GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-20-617 (R5906-OA1) GTRC~~XXX~~ DATE 11 / 10 / 85

Project Director: J. S. Lai School/~~XXX~~ CE

Sponsor: Georgia Department of Transportation

Type Agreement: Task No. 3 under DOT BOA (OCA File #90)

Award Period: From 11/1/85 To ~~12/31/86~~ 9-30-87 (Performance) 12/31/86 (Reports)

Sponsor Amount: This Change | Total to Date

Estimated: $ ______ $ 14,999

Funded: $ ______ $ 14,999

Cost Sharing Amount: $ 5,982 Cost Sharing No: E-20-306

Title: Investigation of Causes and Development of Solutions of Blistering of Asphalt ~~Overlays.~~ Layers.

ADMINISTRATIVE DATA OCA Contact John B. Schonk x-4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

Wouter Gulden
Department of Transportation
Office of Materials Research
15 Kennedy Drive
Forest Park, GA 30050
363-7510

Defense Priority Rating: N/A Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with Sponsor.

COMMENTS:

Minor changes in the Task Order require sponsor notification (See Article IV).

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date December 4, 1987

Project No. E-20-617 School/~~Lab~~ CE

Includes Subproject No.(s) N/A

Project Director(s) J. S. Lai GTRC / ~~GTRI~~

Sponsor Ga. Department of Transportation

Title Invest Causes & Dev. Solutions to Blistering of Asphalt ~~overlayers~~ Layers

Effective Completion Date: 9/30/87 (Performance) 9/30/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [x] None
- [ ] Final Invoice or Final Fiscal Report Already Submitted
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

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FORM OCA 69.285

E-20-6

GEORGIA INSTITUTE OF TECHNOLOGY

CAMPUS MEMO

DATE August 11, 1986

TO: OCA / PPC DEPARTMENT

FROM: James S Lai DEPARTMENT CE

SUBJECT: Copy of Quarterly progress report E-20-617

Enclosed please find copies of Quarterly report #2 ~~and 3~~ for the research contract E-20-617. I have submitted the reports directly to the contract sponsoring agent.

Copies to

Georgia Institute of Technology

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA

ATLANTA, GEORGIA 30332

SCHOOL OF
CIVIL ENGINEERING

TELEX: 542507 GTRC OCA ATL

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(404) 894- 2285

August 22, 1986

Georgia Department of Transportation
Office of Materials and Research
15 Kennedy Drive
Forest Park, Georgia 30050

Attention : Wouter Gouden, Chief
Pavement and Physical Research Branch

Dear Wouter:

Enclosed please find the semi-annual Research Project Progress Reports for the Research Project No. 8503 " Development of a Simplified Test Method to Predict Rutting Characteristics of Georgia Mix Design", and the Research Priject No. 8508 " Investigation of Causes and Development of Solution to Blistering of Asphalt Layers".

Respectfully submitted,

James S. Lai
Professor

RESEARCH PROJECT PROGRESS REPORT
DEPARTMENT OF TRANSPORTATION
STATE OF GEORGIA

Project No.	Project Title	Report No. 2
8508	Investigation of Causes and Development of Solutions to Blistering of Asphalt Layers	Report Period from January 1, 1986 to June 30, 1986

Research Agency(s)	Project Director(s)
Georgia Institute of Technology	Dr. Quentin L. Robnett Dr. James S. Lai

Starting Date	% Time Expended	Schedule Status	Funding Sources(s)
Nov. 1, 1985 Completion Date Dec. 31, 1986		☐ On ☐ Ahead ☒ Behind	HPR Type B

Funds Authorized	Funds Expended		Fiscal Year Funding	
Total	Total, %	Report Period	Authorized	Expended, %
$14,999	$1924.68 12.8%	Same	$14,999.00	12.8%

Project Objectives, Status, Progress

Report Date Aug. 20, 1986

Objective: To identify causes and mechanisms which may contribute to the formation of blisters and asphalt concrete overlays through information gathering and synthesizing.

Progress: Task A. Establish Information Concerning Blister Formation. The purpose of this work task is to establish all information concerning the possible and/or probable conditions and causes for blistering of asphalt concrete overlays. During this report period literature study relating to the subjects of blistering on asphalt overlays and on other materials (roofing, etc.) has been conducted. The information has been analyzed. A system to collect all pertinent information relative to blistering pavements has been developed. Task B. Development of Analytical Models. Development of analytical models has been initiated during this report period.

Progress of this research project during this report period has been somewhat behind schedule. During the months of July and August, the Principal Investigators have light teaching loads and should be able to devote more time on this project. It is anticipated that the project will be completed within the schedule time.

James S. Lai
Professor, School of Civil Engineering
Georgia Institute of Technology

R&D 6R4

RESEARCH PROJECT PROGRESS REPORT
DEPARTMENT OF TRANSPORTATION
STATE OF GEORGIA

Project No.	Project Title	Report No. 3
8503	Development of a Simplified Test Method to Predict Rutting Characteristics of Georgia Mix Design	Report Period from Jan.1, 1986 to June 30, 1986

Research Agency(s)	Project Director(s)
Georgia Institute of Technology	Dr. James S. Lai

Starting Date	% Time Expended	Schedule Status	Funding Sources(s)
June 24, 1985 Completion Date Sept. 24, 1986	99	☐ On ☒ Ahead ☐ Behind	HRB Type B

Funds Authorized	Funds Expended		Fiscal Year Funding	
Total	Total, %	Report Period	Authorized	Expended, %
$23,947	$23,914.24 99%	Same	$23,947	99%

Project Objectives, Status, Progress

Report Date July 31, 1986

Objectives:
a. Develop a simplified rut prediction testing device
b. Evaluate rut prediction capability of the device
c. Compare results with the results from the creep test and repeated load triaxial test to assess the rut prediction capability of the simplified testing method.

Progress: The entire research project has essentially been completed. A draft final report has been completed and submitted to GaDOT for review.

~~Dr.~~ James S. Lai
Professor, School of Civil Engineering
Georgia Institute of Technology

E-20-611

SCEGIT-87-105

Contract Research

GaDOT Research Project No. 8508

FINAL REPORT

INVESTIGATION OF CAUSES AND DEVELOPMENT OF SOLUTIONS TO BLISTERING OF ASPHALT LAYERS

By

James S. Lai
Professor of Civil Engineering
School of Civil Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Prepared for

Georgia Department of Transportation
Office of Materials and Research

September, 1987

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CHAPTER 1

INTRODUCTION

In recent years blistering of asphalt concrete overlays has become apparent in Georgia. Blisters appear to form on certain asphalt concrete overlays in hot weather, particularly in the afternoon. Apparently blisters have been observed to occur on asphalt concrete overlays over asphalt concrete pavemments, over portland cement pavements and over other types of constructions such as rubber asphalt overlays and bituthane joint sealing membranes. Blistering causes asphalt concrete overlays to be weakened and separated from the underlying pavement, resulting in development of corrugation, rutting and tensile cracking on the pavement surfaces.

It is commonly believed that the primary cause of blisters which form in asphalt concrete overlays is due to moisture or other gas-forming materials trapped underneath the overlays. When this moisture or other material is heated, it vaporizes and expands which could cause the asphalt overlay to form blisters if the vapors or gases, generated from moisture or other materials are prevented from escape. Aside from this obvious cause, there could be many other factors which need to be presented also in the pavements to promote the formation of blisters. Each asphalt concrete overlay project has its own characteristics in terms of pavement type, substrate characteristics, asphalt overlay mix type and properties, laydown operation, and climatic conditions, to name a few. The combined effects of any of these characteristics could contribute to the formation of blistering. Because of this, blistering on asphalt overlays is rather unpredictable.

To solve the problem of blistering of asphalt concrete overlays would require, as a first step, to identify the caustive factors and mechanisms associated with the formation of blisters. It is only when these factors and mechanisms of blister formation are identified that effective steps can be taken to minimize or eliminate the blistering problem on asphalt overlays. These are the objectives of this research project.

In Chapter 2, available information concerning blister formation is reviewed and discussed. In Chapter 3 a basic blister model is developed from the fracture mechanics and the implications of the analytical model on the blistering problem are discussed. The conclusions and recommendations are presented in Chapter 4.

Dr. Q. L. Robnett was the co-principal investigator of this research project. Due to his illness, Dr. Robnett was unable to continue with this research activity. The author of the report would like to acknowledge that a significant portion of the information presented in this report was the result of Dr. Robnett's enthusiastic devotion to this project amid his continuous struggle with the illness.

CHAPTER 2

ESTABLISH INFORMATION CONCERNING BLISTER FORMATION

The problem of blistering on asphalt overlays is a complex one. An attempt to understand and solve the blistering problem will require, as a first step, to establish information concerning the possible and/or probable conditions and causes for blisters to develop on asphalt concrete overlays. The sources where information concerning blistering of asphalt concrete overlays were sought consist of (1) Transportation Research Information Service (TRIS) data files, (2) Letter and telephone inquiries, (3) Information from GaDOT Office of Materials and Research, (4) Site visits, and (5) Georgia Tech Library and the author's own literature files.

From evaluating the information available, the most probable causes of blistering will be discussed in the following sections. Problems of blistering in built-up roofing have been widely known and a substantial amount of information in this area is available [1].

2.1 Blistering Due to Air-Water Vapor Pressure

In all the literature reviewed concerning blistering on asphalt overlays, almost all referred to the thermal expansion of entrapped gas (including water vapor) beneath the overlay to be the primary cause. The following describes a typical circumstance where blisters can occur. A thin and relative impervious asphalt concrete overlay is placed over a substratum which contains varying degree of moisture. The thin asphalt overlay is bonded to the substratum by a tack coat. Due to poor construction or contamination of the substratum surface, there exists areas of inadequate bonding between the overlay and the substratum. Upon heating, the trapped gas in the unbonded areas expands which cause the asphalt overlay to form blisters if the expanded gas or vapor are prevented from escape. Furthermore, if the internal pressure generated in the blister is sufficiently high, it may cause the breakage of the bond between the asphalt overlay and the substratum along the perimeter of the blister and cause the growth in size (diameter) of the blister. Also, the diurnal cyclic heating and cooling which results in more inhalation of gas into the blister than exhalation can cause the blister to increase in height.

Based on this mechanism, parameters which potentially can contribute to the formation of blisters include:

Conditions of the substrata

Properties of the asphalt overlays

Bonding betwen the substrata and the overlays

Presence of gas forming substances in the voids

Diurnal cycles

In the course of reviewing the literature, it was found that significant differences in opinions and observations were reported concerning the effects of the abovementioned parameters on the formation of blisters, even though the basic blister forming mechanisms mentioned in the preceeding paragraph were pretty much agreed upon in most of the literature. The different opinions expressed regarding the effects of the various parameters could be due to difference in the conditions existing in the studies which would affect the outcome of the results and leading to the differences in the conclusions. In the following, reviews and evaluations of the literature will be presented which will summarize the essential information leading to the blistering, the extent of the blistering and the conclusions drawn from the studies.

Potts [2] reported that in the summer of 1972 when placing asphalt concrete overlay in Florida, distortions in the forms of random "bubbles" or "blisters" occurred throughout the 11 mile length of the project. An investigation was conducted to evaluate the problem. The existing substrata of the project consists of an asphalt concrete surfacing over an aggregate base. The moisture content in the existing portions of pavement were found to be excessive, ranging from 0.3% to 1.95% for the Type I wearing surface and 1.5% to 1.9% for the binder course. The wearing course and the binder course were reported to be porous due to the gradation and the asphalt content used in the project. The moisture contents on the top 3 inches to 5 inches of the base course were from 9% to 12% and were considered to be within a normal range for the base course materials. The asphalt mix used in the overlay was found to be rather impervious with air voids at 2.5% to 3.6% and VMA at 15.4% to 15.8%. The tack coat used in the project was RS-2. Uniformity of the tacking was not reported. Chemical analyses were made on the aggregates and bituminous materials used in the project and the test results indicated that no conditions were found in the roadway materials which could point to gas formation as a cause for the blistering. Laboratory simulation was conducted where 2' x 2' samples which contain blisters were cut from the roadway and the sides and the bottoms were enclosed in an air-tight box with provisions for introducing water beneath the sample. For 18-day period the movement of the blisters were monitored along with the surface temperatures. It was found that the average maximum measured upward movement of the samples with water beneath the slab was approximately three times that measured for the dry sample. The upward movement took place during the heat of the day with greatest movement occurring after surface temperature was above 120°F to 125°F. In the report, Potts also reported that a portion of the interstate immediately adjacent of the project being investigated was being overlaid by a different paving contractor and the project revealed minor amount of blistering. A comparison of the Marshall design characteristics of the overlay mixtures being used on the two projects, indicated a higher void content about 6.4% in the project with minor blistering vs. 3.1% in the project being investigated. Also cited in the report was that the shoulders of the project being investigated were being overlayed at the same time as the traveling surface, and no blistering was observed on the shoulders. The shoulder (prior to overlay) consisted of a limerock base and surface treatment and did not have a binder or surface course. The moisture content of the base materials in the shoulder areas was about 11.5% vs. approximately 10.5% in the traveling lanes. The conclusion drawn by Potts was that (1) the excessive moisture being held in the existing wearing surface and the mixtures of the binder course and the overlay had low air void contents and high VMA filled contributing to the blistering. As moisture trapped under the "impermeable" overlay expanded in hot weather, the vapor could not be escaped upward through the overlay or downward through the substrata resulting in building up vapor pressure and forming the blister on the asphalt overlay.

