NASA High-Speed Civil Transport Studies

Airframe Systems Studies Review

NASA High-Speed Research Workshop

May 15, 1991

BOEING

HSCT MISSION PERSPECTIVE

The reason for the renewed interest in the HSCT is because our marketing projections are telling us that there will be 500,000 people every day wanting to fly across the Atlantic or the Pacific by the time a fleet of HSCT's will be in service. This creates a potential market for over 1,000 HSCT's.

Required range is longer than for either Concorde or the US SST, which were designed for the North Atlantic.

Payload is two to three times that of Concorde because of the larger market; providing us with the improved economies of scale.

The airplane will also be twice as big as Concorde, but in the same weight class as the 747.

The airplane has to meet Stage III noise goals, which means it has to be much quieter than Concorde (approx. 15 EPNdB).

To capture the large potential market, the airplane must be affordable for the majority of air travellers. Our goal are fares no higher than 10% above equivalent subsonic fares.

NASA High-Speed Civil Transport Studies

HSCT Mission Perspective

	Concorde	U.S. SST	HSCT
Market	North Atlantic	North Atlantic	Atlantic and Pacific
Range, nmi	3,500	3,500	5,000-6,000
Payload (passengers)	103	200	250-300
TOGW, lb	400,000	750,000	800,000
Community noise requirements	None	Stage II	Stage III
Revenue required, cents/RPM	87	60	10

HIGH SPEED RESEARCH- SYSTEMS STUDIES GOALS

The goals of the airplane systems studies are consistent with Phase I of the NASA High Speed Research Program: provide realistic configurations to assess whether or not an HSCT could be environmentally acceptable by exploiting advanced technologies, identify innovative high-risk technologies, and prioritize those technologies for further development during Phase II of the NASA High Speed Research Program.

High-Speed Research - Systems Studies Goals

Maintain direction and focus on realistic configurations:

- Environmental issues technologies
- Innovative, high-risk technologies
- Technology prioritization and timing

COMMERCIALLY VIABLE HSCT

The process that we must use to determine whether we have a commercially viable HSCT or not is shown in this Figure. This process illustrates the systems studies approach of integrating the requirements for:

1) practical commercial airplane designs
2) emissions and noise
3) the market in terms of payload, range and fare

with the projected technology advances into a practical airplane design and then determining:

1) the designs' technical feasibility
2) its' economic viability, and
3) needed technology developments

NASA High-Speed Civil Transport Studies - Phase III

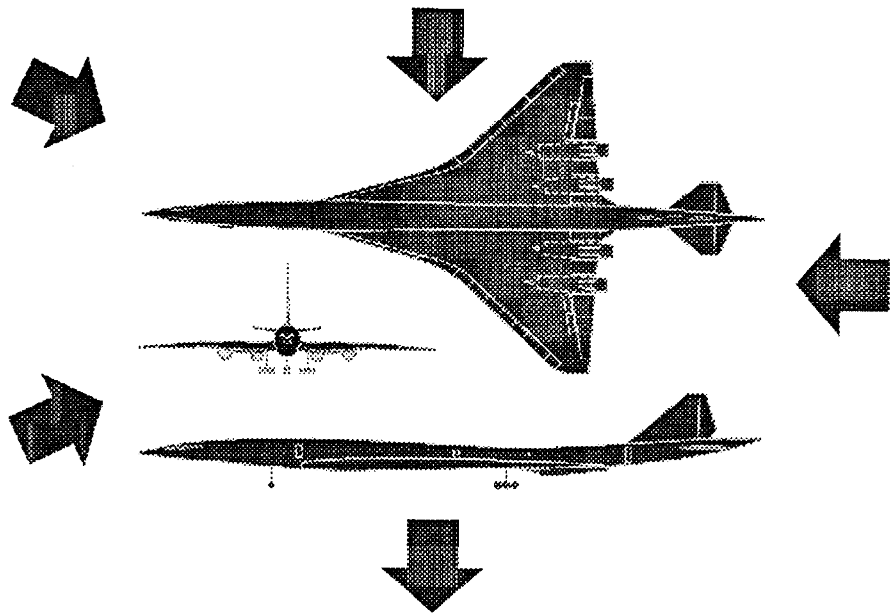
Commercially Viable HSCT

Commercial airplane
design requirements

Environmental
requirements

Market
requirements

Projected
technology



Assessment of -

- Technical feasibility
- Economic viability

HSCT AIRFRAME SYSTEMS STUDIES

Boeing has been participating with NASA in HSCT systems studies under under the High Speed Research Program since 1986.

There have been five program phases. Their objectives and timing are summarized in the Figure.

During Phase I we looked at a very broad range of concepts, with speeds from Mach 2 to 10. We assessed technologies, environmental issues and market physics.

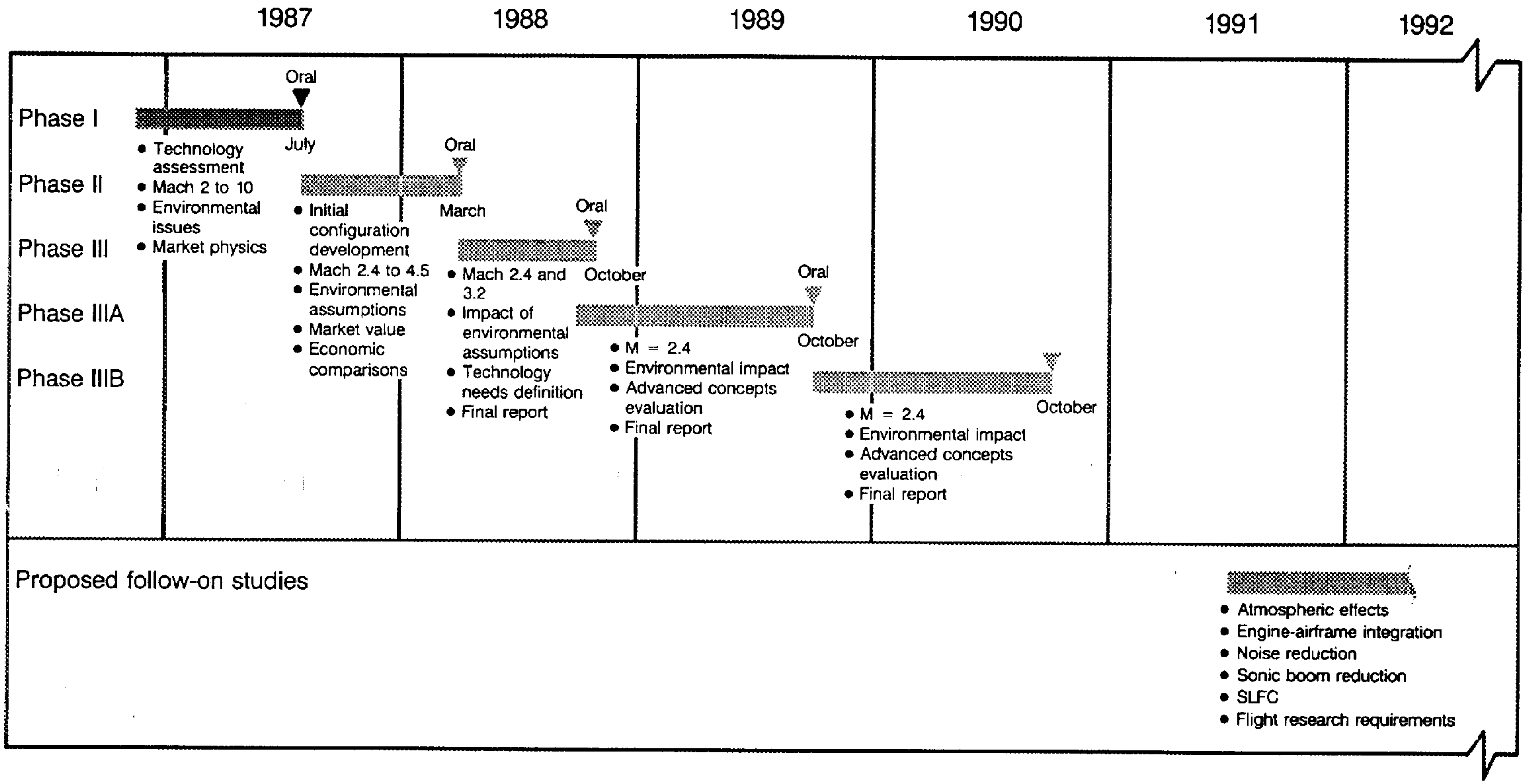
In the later program phases we focused on the lower Mach numbers because they looked most promising for an HSCT.

In this presentation we will summarize for you the highlights of each of these study phases.

We are ready to embark on a 5 year follow-on program of additional NASA/Industry HSR systems studies, to further address and resolve the barrier environmental issues and to advance the relevant high-risk technologies.

I shall briefly discuss the proposed work,as well.

HSCT Airframe Systems Studies



NASA HSCT STUTY - PHASE I

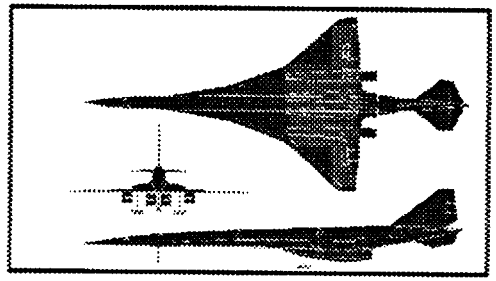
The Phase I objective was to investigate a possible synergism between the National Aerospace Plane and its' technologies and a future HSCT.

The upper Mach number limit for investigation was quickly reduced from Mach 25 to Mach 10. Mach 2.4 was picked as the lower limit. A matrix of concepts was evaluated.

