This document consists of 14 pages,
54 copies, Series A

Ref. No. 67 1573,
Copy No. ____ of ____ Copies

APOLLO HEAT SHIELD: BLOCK II FINAL THERMODYNAMICS REPORT

VOLUME I

SUMMARY

by

D. M. Moodie

AVCO MISSILES, SPACE AND ELECTRONICS GROUP
SPACE SYSTEMS DIVISION
Lowell, Massachusetts

AVSSD-0095-67-RR
Contract M5J3XAX-450035-A

THIS REPORT WAS PREPARED IN ACCORDANCE WITH NAA S&IS LETTER CONTRACT M5J3XAX-450035-A. IT IS SUBMITTED IN PARTIAL FULFILLMENT OF THE CONTRACT AND IN ACCORDANCE WITH NAA S&IS PROCUREMENT SPECIFICATION M0999-0025.

15 April 1967

MAY 1976
RECEIVED
NASA STI FACILITY
INPUT BRANCH

This document ... affecting the ... National Defen... with ... of the ...

(NASA-CR-148079) APOLLO HEAT SHIELD: BLOCK 2 FINAL THERMODYNAMICS REPORT. VOLUME 1: SUMMARY (Avco Corp., Lowell, Mass.) 14 p

N76-74725

Unclas
00/98 42464

Prepared for

NORTH AMERICAN AVIATION
SPACE AND INFORMATION SYSTEMS DIVISION
Downey, California

This document consists of 14 pages,
54 copies, Series A

Ref. No. 67 1573
Copy No. ____ of ____ Copies

APOLLO HEAT SHIELD: BLOCK II FINAL THERMODYNAMICS REPORT

VOLUME I

SUMMARY

by

D.M. Moodie

AVCO MISSILES, SPACE AND ELECTRONICS GROUP
SPACE SYSTEMS DIVISION
Lowell, Massachusetts

AVSSD-0095-67-RR
Contract M5J3XAX-450035-A

This document contains information affecting the National Defense of the United States within the meaning of the Espionage Laws, 18, U.S.C., Section 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

PNF

THIS REPORT WAS PREPARED IN ACCORDANCE WITH NAA S&ID LETTER CONTRACT M5J3XAX-450035-A, IT IS SUBMITTED IN PARTIAL FULFILLMENT OF THE CONTRACT AND IN ACCORDANCE WITH NAA S&ID PROCUREMENT SPECIFICATION M 99-0025.

15 April 1967

APPROVED

J. W. Graham, Chief
Thermodynamics

E. L. Kaminsky, Manager
Vehicle Engineering

for E. Offenhartz, Director
Apollo Program Office

Prepared for

NORTH AMERICAN AVIATION
SPACE AND INFORMATION SYSTEMS DIVISION
Downey, California

CONTENTS

1.0	INTRODUCTION	1
2.0	ENVIRONMENTS, DESIGN CONSTRAINTS, AND DESIGN PROPERTIES	
3.0	ANALYTICAL TECHNIQUES AND MODELS	4
4.0	THERMAL TEST TECHNIQUES	6
5.0	ABLATOR DESIGN	8
6.0	ABLATOR ANALYSIS	10

1.0 INTRODUCTION

The concern of this report is the thermal design and evaluation of the ablative heat shield for the Block II Apollo Command Modules. Although the principal material comprising the shield is Avcoat 5026-39 HC-G, there are a large number of regions where the main ablator continuity is interrupted by the incorporation of other materials which, being exposed to the aerothermodynamic re-entry environment, must also serve as ablative heat shields. These interruptions are the consequence of design, structural, or fabrication requirements and as such with [illegible] the close interdependence of all disciplines affected by the ablative heat shield. Throughout the thermal design and analysis efforts it was necessary to maintain cognizance of this interdependence in order to ensure thermal adequacy for the several heat shield materials used on the Command Module.

Evolution of an adequate heat shield design for Block II was dependent upon the successful integration of analytical techniques with experimental data which characterized the heat shield materials and subsequently verified thermal acceptability. Much of the work associated with both the analytical and the experimental phases of the overall efforts was performed as part of the Block I contract. This background experience was heavily relied upon wherever possible in order to generate the Block II design consistent with budgetary and schedule requirements. It is noted that this report contains information derived from both Block I and Block II work and that no effort is made to distinguish between the two sources. This approach has been followed in order to produce a technically complete report, one which will provide a detailed description of all the information pertinent to the ablator thermal design and evaluation for Block II vehicles.