Gussasphalt and mastic asphalt mixtures used in pavement overlays and in the construction of waterproofing layers for bridge decks are essentially voidless. Blistering on these materials are quite common [3-6]. The problem is again the moisture if it were trapped beneath the impermeable gussasphalt or mastic asphalt, blisters will form during laydown of the hot mixes and after construction. It was also reported that some light fraction of hydrocarbons trapped in the asphalt can promote the pressure build-up.

To alleviate the vapor pressure build-up, use of a vapor pressure relief layer beneath the impermeable gussasphalt or mastic asphalt has often been suggested as a means to dissipate the pressure. The suggestions included an open-graded binder course containing 5-10 percent voids or interlayers consisting of fiberglass fabrics or other materials.

Although moisture vapor is often been cited the major factor causing blistering in asphalt overlays [2], Beijers [7] in an experimental study showed that the presence of water was not a necessary condition for the formation of a blister. To simulate the formation of a blister at the interface of the mastic asphalt and a concrete bridge deck, under laboratory circumstances. Two concrete slabs (one dry and one wet) were overlaid with three layers of waterproofing asphalt mastic. The center portion (see Figure 1) of the slab was not bonded to the asphalt mastic, and the entire area surrounding the 0.2 m diameter center portion was primed with asphalt to provide good adhesion between the asphalt mastic and the concrete slab. The prepared slabs were heated by infrared radiators. Figure 2 shows the intensity of the artificial solar radiation and the duration. It was reported that this heating pattern gave the quickest results. This heating cycle caused the blister to form at the non-adhesive area. Figure 3 shows the height of the blister as the function of number of radiation cycle. Figure 4 shows the measured cross-sections of the blister at different days of radiation. These results were from the "dry" slab. No result from the "wet" slab was reported. The author intended to use this to conclude that the presence of water was not a necessary condition for the formation of blisters. This point will be further discussed later in Chapter 3. Also to be discussed in Chapter 3 are the mechanisms which cause the continuing growth in height of the blister with number of radiation cycles shown in Figure 3.

One of the most thorough and well-documented blistering projects of asphalt concrete overlay was presented by Eckrose and Scribben [8] and Hironaka and Holland [9]. The project is the Runway 14/32 at the Marine Corps Air Station, Beaufort, South Carolina. The original construction of the runway and connecting taxiways was done in 1943 and 1944. The major rehabilitation and widening was applied in 1956 and 1966. The latest construction was performed in 1980 and 1981. As shown in Figure 5, a portion of the runway 14/32 had a reinforced fabric interlayer (Petromat) beneath the 1-1/2 in. asphalt concrete wearing course and the other portion had a single bituminous surface treatment beneath the AC wearing course. Both were installed apparently for the purpose of minimizing the reflective cracking. The typical sections are shown in Figure 6a and 6b. In the summer of 1982, the blistering started to appear and in the summer of 1983 the blisters again occurred.

In the initial investigation by Eckrose and Scribhen [8], it was found by means of infrared scanning and video camera, that the total number of debonded areas located on runway 14/32 was 11514 with the size ranging from 6 in. to 30 in. in diameter. Overall there was approximately 17% of the runway that had debonded. The following are some of the observations and conclusions from this evaluation.

a. The debonded areas ranged in size from 6 in. to 30 in. in diameter.

b. Debonding was occurring both above and below the pavement reinforced fabric and the single surface treatment interlayer.

c. Moisture was observed at the interlayer level. Resident moisture has been observed in all layers.

d. Surface drainage of the runway has been a problem with longitudinal grades at or approaching zero and with flat to negative cross slopes.

e. The AC wearing course has low void contents (as low as 2%) and high VMA filled (as high as 87.7%).

f. Blisters cannot be reliably expected to rebond to the underlying pavement consistently with the single surface treatment achieved a higher degree of rebonding than in the fabric interlayer.

g. It was observed that the debonding occurs with greatest frequency and severity in the "light" pavement sections, while the "dark" pavement sections remain essentially intact. The light sections contained approximately 5.75% asphalt and the densities ranged from 93.7% to 94.1% with air voids in the 5.9% to 6.5% range. The dark sections contained approximately 6.5% asphalt and the densities ranged from 89.8% to 90.0% with air voids in the 9.3% to 10.2% range.

In general, this study concluded that the most probable cause of the blisters is the generation of gas resulting from the heating of trapped or absorbed moisture by incident solar energy. The moisture was originated from the subsurface area under the runway and migrated through the relatively permeable underlayers of the pavement and was then trapped under the impermeable overlay.

The blister problem on the same runway was subsequently investigated by a team from the Naval Civil Engineering Laboratory as was reported by Hironaka and Holland [9]. The investigation consisted of the following measurements, observations and samplings:

(a) Pavement temperature profiles at two locations

(b) Sampling changes of the surface profiles of four blisters

(c) Sampling of gas contained in four other blisters

(d) Sampling of the blistered asphalt overlay at two blisters

(e) Saw cutting and inspecting of five additional blisters

The temperature profiles and the blister profiles at two locations are shown in Figures 7, 8, 9 and 10. The gas samples collected from the blisters were analyzed and showed that the gas contained principally air and that there were no other gases emitted in any measurable amount that could be responsible for the pavement blistering. Saw cutting of the blister showed small droplets of water in the blisters. The pavement contained reinforcing fabric interlayer showed little to no bonding existing.

It was concluded by the authors [9] that "thermal expansion of trapped gas (including water vapor) beneath the overlay is the most feasible cause of the blistering. Because of the diurnal nature of the behavior of the blisters, the gases must be trapped. The blistering cannot be attributed to a continuously accessible diurnal source of new gases because if such a source was present, the same passageway would cause the pressures to vent thus blistering would not occur". This last statement is incorrect. It is possible that diurnal temperature change can indeed cause the blister to inhale air from the atmosphere. This phenomenon will be discussed in Section 3.2.

2.2 Blistering of Asphalt Concrete Overlay in Georgia Highways

Blistering on asphalt concrete overlays over Georgia highways was first observed in late 60's at Appling County where blistering had occurred on asphalt concrete overlay over a surface treatment substratum. The problem was not widespread and did not receive serious attention until 1980. During the hot summer of 1980 blistering occurred in several asphalt highways in southern Georgia. Since then blistering has been observed on many segments of highways in Georgia. Site inspections by the author of this report with Georgia DOT officials and discussions with them of the problems of blistering on asphalt pavements resulted in the following manifestations about blistering.

(a) Use of emulsified asphalt for tack coat has the tendency for residual moisture being left under the overlay and resulting in poor bonding between the substratum and the overlay.

(b) Overlay construction during early spring with a preceeding wet winter season tends to promote blistering on the overlay.

(c) A thin dense AC overlay over a surface treatment, particularly where rubber asphalt surface treatment is used, has a greater tendency to develop blistering.

(d) Asphalt mixes around the blistered areas seem to always exhibit stripping.

In early August, 1986, the author of this report and Dr. Robnett had the opportunity to inspect closely the blisters developed on a newly paved asphalt concrete overlay on Georgia State Route 106 between I-85 and Lavonia. The underlayers consisted of, from bottom up, coarse AC mix, double bituminous surface treatment and a layer of slurry seal using CSS-1h emulsified asphalt. An asphalt concrete leveling course was used which was tacked down to the slurry seal by CRS-2h emulsified asphalt. The overlay was placed near the end of June, 1987, and open to traffic on July 4, 1987. The overlay was a 1-1/4 in. F-mix and the tack coat used was AC-30 asphalt cement. The F-mix placed in the overlay has 5% air voids, and contains 1% lime. The asphalt cement used was AC-30. The field inspector indicated that during construction of the overlay job, there was apparently some looseness of the slurry seal as was evident that some slurry seal was picked up under truck tires during the construction. Very few blisters were noted during construction. Preceeding the construction of the overlay, there was a very long dry period with no rain for over a month. Several days after the construction, numerous blisters were developed on both lanes of the highway in the sections where overlay was placed directly over the slurry seal. In the section toward Lavonia, the old slurry seal was milled off first before placing the AC-30 tack coating the 1-1/4 in. F-mix no blistering was observed in the section with this approach.

A 12 in. diameter core over the blistered area was taken by the GaDOT personnel and was brought to the GaDOT Materials Testing Laboratory. Examining the core showed several interesting features. The slurry seal was readily separated from the materials immediately beneath that; the slurry seal itself appeared to be very rich in asphalt and impervious. The materials immediately beneath the slurry seal was stripped. It appeared that both the slurry seal and the AC overlay got pushed up and the separation was at the interface between the slurry seal and the materials immediately below that.

2.3 Blistering of Asphalt Overlayer Due to Other Causes

In the course of the literature review for this study, the causes of blistering on asphalt overlays cited were many. Besides the air-vapor pressure generated beneath the overlays as the most frequently cited cause, there were several other causes that were mentioned in the literature. These other causes will be discussed in the following.

Blistering Due to Soluble Salts

In the references [10-14] the formation of blisters due to excessive quantities of water soluble salts were reported. The presence of salt in the subsurface could be due to the use of saline water for compaction of base course or could be the subgrade, subbase or base materials containing soluble salt. When there is moisture movement between these layers, salt can accumulate at the interface between the base and surface layer. Also, the salt-rich water migrates upward to the surface and subsequent evaporation of moisture causes the salt to deposit beneath the asphalt overlay. As the water evaporates, growth of salt crystals plus the hydration and swelling of sulfates forces the surfacing upwards to form a blister.

Blisters Due to Bacterial Action

Brown and Darnell [15] investigated the blistering of asphalt overlays and the deterioration of the underlying asphalt occurred in certain areas in Mississippi. On the basis of the composition of the gases and the microbial population in the blisters, the authors concluded that the blistering problem was due to bacterial action. He further concluded that the presence of nitrogenous and phosphorus-containing materials in the sand, gravel and slag used in the asphalt mixes were responsible for supplying sufficient nutrients to allow for the production of sufficient quantities of gases to cause blistering. The addition of lime to the asphalt mix was suggested by the authors to be the most economical means of reducing the problem.

CHAPTER 3

DEVELOPMENT OF A BASIC BLISTER MODEL

Based on the literature review presented in Chapter 2 and the theory of adhesive fracture [16-21], a simple model representing the formation of blistering is proposed in the following. Figure 11A illustrates the existance of an unbonded area, a circular area with radius a_o, between the asphalt overlay and the subsurface.

When the gas or gas-vapor mixture trapped in the void expanded due to increase of the ambient temperature, pressure will develop in the void and starts to push up the unbonded portion of the asphalt overlay and thus initiates the development of a blister as illustrated in Figure 11B. Whether the blister will grow in height and in size, see Figure 11C and 11D, depends on many factors.

In order that a blister can grow in height, the pressure developed in the void should be sufficient to overcome the stiffness of the asphalt overlay material and to induce sufficient deformation in the asphalt overlay to allow the increase in the overall surface area of the material over the fixed unbonded region. This process is dependent upon the intensity of the pressure induced in the void, the characteristics of the overlay material, and the geometry of the void. Furthermore, the diurnal change in temperatures, which causes an inbalance in the inhalation and exhalation of air in the blister, can further induce diurnal growth and recession of the blister. This phenomenon will be discussed in Section 3.2.

For a blister to grow in size, the pressure induced in the void should be strong enough to rupture the bond between the overlay and the subsurface. The adhesion failure could be occurring between the asphalt overlay and the tack coat, or between the subsurface and the tack coat. The failures depend on the magnitude of the pressure in the blister, properties of the materials such as elastic modulus and surface energy, and the geometry of the overlay such as the size of the void and the thickness of the overlay. Analysis of this problem will be presented in the following.

3.1 Analysis of Adhesive Fracture

Consider an axially symmetric system consisting of a flat infinite subsurface covered by a layer of a second material. The covering layer is bonded to the subsurface, except for a circular area centered about an axis of symmetry, see Figure 11A. When the thickness of the covering layer, h, is small compared to the unbonded dimension, $2a_o$, the stretching due to in-plane stress is comparable to the bending. In this case, one finds it necessary to consider both the stretching displacement as well as normal bending deflection. The solution for the deformation is as follows [16,19].

$$w(r) = (1/64)(P/D)(a_o^2 - r^2)^2 \qquad (1)$$

$$w_{max} = (1/64)(P/D)\ a_o^4 \qquad (2)$$

where: $D = E\ h^3/12\ (1-\nu^2)$ (3)
is the flexure rigidity of the covering layer

E = elastic modulus of the covering layer

P = pressure in the void

ν = Poisson's ratio of the covering layer

The critical internal pressure (P_{cr}) which leads to the rupture of the adhesive bonding and causes the size of the blister to increase is given below:

$$P_{cr} = \sqrt{\frac{512\, E h^3 \gamma_a}{3(1-\nu^2)}} \quad \frac{1}{(2a_o)^2} \tag{4}$$

$$= K_1/(2a_o)^2$$

where: γ_a = adhesive fracture energy, in-lb/in^2

If the covering layer is a membrane, that is, the thickness is vanishingly small in comparison with the diameter of the void, the corresponding solution is

$$P_{cr} = \frac{k}{a} \sqrt[4]{\frac{h E \gamma_a^3}{(1-\nu^2)^2}} \tag{5}$$

In deriving these equations it was assumed that the adhesive layer was infinitesmally thin and thus the adhesive fracture energy in (4) and (5) was assumed to be the adhesive bond energy between the overlayer and the subsurface. The effect of a finite thickness of an adhesive layer will be discussed later in this section.

