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Soviet Hypersonics R&D: Applications to Civil and Military Aviation

An Executive Summary

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Soviet Hypersonics R&D: Applications to Civil and Military Aviation

An Executive Summary

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Soviet Hypersonics R&D: Applications to Civil and Military Aviation

Key Judgments

Information available as of 15 August 1990 was used in this report.

We judge that the Soviets are conducting research in technologies that will enable them to develop hypersonic aircraft for civilian and military use. Examination of Soviet aerospace research facilities, as well as Soviet work in aerodynamics, propulsion, fuels, and materials, indicate that there is the infrastructure to support development of a Mach 5 to Mach 7 aircraft. The Soviets lead the United States in several important technology areas, such as experimental test facilities, although they are clearly lagging in others. The Soviets have had a focused program to collect Western hypersonic production data since the early 1980s to offset limitations that constrain their research and ability to build hypersonic hardware. The Soviets are also investigating transatmospheric vehicle technologies, but they have not made a commitment similar to former President Reagan's decision to proceed with the National Aerospace Plane (NASP

Civilian and military uses of hypersonic aircraft have been studied by the Soviets. They have announced the development in the future of a Mach 5 to Mach 6 airliner. [

] The Soviets will soon face a decision, as part of their five-year economic planning cycle, on whether to authorize full-scale engineering development (FSED) of hypersonic aircraft. Such a near-term decision is required if they intend to deploy these aircraft by about the year 2010

Because of the Soviet Union's current economic problems, however, it probably will be difficult to obtain FSED funding for hypersonic aircraft in the near future. As a result, the Soviets are likely to take a cautious, wait-and-see approach regarding the full-scale development of hypersonic aircraft. Such an approach would allow the Soviets to better position themselves economically to undertake FSED and give them time to continue their technology research program and collect Western technologies. Should the West proceed with FSED of civilian and military hypersonic aircraft, the Soviets probably will feel compelled to follow suit. In general, Western technology research and system development motivates corresponding Soviet efforts. Also, Soviet domestic requirements—particularly in military aviation—and technological competition with the West would motivate Soviet development of hypersonic aircraft. In the absence of Western FSED, we judge that sufficient funding will continue

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for the Soviets to proceed with large-scale research on hypersonics technologies. We expect the Soviets to continue hypersonics work by rationalizing that it is necessary because of the needs of domestic requirements and because hypersonics is a dual-use technology that can be applied to civilian and military aviation

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Soviet Hypersonics R&D: Applications to Civil and Military Aviation

Scope Note

This publication summarizes the research and findings of an in-depth analysis, DI Research Paper SW 90-10055X September 1990, *Soviet Hypersonics R&D: Applications to Civil and Military Aviation*

Although this report and the in-depth analysis concentrate on vehicles that can operate in the low hypersonic (Mach 5 to Mach 8) speed range and discuss Soviet research and test capabilities beyond those speeds, they do not specifically address the development of space planes or transatmospheric vehicles by the Soviets or Western nations.

Soviet Hypersonics R&D: Applications to Civil and Military Aviatior

Introduction

During the 1980s, several countries announced their intentions to develop vehicles that will be capable of traveling at hypersonic speeds.[1] For example, in his State of the Union address on 4 February 1986, then President Reagan stated that the United States would go forward with its research on hypersonic aircraft, "which, by the end of the next decade, [will] take off from Dulles Airport; accelerate up to 25 times the speed of sound, attaining low Earth orbit; or fly to Tokyo within two hours." The National Aerospace Plane (NASP), or X-30 as it is now known, is intended to develop and demonstrate technologies for future civil hypersonic aircraft and space transportation systems that will offer technical, cost, and operational advantages over existing aircraft and space transportation systems (see figure 1). Public statements made by various US officials indicate that NASP technologies will be applied to atmospheric military aircraft such as bombers, interceptors, transports, or reconnaissance vehicles. The United Kingdom, West Germany, France, and Japan have all proposed significantly different concepts with capabilities varying from low hypersonic speeds of Mach 5 to Mach 6 to orbital speeds of Mach 25 (see figure 2'

The Soviet Union has kept abreast of Western efforts and has conducted hypersonic research efforts of its own since at least the late 1950s (see figure 3). This paper summarizes our assessments of Soviet efforts to conduct research on hypersonics technologies and to develop hypersonic aircraft

[1] Hypersonic generally refers to a flight vehicle that has the capability to fly at speeds of Mach 5 or greater. Soviet literature distinguishes between two types of horizontal launch, hypersonic flight vehicles: "hypersonic aircraft," which probably refers to an atmospheric, low-hypersonic speed vehicle, and "aerospace planes," which are transatmospheric vehicles capable of achieving orbital speeds of about Mach 25. For definitions and descriptions of other technical terms used in this paper, see appendix

Soviet Technological Capabilities To Develop Hypersonic Aircraft

The Soviets' success in the development of hypersonic aircraft will depend largely on their ability to overcome several key technological hurdles:

