Turbine-Based Combined Cycle Propulsion

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Abstract:
This paper discusses Turbine Based Combined Cycle (TBCC) propulsion. It goes into an overview of its functionality and attractiveness as a method of propulsion for hypersonic vehicles. The principal concepts and configurations are discussed, and the Pratt and Whitney J58 engine is discussed in detail due to its functionality as a TBCC engine on the SR-71 Blackbird. The current state of cycle modeling and development is summarized, as are the current needs for future development. An engine with a configuration similar to the J58 is proposed as a development path due to the proven technology and knowledge base.

Introduction:

Although airbreathing supersonic and hypersonic propulsion systems have been known of for some time, their development and implementation is still in relative infancy. One reason for this is their limitations. The nature of ramjets and scramjets requires airflow from forward motion at high speeds in order for them to start. Thus they cannot be used as the sole propulsion system on aircraft or other systems starting flight from a stationary position. One method of overcoming this limitation is to adapt the technology to be used together with that of turbojet engines in what is termed a Turbine Based Combined Cycle (TBCC) system. TBCC engines would function similarly to a turbojet engine to accelerate the vehicle to speeds high enough to allow transition to a ramjet or scramjet mode. Several variations on this concept exist. A notable example of a successful engine utilizing the TBCC concept is the Pratt and Whitney J58, which was used on the SR-71 Blackbird. Development of new TBCC engines for higher-speed flight is limited by a lack of understanding of and ability to simulate the complex aerodynamics in high-speed flight regimes, which is systemic in the development of high-speed airbreathing propulsion systems.

Ramjets, Scramjets and the benefits of TBCC:

Ramjets and scramjets still use the essential tenets of gas turbine propulsion to generate thrust, but are greatly simplified in the mechanical sense. Rather than using a compressor that must be powered, the incoming air enters the inlet and is compressed and slowed by the vehicle's momentum. Fuel is injected into the flow and combusted in a method very much like a jet turbine afterburner, and this added energy is then extracted through a nozzle. An illustration of the cycle is shown in Figure 1.

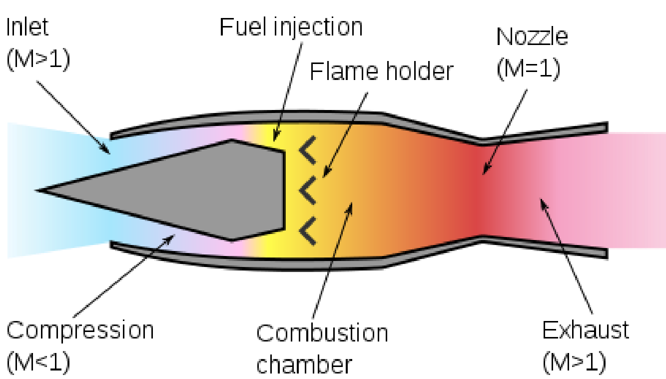

Figure 1: Ramjet Cycle Illustration[1]

Ramjets are named as such due to the "ram effect" that forces air through the engine. While ramjets slow the flow to subsonic speeds for combustion, accomplishing this through a series of shocks if inlet flow is supersonic. Scramjets, which are designed for much higher speeds, still slow the flow somewhat, but combustion takes place in supersonic flow. The name is derived from an abbreviation for "Supersonic Combustion Ramjet." Ramjets, and to a much more significant degree scramjets, are more complex aerodynamically than typical gas turbine engines. The inlet needs to be designed for precise placement of shock waves to slow the flow.

The principal difference between ramjets and scramjets is geometry. While a ramjet needs to slow flow down to subsonic speeds, a scramjet keeps the flow supersonic. Adjusting the inlet can change shock placement, thus changing how much the flow is slowed. Enabling this variation can increase the versatility of the engine, giving it a larger operating range. This variability is included in many TBCC concepts, and is typically termed an integrated ramjet-scramjet.

The idea behind a TBCC engine is to accelerate an aircraft to high speeds using a turbojet engine, then transition to the use of a ramjet or scramjet when its use becomes more efficient. Mass and overall vehicle complexity are reduced by having the modes in the same engine package. Figure 2 shows the specific impulse, a measure of a propulsion system's efficiency, as function of Mach number for various engines.

