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LOW LIFT-TO-DRAG AERO-ASSISTED ORBIT TRANSFER VEHICLES

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The results of a systems analysis study conducted on low L/D aero-assisted orbit transfer vehicles (AOTV's) is presented. The objectives of this activity were to (1) systematically assess the technology requirements for this class of vehicle and formulate technology development plans and funding levels to bring the required technologies to readiness levels, and (2) develop a credible decision data base encompassing the entire range of low L/D concepts for use in future NASA AOTV studies.

The study approach was to select suitable AOTV concepts, address major feasibility issues, and generate workable configurations for use in trajectory/ aerothermal analyses. Subsystem trades examined the impact of different technology levels on vehicle performance and noted the levels required to meet basic operating requirements. Finally, technologies were ranked in order of importance towards meeting low L/D AOTV design goals, and program and technology funding costs were estimated.

Study results showed that each of the candidate low L/D concepts, the aerobrake, the lifting brake, and the aeromaneuvering concept could be made to work with technologies achievable by the early 1990's. All of the concepts required flexible structure with flexible thermal protection system (TPS) to be successfully integrated into the shuttle orbiter for launch, all required improvements in guidance and control (G&C) to fly the dispersed atmospheres at high altitude, and all concepts had potential to evolve from ground-based to space-based operations.

The critical advancements in technologies required to implement the low L/D AOTV concepts were in TPS, especially flexible TPS, in aerothermal prediction methods, and in G&C. Other areas where technology advancements appeared to be cost effective (i.e., savings in use outweighted development costs) were propulsion, atmospheric physics (prediction methods), rarified gas aerodynamics, and composite structures.

Study Objectives

- DEFINITION OF A TECHNOLOGY PLAN FOR LOW L/D AOTV'S
  - ENABLING AND HIGH PAYOFF TECHNOLOGIES IDENTIFIED
  - REALISTIC CONSTRAINTS ON TECHNOLOGY FUNDING LEVEL ASSUMED
  - TIME PHASED PLAN DEVELOPED FOR REASONABLE IOC DATE
- DEVELOPMENT OF A DECISION DATA BASE FOR FUTURE NASA AOTV STUDIES
  - INVESTIGATE CONCEPTS THROUGHOUT THE ENTIRE LOW L/D RANGE
  - ADDRESS THE CRITICAL VEHICLE TECHNOLOGIES
  - INCLUDE OPS ANALYSES
  - DEVELOP EVOLUTIONARY GROWTH SCENARIOS
  - ESTIMATE COSTS (NON-RECURRING, RECURRING AND OPS)

Figure 1

Technical Approach

- SYSTEMS TRADES
  - SELECT CANDIDATE CONCEPTS AND RESPOND TO FEASIBILITY ISSUES
  - USE WORKABLE CONFIGURATIONS IN TRAJECTORY/AEROTHERMAL ANALYSES
  - USE MANNED MISSION TO DESIGN ALTERNATE OPERATIONAL MODES
- SUBSYSTEM TRADES
  - BUILD FROM PHASE A-OTV DATA BASE
  - INCORPORATE ADVANCED TECHNOLOGIES
  - ASSESS TECHNOLOGY PAYOFFS
- TECHNOLOGY PLANNING
  - IDENTIFY CURRENT, NORMAL GROWTH, AND ACCELERATED GROWTH TECHNOLOGIES
  - RANK TECHNOLOGIES WITH RESPECT TO PROGRAM REQUIREMENTS
  - PLAN TECHNOLOGY DEVELOPMENT
- COST ANALYSES
  - USE WORK BREAKDOWN STRUCTURE TO ESTIMATE SUBSYSTEM COSTS
  - ESTIMATE PROGRAM COSTS
  - ESTIMATE TECHNOLOGY FUNDING REQUIREMENTS