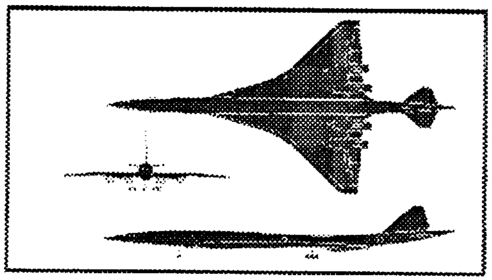
Hydrocarbon was the fuel of choice for the lower Mach number concepts. Cryogenics were the fuels of choice for the higher Mach number concepts.

NASA HSCT Study Phase I

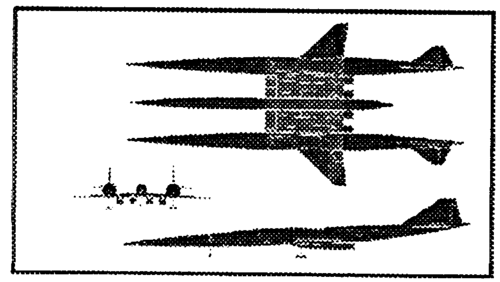
Mach 4.5



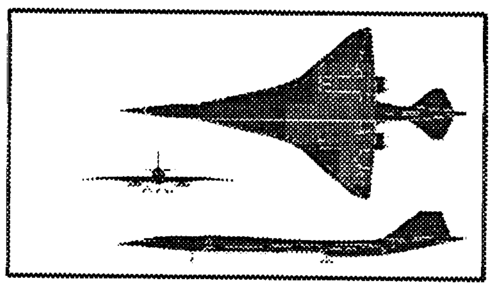
Mach 2.4



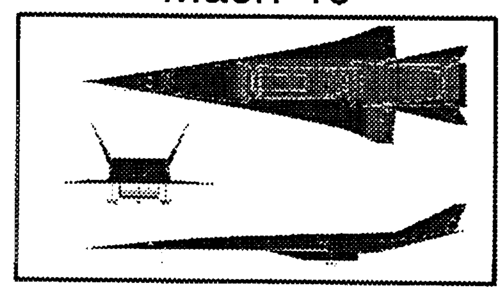
Mach 6.0



Mach 3.2



Mach 10



Hydrocarbon Fuel

Cryogenic Fuel

GROSS WEIGHT VERSUS MACH NUMBER

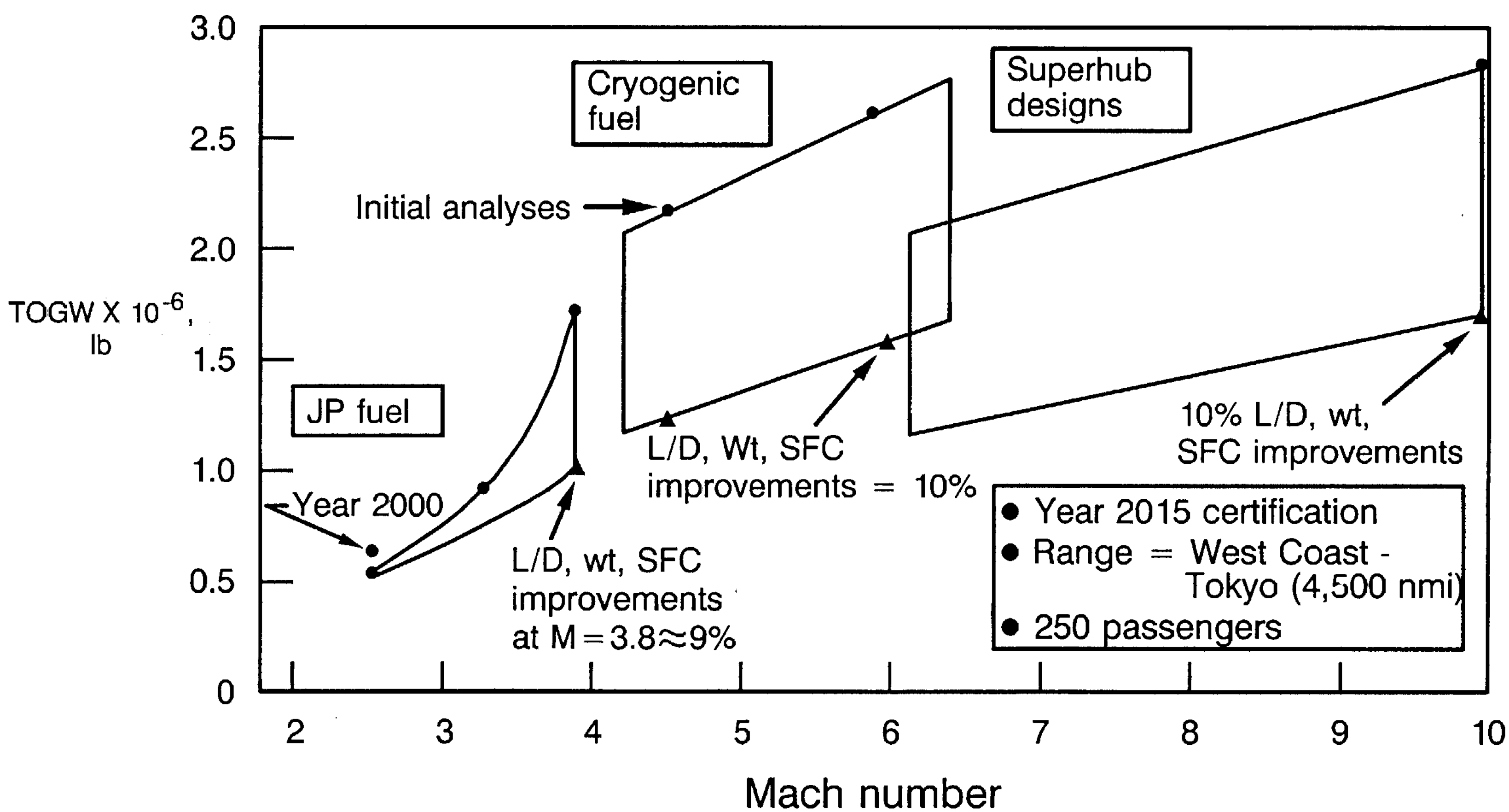
Evaluation of the initial concepts showed this trend in gross weight versus Mach number for vehicles sized to carry 250 passengers over 4,500 mile range.

The upper limit of the band represents year 2015 technology. You can see that any concept above Mach 3.5 exceeds one million pounds in TOGW.

We looked at how much we could reduce TOGW if it were possible to improve by 10%, respectively, aerodynamic lift-to-drag ratio, structural weight and specific fuel consumption. These improvements would reduce TOGW to the lower limit of the band.

Still, any concept above Mach 4 would exceed one mllion pounds, which we feel to be nearing the limit for commercial airports as we know them.

Gross Weight Versus Mach Number



EFFECT OF INCREASING CRUISE MACH NUMBER ON THE SYSTEM AVERAGE MACH NUMBER

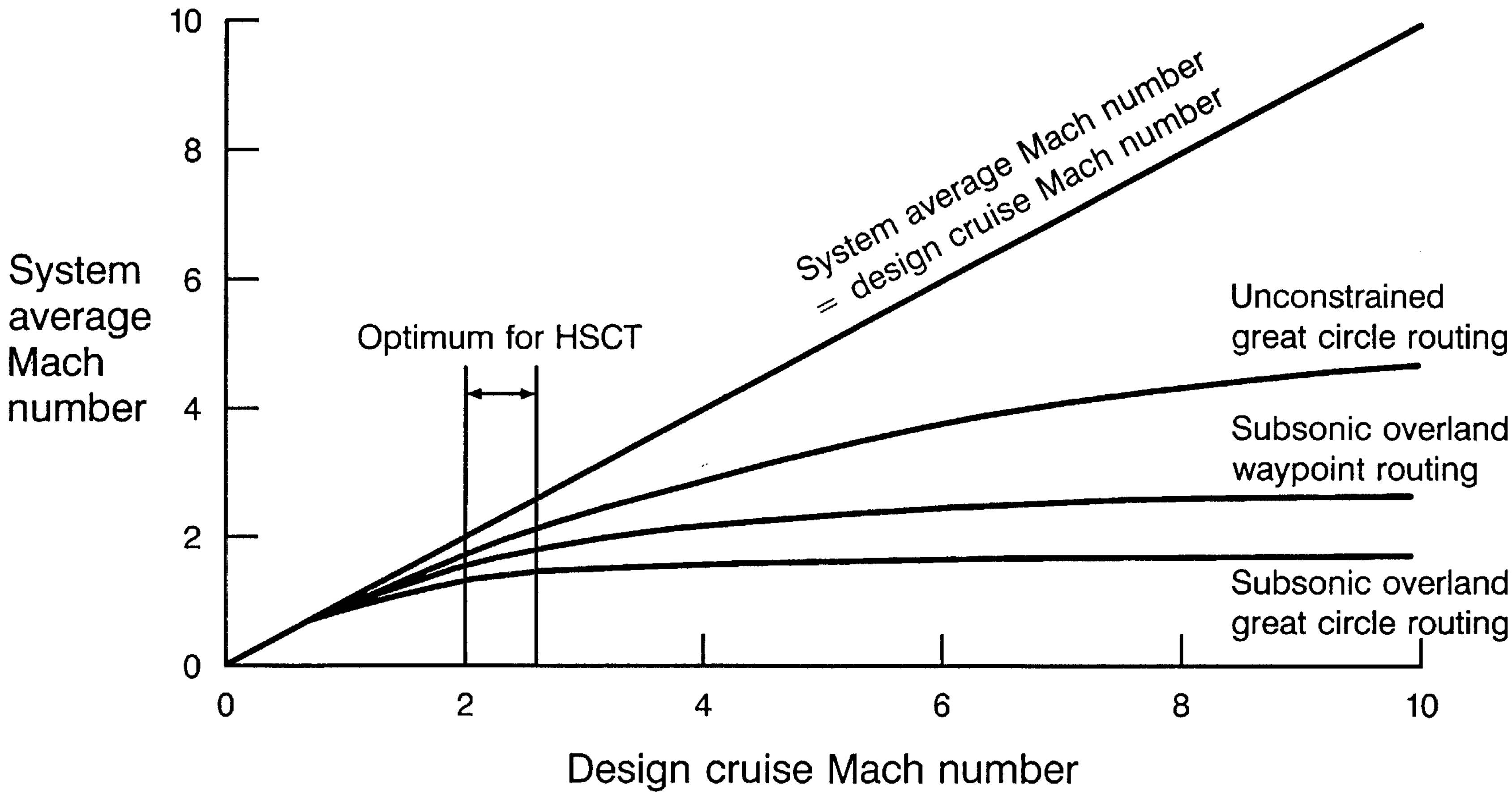
This Figure shows what the system average Mach number would be if you operate a high Mach design on a given airline route system.