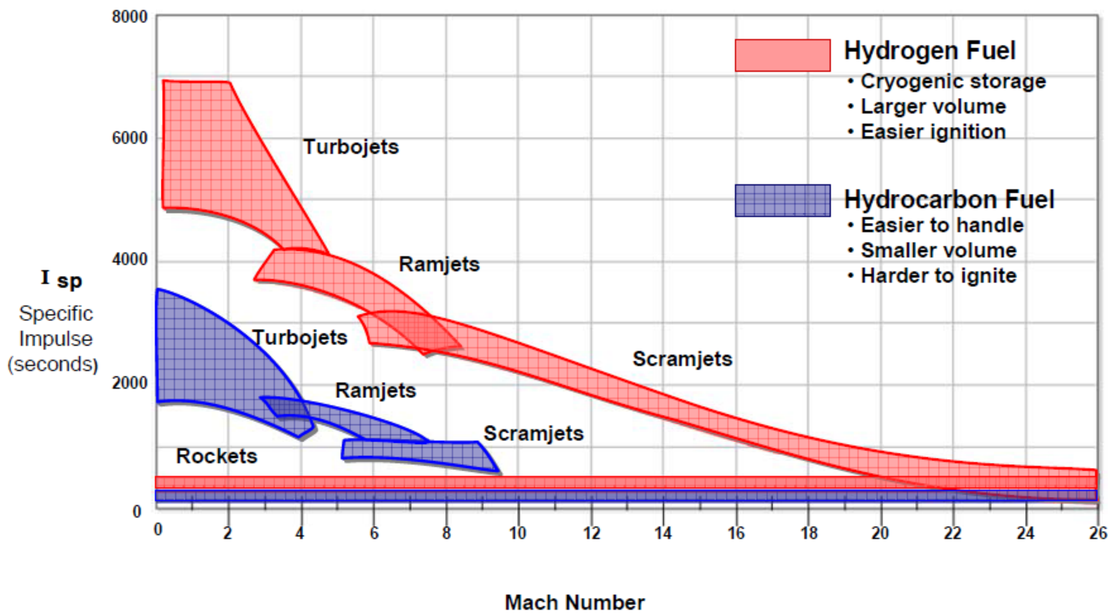

Figure 2: Specific Impulse Curves for Various Engine Types[2]

This picture makes clear the desirability of airbreathing engines for use at supersonic (Mach 1-5) and hypersonic (above Mach 5) speeds. Since these engines do not carry their oxidizer with them, they are much more efficient than rockets in the atmosphere. The figure also illustrates the benefits of hydrogen fuels. They are not conventionally used because the difficulty of storing such fuel, especially on an aircraft undergoing intense aerodynamic heating at high speeds, is very difficult. It requires large, heavy tanks that create significant penalties in terms of mass and drag.

TBCC is attractive for several reasons. For strictly atmospheric flight, it offers the potential for rapid response, very-high speed fighter aircraft, allowing for quick military action on a global scale. A vehicle traveling at Mach 6 could circumnavigate the globe in approximately 4 hours, thus making the maximum response time of that vehicle two hours to a conflict anywhere in the world. Transport based on these designs could enhance global networking, business, and commerce.

TBCC is also discussed in topics of Two-Stage-to-Orbit (TSTO) or Single-Stage-to-Orbit (SSTO) vehicles. A TBCC powered lifter vehicle in a TSTO configuration could allow the second stage to carry much less fuel by accelerating it to higher speeds before separation. A SSTO configuration would likely require some additional rocket mode, but since the airbreathing systems could accelerate the vehicle through the atmosphere, much less oxidizer would be required for the rocket. Both the airbreathing and rocket systems could be designed to use the same fuel.

TBCC concepts:
The simplest method of combining the cycles for a TBCC engine would be to simply strap a combination ramjet-scramjet to a turbojet. However, the non-operational engines would create a large amount of drag, making it very inefficient. This is the most basic way to allow both modes of propulsion on an aircraft, although the cycles are not combined.

A common approach is to do essentially what is described above, but have the turbine engine and integrated ramjet-scramjet operate on a single flowpath via flow diversion. This is illustrated in Figure 3.

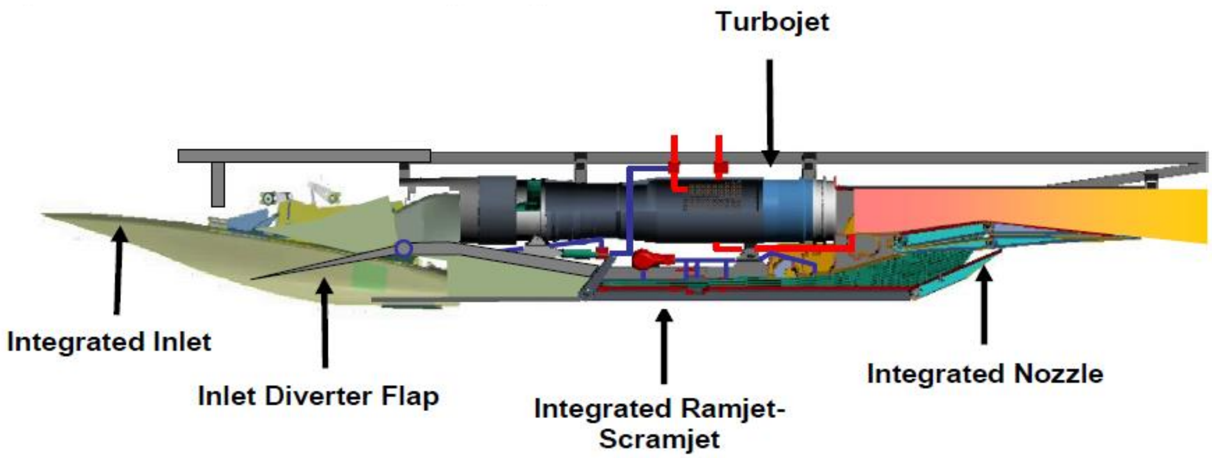

Figure 3: TBCC Concept[2]

