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n 9 5 i0 3 6nasa contractor report 4447 advanced composite structural concept material technology primary aircraft structure design cid 0 manufacturing concept assessment robert l chu bayha h davis j e ingram j g shukla lockheed aeronautical system company marietta georgia prepared langley research center contract nas1 18888 n sa national aeronautics space administration office management scientific technical information program 1992foreword final technical report cover work performed phase evaluation initial development task 1 design manufacturing concept assessment nasa contract nas1 18888 entitled advanced composite structural concept material technology primary aircraft structure may 1989 may 1992 contract administered management direction dr john g davis technical direction dr randall c davis nasa spo nasa langley research center hampton virginia 23665 lockheed aeronautical system company lasc prime contractor mr c jackson lasc program manager directing contract activity mr ron barrie advanced structure material division technical thrust leader performance task key lasc contributor trade study task listed preliminary design trade study robert l chu jay shukla hu davis structural concept development robert l chu tom bayha iii itable content foreword ii vii list figure list table ix abbreviation xl xiii summary 1 0 introductior 1 2 0 preliminary design trade study 4 2 1 baseline wing fuselage 4 2 2 design study wing concept 4 2 2 1 modular wing 11 2 2 2 resin transfer molded wing 20 2 2 3 automatic tow placed wing 25 29 2 2 4 braided wing 2 3 design study fuselage concept 31 2 3 1 sandwich fuselage 38 2 3 2 geodesic fuselage 45 2 3 3 stiffened shell fuselage 49 52 2 4 cost trade study 2 4 1 cost estimating rule methodology 52 2 4 2 cost comparison contributor 54 2 4 2 1 wing design manufacturing concept 54 2 4 2 2 material cost sensitivity study 59 2 4 2 3 wing spar trade study 60 2 4 2 4 fuselage design manufacturing concept 60 2 5 weight trade study 69 2 5 1 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modulus fiber msi e1 c longitudinal compressive modulus fiber msi f fuselage station g12 inplane shear modulus msi gr ep graphite epoxy gt shear modulus thickness msi nx load x direction ib load shear ib nxy outer wing station applied load ib pa critical load ib pc r pmi polymethacrylimide applied distributed load ib qa critical distributed load ib qc r rfi resin film infusion rtm resin transfer molding sow statement work ply thickness tply wd weight cost design wf weighing factor wg weight cost goal xi preceding page blank f_ot f_lmed jgreek stiffener angle geodesic panel degree et tensile strain i_in n compressive strain i_in ec 71 2 shear strain i_in n v poisson ratio xiisummary final report cover work performed phase task 1 advanced composite structural concept material technology primary structure contract part nasa act program focus task develop advanced composite wing fuselage concept using emerging technology order reduce overall cost subtask 1 initial assessment ranking four 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program focus resin transfer molding automated fiber placement textile structure therefore subtask 2 terminated lockheed effort redirected textile structure development xiii1 0 introduction use graphite epoxy conventional medium primary secondary structure demonstrated save weight compared conventional metal structure meet strength stiffness durability requirement transport aircraft commercial airline service also true military transport aircraft however full potential composite material yet realized primarily cost saving demonstrated conjunction efficient structural concept advanced composite technology act program initiated provide creative research new innovative structural concept particular concept wing fuselage primary structure achieve potential future transcentury aircraft new structural concept take advantage improved organic matrix material new emerging fabrication technique validated structure technology developed act program necessary provide confidence essential use composite material future primary aircraft structure lockheed contract consists two phase phase evaluation initial development initiated may 1989 ran may 1992 phase ii development verification technology initiated october 1991 scheduled run april 1995 total program extends 72 month phase consisted five task task 1 design manufacturing concept assessment task 2 structural response failure analysis task 3 advanced material concept task 4 assessment review task 5 composite transport wing technology development phase ii consists four task task 1 advanced resin system textile technology task 2 preform development processing task 3 design analysis fabrication test task 4 low cost fabrication development program master schedule shown figure 1 phase completed final report published task 1 2 3 task 4 assessment phase result plan for1989 1990 1991 1992 mj j son_j f mamj j son e j f j j ondj f j 1 2 3 4 5 6 7i 8 9 10 11 1 13 14 1 516 17 18 1 20 21 22 23 24 2 5 627 8 29 30 31 32 33 34 35 363 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task report oral review conducted acquaint aircraft industry government progress program use commercial product name manufacturer report constitute official endorsement product manufacturer either expressed implied national aeronautics space administration 32 0 preliminary design trade study 2 1 baseline wing fuselage baseline aircraft selected study lockheed tristar l 1011 commercial transport aircraft baseline selected extensive load cost weight data available l 1011 modern design representing current aluminum design technology manufacturing methodology baseline wing l 1011 baseline wing design shown figure 2 swept tapered wing approximately 1000 inch long upper surface skin splice z section spanwise stiffener lower surface continuous j section stiffener typical rib spacing 26 inch component mechanically joined conventional method form wing assembly load design criterion taken ows 151 10 discussed detail section 2 2 baseline fuselaae l 1011 baseline fuselage shown figure 3 composed 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analysis omitted design detail joint cutout taper effect although item may major cost weight driver omitted initial assessment ranking subtask addressed later structural concept development subtask see section 3 0 concept developed similar level detail provide meaningful comparison wing concept labeled atp braided modular rtm representing basic manufacturing approach concept although modular concept restricted one particular manufacturing approach developing concept restriction placed choice material material form process structural arrangement design started blank sheet approach thermoset thermoplastic material acceptable material form considered various application however cost issue generally drove material selection away thermoplastic toward thermosets emphasis placed automated autoclave process reduce hand labor manufacturing cost tooling requirement considered emphasis reducing recurring cost tooling cost amortized production run concept developed using design manufacturing integration dim team approach order develop design timely efficient manner engineering discipline design stress manufacturing producibility material process quality involved early design cycle throughout design phase actually drove concept final design configuration engineering discipline provided input design ensure viable producible supportable dim team developed design package consisted concept drawing material selection list manufacturing plan quality assurance plan completed design package submitted cost weight analysis estimated cost weight compared baseline cost weight determine concept best satisfied program goal see section 2 7

