCULATE COMPONENT WETTED AREAS

XMULT = 0.387D0 * TC + 2.D0
XMULTH = 0.387D0 * TCHT + 2.D0
XMULTV = 0.387D0 * TCVT + 2.D0
SPAN = SQRT( ARX * (SREF - GLOV) )
SPANHT = SQRT( ARHT * SHT )
CRHTTB = 0.D0
IF ( SPANHT .GT. 0.D0 ) CRHTTB = 2.D0 * SHT / (SPANHT*(1 + TRHT))
1 + ( (SPANHT/2.D0 - XDX/4.D0)/(SPANHT/2.D0) )*(1.D0 - TRHT) + TRHT
CROOT = ( (SREF - GLOV) * 2.D0 ) / ( (1.D0 + TAPER) * SPAN )
CROTM = ( (SPAN / 2.D0 - XDX / 2.D0) / (SPAN / 2.D0) ) *
1 (1.D0 - TAPER) + TAPER
CROOTB = CROOT * CROTM
SPANVT = SQRT(ARVT * SVT)
CROTVT = 0.D0

IF ( SPANVT .GT. 0.D0 ) CROTVT = 2.D0*SVT / (SPANVT*(1.D0 + TRVT))

C WING
SWET(1) = XMULT * ( SREF - (NFUSE * XDX/2.D0) * (CROOT + CROOTB) )
C FOR BWB, CALCULATE WETTED SURFACE AREA BASED ON WING STATION
DATA
C AND CURVE FIT FROM BOEING DOCUMENT "D6-8195,C6" BY G. CORNING
IF ( IFITE .EQ. 3 .AND. NETAW .GT. 1 ) THEN
  CKT = 2.D0 - 0.03D0*0.15D0 + 4.D0*0.15D0**2 - 9.D0*0.15D0**3
  SWET(1) = CKT*0.5D0*FWID*(2.D0*BL -
1 (FWID/1.4D0)*DTAN(45.D0/57.296D0))
DO 15 I = 1, (NETAW - 1)
  AVGTOC = (TOC(I) + TOC(I+1))/2.D0
  CKT = 2.D0 - 0.03D0*AVGTOC + 4.D0*AVGTOC**2 - 9.D0*AVGTOC**3
  C1 = CHD(I)
  IF (CHD(I) .GT. 5.D0) C1 = CHD(I) * 2.D0/SPAN
  C2 = CHD(I+1)
  IF (CHD(I+1) .GT. 5.D0) C2 = CHD(I+1) * 2.D0/SPAN
  Y1 = ETAW(I)
  IF (ETAW(I) .GT. 1.1D0) Y1 = ETAW(I) * 2.D0/SPAN
  Y2 = ETAW(I+1)
  IF (ETAW(I+1) .GT. 1.1D0) Y2 = ETAW(I+1) * 2.D0/SPAN
  AREAXP = (Y2 - Y1) * (C1 + C2) * SPAN * SPAN * 0.25D0
  SWET(1) = SWET(1) + CKT * AREAXP
15 CONTINUE
ENDIF
CALL ORIDE ( SWET(1),SWETW )
SWTWG = SWET(1)

C HORIZONTAL TAIL
SWET(2) = XMULTH*SHT*(1.D0 - (0.185D0 + NEF*0.063D0)*(1.D0 - HHT))
IF ( MIKE .EQ. 1 ) SWET(2) = XMULTH * SHT
CALL ORIDE ( SWET(2),SWETH )
SWTHT = SWET(2)

C VERTICAL TAIL
SWET(3) = XMULTV * SVT
CALL ORIDE ( SWET(3),SWETV )
SWTVT = SWET(3)

C FUSELAGE
DB = XD / SQRT( ARX * (SREF - GLOV) )
SPI = 3.14159D0 * ( (XD / 2.D0) ** 2 )
NCRUD = 0
BODYLD = 100.D0
IF ( XD .GT. 0.D0 ) BODYLD = BL / XD
SWET(4) = 0.D0
IF ( IFITE .EQ. 3 ) THEN
  SPI = 0.D0
  GO TO 16
ENDIF
IF ( NFUSE .GT. 0 ) SWET(4) = 3.14159D0*XDX**2 * ((BL/XD)-1.7D0) -
1 (0.673D0*CROOTB * (TC * CROOTB)* 2.D0) -
2 ((0.673D0*CRHTTB * (TCHT*CRHTTB)* 2.D0) * (1.D0 - HHT))
3 -(0.673D0*CROTVT * (TCVT*CROTVT))
CALL ORIDE ( SWET(4),SWETF )
16 CONTINUE
SWTFU = SWET(4)