In the position shown, the engine is operating in the turbojet mode. To transition to ramjet-scramjet mode, the diverter flap moves upward, directing the flow into the integrated ramjet-scramjet. The integrated nozzle also moves upward. This configuration requires a definite mode transition, however, which can be problematic as will be discussed below. This configuration would typically be mounted on the side or bottom wall of an aircraft, as is suggested by the asymmetry. This is typically termed a top-bottom configuration. Figure 4 shows a concept of the NASA X-43B, which was to be a demonstrator aircraft powered by TBCC engines in such a configuration.

Figure 4: Concept of the X-43B, a TBCC Aircraft[3]

Another configuration in a similar vein would be axially symmetric. The turbine engine would be at the center of the engine, and movement of the inlet would adjust the amount of air bypassed around the core to be used in the ramjet. This could allow for a more gradual mode transition process, but could potentially cause more drag due to a larger frontal area. The concept is illustrated in Figure 5.

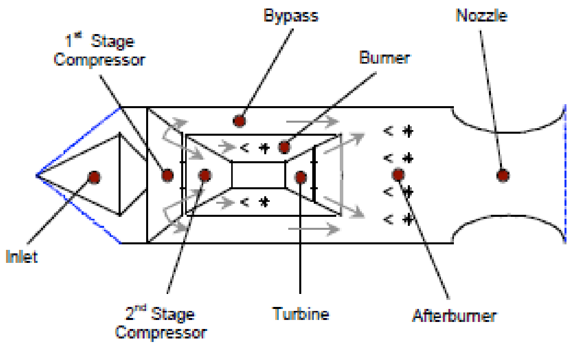

Figure 5: Axial TBCC Concept[4]

The J58

The concept of axially symmetric TBCC engines has been demonstrated, to an extent, in the Pratt and Whitney J58 engine used on the SR-71 Blackbird. The Blackbird had a variable nose cone that controlled the bypass around the engine and kept the flow into the turbine engine subsonic. While not explicitly designed as a combined cycle engine, the essential functionality was there. At the aircraft's top speed the engine's bypass, which was mixed back in to the flow in the afterburner, provided 80% of the engine's thrust [5].

The different operating modes of the engine are illustrated in Figure 6.