7wing stress analysis structural sizing trade study conducted support evaluation four composite wing box concept sizing effort involved determining concept optimum minimum weight dimension wing cover rib spar weight comparison could made basis entire wing box cross section four wing box concept considered trade study filament wound integral blade stiffener ii resin transfer molded integral stiffener iii modular design consisting automated fiber placement skin stiffened co bonded pultruded blade stiffener filament wound spar press formed rib iv braided integral hat stiffener design criterion sizing wing concept summarized table 1 design load shown upper cover load taken l 1011 wing box analysis specifically internal load used outer wing station ows 151 0 result 1 33 g aileron roll condition optimum cover cross section determined conducting parametric study three stiffener cross section analyzed varying stiffener spacing rib spacing skin laminate type parametric analysis summarized table 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0197 0197 0203 0216 0214 0215 0219 0224 0247 0241 0238 0238 0243 j 0192 0193 0197 0206 0208 0206 0208 0210 0216 0223 0226 0224 0226 0230 0233 0227 0238 hat 0176 0175 o0176 0187 0184 0184 0205 0196 0196 single value indicatesthat condition satisfied condition 2 two value given uppervalue condition1 table 4 areal weight summary cover pasco condition 3 stiffener 20 inch rib spacing 20 inch ribspacing 20 inch rib spacing spacing 4 5 6 7 8 4 5 6 7 8 5 6 7 8 blade 0223 0220 0221 0225 0227 0239 0234 0234 0245 0249 0269 0262 0256 0264 0264 j 0213 0212 0213 0210 0216 0229 0228 0228 0230 0233 0246 0245 0244 0246 0248 hat single value indicatesthat condition satisfied condition 2 two value given uppervalue iscondition 1 0 030 _ f _ _ _ _ _ _ _ _ _ l _ ii ii ili ii _j iiiii iiji_i _ _ il_ _ ih _ l l l ii ill 0 029 _ _ _iii il llq _ il_l _ __ p _ _ iillli_ _ 0 028 _ 2 _ _ 7_ r_i ii l _ _ _i _ _ 0 027 3 4 5 6 7 8 9 stringer spacing figure 4 pasco condition 3 blade stiffened panel rib weight 0 0278 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0268 0267 0267 0269 0272 0276 0275 0274 0276 0278 hat 35 blade 5713419 ii 21 skin 33 57 10 i_ 6 17 _ figure 6 optimized upper cover cross section modular wing box concept mechanically assembled see figure 7 design approach kept size individual component within manageable proportion allowed variety low cost fabrication method utilized cost benefit achieved use large one piece component optimal fabrication method sufficient offset additional assembly cost futher help reduce cost automated manufacturing technique selected wherever possible upper lower cover designed continuous blade stiffener running along entire span wing two stiffener configuration considered namely j hat section stiffener configuration stiffener spacing could increased decreasing total number stiffener required added complexity manufacturing assembly cost effective one concern composite stiffened skin design peeling separation stiffener skin load particularly post buckled structure concept shown figure 8 resolved 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600 300 300 load ib two configurational constraint imposed upon optimization manufacturing consideration first restriction height truss core greater 44 inch combination facing total section exceed 50 inch depth second restriction pitch truss tube could exceed 1 5 inch gave minimum corner angle approximately 36 degree minimum gage requirement sized facing panel optimization seven ply verification resulting configuration analyzed panel buckling using bosor4 program 10 inch panel width used analysis good agreement panda2 bosor4 eigenvalue achieved additional sizing study conducted without geometric constraint develop pure weight optimized configuration minimum gage still maintained facing analysis panel configuration resulting two sizing study shown figure 21 geodesic fuselaae 33t 6 ply 7 ply case 1 2 dim 590 307 dim b 1 50 5 15 figure 21 sandwich panel sizing result figure 22 show general configuration geodesic stiffened panel definition design variable used sizing study spacing 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bay missing skin wrap ply made toughened epoxy intermediate modulus fiber mechanical property used sizing analysis e1 22 4 msi et 6000 llin e2 1 5 msi ec 4300 ilin g12 59msi 1 12 12000 l_in v 30 p 057 ib 3 tply 0051 ply estimated im7 filcoat material stiffener following property e1 11 0 msi et 9800 _in f_2_ 9msi ec 8800 ilin g12 4 msi 3 12 16000 i_in v 30 rule mixture 50 50 tape syntactic core laminate minimum weight configuration resulted following set value design variable ref figure 22 o_ 48 25 b 1 25 07 14 57 29 37stiffened shell fuselaae analysis fuselage concept frame spacing 20 inch retained stiffener configuration selected hat section hat angle set 60 manufacturing consideration remaining dimension height thickness spacing etc allowed vary optimization analysis material system considered concept hybrid hercules as4 im7 graphite fiber hercules 8552 toughened epoxy combination believed provide best balance mechanical property processibility cost panel optimized design load previously shown table 11 using lockheed pasco program final dimension resulting analysis shown figure 25 13_ 38 48 15 185 _ 7 87 i55 3_ j l ____ _1 22 1 60 _ _1 3 38 _ 3 87 figure 25 stiffened shell fuselage stiffener configuration 2 3 1 sandwich fuselaae concept 38the sandwich fuselage concept see figure 26 developed order take advantage structural characteristic sandwich construction high stiffness weight ratio design feature concept good load transfer face sheet redundant load path smooth outer mold line oml fastener penetration relatively simple circumferential spice resin transfer molded frame tri axial braided pultruded triangular stiffener sandwich construction developed placing triangular tube side side covering face sheet tube serve two purpose act core material separate face sheet also function stringer providing longitudinal stiffness approach provides failsafe design multiple load path one main benefit tubular core allowed excellent load transfer face sheet also circumferential frame outer skin frame attach point tube added integral flange frame attachment provided direct load path outer face sheet see figure 27 flange also act iongeron providing additional stiffness frame attached skin clip mechanical fastener using approach mechanical fastener penetrate fuselage skin eliminates pressure sealing requirement fastener eliminating fastener reduced cost eliminating need expensive countersunk fastener also provided smooth oml surface braiding eliminated section 2 2 4 consideration braided wing concept could considered smaller component braiding process selected manufacture basic triangular tube flanged triangular tube braiding automated efficient process manufacture relatively small component tri axial braiding selected order produce tube fiber 0 direction well 45 direction allows core act longitudinal stiffener well typical core material shear addition triangular tube bulb