Figure 2

Design Mission Requirements

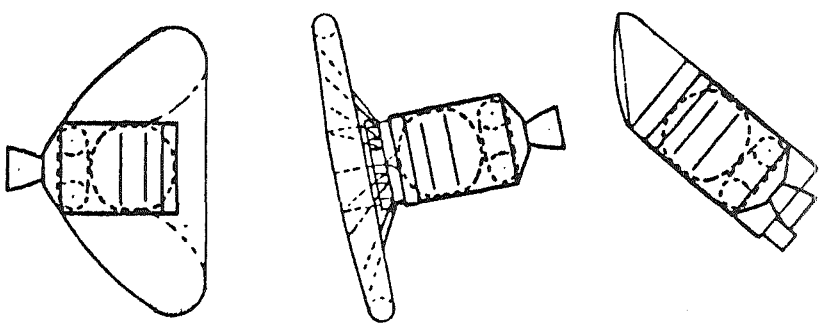
- BASELINE DESIGN MISSIONS (65K STS)
  - GEO DELIVERY
  - 5 x GEO DELIVERY
  - 6 HR. POLAR DELIVERY
- EVOLUTIONARY GROWTH MISSIONS
  - UNMANNED SERVICING (NOT A DESIGN DRIVER)
  - MANNED GEO MISSION (KEY DESIGN MISSION IN ALL MODELS)
    - 14,000 LB. ROUND TRIP
    - REQUIRES ALTERNATE OPERATING MODE

> - BASIC TECHNOLOGY TRADES WERE DONE USING VEHICLES SIZED FOR BASELINE MISSIONS
> - MANNED GEO MISSION WAS USED TO SIZE EVOLUTIONARY GROWTH CONFIGURATIONS AND DETERMINE WORTH OF ALTERNATE OPERATING MODES

Figure 3

Low L/D AOTV Characteristics

(BASELINE CONCEPTS)

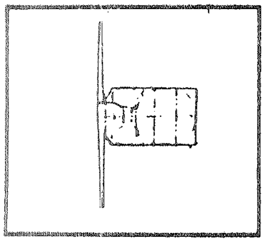


	AEROBRAKE (L/D=0)	LIFTING BRAKE (L/D=0.25)	AEROMANEUVERING (L/D=0.75)
BALLISTIC COEFFICIENT, $\frac{W}{C_D A}$	5-10 PSF	5-10 PSF	25-45 PSF
CONTROL TECHNIQUE	VARIABLE $C_D A$ USING INTERNAL PRESSURE	MOVEMENT OF CG IN Y-Z PLANE USING ELECTROMECHNICAL ACTUATORS	VARIABLE BANK ANGLE USING REDUNDANT RCS THRUSTERS
METHOD OF AERODYNAMIC TRIM	NONE (STABLE)	SAME	AERODYNAMIC TRIM SURFACES
KEY ISSUES	GUIDANCE & CONTROL IN 3σ ATMOSPHERE	GUIDANCE & CONTROL IN 3σ ATMOSPHERE	TRANSPIRATION COOLING OF NOSE CAP
	DYNAMIC STABILITY OF INFLATED STRUCTURE	FLOW INPINGEMENT ON BODY/PAYLOAD	THERMAL CONTROL

Figure 4

Lifting Brake Configuration

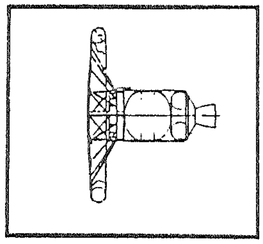
STUDY INITIATION



MAJOR CHANGE:

NON-POROUS & INFLATABLE BRAKE

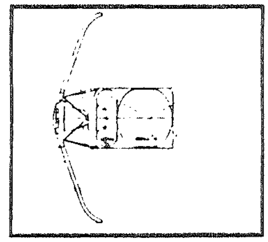
PROPOSED DESIGN



MAJOR CHANGE:

EDGE RADIUS

FINAL BASELINE



AREAS OF CONCERN
- DEPLOYMENT MECHANISM
- STRETCHABLE FABRIC
- POROUS HEAT SHIELD
- BANK ANGLE CONTROL
- GUIDANCE & CONTROL IN 3σ ATMOSPHERE
- FLOW IMPINGEMENT ON BODY/PAYLOAD
- STS INTEGRATION

