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NWC TP 4760

AERODYNAMIC HEATING AND COOLING TEMPERATURE CRITERIA DETERMINATION FOR AIR-LAUNCHED LIQUID ROCKET MOTORS

by

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ABSTRACT. The thermal regime of a 12-inch diameter liquid rocket motor, while carried by F4B and A6A aircraft, is investigated. Aerodynamic heating is measured during carriage by the F4B aircraft. Aerodynamic cooling is investigated during flights of up to 4 1/2 hours on A6A aircraft. The report includes figures which give the heating and cooling profiles, and tables.

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FOREWORD

This report is a result of work conducted from November 1968 through May 1969 to determine the actual temperature criteria for a 12-inch-diameter liquid rocket during carriage by F4B and A6A aircraft. The data are considered valid for these types of aircraft.

The work was requested and supported by AirTask A33-536/216-1/69WF19-332-301. The analytical work (Appendix C and D) was performed by Dr. R. D. Ulrich of Brigham Young University, Provo, Utah under Contract N60530-69-C-0642.

This report has been reviewed for technical accuracy by Warren W. Oshel.

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The author wishes to thank Dr. Richard Ulrich of Brigham Young University for providing the theoretical support for this work. He is completely responsible for the information in Appendices C and D. Credit is also given to Mr. R. J. Morey for technical editing this report. Without the assistance of these personnel, the work would not have been as completely and concisely reported.

CONTENTS

INTRODUCTION

This work was intended to measure the temperature profiles of liquid rocket motor systems during carriage by aircraft in simulated combat missions. The work was necessary because of the criticality of propellant viscosity at temperatures below -50°F. Presently used design temperature criteria for aerodynamic heating of air-launched liquid propulsion systems has been based on theoretical calculation or "best estimate". This procedure has been necessary because of the lack of empirical information from actual flights of similar ordnance. The above has, in some situations, led to large differences between "best estimate" information and actual in-service fact.

The Naval Weapons Center (NWC) equipped a Bullpup "A" missile with a continuous time-temperature recorder to record in-service temperatures and durations in and around the fuel and oxidizer tanks. The missile was carried on F4B and A6A aircraft (Fig. 1). The aircraft flew near-limiting mission profiles that were deemed to be representative of the extreme conditions to which air-launched liquid propulsion systems would be subjected. The F4B Phantom was used for high velocity, short duration flights (aerodynamic heating runs). The A6A Intruder was used for the slow, long duration flights (aerodynamic cooling runs).

PROCEDURE

MISSION PROFILES

Three distinct mission profiles were specified in the problem assignment to duplicate, or exaggerate, the nominal operations of Naval aircraft. The first mission profile was intended to duplicate a fighter intercept situation. The aircraft was to take off and climb to 40,000 feet at a subsonic velocity, then accelerate to maximum velocity while maintaining 40,000 feet altitude; this velocity was held until fuel depletion forced termination of the run. The second mission profile was intended to duplicate a high-speed low-level attack mission. The aircraft would accelerate to maximum velocity at low altitude (less than 900 feet Mean Sea Level (MSL)) and maintain this velocity until fuel depletion forced cancellation of the run. The third mission profile was to take off and climb to 40,000 feet MSL, and level off and loiter at that altitude until fuel depletion required termination of the run. The A6A aircraft could stay on-station for up to 4 1/2 hours for this type of run.

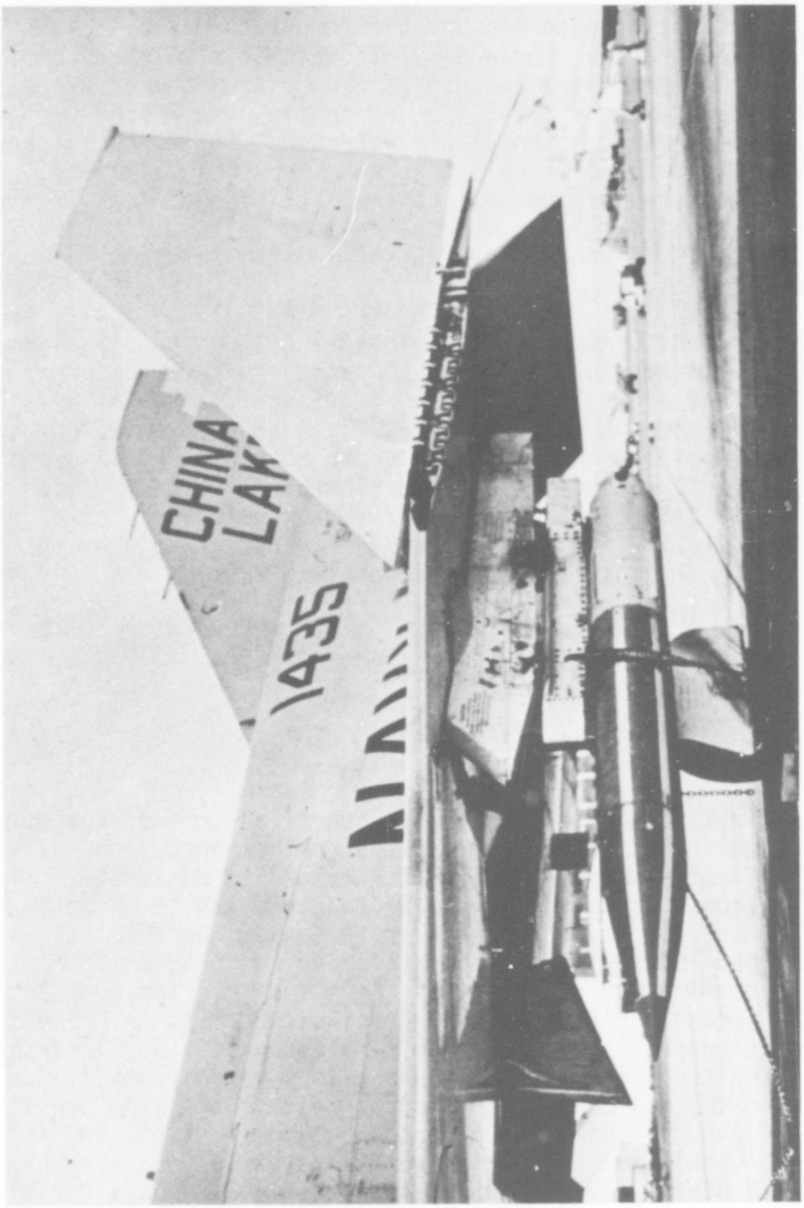

FIG. 1. Installation on F4B Aircraft.

The primary objective was to measure the aerodynamic cooling parameter; however, all available information (Ref. 1 through 5) gave only the aerodynamic heating parameter. Therefore, the aerodynamic heating portion of the measurement sequence was conducted to demonstrate the credibility of the instrumentation. This was accomplished and the aerodynamic heating data are included herein.

Experience gained from work on the Sparrow motor (Ref. 1) indicated that the ground level dash revealed no more severe thermal criterion than the maximum duration dash at 40,000 feet MSL. Also since this low level maneuver is potentially more hazardous to pilot and aircraft, it was deleted from this measurement series.

In all three instances the mission profile intentionally ignores the fact that the aircraft must retain enough fuel to return to its aircraft carrier or landing field, and safely land. This fact was disregarded so that the maximum aerodynamic heating or cooling of the rocket motor could be experienced, within the bounds of reality as it pertains to the combat tactic. In a combat situation the air-launched liquid propulsion system will be subjected to approximately the same environment, but for a shorter time duration. Heat transfer being a time dependent function, the above mission profiles should provide aerodynamic heating data that are equal to or more severe than those resulting from the combat or training situation. The aerodynamic cooling data are representative of conditions experienced during the Carrier Air Patrol (CAP) type of mission.

In general, the last 3 wars (World War II, Korea, and Vietnam) have indicated that the aircraft do not fly at maximum performance continuously throughout any given mission. This tactic would be detrimental to man, mission, and aircraft. The more common situation, even with high performance aircraft, is to go in to the target at less than Mach 1, deliver the ordnance, and then get out. Generally, aerodynamic heating and cooling is of no concern once the ordnance has been delivered.

HARDWARE MODIFICATION

The Bullpup was modified in two respects. The fins were deleted because they are classified Confidential. Since the data required were not dependent on the fins, the program could proceed at a faster, easier pace with unclassified hardware. The other modification was to replace the fuel and oxidizer with a mixture of ethylene glycol and water. The substitution was primarily predicated on safety since no pilot, even in an experimental squadron, wants to carry a liquid propulsion system that leaks, especially if the seepage is hypergolic. Also, it is extremely difficult to thermocouple a flight system that doesn't leak at some time during an extended measurement sequence because the change in temperature between ground storage and thermal soak is conductive to differential contraction and leakage. The secondary reason for using ethylene glycol and water was to assure a liquid state to -65°F.

In keeping with the plan to keep the measurement matrix inert, the gas generator grain was replaced by a cylinder of wood. (The gas generator grain is in the geometric center of the forward half of the Bullpup motor.)

INSTRUMENTATION

Potentiometer type instrumentation was used for this project. A discussion of other types of instrumentation considered is given in Appendix A. The unit was constructed using airborne recorders previously used at NWC as prototypes[1]. The unit was repackaged to fit in an 11-inch-diameter by 24-inch-long cylinder (Fig. 2). The unit was then fitted into the warhead section just forward of the motor of the Bullpup "A" missile. The Bullpup unit, modified as previously noted, included the enclosed recorder and power supply. This allowed the unit to be placed at random on any launcher station of any aircraft equipped to fire Bullpup. The recorder used the aircraft supplied 28 vdc power normally used to power the Bullpup guidance and control system.

THERMOCOUPLES

The Bullpup motor was instrumented with 16 thermocouples. However, some of the thermocouples were damaged during the test series. This was caused by rough handling the extremely cold rocket motor, by installation and removal of the missile from the aircraft, and by the high level of vibration inherent in wing-mounted missiles during aircraft carriage.

The thermocouples were made of copper-constantan (Type T). The junction was formed by twisting the two wires together and resistance welding. The junction was nominally an 0.03-inch-diameter sphere. The thermocouples were grouped into banks of four. The thermocouple wires were formed into a loom at the head end of the motor and led into the warhead where they terminated in a junction connector. (The connector was required so that the missile could be broken down into two sections for easy transportation). The connector was placed in an insulated container. The thermal insulation negated any significant temperature change in the two halves of the connector. Also, the entire connector was exposed to any micro temperature change, not just a few of the 96 soldered junctions. Therefore, any measurement error due to the use of a connector was assessed as negligible.

[1] NAVWEPS Report 7777 and NWC TP 4310.

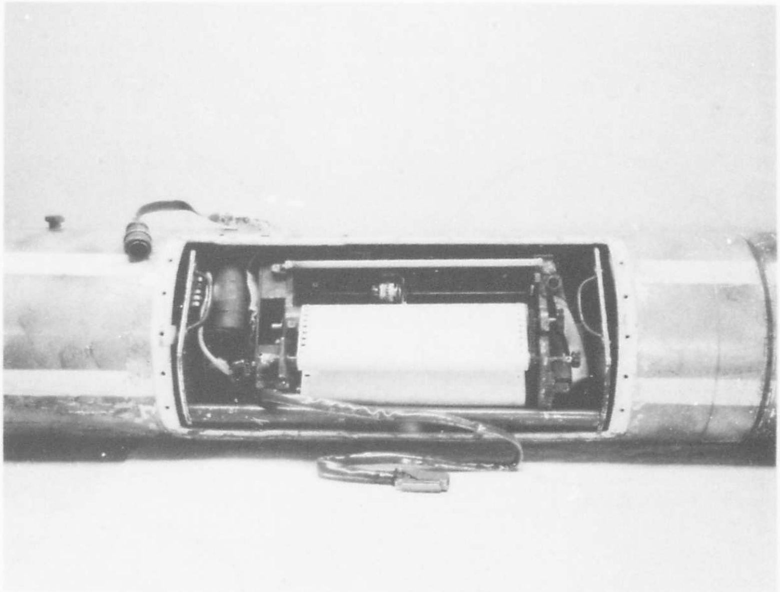

FIG. 2. Recorder.

Figure 3 shows a schematic of the thermocouple placement. The thermocouple locations were organized to give a complete indication of temperature differences. The thermocouples were placed as follows:

1. On outside skin of forward tank, top, outboard of ullage.
2. In rear tank 1/8-inch from center wall, 45 degrees from top of motor.
3. In rear tank, 1/8-inch from outside wall, 45 degrees from top of motor.
4. On outside skin of rear tank, 135 degrees from top.
5. In rear tank, 1/8-inch from outside wall, 135 degrees from top of motor.
6. In rear tank, 1/8-inch from center wall, 135 degrees from top of motor.
7. In forward tank, 1/8-inch from center wall, on bottom.
8. In forward tank, center annulus of tank, on bottom.
9. In forward tank, 1/8-inch from outside wall, on bottom.
10. On outside skin of forward tank, on bottom.

