Supersonic HLFC: Potential Benefits and Technology Development Requirements

NASA High-Speed Research Workshop
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Boeing Commercial Airplane Group
Frank Neumann

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Supersonic HLFC:
Potential Benefits and
Technology Development Requirements

For the last three years Boeing has performed studies on the application of laminar flow control to HSCT configurations.

Large potential net benefits have been identified for laminar flow control, even after accounting for the significant implementation penalties.

However, the technical risks are high at this time, and an early, aggressive technology development program is required if LFC is to be incorporated in a year 2005 HSCT program. This presentation will address the benefits and the required development effort.

Potential Benefits of Laminarization on HSCT

Of all the aerodynamic advances that are being considered for the HSCT, LFC has the largest potential for improving the supersonic Lift/Drag ratio of a given configuration.

Improved L/D leads to reduced fuel consumption, reduced engine size and reduced gross weight; all of which improve economics.

Reduced fuel consumption means reduced emissions.

Reduced aerodynamic heating of the wing fuel tanks reduces tank insulation requirements on long supersonic flights.

Potential Benefits of Laminarization on HSCT

- Largest potential for improvement in L/D
- Reduced gross weight, engine size, and fuel burn improve economics
- Reduced fuel burn means reduced emissions
- Reduced aerodynamic heating
  - Reduced fuel heating rates
  - Possible structural benefits of lowered skin temperatures

HLFC ON HSCT - PAST BOEING/NASA LaRC STUDIES

The majority of the work accomplished to date was sponsored by NASA Langley under three successive tasks beginning in 1988.

> The first task led to the identification of laminarization schemes, supersonic cruise performance benefits and research needs.
>
> The second task addressed the use of the suction system to improve high lift performance during low speed climbout.
>
> The third task addressed the use of the suction system to improve Mach 0.9 cruise performance. Also, economics and community noise impact were quantified.

The next three charts summarize the results of the three successive tasks.

HLFC on HSCT

Past Boeing/NASA LaRC Studies

1. Contract NAS1-15325 (FY '88)
   - Laminarization issues
   - Hybrid laminarization schemes
   - Initial performance benefits
   - Identification of research needs
2. Contract NAS1-18377 (FY '89)
   - Low-speed BLC requirements and compatibility with supersonic cruise HLFC system
   - Revised performance and economics
3. Contract NAS1-18377 (FY '90)
   - $M = 0.9$ cruise HLFC requirements and compatibility with supersonic cruise HLFC system
   - Performance, economics, and community noise

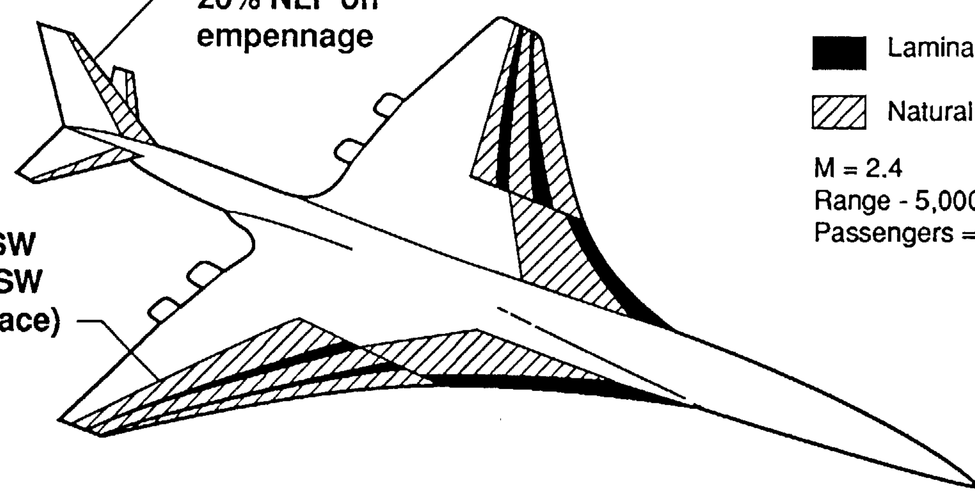
HLFC APPLICATION TO HSCT

The first task defined a HLFC scheme that accomplished a laminar flow run over 40% of the wing surface area; consisting of laminar flow regions with suction, as well as natural laminar flow regions.

The aerodynamic benefit is an impressive supersonic cruise drag reduction of 8.5%. There are significant implementation penalties, as shown. These penalties were identified as a result of indepth design studies. These penalties were accounted for when we determined the net performance benefits of HLFC. The additional maintenance cost is included in the economics. Net benefits are impressive as well.

The economic benefits are due mainly to the reduced fuel consumption.

HLFC Application to HSCT



Aerodynamic benefit
- Cruise drag reduction: 8.5%

Implementation penalties
- System and structural weight increment: 8,000 lb (2.7% of OEW)
- System fuel displacement: 38,000 lb (10.3% of available fuel volume)
- Engine power extraction: 1,185 HP (0.4% TSFC penalty)
- Suction air momentum drag: 0.45 counts (0.4% of cruise drag)

Performance benefits
- MTOW reduction 5.5%
- OEW reduction 1.7%
- Engine size reduction 8.5%
- Block fuel reduction 10.0%

Economic benefit
- 18% reduction in surcharge required for 12% ROI

CRUISE HLFC/LOW SPEED BLC COMPATIBILITY

The achievement of laminar flow on HSCT upper and lower wing surfaces requires the elimination of steps, gaps and discontinuities.; hence a desire to eliminate moveable high lift devices on the leading edge.

Studies were performed on a wing with no leading edge devices on the inboard wing and simple hinged leading edge flaps on the outboard wing.

The supersonic HLFC suction system was employed in a low speed BLC mode to retain attached flow to yield high lift/drag ratios during high lift conditions; so important for low noise over the community.

Engineering studies showed that the supersonic HLFC system can be operated at low speed to provide high lift suction BLC on the inboard wing leading edge and on the outboard wing leading edge flap hingeline.

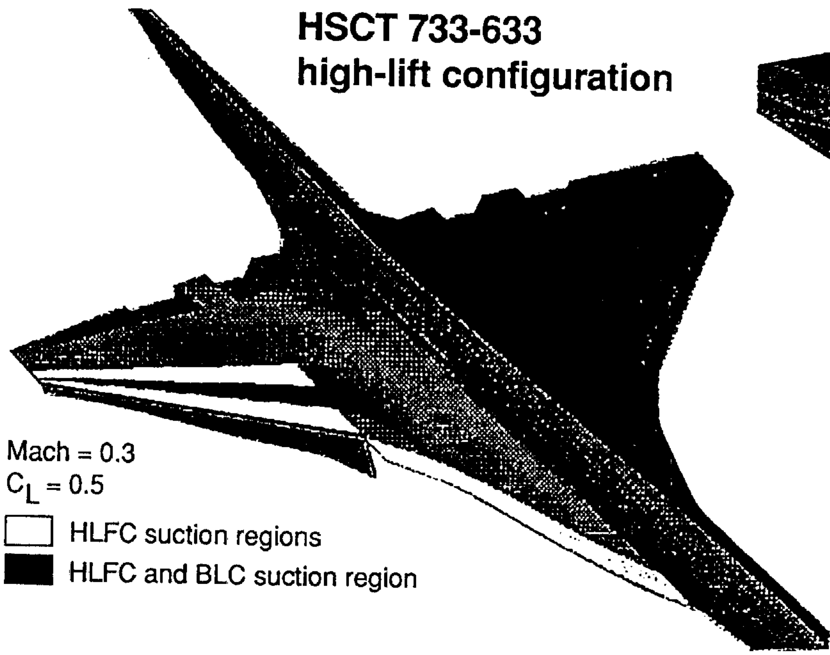
Aerodynamic simulations showed the potential for achieving attached flow with the use of high lift suction BLC and corresponding improvements in lift/drag ratio of 10%.

