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QUARTERMASTER RESEARCH & ENGINEERING COMMAND
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TECHNICAL REPORT
EP-121

OCCURRENCE OF HIGH TEMPERATURES IN YUMA STORAGE DUMPS

QUARTERMASTER RESEARCH & ENGINEERING CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

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QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
Quartermaster Research & Engineering Center
Natick, Massachusetts

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Technical Report
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OCCURRENCE OF HIGH TEMPERATURES IN YUMA STORAGE DUMPS

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Foreword

In the design of military items and in estimates of their durability, it is important to determine the most extreme high-temperature stress to which they will be exposed in storage or transit. The standing boxcar and the tightly-covered storage dump, box, or tent are recognized as such extreme situations. In a program of storage-severity investigations conducted by Quartermaster research personnel, the boxcar and tent have been previously investigated. The research here reported involves temperatures in field storage dumps and the effects produced by varying types of stack exposure or protection. The analysis has been planned to yield storage temperature indices significant for canned food items, but contains data and conclusions relevant to other items in similar field storage.

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CONTENTS

Abstract

Temperatures in ~~four~~ 4 differently protected storage-dump stacks were studied under extreme hot-dry conditions on desert terrain at Yuma, Arizona, during a 43-day period.

Carton air and food temperatures were recorded by thermocouples at critical locations in cartons in stacks exposed in the following four ways:

(1) Open and unprotected;
(2) Protected by a raised paulin fly;
(3) Protected by a tightly-lashed paulin; and
(4) Protected by a raised paulin fly with addition of reflective foil laid on the stack surface.

Each stack was composed of 96 cartons of Army C-rations and approximated a 5-foot cube. Ambient temperature and relative humidity, wind-speed and wind direction, and radiation were recorded 1/2 mile from the site.

~~Results of the study indicate that~~ in both extremes and means of temperature, the tightly-covered paulin stack is a much more severe storage environment than the other three types observed, which differ little among themselves in long-term storage stress. The tight-paulin stack resembles the boxcar; it is one of the most extreme storage environments yet observed. Absolute maximum temperature of food in this stack was 118°F, whereas 107°F was the highest observed in the other stacks.

"Effective" storage temperature in this tight paulin stack for the hottest month (July) was 102°F compared to about 90°F for the other stacks. Comparable temperature in a boxcar was 103°F. "Effective" storage values may be used for constant temperature laboratory simulation of field storage stress.

There was little difference in storage severity among the three stacks having free air circulation (i.e., without a tight covering). In these three stacks, those having greater stack protection showed a reduction in maximum temperatures, range of temperature and duration of higher temperatures, but "effective" storage temperatures were similar.

~~As in the boxcar research,~~ significant coefficients of correlation were obtained between free-air 5-day mean temperatures and top carton food mean temperatures. Prediction of effective food storage temperatures for similar stacks and climatic situations can therefore be made from climatic data.

Mean storage temperature tended to rise with increased airmass moisture, because daily minimum temperatures were raised by back radiation from water vapor and the prevailing thin, high, nocturnal cloudiness. It is possible, therefore, that the greatest long-term storage stress will occur at low latitude stations with high airmass moisture and high mean annual temperature.

OCCURRENCE OF HIGH TEMPERATURES IN YUMA STORAGE DUMPS

PART I. INTRODUCTION

1. Purpose and scope

Temperature regimes at various locations in four types of storage-dump stacks at Yuma, Arizona, were measured during June, July, and August of 1955. The four stacks were identical in size and content, but had different types of shielding from sun and rain.

The purpose of the research was fourfold: (a) To determine temperature means and extremes at the most critical location in each stack; (b) To reduce the daily cycles of temperature at these locations to "effective" temperatures which could be used in simulation of storage stress; (c) To determine correlation of storage-space temperatures with climatic variables; and (d) To determine the comparative effectiveness of 4 types of stack protection.

It had previously been determined (Porter, 1956) that in sterile degradation of canned foods through thermal decomposition (as distinguished from septic micro-organic growth), "effective" storage temperatures* for the period, calculated from maxima and ranges, were adequate for laboratory simulation. Because short periods of temperatures above critical values may sometimes produce permanent changes (as in fats and chocolate), extremes were also measured.

The chief emphasis in research planning and analysis of the results was to determine the temperature regime at the most critical locations. Previous Quartermaster Corps experience indicated that it is useless to take a calculated risk on the assumption that some of the food will not experience the extreme temperature regime of the most critical locations. Nor is it of value to design foods for different geographic areas or lines of supply where less than extreme conditions are met, since it is not feasible to make an areal differentiation in production or supply channels.

However, it is essential that temperature extremes be realistic, i.e., that they represent the actual situation where the can of food is and not the temperature on or immediately below the lower surface of a hot paulin covering (this may be 50F° higher). Thus, temperatures in cartons and in food were sought and analyzed.

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* Derived as shown in Part III and Appendix B.

It was planned to investigate correlation of storage with ambient conditions, in particular mean daily and weekly air temperatures, where this was feasible. The successful extrapolation of derived predictive formulas must, of course, depend on the similarity of conditions to those of the research.

A quantitative evaluation of the effectiveness of various forms of stack protection was also planned to allow comparison of benefits (reduced heat stress) with costs (operational difficulties and hazards).

2. Previous related investigations

Various previous investigations of dump storage temperatures have been carried out by Quartermaster Corps research personnel (Porter 1954). Studies were made at Blythe, California (1943) and in Florida (1944). Questionnaires were distributed to Quartermaster units in all parts of the world (1945). The literature on the subject was reviewed. Authorities in railroad, ship and truck transportation were consulted; warehouse storage authorities were canvassed for their opinions (1952). It was concluded that the tightly covered dump or tent and the standing boxcar or truck were the common situations of the most extreme short-term and cumulative temperature stress on stored goods. Accordingly, research was conducted on standing boxcars during the summer of 1953 (Porter 1956), and on field dumps in the summer of 1955; the latter study is here reported.