As design Mach number increases, the airplane spends more and more time accelerating and decelerating. Which means that even with unconstrained great circle routing the average Mach number is reduced well below the design Mach number.

If you then add the realistic constraints of subsonic overland operation, one hour turn-around time and nighttime curfews, the average Mach number is reduced further. There is an optimum speed for HSCT in the Mach 2 to 3 region. Higher speed results in diminishing or no advantage.

For this reason, and because of the excessive TOGW of the Mach 4.5 plus designs, we focused on the lower Mach range during Phase II studies.

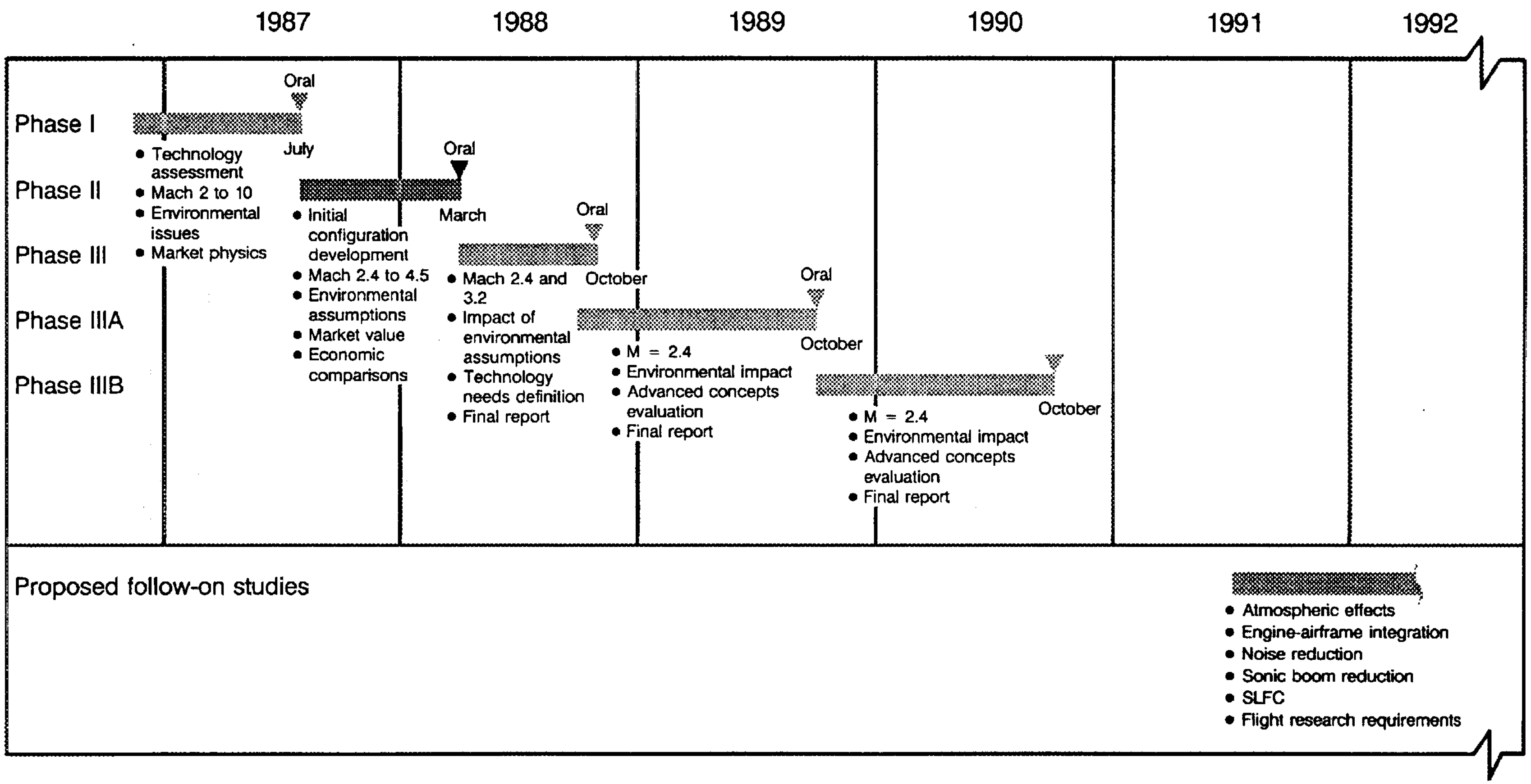
Effect of Increasing Cruise Mach Number on the System Average Mach Number



HSCT AIRFRAME SYSTEMS STUDIES

During Phase II we looked in greater depth at a reduced Mach number range. We looked at a matrix of Mach 2.4 to 4.5 designs, assessed their market value and compared their economics.

HSCT Airframe Systems Studies



AIRPLANE SIZE PROJECTIONS

The results are shown here, in terms of TOGW versus cruise Mach number.

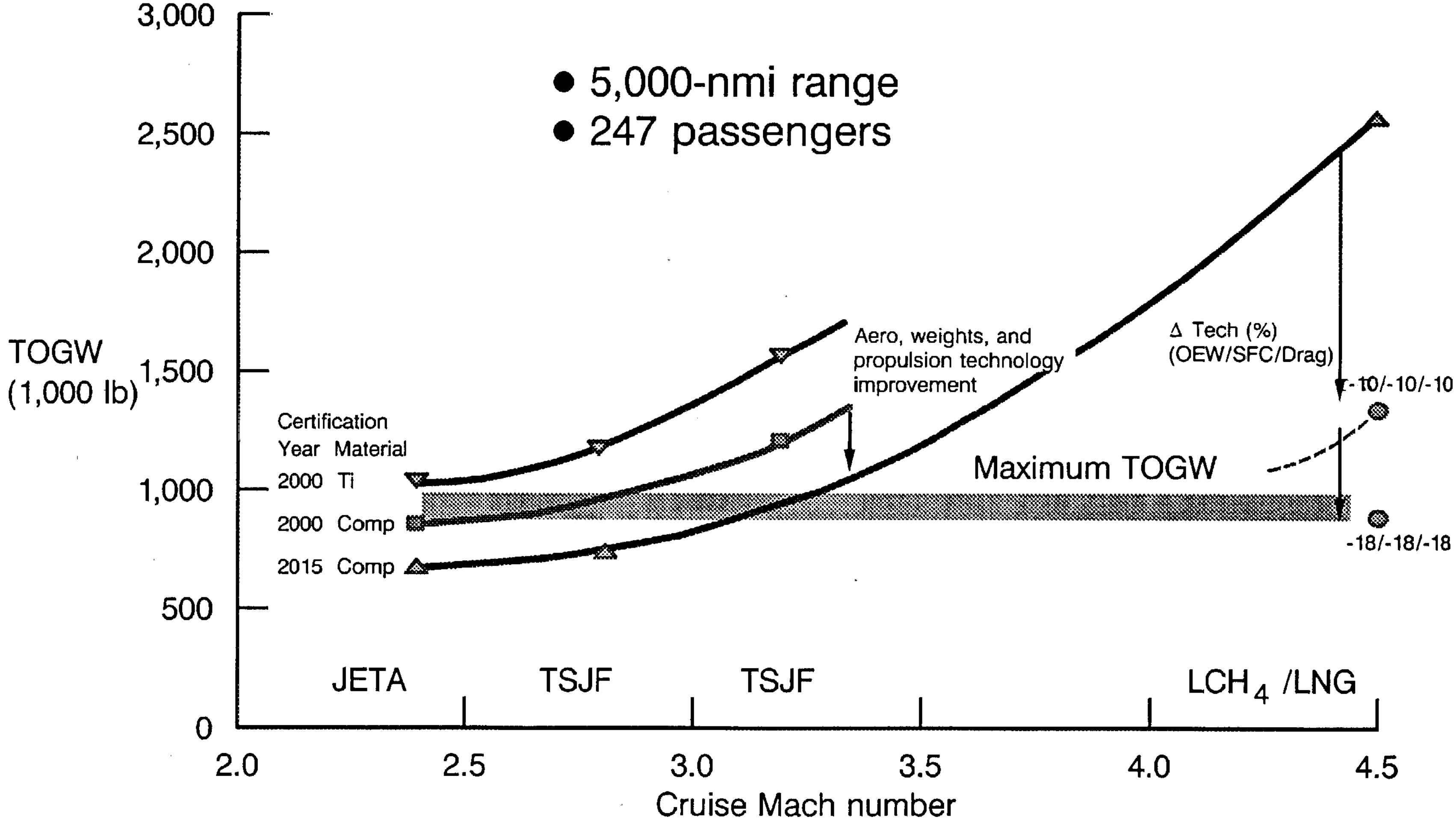
Airport handling considerations limit maximum TOGW to about one million pounds. Even with 2015 technology we exceed that limit somewhere between Mach 3 and 3.5. With current technology and with titanium structure there appears to be no feasible solution at all.