The improvement in lift/drag ratio ,in turn,reduces community noise to the same level that was achieved previously with full-span leading edge flaps, before HLFC was added.

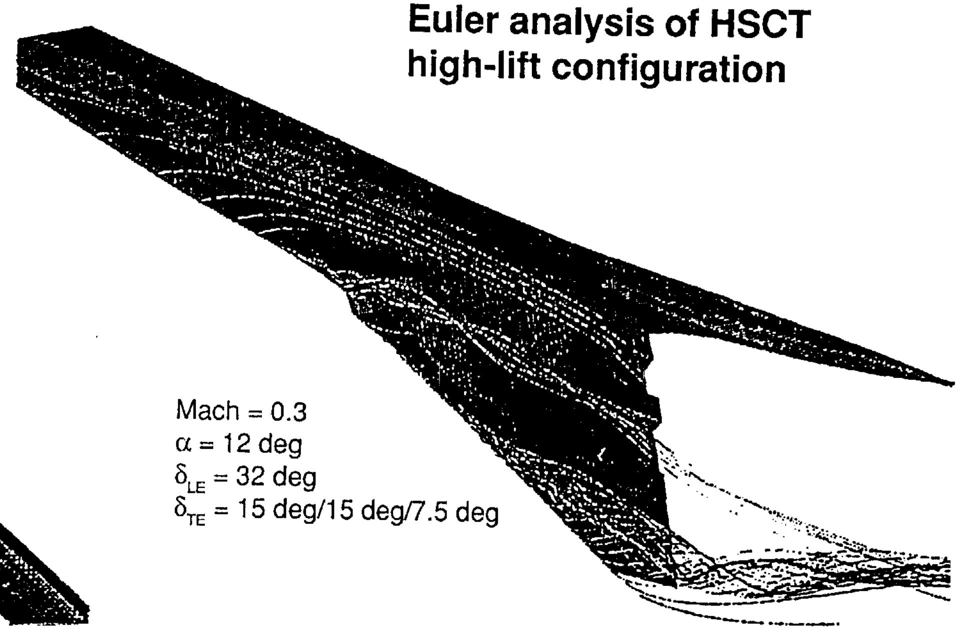
Hence the added cost of the HLFC system is partly offset by a simpler high-lift flap system.