Although the remaining five volumes of this report separate various aspects of the overall thermal effort into discrete units, this separation is made for presentation purposes only. It is considered that the Apollo thermal design and evaluation efforts were performed efficiently and successfully by close working relationships between all personnel involved. By means of constant communication and cognizance of all aspects of the effort, rapid turn-around times were achieved without comprising technical requirements.

The purpose of this summary volume is to present a brief synopsis of the contents of each of the five other volumes. This abbreviated version of the final report is valuable primarily to those who are not concerned with all the technical details which are contained within the remainder of the report. It is also of value to the reader who is concerned with detail since it presents a broad view of the design process. In this fashion, it is possible to keep in mind the total effort while understanding the details of any particular part.

.0 ENVIRONMENT, [illegible] CONSTRAINTS, [illegible] DESIGN PROPERTIES

Definition of the aerodynamic re-entry environments, the ablator design constraints, and the ablator design properties are pre-requisites to the ablator sizing or design effort. The first two items describe the thermal protection requirements which the heat shield must sustain while the last item provides the basic thermal performance parameters to allow description of ablator thicknesses which satisfy the imposed requirements.

The aerodynamic reentry environments as supplied by NAA/S&ID specified time histories of convective and radiant heat flux at a sufficient number of reference heating points such that description of the important heating could be inferred (by linear interpolation between reference points) at any location on the surface of the Command Module. In addition, heating perturbation factors were supplied for the cases influenced by ablator discontinuities which produce aggravated heating effects. The transition times from laminar to turbulent flow were defined for each reference heating point. Stagnation enthalpy histories were defined by NAA/S&ID and were used at all vehicle locations rather than recovery enthalpy, thus introducing a slight conservation into the design. Description of shear histories for all heating points completed the definition of environmental parameters which were considered for a variation of the Block II ablator design. All environmental parameters were supplied by NAA/S&ID for two trajectories which represent the extremes of the reentry flight envelope. The maximum heat rate trajectory (HR-1) is an undershoot condition while the maximum heat load trajectory (HL-1) represents the overshoot case.

The principal constraint affecting the ablator design was the 600°F structure temperature limitation. This restriction was imposed for the entire vehicle and applied to the time of touch-down within the aft and crew compartments. Since the forward compartment is jettisoned at a minimum altitude of 5,000 feet, the 600°F limitation was applicable only to that altitude for the entire forward compartment. It is also required that the ablator be capable of delivering the desired thermal protection after sequential exposure to a variety of temperature, humidity, salt spray, and fungus environments. Ablator testing conducted as a part of the Block I effort determined that these environments for the ranges specified, do not affect the sealed ablator thermal characteristics. Therefore, it was not necessary to consider these constraints for the thermal evaluations of Block II Command Modules.

It was necessary to ascertain the thermophysical, ablation and optical characteristics (as applicable) for the many materials comprising the Block II ablative heat shield. Furthermore, the dependences of these characteristics upon parameters such as temperature, heat flux, enthalpy, or shear stress were determined in order to incorporate the appropriate functional relationships into the design analytical procedure. The definition of design properties relied heavily upon practical engineering judgment to establish the detail in which materials characteristics must be known and upon the substantial background experience obtained from Block I work.

The degree of reliability of the design is a function not only of the possible variations of the design properties but also of the design model accuracy and the factor of safety. For the Apollo heat shield design, no explicit safety factor was permitted; however, per specification, the thermal conductivity and density used in the ablator design are considered to be upper bound properties.

3.0 ANALYTICAL TECHNIQUES AND MODELS

Having defined the environments, the design constraints, and the ablator design properties, the only remaining pre-requisite to the completion of the thermal design and analysis efforts was a series of analytical models. The complexity of the ablative heat shield required the availability of not only one-dimensional ablation techniques but also two- and three-dimensional conduction/radiation techniques. Additionally, special areas required the use of a digital computer program to calculate radiation interchange configuration factors in order to account for re-radiation of energy from cavities in a proper fashion.