For the Mach 4.5 designs we determined that it would take an additional 18% improvement beyond year 2015 technology projections, in drag, structural weight and SFC, respectively, to reduce airplane TOGW below one million pounds.

We do not believe these large improvements are possible. Hence, we focused follow-on work on Mach numbers below 3.2. At these lower speeds we also avoid the need for cryogenic fuels and associated logistics problems. The required thermally stable jet fuels, with temperature limits 100F to 150F above Jet A, are considered a lower risk. They require only minor changes in the refining process.

NASA High-Speed Civil Transport Studies - Phase II

Airplane Size Projections



PHASE III GOALS

Goals for the Phase III studies, performed during 1988, are summarized here.

Read chart

Phase III Goals

Refine commercial viability studies

- Mach 2.4, 2.8, 3.2
- More indepth design work
- Refined economic analysis

Determine impact of environmental requirements

- Emissions reduction
- Community noise reduction trades
- Low sonic boom design

Define key technology needs

ENVIRONMENTAL GOALS

It will take the combined ingenuity of NASA and Industry to come up with the required technology breakthroughs to meet the tough environmental challenges that are facing us.

We are seeing some promising concepts already, but much more remains to be accomplished.

Environmental Goals

Emissions:

- No significant ozone depletion

Airport noise:

- As quiet as Stage III subsonic airplanes

Sonic boom:

- No perceptible boom over populated areas

AIRPLANE SIZE PROJECTIONS

In terms of airplane gross weight, it looks like there is a bucket in the curve between Mach 2.0 to 2.4.

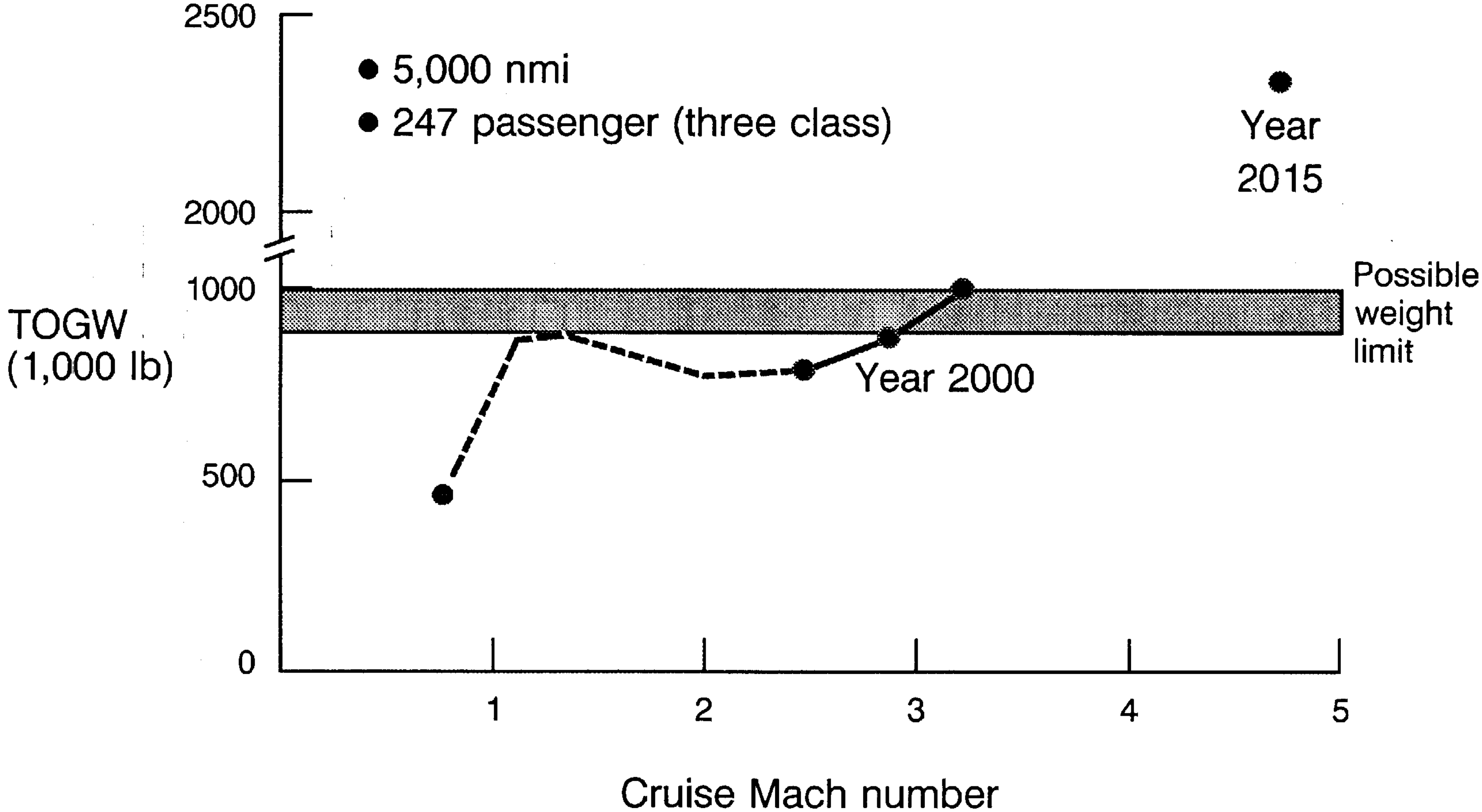
TOGW can be as low as 750,000 lb for a 5,000 mile airplane with 250 passengers, provided we achieve the weight savings associated with composite structures' improved specific strength and stiffness.

Based on that weight trend we have focused in on Mach 2.4, with the understanding that we can back off to Mach 2 if we discover any showstoppers.

NASA High-Speed Civil Transport Studies - Phase III

Airplane Size Projections

Composite Structure



IMPACT OF TECHNOLOGY

In this Figure we are taking a closer look at the impact of individual technology improvements on TOGW. The data is for the Mach 2.4 airplane with 250 passengers, 5,000 mile range.

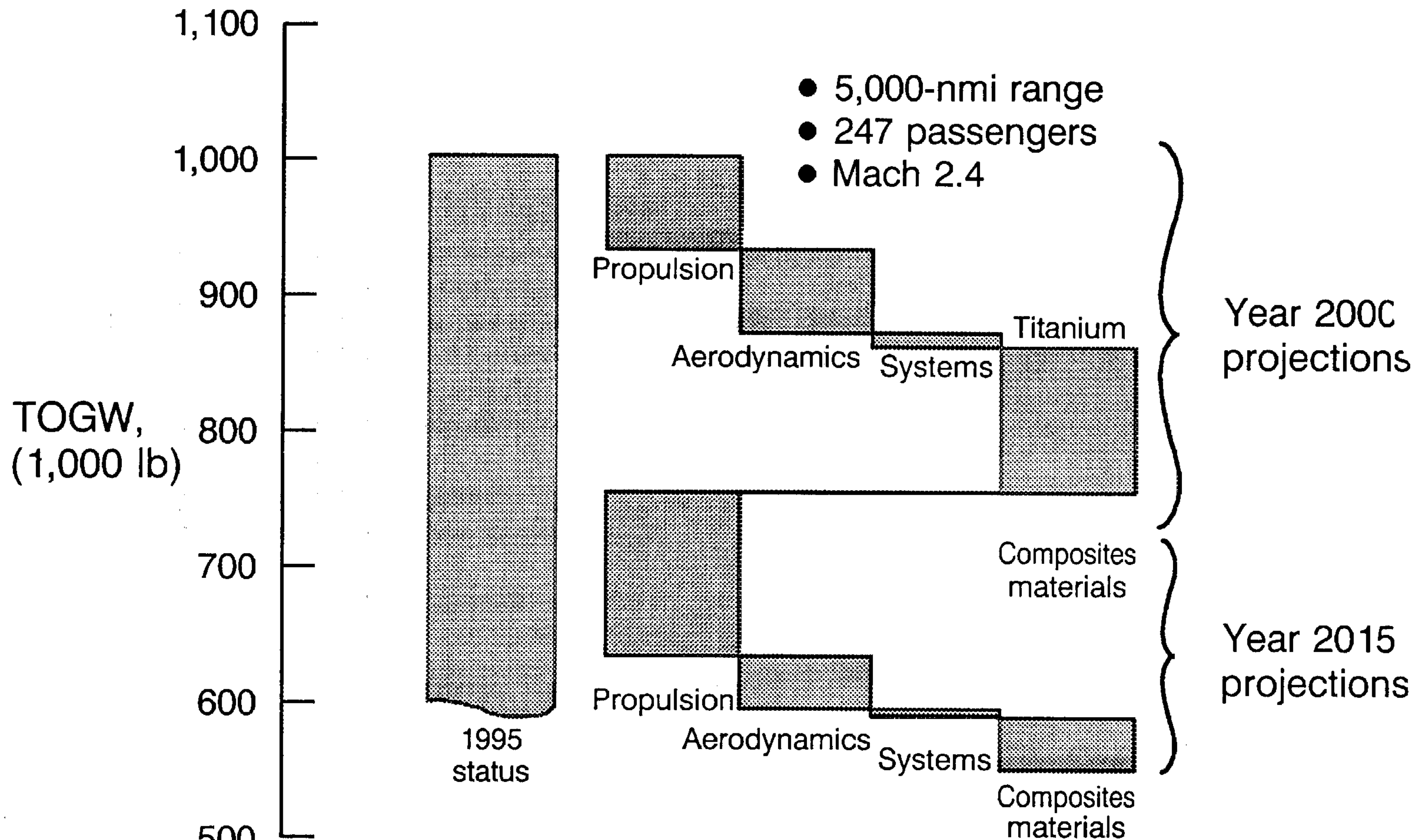
The point of departure is the 1995 technology titanium airplane at one Million pounds TOGW.