Cruise HLFC/Low-Speed High-Lift BLC Compatibility

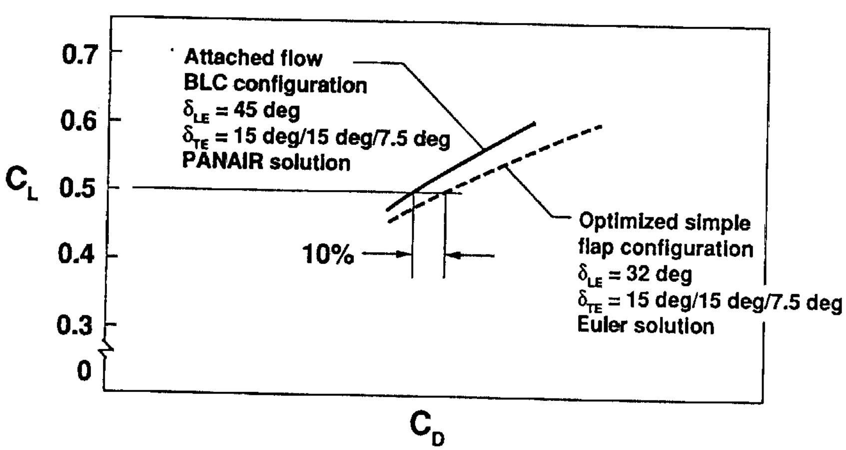
HSCT 733-633 high-lift configuration



Euler analysis of HSCT high-lift configuration

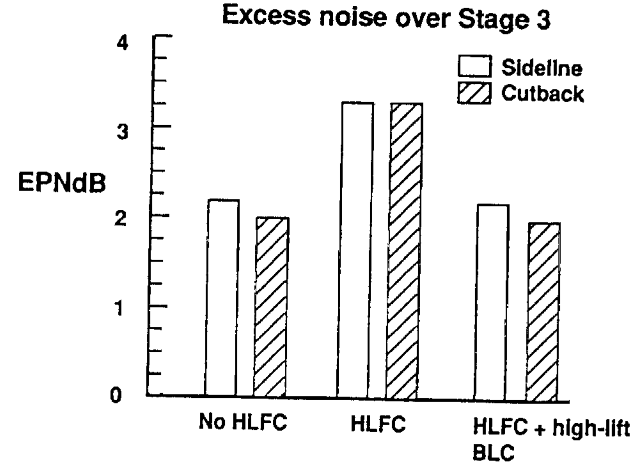


High-lift benefit



Community noise benefit

Excess noise over Stage 3

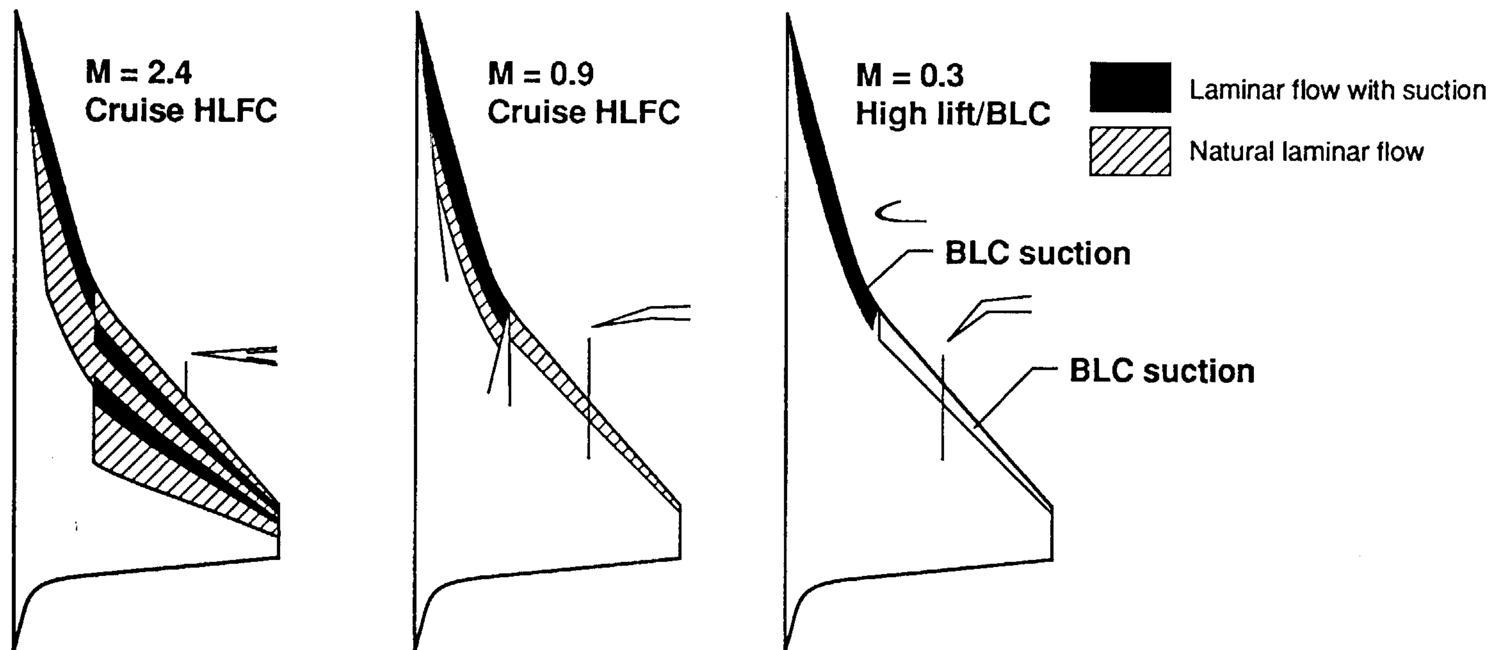


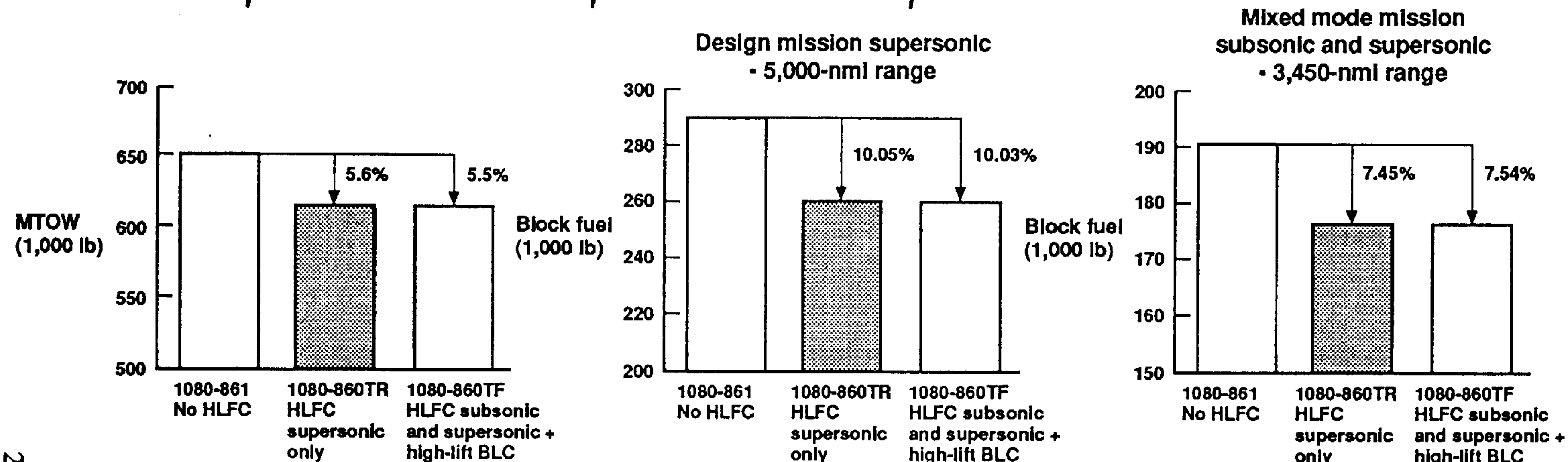
IMPACT OF M 0.9 HLFC AND HIGH LIFT BLC

The illustrations in the upper half of the Figure show the operation of the suction system in the three modes investigated: mach 2.4 cruise, mach 0.9 cruise and mach 0.3 high-lift BLC.
Using the suction system during mach 0.9 cruise showed only minor benefits. The primary reason being that drag benefits due to changing wing camber through leading edge flap deflection outweigh the drag benefits due to laminar flow; which can only be achieved with flaps retracted.

Essentially no change occurred in airplane MTOW and block fuel, as indicated by the small differences between the second and third bars in the barcharts.

Impact of M = 0.9 HLFC and High-Lift BLC





CONCLUSIONS TO DATE

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This concludes the first part of the presentation. The second part focuses on the R&D effort required to mature the LFC technology to the level where it could be considered for incorporation into the HSCT.

Conclusions to Date

Implementation studies on HSCT show:

- Net benefits in terms of reduced MTOW, OEW, fuel burn, engine size, and fuel heating rates are impressive
- Performance benefits outweigh cost penalties for HLFC system and maintenance to yield significant net economic benefit
- Benefits increase with increasing design range
- Annual fuel savings are five times greater than on subsonic aircraft
- Significant R&D effort needed in aerodynamics, structures, manufacturing, and systems technologies to attain level of practical implementation

REQUIREMENTS FOR PRODUCTION COMMITTMENT

Before any airplane manufacturer commits a high risk technology, like laminar flow control, to a production program, a demanding set of requirements must be satisfied.

For example, we must have in hand hard data that prove not only that we can make an efficient design but also that this design is producible, certifiable and cost effective to own and operate.

To do that we must have in hand the capability to predict performance benefits and penalties, the airplane's useful life, production costs and schedules, maintenance and repair costs, to name but a few. These are reasonable requirements, given the uncertainties of a complex new system like HLFC.

The task before us is to define and perform a risk reduction program at the conclusion of which we will have met the majority of these requirements.

Requirements for Production Commitment

Must have in hand:

- Capability for making an efficient, producible, certifiable, cost-effective design
- Capability to predict performance benefits and penalties
- Design criteria and allowables
- Capability for predicting the airplanes' useful life
- Capability for predicting production cost and schedules
- Capability for predicting maintenance and repair costs
- Satisfactory production processes
- Production facility requirements
- Airline acceptance

HSCT - HLFC RISK REDUCTION PROGRAM

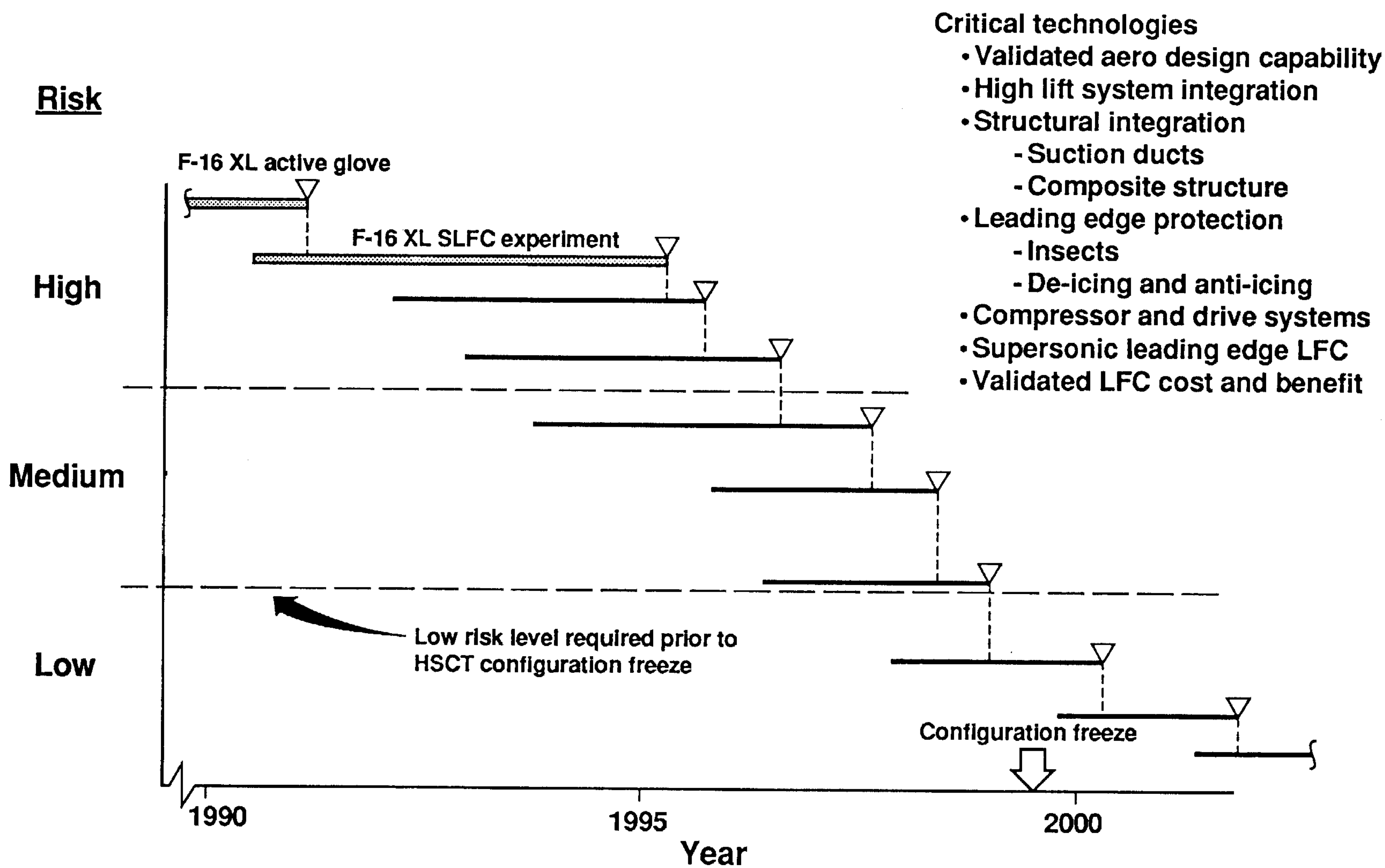
Illustrated here is a typical risk reduction program. A step-by-step systematic approach to develop the critical technologies, and to reduce the technical risk.With each successive step the risk is gradually reduced until it reaches the low risk level required for incorporation into the HSCT, prior to configuration freeze.