Perhaps the most important analytical model is the one-dimensional transient ablation model since it is the tool by which the ablator sizing effort was completed. The model employed for the Block II design includes the hot wall enthalpy correction to aerodynamic convective heating, allows proper consideration of gas cap radiation, and incorporates the transient effects of re-radiation, ablation, and internal conduction. The ablation phenomenon was considered by mass transfer of material from the surface only (no internal decomposition) and utilized a constant ablation temperature concept. Energy absorption due to injection of ablation species into the boundary layer was calculated by linear reduction (in heat of ablation) for the aft compartment spherical plate and by a blockage factor which utilizes an exponential reduction to convective heating at all other vehicle locations. Caution was taken not to allow blockage of more than 90% of the convective heating in order to ensure analysis conservatism. Digital computer program 1600.1 was used to perform the ablator design calculations with this model.

Verification of the design analytical model adequacy(utilizing ablator design properties) was accomplished by means of a series of simulated reentry trajectory heating tests. These tests were conducted on specimens having design thicknesses for specific Command Module reference heating points. Time variations of convective heat flux and gas enthalpy were utilized to simulate reentry profiles. Due to facility limitations, the radiant heating was superimposed at a constant flux for a period of time which produced the integrated value applicable to each body point. In-depth instrumentation provided temperature measurements for direct comparison to predicted values based upon the design analytical model. From these comparisons, it was concluded that the one-dimensional design model is conservative for the prediction of Block II ablator thicknesses.

The relatively large number of thermal discontinuities on Block II vehicles required the availability of multi-dimensional heat transfer techniques for determination of re-entry thermal performance. Two digital computer programs, 1459 and 2228, were used to calculate temperature responses at the regions of thermal discontinuities. Both programs have the capability of handling two-dimensional and three-dimensional heat transfer problems in rectangular coordinates along with an option to use a cylindrical coordinate system for geometries which are rotationally symmetric about a center line. Heat transfer modes (as applicable to Apollo) are limited to transient conduction and radiation either between internal nodes

or from the heated surface. It was necessary, therefore, to calculate ablation at all discontinuities from Program 1600.1, and then proceed with the multi-dimensional heat transfer calculations from the final ablated surface. A conducted heat flux or a temperature history was used as the driving potential at this final surface.

Adequacy of the multi-dimensional heat transfer techniques was demonstrated by means of a mock-up test of a complex thermal discontinuity in the radiant lamp facility. Temperature measurements were made and compared to predicted values. In all cases, the temperatures predicted by the multi-dimensional models were conservative.

Because of the limited re-radiation which is experienced from the cavities at the abort tower wells and the rendezvous window wells, it was necessary to calculate radiation view factors for points on the surfaces of these cavities. Digital computer Program 1647 was provided for this purpose. The actual geometries of the cavities were considered and configuration factors were calculated for a large number of very small areas within the cavities.

Assistance to the evaluation of thermal test data was provided by several digital computer programs. These programs, some of which are directly coupled to a computerized data retrieval system, calculated items, such as, least squares fits to data, formula substitutions, and tolerance/confidence statistics.

This combination of analytical models and associated digital computer programs provided the tools necessary for calculation of the thermal performance of the Block II ablative heat shield.

4.0 THERMAL TEST TECHNIQUES

An extensive thermal and ablation ground test program was accomplished to support the design, development, and manufacture of the Apollo heat shield. This effort included testing designed to screen candidate materials, characterize the selected candidate from a thermal standpoint, develop and qualify an adequate heat shield design, and monitor reproducibility of production parts. The test program faced the classical limitations associated with most aerothermodynamic tests; namely, that simultaneous simulation of all pertinent flight parameters in ground test is impractical, if not impossible. Thus, the approaches taken for Apollo were to utilize parametric variations in order to isolate significant effects wherever possible, and to exercise good engineering judgment where non-desirable elements were present in attempted flight simulations.