In the following, the effects of the various parameters in (2), (3) and (4) on the blistering will be discussed.

Effect of Void Size on Deformation. Equation (2) implies that when the pressure in the void is below the critical pressure, the height of the blister (the maximum deformation) is proportional to the 4th power of the void size, doubling the initial void size will increase the height of the blister by 16 times.

Effect of Layer Thickness on Deformation. The effect of the thickness of the overlayer is given in (3) where the height of the blister is inversely proportional to h^3 of the overlayer thickness. For example, doubling the layer thickness will reduce the height to 1/8.

Effect of Layer Stiffness on Deformation. Equations (2) and (3) show that the maximum deformation of a blister is inversely proportional to the stiffness, expressed by E, of the overlay material. Unlike most of the other construction materials, the stiffness of an asphalt concrete exhibits time and temperature dependence. Due to creep and stress relaxational behavior at long duration of loading and at higher ambient temperature, the stiffness or modulus can be decreased by several orders of magnitude, which could result in continuous "growth" of the blister under a sustained internal pressure and at high ambient temperature. The effect of time and temperature on the modulus of asphalt concrete will be discussed in Section 3.3.

Factors Affecting the Critical Pressure. Equation (4) shows that the critical pressure to cause the adhesive bond to fracture is inversely proportional to the square of the diameter of the void; a small void requires higher pressure to rupture the adhesive bond and thus is less likely to grow into a large blister than a large void would. This also seems to imply that once the pressure developed in the void is sufficiently high to rupture the adhesive bond and cause the unbonded area to be enlarged, the process of adhesive bond rupture will continue and the size of blister will continue to grow even if the pressure developed in the void decreases, so long as the pressure in the blister is greater than the critical pressure given in (4) which decreases rapidly as the diameter of the void increases. This situation is, however, not likely to happen. This will be explained in the following. For a given diameter (2a), the volume (V_a) of a blister can be calculated from (1) as follows:

$$V_a = \int_o^a (1/64)(P/D)(a^2 - r^2)^2 \; 2\pi r dr$$

$$= \frac{\pi a^6}{192} \frac{P}{D} \tag{6}$$

At a constant temperature the product of PxV = constant, resulting in

$$V \; \Delta P + P \, \Delta V = 0$$

or

$$\Delta P = -\frac{P}{V} \; \Delta V \tag{7}$$

In (6), differentiation of the volume with respect to the radius yields

$$\Delta V = \frac{\pi a^5 P}{3 \; 2 \; D} \; \Delta a \tag{8}$$

Inserting (4), (6) and (8) into (7) yields

$$\Delta P = - \frac{3 \; K_1}{2 \; a^3} \; \Delta a \tag{9}$$

Equation (9) implies that as the debonding progress resulting in the radius of the blister increases from a to a+Δa, the pressure in the blister will decrease according to (9). On the other hand, the change of the critical pressure at a+Δa can be calculated by differentiating (4) with respect to the radius (a)

$$\Delta P_{cr} = - \frac{K_1}{2 \; a^3} \; \Delta a \tag{10}$$

Comparison of (9) and (10) indicates that the decrease of the pressure in a blister due to increase in the size is three times greater than the decrease in the critical pressure needed to cause the rupture to continuously propagate. What happens then is that as the adhesive debond occurs along the perimeter of the void, with the radius of the blister increases from a to $a+\Delta a$, the pressure will drop below the critical pressure and debonding will stop. The debonding process may proceed again when the pressure in the blister builds up to the new critical pressure level at the increased size of the blister or until the stiffness of the material E, decreases. These could occur shortly afterward if the temperature in the blister continuously rises. Increase of the temperature can increase the pressure in the blister and lower the stiffness of the overlay material. Even if the ambient temperature and temperature in the blister remain constant, the creep and the stress relaxation behavior of asphalt concrete will cause the stiffness of the overlay material to decrease. Therefore, the increase of the blister size will take a ziz-zag path.

In the above discussions of the process leading toward enlarging the blister, the adhesive fracture energy γ_a is assumed to be constant. This needs not be the case. Temperature and continuous exposure to moisture vapor and cyclic stress due to diurnal change in pressure can contribute to lowering the adhesive bond energy and thus lowering the critical pressure.

Effect of a Finite Adhesive Layer Thickness

Considering a centrally unbonded overlay bonded to a rigid subsurface by an elastic adhesive of different material properties (E', ν') and thickness (h'), see Figure 12. Using the elementary plate theory assuming the adhesive interlayer behaves as a common Winkler foundation of modulus, K, it is possible to estimate the effect of the interlayer on the critical pressure to cause the debonding. According to [19] the following can be obtained.

$$P_{cr} = P_{cr}^{(o)} \left[1 - C \left(\frac{h'}{E'}\right)^{1/4} + \ldots\right] \tag{11}$$

where $P_{cr}^{(o)}$ is the solution given in (4) and C depends on h, a, ν, ν' and E. Equation (11) implies that the critical pressure to cause debonding decreases with either a stiffer interlayer modulus or a reduced interlayer thickness. It should be noted, however, that it is the ratio of h'/E' that is the major controlling parameter, not the modulus or thickness separately. It should be noted also that the overall effect of changing h' and E' are relatively small as their effect to the critical pressure are in 1/4 power.

3.2 Pressure Developed in Blister

In the analysis of adhesive failure presented in Section 3.1 and the literature review presented in Chapter 2, the pressure developed in a blister is one of the most important causes for the blister to grow. The magnitude of the pressure needed to cause the adhesive failure and to cause a blister to grow has often not been substantiated in most of the literature describing the blistering problem. In this section the questions regarding how much presssure can be realistically developed in a blister will be addressed.

It is common knowledge that as the temperature increases, the pressure in a chamber of constant volume will increase. Figure 13 shows the relations between the temperature and the pressure under a constant volume for dry air, for air at 50% relative humidity and at 100% relative humidity. It can be seen from this Figure that at 100% RH, and for temperature rises to 140° F, a 4.5 psia pressure can be generated inside a blister, while for the dry air, the pressure increase will only be 1.5 psi. In [9] analyses were performed to determine if the amount of water required to develop the vapor pressure was reasonable. The results of the analyses showed that from 80°F to 135°F, a vapor pressure increase of 3 to 4 psia in a blister volume of 109 in.^{3} only required 0.1 cm^3 of water, just a small drop of water. It is reasonable that this small amount of water could be presented in a blister. There is another important side of this finding. That is for a fixed volume of a void, say 109 in.^{3} for example, only 0.1 cm^3 of water can be vaporized. Addition of more water at a constant temperature cannot increase the pressure any further because the air is already saturated. Excess water must remain in liquid state. Further growth of the blister requires the entry of additional air into the blister. In Section 3.1, it is pointed out that as the blister growth due to adhesive bond failure, the pressure will drop because of sudden increases in volume. In order to build up the pressure it will require the entry of additional air into the blister. The additional air into the blister will allow the excess water to vaporize to bring the air-vapor back to 100% relative moisture and restore the pressure in the blister.

The following explains the phenomenon of a daily cyclic pumping action, with the daily volume of air inhaled into the blister chamber exceeding the daily volume of exhaled air. Considering the asphalt overlay was placed and that an equivalent state is reached (the internal pressure equal zero) at 80°F. In the morning when the sun warms the asphalt overlay from the top down which decreases the modulus of asphalt concrete of the overlay material and also causes the asphalt cement to expand and seal out some air voids in the asphalt concrete before the air in the blister begins to expand appreciably. If the air in the blister cannot vent as rapidly as the air-vapor expands, a positive pressure is generated. This is occurring when the asphalt overlay is at the softest stage. The positive pressure and low modulus could cause the internal pressure to exceed P_{cr} and therefore can induce adhesive bond failure.

When the temperature drops as the sun goes down or rains, the asphalt overlay cools, again from the top down, and the stiffness of the asphalt overlay increases, resisting the blister to contract. Two phenomena will occur. The blister cannot fully contract to conform to the contraction of air in the blister due to stiffer asphalt concrete at low temperature. This will create a negative pressure in the blister. Secondly, the shrinkage of asphalt concrete upon cooling will open up the pores in the material. These two phenomena together will promote the inhalation of air into the blister. Figure 14 shows the actual measurement of temperatures and the estimated diurnal pressure in a built-up roofing system. The estimated pressure shown in Figure 14C is assuming no mechanical venting, no oxygen absorption and no pressure release by blister formation. The system, under these conditions of constant volume, is under a positive pressure six hours of the 24-hour cycle and under a partial vacuum for 18 hours.

The diurnal pressure change shown in Figure 14 is equally applicable to the blister in an asphalt pavement overlay system. This imbalance of greater inhalation of air into the blister at night and less exhalation of air from the blister during the day augmented by a decreased stiffness of asphalt overlay during the day and an increased stiffness at night will contribute to the growth of blister as shown in Figure 4 and Figure 8.

3.3 Effects of Material Properties

The material properties which have the direct effects on the growth of a blister are stiffness and adhesive bond energy. In the following, various factors that can affect these properties will be discussed.

Thermorheological Behavior of Asphalt Concrete

In equations (3), (4) and (5) the stiffness of the overlay material is represented by E. This implies that the overlay material is assumed to be a linear elastic material. Asphalt concrete is known to exhibit time and temperature dependency and is not an elastic material. Materials exhibiting the dependency of time and temperaature are called "thermorheological" or "thermoviscoelastic" or just "viscoelastic" materials. For such materials the stress and strain are related by such terms as "stiffness S(t,T)", or "stress relaxation modulus E(t,T)" or "creep compliance C(t,T) under quasi-static loading conditions and resilient modulus M_r under repeated loading. All of these are functions of time (t) and temperature (T), instead of just a constant such as an elastic modulus for an elastic material. The definition of the material characterization techniques and the interrelations among these material functions are treated as the general subject of viscoelastic theory by Lai [22] and in specific for asphalt by Finn [23].

Van der Poel [24,25] suggested the term stiffness as a single parameter relating the stress to strain

$$\sigma = S(t,T)\,\varepsilon \tag{12}$$

or

$$S(t,T) = \sigma/\varepsilon \tag{12a}$$

in which S = stiffness, σ and ε are stress and strain and t and T are time and temperature, respectively. He further expressed the stiffness of asphalt concrete S_{mix} to the stiffness of bituminous S_{bit} and the volume fraction of aggregate C_v as follows

$$S_{mix} = S_{bit} \left(1 + \frac{2.5}{n} + \frac{C_v}{1-C_v}\right)^n \qquad (13)$$

in which $n = 0.83 \log (4x10^5/S_{bit})$. In this equation, the time and temperature effects of the stiffness of an asphalt concrete is related to the time and temperature effects of the bituminous binder.

The relaxation modulus can be determined from stress relaxation tests where a constant strain is applied and the resulting stress is measured as a function of time. From these results the relaxation modulus can be determined

$$E(t) = \frac{\sigma (t)}{\varepsilon_o} \qquad (14)$$

Figure 15 represents a typical relaxation modulus expressed as the function of temperature and duration. From this figure it can be seen that as the temperature changes from 40^oF to 77^oF, the relaxation modulus can decrease by more than 10 times. Also, as the duration of the loading increased from 10 seconds (log t = +1) to 10,000 seconds (log t = +4) the modulus decreased from 20,000 psi to 1000 psi. Figures 16 and 17 show the effect of temperature on the modulus and Poisson's ratio of an asphalt concrete.

<u>Adhesive Fracture Energy</u>

In determining the critical pressure which can cause the adhesive bond to failure and cause the blister to grow, one of the important material properties is the adhesive fracture energy, γ_a. Unfortunately there is a lack of information in the literature of this fundamental material property. Perhaps this should not come as a surprise because the blistering problem has not been treated in the past by this fundamental approach.

The use of fracture mechanics and the stress-intensity factor to predict fracture and fatigue cracking of metals has been a common practice.

In the 1970's, FHWA initiated a research program to investigate the feasibility of applying the fracture mechanics concept to predict the fatigue cracking of asphalt concrete [27]. Since then, very little research has been done in this area.

Even though the adhesive energy cannot be ascertained due to lack of data, it is important to point out that the critical pressure to fracture is inversely proportional to the square root of the adhesive fracture energy. A substantial increase of this property can reduce the blistering potential on asphalt overlay. Adhesive fracture energy of different types of asphalt binders used as tack coat and the influence of temperature and moisture on the adhesive fracture energy of these tack coat materials are extremely important to assess the blistering potential of the asphalt overlay system. It is not unreasonable to assume that the adhesive fracture energy of emulsified asphalt could be different from that of the asphalt cement.

Effect of Stripping

In the observation of blistering of asphalt overlays, it was often mentioned that moisture was visible in the blister. The effect of air-vapor pressure on the growth of the blister also pointed to the existance of moisture in the blister. In fact, among several of the field samples cored from the blistered areas, the asphalt concrete overlays and/or the subsurface had exhibited varying degrees of stripping.