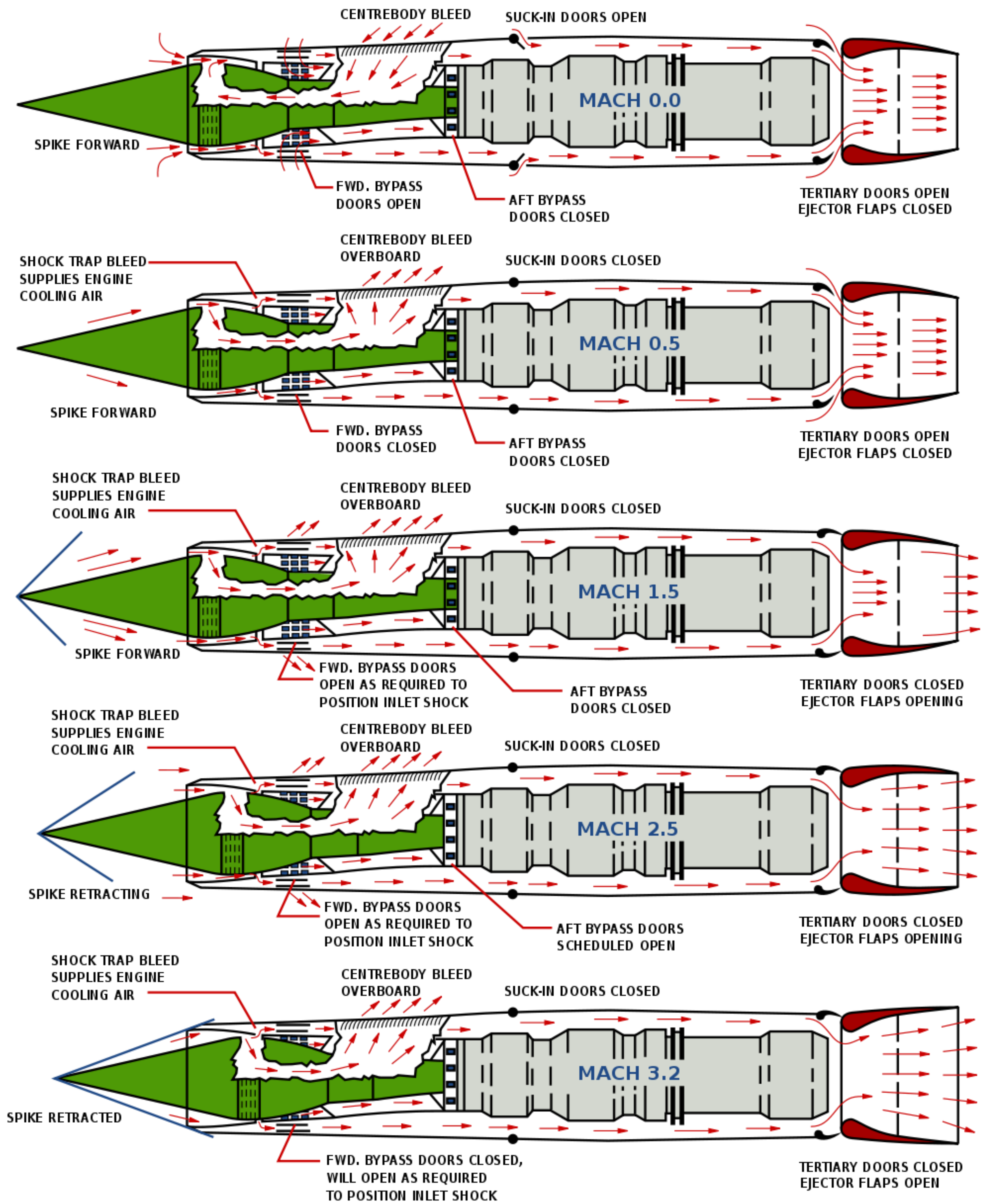

Figure 6: J-58 Modes of Operation[1]

The figure shows how the variable inlet functions at different flight Mach numbers. Retracting it constricts the flow into the turbine portion of the engine, forcing more of it to be bypassed around it.

Although it is not indicated in the illustration, bypass air is used for combustion in the afterburner, thereby essentially making the engine a coaxial turbojet/ramjet. As opposed to the “stacked” configuration in Figure 3, this method offers a smoother mode transition.

A number of closer views of the functionality of the inlet spike is shown below. Since boundary layers can have significant effects on shock formation, boundary flow is bled away and overboard. The flow actually enters the bypass portion of the engine through a number of small holes around the inlet spike, around which doors balance the pressure for placement of the series of oblique inlet shocks and the terminal normal shock [6,7]. Bypass air was also taken aft of the diffuser portion of the spike when necessary to further reduce the airflow through the turbine portion of the engine.