C CHARACTERISTIC LENGTHS
EL(1) = SQRT( (SREF - GLOV) / ARX )
IF ( MIKE .EQ. 1 ) EL(1) = 2.D0*CROOT*(1.D0 + TAPER + TAPER**2)
1 / ( 3.D0 + 3.D0 * TAPER )
EL(2) = 0.D0
IF ( ARHT .GT. 0.D0 ) EL(2) = SQRT(SHT / ARHT)
EL(3) = 0.D0
IF ( ARVT .GT. 0.D0 ) EL(3) = SQRT(SVT / ARVT)

```

```

EL(4) = BL
C FINENESS RATIOS
FR(1) = TC
FR(2) = TCHT
FR(3) = TCVT
FR(4) = BL / XD
C LAMINAR FLOW DATA
LAM = IDINT ( XLLAM + 0.05D0 )
TRU(1) = TRUW
TRL(1) = TRLW
TRU(2) = TRUH
TRL(2) = TRLH
TRU(3) = TRUV
TRL(3) = TRLV
TRU(4) = TRUB
TRL(4) = TRLB
DO 20 I = 5,40
  TRU(I) = 0.D0
  TRL(I) = 0.D0
20 CONTINUE
N = 4 + NEW + NEF
IF ( N .EQ. 4 ) GO TO 50
NN = 100
IF ( NFUSE .GT. 1 ) NN = NN + 1 - NFUSE
IF ( NVERT .GT. 1 ) NN = NN + 1 - NVERT
IF ( SCAN .GT. 0.D0 ) NN = NN - 1
IF ( N .GT. NN ) N = NN
C NACELES
SWTNA = 0.D0
DO 40 I = 5,N
  SWET(I) = 2.8D0 * DNAC * XNAC
  CALL ORIDE ( SWET(I),SWETN )
  SWTNA = SWTNA + SWET(I)
  EL(I) = XNAC
  TRU(I) = TRUN
  TRL(I) = TRLN
DO 30 J = 1,4
  NAME(J,I) = NAME(J,5)
30 CONTINUE
IF ( DNAC .GT. 0. ) FR(I) = XNAC / DNAC
40 CONTINUE
50 IF ( NFUSE .LE. 1 .OR. IFITE .EQ. 3 ) GO TO 80
C MULTIPLE FUSELAGES
IF ( IFITE .EQ. 3 ) GO TO 80
DO 70 I = 2,NFUSE
  N = N + 1
  SWET(N) = SWET(4)
  SWTFU = SWTFU + SWET(N)
  EL(N) = EL(4)
  FR(N) = FR(4)
  DO 60 J = 1,4
    NAME(J,N) = NAME(J,4)
60 CONTINUE
  TRU(N) = TRU(4)
  TRL(N) = TRL(4)
70 CONTINUE
80 IF ( NVERT .LE. 1 ) GO TO 110
C MULTIPLE VERTICAL TAILS
DO 100 I = 2,NVERT
  N = N + 1
  SWET(N) = SWET(3)
  SWTVT = SWTVT + SWET(N)
  EL(N) = EL(3)
  FR(N) = FR(3)
  DO 90 J = 1,4
    NAME(J,N) = NAME(J,3)
90 CONTINUE
  TRU(N) = TRU(3)
  TRL(N) = TRL(3)
100 CONTINUE
110 IF ( SCAN .LE. 0.D0 ) RETURN
C CANARD

```