- Prediction of the aerodynamic and thermodynamic effects of sustained hypersonic flight under extreme physical conditions.
- Investigation and development of propulsion systems and fuels necessary for hypersonic flight.
- Research and development of structural and refractory materials that can endure and survive the stresses of hypersonic fligh

Computational Aerodynamics

Two design tools or methodologies—computer-based simulation and laboratory-based experimentation—currently are used to predict the aerodynamic and thermodynamic effects of hypersonic flight upon a vehicle. The first of these tools, also known as computational fluid dynamics (CFD), relies on numerical methods of solution to mathematical equations that describe the physical phenomena of fluid flow (see figure 4). Presently, CFD provides increasingly better estimates that reduce the amount of work that otherwise must be conducted in wind tunnels. Although some Western proponents of CFD simulation believe it could eventually replace expensive wind tunnel facilities, such facilities will be indispensable for many years to come to validate evolving CFD algorithms for hypersonic flow velocitie

The Soviets' ability to conduct computer-based simulation of aerodynamic flows for design problems depends on their understanding of numerical methods of approximation and their access to powerful computers. The Soviets' basic capability and state of the art in the fundamental numerical and mathematical

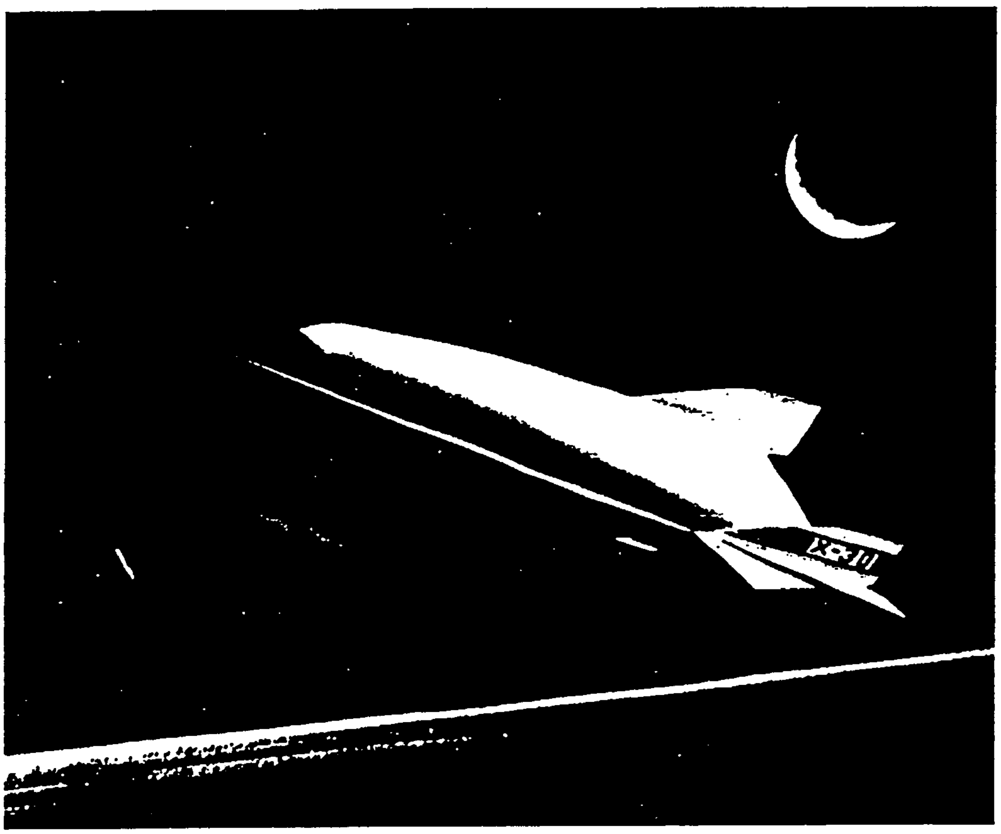


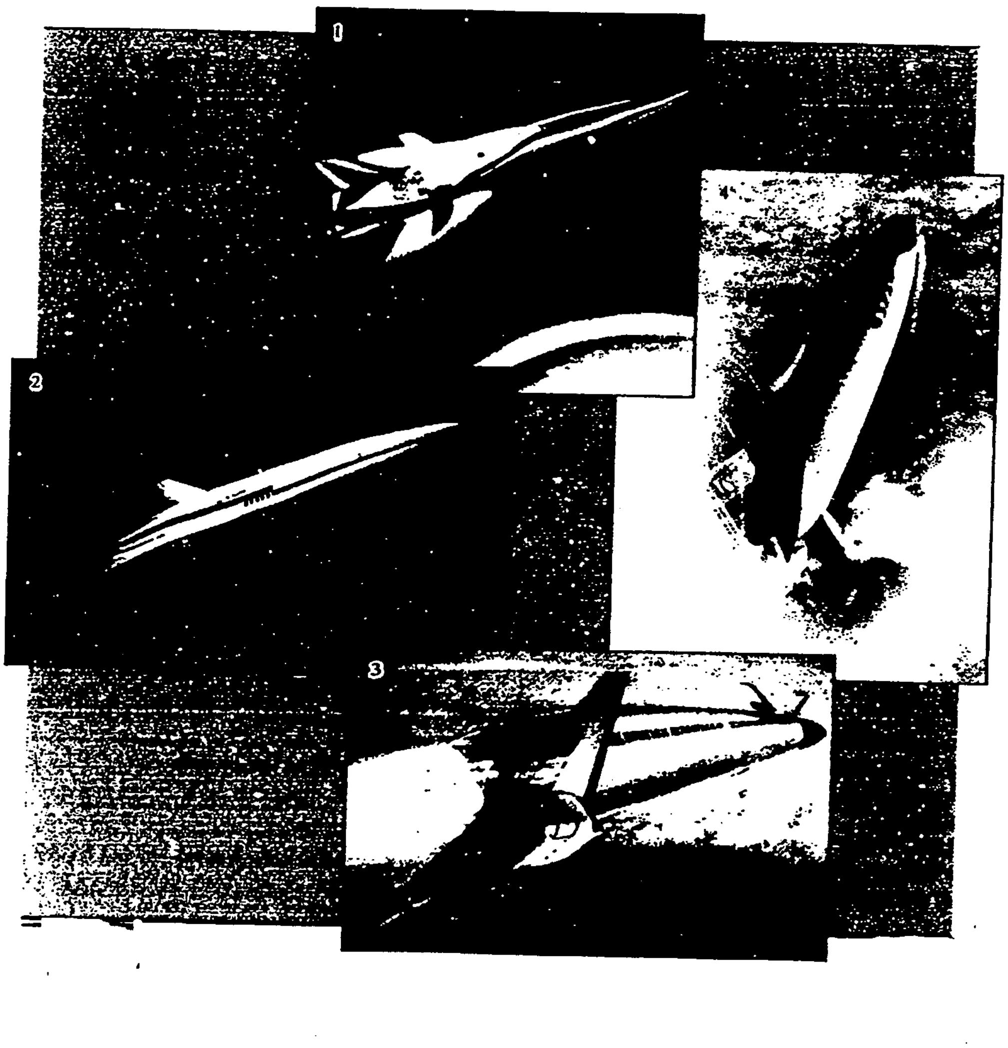
