JOURNAL OF PROPULSION AND POWER
Vol. 23, No. 1, January–February 2007

Scramjets and Surfboards: Some Forgotten History

Edward A. Fletcher*
University of Minnesota, Minneapolis, Minnesota 55455

DOI: 10.2514/1.21160

Anecdotal examples that illustrate the contributions that basic studies have made to aircraft and rocket ignition and combustion behavior are recalled. Some almost forgotten experimental supersonic combustion studies done in the 1950s by a small group at the National Advisory Committee for Aeronautics Lewis Flight Propulsion Laboratory are recalled and described. Those studies anticipated the hypersonic, nearly Mach 10, flight that was achieved 50-some years later by a National Aeronautics and Space Administration aircraft in November 2004. A suggestion for further work related to combustion in the scramjet aircraft is made. Consideration of the use of hydrocarbon fuel spiked with a pyrophoric ignition and combustion enhancer, rather than hydrogen, is suggested.

Introduction

ON 17 November 2004 the National Aeronautics and Space Administration (NASA) issued a press release that announced that NASA's X-43A demonstrated that an air-breathing aircraft can fly at nearly Mach 10. It is now appropriate to call attention to experimental supersonic combustion studies done 50 years before by a small group at the National Advisory Committee for Aeronautics (NACA) Lewis Flight Propulsion Laboratory. It is also pertinent to call attention to other examples of situations in which basic research has contributed to the development of the technology of flight and to problems that have arisen when information provided by basic research is unfamiliar or ignored. Air-breathing supersonic and hypersonic propulsion systems are described in excellent historical review articles by Fry [1], Curran [2], and Walrup et al. [3]. The principle of the scramjet propulsion system was shown to be achievable at the Lewis Flight Propulsion Laboratory about 50 years ago in a series of basic studies conducted by an informally organized group: Harrison Allen, Jr., Robert G. Dorsch, Melvin Gerstein, I. Irving Pinkel, John Serafini, and me. Many technicians and others at NACA/NASA provided the support that made the studies possible.

The original Lewis publications generated by our group called attention to an alternative contrivance, neither a rocket nor a jet engine, that might be used to propel hypersonic aircraft through the atmosphere. Scramjet (supersonic combustion ramjet) is a wonderfully catchy name. I wish we had thought of it. But the propulsion device for the scramjet aircraft is not a jet engine at all. It is a different kind of device. The propulsion mechanism we proposed to explore might be characterized as "lift and thrust achieved in supersonic flight by external combustion in a compressible flowfield." That does not make for a catchy name. LTASFECCFF is a rotten acronym. The device our group advocated mitigates an important shortcoming of ramjet engines in very high-speed flight: the danger of self-destruction by overheating. It keeps the working fluid outside of the aircraft and slows down the external airstream as little as possible. Because the flowfield is compressible, injection of a pyrophoric fuel into a selected region, a rearward-facing lower surface, for example, raises the pressure in that region and produces lift and thrust. The aircraft rides on the pressure wave produced by the combustion. Thus, I like to think of the external burning scramjet as an airborne surfboard riding along on its own self-generated wave, rather than as more conventional jet aircraft. If it flies fast enough, it does not need enclosed diffusers, flame holders, or nozzles. It does not need an engine.

The Effort at Lewis

The experimental effort at the Lewis Laboratory began with a discussion between Pinkel and Gerstein. Pinkel, Serafini, and John L. Gregg had done analytical studies that suggested that combustion under the wing of a supersonic aircraft rather than in the engine would provide more lift than the combustion of an equal amount of fuel in the jet engine [4,5].

Conventional wisdom at that time held that hydrocarbon combustion could not be achieved or maintained in any existing supersonic wind tunnel. Pinkel consulted Gerstein to see if he could suggest any fuel that could be burned in an existing facility to test their analysis. The first fuel that came to Gerstein's mind was aluminum borohydride, $Al(BH_4)_3$. Aluminum borohydride is a volatile liquid that boils at 46°F, a temperature about halfway between the boiling points of normal pentane and normal hexane. It is extremely pyrophoric. The first borohydride was uranium borohydride. Herbert C. Brown and others prepared it at the University of Chicago in a Manhattan Project search for volatile compounds of uranium. At the time of the Browns' marriage, his bride Sarah presented him with the only gift they could afford: a secondhand copy of Alfred Stock's book, *The Hydrides of Boron and Silicon*. In it she wrote, "To a future Nobel Laureate." She turned out to be a prophet. After Brown was denied tenure at the University of Chicago, he moved to Wayne University in Detroit. From there, Brown moved to Purdue, in 1947, taking with him a group of five graduate students. The event was referred to locally as the Brownian movement.