3. Research materials and methods

The present research was undertaken because the dump storage test at Blythe in 1943 was considered too short (3 weeks) to establish reliable correlations of storage with ambient conditions, and the Florida tropical storage tests were too extensive to permit detail in food storage measurements. In addition, Florida does not have the extremes of temperature of Arizona (although radiation values are comparable).

a. Storage stacks

Another aim of the research was to ascertain the relative merits of various forms of stack exposure. For this purpose, four stacks of cartons of combat (C) rations were set up, identical in composition, size, and orientation, but exposed or protected in four different ways (Figs. 1-4):

1. Open, unprotected stack (called "open stack" hereafter)
2. Stack protected by a raised paulin ("raised paulin")
3. Stack covered with a paulin lashed tightly to the ground on all sides ("tight paulin")

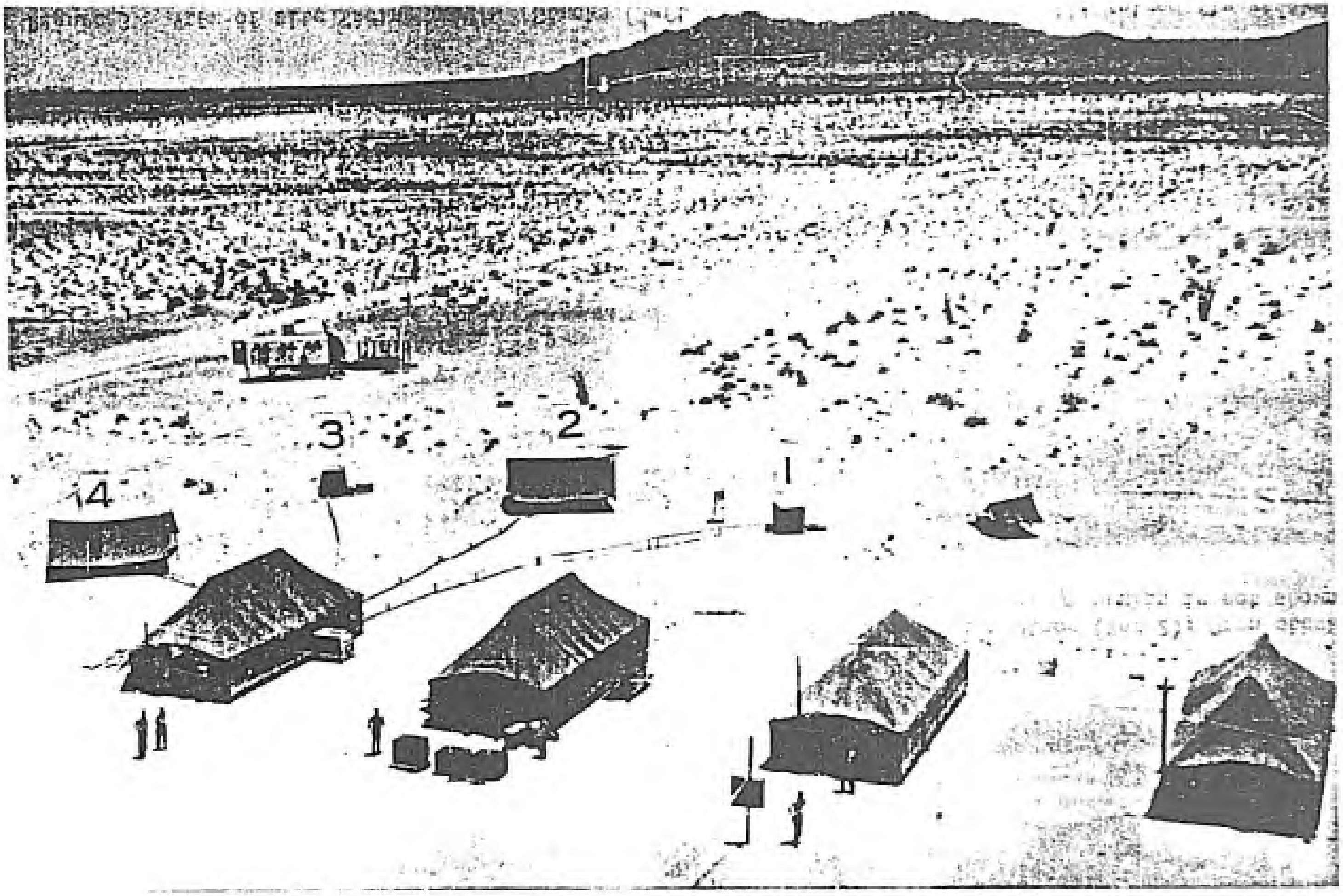

Figure 1. Aerial view of Yuma Dump Storage Research site, facing due east. Recording cables radiate from instrument tent in left center to the four research stacks. The stacks are (left to right): No. 4, Raised fly with foil; No. 3, Tight paulin stack; No. 2, Raised fly stack; No. 1, Open stack. Three dwelling tents are in foreground.

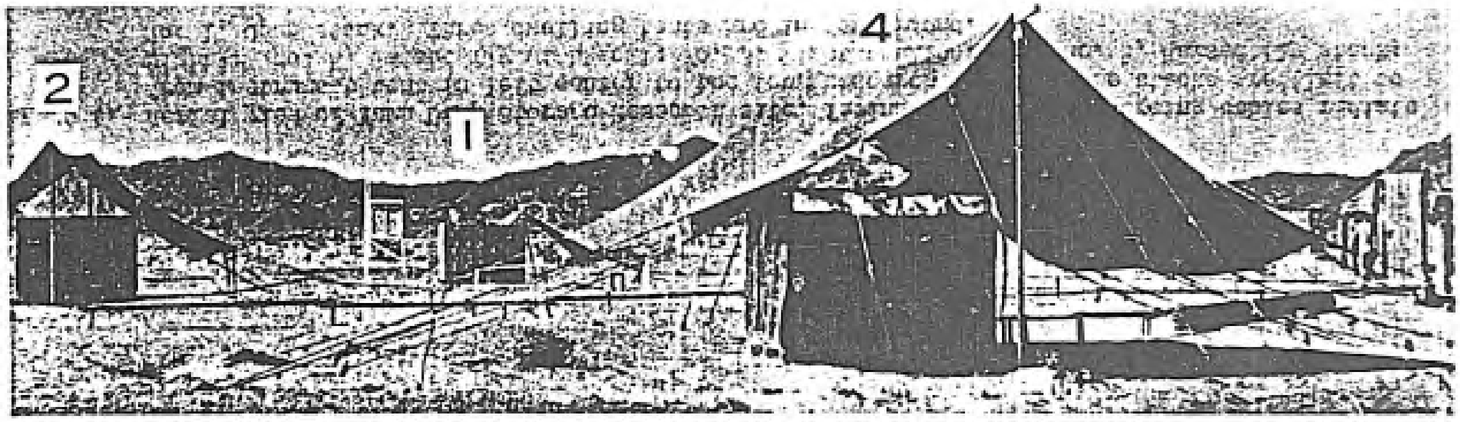

Figure 2. View of site facing south. Stacks (left to right): Raised fly stack (No. 2); Open stack (No. 1); Raised fly stack with foil (No. 4). Stack covered with tight paulin is not shown.