```

N = N + 1
XMULTC = 0.387D0 * TCCAN + 2.D0
SWET(N) = XMULTC * SCAN
CALL ORIDE ( SWET(N),SWETC )
SWTCN = SWET(N)
EL(N) = 0.D0
IF ( ARCAN .GT. 0.D0 ) EL(N) = SQRT(SCAN / ARCAN)
FR(N) = TCCAN
NAME(1,N) = 'CANA'
NAME(2,N) = 'RD '
TRU(N) = TRUC
TRL(N) = TRLC
RETURN
END
SUBROUTINE CDFF (ALT, AMCH, ANS, IPRINT)
C *****
C * * * * *
C * SKIN FRICTION SUBROUTINE * * * * *
C * * * * *
C ALT ALTITUDE
C AMCH MACH NUMBER
C ANS SKIN FRICTION DRAG COEFFICIENT
C IPRINT PRINT SWITCH
IMPLICIT DOUBLE PRECISION ( A-H, O-Z )
COMMON /CONPON/ NAME(4,100)
COMMON /UNITS / IU5, IU6, IU7, IU8, IU9, IU16, IU17, IU18
COMMON /MISSA/ AITEK ,AR ,CAM ,CH ,DB ,BODYLD,SBASE ,
1 SPI ,SREF ,SW25 ,TAPER ,TC ,VCMIN ,
2 CDCTAB(20) ,CDF(102) ,CDFCRD(10) ,
3 CDFTAB(20) ,CDITAB(15) ,CDPTAB(20,15),
4 CDREF(20) ,CF(101) ,CL(15) ,
5 CLBUF(20) ,FF(100) ,FR(100) ,
6 EM(20) ,RN(100) ,SWET(101) ,
7 TRU(100) ,TRL(100) ,EL(100) ,
8 ITAB ,LAM ,MNO ,N ,NCRUD
COMMON /FORT / IFITE
CHARACTER*4 NAME
DIMENSION F(25)
DATA F / 11*0.D0, 4.34255D0, -1.14281D0, .171203D0, -.0138334D0,
1 .621712D-3, .137442D-6, -1.45532D-4, 2.94206D0,
2 7.16974D0, 48.8876D0, -1403.02D0, 8598.76D0, -15834.3D0,
3 4.275D0/
CDF(102) = 0.0D0
ANS = 0.0D0
SWET(101) = 0.0D0
C LOOP ON NUMBER OF COMPONENTS
DO 20 I = 1,N
  IF ( SWET(I) .LT. 0.D0 ) SWET(I) = 0.D0
  IF ( EL(I) .LE. 0.D0 ) THEN
    FF(I) = 1.D0
    FR(I) = 1.D0
    RN(I) = 0.D0
    CF(I) = 0.D0
    CDF(I) = 0.D0
    GO TO 20
  ENDIF
  CALL CFF ( ALT,EL(I),AMCH,CF(I),RN(I) )
  IF ( LAM .EQ. 1 )
1 CF(I) = CF(I) - 0.5D0 * (CF(I) - 1.328D0/SQRT(RN(I)))
2 *(TRU(I)*(0.0064164D0 + TRU(I)*(0.48087D-4 - 0.12234D-6*TRU(I)))
3 + TRL(I)*(0.0064164D0 + TRL(I)*(0.48087D-4 - 0.12234D-6*TRL(I))))
C FORM FACTOR FOR BODIES
IF ( FR(I) .GT. 0.5D0 ) THEN
  FF(I) = F(12) + FR(I) * (F(13) + FR(I) *
1 ( F(14) + FR(I) * (F(15) + FR(I) * ( F(16) + FR(I) *
2 ( F(17) * FR(I) + F(18) ) ) ) ) )
  IF ( FR(I) .GE. 20.0D0 ) FF(I) = 1.0D0
ELSE
C FORM FACTORS FOR SURFACES
FF1 = 1.D0 + FR(I)*(F(19) + FR(I)*(F(20) + FR(I)*(F(21) +

```

```

1   FR(I) * (F(22) + FR(I) * (F(23) + FR(I) * F(24))))))
   FF2 = 1.D0 + FR(I) * F(25)
   FF(I) = FF1 * (2.D0 - AITEK) + FF2 * (AITEK - 1.0D0)
ENDIF

```

```

C   CALCULATE EQUIVALENT FLAT PLATE DRAG FOR BWB BASED ON
C   AVERAGE FRICTION COEFFICIENT, REF: D6-7161

```

```

IF ( IFITE .EQ. 3 .AND. I .EQ. 1 ) THEN

```

```

   CF1 = 9.9319121E-6 * (DLOG10(RN(I)))**4 -
1   3.5505523E-4 * (DLOG10(RN(I)))**3 +
2   0.0048349D0 * (DLOG10(RN(I)))**2 -
3   0.0301837D0 * DLOG10(RN(I)) + 0.0752314D0
   CF2 = 1.22917E-5 * (DLOG10(RN(I)))**4 -
1   4.26806E-4 * (DLOG10(RN(I)))**3 +
2   0.0056315D0 * (DLOG10(RN(I)))**2 -
3   0.03396D0 * DLOG10(RN(I)) + 0.0813276D0
   CF(I) = (0.9D0-AMCH)/0.9D0 * CF1 + AMCH/0.9D0 * CF2
   FF(I) = 1.D0
ENDIF

```

