NACA HIGH ENERGY ROCKET PROPELLANT RESEARCH IN THE FIFTIES

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To better understand the high energy rocket propellant work at the NACA Lewis Flight Propulsion Laboratory during the fifties, we need to take a look at the origins of the work in the forties. Rocket research at the Cleveland laboratory began with the Big Switch in the fall of 1945. The laboratory had been slow in recognizing the advantages of the turbine engine.[b] During the war years, the work was concentrated on ad hoc problem solving for military piston engines. While the laboratory was thus engaged, others were rapidly progressing in jet engine R&D. The moment of truth came to NACA in 1945 and overnight the NACA management switched the laboratory emphasis from piston engines to jet

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[b]There were a few exceptions. Some may recall Eastman Jacob's "Jeep" an experimental jet engine at Langley which the author helped to operate in 1942.

engines and the staff was reorganized from stem to stern in the process. A small group was even assigned to rocket engine research.[c] But the political climate in Washington was such that NACA leaders in Washington did not want to proclaim publicly that they were sanctioning work on guided missiles in an aeronautical laboratory so the group was officially called the High Pressure Combustion Section. The name remained until 1949 when Abe Silverstein, taking over technical management of the laboratory, upgraded the importance and status of the rocket effort and the small group became the Rocket Research Branch.

When the rocket group first got organized in 1945 and surveyed the field, it quickly became apparent that we had a lot of catching up to do. The German work was read with great interest. The publications of the prestigious Jet Propulsion Laboratory, the U. S. leader, became our textbooks. To make a contribution so late and with so few, our leaders

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[c]The sweeping reorganization caught the lower-level supervisors and researchers by surprise. The author went home one night deeply engaged in writing a report on spark plug fouling to find in the morning that his desk was in another building and he was now officially engaged in rocket engine cooling research.

wisely directed that we work in lesser ploughed fields. That is why we concentrated on high-energy liquid rocket propellants, combustion, and cooling and left solid rockets to others. It has remained so to this day.

The propellant work was straightforward. We first computed the theoretical performance of candidate high energy propellant combinations and then selected the most promising for experimental evaluation. This sometimes led into more detailed investigations of propellant characteristics, starting, combustion, and cooling--technical areas being studied in parallel using more conventional propellants. Because of this interaction, and for general interest, a bibliography of the rocket papers published by NACA from 1948 through 1960 for Lewis research is given here.[1-177]

Although not first in the field of theoretical performance calculations of propellants, Vearl Huff and his associates made a major contribution in 1948. They developed a rapidly convergent successive approximation process for the laborous calculations.[6] Huff's method was ideally suited for programming on a computer, which was beginning to come into greater use, and he took full advantage of this powerful aid. Huff, Gordon, and others explored theoretically the field of high energy propellants and provided a guide and reference framework for experimental investigators. By the end of the fifties they had published many reports[1-29] including a refinement to their basic calculation technique.[27] They developed the capability to respond rapidly to the varying needs of analyst and experimentor alike and ground out reams of machine tabulations in the process.

Paul Ordin headed the early work on high energy propellants. The first fuels he and his group investigated were hydrazine,[d] diborane,[e] and ammonia. Oxidizers were chlorine trifluoride, hydrogen peroxide, and liquid oxygen.[30-33]

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[d]The enthusiasm of rocket men sometimes led to taking calculated risks. The author recalls one Lewis man who was given a sample of hydrazine in another city and was confronted with the problem of transporting it. The stability of hydrazine was in question and it could not be readily shipped. He solved the problem by simply putting the sample in his pocket and bringing it home with him on the train.

[e]Our first diborane came from Buffalo Electrochemical Company and the engineer delivered it in his own car. The author remembers walking out to see it nestled in dry ice in a box on the rear seat, complete with a safety device, a whisk broom. The latter was soon put into use. As a small amount of diborane leaked past the valve and ignited, he neatly whisked the flame and problem away.

In May 1948, the Lewis laboratory held a conference on its latest fuels research. Nine papers were presented: two on knock-limited performance of piston engines by some die-hard investigators, six on fuels for turbojets and ramjets, and one on diborane as a rocket fuel.[178] Both theoretical and experimental performance of diborane was presented; the latter with hydrogen peroxide and liquid oxygen as oxidizers. Deposits of boron oxides were encountered and discussed but their significance with regard to later events was not fully realized. Several years later boron hydrides as high energy fuels for jet engines were the focus of a major effort by the Navy (Project ZIP). One of the problems that contributed to its demise was the gluey combustion products of boron that stuck to turbine blades like ice to a wing.[179]

In the late forties, we became intrigued with the ultimate stable oxidizer, liquid fluorine. Our early investigations gave us a healthy respect for this powerful oxidizer which others had already tested in gaseous form. Ordin wanted to use it as a liquid oxidizer and was, we believe, the first to do so. William Rowe devised a fancy rig that served both as a rocket oxidizer system for the test and the fluorine transport trailer. The fluorine tank was suspended on a weigh beam and immersed in a liquid nitrogen bath. The gaseous fluorine from the supplier, Harshaw Chemical Company in Cleveland, was fed directly to the propellant tank and liquefied. Working with local authorities, the best route and time were selected to minimize risk of collision during transport. In the dark hours of early morning, the caravan travelled the streets of Cleveland to the laboratory led by a police car, then a NACA car, the trailer, another NACA car with a police car bringing up the rear. It worked well without mishap.

Of all the fuels he could have chose, Ordin selected diborane for his first experiments with liquid fluorine. Huff's calculations showed the specific impulse to be high, the density to be high, and there would be no deposit problems from boron fluorides. The hooker was the combustion temperature which peaks at nearly 5400 degrees Kelvin at 300 pounds per square inch chamber pressure.[3] On our first attempt, the engine melted so rapidly that we believed that we had achieved every one of those 5400 degrees Kelvin. Ordin and Howard Douglass finally succeeded in operating an engine long enough to measure performance but it required some ingenuity. They had to surround the diborane jet with a flowing sheath of helium to prevent the fluorine from reacting with the diborane at the injector face and burning the wall in the process.[34] After that we became somewhat disenchanted with diborane as a fuel. We saw no reasonable way to cool a diborane-fluorine engine for diborane is not very good as a coolant. Interest in diborane continues, especially as a space-storable fuel,[180-183] but it is still handicapped by cooling problems. (NASA has a current contract with Rocketdyne on this problem.)