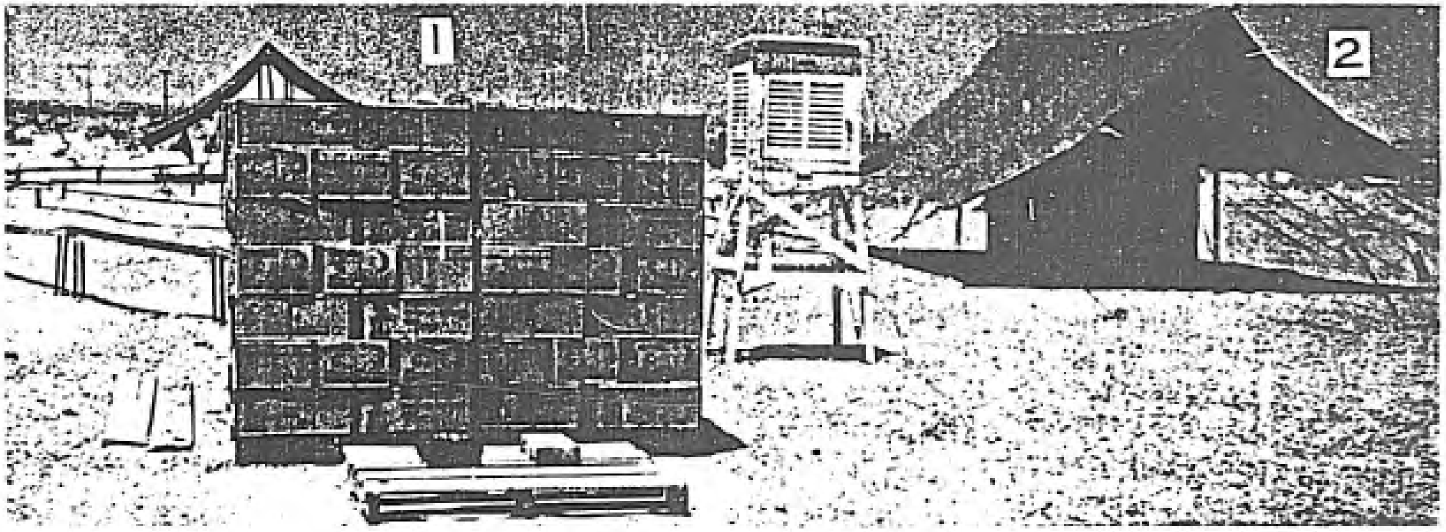

Figure 3. View of site facing north. Stacks (left to right): Open stack (No. 1); Raised fly stack (No. 2). Stack covered with tight paulin is not visible.