Figure 1. The NASP, or X-30 as it also is known, is intended to develop and demonstrate technologies for future US manned hypersonic vehicle

foundations required to implement CFD techniques are excellent. [

] that the Soviets have made substantial contributions to the basic understanding of computational algorithm

Although some Soviet researchers have access to suitable computer hardware, the lack of widespread access to high-speed, powerful computers severely limits overall capabilities to perform CFD analysis. As a result, we project that state-of-the-art CFD development in the Soviet Union will continue to lag behind the West's by about five to 10 years. CFD is one of the most demanding applications in terms of computer hardware capabilities. In the West, CFD has been one of the first and most widely employed uses of the latest generation supercomputers and, in the case of the NASP, requires a significant amount of available supercomputer time nationwide

Figure 2
Artists' Concepts of West European and Japanese Hypersonic Vehicles



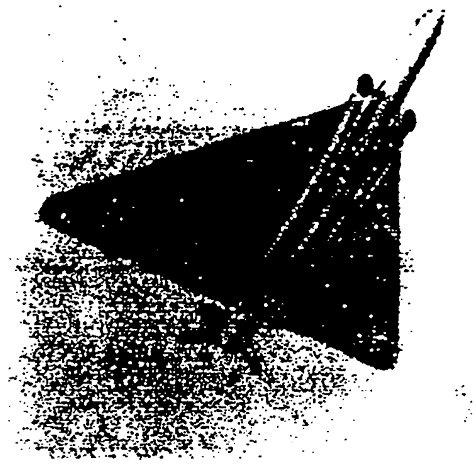


Figure 3. The Soviets have had an active hypersonics research program since the 1950s, and they continued to build an impressive array of test facilities to support the research program even though US interest in hypersonic flight ebbed after cancellation of the X-15 program.

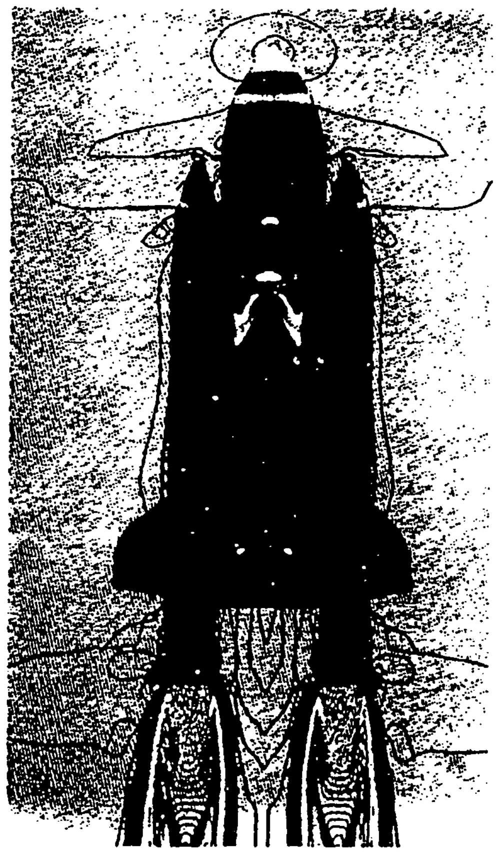


Figure 4. Currently, CFD is used to complement more expensive wind tunnel experiments to evaluate fluid flo