```

CDF(I) = SWET(I) * CF(I) * FF(I) / SREF
ANS = ANS + SWET(I) * CF(I) / SREF
CDF(102) = CDF(102) + CDF(I)
SWET(101) = SWET(101) + SWET(I)

```

```

20 CONTINUE

```

```

IF ( IPRINT .GT. 10 ) RETURN
CDF(101) = 0.06D0 * CDF(102)
IF ( NCRUD .EQ. 0 ) GO TO 40

```

```

C   ADD DRAG FOR EXCRESCENCES

```

```

DO 30 I = 1, NCRUD
   CDF(102) = CDF(102) + CDFCRD(I)
30 CONTINUE

```

```

40 ANS = CDF(102) + CDF(101)
   CFAVG = ANS * SREF / SWET(101)

```

```

C   PRINT RESULTS

```

```

IF ( IPRINT .EQ. 0 ) RETURN
WRITE(IU6, 80)
WRITE(IU6, 90) VCMIN, ALT, SREF, AITEK
WRITE(IU6, 100)
DO 50 I = 1, N
   TEMP = RN(I) * 1.0D-6
   WRITE(IU6, 110) (NAME(J,I), J = 1,4), SWET(I), EL(I), FR(I),
1   FF(I), TEMP, CF(I), CDF(I)
50 CONTINUE
IF ( NCRUD .EQ. 0 ) GO TO 70
DO 60 I = 1, NCRUD
   WRITE(IU6, 120) CDFCRD(I)
60 CONTINUE
70 CONTINUE
WRITE(IU6, 130) CDF(101)
WRITE(IU6, 140) SWET(101), CFAVG, ANS
RETURN

```