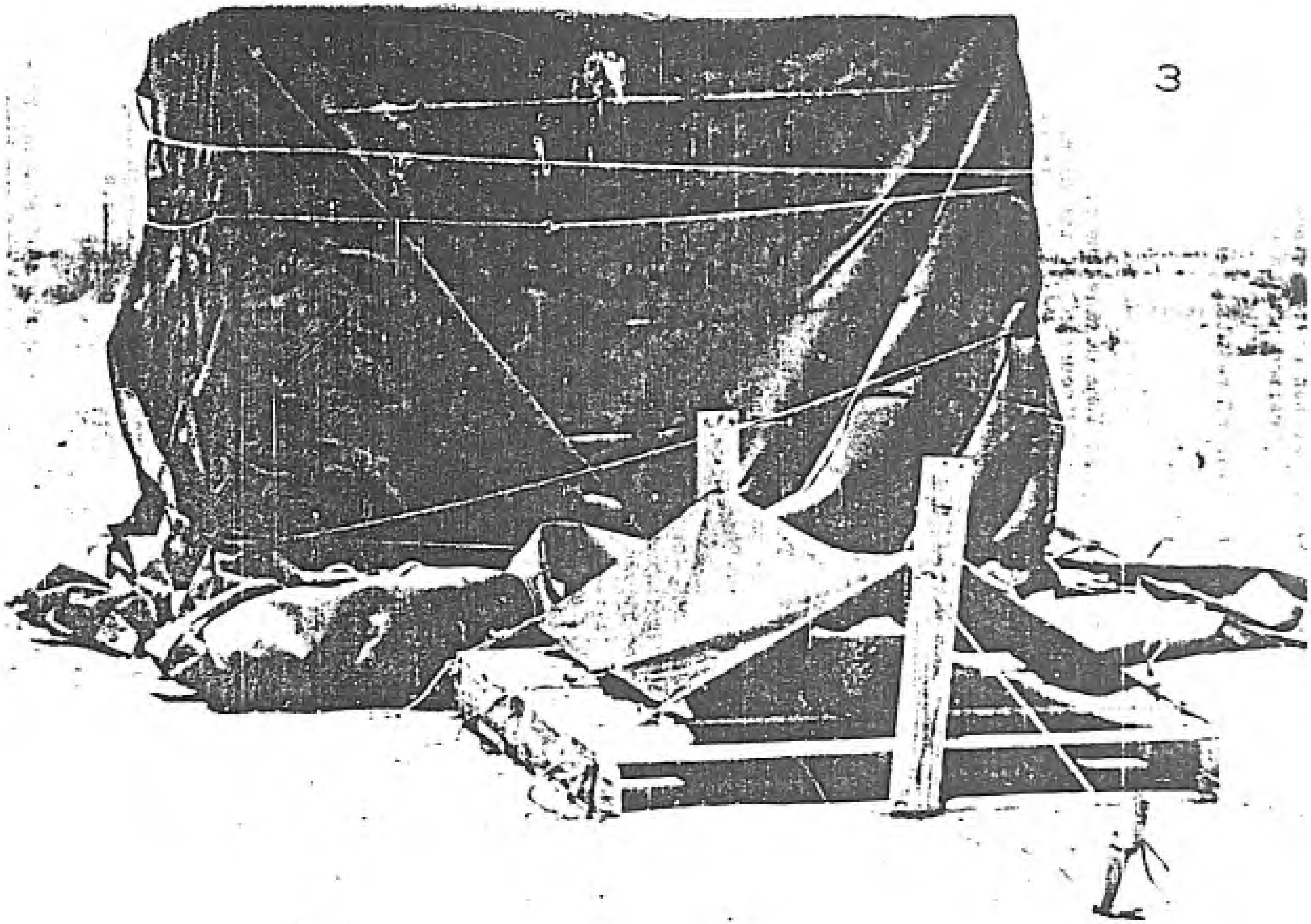

Figure 4. View of tight paulin stack facing north. (Object in foreground is part of another storage research study.)

4. Stack protected by a raised paulin fly, and covered with a layer of reflective foil on the top of the stack and part way down the west and east sides ("raised paulin with foil")

Duplicate instrumentation and analysis of results were carried out for all four types of exposure.

b. Choice of Yuma

As noted during the boxcar research at Yuma during the summer of 1953 (Porter,1956) (this report contains a discussion of the climate), the Yuma area was considered most suitable for the research. It has a summer climate which combines very high daily maximum and mean ambient temperatures with a radiation load very high for an accessible sea-level station, and low windspeeds. Yuma has been shown to be comparable to other areas of extreme heat stress (U.S. Army, EPD, 1953; U.S. Army, EPD, 1954-1957).

c. Location of research area

The site chosen (Fig. 1) was the northeast corner of the Research and Development Area of the Yuma Test Station, U. S. Army, approximately 25 miles by road northeast of the town of Yuma, Arizona, and about 5 miles east of the Colorado River.

The ground surface here and for several miles in all directions is gravel flat with very sparse shrubs. The surface has small pebbles in a sandy matrix, and is darker in appearance than pure sand plain. It has an albedo of 0.20 to 0.25 (i.e., 25% of solar energy striking the surface is reflected, 75% absorbed), as contrasted with about 0.06 for black tarpaulin material. Of all desert surfaces except very densely pebbled (patinated) pavements, or pure unbroken dark rock, this provides maximum absorption for solar wavelengths below 2.6 microns; there is only a very small percentage of solar energy at longer wavelengths (Hand, 1943).

The storage stack receives solar energy from sun and sky and reflected from the ground surface; it also receives long-wave radiation from the gravel surface, as well as long-wave energy radiated downward by the atmosphere. The stack radiates to the sky and surrounding objects, and exchanges heat, by conduction and convection, with the ambient air. During the daytime, in the tight paulin stack and the open, unprotected stack, the net energy flux from these processes is directed into the stack, which attains temperatures well above ambient air temperature.

The site chosen was open to unrestricted solar radiation and to prevailing winds (southwesterly to southeasterly during the period). The tents (Fig. 1) of the maintenance personnel were far enough away from the stack to prevent gross effects from their radiation.*

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*Since storage is generally conducted with large groups of stacks, relatively closely spaced, any such stray radiation would, if anything, enhance the reality of the test.

d. Stack composition and orientation

The stacks consisted of Ration, Individual, Combat-C, in standard overseas carton with sleeve. In all, 96 cartons per stack (3840 lb.) were placed on two 40 x 48 inch open frame pallets in an interlocking stacking comparable to that normally used in operational or depot palletized stacking. Interstices remained. Continuous inter-carton spaces were left throughout the stack (Fig. 3) and allowed a relatively free circulation of air; this air movement could be felt by placing one's hand over a gap on the leeward side of the stack. This arrangement permits more ventilation than a tight, closely-packed stack, but since it is standard stacking procedure, it was considered a realistic samples of field conditions.

Stack faces were oriented accurately with the four cardinal points of the compass. Stack measurements were 7 feet x 4¼ feet in plan and 5 feet in height, of which 6 inches was pallet (Fig. 2). Types of stack are listed in par. 3 a. Paulins were of standard olive-drab duck (No. 8), weighing, with waterproofing, 26 oz/sq yd. The ridges of the flies over stacks 2 and 4 were oriented north-south, and were approximately 5 feet above stack center surface. Fly clearance at edge of stack was about 6 inches. (See Figs. 2, 3, 4.)

C-rations were chosen as the food item because, with a representative portion of several foods in the various components, they offer a representative sample for temperature research. Since the water content of most foods is high, it is relatively immaterial which type of food is used as a stack matrix: water is preponderant in the heat balance.

e. Measurement procedures

Temperature measurements were made with copper-constantan thermocouples at 12 critical locations in each of the four stacks (Figs. 5-7 and Table II), and were recorded on a standard electronic strip-chart recorder in a period of less than 1 minute at intervals of 1/2 hour. Although certain transient maxima may have been missed, the record on the whole seems adequate.

Period of record was from 22 June to 3 August 1955, a total of 43 days.*

Air temperatures in cartons at the locations shown in the schematic diagram (Fig. 5) and listed in Table II, were measured within the ration packages by thermocouples suspended free in the air space between cans