The Soviets have undertaken several measures that should allow them to make up some of the difference in computational power between the USSR and the West. The Soviets, for example, are attempting to develop new computers with significantly greater computational capabilities than what they currently have available. Although we do not know when they expect to produce these computers, [redacted] they have three experimental computers that have 10 processors, each running at 10 million operations per second for a total of 100 million operations per second. The BESM-6 and an advanced BESM, the Soviet state of the art, run at 1 million operations per second and 3 million operations per second, respectivel

In addition to developing more capable computers, the Soviets could undertake other measures to improve their computational capabilities. We judge, however, that in the long term these improvements will not be able to supplant the need for new, more powerful computers. Two areas the Soviets might stress are:

- *Mathematical innovation.* The Soviets have made some innovations to their analytical techniques to simplify complex computations and require less

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powerful computers. [redacted].

- *Parallel processing* [redacted] the Soviets are investigating the use of parallel processing to overcome their lack of supercomputers. Parallel processing involves networking many less advanced computers to simultaneously work on different parts of a problem. Although we judge that they are unlikely to succeed, the Soviets could theoretically solve supercomputer-class CFD problems and minimize the West's lead in the development and application of supercomputers.

Hypersonic Test Facilities

The second tool used in hypersonic research is experimental investigation—use of scale models in wind tunnels, shock tubes, shock tunnels, "hot-shot" tunnels, and ballistic ranges (see figure 5). Because of their inferior modeling capabilities and lack of widespread supercomputer access, the Soviets have stated they have been forced to rely upon experimental investigations of hypersonic phenomena. In contrast with the West, which neglected the development and maintenance of hypersonic facilities from the late 1960s until recent years, construction of [redacted] hypersonic facilities has continued at a steady pace in the Soviet Union. As a result, the Soviets have offered US hypersonics researchers the use of their facilities to validate CFD code.

The Soviets have built research facilities that give them unparalleled capabilities to conduct laboratory simulation of hypersonic flight. Several Soviet research facilities that are subordinate to defense-industrial ministries or the Academy of Sciences have the capability to simulate a wide variety of hypersonic flight conditions in their laboratories [redacted] these facilities would give the Soviets a unique capability to ground test hypersonic flight vehicles for periods of several minutes.

Propulsion

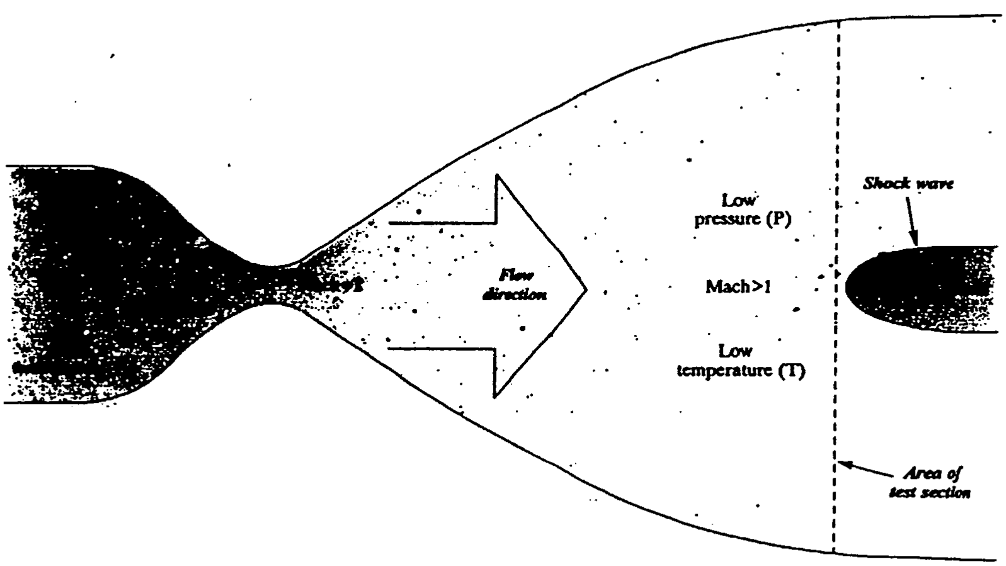
In contrast with conventional aircraft designs, more attention must be paid to propulsion and airframe integration in the design of hypersonic aircraft. Previously, engines were developed independently of the aircraft's design. Advanced technology concepts such as hypersonic aircraft and aerospace planes require that the external flow field around the vehicle becomes a working part of the propulsion and control systems (see figure 6)

[redacted] much of their hypersonic propulsion research concentrates on the Mach 5 to Mach 8 regime, although they are clearly researching much greater speeds. The Soviets are evaluating several different types of propulsion systems as part of their hypersonic research program, including airturborockets, airturboramjets, and scramjets, and have conducted some propulsion research that is quite sophisticated and sometimes unmatched in the West [redacted] the Soviet researchers performed some impressive modeling and the results were promising enough to continue the high-speed inlet work.