material see figure 28 reduce stress concentration corner eliminate possible void area braided preforms made prepreg tow pultruded advance resin rigidized stable shape u shaped inner skin similarly pultruded braided preform basf im7 5225 towpreg previously successfully braided pultruding line braiding also cost effective 39operation pultruding dry braided woven stitched preforms shell 9310 type epoxy system may alternate approach pultruding braided prepreg feasible figure 26 sandwich fuselage concept figure 27 core element integral flange 40some triangle flange corner figure 28 schematic tube filler corner triangular mandrel braided tube fly away mandrel rohacell polymethacrylimide pmi foam another expanded polymer foam similar property withstand 100 psi 350 f cure autoclave cycle removable metal mandrel silicone rubber mandrel expansion hole option considered fabrication manufacturing plan proposed two option assembly fuselage skin core option us female tool requires skin automatic tape laid cured separately spraying layer adhesive skin placing triangular tube side side form first section flanged tube see figure 29 adhesive sprayed mating surface prior final placement initial tubular section position inner skin added flanged tube process repeated form two fuselage section subsequently bagged cured joined form circular section mandrel removed fabrication option b proposed male tool allowed entire circumference made one inner skin segment placed tool 41sprayed adhesive triangular tube added flanged end inner skin segment see figure 30 integrally outer skin atl f_ale assembly figure 29 female tooling concept _ _ 4 _ _ _ _ _ _ _ _ _ _ _ _ l _ _ 4 _ _ _ k bos male tool fit groove tooling block figure 30 male tooling concept 42flanged tube added end skin segment next inner skin segment added note layer adhesive added prior placing tube sequence repeated inner skin segment triangular tube placed final operation automatic tape laying atl outer skin bag cure assembly tooling concept triangular flanged tube fabrication may similar one described option discussed sandwich fuselage design resin transfer molded circumferential frame shown figure 31 final configuration frame approach f frame configuration integral shear tab attachment fuselage attachment accomplished angle clip fastened standing flange flanged triangular core tube design approach allows entire fuselage made fastener penetrating skin fuselage section figure 31 f frame configuration 43the fuselage skin fastener penetration fuselage splice shown figure 32 butt splice used outer skin core inner skin cut back transfer load outer skin additionally iongerons spliced bath tub fitting attach skin standing flange triangular tube bath tub fitting made stretch forming long discontinuous fiber thermoplastic sheet increased material cost thermoplastic material traded case increased flexibility stretch forming process fw e w _ mlanr_ ulkr tube _ v ic ivl f r_ zzz z _ figure 32 proposed fuselage splice summary material chosen component along manufacturing method shown table 12 table 12 material selection fabrication method sandwich fuselage concept material selection summary mf gmethod mat l selected comment triangular tube briading im7 5225 towpreg triangular tube pultrusion im7 5225 towpre g flange towpreg stui er pultr usion im 7 5225 towpreg inner skin channel pultrusion im7 5225 itowpreg ou er skin atp atl im 7 5225 towpreg frame resin film infusion im7 preform 8552 resin autocomp bathtub fitting matched mold forming aligned discontinuous pei 442 3 2 geodesic fuselaae concedt geodesic fuselage concept shown figure 33 feature completely co cured fuselage assembly continuous helical stiffener excellent damage tolerance characteristic fastener penetration pressure shell circumferential stiffener added allow frame attachment note circumferential stiffener discontinuous order allow helical stiffener continuous figure 33 geodesic fuselage concept 45around fuselage section permit use automated manufacturing process automated tape laying helical stiffener wrapped assist stabilizing stiffener provide shear path skin geodesic fuselage concept take advantage lockheed hysol developed material system filcoat composed layer graphite thermoset prepreg layer syntactic material joined form two layer tape ideally suited manufacture lapping structure forming helical stiffener tape laid lapping layer layer manner causing doubling thickness intersection node point doubling thickness intersection normally requires material spread laid eliminate doubling effect one layer discontinuous using filcoat material eliminates doubling thickness effect allowing syntactic material squeezed intersection form solid layer graphite epoxy construction stiffener section node alternating layer gr ep syntactic material see figure

34 main drawback composite geodesic design difficult join splicing fuselage section geodesic stiffener complicated large number stiffener tolerance associated stiffener location lack tapering capability stiffener section one major area concern geodesic fuselage investigated structural concept development part task another concern geodesic concept requirement stiffener covered wrapped greatly increase manufacturing complexity cost due lack fiber continuity stiffener skin interface wrapping stiffener needed increase bond area stiffener skin manufacturing stiffener wrap accomplished pultruding prepreg cutting pultruded segment proper size placing wrap recess fuselage mandrel intersection point see figure 35 stiffener wrap extend made woven preform resin transfer molded placed fuselage mandrel subsequent co bonding 46alternating layer graphite expoxy syntactic material figure 34 stiffener build filcoat material two ply shown previously discussed circumferential stiffener discontinuous intersection point manufacturing circumferential stiffener best accomplished curved pultrusion fiber preform resin infusion stitched preform curved pultrusion successfully demonstrated pultrusion pull forming process allow b staging advancing resin rigidized state laid fuselage tool final assembly helical stiffener blade shaped stiffener made tape placing filcoat material recess fuselage mandrel following installation wrap component see figure 36 47as helical pattern developed material laid form blade stiffener tape overlapping two direction intersection overlapping problem alleviated flowability syntactic half tape cure cycle syntactic material softens flow leaving gr ep material intersection geodesic fuselage mandrel tool figure 35 intersection point cover component placed recess fuselage tool helical stiffener tape laid outer skin tow placed caul sheet placed skin entire assembly envelope bagged cured 48intersection clip stiffener overwrap atp helical stiffener atp fuselage skin figure 36 fabrication sequence circumferential frame geodesic fuselage f configuration cutout helical stiffener intersection xerkon autocomp molding process selected manufacture circumferential frame dry fiber stitched preform resin film placed autocomp matched mold resin infljsed layer material f frame mechanically fastened circumferential stiffener fuselage final assembly summary material chosen component along manufacturing method shown table 13 2 3 3 stiffened shell fuselage concept stiffened shell fuselage concept shown figure 37 developed fully automated concept reduce overall manufacturing 49table 13 material selection fabrication method geodesic fuselage concept material