Stripping of asphalt from the aggregate will, undoubtedly, contribute to the blistering problem in several ways. (1) Stripping will soften the modulus (or stiffness) of asphalt concrete overlay; (2) it will weaken the bond between the tack coat and the overlay and/or subsurface, and (3) blistering will cause the redistribution of the asphalt cement and create an impermeable layer which prevents the air in the blister from venting at high temperature.

3.4 Estimation of Growth of Blisters - A Parametric Study

Based on the analyses presented in this chapter, the critical pressure to cause the blister to grow can be estimated for different overlay systems and under different temperatures. Results from this parametric study could provide valuable information about the conditions whereby blisters can realistically be developed in asphalt overlay systems. All the variables in (4), except the adhesive fracture energy, can be estimated with reasonable confidence. There is unfortunately no data available in the literature for the adhesive fracture energy. In reference [28] the surface energy between asphalt film with certain types of aggregate was reported. This reported value of 25 ergs/cm^2 seems reasonable and will be used as the adhesive fracture energy in the following parametric study.

The following values are assigned for the variables encountered in (4) for the parametric analyses:

Thickness of overlay, h(in.) = 1, 1.5, 2				
Adhesive fracture energy, γ_a = 25 ergs/cm^2 = 0.14 in-lb/in^2				
Initial unbonded diameter 2a(in.) = 2, 4, 8, 12				
Temperature, T(^{o}F) =	80,	100,	120,	140
Poisson's Ratio, ν (see Fig. 17) =	0.42,	0.46,	0.48,	0.49
Modulus E (psi, see Fig. 16) =	3×10^5,	7×10^4,	2×10^4,	8×10^3

Results of the critical pressure determined from (4) are presented in Table 1. When these estimated critical pressures are compared with the air-vapor pressure vs. temperature shown in Figure 13, it is obvious that air-vapor pressures generated in the voids can exceed the critical pressure for even rather small initial unbond voids. The results also indicate that even with no moisture presence in the voids, blisters can still grow under certain conditions. These results therefore support the observations reported in [6].

CHAPTER 4

SUMMARY AND CONCLUSIONS

The objectives of this research project are to identify causes and mechanisms which may contribute to the formation of blisters on asphalt concrete overlays through information gathering and synthesizing.

In all the literature reviewed concerning blistering on asphalt overlays, the major cause often cited was the thermal expansion of entrapped gas and water beneath the unbonded areas between the thin asphalt overlay and the subsurface. Upon heating, the trapped gas in the unbonded areas expands and generates high pressure which causes the asphalt concrete to deform and form blisters. Furthermore, if the internal pressure developed is exceeding certain threshold value, bonding between the overlay and the subsurface could be ruptured and the blister will grow in size.

An analytical blister model based on the fracture mechanics concept was developed. The model considered a thin layer of viscoelastic material bonded to the subsurface, except for a circular area centered about an axis of symmetry and was subjected to an internal pressure. The analytical solutions of the deformed profile and the critical pressure for the onset of adhesive bond failure were obtained.

The solution of the critical pressure for the onset of adhesive bond failure and thus allowing the blister to grow depends on several parameters; the diameter of the initial unbonded area, the thickness of the overlay, the stiffness of the overlay, and the "adhesive fracture energy" of the interlayer. The critical pressure is inversely proportional to the square of the diameter of the unbonded area, therefore a small initial void requires higher presssure and is less likely for the void to grow into a blister than a large initial void. Thinner and less stiffer overlay will require lower critical pressure to rupture the adhesive bond. The magnitude of adhesive fracture energy is also a very important parameter on the development of blistering.

Parametric analyses of the analytical solution indicate that the critical pressure required to cause the voids to grow into large blisters can be exceeded by the pressure developed in the voids due to the expansion of the trapped air and water or air alone at high ambient temperatures.

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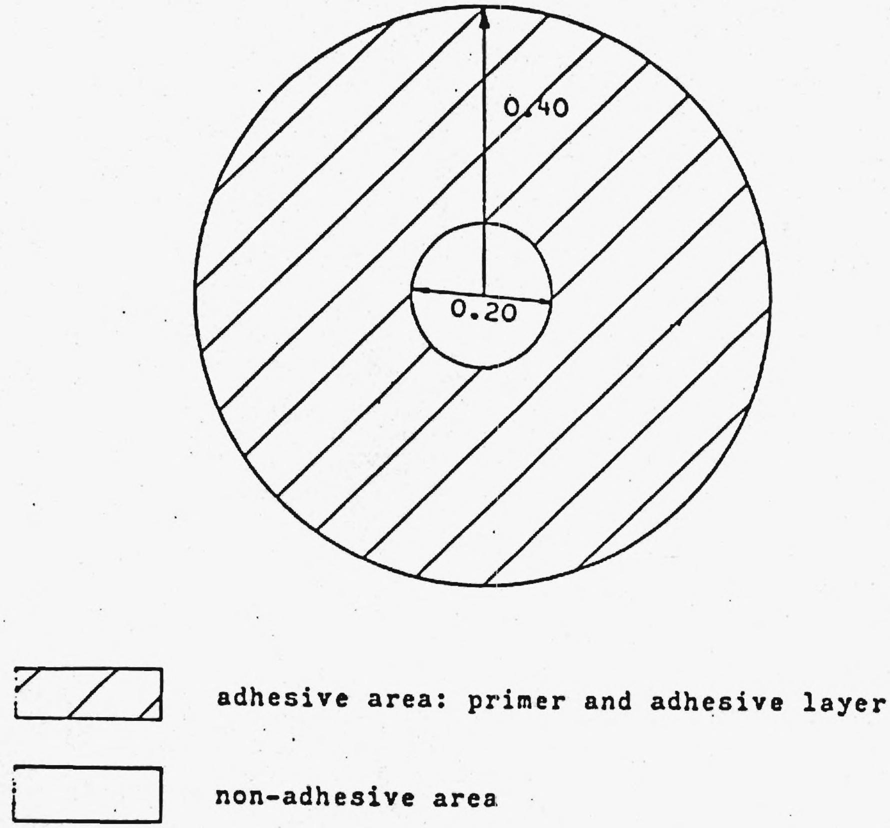
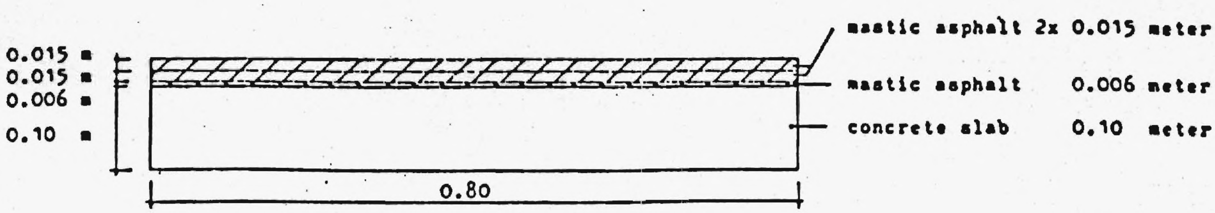
TABLE 1. CRITICAL PRESSURE TO INDUCE ADHESIVE FRACTURE

Overlay Thickness	Diameter of Void 2a (in.)	Temperature (^oF) 80	100	120	140
h=1 (in.)	2	23.65	11.58	6.23	3.97
	4	5.91	2.90	1.56	0.99
	8	1.48	0.72	0.39	0.25
	12	0.66	0.32	0.17	0.11
h=1.5 (in.)	2	43.45	21.27	11.45	7.29
	4	10.86	5.32	2.86	1.82
	8	2.72	1.33	0.72	0.46
	12	1.21	0.59	0.31	0.20
h=2.0 (in.)	2	66.89	32.75	17.62	11.23
	4	16.72	8.19	4.41	2.81
	8	4.81	2.05	1.10	0.70
	12	1.87	0.91	0.48	0.31



The Adhesive and Non-Adhesive Area of the Slab.



Cross-Section of the Tested Slab.

Figure 1. Geometry of the Test Slab [7].

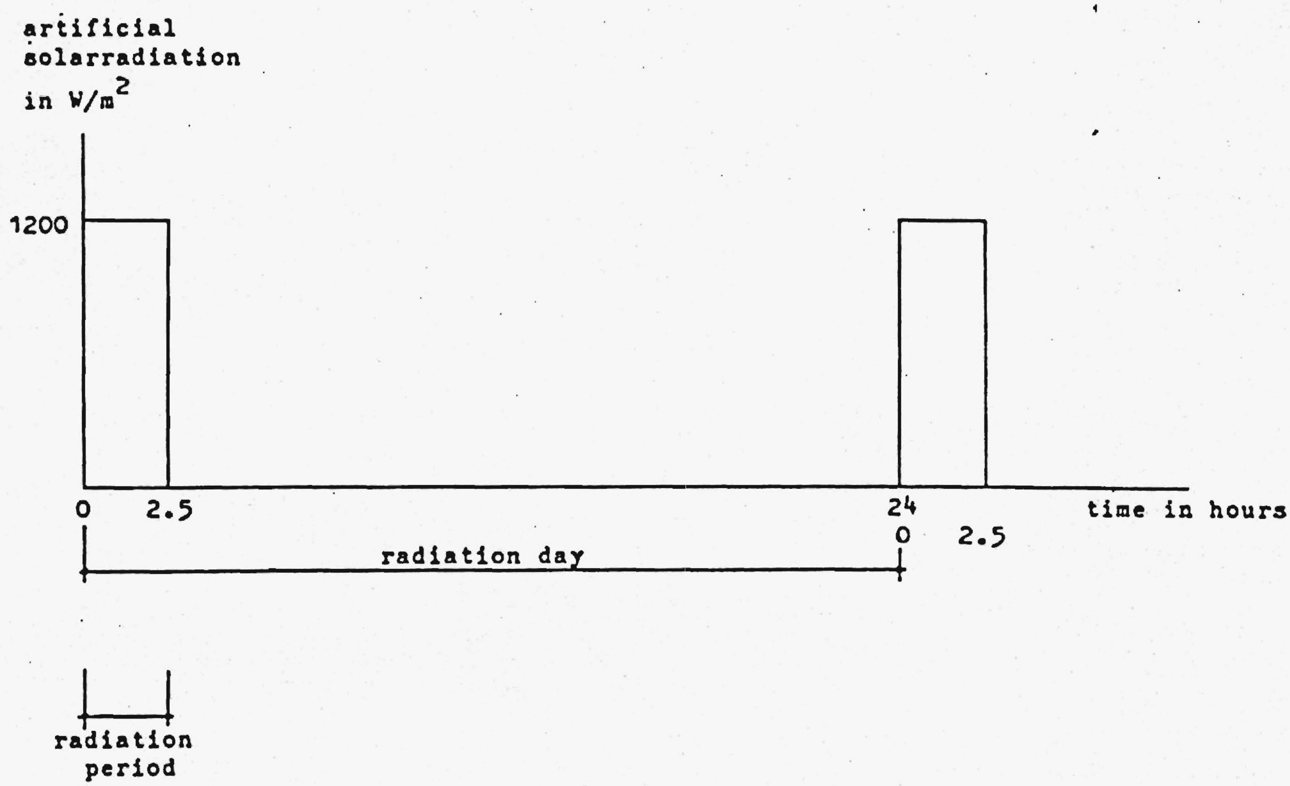


Figure 2. Quality and Duration of the Radiation [7].