Although the Soviets have presented research and results that have impressed some Western propulsion experts, we judge that the presentations probably are not fully representative of their state-of-the-art hypersonic propulsion research:

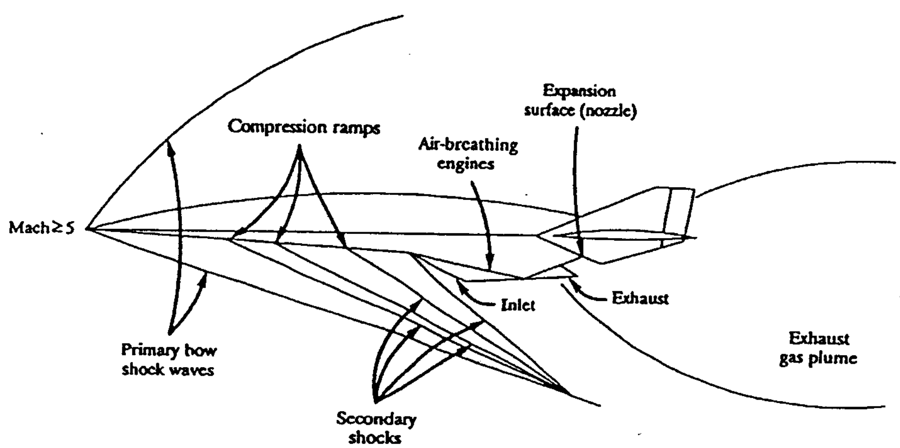
- What is presented at these conferences does not match the capabilities of their research facilities.

Figure 5
Schematic of Supersonic/Hypersonic Wind Tunnel



Note: The concept of a hypersonic wind tunnel is fundamentally the same as a supersonic wind tunnel. The differences are a matter of extreme operating conditions. The supersonic wind tunnel operates on the same principle as a rocket nozzle. Given that the pressure in the chamber on the left is sufficiently greater than the pressure on the right, air will accelerate from left to right as the channel narrows, until it reaches the speed of sound at the narrowest point (the so-called throat). Past the throat, the speed of air is supersonic. The Mach number of the flow at any point along the axis of the nozzle can be related to the cross-sectional area of the channel at that point.

Figure 6
Integrating the Propulsion System With a Hypersonic Vehicle



Note: Advanced technology concepts such as hypersonic aircraft require the external flow field around the vehicle to become a working part of the propulsion and control systems.

• The information presented is dated.

[redacted]

Cryogenic Fuels for Hypersonic Flight

The Soviets currently have a flight research program under way to evaluate candidate fuels for hypersonic aircraft. This program also indicates their interest in two types of vehicles—those that operate in the atmospheric, low-hypersonic regime and those that are designed to attain low Earth orbit [redacted]

[redacted] Two characteristics of these fuels facilitate hypersonic flight. First, cryogenic fuels have greater *heat sink* or cooling capabilities—required for aircraft structures and subsystems at hypersonic speed—than conventional aviation kerosene. Second, LNG and liquid hydrogen have greater energy per unit mass than

[redacted]

[redacted]

aviation kerosene. LNG can extend flight capabilities of hydrocarbon fuels to about Mach 5. More expensive liquid hydrogen is required beyond Mach 5 due to its greater energy and heat sink

[redacted]

Structural Materials
During the late 1960s, US hypersonic vehicle research waned because of the lack of success in developing materials that could endure and survive the stresses of hypersonic flight. Hypersonic flight conditions are radically different from those encountered during supersonic flight and are orders of magnitude more stressful in heat flux, surface temperature, and acoustics. Today, however, many new high-performance materials that have applications to hypersonic flight have been invented, or the technologies required to produce them have matured

[redacted] the Soviets have achieved results in materials research that parallel Western materials research on the NASP and other proposed hypersonic vehicles [redacted] On the basis of the research conducted in the United States on hypersonic vehicles, several approaches are available to the Soviets for the structural and refractory materials layout of a hypersonic vehicle, including metal matrix composites, intermetallics, carbon/carbon composites, and ceramic composites

Although the Soviets' basic research on advanced materials is excellent and they have conducted materials research that has potential application to sustained hypersonic flight, they will need to overcome some obstacles that have consistently plagued them in the aerospace industry. For example, several Soviet aviation and aerospace designers will need to overcome their traditionally conservative approach to the application of advanced materials. We also expect the Soviets to continue to be hampered by the quality control problems in the production and nondestructive testing of advanced aerospace materials

Active/Passive Cooling
Statements made by the Soviets at the 1987 and 1989 Paris Air Shows reflect some study of the effect of *active* and *passive* cooling measures on surface and component heating during hypersonic flight. During the 1987 exhibition, the Soviets stated that their Mach 5 to Mach 6 transport concept would require active cooling. During the 1989 air show, Soviet exhibitors indicated that an aircraft operated in the Mach 6 to Mach 10 range did not necessarily require an active cooling feature. However, no specific materials technologies were discussed. The Soviets added