Getting Started at NACA

I arrived at the Lewis Flight Propulsion Laboratory early in January 1952, after having served a three-year stint as a naval aviator followed by a year as an undergraduate and four years in graduate school. I was assigned to the Combustion Fundamentals Section. Gerstein was my first section head. Lewis was a great place to work. I was in a section that consisted of a congenial group of conscientious coworkers, including Abraham Berlad, who became my section head during the course of our study, when Gerstein was promoted to branch chief. The word *fundamental* was emphasized and the word *propulsion* was loosely interpreted. Berlad and Gerstein allowed, indeed encouraged, us to investigate interesting tangents.

Our first application of aluminum borohydride at Lewis was to ignite turbojet combustors. A particularly vexing problem in the early 1950s was flameout in turbojet engines, and, occasionally, it still is. In normal operation, once a turbojet engine has been started, the compressor keeps the pressure in the combustion chamber high enough so that hydrocarbon jet fuel continues to burn stably, even at high altitudes, where the air is colder and the ambient pressure is

Received 16 November 2005; revision received 8 February 2006; accepted for publication 26 February 2006.

*Department of Mechanical Engineering, 111 Church Street Southeast.

lower. But at altitude, a momentary transient that might have been caused by a change in the attitude of the aircraft or the fuel–air mixture ratio or the combustion chamber pressure can sometimes lead to a flameout.

Gerstein suggested that I try using aluminum borohydride injection to reestablish combustion at high altitudes and thus permit an engine to return to its normal operating state. I joined two experienced engineers in an earthbound low-pressure combustor study that demonstrated that the idea would work [6]. And, more important, that solutions of aluminum borohydride in hydrocarbons would also work [7]. Eventually, injection of pyrophoric triethylborane became an ignition technique for high-altitude aircraft such as the SR-71 Blackbird. A spin-off of that procedure was later used to ignite high-altitude solid propellant rocket engines. Shortly before I left Lewis in 1959 to go to the University of Minnesota, I suggested that the injection of a very reactive oxidizer, chlorine trifluoride, into solid propellant rocket engines to ignite (or reignite) them in space should be explored. I never got a chance to work on it, but it worked, and some time afterward I was listed as a coinventor on two patents and given a small cash award by NASA for the idea.

A related laboratory study of reactions between nitric acid and amines developed guidelines to be used in the ignition of liquid bipropellant rocket engines burning amines and nitric acid [8–10]. An oxidizer lead was strongly recommended to assure reliable ignition at high altitude. That study provides a cogent example of the value that pertinent basic research can have for hands-on engineers. The launch vehicle for the Gemini mission made use of an amine-nitric-acid-propelled Agena second stage. It was ignited successfully in ground testing with an oxidizer lead. The propellant sequence was reversed in an unmanned flight test. The Agena experienced a hard start and was destroyed. The launch group subsequently returned to the use of an oxidizer lead, and the Agena functioned as it was supposed to.

Encouraged by his discussions with Pinkel about Pinkel's analytical studies with Serafini and Gregg, Gerstein suggested that I try to burn aluminum borohydride in a supersonic wind tunnel. The time was ripe. Others were also resurrecting the suggestion that pressure increases produced by heat addition to a supersonic airstream could be used to create lift and thrust [11–16].

Preliminary Considerations

Testing the Pinkel et al. brainchild in an existing wind tunnel at conditions resembling hypersonic flight with conventional hydrocarbon fuels was out of the question. We knew of no wind tunnels that could simulate flight conditions that would be encountered at the high Mach numbers that characterized hypersonic flight. The stagnation absolute temperature of an airstream is roughly proportional to the square of the Mach number. At the flight altitude of the scramjet described in the 17 November 2004 news release, about 110,000 ft, the static temperature of the ambient air is about is about −40°F. In contrast, the stagnation temperature at hypersonic flight speeds is of the order of thousands of degrees Fahrenheit. Simulating free-flight conditions for a hypersonic aircraft would have required that the air flowing through the test section of a wind tunnel be preheated to those stagnation temperatures before it entered the throat. One way that such a wind tunnel might be built is worth mentioning here because it seems to have recently reemerged as a device being studied to be used to produce very high-temperature air [17]. It depends on the fact that a supersonic wind tunnel resembles a rocket engine running backward. If one had a rocket propellant that produces air as its sole combustion product, one would have the makings of a very high-temperature supersonic wind tunnel.

There is a family of chemical compounds, nitrosyls, that behave as if they contain a nitrosyl cation NO^+. There are also compounds in which the azide group $(N_3)^-$, the anionic component of hydrazoic acid HN_3, behaves as if it were an anion. The azide group is unstable and often explosive. I postulated that if one could make nitrosyl azide (NON_3), it would probably be an energetic rocket monopropellant whose decomposition product would be a very hot mixture of four parts nitrogen with one part oxygen. (Dare I say "hot air"?) I asked one of the members of the section I now headed, Harold Lucien, to try to synthesize it. Lucien's observations suggested that he had indeed made it [18], but it was not stable enough to encourage me to pursue the idea further.