Our first experience with fluorine only intensified our interest. We worked with fluorine throughout the fifties. We used it neat with ammonia-hydrazine,[35] ammonia,[36, 38] and hydrazine.[47] Our biggest effort with fluorine, however, came in the second half of the decade in using it with liquid hydrogen.[f]

We also became interested in oxygen bifluoride but did not obtain enough to use it in a rocket engine. Instead we

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[f] Sometime around the mid-fifties Ordin was carried away in another of those laboratory reorganizations and the experimental propellant work was continued by Howard Douglass, George Kinney, Edward Rothenberg, William Tomazic, and others.

turned to fluorine-oxygen mixtures for use with hydrocarbons. Fluorine added to oxygen looked like a promising way to boost the performance of oxygen-JP (jet fuel) engines for rocket boosters. Best performance comes from mixtures where the fluorine-oxygen atom ratio matches the carbon-hydrogen atom ratio. Many experiments were conducted on this combination from 1953 to 1958.[37, 40, 41, 43, 45]

As any student of rocket propulsion quickly finds, liquid hydrogen is an ideal rocket fuel for obtaining high thrust per pound expended. Tsiolkovsky, the Russian rocket pioneer, considered hydrogen-oxygen in 1903 and Goddard in 1909. By the latter forties interest in hydrogen was fairly strong. Dr. Herrick Johnston, his assistants, and students were deeply involved in the study of hydrogen properties and liquefaction and established a rocket laboratory in 1946. By the end of the forties Ohio State University,[184] Jet Propulsion Laboratory,[185] and Aerojet Engineering Corporation[186, 187] had conducted rocket experiments with hydrogen. The largest of these activities was the Navy sponsored work at Aerojet which has recently been documented[188] Aerojet built a hydrogen liquefaction plant, pumped liquid hydrogen, and operated a 3000 pound thrust rocket by 1949.

Plans for experimenting with hydrogen at Lewis began in the early fifties as part of our high energy propellant program. We wanted to work with high energy propellants using larger engines and longer times than had been done previously. The high energy combinations of particular interest were hydrogen-oxygen, hydrogen-fluorine, and ammonia-fluorine but we were hampered by the lack of adequate facilities. At a November 1952 meeting of the Special Subcommittee on Rocket Engines, Walter Olson and the author described a $8.5 million facility which was primarily for high energy propellants but would also be useful for high-availability, low-cost propellants. The proposed facility[189] was unique in four features: 1) the thrust for high energy propellants was to be 20,000 pounds, 2) fluorine was to be generated and liquefied at the site and hydrogen was to be liquefied at the site, 3) special exhaust gas treatment, designed from results of NASA research, would remove hydrogen fluoride from the exhaust, and 4) silencing equipment would muffle the noise of rocket operation. The Subcommittee endorsed the research program and facility proposal.[g]

By the time it was authorized, the facility had been considerably pared down in cost and capability including elimination of the second feature. However, we retained the capability to operate 20,000 pound thrust fluorine-hydrogen rockets and the scrubbing and silencing features.[h]

The facility was placed into operation in 1956 and performed as designed. The engines exhausted into a large duct. Over 50,000 gallons of water per minute, in hundreds of sprays, absorbed the hydrogen fluoride and completely

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[g] Subcommittee membership was: M. J. Zucrow, Chairman, Lt. Col. L. F. Ayers, USAF, R. B. Canright, R. B. Foster, S. L. Gendler, P. R. Hill, Eugene Miller, G. E. Moore, T. E. Myers, J. H. Sheets, J. L. Sloop, R. J. Thompson, P. F. Thompson, P. F. Winternitz, D. A. Young, Cdr. K. C. Childers USN, Capt. Levering Smith USN, and B. E. Gammon (sec'y). Cdr. Childers and Capt. Smith were unable to attend the November 13-14, 1952 meeting.

[h] In negotiations for the facility with NACA Headquarters and with the Bureau of the Budget, we were considerably aided by the hearty endorsement of M. J. Zucrow. In addition to being Chairman of the NACA Special Subcommittee on Rocket Engines, Zucrow as past chairman of the Panel on Propulsion and Fuels of the Research and Development Board and was familiar with rocket facilities and needs.[190]

muffled the noise. The water was held in a tank and later treated with calcium hydroxide and the inert calcium fluoride precipitate was hauled away. We were ahead of the environmentalists.[i]

The supply problems for fluorine and liquid hydrogen were eventually resolved. Hans Newmark of Allied Chemical was interested in fluorine manufacture and transport for rockets and developed a safe method for transporting liquid fluorine. Earlier we had requested and received authorization for a small hydrogen cryostat for making liquid hydrogen and it was placed into operation. About the same time we obtained surplus military equipment of greater capacity. Later, and because of interest in liquid hydrogen for aircraft, we were able to get liquid hydrogen trucked in from an Air Force plant in Painsville, Ohio. During these developments, however, we had to resort to operating first with gaseous hydrogen.[48]

During the build-up of facilities, Huff made a major contribution to experimental testing. About 1952 he proposed

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[i]George Kinney, a key man in the rocket effort, was detached from research to be the principal design engineer of the new facility. He did an outstanding job of making it a success. (A brief description of the facility is in references 48 and 193).

that the rocket's own exhaust could be used in an ejector action to simulate altitude performance of rocket nozzles. With this technique we could test large area ratio nozzles that are characteristic of upper stage engines. Moreover, the concept fitted neatly into plans for scrubbing and silencing the exhaust. Huff, Fortini, and others experimentally tried the concept and it works.[49, 52, 58, 60]

As we continued to increase our capability in the mid fifties, we received an extra boost from the laboratory director. Silverstein became very enthusiastic about the potentials of liquid hydrogen both as a high energy fuel for high-altitude aircraft[191] and as a high energy rocket fuel. With his strong backing we began to make more rapid progress in our objective to build and test lightweight, regenerative cooled hydrogen-oxygen and hydrogen-fluorine engines of 5000 and 20,000 pounds thrust.[j]

With characteristic confidence, Silverstein announced a propulsion conference for November 1957. Liquid hydrogen as a

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[j]One afternoon after work hours, Silverstein held one of his famous bull sessions. This one was a "design conference" complete with beer furnished at his own expense. From this session came his approval of our showerhead injector design which later proved so successful. A description of the injector design is in reference 48 and the chamber design in reference 56.

fuel for turbojets, ramjets, and rockets was a major topic of the conference.[192] The conference required much data that was yet to be obtained. To us it meant much night and weekend work to meet the tight schedule with meaningful data. To Douglass it meant a little more. He was to report on the experimental performance of hydrogen-fluorine using our lightweight regeneratively cooled chamber but he encountered an unusual amount of difficulty. He and his team worked around the clock several times and finally, in the early morning hours of the conference day, he achieved success. At the scheduled time, Douglass casually presented the performance curves with a five hour old key data point dubbed in with grease pencil.

Work continued on both hydrogen-fluorine and hydrogen-oxygen. During 1959 and using our simulated altitude technique, we operated a regeneratively cooled hydrogen-flourine engine with area ratios of 25:1 and 100:1. Actual performance was almost 100 percent of theoretical performance. Measured specific impulse was 480 lb-sec/lb., the highest attained by a chemical rocket at that time.[60]

The difficulties of operating with liquid fluorine, however, had not been lost on Silverstein. Later when he witnessed a hydrogen-oxygen rocket engine operation, the sweetness of the hydrogen-oxygen combination came through to him, and to us, loud and clear. Everything worked smoothly, easily, and performance was high.

By the late fifties, interest in rocket propulsion had greatly increased and Lewis began to shift more emphasis to it. Much consideration was given to rocket propulsion for space vehicles including satellites and moon missions.[193, 194]

We believe that the Lewis work on hydrogen in rocket engines, although not first, was both timely and significant. We showed that lightweight, regeneratively cooled thrust chambers of 5000 and 20,000 pounds thrust could operate at very high efficiencies. We believe this work was significant in the ARPA initiation of the Centaur contract to Pratt & Whitney. Richard Canright, then with ARPA, was a member of the NACA Special Subcommittee for Rocket Engines and was very familiar with our work. Charles King and others from United Aircraft and Pratt & Whitney, who had been working with hydrogen on their own,[195] visited us several times. They later acknowledged the usefulness of our injector design and experimental data in their development of the XLR-15, the first commercial liquid hydrogen-liquid oxygen engine. But perhaps the greatest contribution of the Lewis work was its key role in influencing later decisions regarding Saturn development.