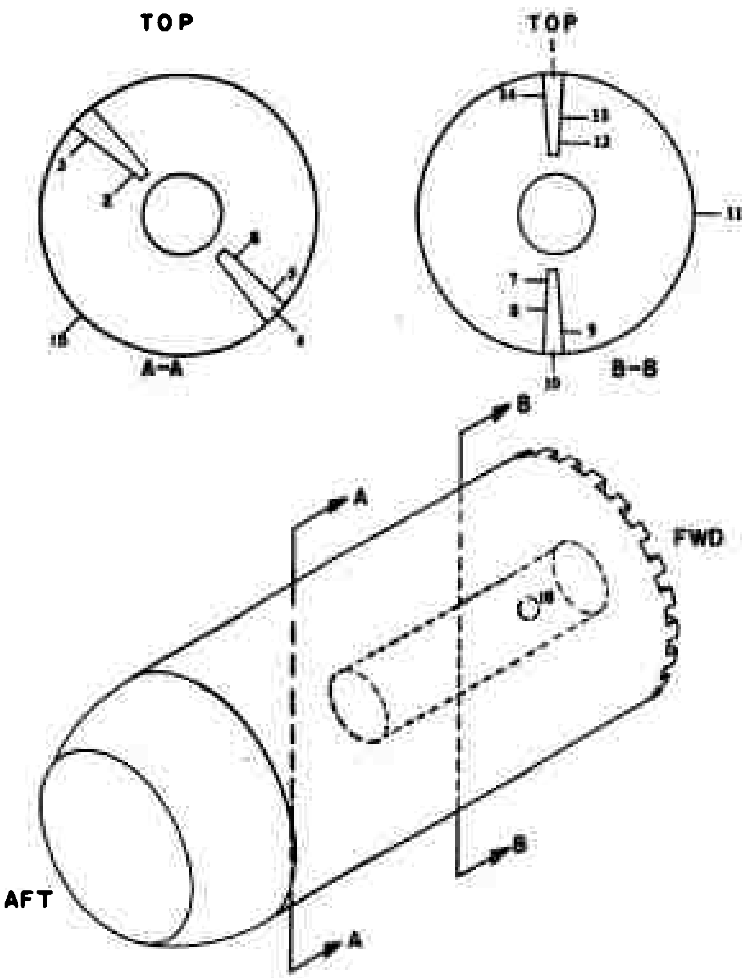

FIG. 3. Thermocouple Location in Bullpup Rocket Motor.

11. On outside skin of forward tank, 90 degrees from top.
12. Inside of forward tank, 1/8-inch from center wall, on top.
13. Inside of forward tank, center annulus of tank, on top.
14. Inside of forward tank, 1/8-inch from outside wall, top, in ullage.
15. On outside skin of rear tank, 135 degrees from top.
16. In center of gas generator grain, in geometric center of forward portion of motor.

FLIGHT DATA

The flight data were manually recorded by the observer onboard both the F4B and A6A aircraft. The program plan called for the observer to record altitude, air speed, and time of day each minute until stabilization, and once each 5 minutes thereafter until the flight mode changed. Also, the observer was to accurately record time of take-off and time of touch-down. Even with this prearranged scheme, it was difficult to match the observers record with the recorder record to any better accuracy than ±2 minutes in four hours. The comparison accuracy of the aircraft instruments in the front and rear cockpits of the F4B can be assumed to be ±5%.

ATMOSPHERIC DATA

The atmospheric data for the flights were taken by the Atmospheric Studies Branch at NWC. These soundings are taken when requested, and can be taken twice per day on requested occasions. The complete record of these soundings is available from the National Weather Records Center, Asheville, North Carolina. Pertinent selections pertaining to this work are shown in Appendix B. Since 29 November 1968 was in the Thanksgiving holiday season no sounding was taken for that day.

RECORDER ACCURACY CHECKS

The recorder was installed in the warhead compartment of the small Bullpup missile and mounted on an F4B aircraft at NAF, China Lake. The high speed 40,000-foot mission profile was then flown by the F4B to subject the recorder to aircraft temperature and vibration. The flight showed a measuring circuit calibration shift that was apparently caused by aircraft vibration. This condition was corrected prior to additional flights.

Based on past experience, it was deemed advisable to check the recorder calibration before and after each individual flight. The procedure was as follows:

1. Before delivery to NAF, the calibration was checked.

2. After installation of the unit on the aircraft, ground power was applied and the electrical integrity of the aircraft and missile-borne recorder was indicated by means of a specially constructed test set and indicator lights.

3. Following the flight, the missile was returned to the instrument shop for calibration recheck.

The accuracy of the instrument during the program was assessed to be on the order of 1/4 of 1% full scale or 0.0025 times 350°F, which is less than 1°F. The amplifier "dead band" was of the order of 2°F for the -100 to +250°F range. Therefore, the worst combination of the two error sources would be ±3°F. The span and linearity were within ±1/2°F so the error was classed as negligible.

RESULTS

The program consisted of 8 flights. These were divided into three flights on the F4B aircraft to investigate aerodynamic heating, and five flights on the A6A to investigate aerodynamic cooling. (There were six additional flights, usually "piggy back" flights flown for other projects on the F4B to indicate recorder and thermocouple function).

It became evident early in the program that the major source of interest should not be aerodynamic heating as had been theorized by the author, but aerodynamic cooling. Since the only aircraft stations capable of accepting the Bullpup and the vast majority of other air launched missiles are located on the wing, these were the only positions investigated. As can be seen from a quick look at Fig. 4 through 6, the maximum aerodynamic heating temperature measured was less than 150°F. The usual situation was that on takeoff, the skin temperature of the Bullpup would be cooled. The onset of the high speed run would warm the outside somewhat but hardly influence the temperature of the fuel and oxidizer. The high speed dash would be terminated too soon to seriously affect the inside of the missile due to fuel depletion. The less than limiting velocities, indicated in the enclosed figures depicting aerodynamic heating, were necessitated because of aircraft-missile interplay at greater velocities. During one aerodynamic heating situation on a 40,000 foot MSL flight the pilot exceeded the "red line" situation. He reported that he "found himself flipped over on his back". This would tend to suggest that the velocities reported herein are probably quite representative of the range to be experienced by the foreseeable generation of aircraft.

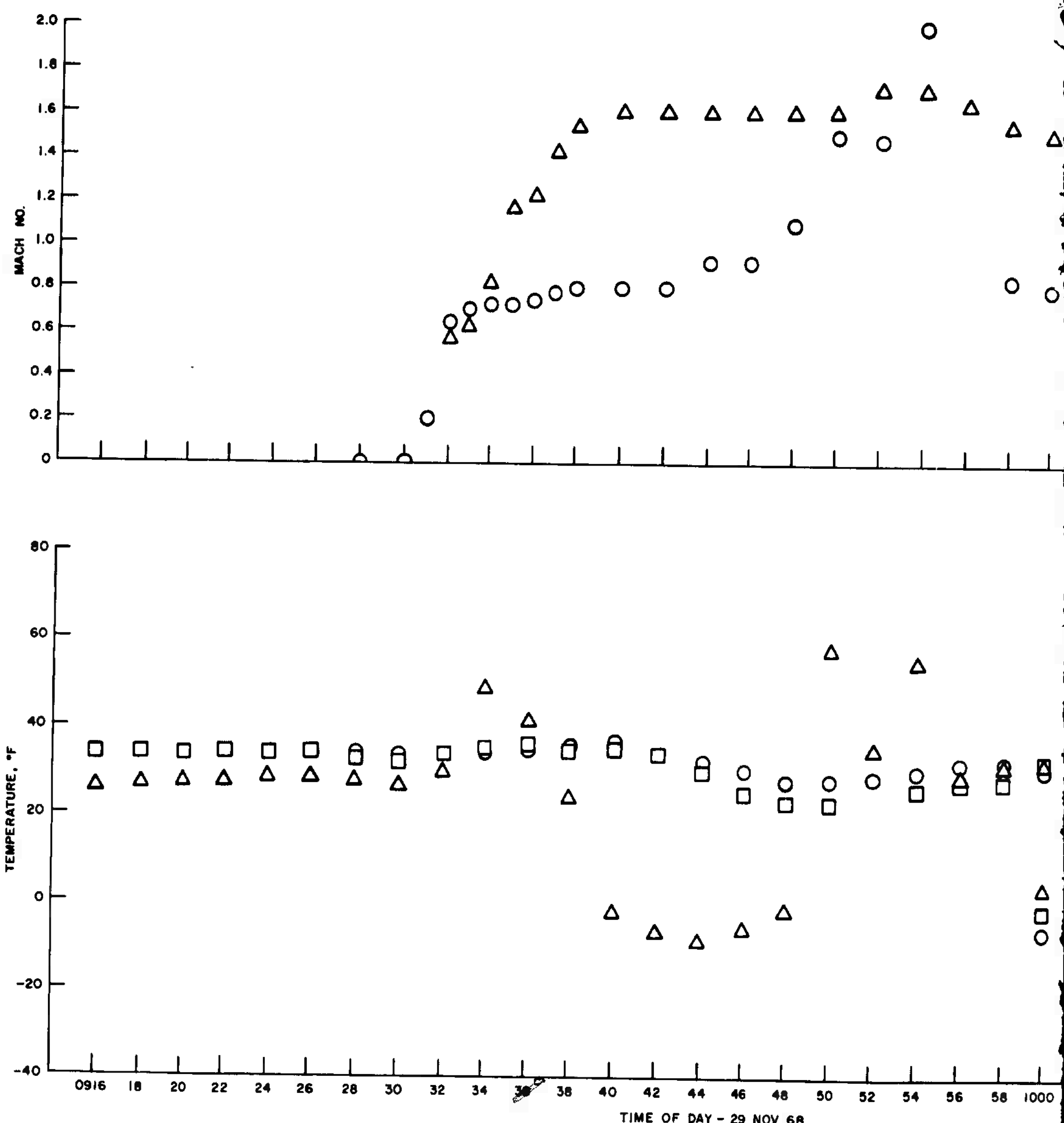

FIG. 4. Aerodynamic Heating Profile for 12-Inch Diameter Liquid Propu

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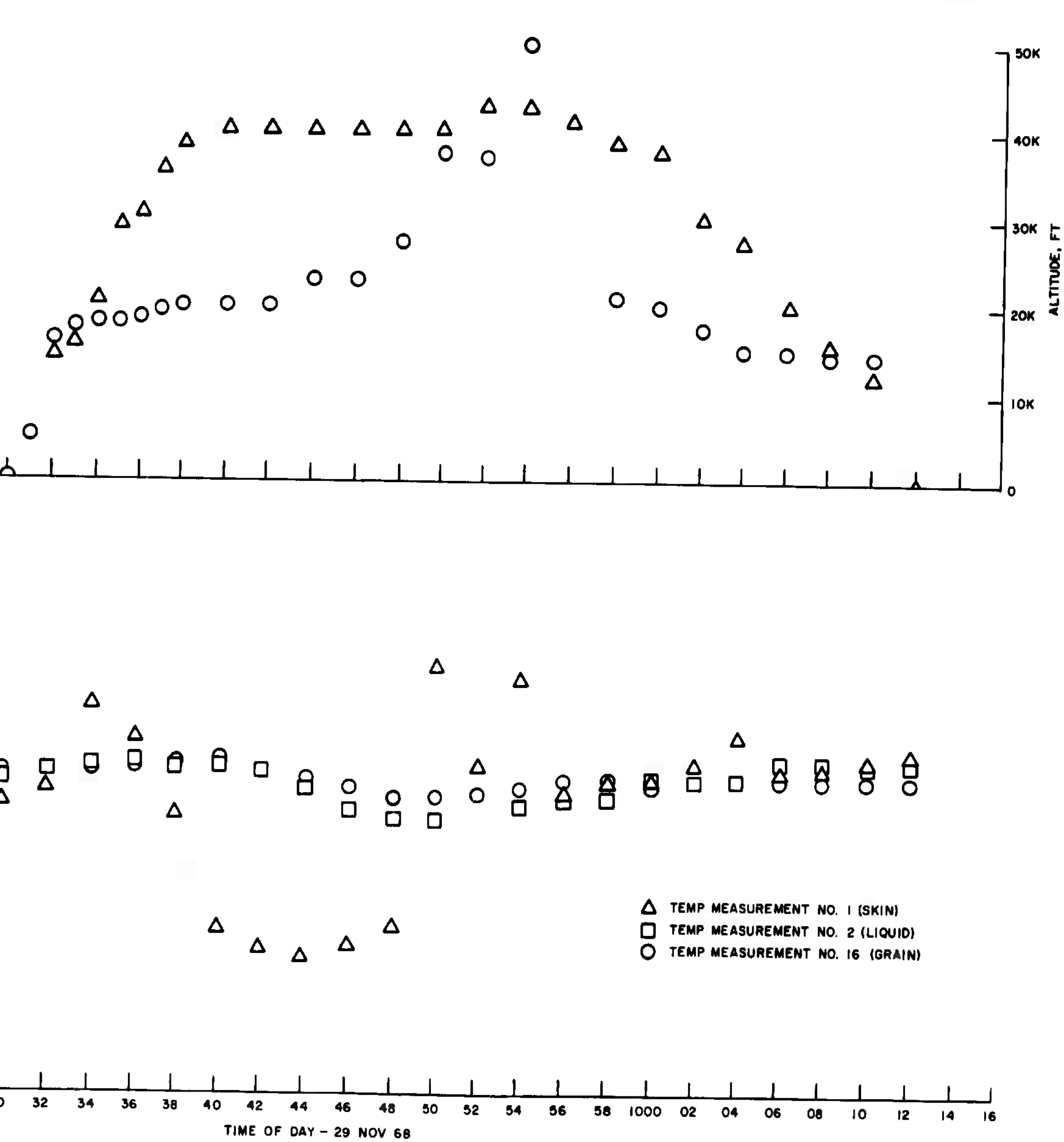

erodynamic Heating Profile for 12-Inch Diameter Liquid Propulsion Systems.