Gerstein suggested that I try to test the proposal in an existing wind tunnel using aluminum borohydride as the fuel. I had had no experience working with wind tunnels and little experience with fluid mechanical problems, but the skills of the members of our motley group complemented each other. In this resume of our studies, I have made extensive use of text and figures from the eight NACA/NASA research documents our group produced during the course of our experimental studies [19–26]. The documents themselves contain references to other related studies.

Supersonic Combustion in a Small, Glass-Walled Tunnel

We did the early experiments in a 3.84 in. wide by 10 in. high rectangular cross-section supersonic wind tunnel equipped with one-inch-thick plate glass walls that ran the entire length of the tunnel. That permitted us to take direct, schlieren, open-shutter, and high-speed motion pictures of our observations at Mach numbers 1.5, 2, 3, and 4. A schematic diagram looking down on the tunnel showing the arrangement of the auxiliary equipment is shown in Fig. 1. We took high-speed, 1000 to 4000 frames per second, direct and schlieren motion pictures of the flames and 8 by 10 in. open-shutter still pictures to give us an integrated picture of the entire zone of visible combustion. At the Mach 4 test-section condition the static temperature was −327°F and the static pressure was about 0.01 bar. In our first tests we gingerly injected small quantities of aluminum borohydride into the airstream from capsules. Figure 2 shows an open-shutter photograph of the combustion of one-half milliliter of aluminum borohydride. My no-longer-slender waistline can be seen about halfway between the point of injection and the throat. Individual frames from the high-speed motion pictures showed that the liquid stream from the capsule spread out and broke up into droplets before it ignited. A delayed ignition that occurred after the cloud of fuel droplets had become dispersed took place after a delay of several milliseconds, suggesting that it may have ignited in the diffuser. It was accompanied by a loud bang and choked the tunnel, driving the flame upstream almost into the throat.

Our more informative studies made use of slower, controlled injections of aluminum borohydride. The duration of these injections varied from 1 to 3 s. For these studies we found it desirable to introduce a one-joule, five-sparks-per-second repeating capacitance spark plug to ensure ignition.

We also identified other fuels and injection patterns that might have practical use and learned more about the flow pattern in the neighborhood of the aluminum borohydride flames. A most useful observation we made was that we could burn hydrocarbons in supersonic streams without having to use flame holders. Solutions

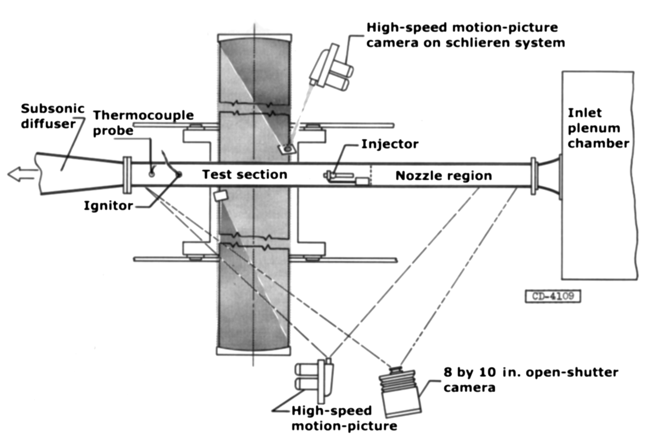


Fig. 1 Schematic diagram looking down on the arrangement of the small-tunnel experiments [19].

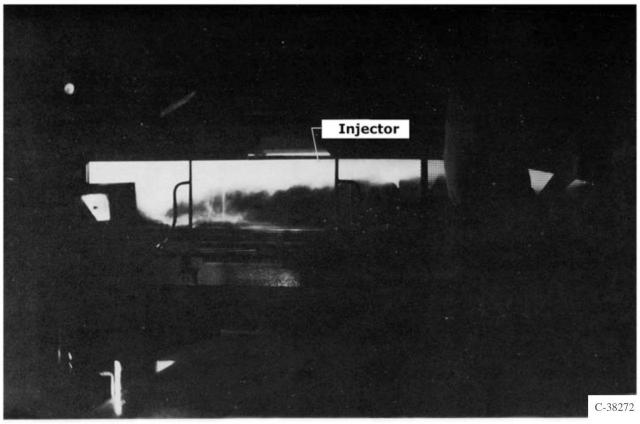


Fig. 2 Combustion of one-half milliliter of aluminum borohydride at Mach 4 [19].

containing 41% JP-4 hydrocarbon jet fuel in aluminum borohydride burned and produced associated pressure rises. Pure JP-4 hydrocarbon fuel burned when it was injected in tandem with aluminum borohydride either upstream or downstream of its point of injection.

We also conducted studies aimed at elucidating the detailed structure and composition of the combustion zone. After having established a stable flame adjacent to the top wall of the tunnel, we withdrew samples of the combustion gases along the centerline into evacuated glass bulbs for later analysis.