selection summary megmethod mat l selected comment stiffened cover pultrusion m7 5225 towpr eg slit tape intersection clip_ resin film infusion im7 preform 8552 resin autocomp isogrid stiffener_ atp m7 5225 towp reg filcoat fuselage skin atp m7 5225 towpreg frame resin film infusion im7 preform 8552 resin autocomp view figure 37 stiffened shell fuselage concept cost consisted outer skin open section hat stiffener j section circumferential frame feature concept includes continuous hat pultruded stiffener good damage tolerance characteristic redundant load path resin film infused rfi frame feature combine form relatively simple design ideally suited co curing conceptual development hat stiffener 5owere selected produce low cost design beneficial effect stiffener could made braiding pultrusion two low cost manufacturing process another main benefit ability reduce total number stiffener required added feature hat stiffener stable stiffening concept blade hat stiffener generally require addition clip stabilize stiffener frame intersection manufacturing plan call j frame textile preform made braiding knitting stitching process preforms fabricated either resin transfer molding resin infusion molding process see figure 38 basic tooling approach resin infusion process allow controlled b staging advancing resin subsequent co cure final assembly shell stiffened fuselage section composite j frame nn aluminum tooling block f 1 rubber figure 38 cross section tooling infusing j preform resin 51the hat stiffener open section formed tri axially braided material hat stiffened preforms pultrudable rigidized b stage form co cured final assembly braiding process allows tailoring property addition 0 fiber cap area structural efficiency pultrusion basf 5225 prepreg carried controlled condition another approach dry preform pultruded using epoxy resin like shell 9310 prior insertion frame fuselage assembly tool mouse hole hat stiffener must cut frame plug inserted fill void hat stiffener frame placed teflon support mandrel recess fuselage assembly tool see figure 39 teflon mandrel easily removable final assembly provide sufficient pressure molding thermal expansion outer skin filament wound tool stiffener assembly entire section bagged cured autoclave final assembly discussed use hat stiffener allows omission shear tie frame also allows fuselage tool simplified reducing tooling assembly cost co curing fuselage shell eliminates use fastener reduces assembly step cost summary material system component along manufacturing method shown table 14 2 4 cost trade study section summarizes estimated cost advanced design concept based

design package received team compare baseline metallic structure cost methodology assumption also included 2 4 1 cost estimating rule methodology 52pultrude stiffener frame fuselage tape lay assemble detail cocure assembly figure 39 final assembly sequence table 14 material selection fabrication method stiffened shell concept material selection summary mfg method mat l selected comment skin atp im7 8552 towpr eg slit tape hat stiffener pultrusion as4 m7 8552 prepreg frame resin film infusion im7 preform 5225 resin b staged 53the cost estimate developed based 300 aircraft lot size 24 production rate 10 aircraft per month estimate assume current state art method procedure exception existing limitation due size cost based 1990 constant year dollar methodology used act program combination variety method depending design concept manufacturing plan associated particular concept use standard hour basis recurring manufacturing labor unit material cost basis material cost recurring cost recurring engineering quality tooling factored manufacturing cost based historical data determination time standard part assembly converted estimated actual hour use variance factor learning curve labor hour converted dollar application appropriate labor rate material cost added applying material burden escalation factor quality sustaining engineering tooling included determine total recurring cost 2 4 2 cost comparison contributor 2 4 2 1 wing desion manufacturing concept cost estimate developed baseline l 1011 wing box advanced design manufacturing concept summarized figure 40 43 shown figure breakdown wing cost component along cost distribution cost element concept modular wing box concept result fewer component assembly lower stringer cost indicated well reduced assembly cost upper lower surface assembly highest cost contributor due generally size co curing multiple rib cap stringer rib web cost assume thermoplastic tape compression molded part configuration result trade study comparing alternative 54engr rib skin 2 82 3 3o _ ngers _fabrication _o_ _ _s_ f _ _ _o o_ quality _ 01 0 1 fromspa_r_ uprsurface rearsurface assembly cost element distribution component cost breakdown figure 40 l 1011 wing boxengr cme rib 2 39 2 37 structural assy materia fabrication u1 o_ frontspar uau ry _ _ 17 47 lwrsurface rearspar uprsurface assembly component cost breakdown cost element distribution figure 41 modular wingengr cme 2 81 3 36 structural assy lwrsurface rtm fabrication material 22 20 stringer 2126 rib 8 73 7 85 17 70 quality cn lwrsurface uprsurface rtm assembly uprsurface cost element distribution component cost breakdown figure 42 rtm wing boxengr cme 2 84 2 51 rib _ _uctural assy frontspar _ 17 44 _ lwrsurface uprsurface quality assembly cost element distribution component cost breakdown figure 43 tow placement wing boxthermoplastic quadrax material graphite epoxy fabric shown table 15 one risk item concept concern accurately part located insure good bond co curing even though expensive cost estimate assumes accurate fit therefore successful joint table 15 rib concept cost comparison thermoplastic tape compression molded 268 364 thermoplastic q uadrax 389 612 graphite epoxy fabric 121 773 resin transfer molded concept high cost contributor identified concept placement assembled wing cover preform rtm tool multiple tool assumed accurate dimensional control resin injected stitching cost could possibly understated since number stitch assumed considered sufficient hold material together automatic tow placement concept overall cost reduction 24 indicated baseline metallic box structure high cost contributor placement assembly wing skin component risk consideration involves credibility extending automated placement process structure size considered 2 4 2 2 terial cost sensitivity study cost 40 dollar per pound graphite composite material assumed cost estimate advanced design manufacturing concept iterated adjusting base material range 20 65 dollar per pound result depicted figure 44 59through 46 shown figure material cost variance significant impact cost composite structure 2 4 2 3 wina soar trade study trade study alternate spar concept conducted result shown table 16 c channel configuration relatively le 1 beam configuration concept considered case c channel consists essentially one half lay ups required 1 channel 2 4 2 4 fuselaae desian manufacturina concedts cost estimate baseline fuselage component advanced design manufacturing concept developed summarized figure 47 50 cost distribution component cost element shown concept cost benefit driver sandwich concept cost moderated automated fabrication method however cost benefit nullified due added number part associated increased assembly time geodesic concept cost benefit achieved commonality detail part high cost due significant increase number