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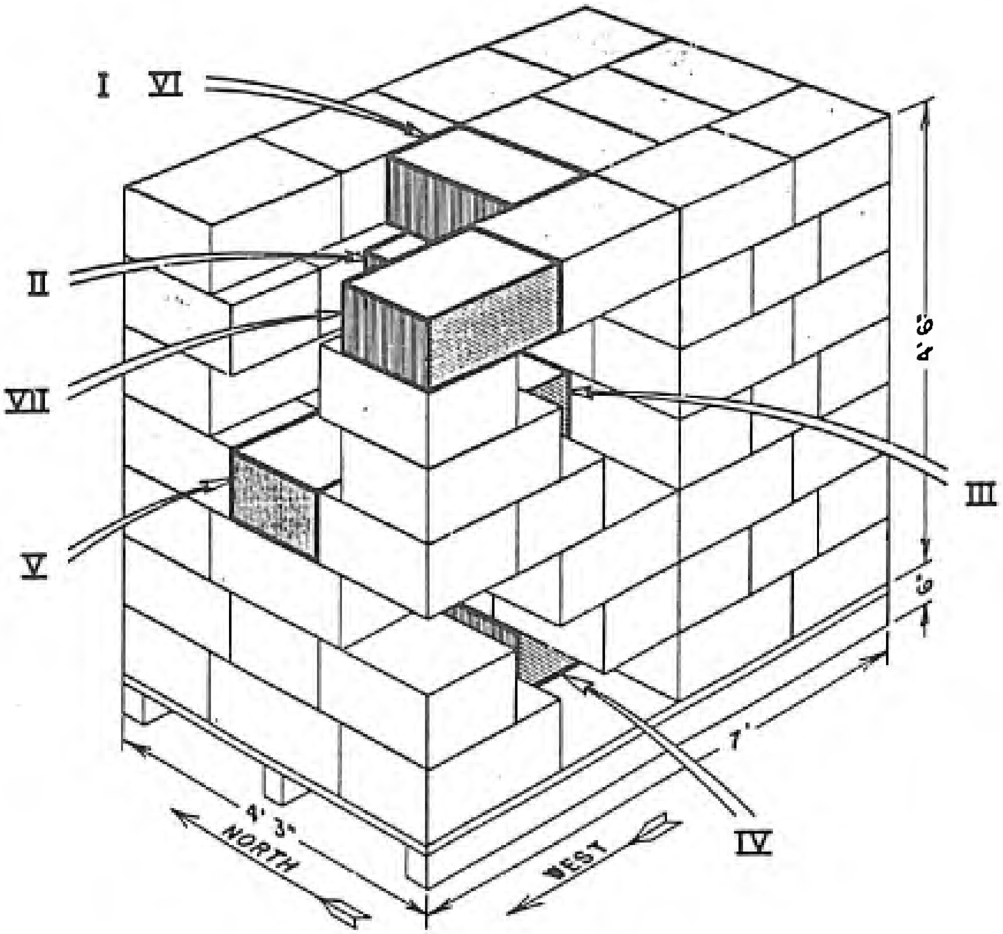
*Actual days of record numbered 39, however, since precipitation caused cessation of record on four days (see last paragraph in section 4b.).



I A	Top Center Carton - Air
I C	Top Center Carton - Food
II A	Carton Below I - Air
III A	Carton In Diametric Center Of Stack -Air
IV A	Center Bottom Carton - Air
V A	Center West Face Carton - Air
V C	Center West Face Carton - Food
VI A	Top Center Carton - Air Outside Ration Package
VII A	Upper Southwest Corner Carton - Air

A = Thermocouple In Ration Package - Air
C - Thermocouple In Can In Ration Package - Food

Figure 5. Location of thermocouple positions in stack.

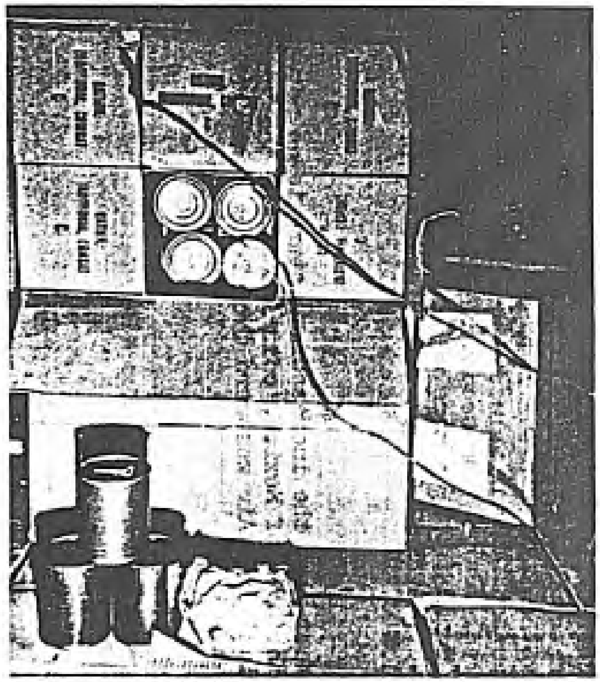


Figure 6. Thermocouple location in cartons (outside retaining sleeve is visible at the right).

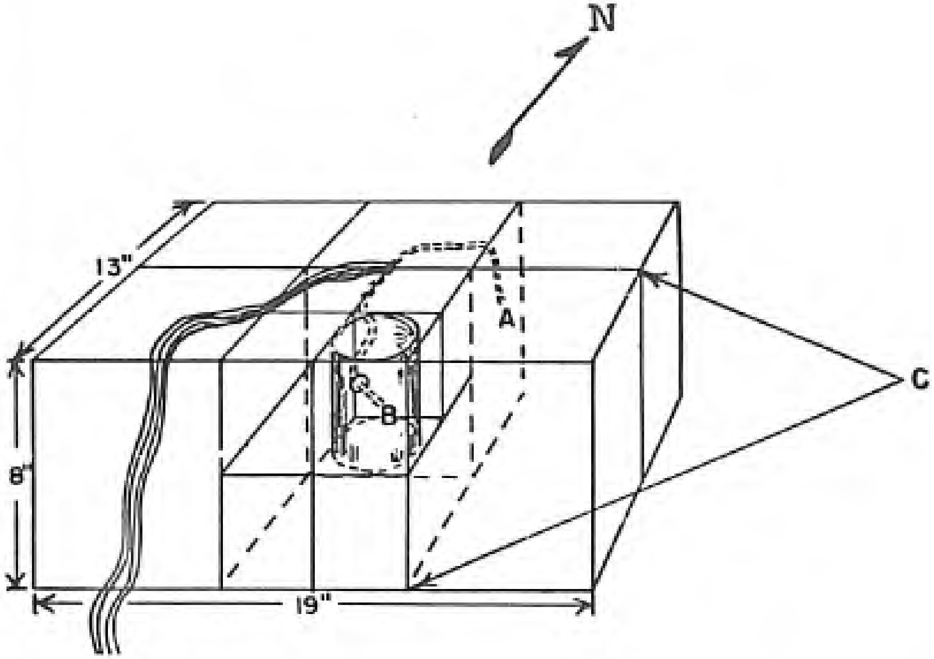


Figure 7. Sectional view of the test carton, showing combat ration package (A: Carton air thermocouple; B: Food thermocouple; C: Ration package).

of the package. The thermocouple was therefore separated from the outside air by the thin fiberboard of the ration package, the corrugated board of the carton, and an overseas retaining sleeve slipped over the carton (see Fig. 6).