Because of the reactivity of the fuel, it was not possible to study the rate of mixing of fuel with air in the absence of combustion. A comparison of motion pictures taken both with and without combustion shows that combustion, with its conspicuous aerodynamic effects on the flow in small tunnels, at least, is an important factor in bringing about mixing. In the absence of combustion, fuel was observed to stay close to the wall as it was swept down the tunnel. When fuel was burning, penetration of the streams was greater. One might expect that a supersonic combustor, which, in some respects, is not unlike a supersonic wind tunnel, would behave similarly.

We injected water streams into the combustion region and its wake to serve as weather vanes to study flow patterns. Figure 3 shows a composite picture we produced from high-speed schlieren and direct photographs. With Arthur Laufman of the Lewis Photo Laboratory, we produced a film supplement to [24] that was made available on loan to those who requested it. The original film was recently reproduced on a DVD disc by Paul Bartolotta of the Glenn Research Center. The water streams are clearly visible in the motion pictures and show that the flame in the small tunnel caused an associated stagnation zone to be built up under the top wall of the tunnel and that the flow beneath that zone remained supersonic. A later study suggested that the stagnation may have been somewhat embellished by a small-tunnel effect.

Larger Wind Tunnel Studies

The aforementioned studies encouraged us to move to a larger tunnel. To study the aerodynamic effects of combustion on flat plates having chords of 13 and 25 in., a body of revolution, and a supersonic wing, we went to a 1 by 1 ft wind tunnel. The move permitted us to use models that were more realistic representations of objects in flight than a tunnel wall, but it did not completely eliminate wind tunnel effects. We measured pressure distributions associated with the stable combustion of aluminum borohydride adjacent to a short, 13-in. chord and to an extended, 25-in. chord, flat-plate model. We measured static-pressure rises during combustion at selected chordwise, spanwise, and base static taps. The increase in static-pressure averaged about 60% of its nonburning value. The ash pattern from a combustion run is shown in Fig. 4.

Figure 5 shows a combination open-shutter photograph and a flash schlieren photograph taken during a steady combustion run. The

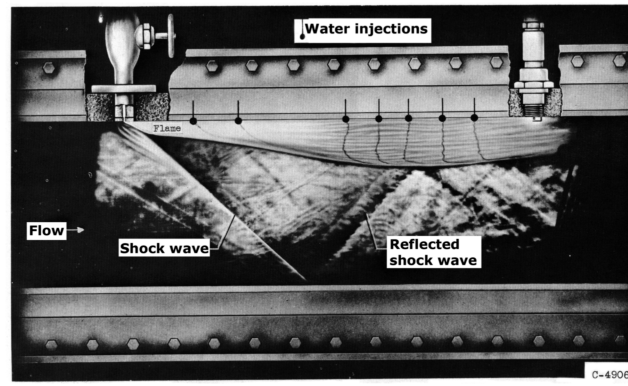


Fig. 3 .Composite schlieren photograph-sketch of the wind tunnel during steady combustion [24].

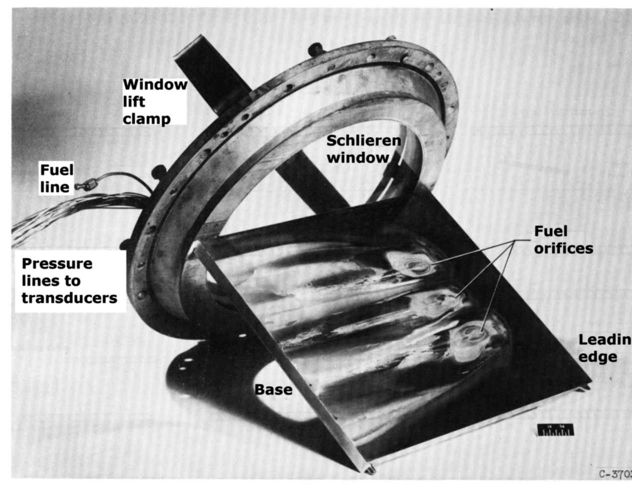


Fig. 4 Ash pattern on short flat-plate [22].

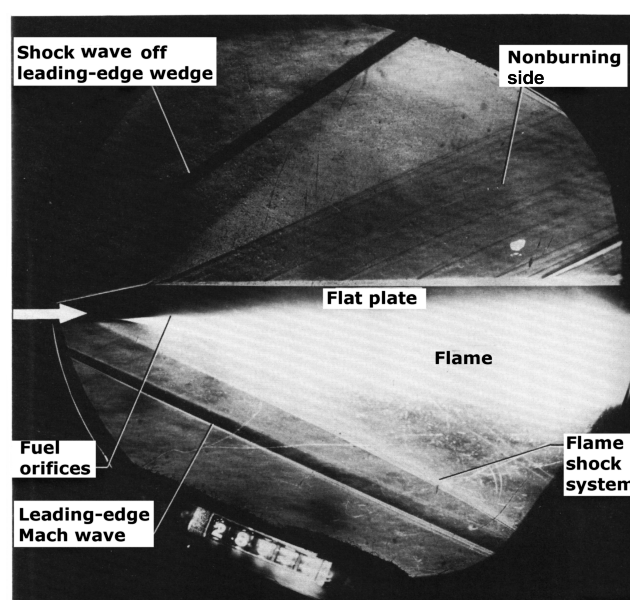


Fig. 5 Combination open-shutter and schlieren photograph of flat-plate combustion [22].

resultant lift force on the flat-plate surface during combustion was of the order of 100 psf at a pressure altitude of about 52,000 ft. We also observed large increases, up to 400%, in the base pressure.