Incremental improvements are shown for advancing technology by five years in the areas of propulsion (IHPTET technology and a more effective noise suppressor allow us to reduce engine size), aerodynamics, systems (shown here is the impact of active flutter suppression), and big improvements due to changing from titanium structure to composites. As a result of these technology improvements TOGW is reduced to 750,000 lb.

Advancing the technology by another 15 years to 2015, would result in significant further reductions in airplane size,primarily due to improvements in propulsion as projected by the IHPTET program.

NASA High-Speed Civil Transport Studies - Phase III

Impact of Technology



MACH 2.4

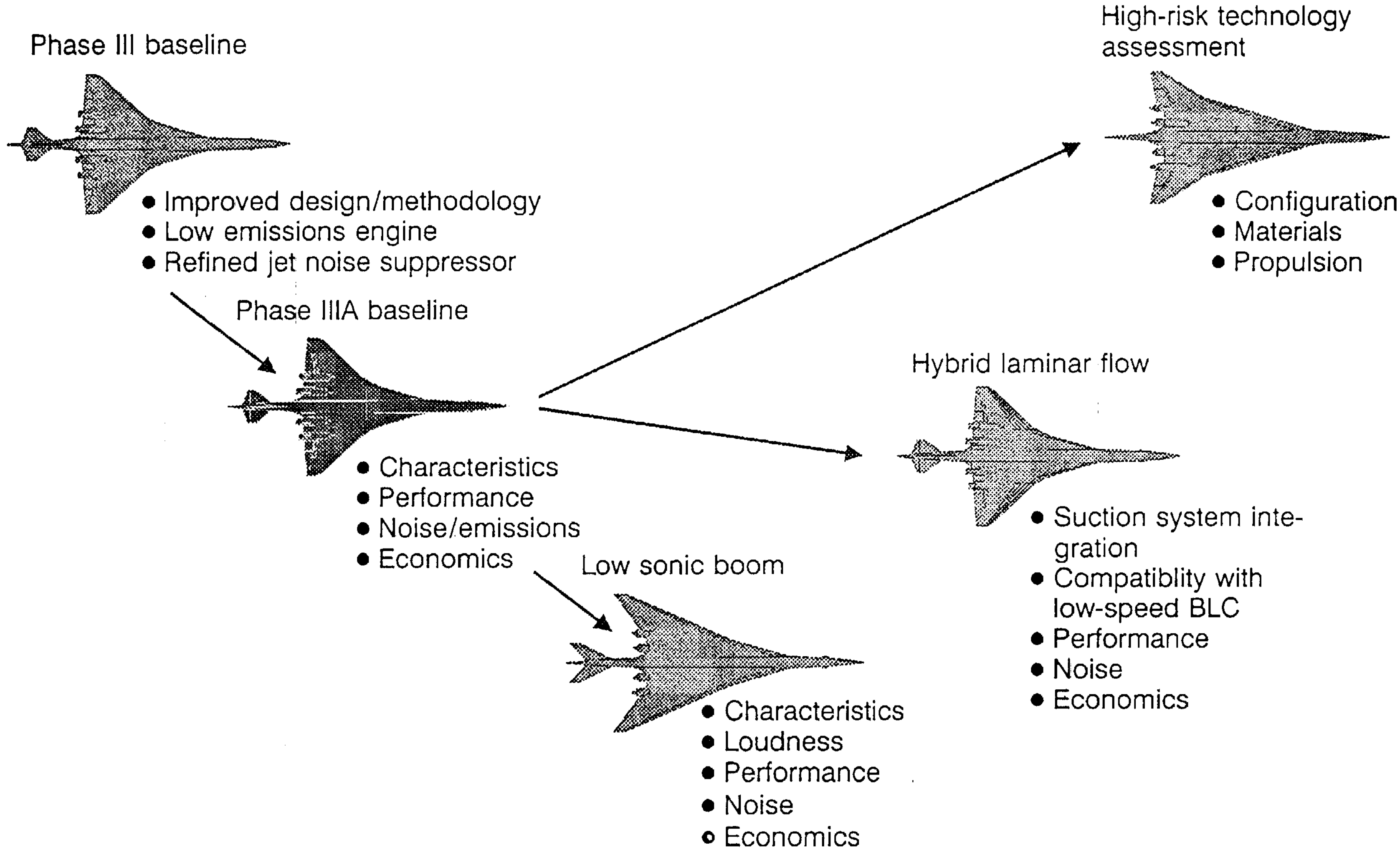
Having defined, at the conclusion of Phase III, an improved Mach 2.4 baseline airplane we performed further refinements during Phase IIIA. In addition, we initiated three innovative configuration trade studies that addressed environmental issues:

1) a low sonic boom design
2) application of laminar flow control to reduce drag, fuel consumption and hence emissions, and
3) high-risk technology assessment on an innovative, tailless arrow wing configuration.

I like to point out here that some of the best technology features that were first assessed on this tailless configuration were incorporated later into baselines. That included the extended wing strake and vortex fences, except that we chose to retain an aft horizontal tail to improve the trimmed lift-to-drag ratio of the configuration.

NASA High-Speed Civil Transport Studies - Phase IIIA

Mach 2.4



REVISED BASELINE

At the conclusion of Phase IIIA, in late 1989, we had thus further reduced the TOGW from 745,000 lb to 679,000 lb, a total savings of 66,000 lb. 40,000 lb was due to resizing the structure in composites. 26,000 lb was due to lower transonic drag.

Changes included a smaller wing and reduced engine size. These changes were biased towards improving economics with a smaller airplane, at the expense of increased noise level. This further emphasizes the need for more effective noise suppressor and improved high-lift aerodynamic efficiency.

Low emissions burner concepts were identified, which came close to meeting our tentative EI goal. The advanced burner had only a small impact on the configuration (+1 to 4% MTOW).

NASA High-Speed Civil Transport Studies - Phase IIIA

Revised Baseline

- R = 5,000 nmi
- Yr 2,000 cert
- M = 2.4
- Polymeric composites

	Phase III	Phase IIIA	Δ
MTOW-lb	745,000	679,000	- 9%
OEW-lb	323,200	287,000	- 11%
Passengers	247	253	+ 2%
Block fuel-lb	325,100	298,300	- 8%
Noise Sideline	+ 1.7	+ 2.2	+ 0.5
(ΔEPNdB Community	- 1.0	+ 2.3	+ 3.3
Stage III) Approach	- 4.3	+ 1.2	+ 5.5
Emissions EI, lbs/1,000 lb	31	8	- 75%
Sonic boom - psf	2.5	2.5	0 (Supersonic over water only)

AIRPLANE SIZING

Economically, a good indicator of the most viable airplane is the minimum TOGW for a given payload/range and wing/engine combination. That airplane would be located at the "eye of the thumbprint".

However, practical design constraints, such as required fuel volume and approach speed, tend to require a larger wing area. Other constraints, such as climb thrust margin and TOFL, tend to require a larger engine. As a result the sized airplane tends to be far off the "eye" of the thumbprint and at much higher TOGW.

With the latest baseline airplane update we had reduced the size of the delta wing planform to the point where we had reached the fuel volume constraint. Hence, we increased the size of the inboard wing strake to gain more fuel volume for a given exposed wing area.

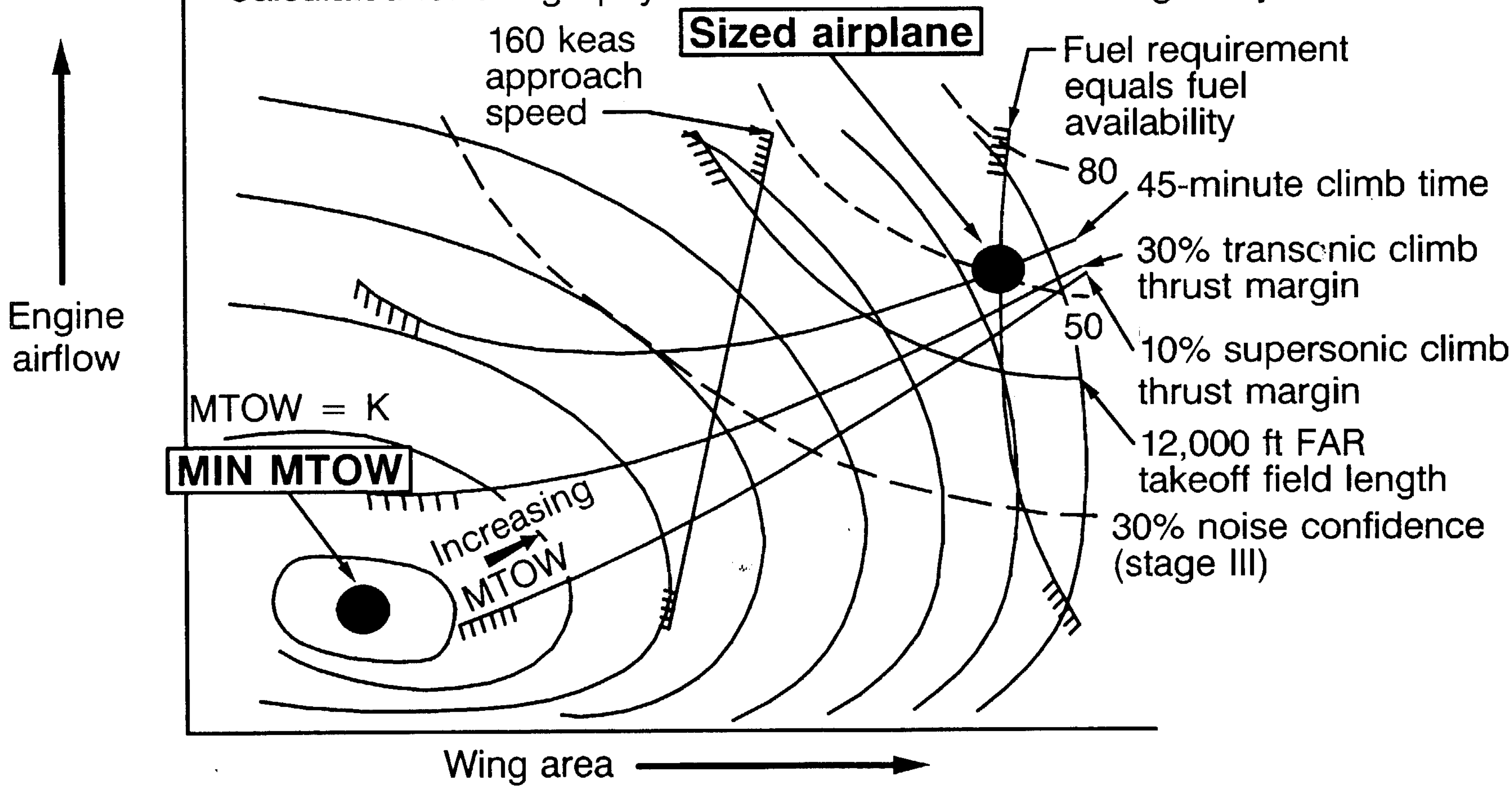
Also, we reduced engine size by adding a mini-augmentor.