The F-16XL supersonic aerodynamic experiment is but one important element; it does not address many of the other critical technology issues, such as high lift system integration, structural integration, compressor and drive system, that will be required on the HSCT.

The message here is that: 1) a lot of work needs to be done in a relatively short time, 2) the F-16 XL experiment needs to be accelerated, and 3) other critical technologies need to be developed in parallel.

In the following charts we will give you our views on the required development program.

HSCT–LFC
Risk Reduction Program



FUTURE DIRECTIONS IN LAMINAR FLOW APPLICATIONS

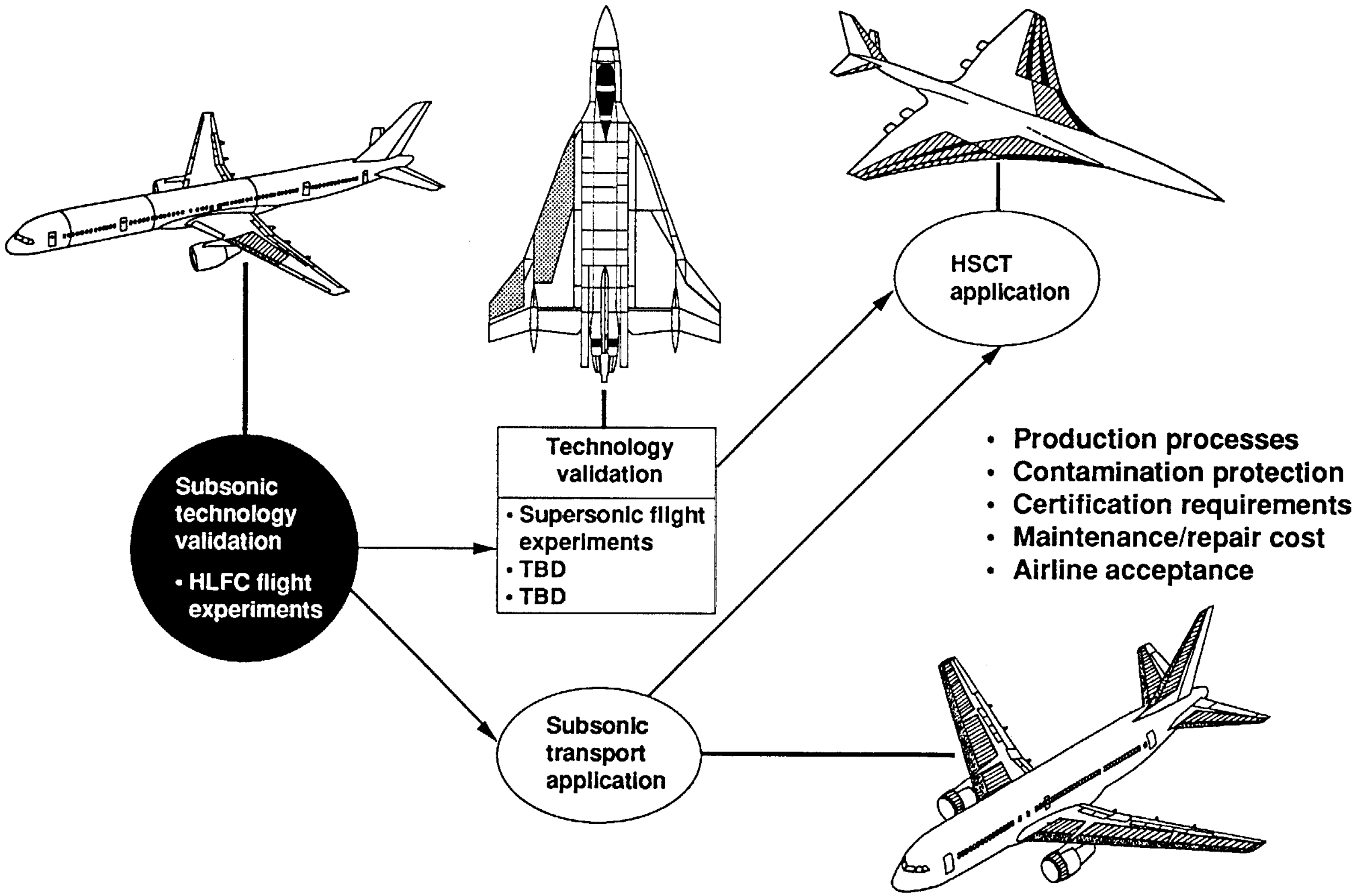
We believe fantastic progress has been made towards applying laminar flow control to commercial transport by the very successful 757 HLFC flight experiment. For example, we have successfully drilled millions of holes with laser beams, formed and bonded large titanium panels and achieved longer laminar runs than predicted with reduced suction requirements.

More development will be required and is being planned to prepare for subsonic transport application of HLFC.

The supersonic technology validation program has to clear similar hurdles, because many of the integration problems are unique to the HSCT application.

However, in many cases the subsonic transport application will pave the way for supersonic application. For example, the experience gained in titanium perforation processes, contamination protection, certification, maintenance, repair and airline acceptance will be transferrable to HSCT.

Future Directions in Laminar Flow Applications



SUPERSONIC HLFC DEVELOPMENT PLANNING

We would like to offer to you our recommendations for a NASA/Industry risk reduction program, that would develop HLFC technology for possible incorporation into a year 2005 HSCT program, year 2000 configuration freeze.

Supersonic HLFC Development Planning

- Define a NASA/industry risk reduction program that would develop HLFC technology for possible incorporation in a year 2005 HSCT program (year 2000 configuration freeze)
- Near-term workshop at Langley to coordinate the planning process

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PLANNING GROUND RULES

The plan was laid out using the ground rules summarized in this chart

read chart

Planning Ground Rules

- Satisfy requirements for production commitment by 1999 (prior to configuration freeze)
- Address technical issues first—do not pace development by availability of people and resources
- Schedule for most rapid technical progress possible
- F-16XL aircraft available for flight experiments

PLAN ELEMENTS

We have addressed:

read chart

We have yet to address:

Priorities and decision gates

Resource estimates

Plan Elements

- Technology development
  - Aerodynamics
  - Systems
  - Structures
  - Manufacturing
- HSCT airplane design studies
- Hardware demonstrations
  - Ground
  - Flight

- Priorities and decision gates (TBD)
- Resource estimates (TBD)

AERODYNAMIC TECHNOLOGY

The objectives of the risk reduction program in aerodynamic technology, in broad terms, are summarized here:

We need to improve and validate prediction methods for transition and suction requirements in order to meet the next objective:

> Optimization of airfoil and wing design, considering laminar flow requirements, to achieve maximum drag reduction with the least amount of suction.