Flow was subsonic in much of the flame zone, becoming sonic and low supersonic in the outer portions of the flame adjacent to the nonburning stream. Because the combustion took place in a small tunnel, the measurements were subject to quantitatively unknown

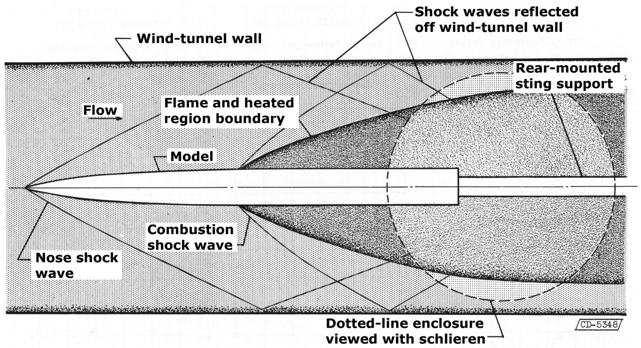


Fig. 6 Sting-mounted body of revolution in the 1 × 1 ft tunnel [21].

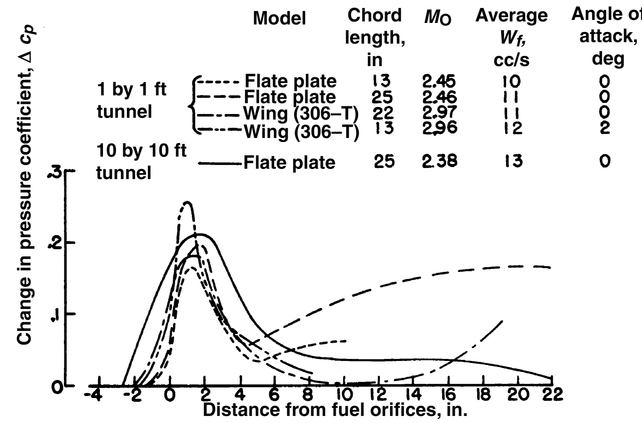


Fig. 8 Variation of change of pressure coefficient on various models [28], used with permission from Fletcher, E. A., *Proceedings of The Combustion Institute*, Vol. 11, 1967, pp. 729–737.

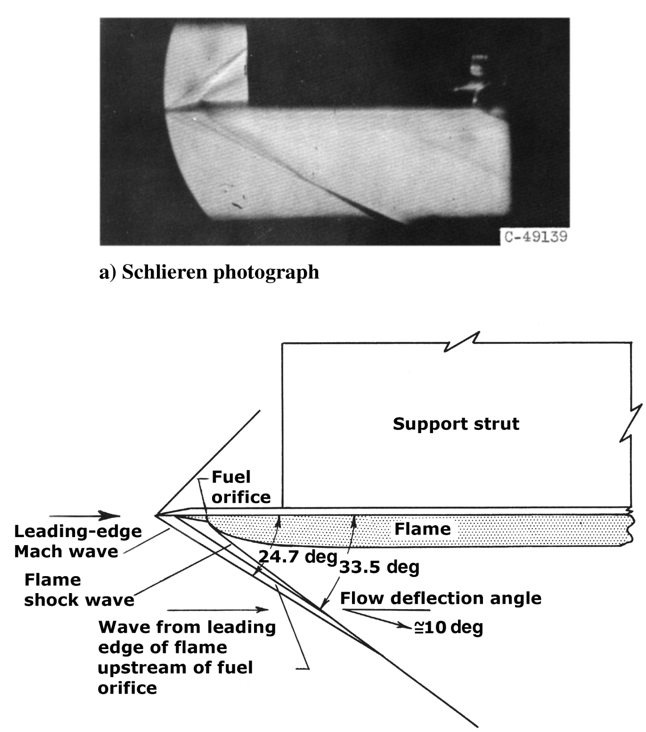
tunnel effects. We suggested that similar large-tunnel or free-flight tests were warranted.

Figure 6 illustrates the combustion and flow about a body of revolution in supersonic flow when aluminum borohydride was injected around its periphery. Tunnel conditions and fuel injection rates were about the same as those used in the flat-plate studies. Large base-pressure increases in the base of the body of revolution suggest that such combustion results in a substantial thrust or a reduction in drag.