Both the new smaller wing and the smaller augmented engine moved us closer to the eye of the thumbprint, hence reduced TOGW and improved economics.

NASA High-Speed Civil Transport Studies - Phase IIIB

Phase IIIA Airplane Sizing

- Design range = 5,000 nmi
- Calculated for design payload
- Fixed wing planform
- Fixed engine cycle



REVISED BASELINE CHARECTERISTICS

Detailed characteristics of the Phase IIIA (1989) baseline and the Phase IIIB (1990) baseline are compared here.

Reduced TOGW, increased payload, reduced engine size all added up to improve economics. The required ticket surcharge was reduced by 40% and is now close to our goal of 10% to 20% relative to a reference subsonic airplane.

TOFL and approach speed increased, but are still within acceptable limits.

Noise levels have increased again. We are heavily relying on innovative proprietary suppressor developments that show promise of providing some of the additional noise reduction. Also, further improvements in high-lift efficiency are needed.

NASA High-Speed Civil Transport Studies - Phase IIIB

Revised Baseline Characteristics

- R = 5,000 nmi
- Year 2000 certification
- M = 2.4
- Polymeric composites
- Emissions EI = 8 lb/1,000 lb
- Sonic boom = 2.5 psf (over water only)

		Phase IIIA	Phase IIIB	Δ
MTOW, lb		679,323	667,857	-2%
OEW, lb		286,973	265,117	-8%
Passengers		253	279	+10%
Wing area, ft		7,970	6,310	-21%
Engine airflow, lb/sec		494	426	-14%
Block fuel, lb/passenger		1,179	1,082	-7%
Payload/MTOW, %		7.6	8.8	+16%
TOFL, ft		10,200	11,700	+15%
Vapp, kt		141	156	+11%
Noise (ΔEPNdB Stage III)	Sideline	+2.2	+6.8	+4.6
	Community	+2.3	+5.7	+3.4
	Approach	-4.3 (+1.2*)	-3.1	+1.2
Δ Required revenue factor, % (relative to reference subsonic)		22	13	-40%

* Including turbine noise

NASA High-Speed Civil Transport Studies - Phase IIIB

Baseline Status - September 1990

- Economics
  - Economic viability has improved since Phase IIIA; further improvements needed in configuration, materials, and engines
- Noise
  - Noise levels have increased since Phase IIIA; more work required on noise suppressors and high-lift systems to achieve Stage III
- Emissions
  - Phase IIIA low-emissions burner retained small impact on configuration. Emissions requirements still not known; no showstoppers in assessments to date

LOW-BOOM TECHNOLGY STUDY

Supersonic operation overland could have a beneficial impact on fleet economics. The level of sonic boom acceptable to the public is as yet unknown.

A possible range of acceptable sonic boom loudness is thought to be 65 to 72 dBA, based on limited human response studies conducted in the 60's NASA is currently conducting research to determine this level.

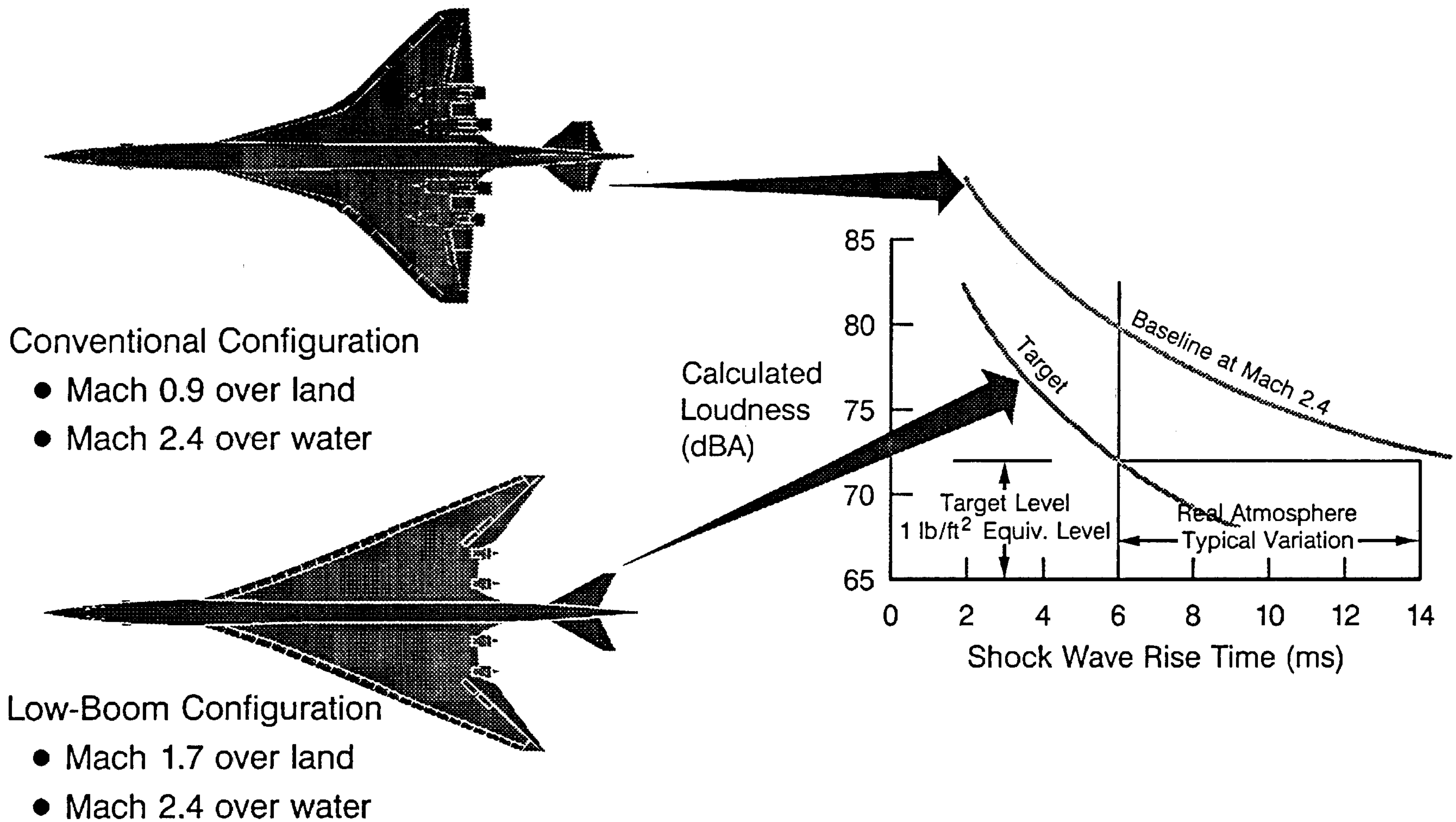
To achieve that level requires a new sonic boom target wave form, which is characterized by a "delayed-ramp shape", in lieu of the familiar N-wave associated with conventional supersonic airplane configurations.

We have designed concepts to these requirements. As shown in the Figure, they incorporate large wings with high sweep-root to tip-to give long lifting length, staggered nacelles, swept tails, long fuselages with contouring for proper aft shock shaping, and longer bulged noses to give the delayed-ramp waveform.

We backed off to Mach 1.7 for low-boom operation. At higher Mach numbers excessive airplane length was required to meet sonic boom targets.

NASA High-Speed Civil Transport Studies - Phase III

Low-Boom Technology Study



SONIC BOOM STUDIES TO DATE

We have completed two iterations of low-boom airplane design and analysis studies to date.

The Phase IIIA configuration exhibited relatively strong shock intensities. The loudness level of 76 dBA exceeded the target of 72.

Because of the larger wing and the more slender configuration, TOGW was up 5% relative to the conventional baseline, OEW was up 14%, community noise was up 2 dB; but improved supersonic efficiency reduced block fuel by 4%.

If this airplane could operate overland at Mach 1.7, then the required revenue would be 6% lower than for the baseline. If, on the other hand, the low boom were still unacceptable and the airplane had to operate subsonically, then the required revenue would be 3% higher than the baseline.

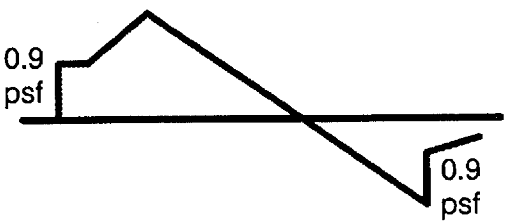
The redesigned Phase IIIB low-boom airplane met the loudness target, but lost 15% of its' passenger payload as a result of required fuselage reshaping.