AREAS OF CONCERN
- NO RETURN PAYLOAD
- FLOW IMPINGEMENT ON BODY/PAYLOAD
- G&C IN 3σ ATMOSPHERE
- STS INTEGRATION

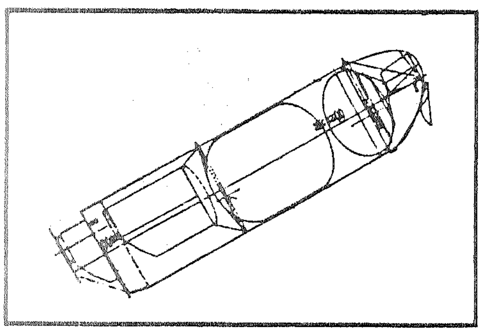
AREAS OF CONCERN
- CONTROL WITH RETURN PAYLOAD
- STS INTEGRATION

RATIONALE FOR CHANGE:
- NON-POROUS FABRIC: BOUNDARY LAYER TEMPERATURE CONTROL
- EDGE RADIUS: ELIMINATES FLOW IMPINGEMENT

Figure 5

Aeromaneuver Configuration

STUDY INITIATION

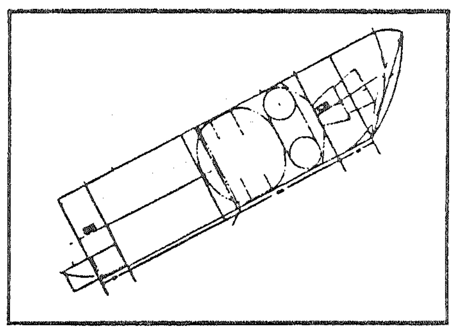


MAJOR CHANGE:

INFLATABLE NOSE,

TRANSPIR – ATION COOLED

BASELINE



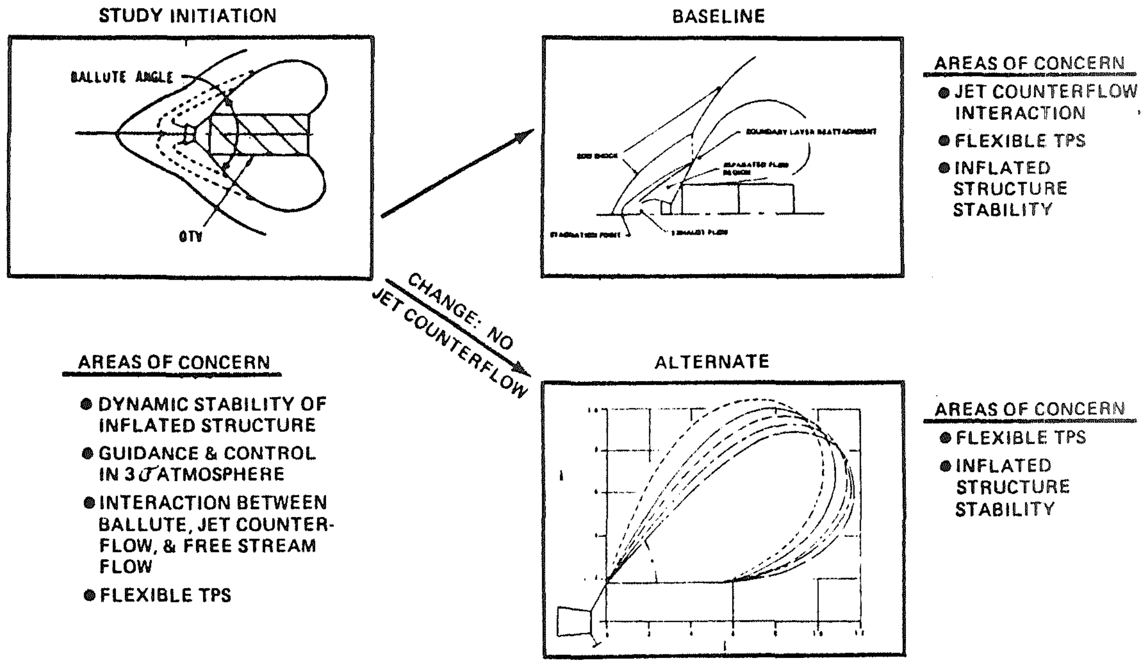
AREA OF CONCERN
- LARGE DOORS/SEALS ADDS COMPLEXITY, WEIGHT

AREAS OF CONCERN
- TRANSPIRATION COOLED NOSE

RATIONALE FOR CHANGE
- LIGHTER
- HIGHER RELIABILITY
- CHEAPER

Figure 6

Aerobrake Configurations



- *TESTING OF FLEXIBLE BALLUTE AND TPS PRODUCED NO BALLUTE "SHOW STOPPERS"*
- ALTERNATIVE PROPOSED TO ELIMINATE JET COUNTERFLOW UNCERTAINTY