part fabricated assembled stiffened shell concept concept offer significant improvement due reduced part count co cured assembly elimination fastener cost increased complexity tooling required 60 2 800 000 2 600 000 2 400 000 cumulative average cost 2 200 000 o_ l 2 000 000 1 800 000 7o 10 20 30 40 50 60 composite material cost per pound figure 44 modular wing design concept composite material cost sensitivity study_pn_s q _ sue _soo lepe_eiaiel sodluoo deouoo u6 sec _uelueoeidmoi _eluomv s_ ejn6 punod jed soo le lelem el sodiuoo 0z 09 0 0_ 0 0z ol 9 aoooo9 l 9 o00008 l 9 a00000 z lso0 e6eje v 9 eooooz z e _elnzuno 9 o0000_ z 9 eoooo9 z 9 aooons z3 40000e 6 3 20000e 6 3 00000e 6 cumulative average cost 2 80000e 6 2 60000e 6 2 40000e 6 10 20 30 40 50 60 70 composite material cost per pound figure 46 resin transfer molded design concept composite material cost sensitivity studytable 16 cost analysis report cost analysis report summary title front spar actspar model nasa date _21 90 premise design quantity 300 acft lot quantity 24 acft spar design compare 1 beam structure c channel structure blade stiffener sandwich web stiffness athird alternative configuration using thermoplastic material design alternative 1 2 3 4 5 6 non recurringcosts 0 0 0 0 0 0 recurring cost raw material 35777 35777 26479 26479 98859 98859 purchased part 0 0 0 0 0 0 major _ipment 0 0 0 0 0 0 labor fab subasy 119004 79256 87870 58399 122136 81341 labor assy instl 0 0 7598 7598 0 0 quality assurance 10399 6926 8342 5767 10673 7108 sustaining cme 5879 3915 4716 3260 6033 4018 sustaining eng 4955 3659 3909 2947 6950 5619 direct cost 0 0 0 0 0 0 sub total recurring 176015 129533 138914 104451 244651 196945 cum averac _ cost 176015 129533 138914 104451 244651 196945 program cost 0 0 0 0 0 0 cum avgprogramcost 176015 129533 138914 104451 244651 196945 design alternative brkak evenpoint 1 1 beam blade stiffener ref hcf 2 c channel blade stiffener 1001 acft 3 beam sandwich material none always le 4 c beam sandwich material none always le 5 1 beam wlth tp beaded stiff none always le 6 c beam wlth tp beaded stiff 47 acft le costly acft quantity shown costly summary target lasc total total net non element unit unit prdg r e3g recli_ng cost cost cost cost saving cost design 1 176015 176015 176015 52804400 0 design 2 129533 129533 129533 38859856 13944544 design 3 138914 138914 138914 41674176 11130224 design 4 104451 104451 104551 31335248 21469152 design 5 244651 244651 244651 73395328 20590928 design 6 196945 196945 196945 59083616 6279216 64engr cme strap 2 85 4 22 stringer 3 80 material bondedskinassy fab sub assy 16 64 24 85 24 67 quality 6 14 5 82 frame 59 23 3 31 45 48 assembly assembly cost element distribution component cost breakdown figure47 l 1011 fuselage segment baseline cost distributionengr cme sandwich skin 3 29 5 86 2 83 2 95 fab sub assy material 12 72 29 37 frame 37 77 bondedassy 46 91 quality 2 41 stringer 3 00 assembly assembly c channel component cost breakdown cost element distribution figure 48 sandwich fuselage cost distribution skin bondedassy engr cme 5 07 2 45 2 71 2 75 frame fab sub assy stiffener material intersection _ assembly quality _ _ j assembly component cost breakdown cost element distribution figure 49 geodesic fuselage cost distribution engr cme bondedassy 2 84 2 44 9 75 fab sub assy stringer material 20 15 frame 3 skin 0o 25 55 assembly 4 32 quality component cost breakdown cost element distribution figure 50 stiffened shell cost distribution 2 _5 weiahts trade study weight analysis preformed three wing concept automatic tow placed resin transfer molded modular braided wing previously dropped three fuselage concept sandwich geodesic stiffened shell developed initial assessment ranking phase task 1 weight developed based design package received design manufacturing integration dim team composite weight compared lockheed l 1011 1 baseline aircraft weight baseline weight obtained l 1011 file reviewed insure component component comparison obtained 2 5 1 weight estimating assumption weight estimating process total weight wing box structure developed weight broken include upper cover lower cover rib bulkhead spar structure body main landing gear support structure weight reported based per aircraft estimate weight first estimated outer wing station ows 151 1 composite design drawing spanwise variation see figure 51 based l 1011 data applied arrive total weight wing concept actual weight determined upper lower cover rib spar web additional estimated weight added landing gear engine mount access door result wing weight analysis shown table 17 fuselage concept total weight estimated fuselage shell fuselage station f 235 f 983 based composite design drawing developed team sizing drawing developed f 750 included skin stiffener frame circumferential variation assumed applied average section analyzed result fuselage weight analysis shown table 18 69 50 r 3 z upper surface variation 03 4o w z rtm 0 _ mod z 30 w 0 w 1 2o 200 400 600 150 350 55o iw ows 50 lower surface variation z 40 03 03 rtm w z o_ 30 mm _ mod z w j 20_ e3 w 200 400 600 150 350 550 iw o_ figure 51 wing box upper lower surface weight variation 70table 17 summary wing box weight advanced composite modular rtm atl upper surface 6518 6989 6316 lower surface 7497 8869 6713 rib blkhds 2565 2565 2565 spar web 1071 1257 1229 cap 680 693 630 body joint 1500 1500 1500 mlg supt 19873 21873 18953 total lb table 18 summary fuselage weight composite concept sandwich stiffened geodesic skin stiffener 6313 5568 6989 minor frame 1054 1132 1186 7367 6700 8175 total lb 2 5 2 weight driver several item identified weight driver weight analysis based past experience item 71identified listed discrete v integral stiffener number fastener material form discussed design wing fuselage concept strove minimize cost weight use co cured co bonded structure using design philosophy effect first two item listed diminished leading selection integrally stiffened structure wherever possible additional item known potential weight driver investigated detail initial assessment ranking part task 1 topic joint cut out uniform v tailored thickness developed next part task 1 structural design development 2 5 3 weight com oarison figure 52 show result composite design weight analysis aluminum l 1011 baseline weight seen automatic tow placed wing concept highest weight saving 31 8 modular wing concept second 28 7 weight saving finally resin transfer molded wing concept 21 3 weight saving figure 53 show result fuselage weight analysis baseline fuselage weight stiffened shell concept lightest 30 3 weight saving sandwich concept second 23 3 weight saving geodesic concept last 14 9 weight saving program goal weight saving 40 sized aircraft approach taken adjust weight goal account sizing aircraft use l 1011 baseline configuration 7230000 joint spar rm blkhd cowrs 20oo0 10oo0 baseline modular rtm atp figure 52 wing weight comparison 10000 minor frame sk n stn_ j 8000 6ooo 4000 2000 0 sandwlc h geodesic gi ffshell baseline figure 53 fuselage weight comparison 73is sized therefore 40 goal modified 34 account sizing aircraft 6 reduction conservative estimate gain possible sizing effect sizing aircraft would reduce amount fuel required meet flight range requirement also fuel weight reduction allows engine sized creates snow ball effect lead substantial reduction increase range payload etc 2 6 sudoortability trade study wing fuselage design concept developed