```

80 FORMAT (' MACH NUMBER   ALTITUDE   REFERENCE AREA',5X,
1   'TECHNOLOGY LEVEL')
90 FORMAT ( F9.2,F15.0,' FT',F13.2,' SQ FT',F15.2 / )
100 FORMAT ( 3X,'COMPONENT',14X,'SWET',6X,'LENGTH   FINENESS',
1   5X,'FORM',7X,'RN',7X,'CF   CDF',26X,'SQ FT',
2   7X,'FT',8X,'RATIO',5X,'FACTOR   MILLIONS' )
110 FORMAT ( 1X,4A4,F14.2,F11.2,F11.4,F11.3,F9.1,2F11.5 )
120 FORMAT ( ' EXCRESCENCE',73X,F10.5 )
130 FORMAT ( ' MISCELLANEOUS',71X,F10.5 )
140 FORMAT ( / ' TOTAL',10X,F14.2,42X,2F11.5 )
END

```

10.0 Appendix C

FLOPS input file for 468-pax BWB

468 passenger BWB - Based on
Boeing BWB450-1U, Karl Geiselhart

\$OPTION

MPRINT=1,
IOPT=1,
IANAL=3,
INENG=1,
ICOST=0,
ITAKOF=0,
ILAND=0,
NOPRO=0,
NOISE=0,
IFITE=3,
IXFL=1,
IPOLP=0,
IPLTTH=0,
\$END

\$WTIN

DGW=874099,
VMMO=0.85,
DIH=3,
FLAPR=0.333,
GLOV=121.05,
VARSWP=0,
FCOMP=1,
FAERT=0,
FSTRT=0,
NETAW=14,

ETAW=0.35,0.4,0.45,0.5,0.55,0.6,0.6
499,0.7,0.75,
0.8,0.85,0.8999,0.95,1,

CHD=58.03,0.4491,0.3884,0.3317,0.2
886,0.2537,0.2269,0.2121,0.1983,

0.1843,0.1704,0.1565,0.1426,0.1287,

TOC=0.15,0.1132,0.0928,0.0822,0.07
64,0.0742,0.0746,0.0758,0.0758,0.075
6,

0.0756,0.0758,0.076,0.076,
SWL=0,0,0,0,0,0,0,42.9,42.9,
42.9,42.9,42.9,42.9,42.9,0,0,0,0,
0,
SHT=0,
SWPHT=0,
ARHT=0,
TRHT=0,

TCHT=0,
NVERT=0,
NFIN=2,
SFIN=184.89,
ARFIN=1.952,
TRFIN=0.464,
SWPFIN=39.42,
TCFIN=0.08,
NFUSE=0,
XL=0, (XL=137.5 for fixed geom.)

WF=64.58,
DF=17,
XLP=40,
ACABIN=0,
FPITCH=61,
NFABR=4,
BPITCH=39,
NBABR=4,
TPITCH=32,
NTABR=6,
XMLG=85,
XNLG=87,
CARBAS=0,
NEW=0,
NEF=3,
THRSO=86459.2,
WENG=22017,
EEXP=1,
WINL=0,
XNAC=17.433,
DNAC=12.608,

NPF=28,
NPB=100,
NPT=340,
NSTU=22,
NFLCR=2,
CARGF=0,
FRWI=1,
FRHT=1,
FRVT=1,
FRFU=1,
FRNA=0,
WTHR=0,
WPMSC=0,
WHYD=1,
WAVONC=1,
WFURN=1,
ISPOWE=0,
\$END

\$SCONFIN

DESRNG=7750,
OFG=1,
OFF=0,
GW=874099,
AR=7.557,0,
THRUST=70000,1,0,0,0,0,
SW=7621.66,1,
TR=0.311,
SWEEP=35.7,
TCA=0.11,
VCMN=0.85,
CH=39000,
\$END

\$AERIN

MYAERO=0,
ITPAER=2,
CAM=2,
AITEK=2,
XLLAM=0,
E=0,
WRATIO=0.8,
VAPPR=140,
FLTO=11000,
FLLDG=11000,
THROFF=0.25,
\$END

\$ENGDIN

IGENEN=-1,
EIFILE='baseline engine',
IDLE=1,
MAXCR=1,
NOX=1,
\$END

\$MISSIN

FCDO=1,
FCDI=1,
ISKAL=1,
IFLAG=2,
MSUMPT=1,
IRW=2,
IATA=0,
NPCON=1,
TAKOTM=2,
TAXOTM=9,
APPRTM=4,
TAXITM=5,
ITTFF=1,
NCLIMB=1,

CLAMIN=0,
FWF=-0.001,
NCRUSE=3,
IOC=1,4,4,
CRMACH=0.85,0.6,0,
CRALT=45000,25000,1500,
RCIN=300,
IVS=1,
DEAMIN=0,
IRS=1,
RESTRP=0.05,
TIMMAP=2,
ALTRAN=200,
NCLRES=1,
NCRRES=2,
HOLDTM=30,
NCRHOL=3,

IHOPOS=1,
THOLD=0.1,
NCRTH=1,
\$END
START
CLIMB
CRUISE
DESCENT
END

\$PCONIN
CONALT=35000,
CONMCH=0.85,
CONPC=1,
ICONSG=2,
CONLIM=300,
ICONTP=5,

\$END

\$RERUN
\$END

\$MISSIN
IRW=1,
NPCON=0,
\$END
START
CLIMB
CRUISE
DESCENT
END

FLOPS input file for 600-pax BWB

<p>571 passenger BWB - Based on UEET design, CR-2002-211754</p> <p>\$OPTION MPRINT=1, IOPT=1, IANAL=3, INENG=1, ICOST=0, ITAKOF=0, ILAND=0, NOPRO=0, NOISE=0, IFITE=3, IXFL=1, IPOLP=0, IPLTTH=0, \$END</p> <p>\$WTIN DGW=1076000, VMMO=0.855, DIH=3, FLAPR=0.333, GLOV=0, SPAN=253.75, VARSWP=0, FCOMP=1, FAERT=0, FSTRT=0, NETAW=14, ETAW=0.35,0.4,0.45,0.5,0.55,0.6,0.6499,0.7,0.75, 0.8,0.85,0.8999,0.95,1, CHD=58.03,0.4491,0.3884,0.3317,0.2886,0.2537,0.2269,0.2121,0.1983, 0.1843,0.1704,0.1565,0.1426,0.1287, TOC=0.15,0.1132,0.0928,0.0822,0.0764,0.0742,0.0746,0.0758,0.0758,0.0756, 0.0756,0.0758,0.076,0.076,0.076, SWL=0,0,0,0,0,0,0,42.9,42.9, 42.9,42.9,42.9,42.9,42.9,0,0,0,0, 0, SHT=0, SWPHT=0, ARHT=0, TRHT=0, TCHT=0,</p>	<p>NVERT=0, NFIN=2, SFIN=184.89, ARFIN=1.952, TRFIN=0.464, SWPFIN=39.42, TCFIN=0.08, NFUSE=0, XL=0, WF=0, DF=0, XLP=0, ACABIN=0, FPITCH=61, NFABR=4, BPITCH=39, NBABR=4, TPITCH=32, NTABR=6, XMLG=85, XNLG=87, CARBAS=0, NEW=0, NEF=3, THRSO=86459.2, WENG=22017, WINL=0, XNAC=17.433, DNAC=12.608, NPF=33, NPB=110, NPT=428, NFLCR=2, CARGOF=0, FRWI=1, FRHT=1, FRVT=1, FRFU=1, FRNA=0, WTHR=0, WPMSC=0, WHYD=1, WAVONC=1, WFURN=1, ISPOWE=0, \$END</p> <p>\$SCONFIN