Figure 7

System/Concept Findings

- NONE OF LOW L/D CONCEPTS ELIMINATED BY TECHNOLOGY ISSUES
  - MUCH OF THE TECHNOLOGY REQUIRED IS COMMON
- ALL CONCEPTS SIGNIFICANTLY BETTER UNDERSTOOD/IMPROVED
  - PERFORMANCE AND OPERATIONAL FLEXIBILITY ADVANTAGE TO AEROBRAKE
  - LIFTING BRAKE AND AEROMANEUVERING APPLICATIONS LIMITED BY AFT C.G. AND/OR FLOW IMPINGEMENT CONCERNS
- ALTERNATE OPERATIONAL SCENARIOS
  - ACC: EXCELLENT CONFIGURATION FOR LIFTING BRAKE; NO SIGNIFICANT IMPACT ON AEROBRAKE; AEROMANEUVERING IS NOT APPLICABLE
  - SPACEBASING/MANNED MISSION: NOT A SIGNIFICANT DISCRIMINATOR EXCEPT FOR PERFORMANCE
  - SDCLV: ATTRACTIVE OPTION WITH AEROASSIST
- FOR ALL CONCEPTS THE MAJOR UNRESOLVED ISSUES CONCERN REAL GAS FLOW EFFECTS AND THE DYNAMICS OF FLEXIBLE STRUCTURE AT THESE CONDITIONS
  - MORE TESTING REQUIRED TO PROVIDE DESIGN DATA
  - FLIGHT EXPERIMENTS NEEDED TO RESOLVE ALL DOUBTS
- FOR ALL CONCEPTS UPPER ATMOSPHERIC DISPERSIONS ARE A MAJOR DESIGN DRIVER
  - DESIGN DATA NEEDED – SOME TESTING REQUIRED
  - FLIGHT EXPERIMENTS IMPORTANT TO PROVE GN&C SYSTEMS
- NO SIGNIFICANT COST DISCRIMINATORS FOUND BETWEEN LOW L/D CONCEPTS

Figure 8

Technology Drivers

	TECHNOLOGY	ISSUE	COMMENTS
ENABLING	THERMAL PROTECTION	PEAK TEMPERATURE CAPABILITY	NEED TO ACCELERATE TECHNOLOGY GROWTH OF FLEXIBLE SURFACE INSULATION (FSI)
	AEROTHERMAL METHODS	THERMAL ENVIRONMENT PREDICTION	INCREASED ACCURACY IS REQUIRED TO FULLY CHARACTERIZE THERMAL ENVIRONMENT
	GN&C	ATMOSPHERIC GUIDANCE	AEROPASS REQUIRES MORE ADVANCED ADAPTIVE GUIDANCE SYSTEM
HIGH PAYOFF	PROPULSION	HIGHER PERFORMANCE ENGINE	DEVELOPMENT OF AN ADVANCED LH_2/LO_2 HIGHER I_{SP} ENGINE IS COST EFFECTIVE
	ATMOSPHERIC PHYSICS	HIGH ATMOSPHERE DESCRIPTION	BETTER UNDERSTANDING OF THE UPPER ATMOSPHERE SIMPLIFIES GN&C AND THERMAL PROBLEMS
	AERODYNAMICS	RAREFIED FLOW EFFECTS	ENHANCE GUIDANCE SYSTEM ACCURACY
	STRUCTURES	STRUCTURAL WEIGHT REDUCTION	UTILIZING ACCELERATED TECHNOLOGY GROWTH IS COST EFFECTIVE