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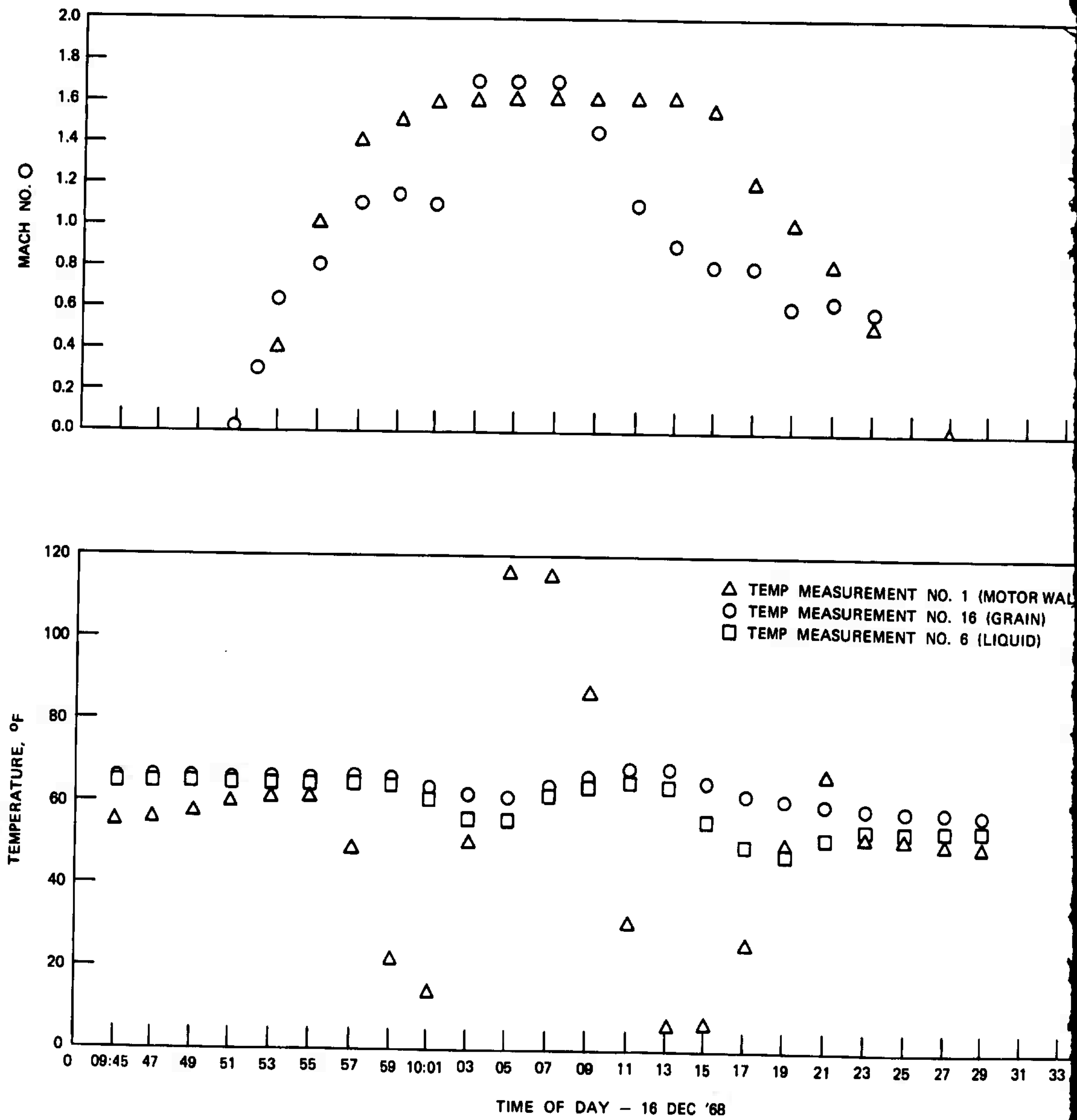

FIG. 5. Aerodynamic Heating Profile for 12-Inch Diameter Liquid Propulsion Syst

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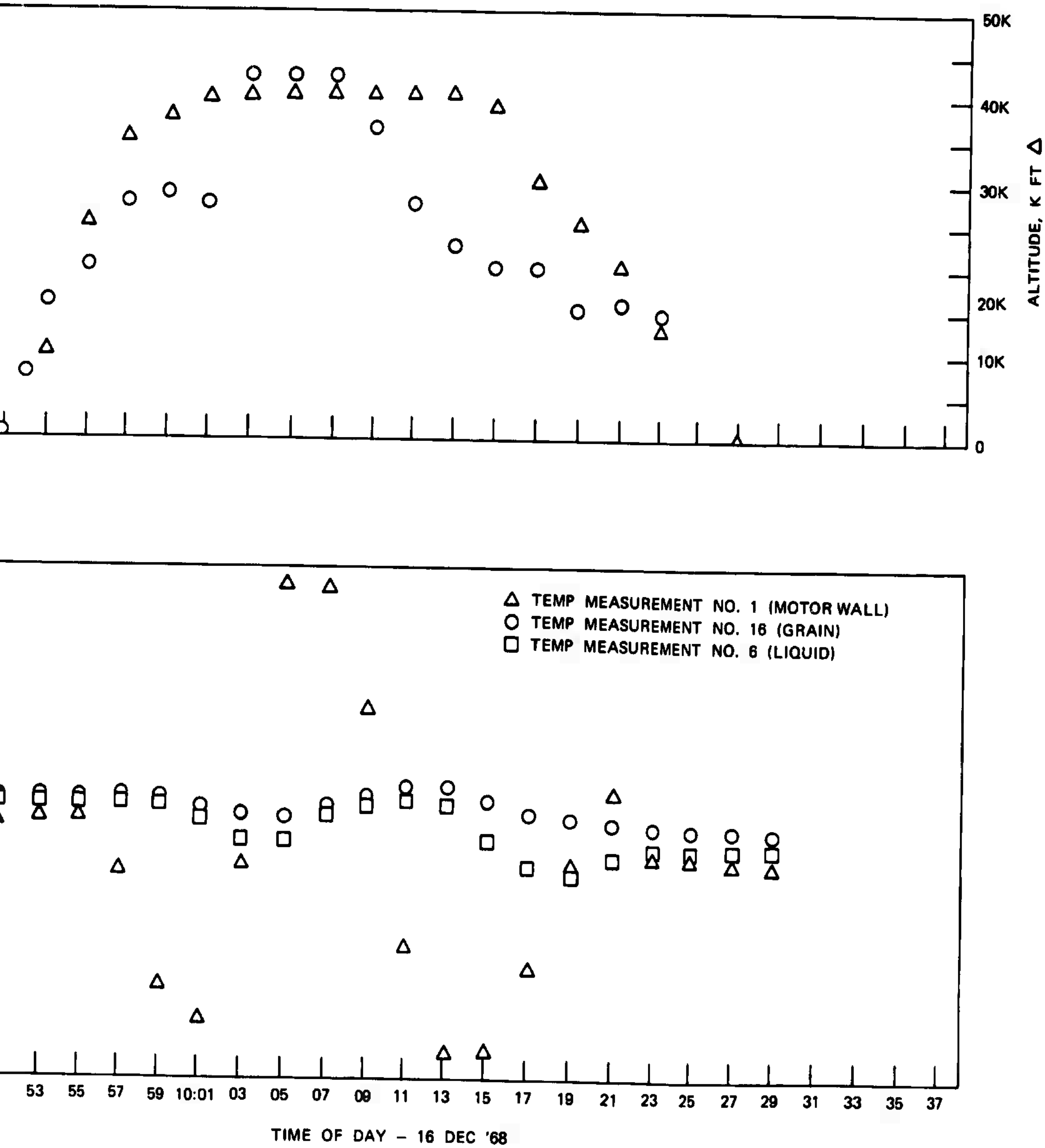

5. Aerodynamic Heating Profile for 12-Inch Diameter Liquid Propulsion Systems.

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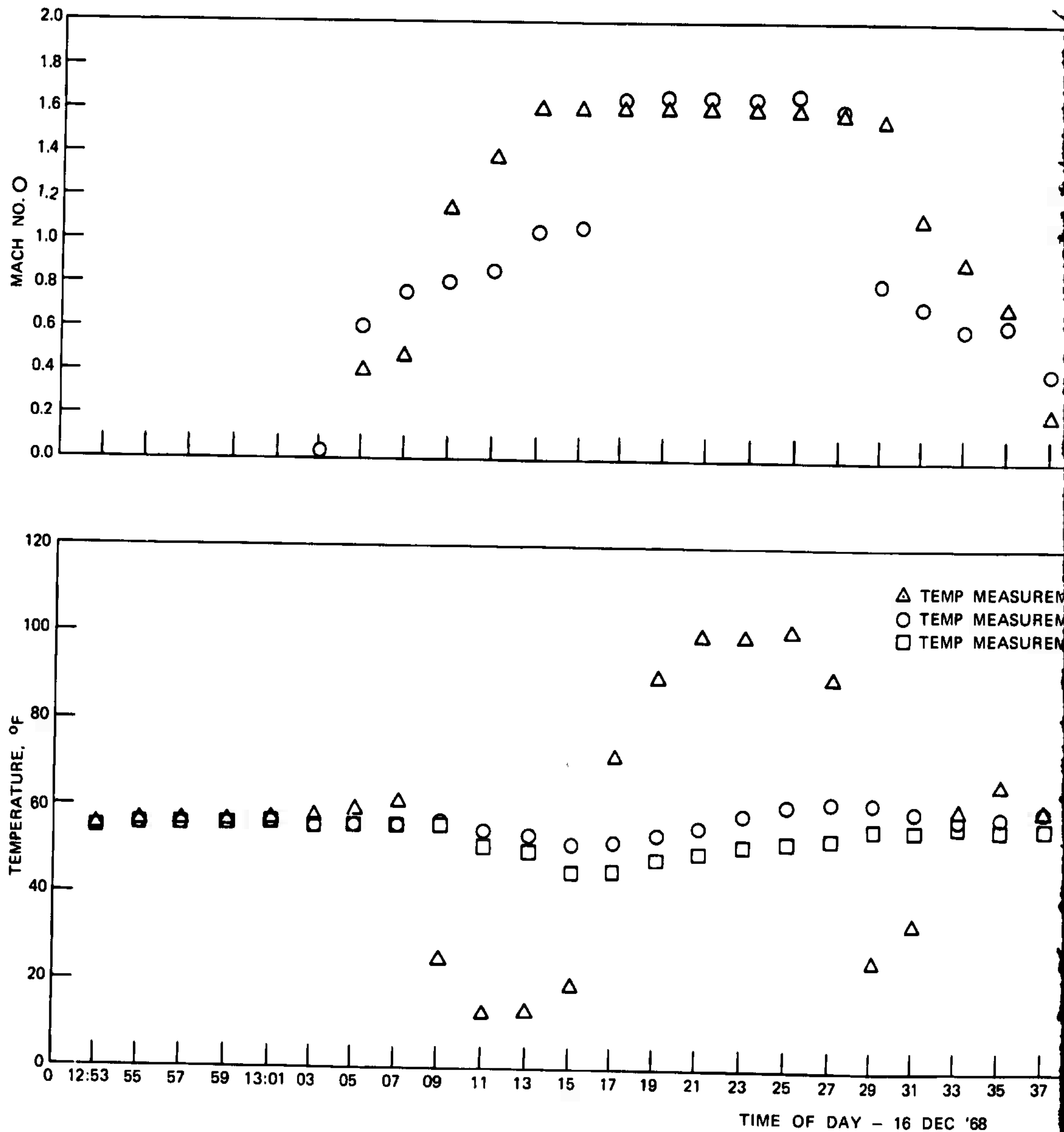

FIG. 6. Aerodynamic Heating Profile for 12-Inch Diameter Liquid Propulsi

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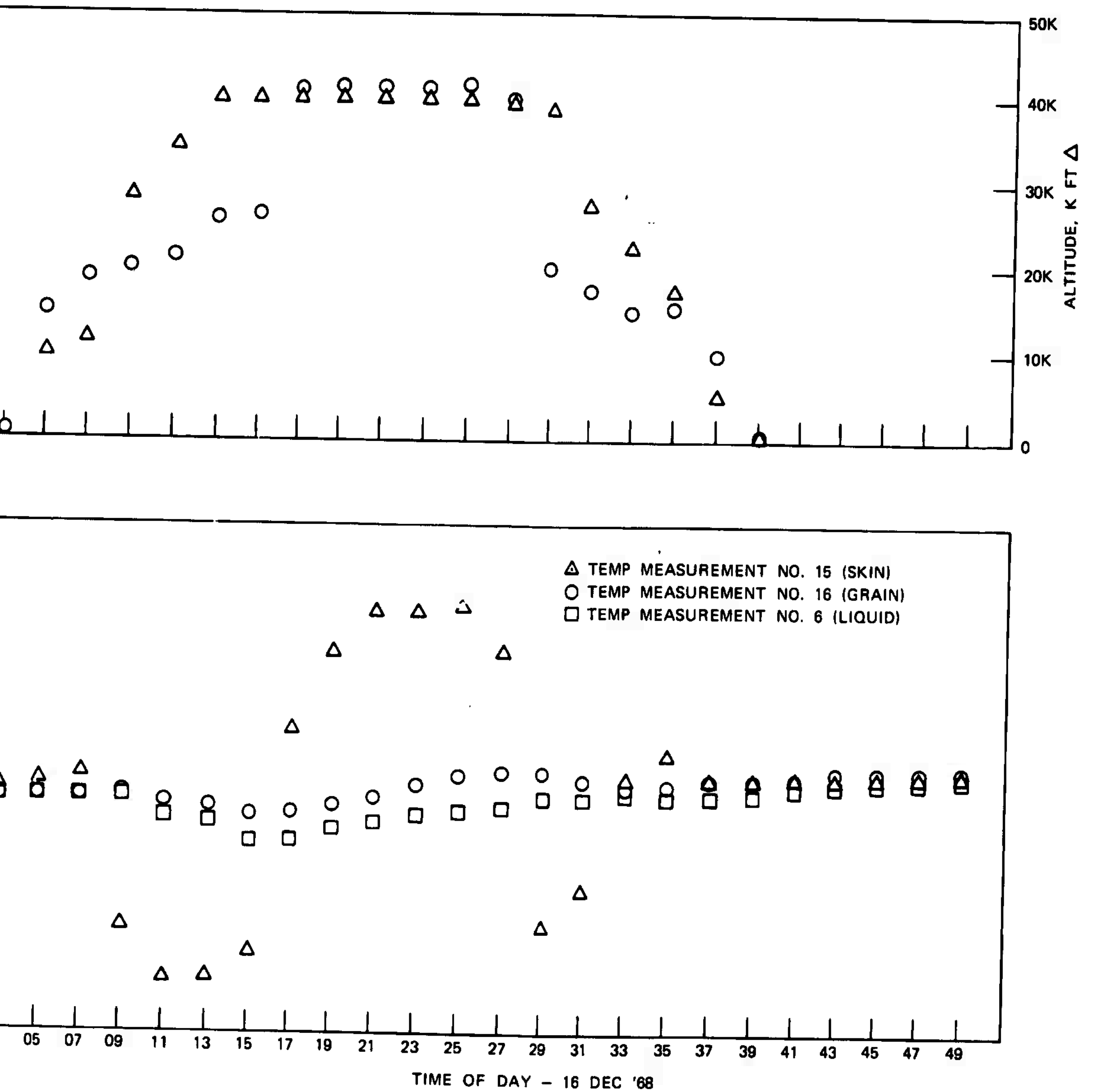

. Aerodynamic Heating Profile for 12-Inch Diameter Liquid Propulsion Systems.