We also conducted an experimental investigation of the aerodynamic effects of external combustion in the airstream below a two-dimensional 13 in. chord, blunt-based supersonic wing at a 2 deg AOA at Mach 2.47 and Mach 2.96. Underwing burning increased both the lift and the drag. Even so, the lift/drag ratio of the wing was nearly doubled by the combustion. The experimentally measured values of lift during heat addition agreed with those predicted by analytical calculations. It was evident that with sufficient heat addition under a rearward-facing portion of a wing (or a wing flying at a negative angle of attack), the wing delivers both lift and thrust. An engine is unnecessary. I like to think of it fancifully as an airborne surfboard.

Flat Plate in a 10 by 10 ft Wind Tunnel

Our final experimental study was an investigation of the aerodynamic effects of supersonic combustion below a flat plate in a very large, 10 by 10 ft, supersonic wind tunnel. Figure 7 summarizes our visual and schlieren observations. We conducted the study at Mach 2.4 at a nominal pressure altitude of 62,000 ft. The static temperature was −200°F and the static pressure was about 0.064 bar. We heated the supersonic airstream below a flat-plate model by the external combustion of aluminum borohydride. We used a small, 25-in.-chord model in a large (10 by 10 ft) wind tunnel to avoid any tunnel effects. The results, therefore, were indicative of the magnitude of the lift forces that could be generated by heat addition during free flight. Lift forces of 55 to 60 psf were obtained over the first foot of chord at a nonburning static temperature of 259°R (−200°F) and a pressure altitude of 62,000 ft by a moderate addition of heat.



a) Schlieren photograph

b) Sketch

Fig. 7 Ten by 10 ft tunnel study [26].

We compared the pressure data with similar data obtained in our smaller wind tunnels to appraise the effects that may have been encountered in testing external combustion models in small tunnels [27]. The results of such a comparison are shown in Fig. 8, which is taken from [27]. The small-tunnel short-chord models gave results that were in substantial agreement with the large-tunnel test, but the longer-chord models used in the small-tunnel investigations tended to have spurious static-pressure increases at large distances from the fuel orifices, an effect we noted in our previous publications. In general, the upstream regions of the chordwise pressure-change profiles caused by heat addition below various models agreed quite closely and appeared to be independent of any tunnel effects occurring further downstream on the models.

We concluded that the aerodynamic effects of adding heat to a supersonic airstream adjacent to a bounding surface would have several applications: use as a primary external-propulsion system for cruise in the Mach 5 to Mach 10 range, thrust and lift augmentation for supersonic aircraft, auxiliary-thrust generation for high-speed dash and maneuvers, high-altitude lift implementation to minimize wing area or to increase climbing rate, and to provide trajectory-control forces for boost-glide vehicles. We made no mention at that time of hypersonic surf boards. That notion hadn't occurred to us.

Alternatives to Hydrogen for Scramjets

The November 2004 flight of the scramjet aircraft was such an exciting and beautifully orchestrated event that one hesitates to suggest any activity that smacks of gilding the lily. Nevertheless, I am going to suggest that NASA consider using a more manageable fuel than hydrogen in the scramjet; hydrocarbon jet fuel is the first one that comes to my mind now.

To rationalize what may now seem to be a very surprising suggestion in light of what I have written so far, I would like to compare and contrast the conditions in which we achieved combustion in wind tunnels with the conditions that characterize the scramjet aircraft. I want to explore the implications of that comparison. What does it tell us about the difference between the difficulty of establishing and maintaining combustion in the scramjet aircraft and the difficulty of doing the same thing in our wind tunnel?

In our early studies we were forced to use very pyrophoric fuels because of limitations imposed by the wind tunnels we had. If we had had a wind tunnel capable of simulating the flight conditions of a ramjet, especially the high temperatures that can be made available by slowing down the adjacent combustion air just a little, we might have tried using a hydrocarbon fuel first. The rates of chemical reactions usually increase both with increasing pressure and with increasing temperature. In the November 2004 flight of the scramjet aircraft, the ambient air pressure was in the neighborhood of 0.007 bar. The static pressure in our glass-walled Mach 2 tunnel was 0.19 bar. Thus the effect of the higher pressure in the tunnel might be expected to make the rate of a second-order process leading to ignition and combustion about 700 times faster in the tunnel than in the scramjet aircraft. From a consideration of the pressure alone, if the airstream were not slowed down at all in the combustion zone, ignition and combustion would have been more difficult in the aircraft than they were in our tunnel. But temperature plays a far greater role than pressure in determining the rates of chemical reactions. The temperature of the ambient air through which the scramjet aircraft was flying was −41°F. That was 107°F hotter than the static temperature in the tunnel. The rates of chemical and physical processes, that is, the rates of the processes leading to ignition and maintaining stable burning, increase exponentially with the absolute temperature.