The achievement of laminar flow and high-lift must go hand in hand. The objective is to develop and validate a laminar flow/high-lift compatible aerodynamic system.

Aerodynamic Technology

Objectives:

- Improve and validate prediction methods for transition and suction requirements
- Optimize airfoil/wing design, considering laminar flow requirements
- Validate laminar flow/high-lift compatibility
- Understand HLFC impact upon HSCT stability and control

LAMINAR FLOW/HIGH - LIFT INTEGRATION

As pointed out earlier, studies at Boeing to date indicate that an aerodynamic concept for achievement of laminar flow and high-lift might use the following approach:

1) on the subsonic, inboard portion of the wing-a blunt leading edge without flaps. At high angles-of-attack attached flow is maintained through suction BLC at the leading edge

2) on the supersonic, outboard portion of the wing- a sharp leading edge with simple hinged flaps. At high angles-of-attack attached flow is maintained through suction BLC at the hingeline.

The technical issues to be solved during the risk reduction program are:

read chart

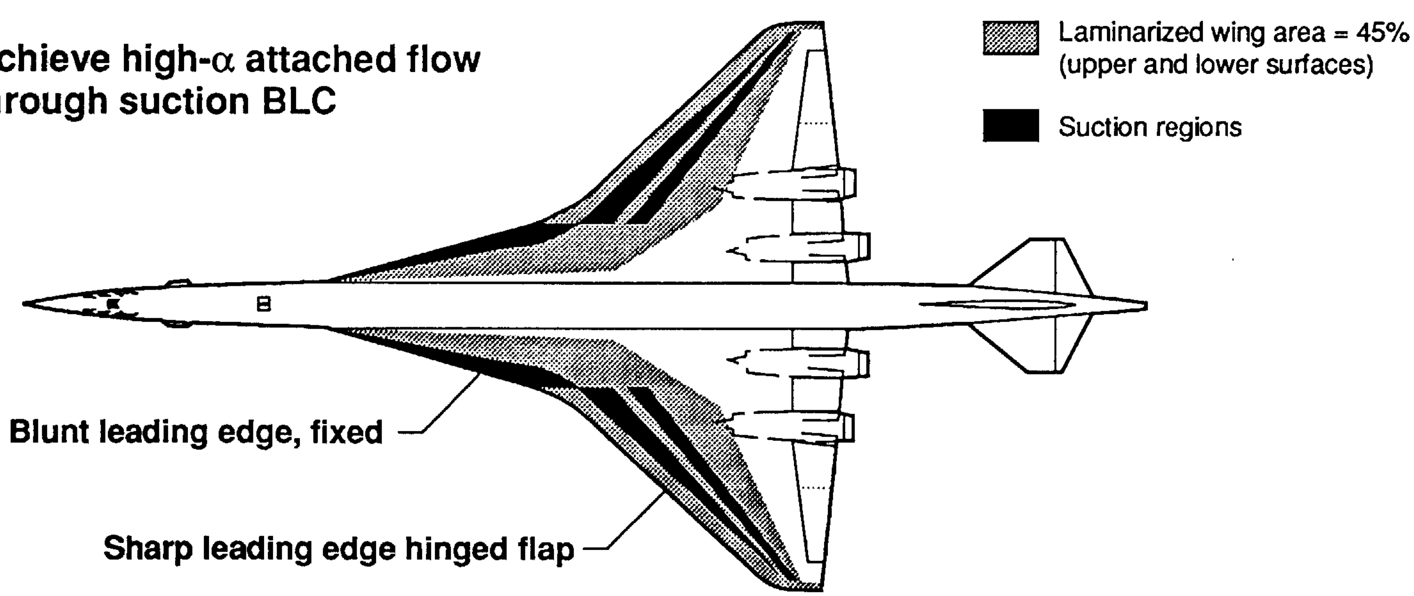
We are proposing incremental modifications of F-16 XL aircraft-beyond the planned extended suction glove experiment- for HLFC and high-lift compatibility experiments.

Laminar Flow/High Lift Integration

Issues:

- Leading edge radius and camber
- Suction for LFC and separation control
- Impact of hinge lines, steps, and gaps
- Insect protection, anti-ice, de-ice
- Subsystem design
- Subsystems compatibility

Objective: Achieve high-α attached flow through suction BLC



F 16-XL MODIFICATIONS FOR HLFC AND HIGH-LIFT EXPERIMENTS

We do not expect the HSCT wing planform to have the F-16 XL "S"curve in the apex region.We propose supersonic HLFC experiments on the F-16XL, depicted on the left of the Figure, which would eliminate the "S" curve by extending the suction glove to the side of the fuselage. In addition, a suction glove could be added to the supersonic, sharp leading edge, outboard wing for follow-on experiments

.

Flight demonstration of the modified glove and suction system in the high-lift mode is illustrated on the right side of the Figure. The HLFC suction system would be designed and operated in the high-lift BLC mode to demonstrate the ability to maintain attached flow.

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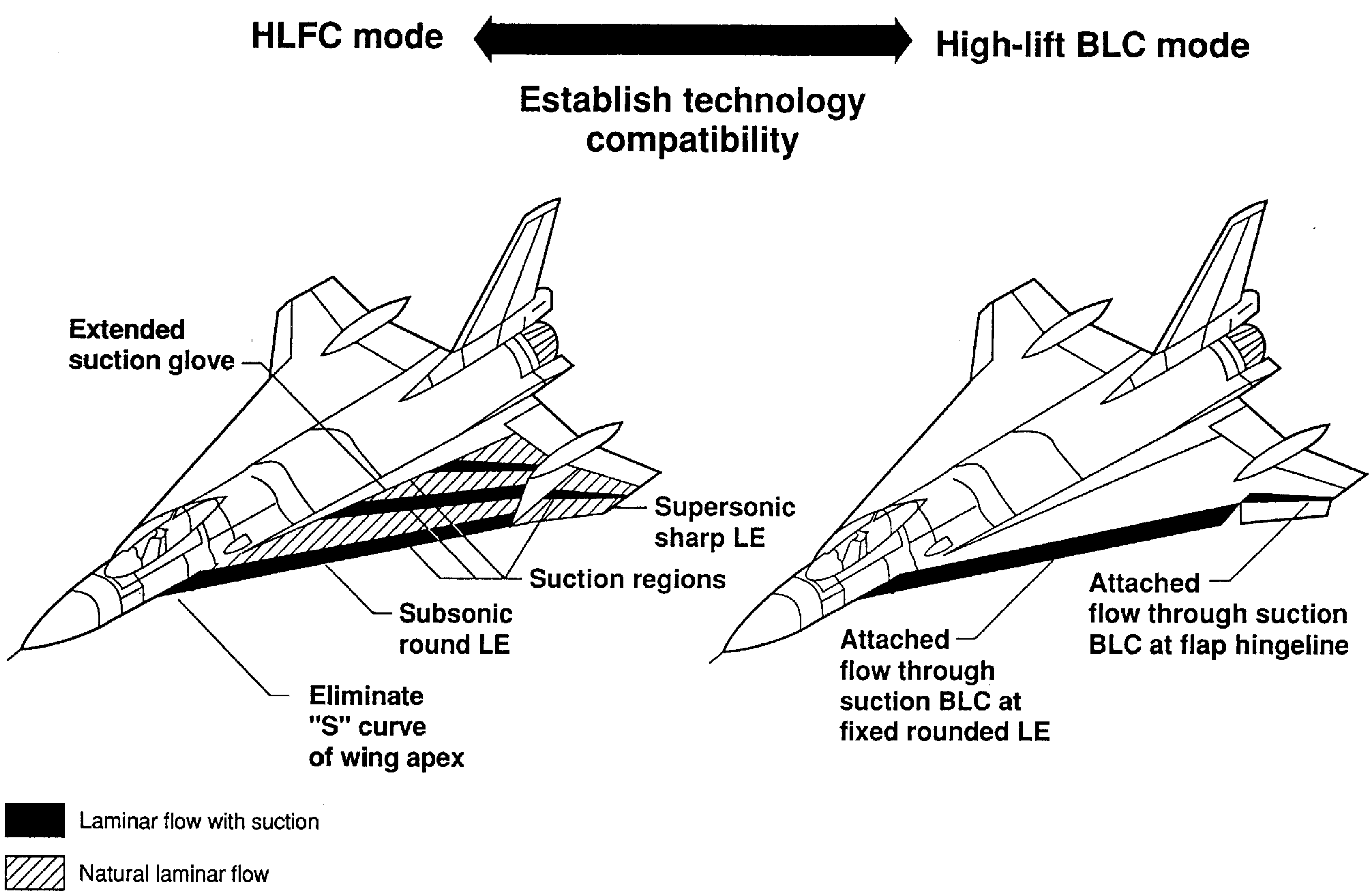
F-16 XL Modifications for HLFC and High-Lift Experiments