AERODYNAMIC HEATING

The work on aerodynamic heating is summarized in Fig. 4 through 6. It is obvious that there is not a general heating problem. Of the three flights on the F4B type aircraft, the maximum recorded transient temperature on the propulsion system was less than 150°F. While the maximum temperature was being experienced on the outside skin over the ullage portion of the motor, the fluid temperature did not exceed 70°F. The fluid mixing due to missile vibration seemed to somewhat negate thermal stratification. It was found that a difference of 12°F can be measured between the fluid and ullage space wall temperatures. This would indicate that during any extreme maneuver such as a high speed dash, the fuel and oxidizer would be relatively unaffected by the short duration maximum situation.

The meterological data for the two days of interest to the three aerodynamic heating flights are given in Appendix B.

The second and third aerodynamic heating flights were performed on the same day, 16 December 1968. The reason for this was to simulate the return from a maximum performance flight, refuel and a repeat. Notice that even though the fuel and oxidizer are no longer at equilibrium with the rest of the missile, there is no major thermal build up after the second flight.

(Thermocouple No. 1 was "knocked out" of commission between the two 16 December 1968 flights by ground crew members. Therefore the "skin" temperature profile of Fig. 6 is from thermocouple No. 15.)

AERODYNAMIC COOLING

The work on aerodynamic cooling is summarized in Fig. 7 through 11. The figures reveal that the lower limit to aerodynamic cooling soak temperature is governed by the physics of aircraft flight. This lower limit is the missile recovery temperature, which results from aerodynamic heating.

The heat transfer between the missile skin and ambient air governs the steady state missile skin temperature. As the missile impacts particles of air they deliver their kinetic energy to the air stream near the missile (called the boundary layer). Also, the impacted air delivers its momentum to the aircraft to keep it aloft. It takes a given amount of air particles per unit time passing over the wing surfaces to hold the aircraft at altitude. If we assume that the wing loading of military fighter and attack bomber aircraft are all about the same, which they are, then it becomes evident that there is a lower limit of aerodynamic cooling experienced by carried ordnance. This limit being set by the number of particles necessary to deliver the lifting momentum (mv) also carrying their kinetic energy ($mv^2/2$).

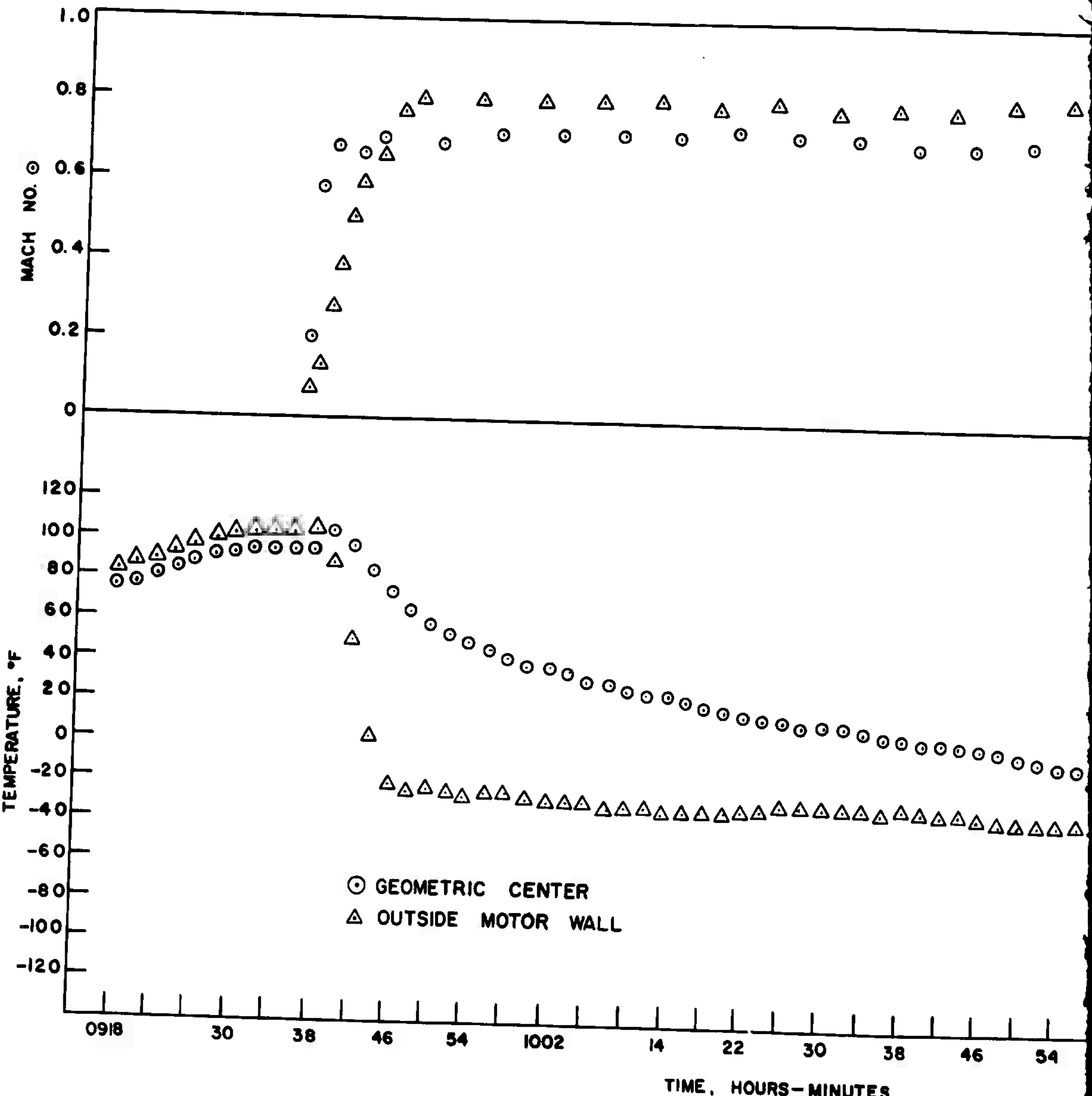

FIG. 7. Aerodynamic Cooling Profile for 12-Inch Diamete

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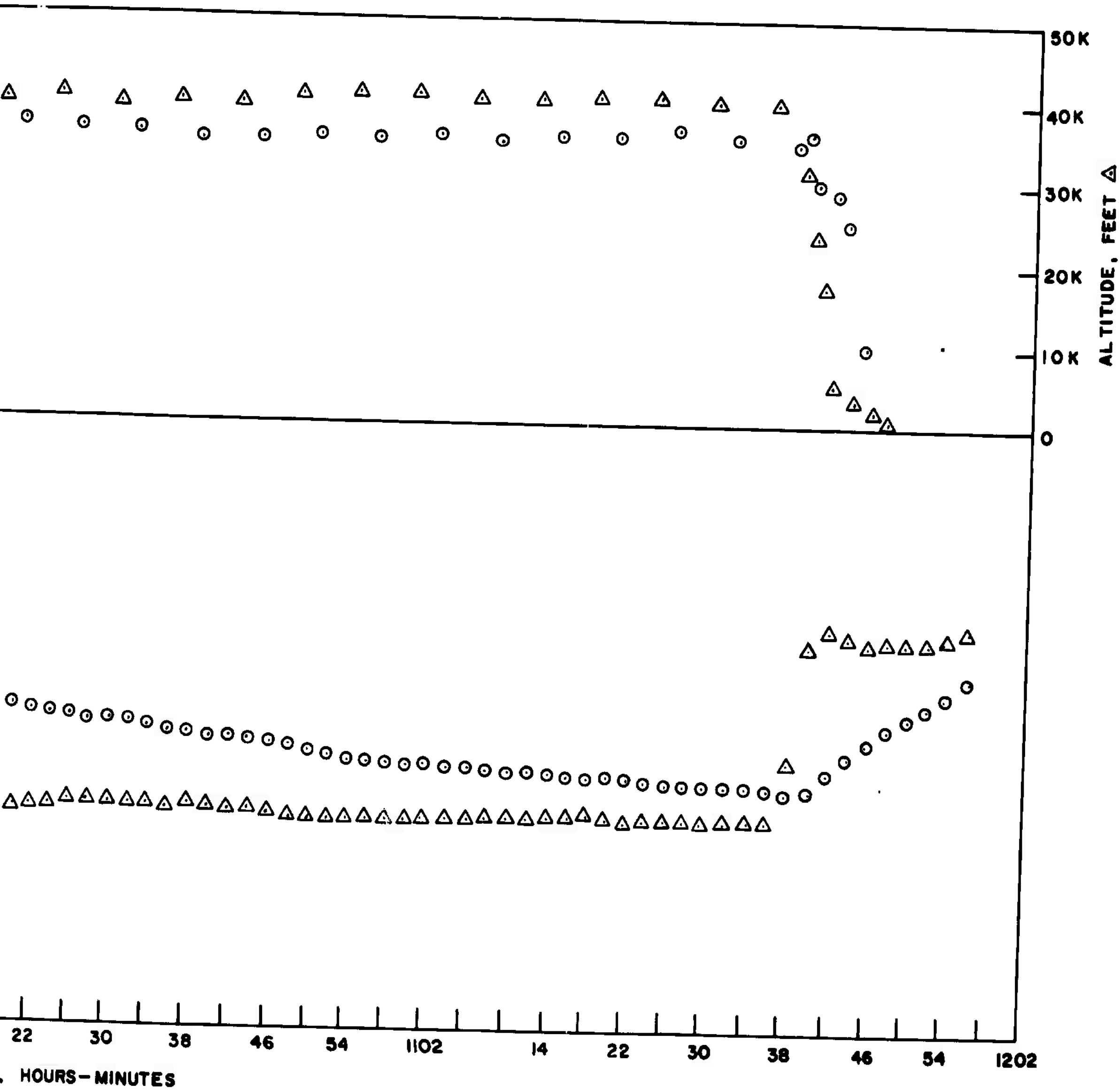

ooling Profile for 12-Inch Diameter Liquid Propulsion Systems.

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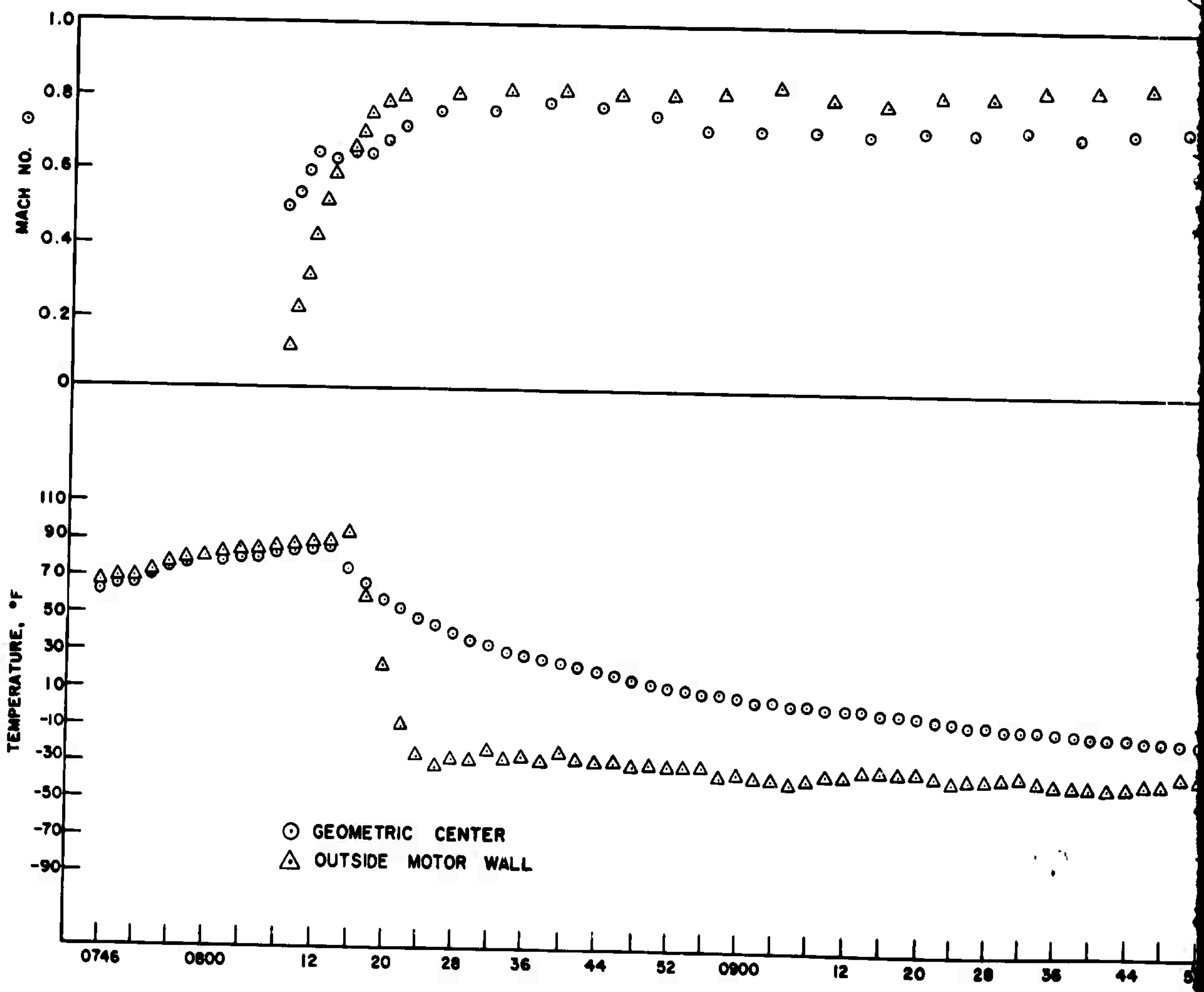