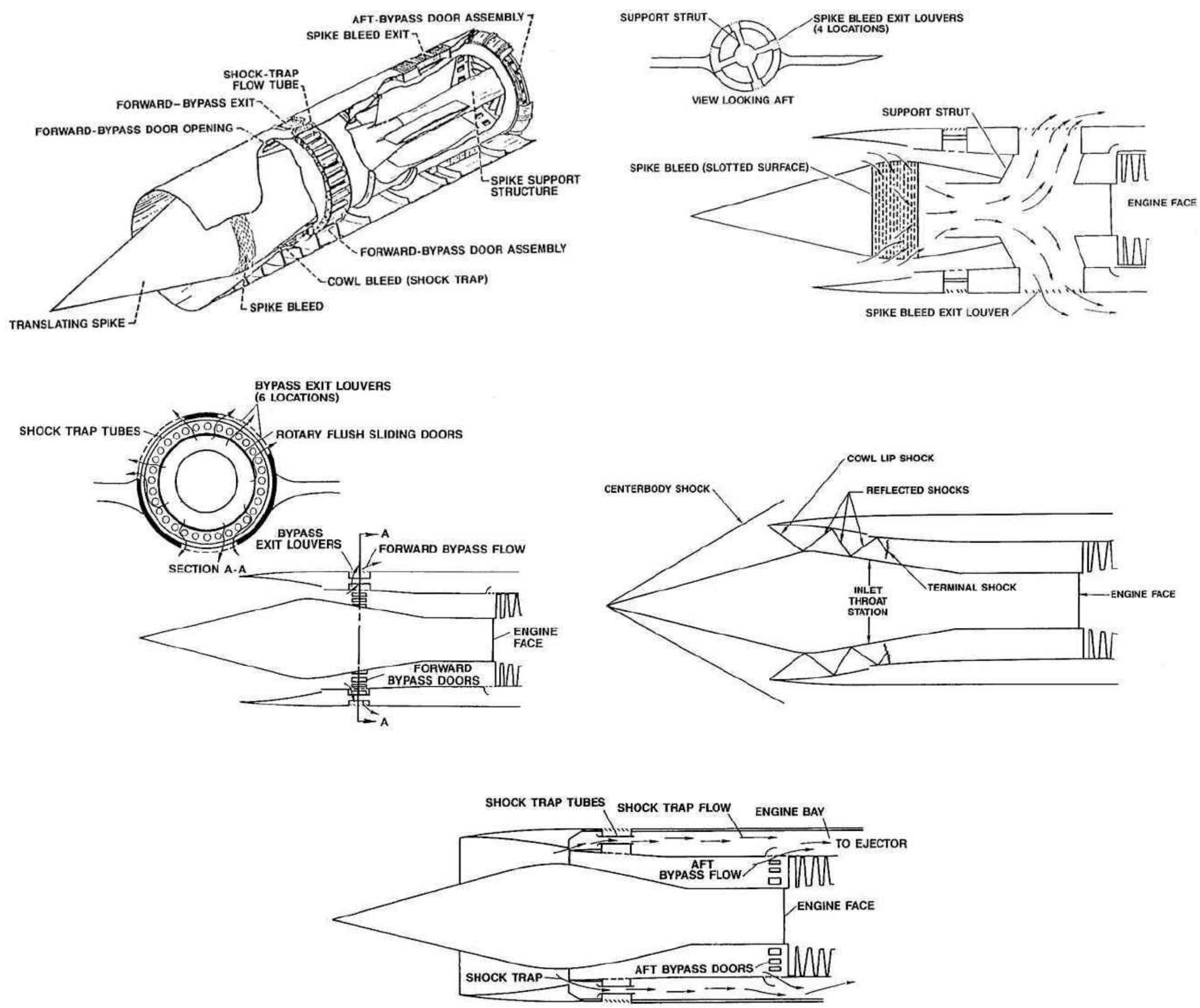

Figure 7: Views of the J58 Inlet[7]

This ingenious design was very effective, and actually managed to reduce fuel flow when flying at higher speeds [6]. This was due to a combination of thrust from the inlet itself and the exhaust.

At the time of the engine’s development, there were no methods for supersonic combustion (scramjets). Thus the engine inlet is designed such that flow is always slowed to subsonic speeds inside the engine. Additionally, the turbine portion was never completely removed from the flowpath, so the maximum speed was dependent on the temperature limits of the compressor inlet. This was limited to 700 K, which it reached very shortly after Mach 3.2 due to aerodynamic heating of the flow entering the engine [6]. At this point the turbine portion was only providing 20-30% of the thrust of the engine, however. Aerodynamic analysis suggests that the inlet would be capable of speeds up to Mach 6, however, were it not for these material limits.

When the inlet was not properly positioned or airflow into the engine was significantly disturbed, the engine was prone to “unstarting.” In this situation the normal shock would be ejected from the inside of the inlet, create a severe drop in pressure that caused the engine to stop. This phenomenon is not limited to the J58 and its inlet, rather it is an issue with all supersonic engine inlets. Modern computer controls can prevent it by rapidly adjusting inlet geometry in most cases, however, so were the engine to be remade today this would likely not be problematic.

Top-Bottom engine designs similar to that in Figure 3 are attractive, largely because they are better lent toward hypersonic aircraft integration. Design of such aircraft requires highly streamlined aerodynamics to reduce drag and aerodynamic heating, so a package that can largely be tucked underneath and into the body of an aircraft carries several advantages. The J58’s inlet was so effective because it was a wing-mounted engine. Figure 8 illustrates the differences between the typical engine placement in a hypersonic vehicle concept and the SR-71.

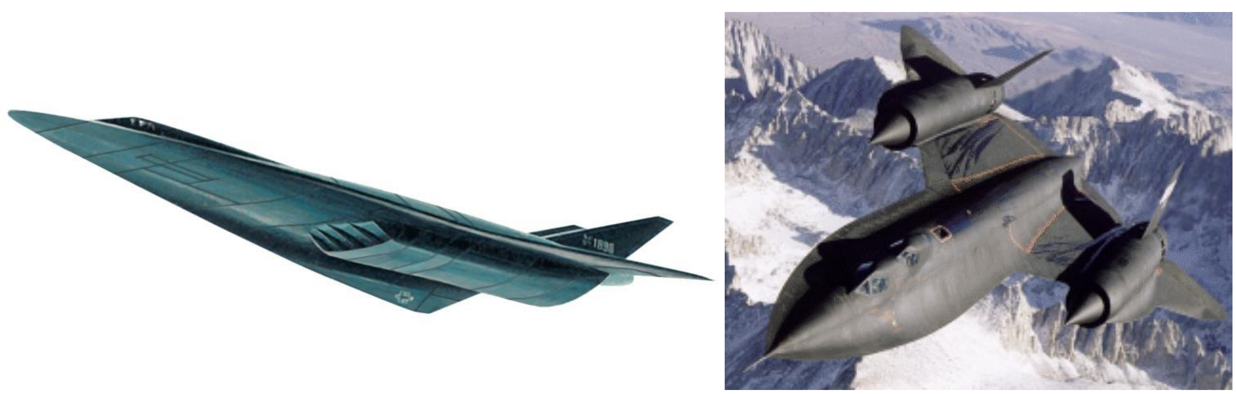

Figure 8: Comparison of Engine Placement[8,9]