INTEGRATED SCHEDULE-HLFC/HIGH-LIFT EXPERIMENT

Here is our view of an integrated schedule for HLFC/high-lift experiments.

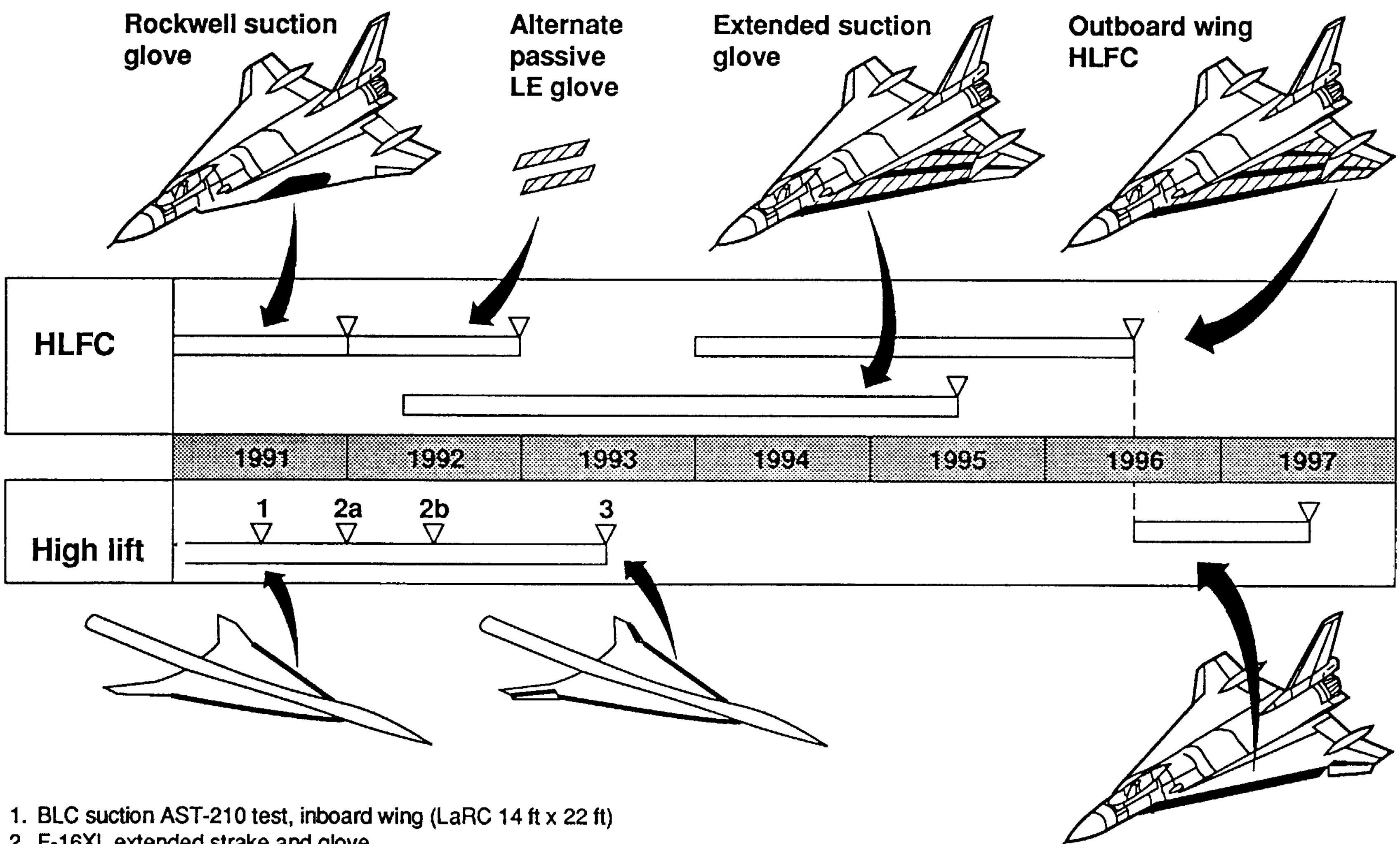
Some of the experiments are already planned by NASA, but they remain to be finalized and accelerated. HLFC experiments include:

- additional experiments on ship 1
- experiments with alternate passive gloves
- F-16 XL extended suction glove experiments, and
- additional proposed experiments to laminarize the outboard wing, and the elimination of the "S" curve, in case that cannot be accomplished in connection with the planned extended suction glove experiment.

A high-lift experiment already planned is a BLC suction test on the inboard wing of a modified AST-210 model (milestone 1). A BLC suction test on the inboard & outboard wing of the same model (milestone 3) should also be conducted.

Milestone 2a indicates the need for F-16 XL high speed and low speed wind tunnel tests with the extended suction glove; and milestone 2b indicates the need for flight simulations.

Integrated Schedule, HLFC/High-Lift Experiment



1. BLC suction AST-210 test, inboard wing (LaRC 14 ft x 22 ft)
2. F-16XL extended strake and glove
   2a. S & C wind tunnel test (HS and LS)
   2b. S & C flight simulation
3. BLC suction AST-210 test, inboard and outboard wing (LaRC 14 ft x 22 ft)

ADDITIONAL AERODYNAMIC EXPERIMENTS

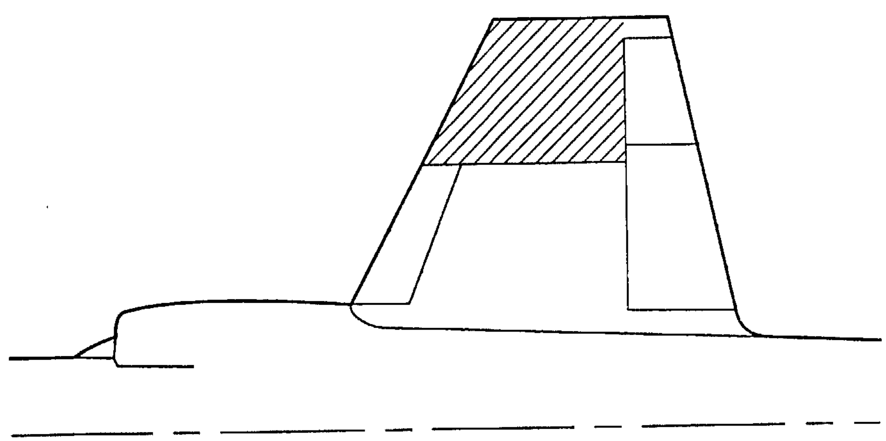
We have identified the need for at least three additional aerodynamic experiments:

1) a high speed pressure model test for the purpose of validating CFD codes for wing cp prediction.