FIG. 8. Aerodynamic Cooling

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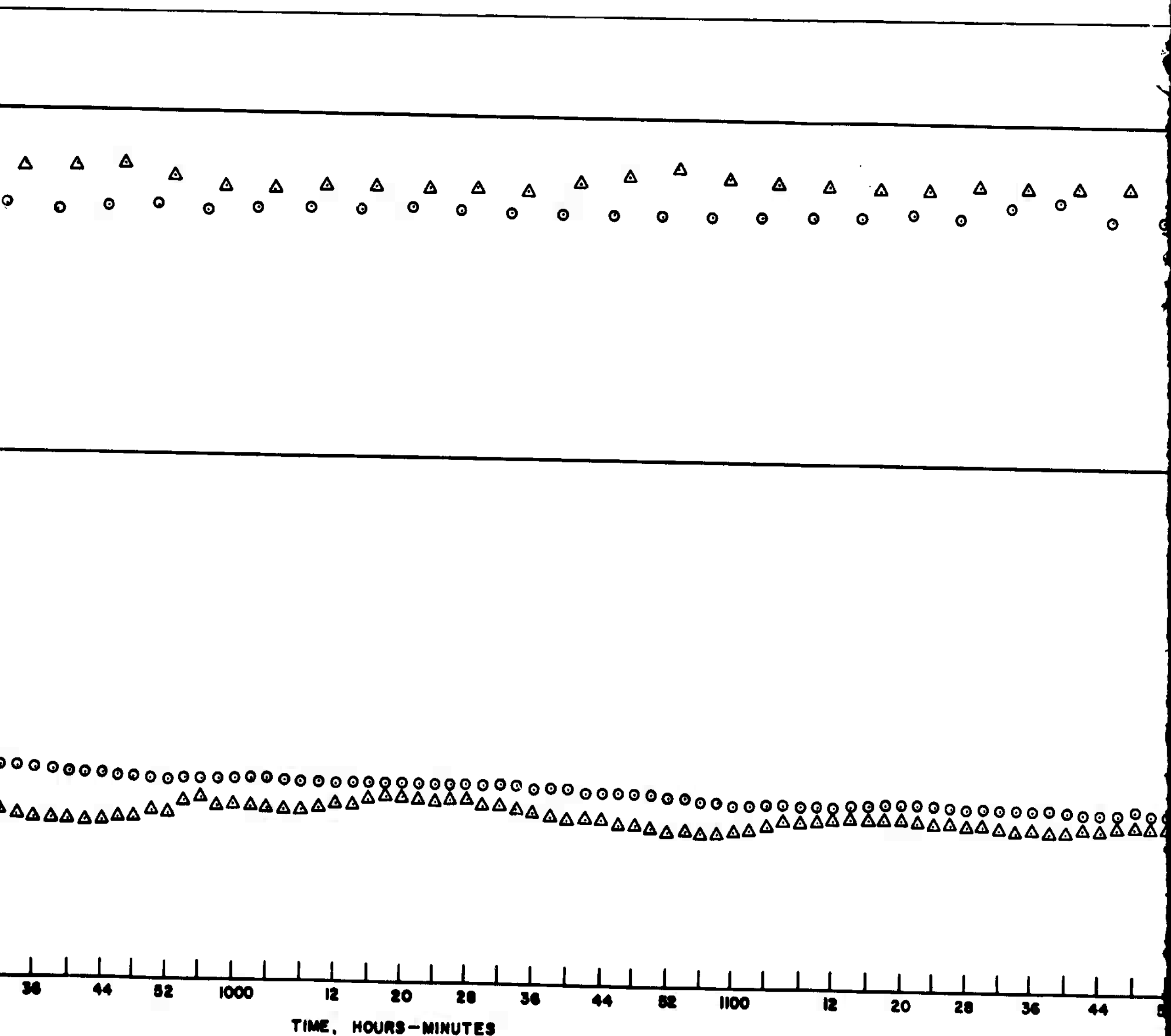

erodynamic Cooling Profile for 12-Inch Diameter Liquid Propulsion System, 60°F Presoak.

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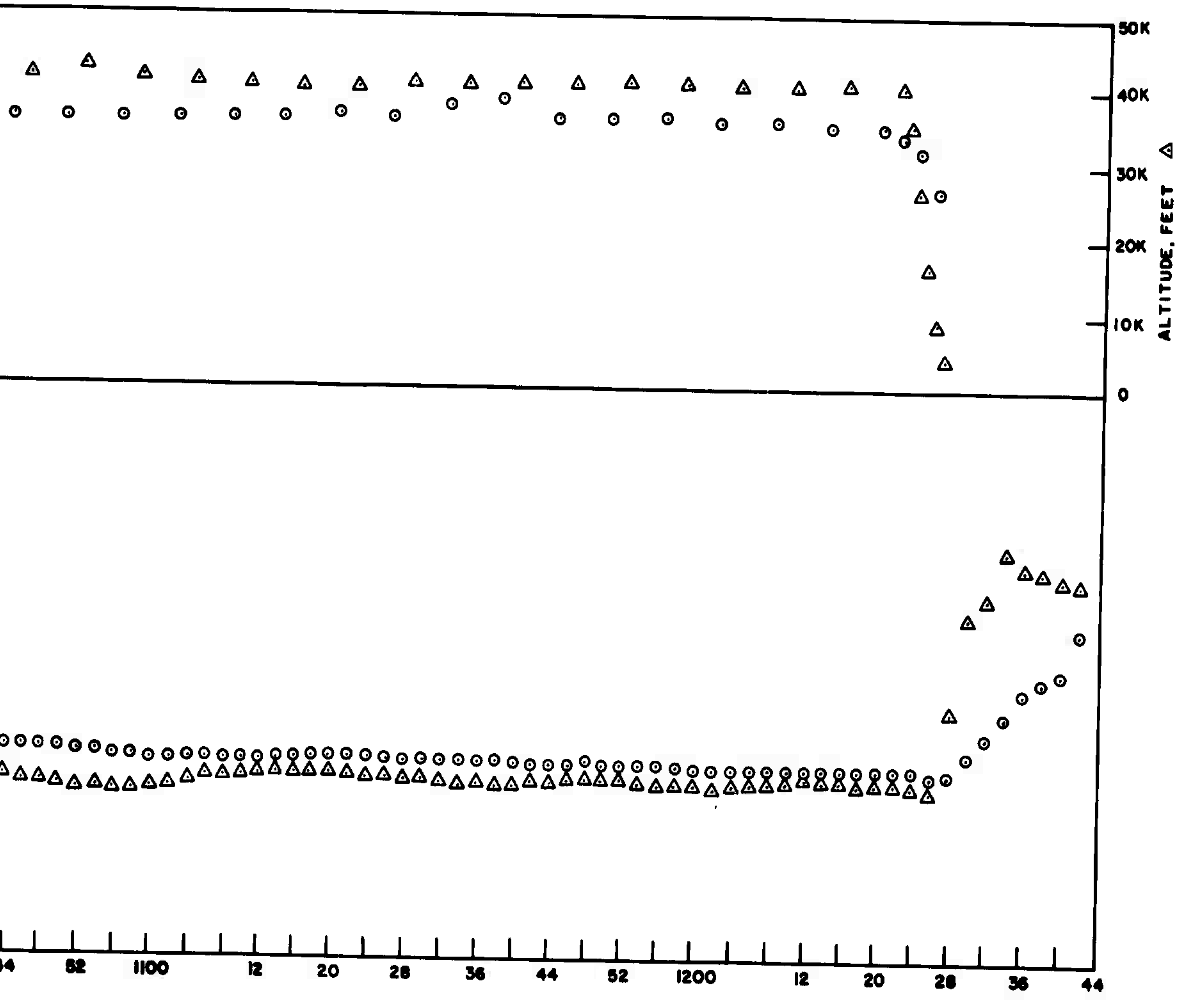

n System, 60°F Presoak.

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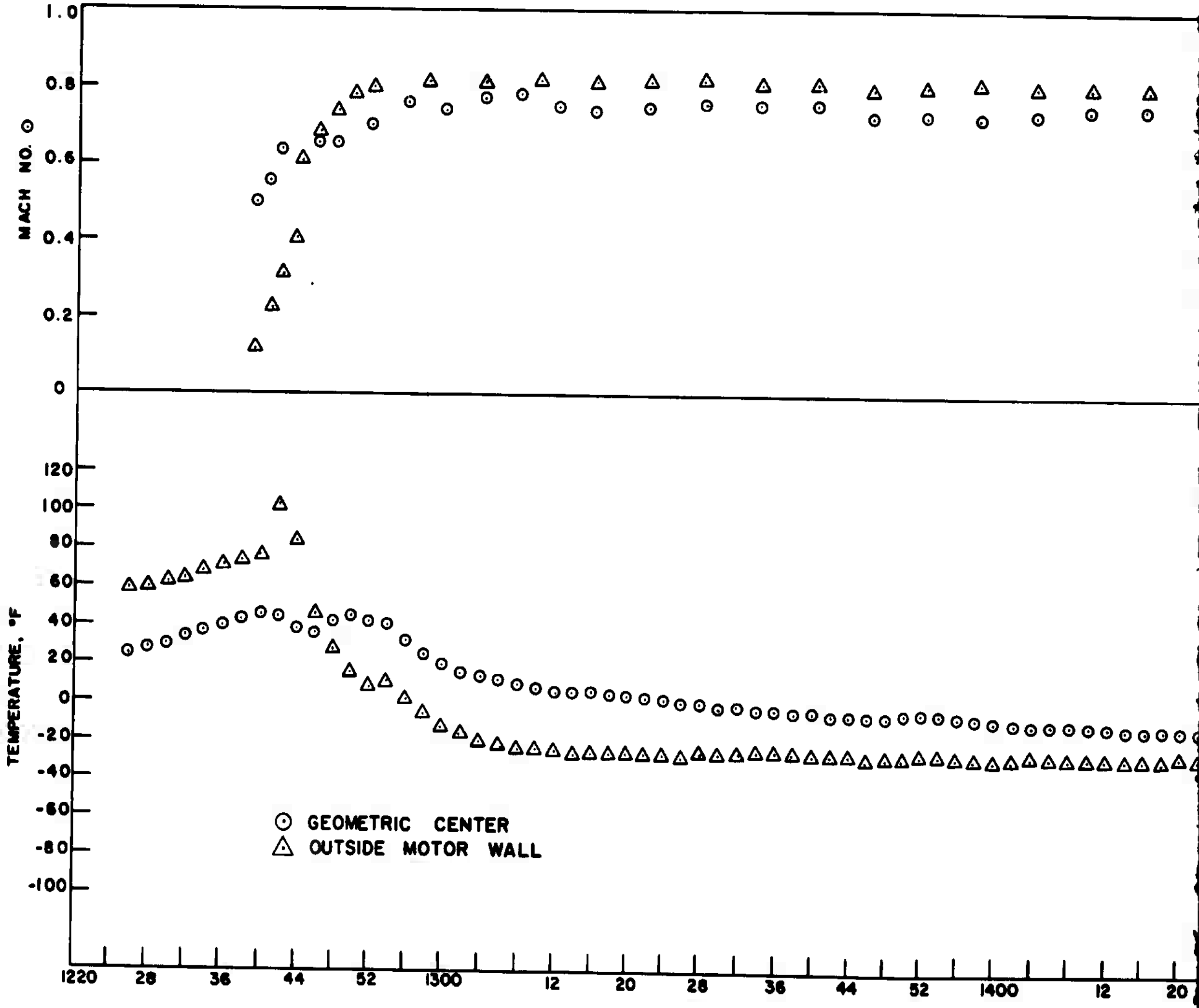

FIG. 9. Aerodynamic Cooling

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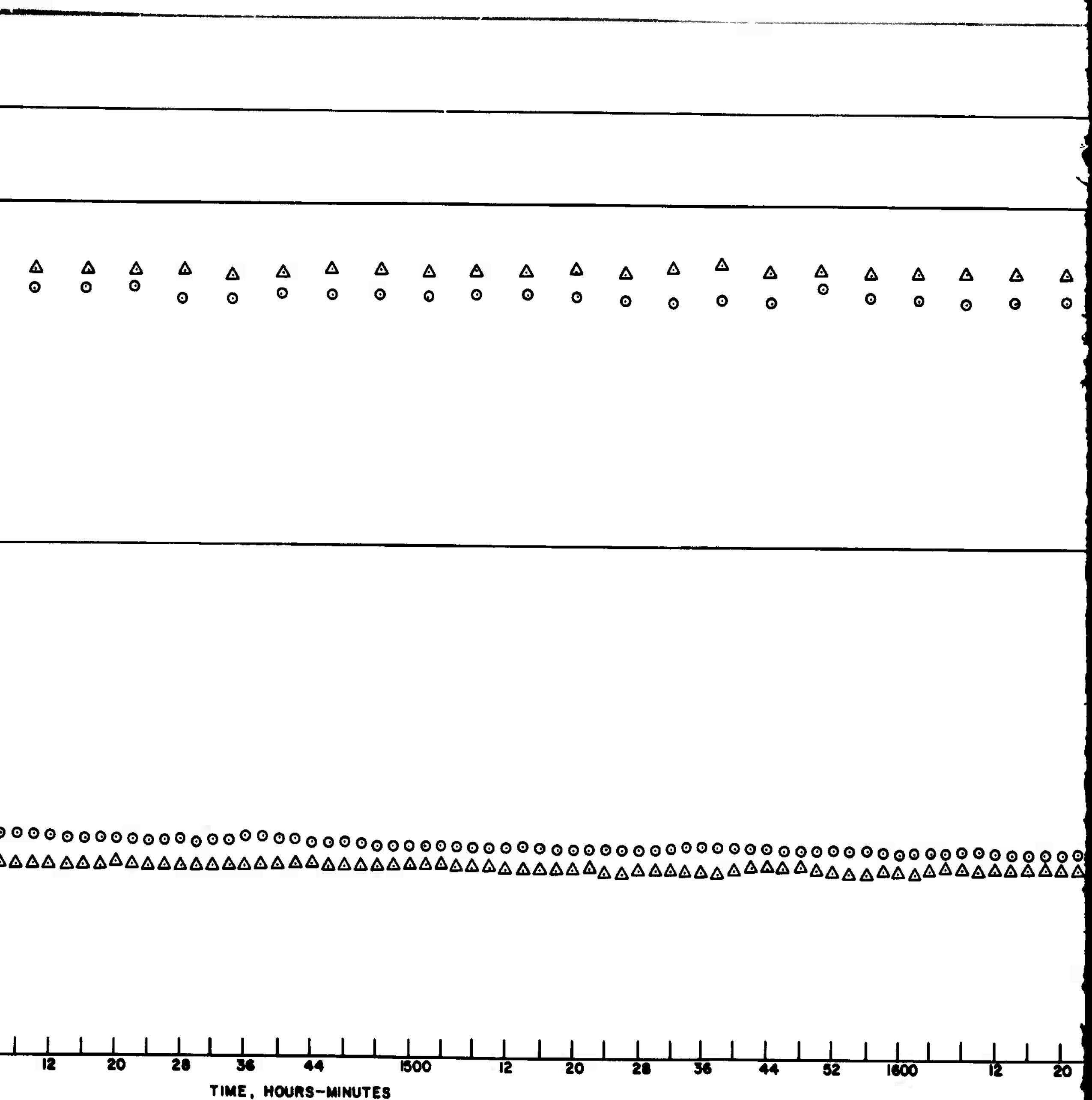

ynamic Cooling Profile for 12-Inch Diameter Liquid Propulsion System, 20°F Presoak.