supportability issue mind major emphasis developing maintainable cid 0 repairable structural concept could supported field standard repair procedure 2 6 1 rationale following completion design package concept evaluated maintainability repair inspectability durability damage tolerance concern expert respective field evaluated concept rated accordingly 1 10 10 highest result evaluation shown table 19 21 2 7 trade study result_ cost weight llities evaluation completed select process discussed used determine concept carry structural concept development subtask task 1 development subtask concept would developed detail focusing detail design joint cutout etc original plan take top two wing fuselage concept development part task 1 however following nasa redirection top wing top fuselage carried development subtask 74table 19 maintainability evaluation rationale maintain concept rationale ability modular modular construction facilitates le costly repair wing technology heavy structural damage unrepairable field level rtm leak path eliminated construction facilitates le costly repair technology heavy structural damage unrepairable wing field level atp leak path eliminated repair field level le costly wing heavy damage induce remove replacement entire structure sandwich composite material eliminate maintainability issue fuselage repair easily done field level geodesic creates repair problem satisfied without fuselage major reconstruction large area reqiures excessive spare repair part inventory stiffened shell repair problem transfering load across damaged area fuselage table 20 inspectability evaluation rationale inspect concept ability rationale separate component inspected also require modular 6 extensive post process inspection due coconsolidation wing bonding preform may inspected mold filling wide range rtm wing 8 processmethods could used monitoring mold fill cure including process model atp tow quality size placement must monitored time wing 6 depend machine placement monitoring need developed sandwich tube could inspected line post process fuselage difficult tube geodesic complex geometry truss intersection fuselage uninspectable high score component may inspected final stiffened shell fuselage 8 cure process inspection pultruded hat rtm frame easy goemetry 75table 21 durability evaluation rationale durability concept damage rationale tolerance concern impact damage cause stiffener pull wing away skin drastically reducing mechanical property rtm thickness reinforcement prevent stiffener wing unbond minimize impact damage lowerfiber volume still concern ra itwould reduce structural integrity atp typical current structure wing thinness facing adurability concern impact could cause sandwich seperation triangular tube large region could fuselage reduce residual property configuration highly redundant geode_ standing durability damage tolerance however _lage high risk critical manufacturing flaw diagonal stiffenedshe_ considered slightly better current structure _lage elimination fastener hole program goal 40 weight saving 25 cost saving 50 part count reduction assigned weighting factor 30 40 30 respectively cost previously selected main program goal therefore weighted highest weight llities weighted equally select score cost weight developed comparing actual weight cost target weight cost following formula score wg wd x wf wg weight cost goal wd weight cost design wf weighting factor 30 weight 40 cost possible concept earn bonus point surpassing target goal example weight goal 20 000 ibs concept estimated weight 18 000 ibs concept would score 33 3 point 20000 18000x30 exceeding weighting factor 76the llities evaluation conducted expert various discipline score concept one ten 10 best taking average multiplying weighting factor 3 llities discipline involved design manufacturing producibility evaluation combined developed section 1 6 inspectability maintainability repair damage tolerance durability form complete overall evaluation concept table 22 show result llities trade study result score added cost weight score arrive total score concept 2 7 1 wing result table 23 show final result select ranking wing concept automatic tow placed wing clear winner score 85 65 well modular wing concept ranking second score 73 77 finally rtm wing score 71 95 therefore atp wing concept carried development subtask task 1 atp wing concept scored well cost weight area nearly matching target goal three concept scored fairly closely weight area interesting note rtm concept scored well llities area penalized cost area due difficulty loading preform tool high tool cost summary detail atp wing concept shown figure 54 concept integral co cured blade stiffener spar cap co cured rib cap mechanically attached rib web table 23 wing trade study result final ranking concept weight cost ilities total rank modular 26 91 34 36 12 5 73 77 2 wing rtm 24 29 27 16 20 5 71 95 3 atp 28 16 39 49 18 0 85 65 1 77technology advancement damagetoll maintainability concept producibility durability inspectability repair total score design mfg modular wing 4 3 3 6 25 12 5 41 20 5 rtm wing 5 9 j go atp wing 5 7 6 6 36 18 0 sandwich 8 7 3 5 34 17 0 fuselage geodesic 6 7 3 9 2 4 31 15 5 fuselage stiffened shell 4 3 8 6 6 35 17 5 fuselage table 22 llities trade study result simple spar web cover mechanical integral attachment spar cap cocured rib cap shear tie figure 54 atp wing concept detail 2 7 2 fuselage result result fuselage select ranking shown table 24 indicate stiffened shell concept 87 99 point winner substantial margin 20 point second place sandwich fuselage concept 63 90 point finally geodesic concept 48 88 point therefore stiffened shell concept carried development subtask task 1 large spread score attributed substantial difference design configuration stiffened shell concept awarded bonus point exceeding cost target goal geodesic penalized heavily cost many part addition stiffener cover greatly increased manufacturing assembly cost sandwich concept scored best weight area expected sandwich construction generally weight efficient figure 55 show 79the detail stiffened shell concept consisted simple design co cured hat stiffener j section circumferential frame table 24 fuselage trade study result final ranking concept weight cost ilities total rank sandwich 25 05 21 85 17 0 63 90 2 fuselage geodesic 22 57 10 81 15 5 48 88 3 stiffened 27 54 42 95 17 5 87 99 1 shell j section frame continuous hat stiffener co cured assembly figure 55 stiffened shell fuselage concept 803 0 structural desian conce0t completion design trade study result presented nasa personnel formal review since one wing fuselage concept emerged clear winner agreed remainder task 1 would concentrate two concept backup would carried next subtask boeing douglas performed similar trade study following full review three contract nasa determined boeing lockheed reached similar conclusion nasa act steering committee discussed result three program trade study fall 1990 recommended future work focused three area resin transfer molding automated fiber placement textile structure mutual agreement lockheed selected concentrate textile structure restructure phase ii program end section discus remaining task 1 effort terminated effort subtask 2 prior termination following august 1 1990 program review nasa directed back concept eliminated consideration winner ahead considerable margin showed potential meeting program goal therefore automatic tow placed wing stiffened