The net effect was an increase in the required revenue to 14% and 25%, respectively, relative to the baseline. Very discouraging results.

We conclude that low-boom airplanes are high-risk at this time. There are still numerous unknowns.

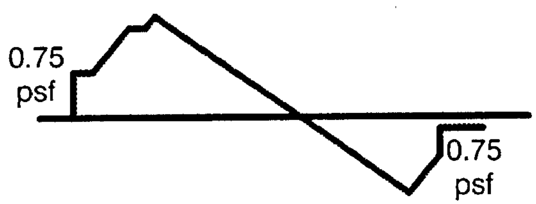
Sonic Boom Studies to Date

Phase IIIA



+5% MTOW	+14% OEW	Constant payload
+2EPNdB	-4% Block fuel	
ΔRevenue requirement = -6% to +3%		
76 dBA, target = 72 dBA		

Phase IIIB



+1% MTOW	+8% OEW	-15% payload
-2EPNdB	-1% Block fuel	
ΔRevenue requirement = +14% to +25%		
71 dBA, target = 72 dBA		

- Acceptable waveform not known (level and shape)
- Real atmospheric effects not kncwn (design margins necessary)

HLFC APPLICATION TO HSCT

An HSCT has greater sensitivity to aerodynamic drag reduction than its' subsonic counterpart.

Skin friction drag accounts for approximately 40% of the total drag at cruise conditions. In regions were laminar flow is maintained, skin friction drag is reduced by a factor of 8 to 9.

Under NASA/Boeing systems study contracts we have performed extensive HLFC applications studies. We have evolved a laminarization scheme as illustrated in the Figure. The scheme includes suction regions as well as natural laminar flow regions.on both the wing upper and lower surfaces.

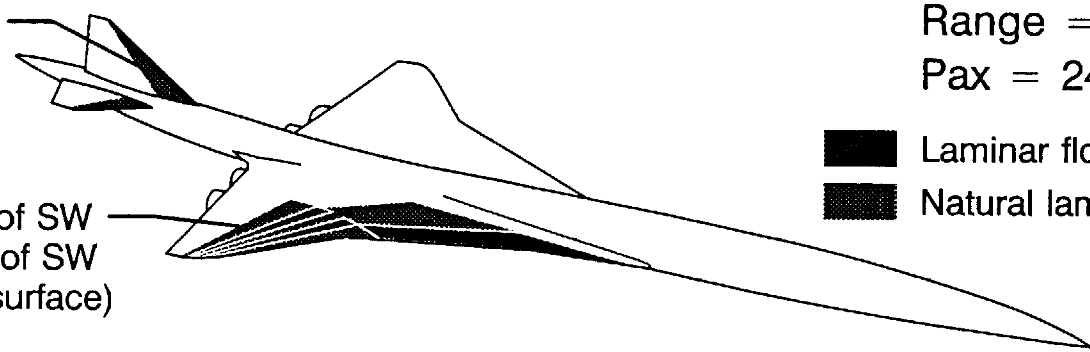
The aerodynamic benefits include a cruise drag reduction of 8.5%. The suction system can also be used in a suction BLC mode during low speed high-lift conditions to maintain attached flow over the wing

We have studied, in some depth, the implementation of the HLFC system. We have identified significant implementation penalties, as summarized in the Figure. However, the benefits far outweigh the penalties.

Economic benefits are due, primarily, to the reduced fuel consumption of the smaller airplane.

Because of its' high potential we recommend that this high-risk technology be pursued aggressively.

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	6.5%
OEW reduction	2.7%
Engine size reduction	9.9%
Block fuel reduction	11.1%

Economic Benefit

18% reduction in surcharge required for 12% ROI

CONCLUSIONS

The conclusions from the NASA systems studies to date are:

Projected HSCT economics have improved. Required revenue is 10 to 15% above the reference subsonic.

Major issues and technology development needs remain:

We do not meet stage III noise goals with small engines using augmentors. The effectiveness of noise suppressors needs to be improved. Results of proprietary developments in the noise suppressor area look promising.

Low emissions burner concepts have only a small adverse impact on the airplane. However, emissions requirements are still not known. There have been no show stoppers in assessments to date.

The final engine cycle needs to be defined. We need the performance level projected by the IHPTET program for year 2000 technology.

Low cost durable composite materials with improved specific strength and stiffness are crucial to meeting structural weight goals.

Improved high-lift systems ,that maintain attached flow over the wing during takeoff and climbout are needed to contribute to noise reduction.

In addition, we have identified large payoff potential for high-risk technologies, such as laminar flow control.

NASA High-Speed Civil Transport Studies - Phase IIIA

Conclusions

- Economic viability has improved since Phase III. Improvements still needed, but with projected technology looks promising
  Major issues:
  - Noise suppression
  - Emissions requirements
  - Engines
  - Materials development
  - High-lift systems

- Potential large payoff for high-risk technology for post year 2000 HSCT
  Key elements
  - Advanced aerodynamics, stability and control, aeroelastics
  - Advanced engine technology
  - Advanced materials
  - Supersonic laminar flow control
  - Low-boom technology

PROPOSED HSR SYSTEMS STUDIES' 1991 - '95

We are currently finalizing plans with NASA for the follow-on airplane systems studies.

We have proposed to work in six areas; emphasizing the environmental issues technologies. The proposed distribution of effort during 1991 is indicated:

Further study of atmospheric effects. - Here we expect to support NASA's atmospheric modelling studies by developing detailed emissions scenarios for projected HSCT and subsonic fleets.

Engine-airframe integration. - Here we expect to continue to take part in designing and selecting candidate engines from NASA Lewis and the engine manufacturers and evaluating them on our airplanes.

Noise reduction and laminar flow control. - We believe these are the most important areas to work now; the former because of the need for success, the latter because of its' high potential for improving economics.

Sonic boom reduction. - We need to continue some effort in this area in spite of the discouraging results to date. Also important to understand boom physics, e.g., secondary booms.

Flight Research Requirements. - Here we propose to look at what flight research will be required to answer important questions on emissions and to validate key technologies. We will evaluate potential aircraft to be used for the research, and identify cost-effective approaches.

Proposed HSR Systems Studies, 1991-95

	1991 effort
• Atmospheric effects and impact	9%
• Engine-airframe integration	9%
• Noise reduction	27%
• Sonic boom reduction	5%
• Supersonic laminar flow control	32%
• Flight research requirements	18%

SYSTEMS STUDIES PERSPECTIVE

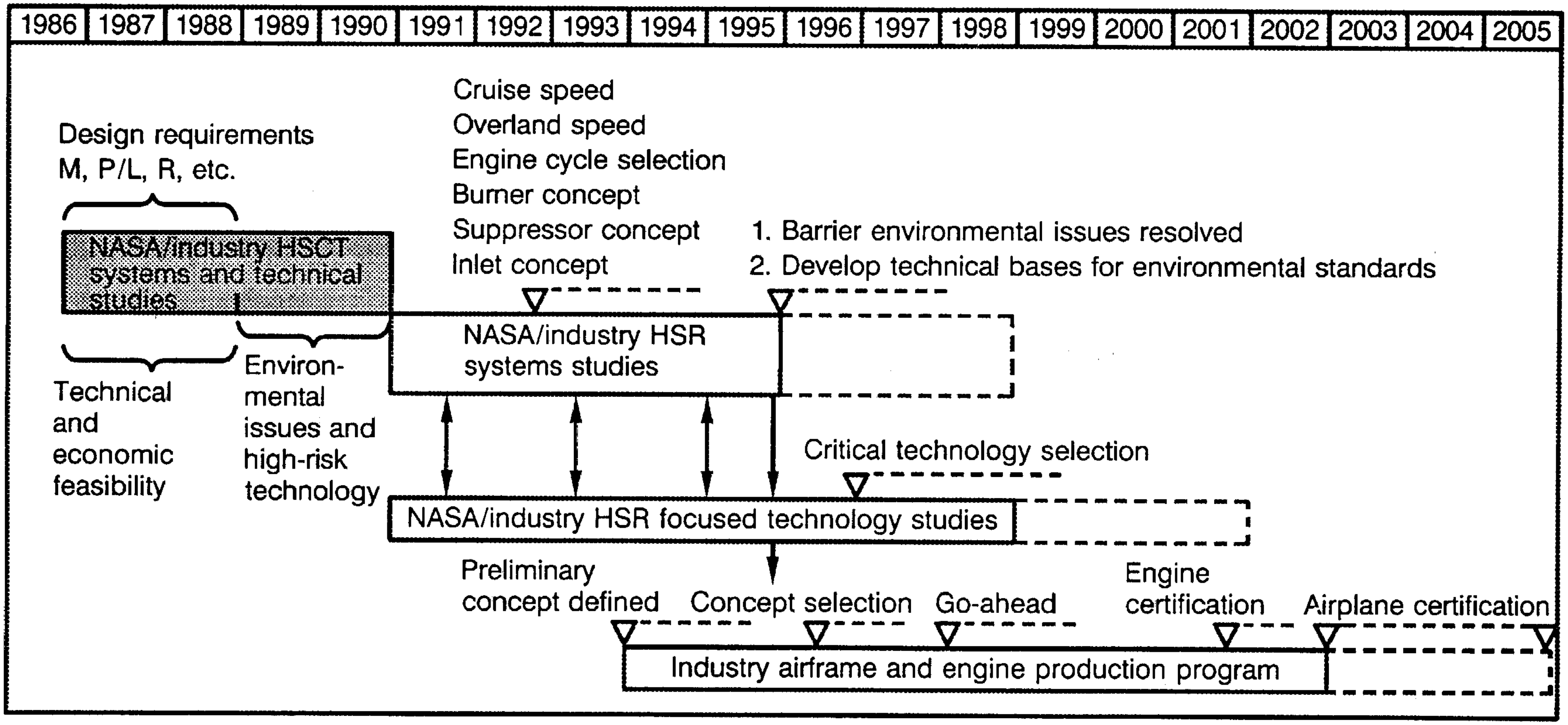
In perspective, the NASA/Industry systems studies are an essential element of the NASA High Speed Research Program.