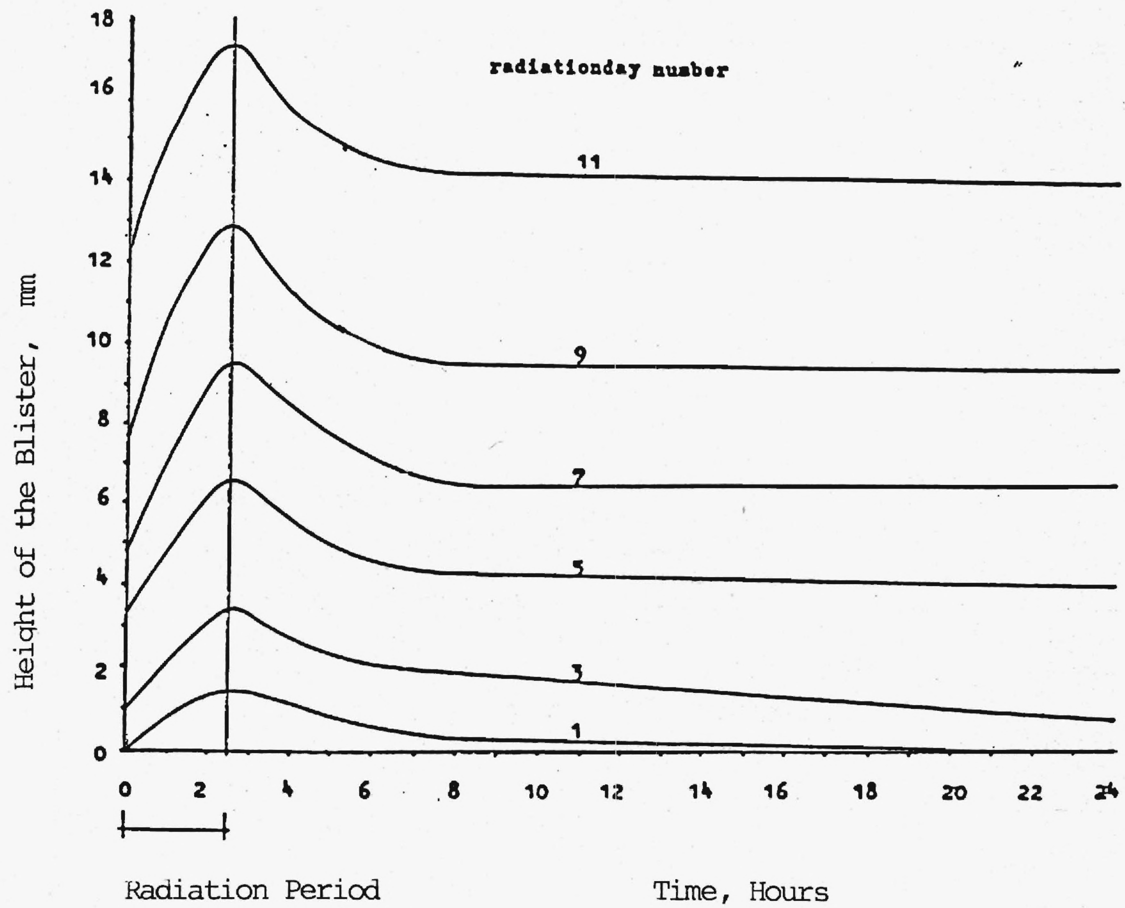
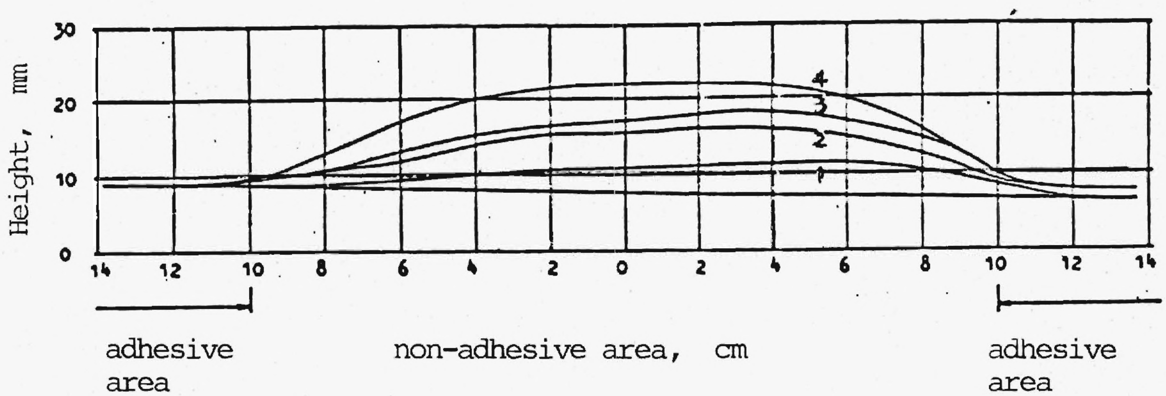


Figure 3. The Height of the Middle of the Blister [7].



1. after 4 days of radiation
2. after 6 days of radiation
3. after 9 days of radiation
4. after 11 days of radiation

Figure 4. Measured Cross-Sections During the Formation of a Blister [7].

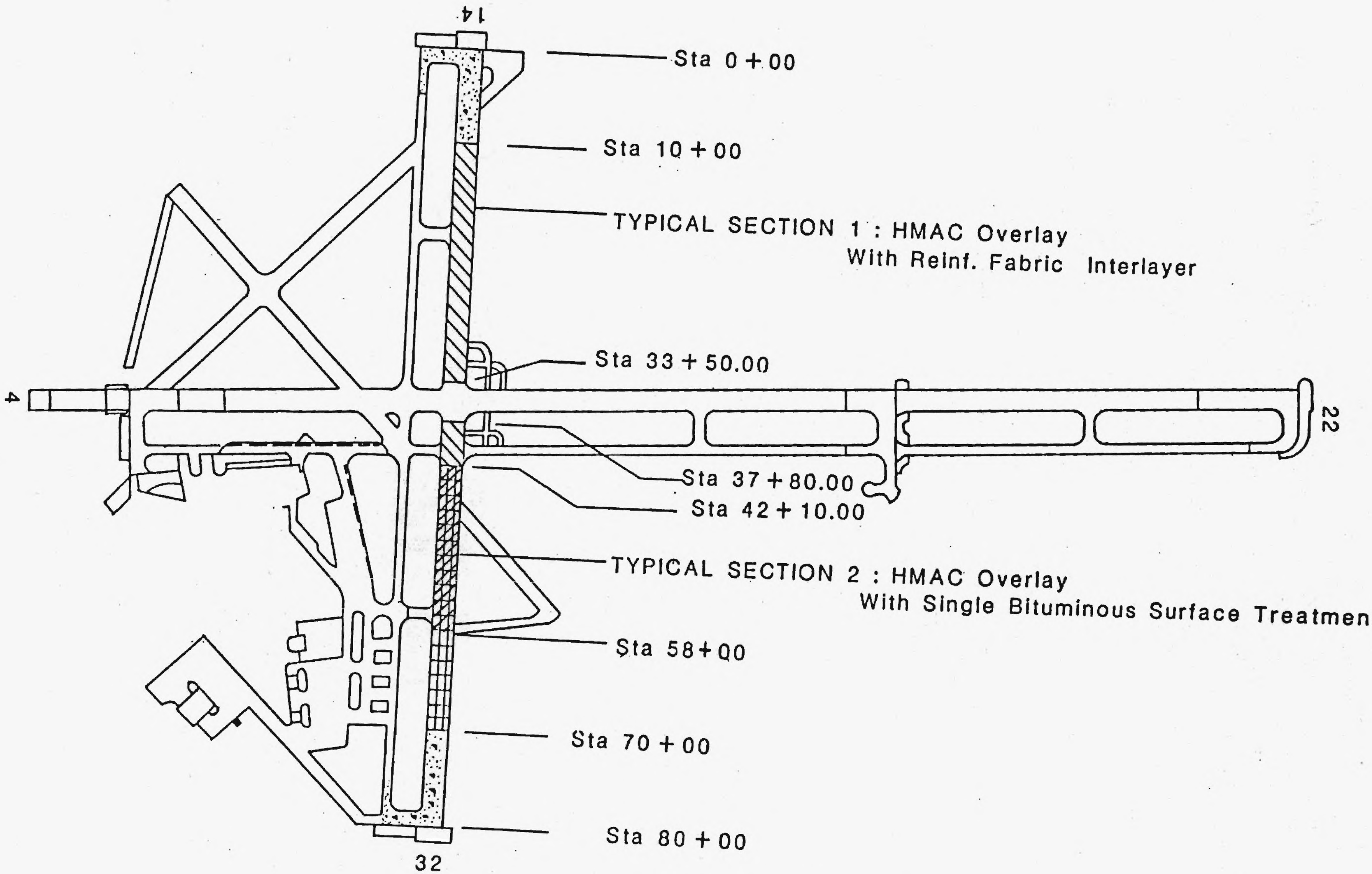


Figure 5. Project Airfield Layout [8].
Marine Corps Air Station
Bauford, S. C.

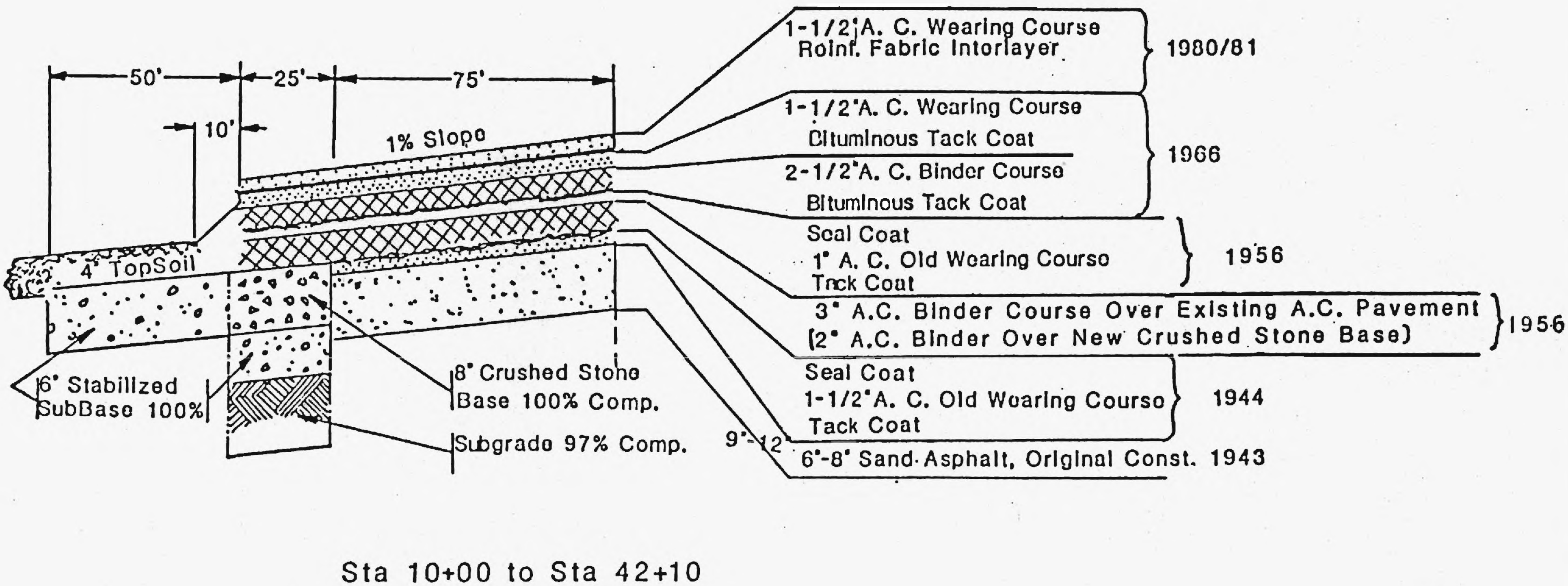
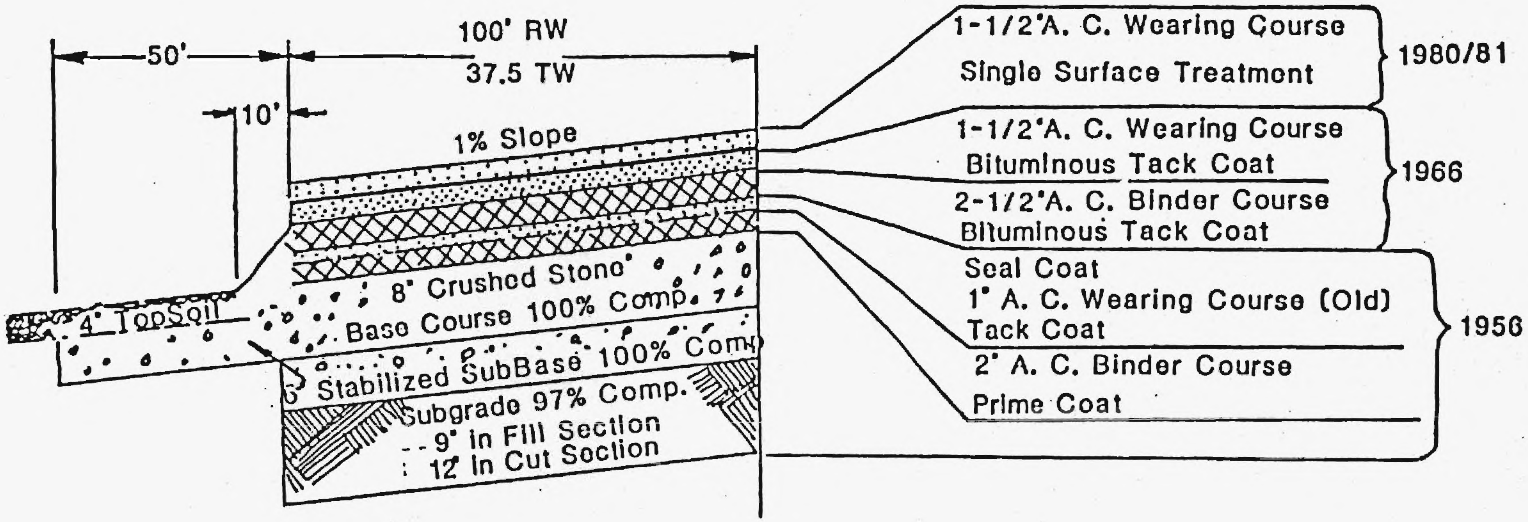


Figure 6a. Typical Airfield Pavement Section [8].
Section 1 & 2



Typ. from Sta. 58-00.0± to Sta. 70-00.0±

Figure 6b. Typical Airfield Pavement Section [8].