Many different types of tests were conducted in order to gain as complete an understanding of ablator performance as possible consistent with facilities capabilities. For basic ablation data, uninstrumented specimens were tested in the Model 500 and Ten Megawatt arc facilities to obtain overall performance characteristics. Heavily instrumented specimens were tested in the ROVER and Giannini arcs to obtain detailed quantitative information necessary to support and verify mathematical predictions of the ablation phenomena. "Go-no-go" proof tests were conducted for various design concepts in necessarily off-design but definitely conservative test environments. Comparative testing of various heat shield discontinuities in parallel with so called "control" specimens (smooth surfaced main ablator) was used extensively to ascertain the degree of compatibility between the discontinuity and the main ablator. Thermal properties facilities were utilized extensively to determine the dependences of thermal conductivity and specific heat upon density and/or temperature. Finally, many basic laboratory experiments (e.g. char chemical analysis) were conducted to support the testing performed in simulated re-entry heating environments.

Penetrations through the ablative shield present special design problems. In order to verify the adequacy of the thermodynamic design in the areas of these geometric singularities, two types of thermodynamic testing were required. Since different materials are used in these areas, arc tests were conducted to determine the basic ablation characteristics of each material. Tests were also conducted on composite specimens to determine ablation compatibility. The second type of test was performed in the radiant lamp facility. A complete mock-up of the area of the singularity was shaved to the predicted final ablated contour and tested using a heat flux history corresponding to the design environment. This test provided a good mock-up of the areas using large specimens (in most cases full scale) and test measurements were available for assessing conduction heat transfer in the area of the singularity. Measured and predicted temperatures were compared to insure that multi-dimensional heat transfer analyses were adequate.

Throughout this rather extensive program many new test techniques have

evolved and requirements for new areas of study have been identified that could have important effects on the direction and emphasis of future test programs. Two of the most significant contributions to current testing technology derived from the Apollo program are:1) the successful utilization of the trajectory simulation technique in the arc facilities; and 2) the increased utilization and refinement of instrumentation techniques to gain quantitative information from arc tests. During the program, an increasing dependence evolved in in-depth thermocouple data and optical measurements of surface temperature. The information thus obtained has brought into focus many of the problems associated with prediction of the very complex energy management phenomenon that occur during the ablation process.

Thermal testing and analyses of results have been of sufficient scope to assure the conservatism of the Apollo heat shield design. However, experience shows that two general areas of study require additional work in order to refine the understanding of ablator performance. These are: 1) increased study of the chemical reactions occurring in the ablator pyrolysis and char zones; and 2) the effects of combined convective and radiative heating on ablator performance. Test techniques are available to accomplish these studies.

5.0 ABLATOR DESIGN

Specification of the parameters discussed in sections 1.0 and 3.0, above, provides all the information pertinent to completion of the tasks associated with the sizing of the ablator for Block II vehicles. The task of the thermal designer was to integrate this information in such a manner that the resultant ablator thicknesses satisfied the thermal protection requirements. Completion of the design effort was necessarily predicated upon a framework of parameters and factors which accounted for a significant part of the overall program direction and results. This framework included: the environments as defined by the convective and radiant heating for re-entry trajectories HF-1 and HF-1; the design constraints in the form of allowable structural temperature rise; ablator properties as they were either available or readily attainable; analytic techniques in the form of operational mathematical design tools; special materials requirements as imposed by structural or manufacturing considerations; and required schedules for design and manufacturing.

The initial task of the design effort is to ensure compatibility between the mathematical model to be used, the ablator performance characteristics and the anticipated environmental conditions. Thus, it was necessary to develop certain design procedures. In the present case, these procedures are concerned primarily with description of the ablation phenomenon. Ablation temperatures were defined for each of two distinct heating zones at each heating location such that ablation occurred at an average imposed heat flux. The lower limit to ablation was selected as 1100°F based upon available test data. This definition of ablation temperatures was made for both re-entry trajectories.

Treatment of combined radiant and convective heating by use of a single technique (i.e. solution using the digital computer routine) proved impractical because of the high radiant heating imposed at certain locations on the spherical plate portion of the nose compartment. The difficulty became evident when extremely large thicknesses were predicted with associated gross conservatism of the analytical technique when compared to ground test data. It was necessary, therefore, to calculate design thicknesses on the spherical plate by separating the two heating modes and using a heat-of-ablation boundary condition.

Data evaluations were performed to determine whether or not imposed shear levels were sufficiently high to require specific consideration in the design. It was concluded that the main ablator is not sensitive to shear up to the maximum specified level and that there was no requirement for explicit consideration of a shear dependence in the design calculations.