DESRNG=7100, OFG=1, OFF=0, GW=1076000, THRUST=96000,1,0,0,0,0,</p>	<p>SW=7700,1, TR=0.311, SWEEP=35.7, TCA=0.11, VCMN=0.855, CH=39000, \$END</p> <p>\$AERIN MYAERO=0, ITPAER=2, CAM=2, AITEK=2, XLLAM=0, E=0, WRATIO=0.8, VAPPR=140, FLTO=11000, FLLDG=11000, THROFF=0.25, \$END</p> <p>\$COSTIN \$END</p> <p>\$ENGDIN IGENEN=-1, EIFILE='baseline engine', IDLE=1, MAXCR=1, NOX=1, \$END</p> <p>\$MISSIN FCDO=1, FCDI=1, ISKAL=1, IFLAG=2, MSUMPT=1, IRW=2, IATA=0, NPCON=1, TAKOTM=2, TAXOTM=9, APPRTM=4, TAXITM=5, ITTF=1, NCLIMB=1, CLAMIN=0, FWF=-0.001, NCRUSE=3, IOC=1,4,4, CRMACH=0.855,0.6,0,</p>
---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

CRALT=45000,25000,1500,
RCIN=300,
IVS=1,
DEAMIN=0,
IRS=1,
RESTRP=0.05,
TIMMAP=2,
ALTRAN=200,
NCLRES=1,
NCRRES=2,
HOLDTM=30,
NCRHOL=3,
IHOPOS=1,
THOLD=0.1,
NCRTH=1,

\$END
START
CLIMB
CRUISE
DESCENT
END

\$PCONIN
CONALT=35000,
CONMCH=0.85,
CONPC=1,
ICONSG=2,
CONLIM=300,
ICONTP=5,
\$END

\$RERUN
\$END

\$MISSIN
IRW=1,
NPCON=0,
\$END
START
CLIMB
CRUISE
DESCENT
END

REPORT DOCUMENTATION PAGE

*Form Approved
OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 01-09-2004	2. REPORT TYPE Contractor Report	3. DATES COVERED (From - To)
--------------------------------------------------	--------------------------------------------	-------------------------------------

4. TITLE AND SUBTITLE A Sizing Methodology for the Conceptual Design of Blended-Wing-Body Transports	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Kevin R. Bradley	5d. PROJECT NUMBER NCC1-03006
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 23-319-30-02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199	8. PERFORMING ORGANIZATION REPORT NUMBER
The George Washington University JIAFS 303 Butler Farm Rd. Suite 106a Hampton, VA 23666	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	10. SPONSOR/MONITOR'S ACRONYM(S) NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA/CR-2004-213016

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 05
Availability: NASA CASI (301) 621-0390 Distribution: Nonstandard

13. SUPPLEMENTARY NOTES
The information submitted in this report was offered as a major report by the author in partial fulfillment of the requirements for the Degree of Master of Science, The George Washington University, JIAFS. Langley Technical Monitor: William M. Kimmel

14. ABSTRACT
This paper describes the development of a methodology for sizing Blended-Wing-Body (BWB) transports and how the capabilities of the Flight Optimization System (FLOPS) have been expanded using that methodology. In this approach, BWB transports are sized based on the number of passengers in each class that must fit inside the centerbody or pressurized vessel. Weight estimation equations for this centerbody structure were developed using Finite Element Analysis (FEA). This paper shows how the sizing methodology has been incorporated into FLOPS to enable the design and analysis of BWB transports. Previous versions of FLOPS did not have the ability to accurately represent or analyze BWB configurations in any reliable, logical way. The expanded capabilities allow the design and analysis of a 200 to 450-passenger BWB transport or the analysis of a BWB transport for which the geometry is already known. The modifications to FLOPS resulted in differences of less than 4 percent for the ramp weight of a BWB transport in this range when compared to previous studies performed by NASA and Boeing.

15. SUBJECT TERMS
Blended-Wing-Body, Transport Aircraft, Aircraft Design

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 39	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (301) 621-0390