Many complex processes are characterized by an experimentally determined number, the activation energy, which describes the observed variation of the rates of processes with the absolute temperature A useful activation energy for the ignition and combustion of hydrocarbon-air mixtures is about 40 kcal/mol [28]. Using that activation energy, one can calculate the ratio of the reaction rate constants for hydrocarbon–air mixtures at the scramjet aircraft and tunnel conditions. When one considers both the pressure effect and the temperature effect, one concludes that hydrocarbon–air reaction rates in the scramjet aircraft would be about 10 orders of magnitude higher in the scramjet aircraft than they were in our Mach 2 glass-walled tunnel, even if the velocity of the air in the region of the intended ignition and combustion were not slowed down in the slightest from its freestream condition. However, deceleration of the combustion air from its freestream Mach 10 velocity would raise its temperature and pressure substantially and dramatically increase the rates of chemical processes by many more orders of magnitude, hence the likelihood that hydrocarbons would burn. This conjecture is supported by our observation that we could not get vinylsilane to burn in our tunnel, but that silane itself was used effectively as an igniter for the hydrogen that fueled the scramjet aircraft in its historic flight.

Hydrogen is a superb coolant, and hypersonic aircraft use a lot of cooling capacity, but that may be hydrogen's only redeeming feature. NACA/NASA has had 50 years of experience using liquefied gases in rocket engines. The NASA John H. Glenn Research Center at Lewis Field has had practical experience in using hydrogen as an aviation fuel dating back to the 1950s, having actually flown a hydrogen fueled jet engine in an airplane. But in all the time that has elapsed since then, hydrogen has apparently never been seriously considered worthy of further development for use in conventional aircraft.

I have neither the knowledge nor the expertise of those who made possible the superb November 2004 flight of the scramjet aircraft, but I feel I must ask those who do if it might be worthwhile to consider the use of hydrocarbons rather than hydrogen as the major component of scramjet aircraft fuel. I believe that burning hydrocarbon-based fuel, perhaps spiked with a combustion enhancer rather than liquid hydrogen, is an option that deserves consideration. You can pack about four times as much energy into a given sized fuel tank as liquid hydrocarbons than as liquid hydrogen. Liquid hydrocarbons can be stored indefinitely on the ground in the flight vehicle. The use of liquid hydrogen requires a larger tank, refrigeration and/or insulation for storage, and a protracted countdown, which sometimes engenders icing and other problems before a launch. Might external combustion make the coolant capability of hydrocarbons adequate for the job?

Summary

Old experimental studies of supersonic combustion about aerodynamic models are recalled. The results of those studies are interpreted to suggest that liquid hydrocarbon fuel spiked with pyrophoric materials rather than liquid hydrogen should be considered for the propulsion of hypersonic aircraft.

Acknowledgements

Thanks to Nancy Johnson for help with the figures; Ralph Shapiro, Norman Yunis, Richard Golden, and Rosalie Siy, who repaired the outer man; Carolyn, Deborah, and Judith, who nurtured the soul; and Roslyn, who fed the inner man and gave me an inspiring 81st birthday gift.

References

[1] Fry, R. S., "A Century of Ramjet Propulsion Technology Evolution," *Journal of Propulsion and Power*, Vol. 20, No. 1, 2004, pp. 27–58.

[2] Curran, E. T., "Scramjet Engines: The First Forty Years," *Journal of Propulsion and Power*, Vol. 17, No. 6, 2001 pp. 1138–1148.

[3] Walrup, F. J., White, M. E., Zarlingo, F., and Gravlin, E. S., "History of the U.S. Navy Ramjet and Mixed-Cycle Propulsion Development," *Journal of Propulsion and Power*, Vol. 18, No. 1, 2002, pp. 14–27.

[4] Pinkel, I. I., and Serafini, J., "Graphical Method for Obtaining Flow Field in Two-Dimensional Supersonic Stream to Which Heat is Added," NACA TN2206, 1950.

[5] Pinkel, I. I., Serafini, J., and Gregg, J. L., "Pressure Distribution and Aerodynamic Coefficients Associated with Heat Addition to Supersonic Airstream Adjacent to Two-Dimensional Wing," NACA RM E51K26, 1952.

[6] Straight, D. M., Fletcher, E. A., and Foster, H. H., "Aluminum Borohydride as an Ignition Source for Turbojet Combustors," NACA RM E55G15, 1953.

[7] Foster, H. H., Fletcher, E. A., and Straight, D. M., "Aluminum Borohydride–Hydrocarbon Mixtures as a Source of Ignition for a Turbojet Combustor," NACA RM E54K12, 1955.

[8] Schalla, R. L., and Fletcher, E. A., "Behavior of the System Triethylamine-White Fuming Nitric Acid Under Conditions of Rapid Mixing," *Sixth Symposium (International) on Combustion*, Reinhold, New York, 1957, pp. 911–917.