The placement of the J58 on the wing of the SR-71 allowed it to have more uniform flow around the inlet. In the concept vehicle, the rectangular holes in the bottom are engine inlets, where the turbine would likely be inside the main body of the aircraft. This configuration would present many advantages in terms of drag reduction, as the frontal area due to the engine is reduced and skin friction and heating are also reduced by the elimination of the large engine nacelles.

Mode Transition

While the typical concept is more attractive in terms of the design of whole vehicles, the functionality and mode transition of the J58 has been proven whereas transition is a significant obstacle for most top-bottom configurations. The essentially functionality of the J58 could conceivably be updated to allow for supersonic combustion in the afterburner section and full cutoff of the turbine engine, as well as by updating material choices and compressor designs to push back the influence compressor exit temperature on maximum speed. Conversely, hypersonic inlets could be designed to vary in geometry in a way that provides the same gradual transition for a top-bottom configuration. This would require complex and precise aerodynamic design that could vary not only the inlet channel shock placement but also the amount of flow diverted to the turbine engine.

From a development standpoint it makes more sense to prove the concept of combined-cycle propulsion on a hypersonic scale using a design based around the J58. The engine has already been designed and has already demonstrated the feasibility to the extent technology allowed at the time of its development. While it may not be an optimal design for a manned vehicle, the concept could be demonstrated by essentially making the engine the centerbody of a small test aircraft. This could help provide a lot of empirical data and practical experience in the subsequent design of an engine with a form factor more suited to manned hypersonic travel. This is important, because most modeling is done based on assumptions and numerical approximations to theoretical equations and empirical data could provide corrections for more accurate models.

TBCC Modeling and Testing:
With exception of the J58, most TBCC development has been theoretical and ground-based. TBCC is a high-risk, unexplored field that requires substantial investment to develop a flight engine. The aerodynamic characteristics of these engines are complex, as they are intended to operate over a wide range of Mach numbers.

One-dimensional thermal analysis is commonly used in the preliminary design of conventional gas turbine engines, and TBCC engines are no exception. Figure 9 shows a one-dimensional analysis of the specific impulse of the engine diagrammed in Figure 5.

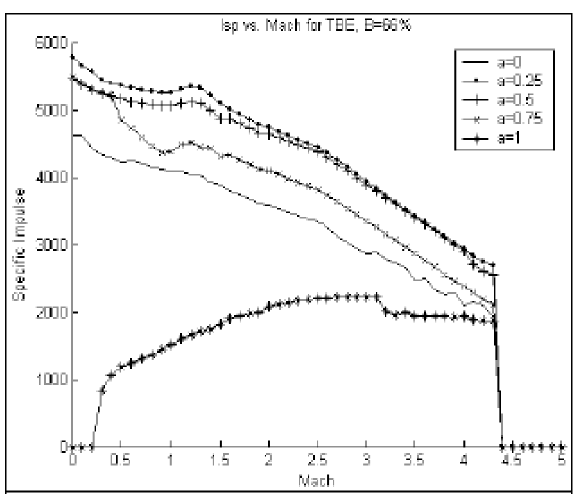

Figure 9: A TBCC Model[4]

The “B” specified in the title is the compressor staging ratio. This is a significant factor in this model, because as Figure 5 shows, the flow in this particular engine is diverted after the first stage. The “a” for which the various values are plotted is the bypass ratio. The plot suggests that there would be an optimal design for such an engine, even though the compressor exit temperature limits the maximum achievable Mach number, similar to the J58.

Other studies have been performed on axial engine configurations that suggest the feasibility of a smooth mode transition [10].

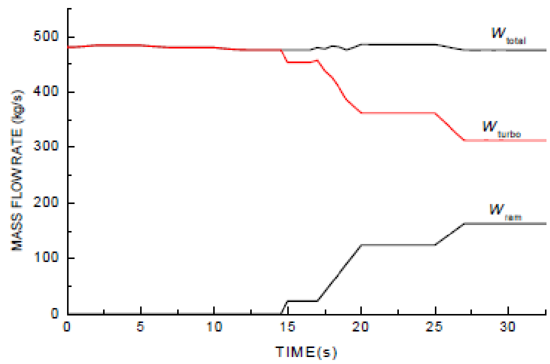

Figure 10: Axial TBCC Model Results[10]

The plot shows that only very small fluctuations in mass flow are predicted during mode transition for the particular engine under analysis. The paper discussing the study indicates that engine performance parameters were conservative, but that engine operation and bypass was very finely controlled.