Food temperatures were recorded in the can by thermocouples inserted with bushings into the center; after this, the can was restored to vacuum. The cans chosen for food temperatures were in the center top carton and in the center carton, west face.

Climatic conditions were recorded approximately 1/2 mile southwest of the stacks, at Signal Corps Meteorological Field Station No. 1. Hourly values of free-air temperature, windspeed and wind direction, cloud cover, and total solar radiation on a horizontal surface were available from this source.

4. Climatic summary

a. For the entire period

Since the period of research included only 9 days in June and 3 days in August, these cannot be compared with June and August monthly climatic means. However, July "normals" offer an approximate comparison for the 43 days (Table I). Free-air mean temperature in 1955 was about 1F° below the July normal; mean maximum temperature was about 4F° below the July normal. Windspeed of the research period was low. However, total precipitation was high compared to the average July, as a result of short showers on 3 days.

b. For the 2 subperiods

Average cloud cover from sunrise to sunset (2.7 tenths) was noticeably higher than the July normal. This figure, however, covers a rather sharp division of the research period into two well-defined subperiods of nearly equal lengths. In the first subperiod, from 22 June to 12 July, low absolute and relative humidities prevailed, cloudiness was nearly nil, and daily radiation reached maximal values, approaching the highest ever recorded in the area. During the second subperiod, from 13 July to 3 August, the Yuma area was dominated by a more moist airmass; this moves in with some regularity every summer (Ohman and Pratt, 1956, p. 5; Bryson and Lowry, 1955, pp. 329-339).*

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*These authors concur that the increased moisture is an advection phenomenon from the Gulf of Mexico, coinciding with the gradual advance of modified Tropical Gulf Air westward from Texas during the summer months.

TABLE I. COMPARISON OF CLIMATIC CONDITIONS OF RESEARCH PERIOD* WITH THOSE OF JULY NORMAL

	Research Period*	July Normals**
TEMPERATURE (°F)		
Absolute Maximum	113	120
Absolute Minimum	67	61
Mean Maximum	102.3	106.0
Mean Minimum	77.5	76.7
Mean	89.9	91.3
MEAN WINDSPEED (mph)	6.1	9.8
DAILY RADIATION (langleys)		
Maximum Total	840***	867
Mean Total	761	697
TOTAL PRECIPITATION (inches)	0.58	0.19
AVERAGE CLOUD COVER-SUNRISE TO SUNSET (tenths)	2.7	1.6

* Period of research: 22 June to 3 August 1955

** Temperature, precipitation, and cloud cover normals were obtained from U.S.W.B., (Local Climatological Data, 1952, Yuma, Arizona), and are based on 70-year records of U.S.W.B. Station near the city of Yuma Arizona. Radiation and windspeed normals were prepared from records of the Signal Corps Meteorological Field Station No. 1, Yuma Test Station. A 4-year record was used for windspeed and a 3-year record for radiation observations (1952, 1953, 1954).

*** 3 July 1955.

This change in air mass characteristics in mid-July brought higher dewpoints (May-June, about 35°F; July-August, about 60°F), which are indices of higher vapor pressures or specific humidity. There was an increase in cloudiness (the first subperiod had an average sunrise-to-sunset cloudiness of 0.9 tenths, the second subperiod had 4.5 tenths cloudiness). Total daytime incoming radiation was reduced in the second subperiod, but loss of heat to space by outgoing long-wave radiation was also markedly reduced. As a result, the free air, soil, and storage stack temperatures did not reach the low minima at night characteristic of the dry, clear nights of the earlier subperiod. There is thus the paradox that mean daily temperatures rose in a period of reduced daytime radiation; this rise was pronounced in mean daily soil surface and storage stack temperatures. The highest effective storage temperatures were therefore recorded during periods of reduced daytime solar radiation.*

Arrival of this airmass also brought sporadic thundershowers (these give Yuma its slight summer precipitation), with amounts as below:

Date	Time	Amount of Precipitation (inch)
18 July	1330-1430	0.11
23 July	2230-2330	T
24 July	1330-1430	0.38
30 July	2030-2330	T
31 July	2130-2330	0.09
3 August	1200-1300	T

T=Trace

The temperature records reflect to a greater or lesser degree these showers, with the attendant evaporative cooling, higher winds, and reduced radiation. On two occasions, from 1830, 18 July to about noon, 20 July, and from 1830, 30 July to 1230, 1 August, paulins had to be lowered on the protected stacks as a precaution against high winds; comparative readings are not valid for these periods. The stacks became thoroughly wet during the periods of pronounced rainfall, but the records suggest that drying was rapid throughout the stack and that temperature cycles were only temporarily affected by evaporative cooling.

5. Limitations of the study

As in the boxcar study (Porter, 1956), to which this present study is analogous, generalizations are limited by the following factors:

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* See paragraph 14, Part III for data and further detailed analysis.

1. Specificity of commodity (canned food) stored in dumps. Since, however, canned foods are usually high in water content, the actual thermal characteristics of the items used may be representative.

2. Specific type of packing and location of thermocouples within packing. Temperatures attained in cartons other than the C-ration type, where thermocouples were located closer to the radiating lower surface of the top of the carton, might differ from those observed in this study. For example, a difference of 10F° in daily maxima was observed -- within the same carton -- between thermocouples located inside and those outside a ration package.

3. Specific size of stack and distances of stacks from one another. Larger stacks have a larger thermal mass, resulting in greater lag in response to ambient conditions, particularly in the interior. Results of this study indicate, however, that over a long period their effective temperature would be similar to those in stacks of the size used in the present research.

4. Specific site. Areas like Death Valley, Iran, or the Sahara have climatic conditions favoring slightly greater short-term and cumulative summer heat stress. Indeed, as will be shown (in paragraph 14, Part III), it is probable that in areas like the Southwest Pacific and the Persian Gulf littoral, with only moderately high daily radiation, and limited or no cloud cover, but with high moisture content in the lower atmosphere, effective storage temperatures will equal or exceed those at Yuma. If yearly effective storage temperature is considered, stations with such conditions located near the Equator and having high yearly mean air temperature may present a much greater cumulative storage hazard than seasonally extreme spots like Yuma, Iran, or the Sahara.