When NASA was established, Silverstein was called to Washington to be the Director of Space Flight Development. The President had determined that the Army Saturn rocket was to be transferred to NASA.[k] In preparation for this, the NASA Associate Administrator named Silverstein to head an interagency committee to prepare recommendations on Saturn development and specifically for the selection of upper stage configurations. Wernher von Braun, then with the ABMA, was a member of the committee.[l]

The committee reported to the NASA Administrator on December 15, 1959. With a persuasive Chairman occupying a key position and sold on hydrogen-oxygen, it is not

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[k] The Saturn project was initiated 15 August 1958 by ARPA to the Army Ordnance Command to develop a 1.5 million pound thrust booster using available engines. Emphasis was on the first stage; three launchings were to be with dummy upper stages and one with a live upper stage.

[l] Other members were Col. N. Appold, USAF, Mr. Abe Hyatt, NASA Mr. T. C. Muse ODDR&D, Mr. G. P. Sutton ARPA, and Mr. E. Hall (Sec'y) NASA.

surprising that the group recommended that the upper stages of Saturn be hydrogen-oxygen[196] and it became so. Saturn and Apollo success has demonstrated the soundness of the decision.

The Lewis group worked with other propellants and on other significant improvements in rocket engines but these must await another opportunity for recounting.

BIBLIOGRAPHY
NACA/NASA LEWIS RESEARCH REPORTS ON ROCKET ENGINES
1948 - 1960 INCLUSIVE

A. THEORETICAL PERFORMANCE

1. Miller, R. O. and Ordin, P. W.: Theoretical Performance of Containing Hydrogen, Nitrogen, and Oxygen. NACA RM E8A30, May 1948.

2. Huff, V. N. and Calvert, C. S., Jr.: Charts for the Computation of Equilibrium Composition of Chemical Reactions in the Carbon-Hydrogen-Oxygen-Nitrogen System at Temperatures from 2000° to 5000°K. NACA TN 1653, July, 1948.

3. Huff, V. N., Calvert, C. S. and Erdmann, V.: Theoretical Performance of Diborane as a Rocket Fuel. NACA RM E8117a, January, 1949.

4. Morrell, V. E.: Effect of Combustion-Chamber Pressure and Nozzle Expansion Ratio on the Theoretical Performance of Several Rocket Propellant Systems. NACA RM E50C30, May, 1950.

5. Gordon, S. and Huff, V. N.: Theoretical Performance of Lithium and Fluorine as a Rocket Propellant. NACA RM E51C01, May, 1951.

6. Huff, V. N., Gordon, S. and Morrell, V. E.: General Method and Thermodynamic Tables for Computation of Chemical Reactions. NACA Report 1037, 1951. (Supersedes TN 2113 and TN 2161).

7. Huff, V. N. and Gordon, S.: Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines. 1 - Mixture of Liquid Ammonia and Hydrazine. NACA RM E51L11, February, 1952.

8. Huff, V. N. and Gordon, S.: Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines. 11 - Hydrazine. NACA RM E52G09, September, 1952.

9. Huff, V. N. and Gordon, S.: Theoretical Performance of Liquid Ammonia, Hydrazine and Mixture of Liquid Ammonia and Hydrazine as Fuels with Liquid Oxygen Bifluoride as Oxidant for Rocket Engines. 111 - Liquid Ammonia. NACA RM E52H14, October, 1952.

10. Gordon, S. and Huff, V. N.: Theoretical Performance of Liquid Hydrogen and Liquid Fluorine as a Rocket Propellant. NACA RM E52L11, February, 1953.

11. Gordon, S. and Huff, V. N.: Theoretical Performance of Liquid Ammonia and Liquid Fluorine as a Rocket Propellant. NACA RM E53A26, March, 1953.

12. Gordon, S. and Huff, V. N.: Theoretical Performance of Liquid Hydrazine and Liquid Fluorine as a Rocket Propellant. NACA RM E53E12, July, 1953.

13. Gordon, S. and Huff, V. N.: Theoretical Performance of Mixtures of Liquid Ammonia and Hydrazine as Fuel with Liquid Fluorine as Oxidant for Rocket Engines. NACA RM E53F08, July, 1953.

14. Gordon, S. and Wilkins, R. L.: Theoretical Maximum Performance of Liquid Fluorine-Liquid Oxygen Mixtures with JP-4 Fuel as Rocket Propellants. NACA RM E54H09, October, 1954.

15. Gordon, S. and Huff, V. N.: Theoretical Performance of JP-4 Fuel with a 70-Percent-Fluorine - 30-Percent-Oxygen Mixture as a Rocket Propellant. I - Frozen Composition. NACA RM E56A13a, April 11, 1956.

16. Huff, V. N., Fortini, A. and Gordon, S.: Theoretical Performance of JP-4 Fuel and Liquid Oxygen as a Rocket Propellant. II - Equilibrium Composition. NACA RM E56D23, September 7, 1956.

17. Gordon, S. and Huff, V. N.: Theoretical Performance of JP-4 Fuel with a 70-30 Mixture of Fluorine and Oxygen as a Rocket Propellant. II - Equilibrium Composition. NACA RM E56F04, October 2, 1956.

18. Huff, V. N. and Gordon, S.: Theoretical Rocket Performance of JP-4 Fuel with Mixtures of Liquid Ozone and Fluorine. NACA RM E56K14, January 28, 1957.

19. Morrell, Gerald: Rocket Thrust Variation with Foamed Liquid Propellants. NACA RM E56K27, 1957.

20. Tomazic, William A., Schmidt, Harold W. and Rischler, Adelbert O.: Analysis of Fluorine Addition to the Vanguard First Stage. NACA RM E56K28, January 24, 1957.

21. Fortini, A. and Huff, V. N.: Theoretical Performance of Liquid Hydrogen and Liquid Fluorine as a Rocket Propellant for a Chamber Pressure of 600 Pounds Per Square Inch Absolute. NACA RM E56L10a, January 25, 1957.

22. Gordon, S. and Drellishak, K. S.: Theoretical Rocket Performance of JP-4 Fuel with Several Fluorine-Oxygen Mixtures Assuming Frozen Composition. NACA RM E57G16a, 1957.

23. Gordon, S.: Theoretical Rocket Performance of JP-4 with Several Fluorine-Oxygen Mixtures Assuming Equilibrium Composition. NACA RM E57K22, 1958.

24. Gordon, S. and Glueck, A. R.: Theoretical Performance of Liquid Ammonia with Liquid Oxygen as a Rocket Propellant. NACA RM E58A21, 1958.

25. Gordon, Sanford, and Kastner, Michael E.: Theoretical Rocket Performance of Liquid Methane with Several Fluorine-Oxygen Assuming Frozen Composition. NACA RM E58B20, 1958.