2) a high speed test of an HSCT model where the wing has been optimized for HLFC. Comparison with test data for a baseline non-HLFC wing design would yield the incremental drag due-to-lift and wave drag, if any.

3) a flight test on the F-104 supersonic leading edge wing (in case that cannot be accomplished on the F-16 XL) for the purpose of obtaining 3D supersonic boundary layer transition data to calibrate boundary layer stability codes.

Additional Aerodynamic Experiments

Experiment	Purpose
High-speed pressure model test (LaRC unitary plan)	Validate CFD codes for wing C_P prediction
High-speed test of HSCT model with wing optimized for HLFC (LaRC unitary plan)	Determine impact on drag due to lift and wave drag
F-104 laminar flow flight test 	NLF and HLFC tests on supersonic leading-edge wing to calibrate stability codes

SUB-SYSTEMS TECHNOLOGY

The challenge facing us in the sub-systems technology area is to minimize the penalties associated with providing the HLFC capability. Hence, the objective is to integrate the HLFC system functions with other system functions on HSCT as much as possible.

To meet this objective the following major issues need to be addressed through design, analyses and experiments:

1) flow control to provide optimum flow distribution for LFC, high-lift BLC ,anti-ice and insect protection. The former two will be accomplished through appropriate suction control. The latter two can be accomplished, possibly, through "glycol-sweating". All four using the same flutes and skin perforations.

2) another issue is the integration of the extensive ducting system with load carrying wing structure to minimize the parasitic weight increment.

3) an intriguing idea is to integrate the air cycle machinery for the LFC and the Environmental Control System (ECS) to minimize system duplication, power extraction and power transmission losses. It is expected that novel integrated system architectures can be evolved as we intensify our studies on HSCT during the coming years.

Ground test requirements will need to be defined to demonstrate the new multi-function subsystem capability. Appropriate hardware-in-the-loop ground tests will need to be designed and conducted with support from suppliers.

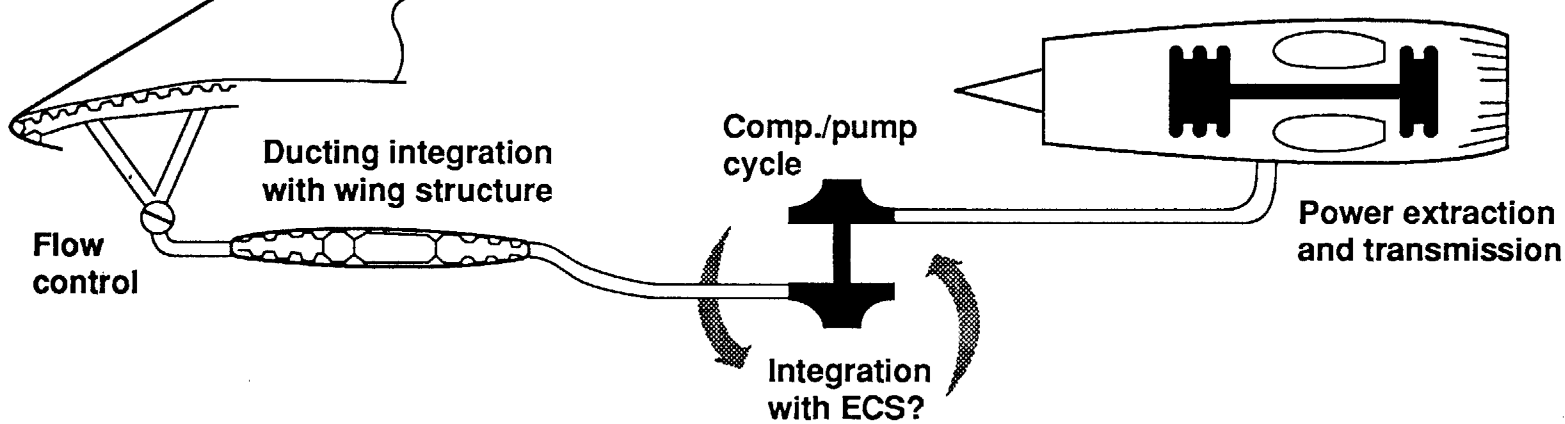
Subsystems Technology

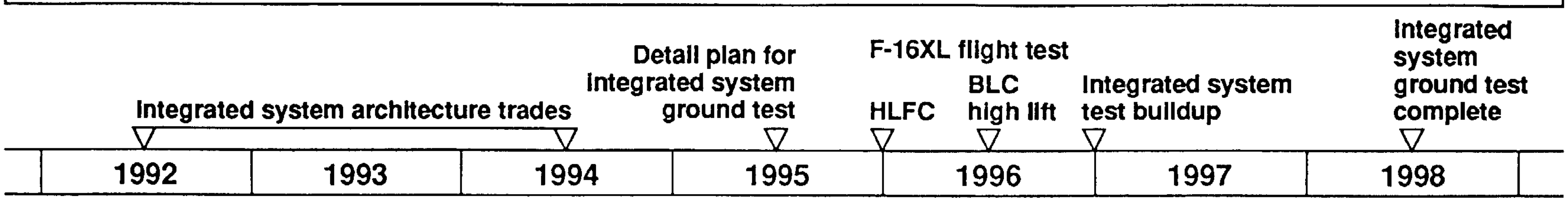
Objective:

- Integrate HLFC system requirements with other system functions on HSCT to minimize implementation penalties

Issues: Optimum flow distribution

- LFC function
- High-lift BLC
- Anti-ice
- Insect protection





STRUCTURES AND MANUFACTURING TECHNOLOGY

A substantial risk reduction program will be required in structures and manufacturing technology. Whereas on subsonic applications like 757, the suction panels and ducting are located in the wing leading edge region, on the HSCT the suction panels and ducting may have to coexist with wing fuel tanks. On the outboard wing, in addition, these systems have to be integrated into thin, highly loaded primary wing structure.

Hence, the objectives of the risk reduction program will be to validate the integration of the HLFC system with primary wing structure; and to establish weight and cost parameters.