6. Information sought

As in previous studies of high storage temperatures, test results have been evaluated to obtain the following information for each of the four stacks:

1. Absolute short-term extremes of temperature recorded at the most critical location, in the top carton in each stack.

2. Frequency of occurrence by class intervals of daily maximum temperatures of food in the critical top carton.

3. Cumulative daily cycles of food temperature in the critical top carton, normalized to unit range to show the regularities of the daily cycle.

4. Frequency and duration of occurrence at all temperature class intervals of all half-hourly temperatures of food in the critical top carton.

5. Temperature regimes of the interior cartons.

6. Degree of correlation of food temperatures in the critical carton with free air mean temperatures.

7. Arithmetic mean and "effective" food storage temperatures in the top center carton for constant temperature replication of the observed cyclical temperature stress.

8. Analysis of the different effects of increased airmass moisture in a climatic subperiod on storage temperature cycles.

9. Determination of comparative effectiveness of the various forms of stack protection employed.

PART II. ANALYSIS OF TEMPERATURE DATA

7. Hottest day temperatures

a. Extremes and means, all stack positions

To evaluate absolute extremes for the period of research, 15 July was selected as the hottest day* on the basis of highest daily mean and maximum temperatures at several key locations. Figures 8 to 11 illustrate the cycles on this day in each of the four stacks in turn. Table II summarizes the data for 12 locations and for ambient air.**

b. Temperatures in top center carton food (I-C)

Of the heat stress indices, the most definitive index of stack storage conditions for purposes of this study is the daily mean food temperature. In the ranges observed, this can be used, with an increment of one or two degrees, as a constant effective testing temperature (see Part III) to replicate the effects of the observed daily temperature cycle. In particular, the most useful of the food temperatures is Position IC, top carton mean food temperature, since it represents the surface portion of the stack, which is subjected to greatest stress. For almost all problems, however (as in the boxcar situation), carton air temperature (within the ration package) may be substituted for food temperature, since at the low daily ranges observed, the deviation is no more than 1 to 2 F° at maximum and 1 F° in the mean. At Position I-C in the food in the top center carton, the temperatures (°F) were as follows:

	Maximum	Mean
Tight paulin stack	118	108
Open stack	107	100
Raised paulin stack	104	98
Raised paulin & foil	98	94
Ambient air	112	100

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* Since no single day showed peak values at all locations in the stacks, a judicious compromise was necessary in the choice. (For example, the behavior of the interior cartons of the tight paulin stack is atypically cool on 15 July, as is seen by comparing Table II with Table IX.)

**In the discussion of test results, only maximum, minimum, mean, and range of temperature will be used, since other possible analyses based on form of temperature cycles, lag of various cycles behind others, rate of rise and fall of temperature, are of little relevance in the problem of sterile food degradation, with which this study is principally concerned.

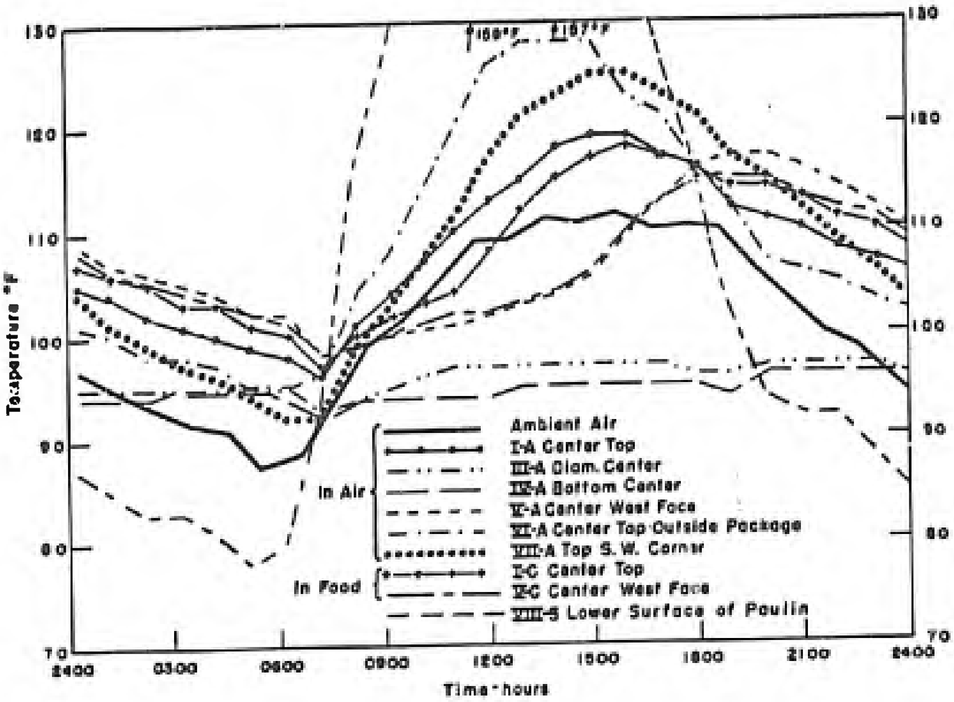

Figure 8. Daily temperature cycles on hottest day (15 July 1955): Tight paulin stack.