The evaluation of environmental issues and technological solutions on practical HSCT concepts puts us in a position to make realistic projections of the environmental impact, of the economic viability and the technology needs for the HSCT. In this way, the systems studies provide guidance for the needed technology developments that have to take place in the HSR Phase II.

Only with that guidance can the objectives of Phase II be met; to develop and verify in cooperation with US Industry, the critical technologies for economic viability.

The development and verification of the critical technologies must have been completed before a production program go-ahead can occur.

HSR Systems Studies Perspective



1991 HSCT BUDGET BREAKDOWN

In addition to the NASA-funded research there is now a very significant Boeing-funded HSCT program. It started in 1988 in response to the encouraging results shown by the NASA-funded studies of environmental, technical and economic viability of an HSCT.

Currently, Boeing funding of internal HSCT studies is expanding to build a core HSCT team for preliminary design and technology development.

In 1991, we have approximately 150 engineers working on HSCT. The figure shows the distribution of effort among the three key areas of Technology and Test, Design Development and Manufacturing Research and Development (MR&D).

67% of the effort is focused on technology developments and test in the critical areas of aerodynamics, structures, propulsion and noise.

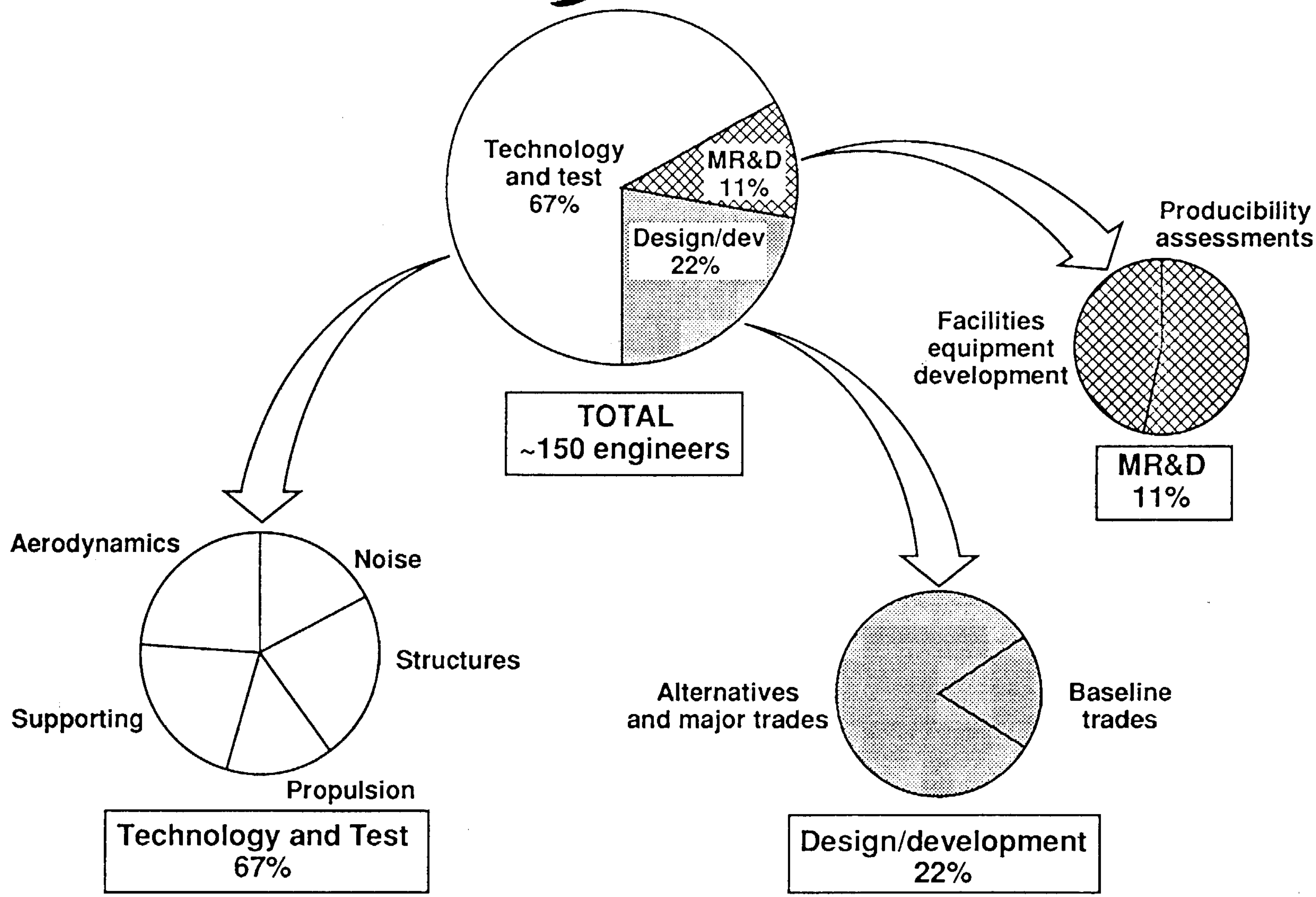
22% of the effort is directed towards developing a baseline airplane and conducting trade studies.

11% of the effort is on MR&D, to answer the question on how we would produce an HSCT of composite structure and at a low cost.

Large increases in on-year funding are planned.

1991 HSCT Budget Breakdown

Boeing IR&D



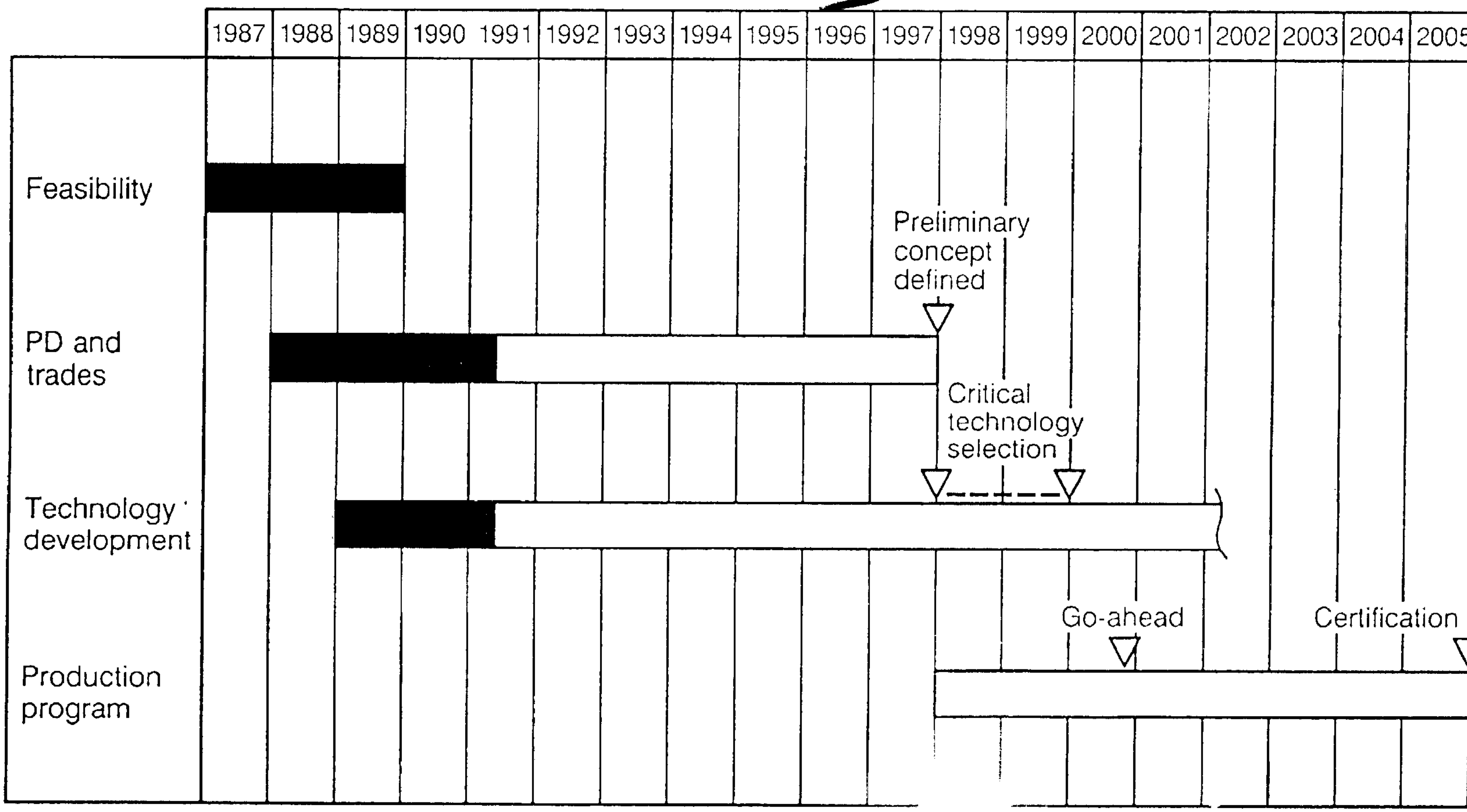
HSCT PLANNING SCHEDULE

The planned increases in funding are aimed at providing the technology and design information necesary for certification of an HSCT in the year 2005.

To meet that date would require the definition of a preliminary concept by 1997, selection of the critical technology by 1999; and a production program go-ahead in the year 2000 - nine years from today.

HSCT Planning Schedule

Boeing



THIS PAGE INTENTIONALLY BLANK