26. Gordon, Sanford, and McBride, Bonnie, J.: Theoretical Performance of Liquid Hydrogen with Liquid Oxygen as a Rocket Propellant. NASA MEMO 5-21-59E, 1959.

27. Gordon, Sanford, Zeleznik, Frank J., and Huff, Vearl N. A General Method for Automatic Computation of Equilibrium Compositions and Theoretical Rocket Performance of Propellants. NASA TN D-132, 1959.

28. Zeleznik, Frank J., and Gordon, Sanford: An Analytical Investigation of Three General Methods of Calculating Chemical-Equilibrium Compositions. NASA TN D-473, 1960.

29. King, Charles, R.: Compilation of Thermodynamic Properties, and Theoretical Rocket Performance of Gaseous Hydrogen. NASA TN D-275, 1960.

B. EXPERIMENTAL PERFORMANCE

30. Ordin, P. M., Miller, R. O. and Diehl, J.: Preliminary Investigation of Hydrazine as a Rocket Fuel. NACA RM E7H21, May, 1948.

31. Rowe, W. H., Ordin, P. M. and Diehl, J.: Investigation of the Diborane-Hydrogen Peroxide Propellant Combination. NACA RM E7K07, May, 1948.

32. Rowe, W. H., Ordin, P. M. and Diehl, J.: Experimental Investigation of Liquid Diborane-Liquid Oxygen Propellant Combination in 100-Pound-Thrust Rocket Engines. NACA RM E9C11 May 1949.

33. Ordin, P. M. and Miller, R. O.: Experimental Performance of Chlorine Trifluoride-Hydrazine Propellant Combination in 100-Pound-Thrust Rocket Engines. NACA RM E9Fol, August, 1949.

34. Ordin, P. M., Douglass, H. W. and Rowe, W. H.: Investigation of the Liquid Fluorine-Liquid Diborane Propellant Combination in a 100-Pound-Thrust Rocket Engine. NACA RM E51I04, November, 1951.

35. Ordin, P. M., Rothenberg, E. A. and Rowe, W. H.: Investigation of Liquid Fluorine and Hydrazine-Ammonia Mixture in 100-Pound-Thrust Rocket Engines. NACA RM E52H22, October, 1952.

36. Rothenberg, E. A. and Douglass, H. W.: Investigation of the Liquid Fluorine-Liquid Ammonia Propellant Combination in a 100-Pound-Thrust Rocket Engine. NACA RM E53E08, July, 1953.

37. Rothenberg, E. A. and Ordin, P. M.: Preliminary Investigation of the Performance and Starting Characteristics of Liquid Oxygen-Liquid Fluorine Mixtures with JP Fuel. NACA RM E53J20, January, 1954.

38. Douglass, H. W.: Experimental Performance of Fluorine-Ammonia in 1000-Pound-Thrust Rocket Engines. NACA RM E54C17, May, 1954.

39. Tomazic, W. A. and Kinney, G. R.: Experimental Performance of the Mixed-Oxides-of-Nitrogen - Ammonia Propellant Combination with Several Injection Methods in a 1000-Pound-Thrust Rocket Engine. NACA RM E55A07, March 28, 1955.

40. Douglass, H. W.: Experimental Performance of Fluorine-Oxygen with JP 4 Fuel in a Rocket Engine. NACA RM E55D27, July 7, 1955.

41. Tomazic, W. A. and Rothenberg, E. A.: Experimental Rocket Performance with 15 Percent Fluorine - 85 Percent Oxygen and JP-4. NACA RM E55D29, August 29, 1955.

42. Tomazic, W. A.: Rocket-Engine Throttling. NACA RM E55J20, December 9, 1955.

43. Tomazic, W. A., Kutina, F. J. Jr., and Rothenberg, E. A.: Experimental Performance of a 5000-Pound-Thrust Rocket Chamber Using a 20-Percent-Fluorine - 80-Percent-Oxygen Mixture with RP-1. NACA RM E57B08, 1957.

44. Hendricks, Robert C., Ehlers, Robert C., and Humphrey, Jack C.: Evaluation of Three Injectors in a 2400-Pound Thrust Rocket Engine Using Liquid Oxygen and Liquid Ammonia. NACA RM E58B25, 1958.

45. Nored, Donald L., and Douglass, Howard W.: Performance of a JP-4 Fuel with Fluorine-Oxygen Mixtures in 1000 Pound-Thrust Rocket Engines. NASA RM E58C18, 1958.

46. Hendricks, Robert C., Ehlers, Robert C. and Graham, Rob Robert W.: Evaluation of Injector Principles in a 2400-Pound-Thrust Rocket Engine Using Liquid Oxygen and Liquid Ammonia. NASA MEMO 12-11-58E, 1959.

47. Rollbuhler, R. James, and Tomazic, William A.: Investigation of Small-Scale Hydrazine-Fluorine Injectors. NASA MEMO 1-23-59E, 1959.

48. Rothenberg, Edward A., Kutina, Franklin J., Jr. and Kinney, George R.: Experimental Performance of Gaseous Hydrogen and Liquid Oxygen in Uncooled 20,000 Pound-Thrust Rocket Engines. NASA MEMO 4-8-59E, 1959.

49. Fortini, Anthony, Hendrix, Charles D., and Huff, Vearl N.: Experimental Altitude, Performance of JP-4 Fuel and Liquid-Oxygen Rocket Engine with an Area Ratio of 48. NASA 5-14-59E.

50. Miller, Riley O., and Brown, Dwight D.: Effect of Ozone Addition on Combusion Efficiency of Hydrogen-Liquid-Oxygen Propellant in Small Rockets. NASA MEMO 5-26-59E, 1959.

51. Richmond, Robert J.: Experimental Performance of a 200-Pound Thrust Liquid-Pentaborane-Liquid-Hydrazine Rocket. NASA TM X-58, 1959.

52. Sivo, Joseph N., and Peters, Daniel J.: Comparison of Rocket Performance Using Exhaust Diffuser and Conventional Techniques for Altitude Simulation. NASA TM X-100, 1959.

53. Stein, Samual: A High-Performance 250-Pound-Thrust Rocket Engine Utilizing Coaxial-Flow Injection of JP-4 Fuel and Liquid Oxygen. NASA TN D-126, 1959.

54. Rollbuhler, R. James, and Tomazic, William A.: Comparison of Hydrazine - Nitrogen Tetroxide and Hydrazine - Chlorine Trifluoride in Small-Scale Rocket Chambers. NASA TN D-131, 1959.

55. Ciepluch, Carl C.: Performance of a Composite Solid Propellant at Simulated High Altitudes. NASA TM X-95, 1959.

56. Douglass, H. W., Hennings, G., and Price, H. G., Jr.: Experimental Performance of Liquid Hydrogen and Liquid Fluorine in Regeneratively Cooled Rocket Engines. NASA TM X-87, 1959.

57. Otto, Edward W., and Flage, Richard A.: Control of Combustion-Chamber Pressure and Oxidant-Fuel Ratio for a Regeneratively Cooled Hydrogen-Fluorine Rocket Engine. NASA TN D-82, 1959.

58. Fortini, Anthony: Performance Investigation of a Nonpumping Rocket-Ejector System for Altitude Simulation. NASA TN D-257, 1959.