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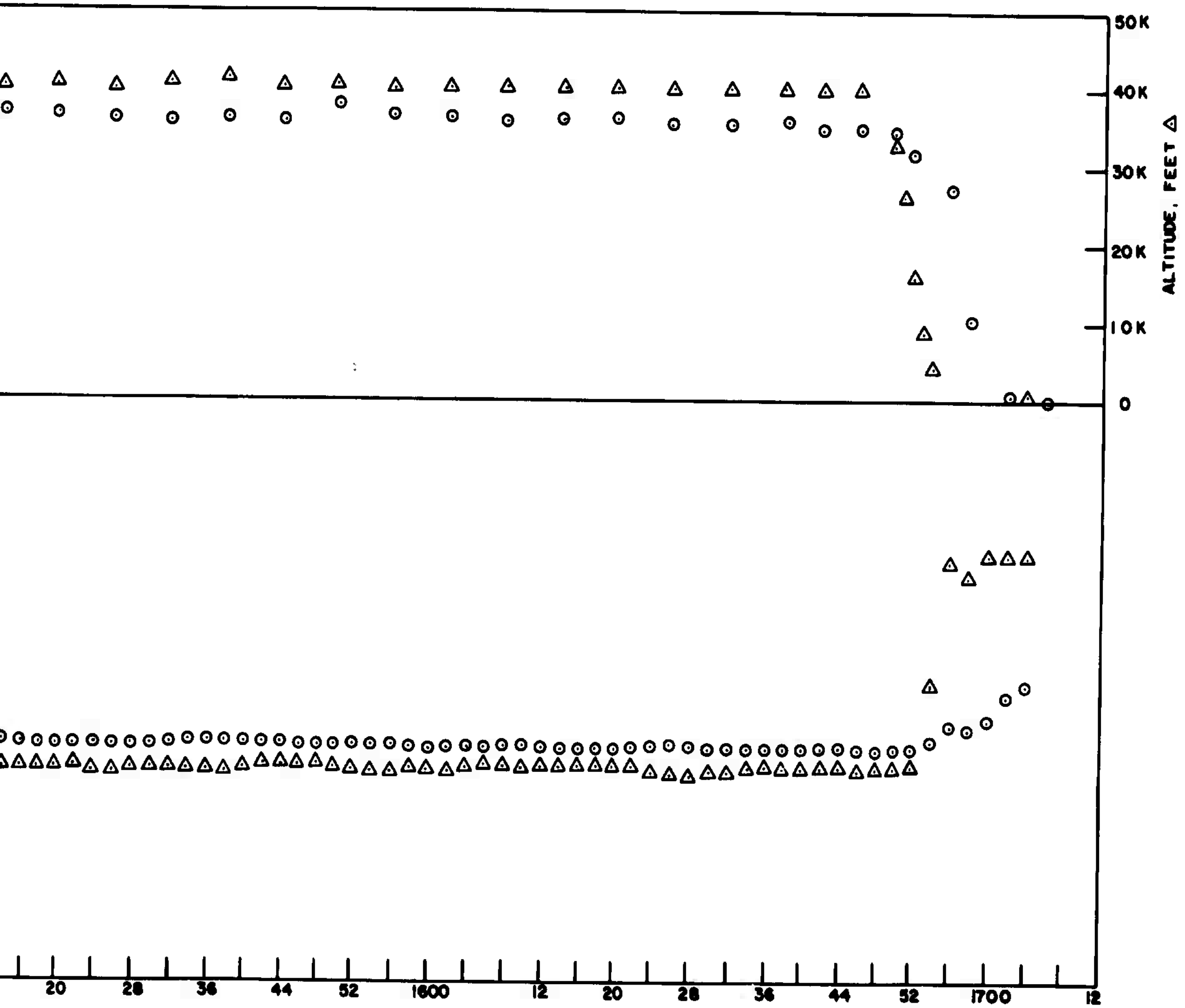

sion System, 20°F Presoak.

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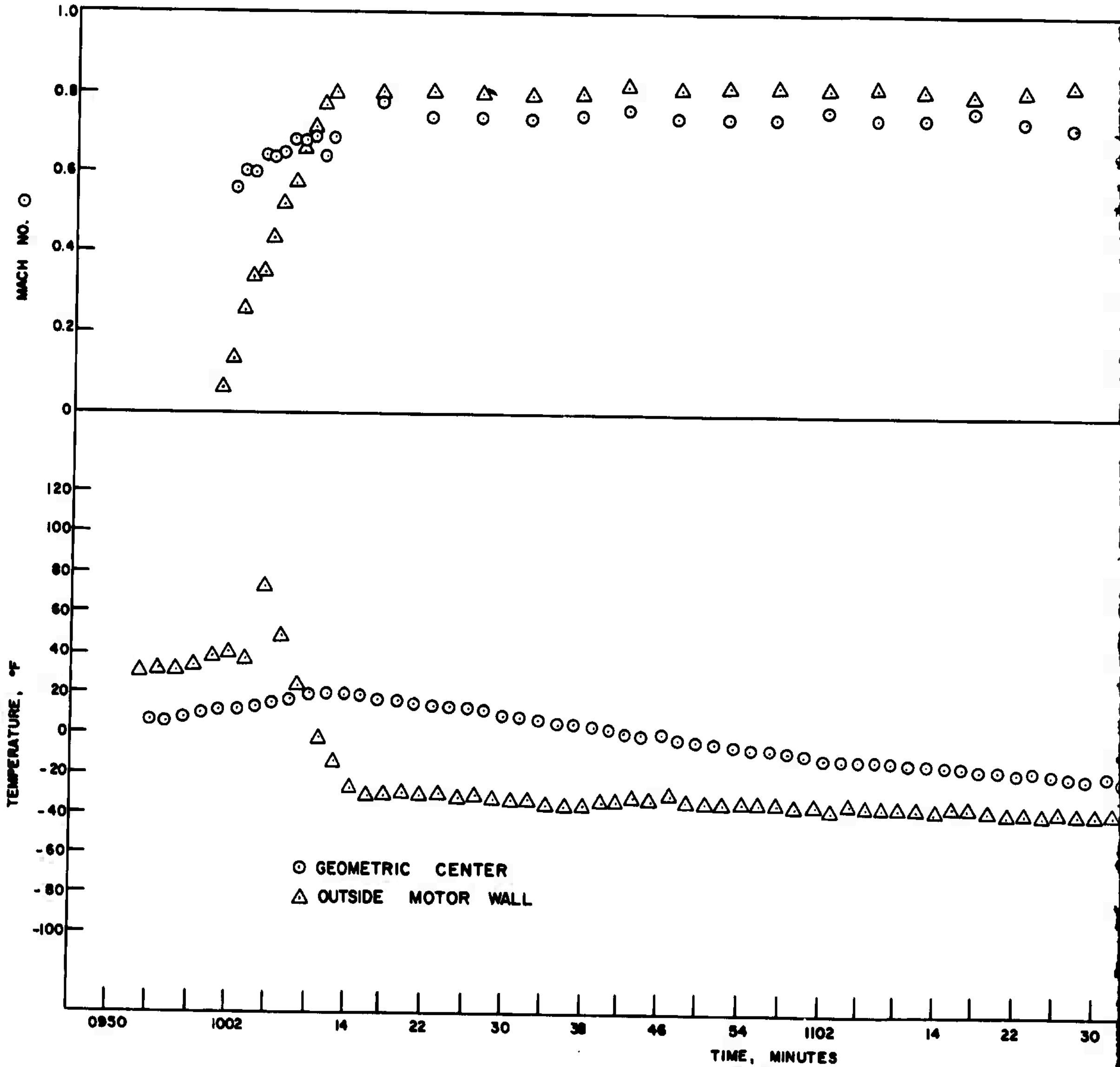

FIG. 10. Aerodynamic Cooling Profile for 12-Inch Diameter Liquid Propulsion

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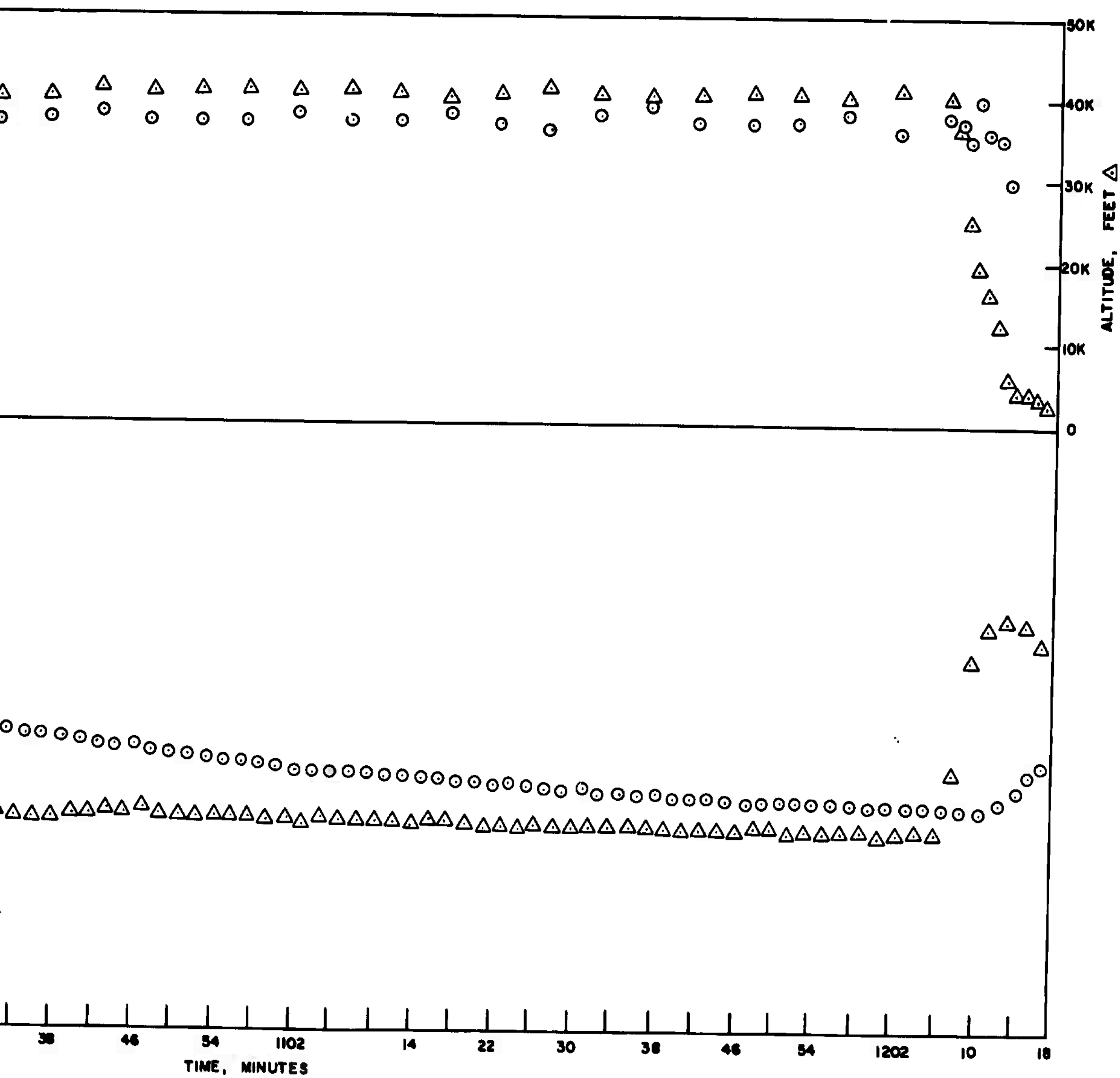

Cooling Profile for 12-Inch Diameter Liquid Propulsion System, 5°F Presoak.