shell fuselage carried detail design subtask modular wing sandwich fuselage concept dropped consideration initial assessment ranking subtask wing fuselage concept developed enough detail generate cost weight data second subtask structural concept development winning concept defined greater detail paying particular attention detail cutout joint taper effect etc structural design development subtask new manufacturing 81processes evaluated attempt reduce cost wing two manufacturing process evaluated compared one panel concept original fully automatic tow placed panel panel concept braided automatic tow placed concept u channel blade stiffener braided skin automatic tow placed allowed cost well structural comparison final selection best process application material material system proposed atp wing stiffened shell fuselage concept hybrid hercules as4 im7 graphite fiber hercules 8552 toughened epoxy combination believed provide best balance mechanical property processibility cost as4 im7 hybrid allows tailoring mechanical property example wing cover high modulus high cost im7 fiber used stiffener high strength low cost as4 fiber skin area 8552 toughened epoxy 350 f cure 180 f service system available material form required task hybrid system estimated hercules cost 40 ib 66 as4 34 im7 8552 mix large production volume range estimated material cost consistent cost data generated initial assessment ranking subtask 3 1 wina structure _ j lojm planned work joint wing structure begun time program redirection 3 1 2 cutout cutout required access door fuel probe etc laid upper lower wing cover different skin stiffener tapering configuration developed discussion hercules order get better understanding capability tow placement 82machine five design approach see figure 56 60 handling cutout developed presented dim team review first two concept used metallic insert local reinforcement final three concept composite design concept 1 attempted redistribute cutout load metallic ti insert u channel section concept 2 similar concept 1 except load redistributed metallic doubler outer skin panel concept 3 fully utilized atp process placing material around cutout area concept 4 placed gr ep doubler material u channel section constant section outer skin finally concept 5 placed gr ep doubler material u channel section outer skin sectzon iann _ _ rf nf circe mi ni iiii iannel z j r nforce neni f l iaiqne i_ 1 71if qitc 41ni 1 ir iil mi ii ah l figure 56 cutout concept 1 83acci s hole 16 x 5 figure 57 cutout concept 2 front spai _ dailim sect20n ui ul figure 58 cutout concept 3 84 original page poor qualityaccess ii e 16 x 5 sectzon q const ssekcintion nforcehent infqrci hin ah l figure 59 cutout concept 4 fro_t sprr d_tum access hole 16 x 11 5 secttgn _ _ i1 _ li _ f _ __l __ i_i l tof __ ii iii _ osi te 11liler td l feii lilfief hin aieea ci utou figure 60 cutout concept 5 85 origtna _ _ poor qualri ytable 25 show pro con identified concept following review team promising concept developed examined determine impact cost weight five cutout concept consideration two eliminated consideration concept 1 2 metal insert dropped thought le effective created several manufacturing cid 0 inspection problem also concept 3 curved ply heavy channel concept 5 heavy skin channel combined similar concept concept 5 would back curved ply concept feasible therefore remaining concept composite design concept 3 local reinforcement outer skin curved ply u channel concept 4 heavy u channel constant section outer skin two concept developed analyzed cost weight impact however activity task 1 terminated 2 1 3 ta0er effect atp wing detailed layout l 1011 baseline wing started investigate weight impact changing blade stiffener spacing better match rib spacing attempt reduce cost simplifying stiffener termination front spar investigating several different spacing taper scheme wing stiffener determined option practical mainly due high spanwise taper ratio wing causing many stiffener terminate along span terminating stiffener cause manufacturing difficulty well creating poor design causing relatively large jump panel size therefore option eliminated consideration 2 1 4 test plan wing structure test plan shown table 26 test plan made use building block approach allow refinement design manufacturing approach used critical feature wing fuselage concept examined wing element test evaluate different manufacturing approach material form 86table 25 comparison cutout concept _no pro g3ns u channel joggle difficult obtain proper compaction composite matl cte mismatch reduced overall thickness metal u channel questionable bond metal reduced lay time composite difficult inspect thickness mismatch stringer along span cte mismatch machined laminated doubler gradual pad ups questionable bond metal composite balanced stringer build ups metal skin composite difficult inspect eliminates compaction problem thickness mismatch stringer along span minimizes load path interuptions requires advanced analysis fea 3 curved ply fully automated fabrication heavy chl gradual stringer taper load shared evenly channel stringer increased eccentricity _s required poor load transfer 4 heavy_ automated fabrication easy taper stringer constant section outer skin automated fabrication requires stringer channel heavy skin gradual stringer taper channel reduced eccentricity 87table 26 task 1 wing structure test matrix specimen total test test configuration number condition instrumentation configuration replicates teat planned cover blade 32 rtd none pull 2 rib cap cover 3 rtd nolle pull cover blade compression 2 3 6 rtd 6 axial gage wing element test specimen total test test configuration number condition instrumentation configuration replicates test planned load normal spar 2 spar cap load parallel tospar none element 9 shear notched 2 8 axial 3 stringer impact gage compression 2 damage wing subcomponent test cover blade pull test validate structural integrity interface blade skin test different material form braiding instead automatic tow placement would evaluated rib cap cover pull test designed validate design manufacturing concept integral rib cap different material form cap configuration would evaluated final wing element test cover blade compression test 88to validate upper lower cover design manufacturing concept following element test two wing cover configuration evaluated wing subcomponent testing subcomponents tested spar cap three stiffener compression panel spar cap test validate integral spar cap configuration joint spar web three stiffener panel test intended validate design compare damage tolerance selected concept selected wing concept relied heavily availability totally automated lay method capability planform thickness tapering hercules cincinnati milacron two company unique manufacturing capability considered potential subcontractor manufacture test component lockheed personnel visited hercules aerospace co magna utah witness first hand automated fiber placement machine operatior discus design cid 0 manufacturing approach test panel fabrication demonstration machine capability showed equipment capable producing structural requirement 3 2 fuselaae structure structural concept development stiffened shell fuselage concept concentrated designing fuselage section door although plan existed build door section effect door adjacent section pertinent topic concern area skin splice location stringer transition one barrel section another major