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[redacted]

that they have examined several active cooling concepts should they consider development of a Mach 6 to Mach 10 vehicle, but that these concepts imposed significant structural weight penalties that they probably are seeking to avoid

Soviet Efforts To Acquire Western Hypersonics Technologies

A comprehensive Soviet program to collect Western hypersonics data has been under way since at least the early 1980s [redacted]

We believe that the hypersonics technology collection program continues to be active. Citing exorbitant costs to develop hypersonic vehicles and highlighting their unique testing capabilities [redacted] The Soviets are also taking advantage of *glasnost* and *perestroyka* to forge new ties to Western organizations involved in hypersonic research [redacted].

Soviet Motivations

The Soviets' attempts to access information and facilities identified in their collection program are motivated by a variety of factors, including being able to gauge the status of Western research programs and to exploit Western technologies [redacted].

Although some research institutes have suitable computer hardware, lack of widespread access to high-speed, powerful computers hinders Soviet ability to perform CFD analysis. The Soviets are trying to overcome this handicap and verify their hypersonics research through access to US supercomputers and computer codes

The overall Soviet technology acquisition program emphasizes the collection of advanced production and testing capabilities—especially multiple-use instrumentation and production equipments—rather than military system engineering data

Applications of Soviet Hypersonic Research

The Soviets have openly discussed civilian aircraft applications for their hypersonic research program. They have announced that they will develop a Mach 5 to Mach 6, 300-passenger airliner

Hypersonic Airliner

At the 1987 and 1989 Paris Air Shows, Soviet aviation officials indicated that a civil hypersonic transport would undergo development in the near future (see figure 9). According to these officials, the Tupolev Design Bureau—which, according to Central Aerohydrodynamics Institute (TsAGI) Director German Zagaynov, conducts "extensive" work in hypersonics—will design the six-engine, Mach 5 to Mach 6, 300-passenger aircraft that would fly from Moscow to Tokyo (about 7,250 km) in about two hours. Central Scientific Research Institute of Aviation Motor Building (TsIAM) Deputy Director Vladimir Sosunov has stated that the proposed airliner "could" use turboramjets. The airliner—about 100 meters in length and 4 meters in fuselage diameter—reportedly will use a cryogenic fuel, likely to be liquid methane, for the propulsion system and to actively cool aircraft

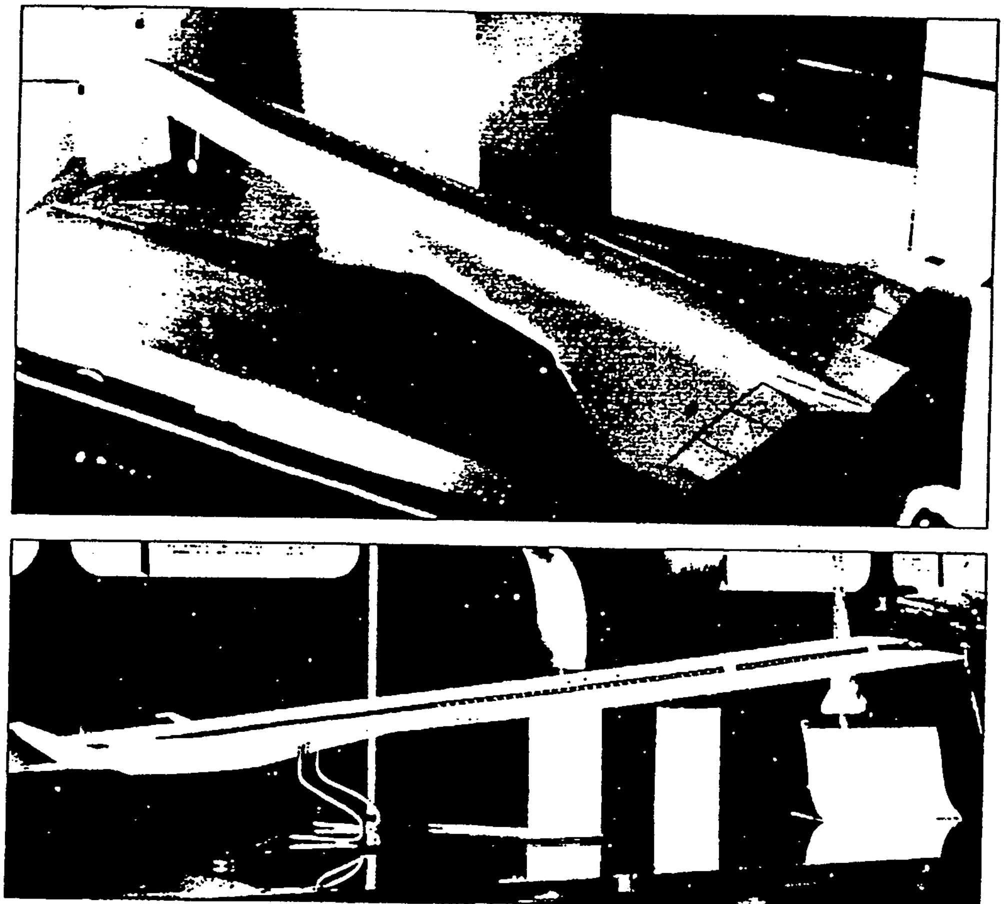

Figure 9. Models of future Soviet hypersonic airliners displayed at international air sho··: (top) 1987 Paris Air Show, (bottom) 1989 Paris Air Shc