59. Tomazic, William A., Bartoo, Edward R., and Rollbuhler, R. James: Experiments with Hydrogen and Oxygen in Regenerative Engines at Chamber Pressures from 100 to 300 Pounds per Square Inch Absolute. NASA TM X-253, 1960.

60. Jones, William L., Aukerman, Carl A., and Gibb, John W.: Experimental Performance of a Hydrogen-Fluorine Rocket Engine at Several Chamber Pressures and Exhaust-Nozzle Expansion Area Ratios. NASA TM X-387, 1960. RA P81E45, JO 2C-653R2.

C. COMBUSTION

61. Bellman, D. R. and Humphrey, J. C.: Photographic Study of Combustion in a Rocket Engine. 1 - Variation in Combustion of Liquid Oxygen and Gasoline with Seven Methods of Propellant Injection. NACA RM E8F01, June, 1948.

62. Heidmann, M. F. and Humphrey, J. C.: Fluctuations in a Spray Formed by Two Impinging Jets. NACA TN 2349. April, 1951.

63. Sloop, J. L. and Morrell, G.: Temperature Survey of the Wake of Two Closely Located Parallel Jets Emerging at Sonic Velocity. NACA RM E9121.

64. Jaffe, L. Coss, B. A. and Daykin, D. R.: An Electro-magenetic Flowmeter for Rocket Research. NACA RM E50L12, March 6, 1951.

65. Dalgleish, J. E. and Tischler, A. O.: Experimental Investigation of a Light-weight Rocket Chamber. NACA RM E52L19a, March 23, 1953.

66. Heidmann, M. F. and Priem, R. J.: Application of an Electro-Optical Two-Color Pyrometer to Measurement of Flame Temperature for Liquid Oxygen-Hydrocarbon Propellant Combination. NACA TN 3033, October, 1953.

67. Bellman, D. R., Humphrey, J. C. and Male, T.: Photographic Investigation of Combustion in a Two-Dimensional Transparent Rocket Engine. NACA Report No. 1134, 1953. (Supersedes NACA RM E8F01).

68. Kuhns, P. W.: Determination of Flame Temperatures from 2000^{o} to 3000^{o}K by Microwave Absorption. NACA TN 3254, August, 1954.

69. Heidmann, M. F. and Auble, C. M.: Injection Principles from Combustion Studies in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E55C22, June 7, 1955.

70. Miller, R. O.: Flame Propagation Limits of Propane and n-Pentane in Oxides of Nitrogen. NACA TN 3520, August, 1955.

71. Heidmann, M. F.: Injection Principles for Liquid Oxygen and Heptane Using Two-Element Injectors. NACA RM E56D04, June 26, 1956.

72. Heidmann, M. F., Priem, Richard J. and Humphrey, J. C.: A Study of Sprays Formed by Two Impinging Jets. NACA TN 3835, June 26, 1956.

73. Auble, C. M.: Study of Injection Processes for Liquid Oxygen and Gaseous Hydrogen in a 200-Pound-Thrust Rocket Engine. NACA RM E56125a, January 9, 1957.

74. Heidmann, M. F.: A Study of Injection Process for 15-Percent Fluorine - 85 Percent Oxygen and Heptane in a 200-Pound-Thrust Rocket Engine. NACA RM E56J11, January 15, 1957.

75. Heidmann, M. F.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Experimental Effect of Fuel Temperature on Liquid-Oxygen - Heptane Performance. NACA RM E56E03, 1957.

76. Neu, R. F.: Injection Principles for Liquid Oxygen and Heptane Using Nine-Element Injectors in an 1800-Pound-Thrust Rocket Engine. NACA RM E57E13, 1957.

77. Priem, R. J.: Propellant Vaporization as a Criterion for Rocket Design; Numerical Calculations of Chamber Length to Vaporize a Single Hydrocarbon Drop. NACA TN 3985, 1957.

78. Priem, R. J.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Calculations Using Various Log-Probability Distributions of Heptane Drops. NACA TN 4098, 1957.

79. Priem, R. J. and Clark, B. J.: Comparison of Injectors with a 200-Pound Thrust Ammonia-Oxygen Engine. NACA RM E56H01, 1958.

80. Priem, R. J. and Hersch, M.: Effect of Fuel-Orifice Diameter on Performance of Heptane-Oxygen Rocket Engines. NACA RM E56126, 1958.

81. Ingebo, R. D.: Drop-Size Distributions for Impinging-Jet Breakup in Airstreams Simulating the Velocity Conditions in Rocket Combustors. NACA TN 4222, 1958.

82. Heidmann, M. F. and Priem, R. J.: Propellant Vaporization as a Criterion for Rocket Engine Design; Relation Between Percentage of Propellant Vaporized and Engine Performance. NACA TN 4219, 1958.

83. Baker, Louis, Jr.: Chemical and Physical Factors Affecting Combustion in Fuel - Nitric Acid Systems. NACA RM E58D03, 1958.

84. Baker, Louis, Jr.: A Study of the Combustion Rates of Hydrocarbon Fuels with Red Fuming Nitric Acid in a Small Rocket Engine. NACA RM E58D03a, 1958.

85. Heidmann, M. F. and Baker, Louis, Jr.: Combustor Performance with Various Hydrogen-Oxygen Injection Methods in a 200-Pound-Thrust Rocket Engine. NACA RM E58E21, 1958.

86. Priem, Richard J.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Calculations of Chamber Length to Vaporize Various Propellants. NACA TN 3883, 1958.

87. Bittker, David A.: An Analytical Study of Turbulent and Molecular Mixing in Rocket Combustion. NACA TN 4321, 1958.

88. Clark, Bruce, J., Hersch, Martin, and Priem, R. J.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Experimental Performance, Vaporization, and Heat-Transfer Rates with Various Propellant Combinations. NASA MEMO 12-29-58E.

89. Heidmann, Marcus F.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Experimental Effect of Chamber Diameter on Liquid Oxygen - Heptane Performance. NASA TN D-65, 1959.

90. Ingebo, Robert D.: Photomicrographic Tracking of Ethanol Drops in a Rocket Chamber Burning Ethanol and Liquid Oxygen. NASA TN D0290, 1960.

91. Foster, Hampton, H., and Heidmann, Marcus F.: Spatial Characteristics of Water Spray Formed by Two Impinging Jets at Several Jet Velocities in Quiescent Air. NASA TN D-301, 1960.

92. Somogyi, Dezso, and Feiler, Charles E.: Liquid-Phase Heat-Release Rates of the Systems Hydrazine - Nitric Acid and Unsymmetrical Dimethylhydrazine - Nitric Acid. NASA TN D-469. 1960.

D. COMBUSTION OSCILLATIONS

93. Tischler, A. O. and Bellman, D. R.: Combustion Instability in an Acid-Heptane Rocket with a Pressurized Gas Propellant Pumping System. TN 3936. May, 1953. (Supersedes NACA RM E51G11).

94. Tischler, A. O., Massa, R. V. and Mantler, R. L.: An Investigation of High-Frequency Combustion Oscillations in Liquid Propellant Rocket Engines. NACA RM E53B27, June, 1953.

95. Male, T., Kerslake, W. R. and Tischler, A. O.: Photographic Study of Rotary Screaming and Other Oscillations in a Rocket Engine. NACA RM E53A29, May, 1954.