[9] Schalla, R. L., and Fletcher, E. A., *ARS Journal*, Jan. 1959, pp. 33–39

[10] Fletcher, E. A., and Morell, G., *Ignition in Liquid Propellant Rocket Engines*, edited by J. Ducarme, M. Gerstein, and A. H. Lefebvre, Vol. 1, Progress in Combustion Science and Technology, Pergamon, Oxford, 1960, pp. 183–215.

[11] Shapiro, A. H., and Hawthorne, W. R., "The Mechanics and Thermodynamics of Steady One-Dimensional Flow, "*Journal of Applied Mechanics*, Vol. 14, 1947, pp. A-317–A-336.

[12] Tsein, H. S., and Beilock, M., "Heat Source in Uniform Flow," *Journal of the Aeronautical Sciences*, Vol. 16, 1949, p. 765.

[13] Smith, E. H., and Davis, T., "The Creation of Thrust and Lift by Combustion on External Surfaces and Airfoils," Bureau of Ordnance of the Navy Dept., NOrd 12141, Sep. 1952.

[14] Baker, W. T., Davis, T., and Mathews, S. E., "Reduction of Drag of a Projectile in a Supersonic Stream by the Combustion of Hydrogen in the Turbulent Wake," Johns Hopkins Univ. Applied Physics Lab., Rept. CM-673, under Bureau of Ordnance of the Navy Dept. Contract NOrd 7386, June 1951.

[15] Hicks, B. L., Montgomery, D. J., and Wasserman, R. H., "On the One-Dimensional Theory of Steady Compressible Flow with Friction and Heat Addition," *Journal of Applied Physics*, 1947, pp. 891–903.

[16] Scanland, T. S., and Hebrank, W. H., "Drag Reduction Through Heat Addition to the Wake of Supersonic Missiles," U.S. Army Ballistic Research Laboratory, Rept. 596, Aberdeen Proving Ground, June 1952.

[17] Galbraith, J. M., and Schaefer, H. F., III, "The Nitrosyl Azide Potential Energy Hypersurface: A High-Energy-Density Boom or Bust?" *Journal of the American Chemical Society*, Vol. 118, 1996, pp. 4860–4870.

[18] Lucien, H. W., "The Preparation and Properties of Nitrosyl Azide, "*Journal of the American Chemical Society*, Vol. 80, 1957, p. 4458.

[19] Fletcher, E. A., Dorsch, R. G., and Gerstein, M., "Combustion of Aluminum Borohydride in a Supersonic Wind Tunnel," NACA RM

E55D07a, June 1955.
[20] Dorsch, R. G., Serafini, J. S., and Fletcher, E. A., "A Preliminary Investigation of Static Pressure Changes Associated with Combustion of Aluminum Borohydride in a Supersonic Wind Tunnel," NACA RM E55F07, Aug. 1955.
[21] Serafini, J. S., Dorsch, R. G., and Fletcher, E. A., "Exploratory Investigation of Static and Base Pressure Increases Resulting from Combustion of Aluminum Borohydride Adjacent to a Body of Revolution in a Supersonic Wind Tunnel," NACA RM E57E15, Oct. 1957.
[22] Dorsch, R. G., Serafini, J. S., and Fletcher, E. A., "Exploratory Investigation of Aerodynamic Effects of Combustion of Aluminum Borohydride in Airstream Adjacent to Flat Plate in Mach 2.46 Tunnel," NASA RM E57E16, 1957.
[23] Dorsch, R. G., Serafini, J. S., Fletcher, E. A., and Pinkel, I. I., "Experimental Investigation of Aerodynamic Effects of External Combustion in Airstream Below Two-Dimensional Supersonic Wing at Mach 2.5 and 3.0," NASA MEMO 1-11-59e, March 1959.
[24] Allen, H., Jr., and Fletcher, E. A., "Combustion of Various Highly Reactive Fuels in a 3.84- by 10-Inch Mach 2 Wind Tunnel," NASA Memorandum 1-15-59E, April 1959.
[25] Allen, H., Jr., and Fletcher, E. A., "A Study of the Combustion of Aluminum Borohydride in a Small Supersonic Wind Tunnel," NASA TN D-296, July 1960.
[26] Dorsch, R. G., Allen, H., Jr., and Dryer, M., "Investigation of Aerodynamic Effects of External Combustion Below Flat-Plate Model in 10- by 10- Foot Wind Tunnel at Mach 2.4," NASA TN D-282, April 1960.
[27] Fletcher, E. A., "Early Supersonic Combustion Studies at NACA and NASA," *Eleventh Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, PA, 1967, pp. 729–737.
[28] Potter, A. E., Jr., *Flame Quenching*, edited by J. Ducarme, M. Gerstein, and A. H. Lefebvre, Vol. 1, *Progress in Combustion Science and Technology*, Pergamon, London, 1960, pp. 145–181.

L. Maurice
Associate Editor