structures and subsystems. A. A. Systsov, Soviet Minister of the Aviation Industry, stated in 1987 that the aircraft would be created in the next 15 to 20 year

We have examined some conflicting reporting about Soviet resolve to develop the hypersonic airliner [redacted] the USSR does not have an active program for a hypersonic airliner program under way and that publication of such a program at international symposiums should be viewed as a "symbolic response" to the US NASP effort. We judge, however, that the Soviets have the development of a hypersonic airliner under serious

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consideration. [redacted]

[redacted] regarding the lack of a hypersonic airliner program are consistent with the state of their research. At present, no hypersonic vehicle has yet entered full-scale development: the Soviets continue to conduct research to prove enabling technologies intended to support vehicle development. [redacted]

Military Applications

It is unlikely that the Soviets have undertaken a hypersonic aircraft research program without the direct participation of the Soviet Air Forces. First, in practice, all aircraft technologies and aircraft researched, developed, and produced by the Ministry of the Aviation Industry—a defense industry—have military applications. Second, hypersonic flight offers significant advantages over today's aircraft, including the ability to overcome conventional air defense systems and rapid deployment for operations. Third, we believe that the expense to develop the necessary technologies, desire to prevent duplication of effort, and high potential for military application have necessitated cooperation between the researchers of the airliner and their military counterparts

[redacted] the Soviets have investigated the direct application of hypersonic technologies to offensive and defensive military aviation. These applications include, but probably are not limited to, a new bomber aircraft that could be used in an intercontinental or theater role, a long-range interceptor, reconnaissance asset, and perhaps a military transport.

Bomber

At present, we judge that the Soviets have not authorized development of a hypersonic bomber. However, we believe that the Soviets have evaluated the technologies required to develop the aircraft as well as its impact upon their military capabilities. The designer of all Soviet strategic bombers—the Tupolev Design Bureau—developed the cryogenic fuel test bed aircraft and is working on the proposed hypersonic airliner. Also [redacted] indicate a clear Soviet understanding of the impact that hypersonic flight could have upon strategic aviation. [redacted] the Soviets have likened the deployment of a strategic hypersonic bomber to an ICBM in terms of its payload, range, flexibility of use, and speed and effectiveness in overcoming air defenses. The Soviets have also been concerned about short-term US development of hypersonic technologies for offensive aircraft systems [redacted] such a development would seriously alter the alignment of strategic forces. In addition, the Soviets are concerned about military spinoffs from the US NASP program [redacted].

Interceptor

[redacted] the Soviets have considered the development of a long-range hypersonic interceptor to improve air defense of the country. The primary mission is to intercept US air-launched cruise missile (ALCM) carriers before missile launch [redacted].

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[redacted] the Mikoyan Design Bureau—one of the major developers of Soviet fighter aircraft—is examining the application of hypersonic technologies to future designs. [redacted] discussed the concept amid reports about US development of a manned Mach 4 to Mach 5 reconnaissance vehicle [redacted] such a perceived threat would need to be countered with a follow-on to their MiG-31 Foxhound supersonic interceptor or by a more advanced technology aircraft.

Outlook for Development

Soviet development of hypersonic vehicles, as the United States has experienced with the NASP, promises to be an expensive and difficult undertaking. Current economic constraints and the need to produce everyday consumer goods, a linchpin of General Secretary Gorbachev's restructuring program, probably will preclude extensive near-term resource commitments for development of hypersonic aircraft.

Although some research facilities may face funding cuts, we believe that sufficient funding will be available to continue large-scale research on hypersonic technologies. Furthermore, should the West proceed with FSED of civilian and military hypersonic aircraft, the Soviets probably will feel compelled to follow suit. These judgments are based on several factors:

- *Action-reaction.* Generally, an important factor that motivates Soviet technology research and system development is Western work in a particular area. [redacted] however, that economic problems will no longer allow them to emulate many Western research and system development efforts.[4] Although this signals a change in Soviet practice, statements [redacted] hypersonics technology research thus far has not suffered.
- *Technological competition.* We believe the Soviets will increase their efforts to portray themselves as technologically competitive to the West in the aerospace arena. This competitive nature has been highlighted by unprecedented Soviet participation at international air shows over the past four years. Worldwide standards are often used as benchmarks in technical forecasts of Soviet system performance, and competition with these standards has grown in importance as the Soviets restructure their economy. Several prominent Soviet aerospace personalities have underscored this theme because of a perception that they are falling further behind the West in the development and application of advanced technologies.
- *Dual-Use technology.* [redacted] draft *State Program for the Conversion of the Defense Industry*

[redacted]

[redacted]

for the Period Through 1995 emphasizes development of dual-use technologies. [redacted] R&D work must consider civilian and military uses of a particular technology from the outset. Because hypersonics is a dual-use technology, solicitation for funding of the research program in the Soviet budget process will probably be more successful than attempts to garner funds for other, perhaps more narrowly focused, technologies.