emphasis structural concept development stiffened shell fuselage configuration placed 1 establishing suitable splice location fuselage panel assembly 2 developing design philosophy window belt structure 3 evaluating alternate design concept circumferential longitudinal splice major cost driver aircraft structure shown 89assembly cost order minimize assembly cost large co cured panel proposed stiffened shell fuselage large panel spliced longitudinally location deemed convenient assembly ideally lower fuselage section consisting skin floor beam would go together first upper skin panel would installed complete barrel section figure 61 show example splice concept one recurring concern expressed team mandrel requirement hat stiffener therefore manufacturing assigned task finalizing requirement determine specific capability available current emerging technology provide input direction stiffened shell concept take mandrel capability influence design either requiring fully cured hat stiffener bonded final cure cycle allowing use b staged hat stiffener co curing final assembly another task assigned team finalize inspection requirement hat stiffener task also influenced selection mandrel hat stiffener configuration l 1011 baseline rely upon stringer door cutout lateral bending load us thicker skin area study initiated compare design philosophy versus using continuous stringer along thinner skin window door cutout also evaluated need circumferential fail safe strap used l 1011 several tooling method hat section stringer evaluated would apply double contoured section constant section considered appeared pultrusion worked well constant section outside surface tool surface gave better fit adjacent part however different approach required double contour section figure 62 show stringer penetrating frame pre molded clip bond together design stringer termination decided upon tooling concept developed 90framejoggle _ cker skin splice clip _ frame joggle kin joggle splice clip f 1 1 i_l_ i_ _l ti figure 61 splice concept 3 2 1 test plan fuselage structure fuselage element test shown table 27 evaluate different manufacturing approach candidate material form 91trimmed edge frame small nominal gap pre molded clip frame pultruded stringer figure 62 stringer frame intersection fuselage element test conducted stringer shell pull frame shell pull shell stringer compression pressure integrity low velocity impact test stringer shell pull test evaluate 92various configuration fuselage shell stringer joint frame shell pull test would determine structural property co cured joint shell stringer compression test used validate shell design manufacturing concept pressure integrity low velocity impact test designed demonstrate effectiveness design sustain service impact using building block approach fuselage subcomponent test conducted following element test intended evaluate two configuration frame bending three stringer panel compression shear panel five stringer compression panel test evaluate promising configuration frame bending test performed validate innovative manufacturing process proposed frame three stringer compression panel test designed evaluate structural integrity damage tolerance shell design shear panel test simulate structure highest shear loading fuselage panel tested undamaged damaged two lifetime fatigue damage finally five stringer compression panel represents structure area highest compression loading tested impact damage critical area support test plan first panel design drawing coupon element test specimen initiated planned fabricate one panel comprises test specimen panel would cut obtain individual specimen activity halted completion however pending redirection nasa 93table 27 task 1 fuselage structure test matrix specimen total test test configuration number condition instrumentation configuration replicates test planned stringer shall 2 pull 3 6 rtd none 1 l frame shall pull 2 6 rtd none 3 shall stringer 2 compression 6 rtd 4 axial gage 3 pressure 2 low energy integrity 4 impact damage none impact 2 fuselage element test total test configt ure tt ion con fp ige uc ri tie n fum tb ee sr t condition instrumentation replicates planned 2 4 axial gage frame bending 4 point bending 2 2 rosette 1 notched

2 2 3 stringer compression 2 2 w dait mh agi empact 8 axial gage iundamaged 1 shear panel 1 impact damage 4 axial gage 3 1 2 ufetimes fatigue 4 rosette 1 damaged 5 stringer 1 compression 1 impact 15 axial gage 1 damage fuselage subcomponent test 944 0 reference 1 c jackson advanced composite structural concept material technology primary aircraft structure presented first nasa advanced composite technology conference seattle wa october 29 november 1 1990 nasa cp 3104 pp 39 70 2 c jackson r e barrie b shah j g shukla advanced textile application primary aircraft strucutures presented second nasa advanced composite technology conferrence reno nv november 4 7 1991 95 j ireport documentation page f oo mrm e np oprov oe _d 04 0 ae l r hr r_ 3 _ _u d_n _rr hi _ tlon _totm lrjot_ _tlrnatpd verage 1hour per resoonse tnctuding time tot reviewing ifl tructlon ear njnq et _t_ng _lata cut_ _ 1i_h r _ jr _ _ _ _ _ nq lh_ d_t _ ne _ded n _ _orndie_ln _nd r v pw t_q _hp ollectlon information send comment regarding thi_ burd_ n e e _r inv a_dect t_ c ile_t _n _f n _ _ _ n _1luc_ nq sugge_t on_ _ r r_du_lnq ih _ buraen _ v _shjnqton neadauarter_ _ tw_e 2 rectorate inform_lt_on _9o_r _tl _ns _nd _ _dort 121_ jeffet _v_ _ _h _ _ 2 _ _ n j _ 2202 4 02 anci _h_ offj_e _lana l_ nt budget p_lderwork reduction prolect 0704 0188 v_ t_ ng _ _c 20s0 1 agency use leave blank 2 report date 3 report type date covered september 1992 contractor re_ort may 89 may 92 4 title subtitle 5 funding number advanced composite structural concept material technology primary aircraft structure design manufacturing concept assessment c nasi 18888 6 author robert l cbu bayha h davis j e ingram j g shukla wu 510 02 13 01 7 performing organization name address e 8 performing organization lockheed aeronautical system company report number advanced structure material division 73 cl 86 south cobb drive marietta ga 30063 9 sponsoring monitoring agency name address e 10 sponsoring monitoring nasa langley research center agency report number hampton va 23681 0001 nasa cr 4447 11 supplementary note langley technical monitor randall c davis task 1 final report 12a distribution availability statement 12b distribution code subject category 05 13 abstract maximum 200words composite wing fuselage structural design manufacturing concept developed evaluated trade study performed determine well concept satisfy program goal 25 cost saving 40 weight saving aircraft resizing 50 part count reduction compared aluminum lockheed l 1011 baseline concept developed using emerging technology large scale rtm atp braiding autoclave automated manufacturing process thermoset thermoplastic material evaluated possible application design concept trade study used determine concept carry detailed design development subtask 14 subject term 15 number page composite design manufacturing concept cost weight 112 select trade study i6 pricecode 17 security classification 18 security classification 19 security classification 20 limitation ofabstract report page abstract unclassified unclassified nsn 7540 01 280 5500 standard form 298 rev 2 89 ipr_ cr b_ n½1 _td j_ io 29t tlj2 nasa langley 1992

Top Keywords

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