Figure 9

Technology Ranking

RANK	TECHNOLOGY ITEM	BENEFIT	COST (FY 84→88) (MILLIONS OF DOLLARS)
1	THERMAL PROTECTION SYSTEM	• INCREASE FLEXIBLE & RIGID INSULATION TEMPERATURE CAPACITY • IMPROVE OPTICAL COATINGS • DEVELOP TRANSPIRATION COOLING	4.2
2	AEROTHERMAL METHODS	• BLUNT BODY FLOW UNDERSTANDING WITH AND WITHOUT JET COUNTERFLOW • BOUNDARY LAYER TRANSITION CRITERIA • NON-EQUILIBRIUM RADIATION	4.2
3	GN&C	• OPTIMAL GUIDANCE APPROACHES • CONTROL FUNCTION DEVELOPMENT • SYSTEM VALIDATION • FLEXIBLE MATERIAL CONTROL TESTS	5.3
4	PROPULSION	• RL10 IIB ENHANCEMENT • ADV EXPANDER ENGINE DEVELOPMENT • ADV ENGINE IMPROVEMENTS	8 TO 15.7
5	ATMOSPHERIC PHYSICS	• TETHER DATA ANALYSIS • LASER RALEIGH BACKSCATTER	2.4
6	AERODYNAMICS	• DETERMINE RAREFIED FLOW EFFECTS • FLEXIBLE BALLUTE DYNAMICS	3.8
•	FLIGHT DEMONSTRATION EXPERIMENT	• INTEGRATED SYSTEMS VERIFICATION • DEMONSTRATE & GN&C ALGORITHMS • PROVIDE AERODYNAMIC/AEROTHERMAL DATA • VERIFY DYNAMIC STABILITY OF FLEXIBLE BALLUTE • VERIFY TPS PERFORMANCE IN ACTUAL FLIGHT ENVIRONMENT	30

Figure 10

Technology Plan Summary

- REASONABLE DEFINITION OF TECHNOLOGY REQUIREMENTS AND OBJECTIVES
- CLEAR DISCRIMINATION BETWEEN REQUIRED VERSUS ENHANCED TECHNOLOGIES
- ENABLING TECHNOLOGY PROGRAM CAN BE ACCOMPLISHED TO SUPPORT PROGRAM START IN LATE 1980's FOR APPROXIMATE TOTAL $ = 65.6 MILLION
- FLIGHT DEMONSTRATION EXPERIMENT(S) EXTREMELY DESIRABLE—POWERFUL BENEFITS—
  - DEMONSTRATES GN&C CONCEPTS AND ALGORITHMS
  - PROVIDES NEEDED AERODYNAMICS/AEROTHERMAL DATA
  - VERIFIES DYNAMIC STABILITY OF FLEXIBLE BALLUTE
  - VERIFIES TPS PERFORMANCE IN ACTUAL FLIGHT ENVIRONMENT
- ENHANCING TECHNOLOGIES APPEAR TO HAVE HIGH PAYOFF (NOT QUANTIFIED IN ALL CASES)
- THIS IS STILL A "FIRST CUT" PLAN AND NEEDS ITERATION

Figure 11

AOTV Thermal Criteria

SURFACE TEMPERATURE – 100 REUSES

TPS MATERIAL	MAXIMUM TEMPERATURE		
	CURRENT TECHNOLOGY	1990 TECHNOLOGY (1995 IOC)	
		NORMAL GROWTH	ACCELERATED GROWTH
FLEXIBLE SURFACE INSULATION (FSI)	1500°F – 1800°F (AFRSI)	2500°F	3000°F
RIGID SURFACE INSULATION (RSI)	2700°F (FRCI)	3000°F	3500°F
HIGH DENSITY REFRACTORY (HDR)	3200°F (ACC)	3500°F	4000°F