- *Domestic requirements.* The Soviets probably would not be able to justify resource commitments for research and development without demonstrating domestic needs for hypersonic aircraft [redacted]

We judge at present that no Soviet hypersonic aircraft—civil or military—has entered FSED. However, the Soviets will soon face a decision, as part of their five-year economic planning cycle, as to whether to authorize development of hypersonic aircraft if they intend to deploy these aircraft in the 2010 time frame. Regarding full-scale development, we believe that the Soviets are likely to take a cautious, wait-and-see approach. This strategy has been typical of many Soviet civilian and military programs. We believe that such an approach would yield economic, technological, and military benefits to the Soviets.

In the short term, the Soviets would be able to commit resources, otherwise earmarked for development of hypersonic aircraft, to areas deemed critical to the economic restructuring program. Large-scale investment in the publicized airliner could be met with dissent, as has been the case with the Soviet space shuttle program, if progress has not been made to solve problems in the consumer sector. By forgoing near-term full-scale development of military hypersonic vehicles, the Soviet leadership can also devote these resources to the civilian economy and continue their public relations campaign regarding defense expenditure reduction. Waiting will also allow Soviet military planners to more accurately gauge the direction and potential for US development of military NASP-derived vehicles

In the long term, the Soviets could be in a better position economically to undertake full-scale development of hypersonic aircraft. The additional time will allow them to continue scientific research programs aimed at the development of these technologies and to collect vital Western technical and programmatic data. Such information would play a critical role in Soviet justification of full-scale development and would save time and expenses in establishing many of the production technologies [redacted]

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Appendix

Glossary

Active cooling
Also known as direct cooling, this concept involves the transferring of surface heat from a secondary fluid to circulating cryogenic fuel. For example, superalloys cooled with heat pipes filled with cryogenic fuel can be substituted for carbon/carbon composite materials.

Airturboramjet
An aeropropulsion system that combines a conventional turbojet engine with an afterburner/ramjet-type combustor. The system operates as a turbine engine at lower Mach numbers. At higher Mach numbers the turbine engine is bypassed with only the afterburner functioning as a ramjet.

Airturborocket
A propulsion system that combines the features of a turbine engine with those of a rocket. A rocket chamber/gas generator provides the energy to a turbine. The turbine provides power to a compressor that supercharges an afterburner type combustor.

Arc-heated
Refers to an impulse facility that uses an electric arc to achieve high stagnation temperatures and pressures in gas. See hot-shot tunnel and shock tube.

Carbon/carbon composites
Prewoven graphite carbon form into which either liquid or gaseous carbon is impregnated and carbonized to make a strong carbon base.

Ceramic composites
A ceramic base that is reinforced with a stronger or stiffer material in a particulate, whisker, or fiber form.

Cryogenic propellant
A rocket fuel, oxidizer, or propulsion fluid that is liquid only at very low temperatures.

Hot-shot tunnel
A commonly used name for an impulse-driven test facility; may be arc-heated or combustion-heated. See impulse, arc-heated, and shock tunnel.

Hypersonic cruise
Sustained flight at hypersonic speeds.

Impulse
Generic term to describe a device to generate high-speed gas flows for a short time, by the sudden release of stored high-pressure, high-temperature gas. See hot-shot tunnel and shock tube.

Intermetallics
A compound consisting of two or more metals with distinctive crystal structure and definite compositional range. Generally they have aggregate properties better than constituent properties.

Metal matrix composites
A metal base that is reinforced by one or more stronger or stiffer materials in a particulate, whisker, or fiber form.

Passive cooling
This concept requires that structural materials transfer and dissipate surface heat encountered during high-speed flight.

Ramjet
Air-breathing engine similar to a turbojet but without a mechanical compressor or turbine. The intake air is "rammed" into the engine by its forward motion. It cannot operate under static conditions and is inefficient below Mach 3 to Mach 3.5.

Scramjet
A ramjet with supersonic flow-through, that is, inlet airflow is not diffused to subsonic velocity. The combustion flamefront is stabilized in a supersonic stream.

Shock tube
A simple impulse device consisting of a tube divided into two parts by a diaphragm. One side—containing a test model and instrumentation—is evacuated. The

other side is pressurized and heated quickly (for example, by discharging a capacitor through an electric arc) until the diaphragm breaks. A resulting shock wave forces the low-pressure gas to move at high speed for a brief time; used primarily to study the chemical physics of dissociated and ionized gases.

Shock tunnel
A shock tube whose low-pressure end is attached to a nozzle for further expansion to higher Mach numbers.