96. Male, T. and Kerslake, W. R.: A Method for Prevention of Screaming in Rocket Engines. NACA RM E5 4F28a, August, 1954.

97. Moore, F. K. and Maslen, S. H.: Transverse Oscillations in a Cylindrical Combustion Chamber. NACA TN 3152. October, 1954.

98. Pass, Isaac and Tischler, Adelbert O.: Effect of Fuels on Screaming in 200-Pound-Thrust Liquid-Oxygen - Fuel Rocket Engine. NACA RM E56C10, June 22, 1956.

99. Priem, R. J.: Attenuation of Tangential-Pressure Oscillations in a Liquid-Oxygen - *n*-Heptane Rocket Engine with Longitudinal Fins. NACA RM E56C09, June 28, 1956.

100. Feiler, Charles E.: Effect of Fuel Drop Size and Injector Configuration on Screaming in a 200-Pound-Thrust Rocket Engine Using Liquid Oxygen and Heptane. NACA RM E58A20a, 1958.

101. Baker, Louis, Jr. and Steffen, Fred W.: Screaming Tendency of the Gaseous-Hydrogen-Liquid-Oxygen Propellant Combination. NACA RM E58E09, 1958.

102. Hurrell, Herbert G.: Analysis of Injection-Velocity Effects on Rocket Motor Dynamics and Stability. NASA TR R-43, 1959.

103. Wieber, Paul R., and Mickelsen, William R.: Effect of Transverse Acoustic Oscillations on the Vaporization of a Liquid-Fuel Droplet. NASA TN D-287, 1960.

E. IGNITION DELAY OF ACID - FUELS

104. Miller, R. O.: Low Temperature Ignition-Delay Characteristics of Several Rocket Fuels with Mixed Acid in Modified Open-Cup-Type Apparatus. NACA RM E50H16, October, 1950.

105. Miller, R. O.: Ignition Delay Characteristics in Modified Open-Cup Apparatus of Several Fuels with Nitric Acid Oxidants within the Temperature Range 70° to -105°F. NACA RM E51J11, December, 1951.

106. Ladanyi, D. J.: Orthotoluidine and Triethylamine in Rocket Engine Applications. NACA RM E 52K19, January, 1953.

107. Miller, R. O.: Ignition Delays of Some Nonaromatic Fuels with Low-Freezing Red Fuming Nitric Acid in Temperature Range -40° to -105°F. NACA RM E52K20, January, 1953.

108. Miller, R. O. and Ladanyi, D. J.: Ignition Delays of Alkyl Thiophosphite with White and Red Fuming Nitric Acids within Temperature Range 80° to -105°F. NACA RM E52K25, February, 1953.

109. Ladanyi, D. J. and Miller, R. O.: Comparison of Ignition Delays of Several Propellant Combinations Obtained with Modified Open-Cup and Small-Scale Rocket Engine Apparatus. NACA RM E53D03, June, 1953.

110. Miller, R. O.: Preliminary Appraisal of Ferrocene as an Igniting Agent for JP-4 Fuel and Fuming Nitric Acid. NACA RM E53H21.

111. Miller, R. O.: Effects of Nitrogen Tetroxide and Water Concentration on Freezing Point and Ignition Delay of Fuming Nitric Acid. NACA RM E53G31, September, 1953.

112. Ladanyi, D. J. and Hennings, G.: Organosphosphorus Compounds in Rocket-Engine Applications. NACA RM E54A26, April, 1954.

113. Ladanyi, D. J., Miller, R. O. and Hennings, G.: Ignition Delay Determinations of Furfuryl Alcohol and Mixed Butyl Mercaptans with Various White Fuming Nitric Acids Using Modified Open-Cup and Small-Scale Rocket Engine Apparatus. NACA RM E53E29, February, 1955.

114. Feiler, C. E. and Baker, Louis, Jr.: A Study of Fuel-Nitric Acid Reactivity. NACA RM E56A19, April 6, 1956.

115. Ladanyi, D. J.: Effects of Variations in Combustion-Chamber Configuration on Ignition Delay in a 50-Pound Thrust Rocket. NACA RM E56F22, October 5, 1956.

116. Miller, R. O.: Ignition Delays and Fluid Properties of Several Fuels and Nitric Acid Oxidants in Temperature Range from 70° to -105°F. NACA TN 3884, December, 1956.

F. <u>ENGINE STARTING</u>

117. Ladanyi, D. J., Sloop, J. L., Humphrey, J. C. and Morell, G.: Starting of Rocket Engine at Conditions of Simulated Altitude Using Crude Monoethylaniline and Other Fuels with Mixed Acid. NACA RM E50D20, July, 1950.

118. Ladanyi, D. J.: Ignition Delay Experiments with Small-Scale Rocket Engine at Simulated Altitude Conditions Using Various Fuels with Nitric Acid Oxidants. NACA RM E51J01, January, 1952.

119. Hennings, G. and Morrell, G.: Preliminary Investigation of a Chemical Starting Technique for the Acid-Gasoline Rocket Propellant System. NACA RM E52K21, January, 1953.

120. Kinney, G. R., Humphrey, J. C. and Hennings, G.: Rocket Engine Starting with Mixed Oxides of Nitrogen and Liquid Ammonia by Flow-Line Additives. NACA RM E53F05, August, 1953.

121. Hennings, G., Ladanyi, D. J. and Enders, J. H.: Ignition of Ammonia and Mixed Oxides of Nitrogen in 200-Pound-Thrust Rocket Engines at 160°F. NACA RM E54C19, May, 1954.

122. Hennings, G. and Morrell, G.: Low Temperature Chemical Starting of a 200-Pound Thrust JP-4 Nitric Acid Rocket Engine Using a Three-Fluid-Propellant Valve. NACA RM E55E04.

123. Krebs, Richard F.: Effect of Fluid-System Parameters on Starting Flow in a Liquid Rocket. NACA TN 4034, 1957.

124. Morrell, Gerald: Summary of NACA Research on Ignition Lab of Self-Igniting Fuel - Nitric Acid Propellants. NACA RM E57G19, 1957.

125. Morrell, Gerald, Ladanyi, D. J.: Chemical Igniters for Starting Jet Fuel-Nitric Acid Rockets. NACA RM E57G26, 1957.

126. Krebs, Richard P., and Hart, Clint E.: Analysis of Flow-System Starting Dynamics of Turbopump-Fed Liquid-Propellant Rocket. NASA MEMO 4-21-59E, 1959

127. Straight, David M., and Rothenberg, Edward A.: Ignition of Hydrogen-Oxygen Rocket Engine with Fluorine. NASA TM X-101, 1959.

128. Wanhainen, John P., Ross, Phil S., and DeWitt, Richard L.: Effect of Propellant and Catalyst Bed Temperatures on Thrust Buildup in Several Hydrogen Peroxide Reaction Control Rockets. NASA TN D-480, 1960

G. COOLING

129. Sloop, J. L. and Kinney, G. R.: Internal-Film Cooling of Rocket Nozzles. NACA RM E8A29a, June, 1948.

130. Kinney, G. R. and Lidman, W. G.: Investigation of Ceramic, Graphite, and Chrome-Plated Nozzles on Rocket Engine. NACA RM E8L16, March, 1949.