Typical Section 3

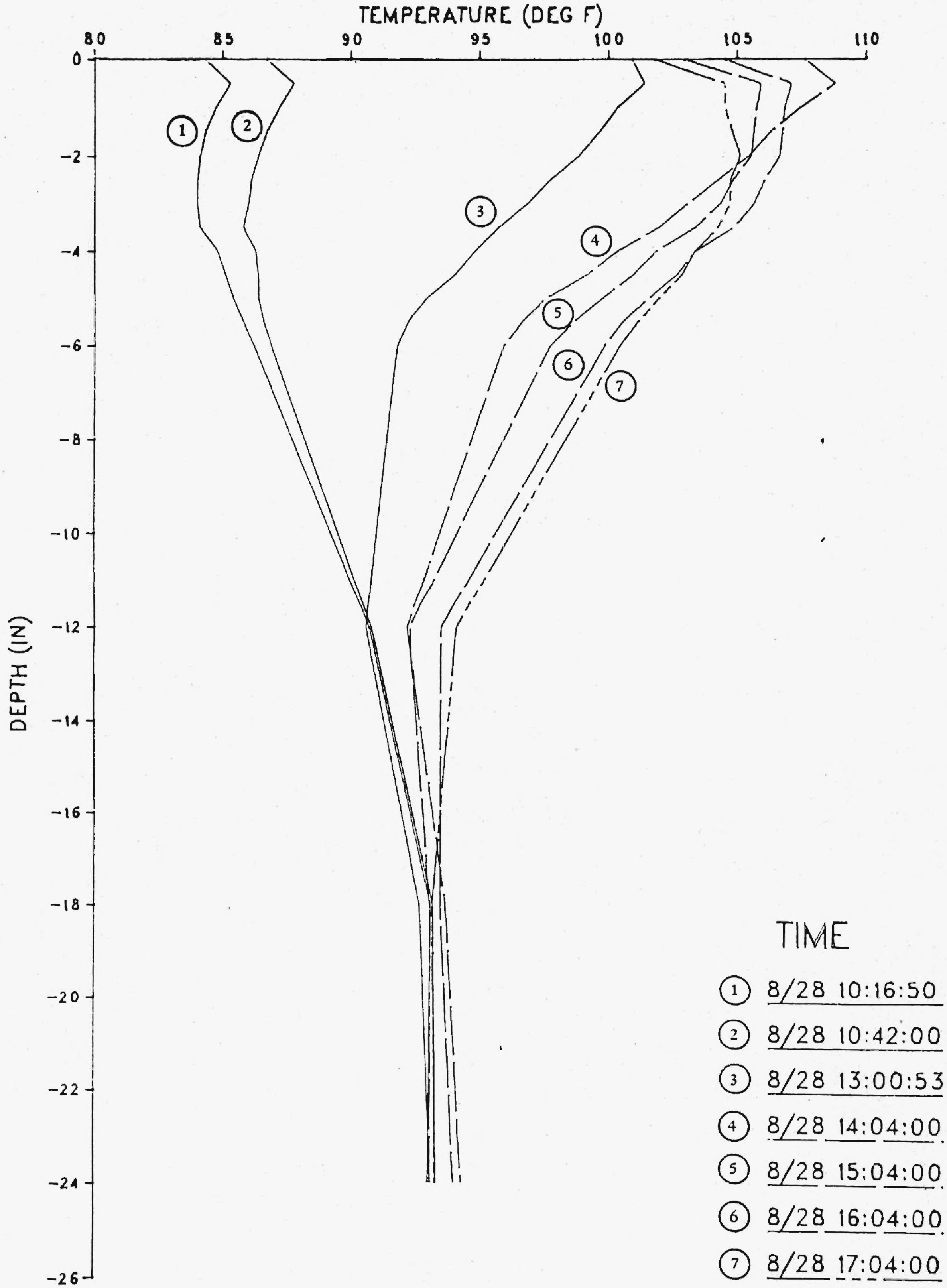
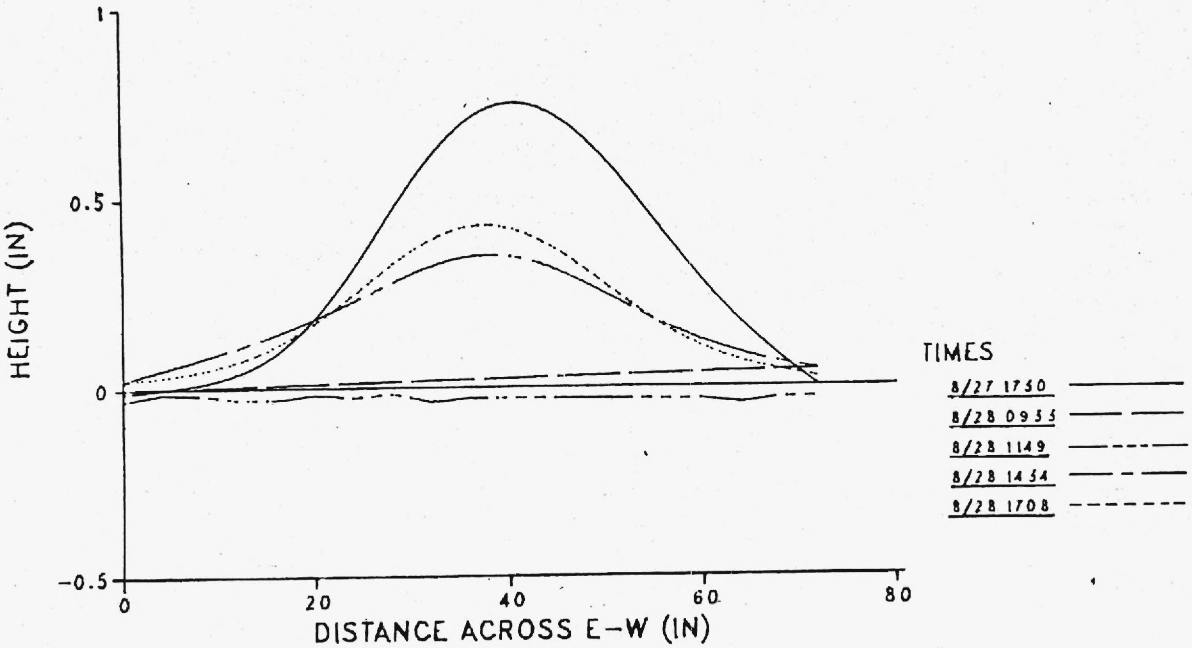
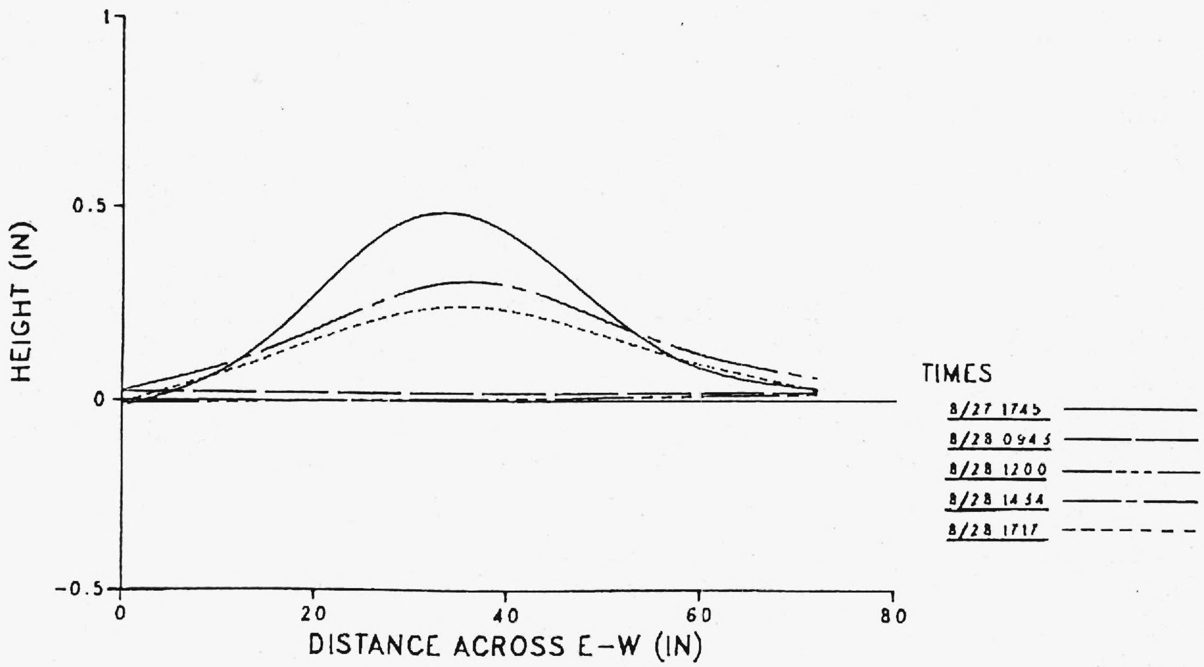


Figure 7. Temperature Profiles at Site 1 near Blister 1 and 2 [9].



(b) East-West profile

Profile changes of blister 1.



(b) East-West profile

Profile changes of blister 2.

Figure 8. Profile Change of Blisters [9].