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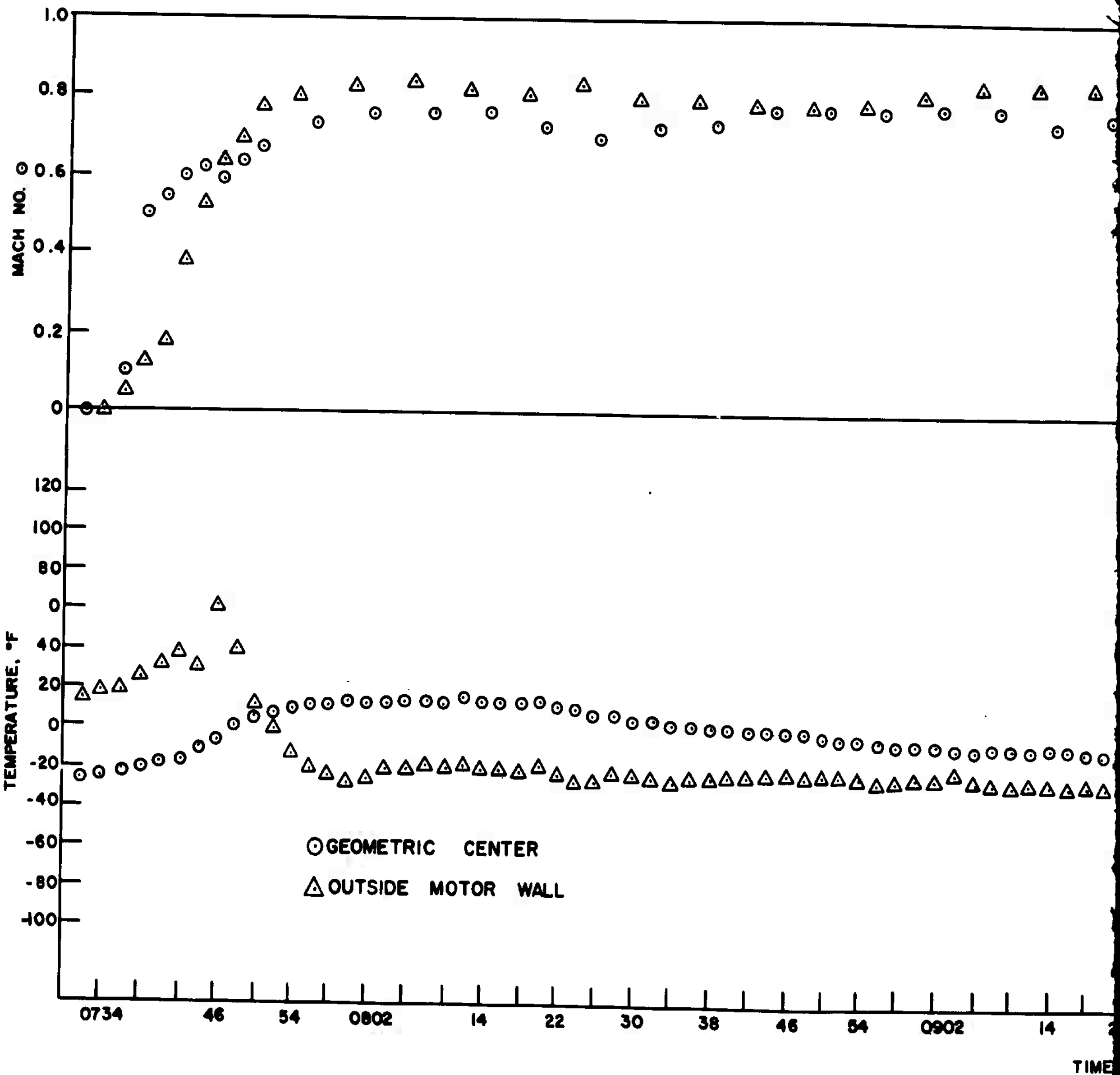

FIG. 11. Aerodynamic Cooling Profile f

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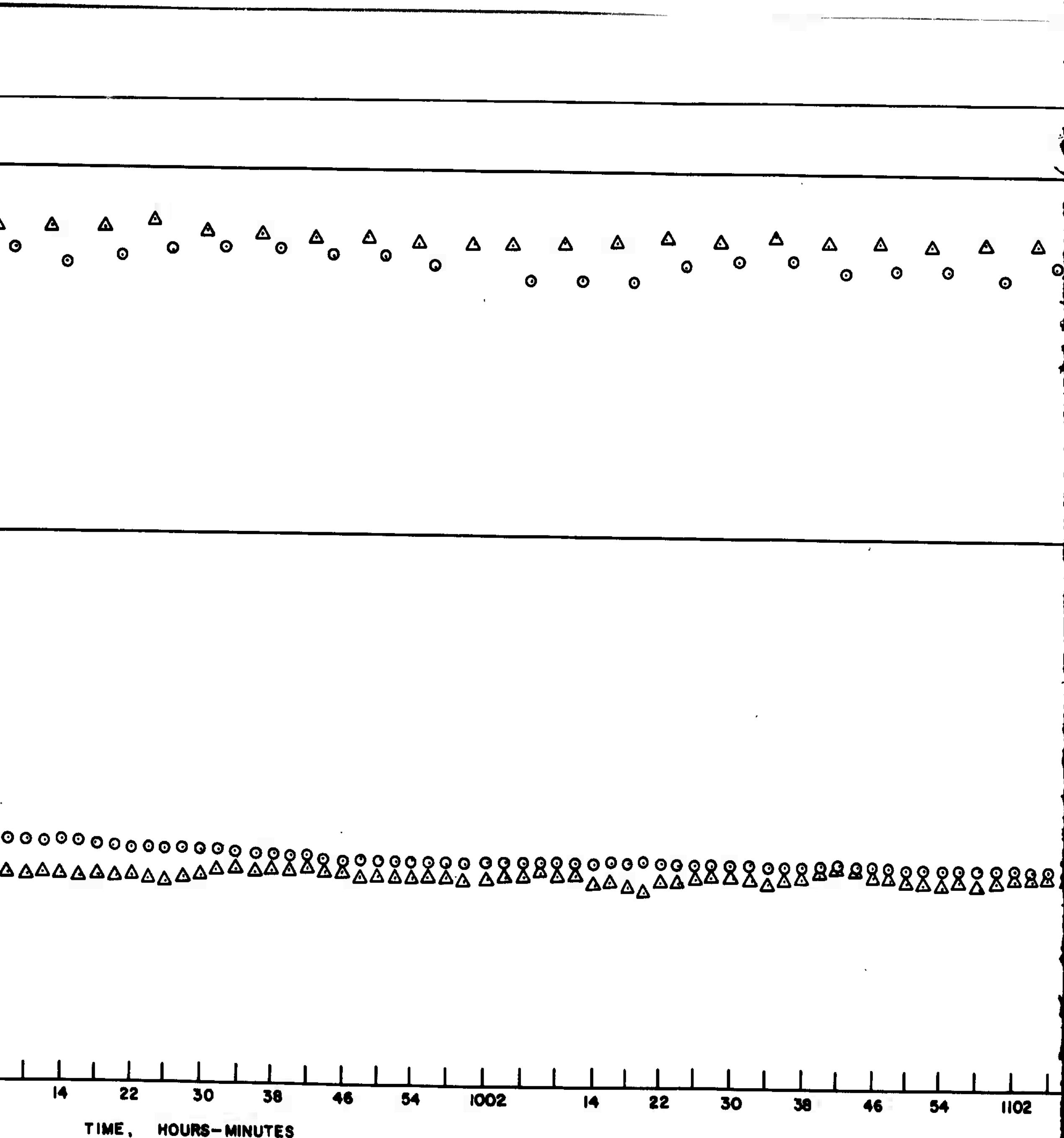
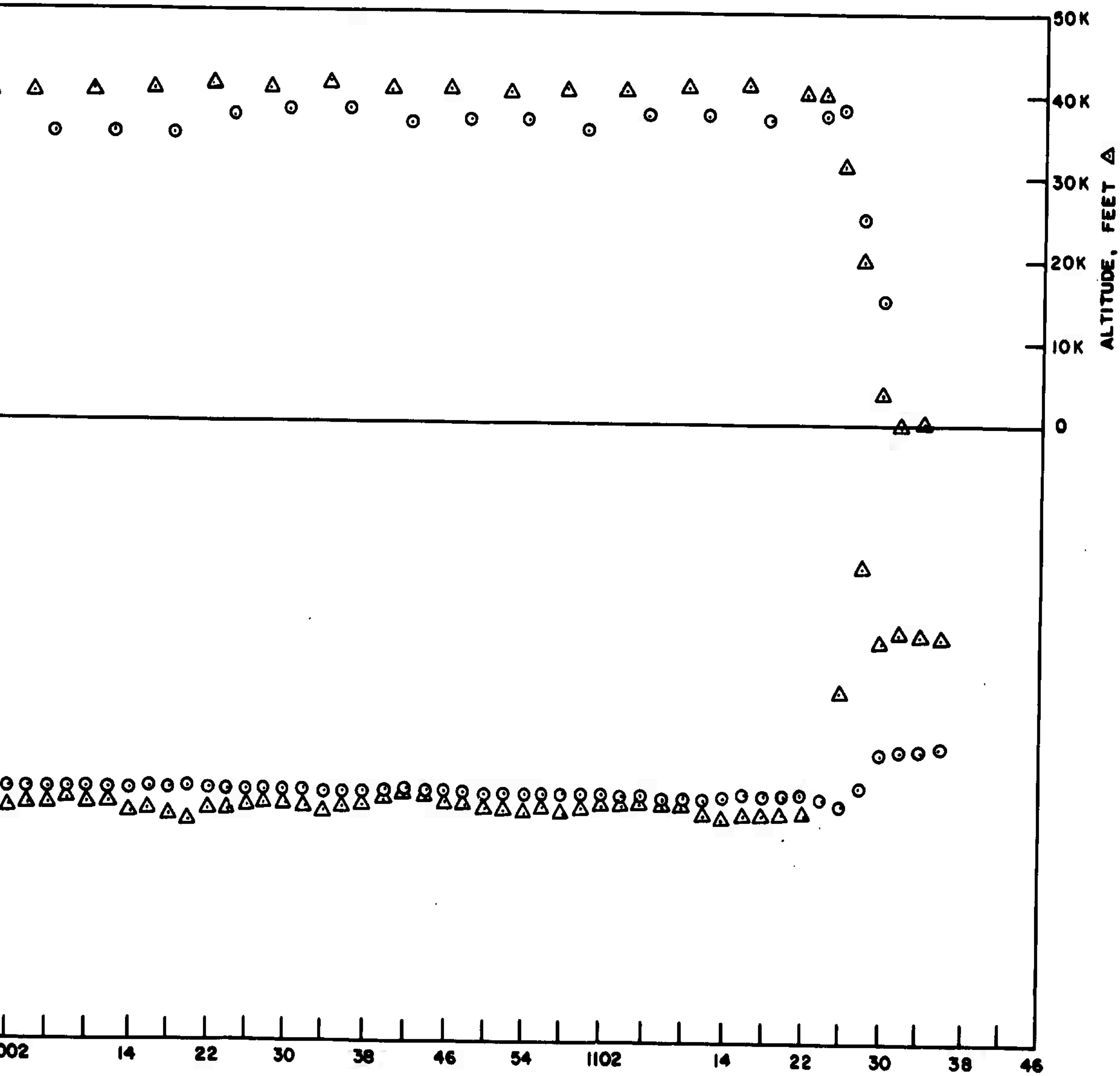


ng Profile for 12-Inch Diameter Liquid Propulsion System, -25°F Presoak.

B



n System, -25°F Presoak.

C

For example, assume that the ambient air temperature is very cold (-60 or -70°F). As the aircraft flies through the air at sufficient speed to maintain lift and good control, the ambient air is compressed (and thus its temperature increases) near the leading exposed surfaces. These surfaces include the externally carried missile.

Near the surfaces which are almost parallel to the air flow the air is sheared and the local kinetic energy of the air is dissipated into internal energy showing up as an increase in temperature. Both of these effects cause the missile to be subjected to external air temperatures higher than ambient. This is the cause of the seeming asymptotic values indicated in Fig. 7 through 11, even though the outside air temperature was measured at between -61°F and -76°F at 40,000 feet MSL for the five figures. This phenomenon is discussed in detail in Appendix C.

Since this concept was of interest to the author, it was "tested" to see if other indications could be found. The concept was presented to theoretical review with the "numbers" as measured during an actual flight. The results are presented in Appendix D. Concurrent with this work, NWC was measuring the cargo temperatures of air carried munitions (Ref. 6). It was noted on all high altitude flights in pure jet, turbo prop, or piston powered aircraft that the measured outside air temperature had to be corrected. The correction was to subtract a given number of degrees from the indicated reading to provide "true outside air temperature". A measured example is a C-141 flying at 37,000 feet over the Arctic Atlantic in winter indicated outside air temperatures of -32°C (-26°F). The true outside air temperature was obtained by adding -26°C to the indicated value at 440 knots air speed. Therefore, even in -58°C (-72°F) outside air the aircraft velocity recovered about 26°C (46°F).

As indicated by the information displayed in Fig. 7 through 11, the soak down is quite rapid, even for the center of the missile motor. It would seem that the missile outside skin has fully responded within the first half hour. A comparison of those figures depicting 2-hour flights and those over 4 hours would indicate that for all intents and purposes the missile has reached dynamic thermal equilibrium by 2 hours. It is interesting to note that the equilibrium temperature for fighter and attack bomber aircraft is above -45°F even though the true air temperature, as measured by soundings conducted by the Class A weather bureau station at NWC, varied between -61 and -76°F at 40,000 feet MSL.

The preflight presoak condition of the rocket motor was varied. It was attempted to presoak the round to progressively lower temperatures before each successive flight. As can be seen from a comparison of Fig. 7 through 11, this was not totally successful. Since the aircraft was physically some distance (7 miles) from the missile conditioning oven, the missile gained some heat in transit. The A6A aircraft was not always successful in performing an immediate take off on completion of missile installation and, as any experienced ordnanceman can relate, as the missile temperature is reduced it is that much harder to handle. During one presoak condition the missile was temperature conditioned to -65°F and during installation on the aircraft, the missile was cold enough to stick to the ordnanceman's skin. However, as a check of the aero cooling flights will indicate, by the time of A6A takeoff, the missile temperature had raised to above zero. Experience has shown that it is the exception when ordnance can be loaded onboard a sophisticated aircraft and flown within a 30 to 45 minute period.