131. Kinney, G. R. and Sloop, J. L.: Internal Film Cooling Experiments in 4-Inch Duct with Gas Temperatures to 2000°F. NACA RM E50F19, April, 1950.

132. Kinney, G. R. and Abramson, A. E.: Investigation of Annular Liquid Flow with Concurrent Air Flow in Horizontal Tubes. NACA RM E51C13, May, 1951.

133. Morrell, Gerald: Investigation of Internal Film Cooling of 1000-Pound-Thrust Liquid Ammonia-Liquid Oxygen Rocket Engine Combustion Chamber. NACA RM E51E04, July, 1951.

134. Kinney, G. R.: Internal Film Cooling Experiments with 2- and 4-Inch Smooth-Surface Tubes and Gas Temperatures to 2000° F. NACA RM E52B20, April, 1952.

135. Abramson, A. E.: Investigation of Internal Film Cooling of Exhaust Nozzle of a 1000-Pound-Thrust Liquid Ammonia-Liquid Oxygen Rocket. NACA RM E52C26. June, 1952.

136. Kinney, G. R., Abramson, A. E. and Sloop, J. L.: Internal-Liquid-Film-Cooling Experiments with Air-Stream Temperatures to 2000°F in 2- and 4-Inch-Diameter Horizontal Tubes, NACA Report No. 1087, 1952. (Supersedes NACA RM's E50F19, E51C13, and E52B20).

137. Reese, Bruce A. and Graham, R. W.: Experimental Investigation of Heat-Transfer and Fluid-Friction Characteristics of White Fuming Nitric Acid. Purdue University. May, 1954. NACA TN 3181.

138. Tischler, A. O. and Humphrey, J. C.: Regenerative-Cooling Studies in a 5000-Pound-Thrust Liquid-Oxygen - JP-4 Rocket Engine Operated at 600 -Pounds-Per-Square Inch Combustion Pressure. NACA RM E56B02, April 17, 1956.

139. Graham, Robert W., Guentert, Elanor Costilow, and Huff, Vearl N.: A Mach 4 Rocket-Powered Supersonic Tunnel Using Ammonia-Oxygen as Working Fluid. NACA TN 4325, 1958.

140. Weston, Kenneth C., and Lunney, Glynn S.: Heat-Transfer Measurements on an Air Launched, Blunted Cone-Cylinder Rocket Vehicle to Mach 9.7. NASA TM X-84, 1959.

141. Curren, Arthur N., Price, Harold G., Jr. and Douglass, Howard W.: Analysis of Effects of Rocket-Engine Design Parameters on Regenerative-Cooling Capabilities of Several Propellants. NASA TN D-66, 1959.

142. Hatch, James E., and Papell, S. Stephen: Use of a Theoretical Flow Model to Correlate Data for Film Cooling or Heating an Adiabatic Wall by Tangetial Injection of Gases of Different Fluid Properties. NASA TN D-130, 1959.

143. Hatch, James E., Schacht, Ralph L., Albers, Lynn U., and Saper, Paul G.: Graphical Presentation of Different Solutions for Transient Radial Heat Conduction in Hollow Cylinders with Heat Transfer at the Inner Radius and Finite Slabs with Heat Transfer at One Boundary. NASA TR R-56, 1959.

144. Robbins, William H.: Analysis of the Transient Radiation Heat Transfer of an Uncooled Rocket Engine Operating Outside Earth's Atmosphere. NASA TN D-62, 1959.

145. Liebert, Curt H., Hatch, James E., and Grant, Ronald W.: Application of Various Techniques for Determining Local Heat-Transfer Coefficients in a Rocket Engine from Transient Experimental Data. NASA TN D-277, 1960.

146. Neu, Richard F.: Comparison of Localized Heat-Transfer Rates in a Liquid-Oxygen - Heptane Rocket Engine Employing Several Injection Methods and Oxidant-Fuel Ratios. NASA TN D-286, 1960.

147. Papell, S. Stephen: Effect on Gaseous Film Cooling of Coolant Injection Through Angled Slots and Normal Holes. NASA TN D-299, 1960.

H. PROPELLANT PROPERTIES

148. Feiler, C. E. and Morrell, G.: Investigation of Effects of Additives on Storage Properties of Fuming Nitric Acids. NACA RM E52J16, December, 1952.

149. Ladanyi, D. J., Miller, R. O., Daro, W. and Feiler, C. E.: Some Fundamental Aspects of Nitric Acid. NACA RM E52J01. January, 1953.

150. Sibitt, W. L., St. Clair, C. R., Bump, T. R., Pagerey, P. F., Kern, J. P. and Fyfe, D. W.: Physical Properties of Concentrated Nitric Acid. Purdue University. June, 1953. NACA TN 2970.

151. McKeown, A. B. and Belles, F. E.: Vapor Pressures of Concentrated Nitric Acid Solutions in the Composition Range 83 to 97 Percent Nitric Acid, 0 to 6 Percent Nitrogen Dioxide, 0 to 15 Percent Water, and in the Temperature Range 20° to 80° C. NACA RM E53G08, September, 1953.

152. Feiler, C. E. and Morrell, G. M.: Investigation of the Effects of Fluoride on Corrosion and 170°F of 2S-0 Aluminum and 347 Stainless Steel in Fuming Nitric Acid. NACA RM E53L17b, February, 1954.

153. Gundzik, R. M. and Feiler, C. E.: Investigation of the Corrosion of Metals of Construction by Alternate Exposure to Liquid and Gaseous Fluorine. NACA TN 3333, December, 1954.

154. Ordin, P. M.: Transportation of Liquid Fluorine. NACA RM E55I23, November 8, 1955.

155. Price, H. G., Jr. and Douglass, H. W.: Material Compatibility with Gaseous Fluorine. NACA RM E56K21, January 23, 1957.

156. Price, Harold G., Jr. and Douglass, Howard W.: Nonmetallic Material Compatibility with Liquid Fluorine. NACA RM E57G18, October 2, 1957.

157. Schmidt, H. W.: Reaction of Fluorine with Carbon as a Means of Fluorine Disposal. NACA RM E57E02, 1957.

158. Ordin, P. M.: Hydrogen-Oxygen Explosions in Exhaust Ducting. NACA TN 3935, April 29, 1957.

159. Schmidt, H. W.: Compatibility of Metals with Liquid Fluorine at High Pressures and Flow Velocities. NACA RM E58D11, 1958.

160. Spakowski, Adolph E.: The Thermal Stability of Unsymmetrical Dimethyl-Hydrazine. NASA MEMO 12-13-58E, 1958.

161. Schmidt, Harold W.: Design and Operating Criteria for Fluorine Disposal by Reaction with Charcoal. NASA MEMO 1-27-59E, 1959.

162. Slabey, Vernon A., and Fletcher, Edward A.: Rate of Reaction of Gaseous Fluorine with Water Vaper at 35^{o} C. NACA TN 4374, 1958.

163. Rollbuhler, R. James, Kinney, George R., and Leopold, Lorenz C.: Field Experiments on Treatment of Fluorine Spills with Water or Soda Ash. NASA TN D-63, 1959.

164. Antoine, Albert C., and Seaver, Robert E.: Impact Sensitivity of Liquid Ozone. NASA TM X-88, 1959.

I. TURBOPUMPS

165. Biermann, Arnold E., and Kohl, Robert C.: Preliminary Study of a Piston Pump for Cryogenic Fluids. NASA MEMO 3-6-59E, 1959.