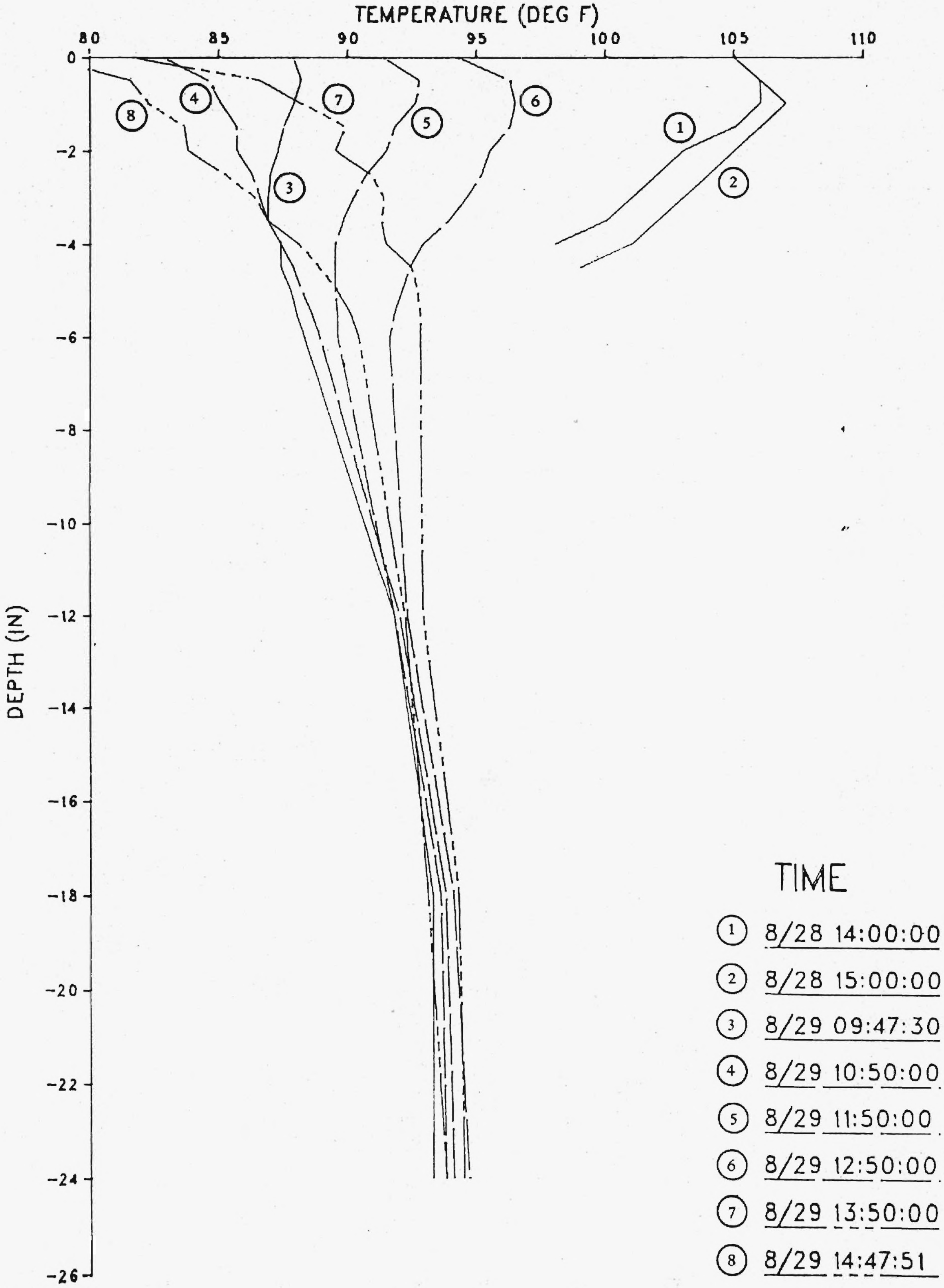
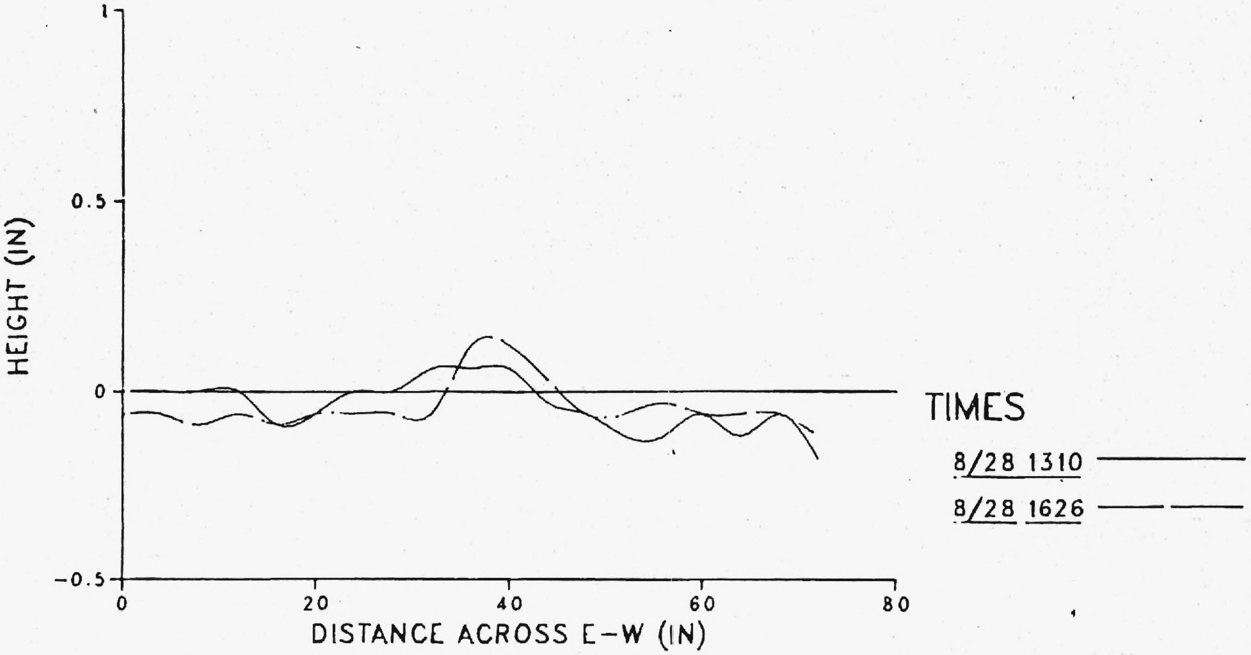
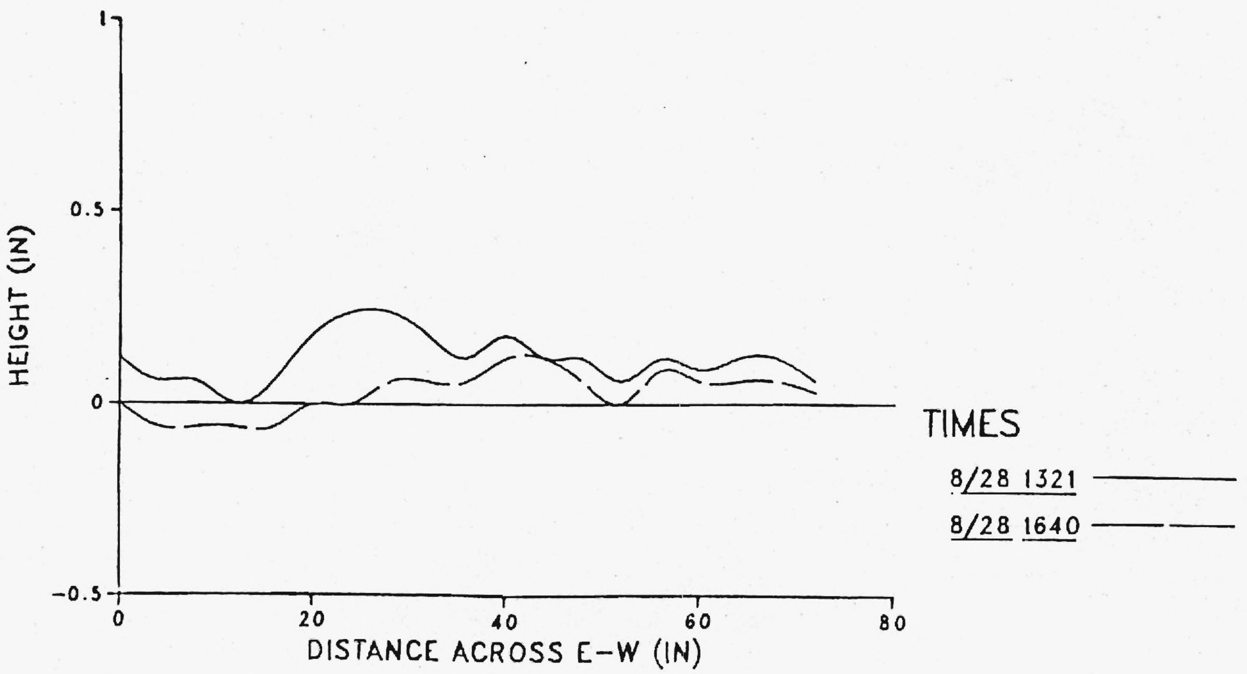


Figure 9. Temperature Profiles at Site 2 near Blisters 3 and 4 [9]



(b) East-West profile

Profile changes of blister 3.



(b) East-West profile

Profile changes of blister 4.

Figure 10. Profiles of Blisters [9]

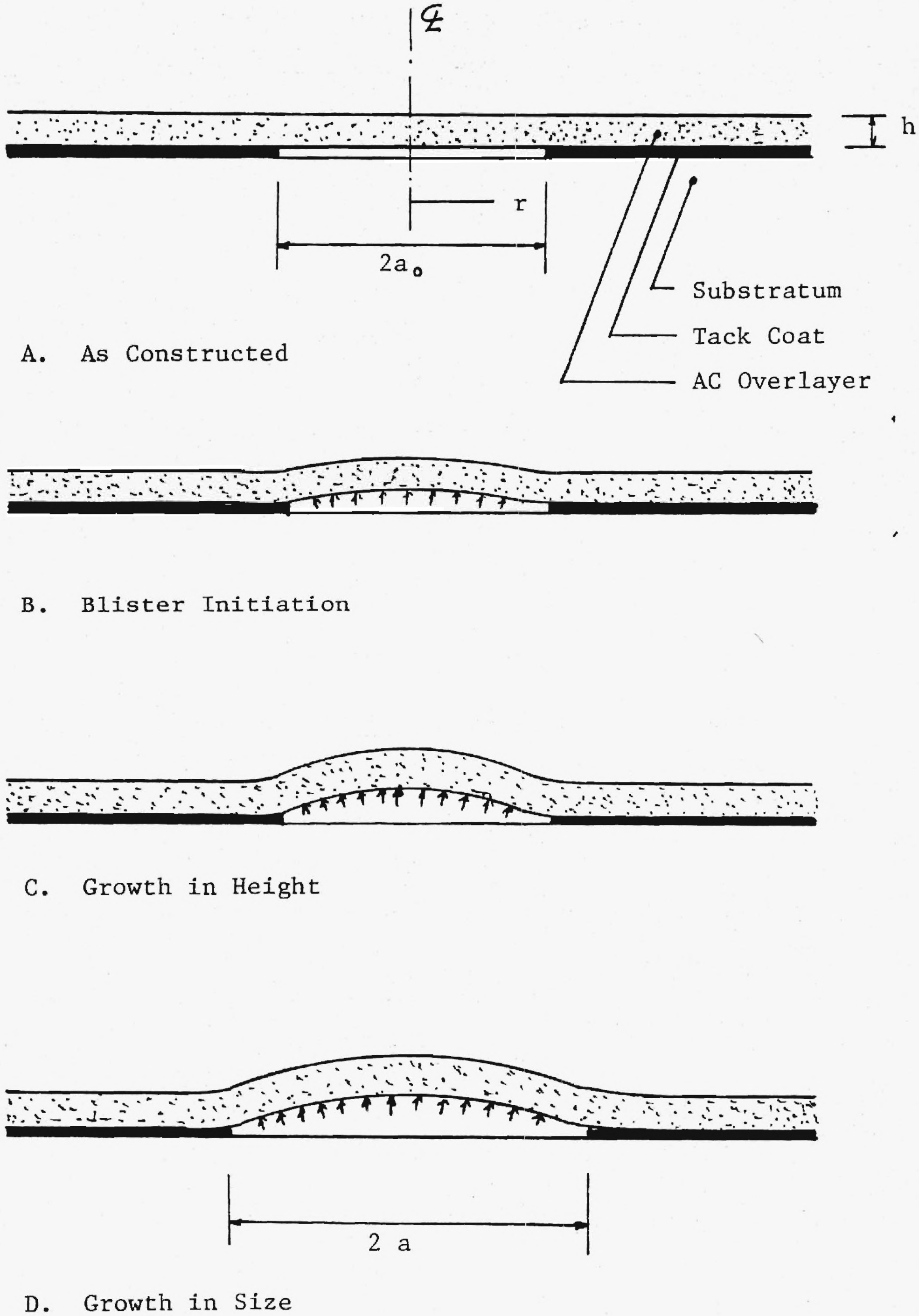


Figure 11. Initiation and Grow of A Blister

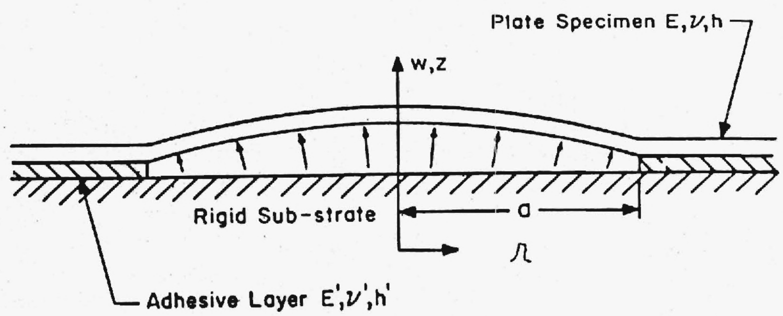


Figure 12. Blister Specimen with Finite Thickness Adhesive Interlayer

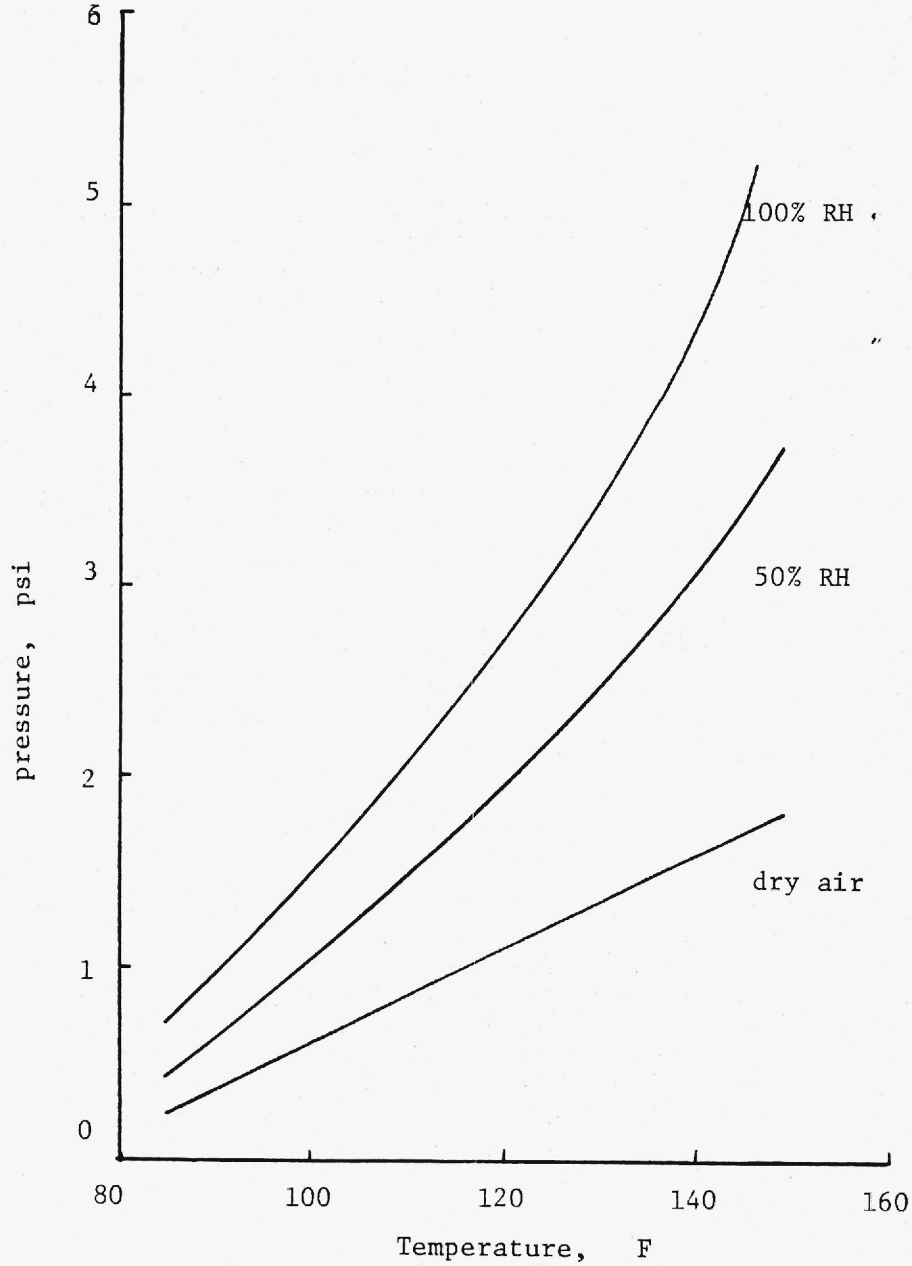
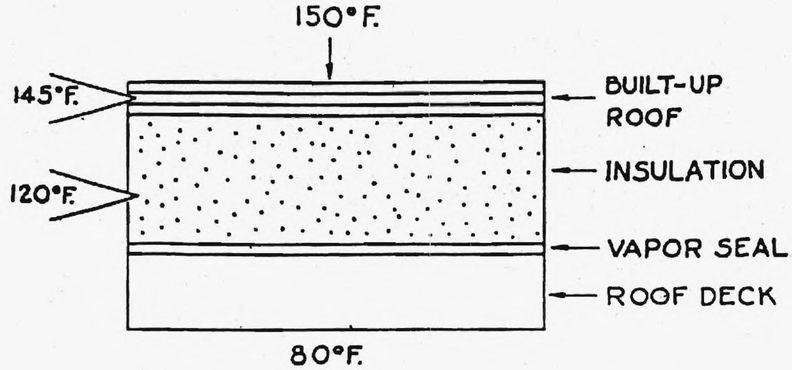
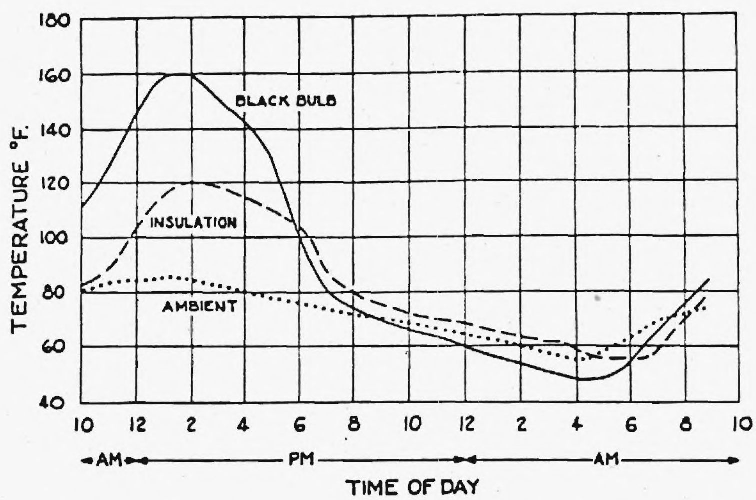