If the propellant and oxidizer temperature is taken as representative of the "take off soak" temperature, it can be seen that the five flights are indicative of a range of 105°F in take off temperatures. The "take off soak" temperature values being 80, 60, 20, 5, and -25°F. The 80°F temperature (Fig. 7) is indicative of a motor just removed from a storage building and placed in the sun awaiting installation and flight. The meteorological information pertaining to the five aerodynamic cooling flights is presented in Appendix B.

The results may have been modified by the lack of fins on the Bullpup motor; however, this modification would have been in the direction of higher temperature. The added turbulance possibly caused by the fins, above that caused by the fin mounting stubs already in place, could raise the percent of temperature recovery in the aft half of the motor. Also, the interplay between fins, launcher and/or wing of aircraft could cause an increase in motor temperature. In no case could the addition of the fins cause a reduction in the aerodynamic cooling temperatures measured and reported herein.

CONCLUSIONS

Based on the information displayed in Fig. 4 through 6, and Fig. 7 through 11, it appears that the aerodynamic cooling phenomenon is a more important consideration than the aerodynamic heating phenomenon for aircraft-carried missiles. The possibility of aerodynamic heating providing extreme missile motor temperatures in actual combat situations is remote. In fact, it would seem that instead of being detrimental to a missile motor, aerodynamic heating acts as a thermal equalizer to negate the effects of environmental cooling.

When aircraft are flying "on the step" for long periods of time, a design minimum temperature of -40 to -50°F is appropriate for externally carried stores (based on a MIL-STD-210A cold day of -85°F).

A comparison of the data presented in this report with the information given in Ref. 1 through 5 indicates that the aerodynamic heating and cooling regime herein stated is typical and probably representative of the majority of air-launched tactical propulsion systems, regardless of size.

Appendix A

INSTRUMENTATION DISCUSSION

There are generally four methods of instrumentation usable in this type of work. They are telemetry, airborne tape recorders, chemically active temperature indicators and airborne potentiometer type instrumentation.

TELEMETRY

The general drawbacks of telemetry are:

1. Initial cost of equipment

2. Calibration and/or transmission and reception errors

3. The restriction of flight time schedule and flight distance radius because the telemetered signal must be received at a ground station for further processing. The received signals also must be converted, at a remote site, from electronic pulses to temperature information. There are many places for error.

AIRBORNE TAPE RECORDERS

On-board aircraft tape recorders also convert the temperature signal into an electronic equivalent on tape. The tape must be "decoded" at a remote ground station at the conclusion of the flight. Again there are many places for error from the time the temperature signal is incoded until the ground facility decodes the temperature information at a later time and place. The tape recorder is also limited by recording time and the number of channels of information because the tape reels are of finite size. The airborne tape recorder is relatively expensive and can be a relatively delicate piece of equipment.

CHEMICALLY ACTIVE TEMPERATURE INDICATORS

The chemically active temperature indicators are an inexpensive, reliable means of obtaining a maximum temperature. Their accuracy is also quite good depending on the manufacturer. They can be easily installed on the most nonaccessible surface of interest, and in places where no other temperature sensor can be located, because wires are not required for connecting the sensor to a recorder. The big drawback is that they give only maximum temperature at the location where they are installed rather than a continuous time-temperature history as is given by the two proceeding instrumentation modes. The chemically active temperature indicators are used most effectively to indicate the scope of the temperature problem, so that other temperature recording modes can be used more effectively.

POTENTIOMETER RECORDER

The last mode of instrumentation, the potentiometer type recorder is, in general use, the most accurate, simple, dependable system devised for a temperature-time measurement of long duration. The system consists of balancing a bridge circuit consisting of the temperature input signal, a standard reference voltage signal, the temperature range resistances, and a variable resistance. It is electrically and mechanically simple and lends itself to a simple, rugged, self contained, dependable unit. This system of instrumentation can be used for up to one flight month (10-40 flight hours) of aircraft time without checking or servicing the recorder. The one drawback was that the unit was not "off the shelf" for this application, and had only been used in fighter or attack bomber jet aircraft at NWC. These units were "one of a kind" items built in the Propulsion Development Department at NWC.

Appendix B

ATMOSPHERIC STUDIES BRANCH, UPPER AIR INFORMATION OF INTEREST FOR DAYS FLOWN

The Atmospheric Studies Branch of the Systems Development Department, NWC, is responsible for the operation of a Class A weather station. Their facility is in the same portion of the Indian Wells Valley as the Naval Air Facility at China Lake. The information is available from ground level (2,185 feet MSL) to 54,000 feet MSL. The information recorded in this appendix covers only ground and 40,000 feet MSL, as these are the entries of immediate interest. The remainder, however, is readily available.

The dates of flight are divided into two sections: Aerodynamic heating and aerodynamic cooling. The dates of the aerodynamic heating flights were 29 November 1968 and 16 December 1968. The dates of the aerodynamic cooling flights were 18 March, 29 March, 5 April, 15 May, and 21 May 1968. The soundings are usually released in the morning between 0700 and 1000 Pacific Time. It is assumed that the upper atmosphere doesn't change temperature as rapidly as earth's surface. It is on this assumption that these data are provided.

The complete records, as submitted by NWC under the code name of "Inyokern" are available from the National Weather Records Center, Asheville, North Carolina. This organization is able to process the complete record of reported meteorological variables by computer. If the program has been written, the cost of data reduction re-run is minimal. The cognizant Naval office is the U. S. Naval Weather Service Environmental Detachment, National Weather Records Center, Asheville, North Carolina.

Date	Pressure millibars (PMB)	Temp, °C (T°C)	Relative humidity (RH)	Density (RHO)	Speed of sound (SSF)	Temp, °F (T°F)
			AERODYNAMIC HEATING			
29 Nov						
2,185						
40,000						
16 Dec						
2,185	937.6	13.1	24.3	2.21069	1113.4	56
40,000	188.6	-57.0	13.6	.58991	966.8	-71
			AERODYNAMIC COOLING			
18 Mar						
2,185	939.6	4.3	54.2	2.28453	1096.5	40
40,000	182.9	-51.9	10.0	.55885	978.1	-61
29 Mar						
2,185	942.1	9.1	49.9	2.25124	1106.0	49
40,000	193.4	-55.7	11.45	.60119	969.8	-68
05 Apr						
2,185	935.0	21.1	19.5	2.14381	1129.1	70
40,000	189.3	-52.3	10.1	.57934	977.3	-62
15 May						
2,185	941.6	12.3	52.3	2.27218	1100.6	54
40,000	195.0	-59.7	13.3	.61738	960.8	-75
21 May						
2,185	930.5	19.5	28.4	2.13290	1129.3	67
40,000	198.5	-59.7	15.7	.62881	960.7	-75

NOTE: Temperatures are given in °C. °F was added by the author for ease of discussion, since °F is used throughout the remainder of the report.

Appendix C

THEORETICAL EVALUATION OF AERODYNAMIC COOLING FLIGHT

The object of this discussion is to consider the problem of estimating the minimum temperature which an external store may attain during carriage on a jet plane while flying "on the step".

Consider first the concept of aerodynamic heating. As an object moves through air, a layer of air sticks to its surface and has no relative velocity to the object. The next layer slips a little, etc., until at a distance far from the object the air is essentially undisturbed. These layers near the body are called the boundary layer and are characterized by viscous (frictional) dissipation of energy. This shows up as a local increase in temperature due to "heat" being generated. The heat may be conducted into the object or out into the main body of air. Of course the object increases in temperature as it receives this heat. Finally the body temperature reaches a value as high as the maximum temperature in the boundary layer and from that time on all the heat generated is conducted out into the ambient air. The temperature attained by the body is called a recovery temperature. (Another term is adiabatic (no heat) wall temperature, which means the same thing.)

The mathematical equation for the recovery temperature is

$$T_R = T(1 + \frac{k-1}{2} rM^2) \qquad (1)$$

Where:

T = the ambient air temperature

k = the ratio c_p/c_v = 1.4 for air

M = the Mach number

r = the recovery factor

The recovery factor depends upon the ratio, the rate at which the boundary layer diffuses momentum to the rate it diffuses heat. This ratio is (specific heat x viscosity/thermal conductivity) called the Prandtl Number (P_r) for turbulent flow, which is the usual case being discussed here, $r = (P_r)^{1/3}$. For air at -67°F, P_r = 0.73 and r = 0.9. This leads to the equation for recovery temperature of

$$T_R = T(1 + 0.18M^2) \qquad (2)$$

Figure 12 is a graph of Eq. 2 for an NACA standard day.

In order to obtain an approximate value which may be useful in quickly estimating to within 2 or 3 degrees of a minimum temperature a store may attain, let's consider a typical flight situation. The standard day minimum temperature is -67°F at altitudes of interest above 37,500 feet, so this temperature will be used in the estimate. Indications are that at this altitude a typical "on step" flight Mach number might be 0.75. These simple assumptions lead to an estimate of recovery temperature of 40°F in excess of ambient temperature. This means that the estimated recovery temperature would be -27°F for a NACA standard day. Even when one considers a MIL-STD-210A cold day the low temperature is expected to be -45°F (i.e., -85 + 40°F due to aerodynamic heating).

Of course at any altitudes lower than where these minimums may occur or at higher Mach numbers the minimum attainable temperature would be a higher value.

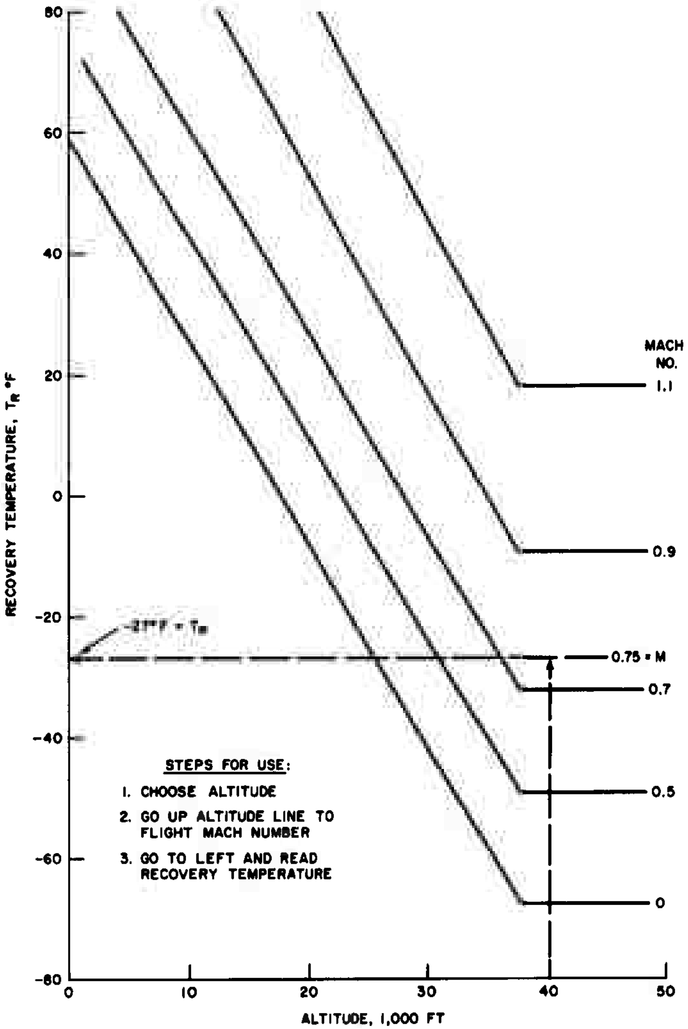


FIG. 12. Graph of $T_R = T\ (1 + 0.18M^2)$ for an NACA Standard Day.

Appendix D

COMPARISON OF PREDICTED AND MEASURED TEMPERATURE

The object of this appendix is to calculate the "steady state" temperature which an externally carried Bullpup missile would reach during a specified long time mission and compare the calculated result with the experimental result.

The flight to be compared is the one described in Fig. 11 (called the -25°F soak temperature). Appendix B indicates that the ambient air temperature was -75°F (385°R) at 40,000 feet altitude. The Mach number was about 0.74. Equation 2 from Appendix C yields

$$T_R = 385\ [1 + 0.18\ (0.74)^2]$$

$$= 385\ (1.101)$$

$$= 423°R$$

$$= 35°F$$

This calculated recovery temperature compares with the measured skin temperature after steady state of -31°F.

The test shown in Fig. 11 was chosen as the example since it was the longest steady flight. However, all of the tests for aerodynamic cooling (Fig. 7 through 11) were compared and the results are shown in Table 1.

TABLE 1.

Fig.	Date	Time of day		Temperature			Mach no.	Calculated temp range*	
		Air	Test	Calculated	Air	Measured		Low	High
7	18 Mar	0725	1130	-24	-61	-36	0.72	-29	-18
8	5 Apr	1000	1200	-23	-62	-36	0.73	-28	-18
9	29 Mar	0723	1630	-31	-68	-29	0.72	-36	-27
10	15 May	0715	1200	-36	-75	-41	0.75	-37	-28
11	21 May	0736	1100	-40	-75	-31	0.74	-42	-32

*This assumes a ±0.05 error in Mach number.

The difference between measured surface temperature after "steady state" and the calculated recovery temperature is about ±10°F. There seems to be no effect of initial soak temperature. As a matter of fact no pattern for these deviations was detected. An unanswered question is: If steady state exists, why is the surface temperature always 10°F or so lower than the central temperature?

After considering many possible sources for the differences between calculated and measured surface temperatures, the conclusion is that the results are very much within the expected (from hindsight) range of deviation.

Another conclusion is that when planes are flying "on the step" for long periods of time, a design minimum temperature of -40 to -50°F is appropriate for externally carried stores.

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13. ABSTRACT

The thermal regime of a 12-inch diameter liquid rocket motor, while carried by F4B and A6A aircraft, is investigated. Aerodynamic heating is measured during carriage by the F4B aircraft. Aerodynamic cooling is investigated during flights of up to 4 1/2 hours on A6A aircraft. The report includes figures which give the heating and cooling profiles, and tables.

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