BACKWALL TEMPERATURE

MATERIAL	MAXIMUM TEMPERATURE
GRAPHITE/POLYIMIDE *	600°F
KEVLAR CLOTH	600°F

HIGHER TEMPERATURE STRUCTURES ARE POSSIBLE, BUT ARE NOT CONSIDERED ADVANTAGEOUS BECAUSE OF THERMAL CONTROL CONSTRAINTS

Figure 12

Flexible Surface Insulation Technology Assessment

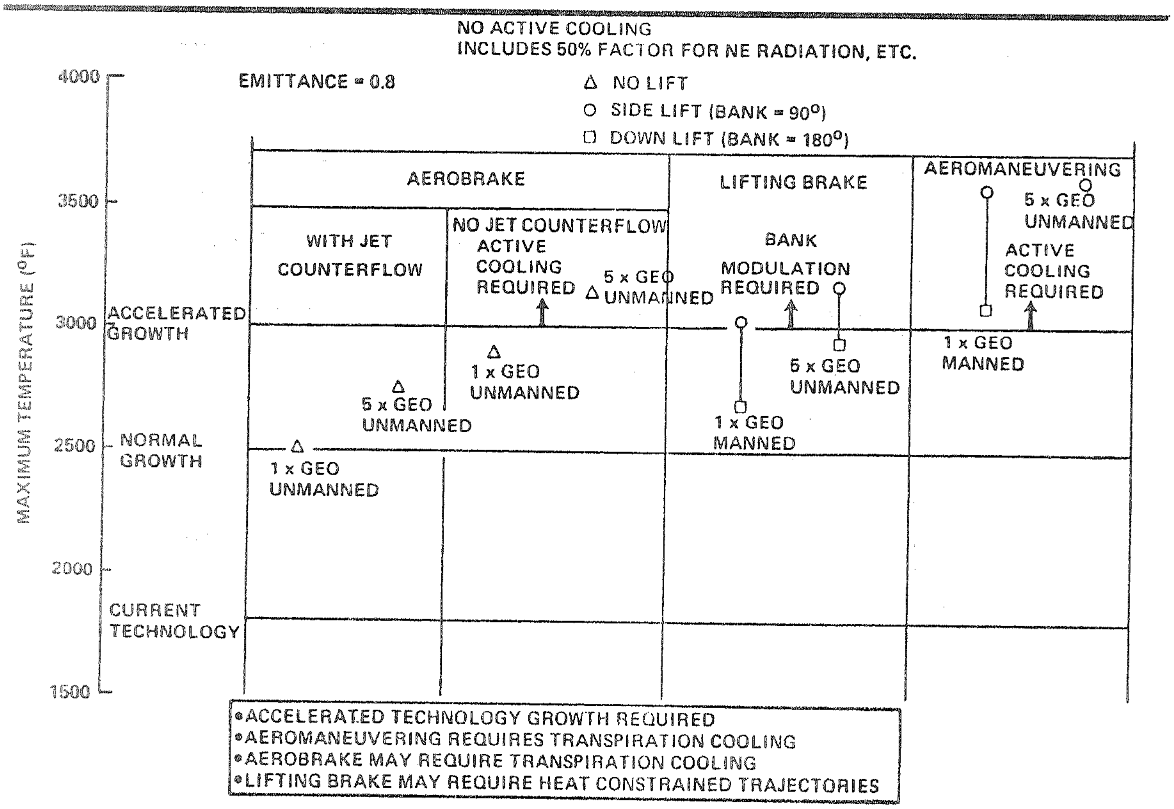


Figure 13

Rigid Surface Insulation Technology Assessment

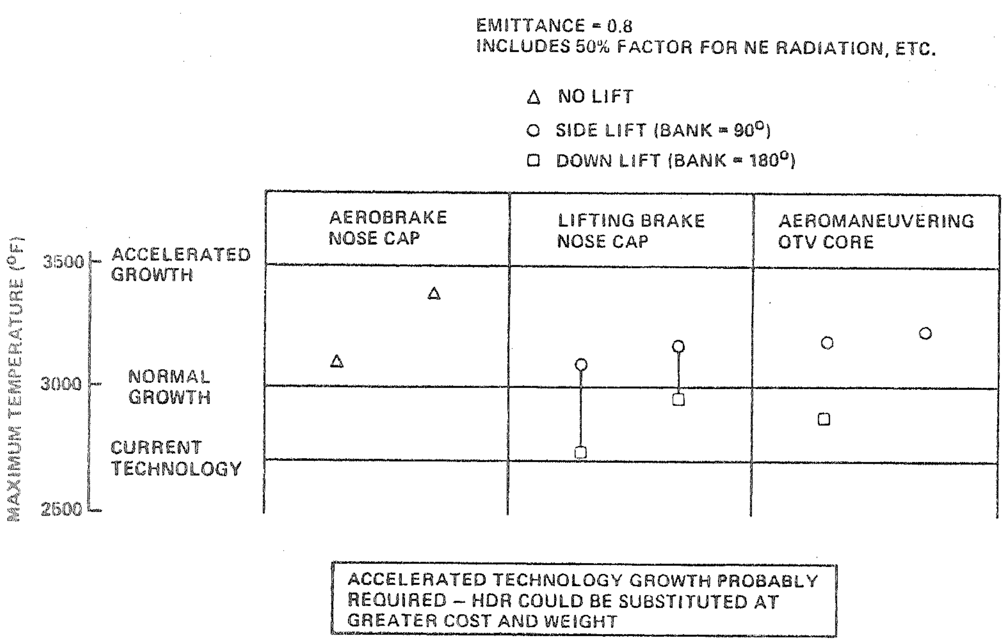


Figure 14

High Density Refractory Technology Assessment

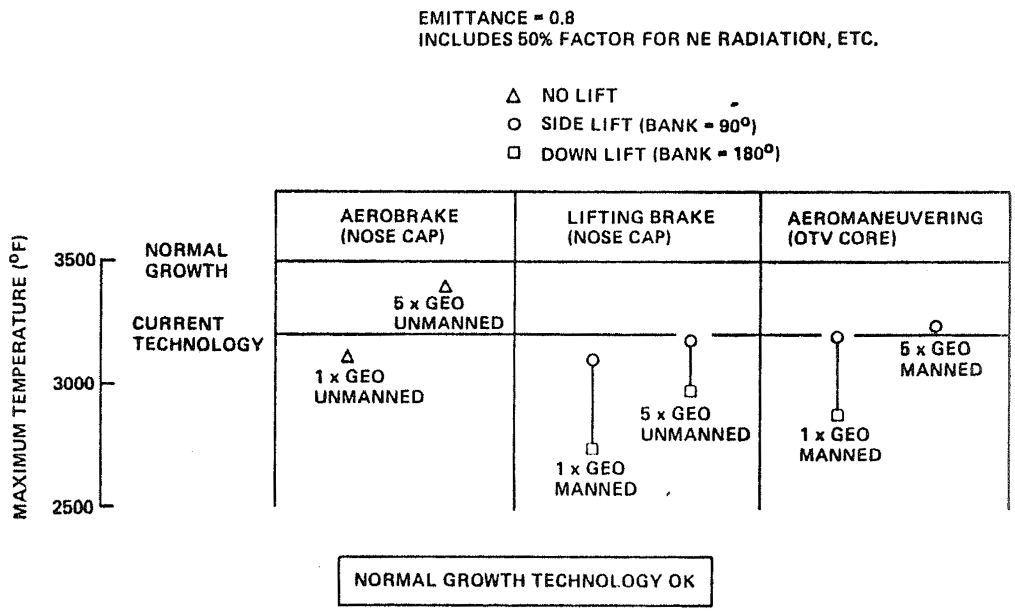


Figure 15

Examples of High Payoff Technology Assessment

SUBSYSTEM	DELTA GEO PAYLOAD	DELTA TECHNOLOGY DEV COST	DELTA DDT&E COST	GEO PAYLOAD COST [1]	RELATIVE SAVINGS [2]
ACCELERATED GROWTH STRUCTURAL COMPONENTS (10% WEIGHT REDUCTION)	280 LB	[3]	$ 35M	10,490 $/LB	210 $/LB
NORMAL GROWTH EXPANDER CYCLE ENGINE (480 SEC ISP)	1,330 LB	$ 8M	$430M	10,013 $/LB	687 $/LB
ACCELERATED GROWTH EXPANDER CYCLE ENGINE (490 SEC ISP)	1,903 LB	$17M	$630M	9,802 $/LB	898 $/LB

ACCELERATED GROWTH TECHNOLOGY COST EFFECTIVE FOR AOTV'S

[1] COSTS BASED ON 6 FLIGHTS/YEAR FOR TEN YEARS (NOM MISSION COST = $81.8M)