It was recognized that the design procedure and associated mathematical routine do not describe the ablator thermal performance in as scientific or rigorous manner as may be desired. However, it was necessary to apply practical engineering judgment to the imposed framework, (particularly schedule requirements) and it was on this basis that the design procedure evolved.

Once the design procedure was established, it was necessary that calculations be made to determine the thermal design trajectory which by definition is that trajectory which requires the largest heat shield thickness. This trajectory evaluation established that the maximum heat trajectory dictated the ablator design for all regions of the Block II Command Module. This result confirmed a fact observed during Block I efforts, that the heat shield for Apollo acts primarily as a high temperature radiator and insulator rather than as an ablator. It is important to remember, however, that satisfactory ablation capability must be and is available in order that the heat shield sustain re-entry for any trajectory within the flight corridor.

Main ablator thicknesses were defined at 3.0 vehicle reference heating stations (considering heating symmetry) and for 11 areas associated with heating perturbations. This definition has proven adequate for use by Design to generate the detailed surface contour for final ablator machining. Similar detailed thickness definition was made at regions using ablators other than Avcoat 50.6-39/HC-G in order to support fabrication of parts. Adequacy of the ablator design was demonstrated at reference heating locations by a series of simulated re-entry heating tests. Direct comparison of measured temperatures to temperatures predicted with the design procedure supported the conclusion that the ablator thicknesses are adequate to provide the thermal protection required for Block II thicknesses. Adequacy of the thicknesses at points between reference heating locations was established by plotting the faired ablator thicknesses, superimposing minimum thermal requirements and judging intermediate locations by a straight line interpolation technique. It was also required that design adequacy be established for possible ablator cracks which may develop in the cold environment. Particular sizes and geometries as predicted by structural analyses were evaluated. Design acceptability was verified by a combination of experimental and analytical investigations specifically concerned with crew and aft compartment ablator cracks.

6.0 ABLATOR ANALYSIS

The description of ablator thicknesses over the entire surface of the Block II Command Modules permitted the performance of detailed thermal analyses of the general heat shield and of thermal discontinuities. Calculation of temperature and ablation histories for the nominal heat shield geometry provides basic ablator performance information. Ablator analyses were necessary at discontinuities to verify that the design thicknesses are thermally adequate in these areas. It was necessary to show that effects such as the added structural capacitance at ablator discontinuities will more than offset the thermal performance of the dissimilar ablation materials in these regions. This involves detailed evaluation of multi-dimensional heat transfer in regions of thermal discontinuities over the entire vehicle.

Analyses at all NAA/Avco interfaces were based upon a no plasma flow-through condition. Therefore, all analyses were performed on the basis of thermal seals at the substructure around all cut-outs and gaps.

The analyses at discontinuities were conveniently separated into two categories, those for which Avco maintained design responsibility and those where an NAA/Avco interface divided design responsibility. The regions which were analyzed as Avco design responsibility were:

a. shear/compression pads

b. compression pads

c. short tower walls

d. intercompartment gaps

e. edge members and gaskets

f. bolt plugs

The analyses at NAA/Avco interfaces considered the following regions:

a. RCS fuel dump

b. C-band antennas

c. Windward S-band antennas

d. C/M-S/M umbilical

e. crew hatch access port

f. micrometeoroid windows

g. RCS engine apertures

h. air vent

i. steam vent

j. urine dump

Specifically excluded from the analyses of NAA/Avco interfaces was the retro-sextant area. Avco assumed no design or analysis responsibilities for this area due to a change by NAA/S&ID.

The evaluations of ground test results were used to support the thermal analysis effort. These test results were integrated with the performance predictions obtained from the analytical studies to establish the design adequacy of both the main ablator and the thermal discontinuities.

The analytical studies revealed no structural overheating with the exception of the unablated areas at the throats of the RCS roll engines. However, the excessive temperatures are encountered late in the trajectory and in fact occur approximately 100 seconds after parachute deployment.

All ground test thermocouple data revealed that the analytical predictions of in-depth temperature responses are conservative. Surface recession predictions and differential ablation effects were not always conservative due to necessary test condition approximations. However, the predicted value of backface temperature, which is the overall important item, was conservative in all cases.

Analyses of main ablator performance were also performed using more rigorous charring analytical techniques. These evaluations considered char composition, density profiles, and surface recession phenomena.