More complex analyses are also performed regarding shock placement and mode transition. A program that performs such analysis is discussed in Reference 11. It designs a top-bottom configuration TBCC engine, calculating shock locations and diverter/ejector placement for varying flight speeds up to Mach 10. Figure 10 shows a screenshot from the program under discussion.

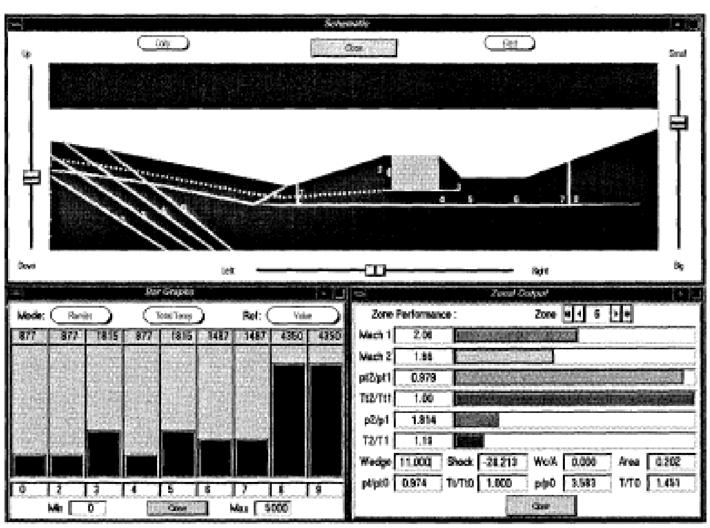

Figure 11: Modeling Program[11]

However rudimentary and nonspecific as to actual engine parameters the program may be, it suggests that such modeling is feasible and that more complex models could be developed.

Not all development is limited to modeling. In 1998, Japan successfully ground-tested the HYPR engine depicted below [12]. It is interesting to note that the engine has an axial design, similar to the J58.

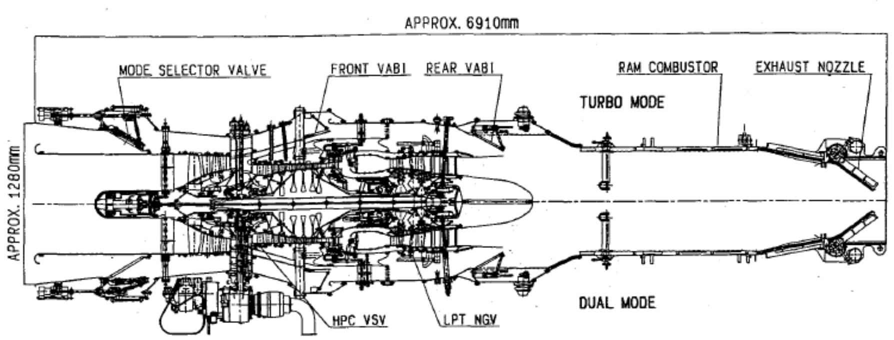

Figure 12: Japanese HYPR[12]

The engine was demonstrated to function in close agreement with the models used in its development, suggesting that, at least for axial flow configurations, the modeling of combined cycle propulsion systems to levels of realistic detail is possible. The fact that the engine's development has progressed to the point it has also suggests that axial TBCC engines can be developed for flight testing.

TBCC limitations and Areas for further development:

TBCC engines are limited largely by their level of development. Part of the issue is that for hypersonic vehicle design, the design of the vehicle body and the engine become highly coupled. This is why top-bottom engines are more often considered in design. Regardless, however, the engine development is still subject to the same development needs as hypersonic vehicles in general. Figure 13 highlights some of the necessary development areas, particularly as they relate to top-bottom configurations.

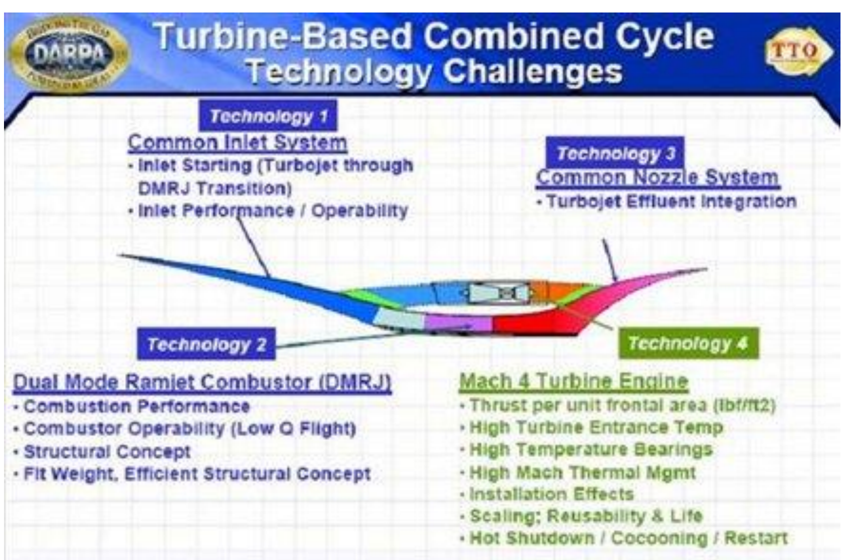

Figure 13: TBCC Challenges[13]

Thermal issues become extreme at high speeds and high thrust, so accurate thermal and cooling modeling is important for hypersonic vehicle and engine design. New material development is also likely to be necessary [14]. Relatedly, aerodynamics at high Mach numbers are complex and difficult to model. Little empirical data is available for such situations.