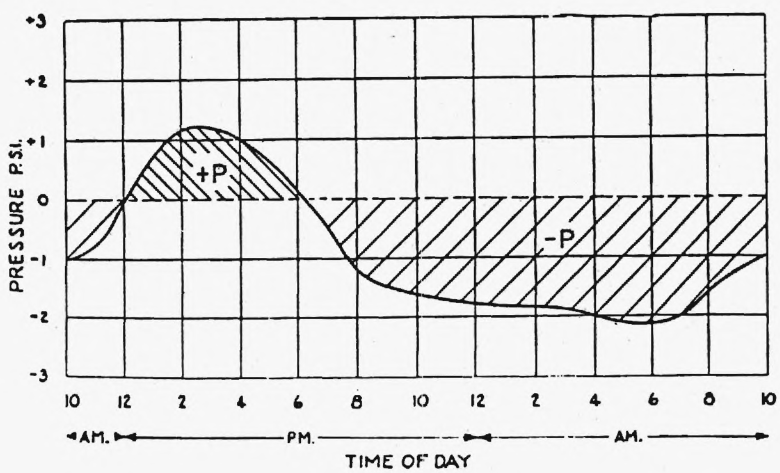
Figure 13. Vaper pressure VS Temperature



A. Temperatures within an Insulated Roof Exposed to Solar Radiation.



B. Built-Up Roof Temperatures for an Average Day in October.



C. Built-Up Roof Pressures for an Average Day in October.

Figure 14 Temperature and Pressure in Built-Up Roof for an Average Day

(Discussion of [7] by W. B. Warden)

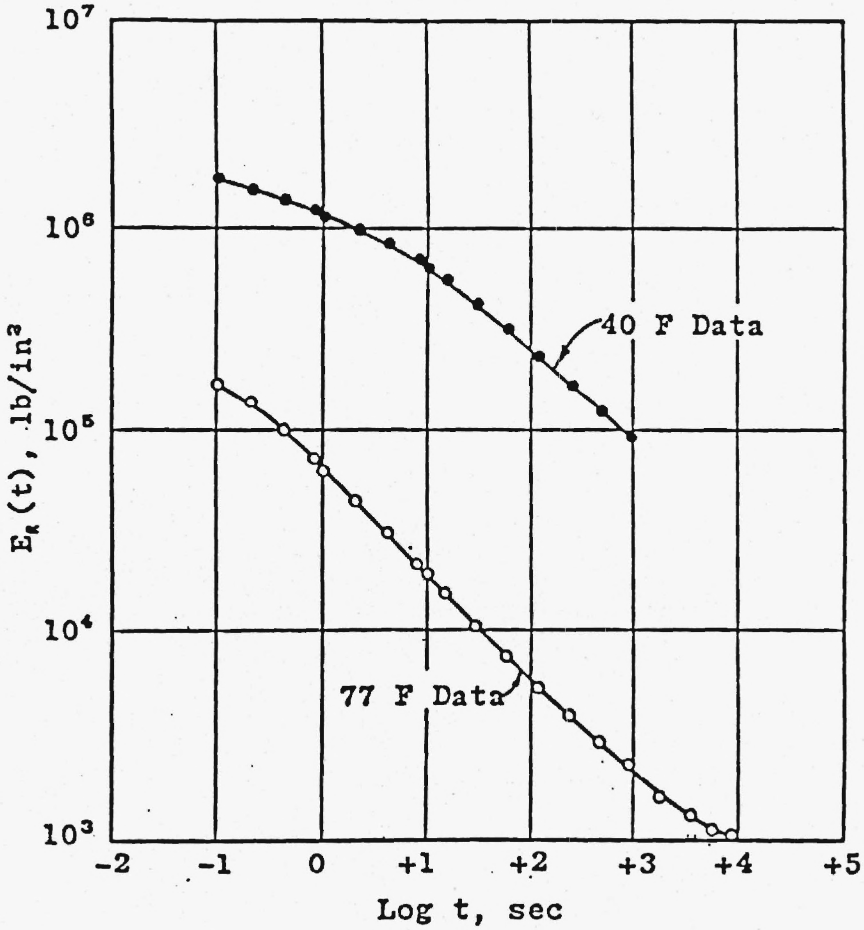


Figure 15 Relaxation Modulus at 40 F and 77 F vs Time [23].

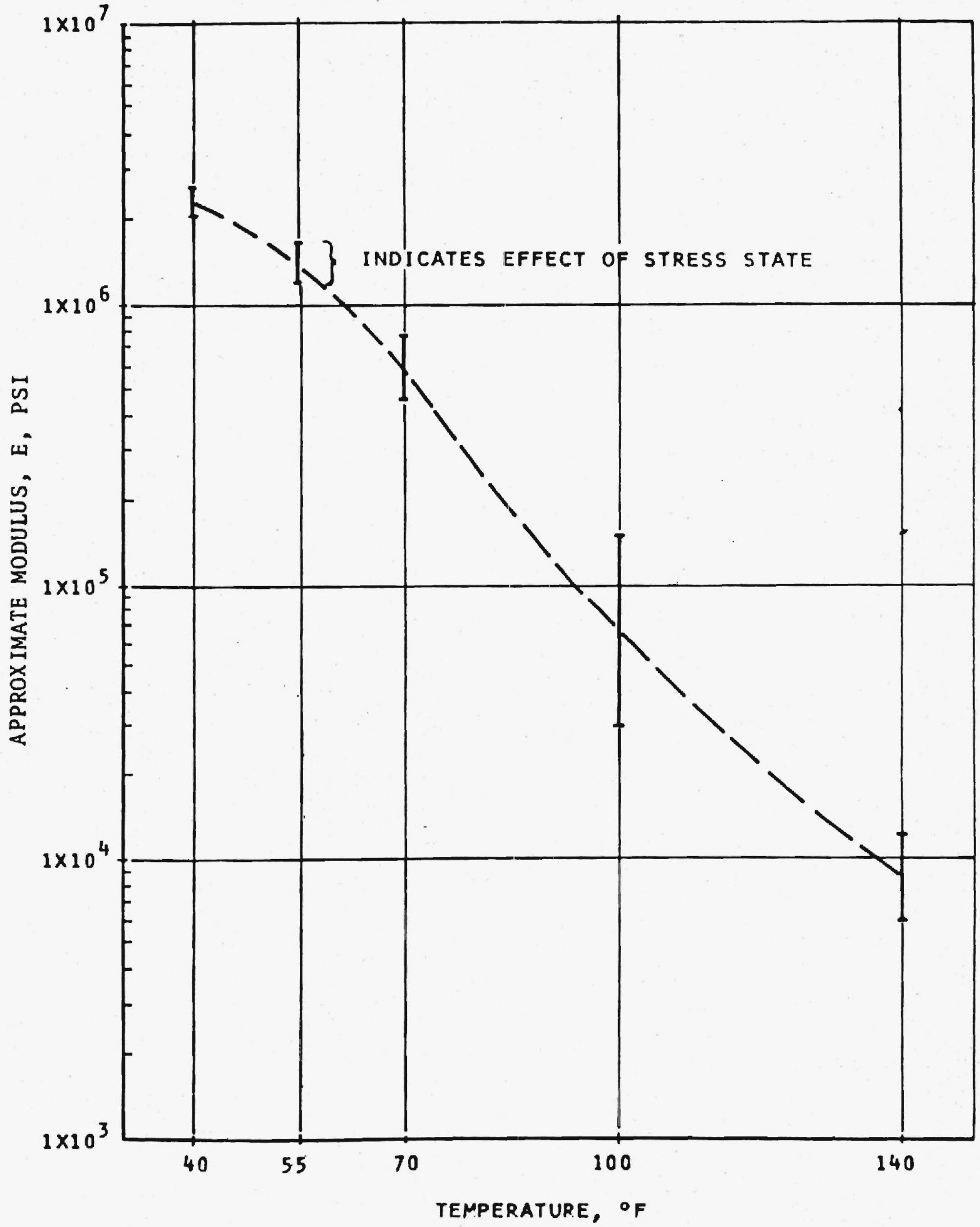


Figure 16. Variation of Approximate Modulus With Temperature for an Asphalt Concrete. [25]

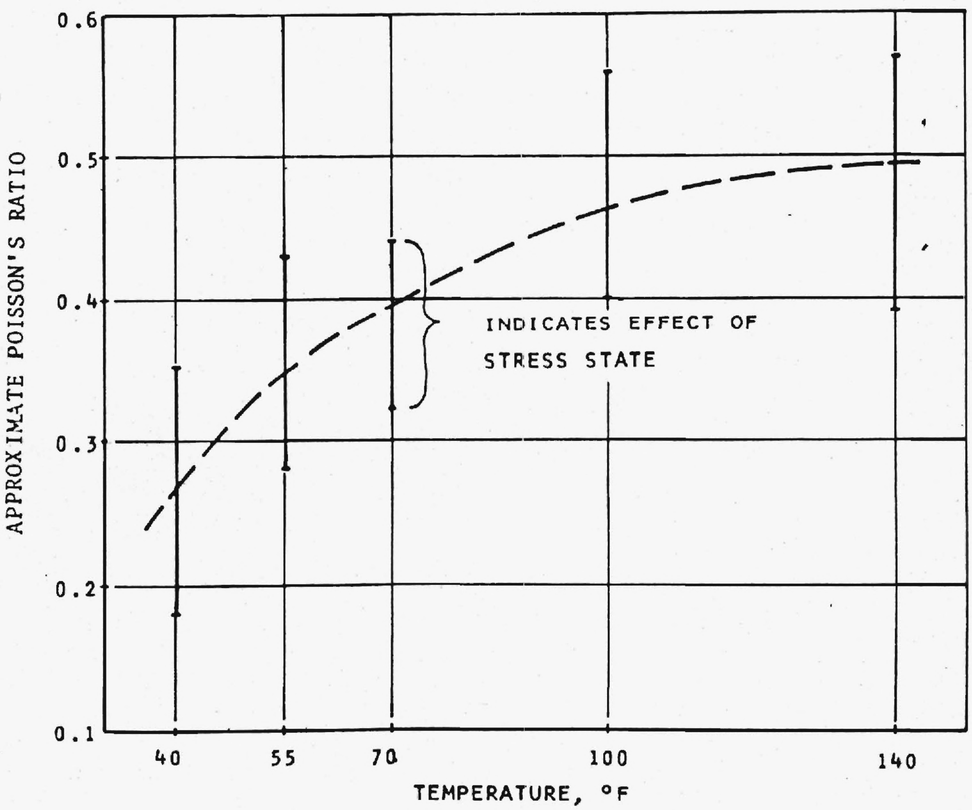


Figure 17. Variation of Approximate Poisson's Ratio With Temperature for an Asphalt Concrete [25]