[2] BASELINE LCC = $5,632M, BASELINE GEO PAYLOADS = 526,400 LB (10,700 $/LB)

[3] TECHNOLOGY DEVELOPMENT FINANCED BY OTHER PROGRAMS

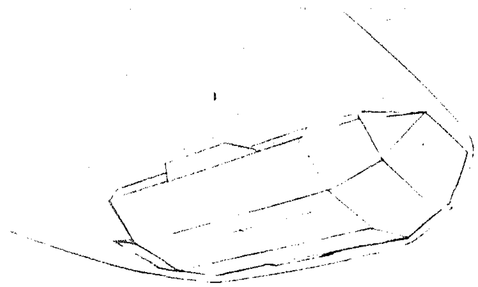
Figure 16

Recommendation

- AEROBRAKED AOTV IS RECOMMENDED CONCEPT IF DEVELOPMENT WERE TO START TODAY
  - BEST PERFORMANCE, LEAST COST, MOST STS COMPATIBLE, ETC.
  - CONTROL METHOD REQUIRES MORE DEVELOPMENT (NEEDS TESTING)
- BEGIN DEVELOPMENT OF TECHNOLOGIES SUITABLE FOR GENERIC AOTV
  - REUSABLE TPS (RIGID AND FABRIC) WITH CAPABILITY TO 3000°F
  - MORE ACCURATE AEROTHERMAL PREDICTION METHODS
  - GN&C SYSTEMS SUITABLE FOR AEROASSIST REENTRY TRAJECTORIES
  - ADVANCED EXPANDER CYCLE ENGINE TECHNOLOGY
- IF SPACE BASING BECOMES PRIMARY OPERATING MODE THEN A SPACE ASSEMBLED LIFTING BRAKE/AEROMANEUVERING CONCEPT SHOULD ALSO BE PURSUED
  - DESIGN FOR COMPLETE REUSABILITY
  - USE L/D TO REDUCE PROPULSIVE ΔV, PEAK HEATING, AND EFFECT OF ATMOSPHERIC DISPERSION

Figure 17

Fresh Look Lifting Brake Designed for Space Assembly



- STS COMPATIBLE OTV MOUNTED USING SHUTTLE FIXTURES
- OTV CAN BE EITHER GROUND BASED OR SPACE BASED
- NO NOZZLE RETRACTION REQUIRED
- GROSS TRIM ACCOMPLISHED BY SLIDING OTV ON RAILS
- CONTROL WITH AERODYNAMIC SURFACES & RCS

- COMBINE BEST FEATURES OF LIFTING BRAKE & AMOTV TO INCREASE L/D AND REDUCE SCAR WEIGHT
- SPACE ASSEMBLED PREFABRICATED COMPOSITE PANELS
- RIGID OR FABRIC REUSABLE TPS
- LARGE PLANFORM AREA REDUCES TEMPERATURES
- NO IMPINGEMENT PROBLEM

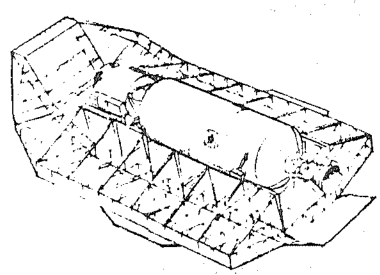


Figure 18

Objectives of Follow-on Study

- DESIGN DEVELOPMENT OF SPACE ASSEMBLED LIFTING BRAKE CONCEPT
- FURTHER APPLICATION OF OPTIC GUIDANCE CONCEPT TO GN&C TRADES
  - AEROBRAKE CONCEPT
  - LIFTING BRAKE CONCEPT
- PROPULSION SYSTEM TRADES
  - SIZE AND NUMBER OF ENGINES OPTIMUM FOR AOTVs
  - TECHNOLOGY LEVELS OPTIMUM FOR LCC
- TECHNOLOGY DEVELOPMENT PLANNING
  - ATMOSPHERIC DISPERSION TESTING
  - TPS
  - AEROTHERMAL
  - AERODYNAMICS

Figure 19