Another important issue is the variation of geometry, not only for transitioning from turbojet to ramjet modes, but also from ramjet to scramjet. This would likely require variation in the geometry of the engine flowpath, and would not just be an issue of flow diversion.

Combustion in high-speed flows is also an important consideration. While fuel injectors and flame holders exist for subsonic combustion, even at high speeds, supersonic combustion is a challenging problem requiring more research [4].

Even if vehicle design in the long term will require top-bottom engine considerations, large amounts of useful data could be generated from a test vehicle based around an axial TBCC engine, including ramjet-to-scramjet transition, combustion, and aerothermodynamics. Such a vehicle, as described in the Mode Transition section of this document, could potentially operate well enough to carry a top-bottom engine for testing, if present modeling and data of axial TBCC engines is accurate.

Conclusions

TBCC engines are a very exciting concept in the field of high-speed propulsion. They offer superior performance over a large range of flight speeds, and would allow hypersonic aircraft to take off under their own airbreathing power. Top-bottom engine configurations are attractive from a vehicle design perspective, but taking a smaller step forward in design could be very beneficial in the long term. An axial configuration like that of the J58 could be more easily integrated into a test aircraft that in itself could provide empirical data to assist in hypersonic engine and vehicle design, but even act as a test bed for other engine geometries. This is supported by the results of engine modeling, and even the manufacturing and ground testing of the Japanese HYPR engine. Hypersonic vehicles have faced the same significant obstacles for some time in their development, and an intermediate test vehicle could be the key to understanding phenomena at high speeds and lead to a more rapid development and implementation of such vehicles.

References:

1. Wikipedia Creative Commons. [http://en.wikipedia.org/ Accessed 12/10/2009.]
2. Ming, T., and Chase, R.L. "The Quest for Hypersonic Flight with Air-Breathing Propulsion," *15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Dayton, OH, April 2008.
3. "NASA developing Hypersonic Technologies," NASA News Release, 22 July 2002. [http://www.msfc.nasa.gov/news/news/releases/2002/02-182.html Accessed 12/10/2009]
4. Marshall, A.W., Gupta, A.K., Lewis, M.J., and Lavelle, T., "Critical Issues in TBCC Modeling," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Fort Lauderdale, FL, July 2004.
5. "J58 Engine Factsheet," Hill Air Force Base, United States Air Force. [http://www.hill.af.mil/library/factsheets/factsheet.asp?id=5786, Accessed 12/10/2009.]
6. Merlin, P.W., "Design and Development of the Blackbird: Challenges and Lessons Learned," *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, Orlando, Florida, January 2009.
7. Kucher, P.R., "JT11D-20A/J58 Engine,"*SR-71.org*. [http://www.sr-71.org/blackbird/j-58/, Accessed 12/11/2009.]
8. Noor, A.K., Center for Advanced Engineering Environments web page, Old Dominion University. [http://www.aee.odu.edu/fas.php?id=5, Accessed 12/11/2009.]
9. "SR-71 History" [http://www.grc.nasa.gov/WWW/K-12/aerosim/LessonHS97/SR71.html Accessed 12/11/2009.]
10. Chen, M., et al. ,"Mode Transition Study of Turbine Based Combined Cycle Engine Concepts," *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit,* Cincinnati, Ohio, July 2007.
11. Benson, T.J., Trefny, C.J, and Walker, J.F., "Interactive Design Tool for Turbine Based Combined Cycle Engines," *33rd AIAA/ASME/SAE/ASEE Joint PropulsionConference & Exhibit,* Seattle, Washington, July 1997.
12. Miyagi, H., et al., "Combined Cycle Engine Research in Japanese HYPR Program," *AIAA*, 1998.
13. Warwick, G., "DARPA Lifts the Covers on Vulcan Engine," *Ares: A Defense Technology Blog*, Aviation Week, 20 June 2008. [http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckScript=blogscript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post:6adbffb4-6533-460f-b531-62f7dd64ea61, Accessed 12/11/2009.]
14. Barber, T.A., Maicke, B.A., and Majdalani, J., "Current State of High Speed Propulsion: Gaps, Obstacles, and Technological Challenges in Hypersonic Applications," *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Denver CO, August 2009.