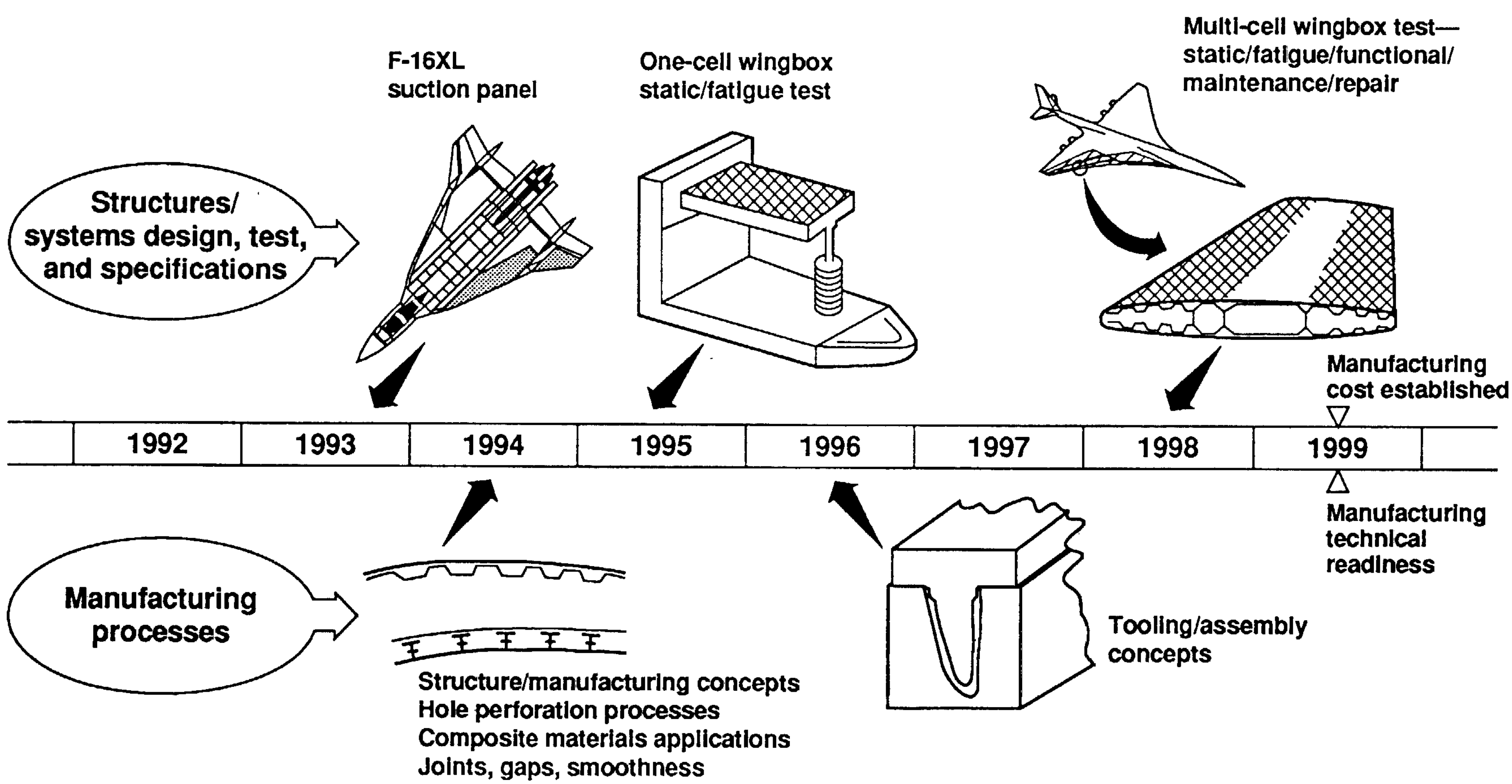
The proposed approach is to build a multi-cell wing box section representative of the outboard wing with suction panels in the fuel tank area. Perform ground tests to validate static and fatigue performance, functional compatibility of the HLFC - and fuel systems, and to demonstrate maintenance and repair approaches.

Some of the intermediate steps along the way are illustrated on the schedule.

Structures and Manufacturing Technology

Objective:
- Validate integration of HLFC with primary wing structure
- Establish weight and cost parameters

Approach:
- Build a multi-cell wing box section with suction belts in tank area
- Ground test – static/fatigue/functional/maintenance



HSCT AIRPLANE DESIGN STUDIES

The objectives of concurrent airplane design studies are to develop the best possible HSCT configuration that derives maximum benefits from incorporation of HLFC.

In addition, airplane design studies are essential for:

- providing a focus and direction for HLFC technology development
- and to evaluate net performance and economic benefits

Earlier during this presentation we showed the benefits of HLFC on the initial HSCT concept which is illustrated in the Figure.

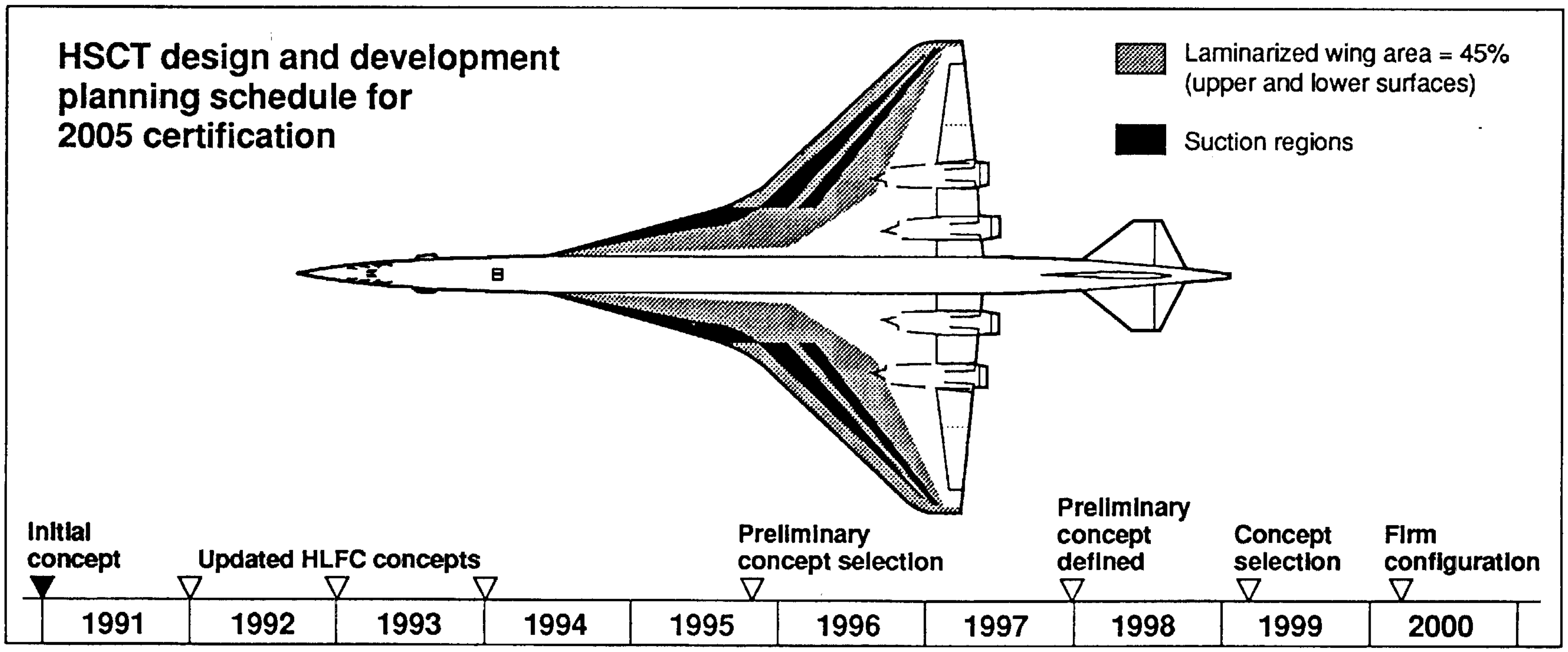
Currently,we are investigating HLFC on an updated HSCT configuration, which has a smaller supersonic leading edge outboard wing panel. Comparing results of the two studies will provide guidance on how to tailor configuration elements, such as the wing, for further improvements of the HSCT configuration

Key HSCT program decision gates relating to airplane concept selection , according to the current Boeing schedule, will occur between 1995 and 1999. If HLFC is to be aboard the selected airplane concept, risk reduction programs as outlined on the previous charts must have been completed successfully during that time period.

HSCT Airplane Design Studies

Objectives:

- Provide focus and direction for HLFC research
- Develop and evaluate HLFC integration concepts (Aero, Structures, Systems, Manufacturing)
- Minimize HLFC implementation penalties
- Develop best HSCT configuration with HLFC
- Evaluate net performance and economic benefits



SUMMARY AND RECOMMENDATIONS

Results of HLFC studies to date have shown that the technology has very high leverage on improving HSCT economic viability.

However, technical risk is high at this time, and an aggressive risk reduction program is required. The elements of the required risk reduction program have been outlined in this paper.

It is recommended that a NASA/Industry study group be formed and tasked to prepare a plan for such a risk reduction program by the end of 1991.

F-16 XL experiments have been identified that offer opportunities for accelerated validation of HLFC benefits

Summary and Recommendations

- LFC is a high-leverage technology for HSCT
- Technical risk is high; an aggressive risk reduction program is required to meet HSCT program schedule
- A NASA/industry study group should prepare a program plan in 1991
- F-16XL experiments offer an opportunity for accelerated validation of LFC benefits

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