166. Rohlik, Harold E., and Crouse, James E.: Analytical Investigation of the Effect of Turbopump Design on Gross-Weight Characteristics of a Hydrogen-Propelled Nuclear Rocket. NASA MEMO 5-12-59E, 1959

167. Wintucky, William T.: Analytical Comparison of Hydrazine with Primary Propellants as the Turbine Drive Fluid for Hydrogen-Fluorine and Hydrogen-Oxygen Altitude Stage Rockets. NASA TN D-78, 1959.

168. Fenn, David B., Acker, Loren W., and Algranti, Joseph S.: Flight Operation of a Pump-Fed Liquid-Hydrogen Fuel System. NASA TM X-252, 1960.

169. Evans, David G., and Crouse, James E.: Analysis of Topping and Bleed Turbopump Units for Hydrogen-Propelled Nuclear Rockets. NASA TM X-384, 1960.

170. Lewis, George W., Rysl, Edward R., and Hartmann, Melvin J.: Design and Experimental Performance of a Small Centrifugal Pump for Liquid Hydrogen. NASA TM X-388, 1960.

J. EXHAUST NOZZLES

171. Guentert, Eleanor Costilow, and Neumann, Harvey E.: Design of Axisymmetric Exhaust Nozzles by Method of Characteristics Incorporating a Variable Isentropic Exponent. NASA TR R-33, 1959.

172. Chiccine, Bruce G., Valerino, Alfred S., and Shinn, Arthur M.: An Experimental Investigation of Base Heating and Rocket Hinge Moments for a Simulated Missile Through a Mach Number Range of 0.8 to 2.0. NASA TM X-82, 1959.

173. Musial, N. T., and Ward, James J.: Over-expanded Performance of Conical Nozzles with Area Ratios of 6 and 9 with and without Supersonic External Flow. NASA TM X-83, 1959.

174. Lovell, J. Calvin, Samanich, Nick E., and Barnett, Donald O.: Experimental Performance of Area Ratio 200, 25, and 8 Nozzles on JP-4 Fuel and Liquid-Oxygen Rocket Engine. NASA TM X-382, 1960.

175. Sivo, Joseph N., Meyer, Carl L., and Peters, Daniel J.: Experimental Evaluation of Rocket Exhaust Diffusers for Altitude Simulation. NASA TN D-298, 1960.

176. Campbell, C. E., and Farley, J. M.: Performance of Several Conical Convergent-Divergent Rocket-Type Exhaust Nozzles. NASA TN D-467, 1960.

177. Farley, John M., and Campbell, Carl E.: Performance of Several Method-of-Characteristics Exhaust Nozzles. NASA TN D-293, 1960.

ADDITIONAL REFERENCES, THIS PAPER

178. Sloop, J. L., Ordin, P. M., and Huff, V. N.: Theoretical and Experimental Investigation of Diborane is a Rocket Fuel. NACA Conference on Fuels - A Compilation of the Papers Presented by NACA Staff Members. Flight Propulsion Research Laboratory, Cleveland, Ohio, May 26, 1948 (Not generally available). See also Reference 3, 31, 32.

179. Boron High-Energy Fuels. Report of the Committee on Science and Astronautics - U. S. House of Representatives - Eighty-sixth Congress, First Session House Report No. 1191 October 13, 1959.

180. Burlage, H.; Gin, W.; and Riebling, R.; "Unmanned Spacecraft Chemical Rocket Propulsion. Presented at 6th AFOSR Symposium on Advanced Propulsion Concepts, Niagara Falls, N. Y., May 5, 1971.

181. Young, D.: "Study of High Performance Liquid Propulsion Systems for Unmanned Planetary Orbiters," Presented at 12th JANAF Liquid Propulsion Symposium Los Vegas, Nevada, November 1970 CPIA Publication 201, Vol. 1.

182. Aerojet Liquid Rocket Co. Final Report CR 109973, Contract NAS7-473 July 1970. "Systems Analysis of Gelled Space Storable Propulsion."

183. TRW Report 14051 - 6009 - RD - 00, Contract NAS 7-750, March 15, 1971. "Space Storable Propulsion Module Thermal Control Technology."

184. Johnston, Herrick L. and Doyle, William L.: Development of Liquid Hydrogen-Liquid Oxygen Combination for Rocket Motors. Technical Report No. 7, Research Foundation, Ohio State University, 1951.

185. Baker, Dwight J.: Regenerative Cooling Tests of Rocket Motors using Liquid Hydrogen and Liquid Oxygen Report 4-53, Jet Propulsion Laboratory, CIT, August 11, 1949 (Contract W-04-200-ORD-455).

186. Young, D. A.: Research and Development of Hydrogen-Oxygen Rocket Engine Model XLR 16-AJ-2, Report 378 January 1 - March 31, 1949. Aerojet Engineering Corporation May 11, 1949 (Contract NO a(s) 8496).

187. Young, D. C.: Research and Development of Hydrogen-Oxygen Engine XLR 16-AJ-2 Report 397 Aerojet Corporation, September 28, 1949 (Contract NO a(s) 8496)

188. Osborn, G. H.; Gordon, R.; and Coplen, H. L.: Liquid Hydrogen Rocket Fuel Development 1944-1950 Fourth History of Astronautics Symposium, XXIst International Astronautical Congress, Constance, West Germany, October 9, 1970.

189. Minutes of Meeting of NACA Special Subcommittee on Rocket Engine, Lewis Laboratory, Cleveland, Ohio. November 13-14, 1952 (Not generally available).

190. Memorandum, Lewis to NACA Headquarters, November 24, 1952. (Not generally available). Reports Zucrow's hearty endorsement of the proposed rocket facility and promise to write Dr. Dryden on the subject.

191. Silverstein, Abe and Hall, E. H.: Liquid Hydrogen is a Jet Fuel for High Altitude Aircraft. NACA Research Memorandum E55C28a 1955.

192. NACA 1957 Flight Propulsion Conference, Lewis Flight Propulsion Laboratory, Cleveland, Ohio November 21-22, 1957. (Not generally available). Contains three papers on rocket propulsion:
   a) Propellants by E. A. Fletcher, H. W. Douglass, R. J. Priem and G. Vasa.
   b) Turbopumps for High Energy Propellants by Ambrose Ginsberg, Ward W. Wilcox and David G. Evans.
   c) Performance and Missions by J. L. Sloop, A. B. Boksenbom, S. Gordon, R. W. Graham, P. M. Ordin, and A. O. Tischler.

193. Sloop, John L.: Propulsion Requirement of Satellites and Moon Missions. Aero/Space Engineering, November 1958.

194. Gabriel, D. S.; Himnel, S. C.; and Sloop, J. L.: Application of High Energy Propellants to Space Vehicles. 4th Symposium on Ballistic Missiles Space Technology, Los Angeles, August 24-28, 1959. (Not generally available).

195. Coar, Richard J., and King, C. H.: Hydrogen for the Space Age. Astronautics March 1960.

196. Report to the Administrator, NASA, on Saturn Development Plan by Saturn Vehicle Team. December 15, 1959. (Not generally available).