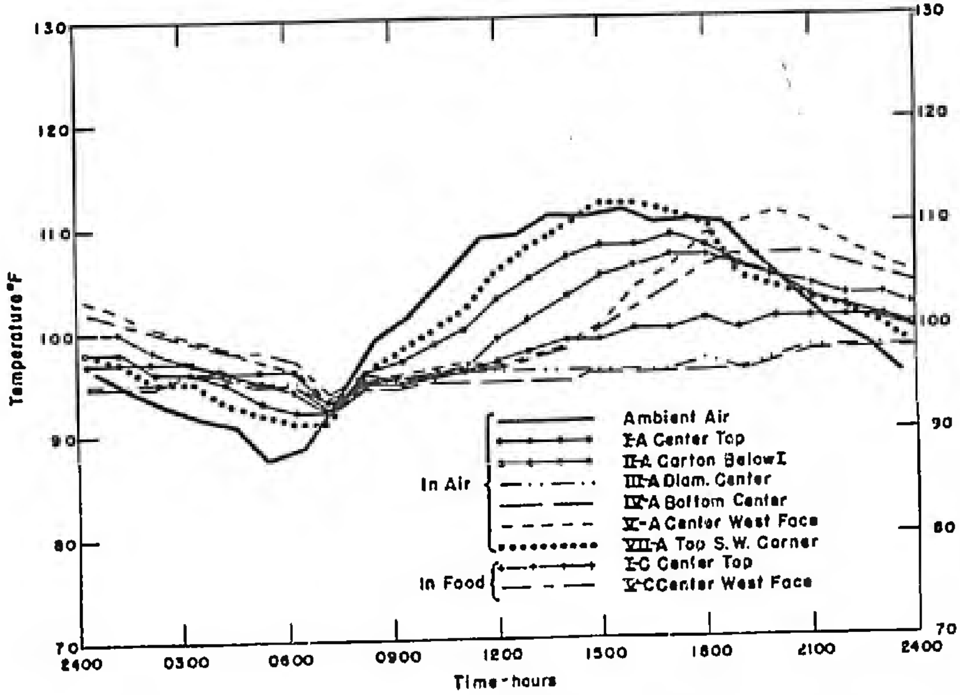

Figure 9. Daily temperature cycles, hottest day (15 July 1955): Open stack.

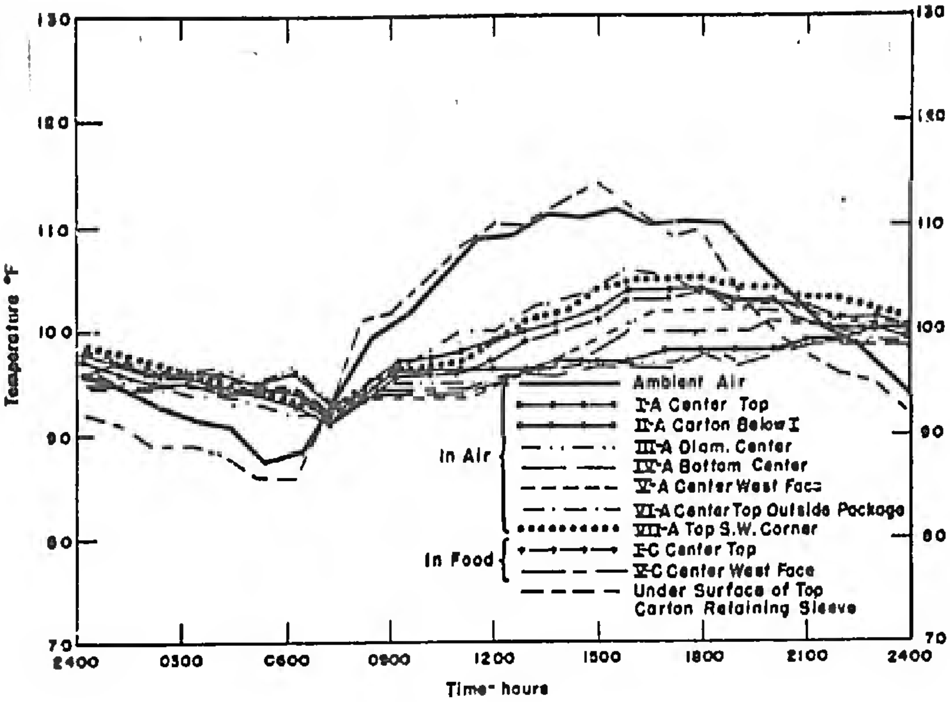

Figure 10. Daily temperature cycles, hottest day (15 July 1955): Raised fly stack.

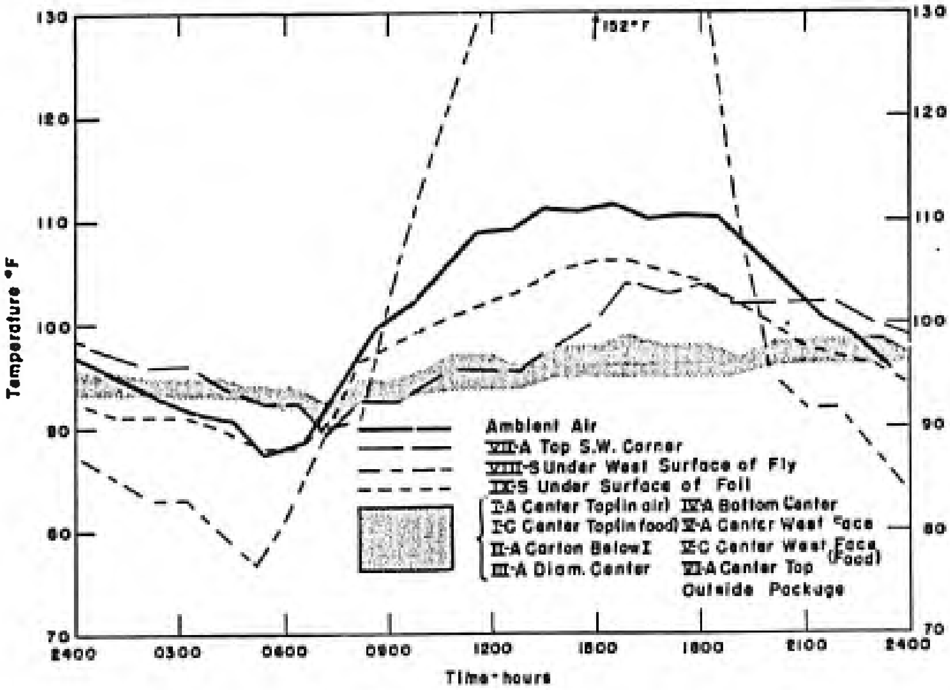

Figure 11. Daily temperature cycles, hottest day (15 July 1955): Raised fly stack with foil

TABLE II. TEMPERATURE MEANS AND EXTREMES FOR 12 POSITIONS OBSERVED IN FOUR STACKS (°F)
FOR HOTTEST DAY -- 15 JULY 1955

Position	Location	Open Stack				Raised Fly Stack				Tight Paulin Stack				Raised Fly & Foil			
		Max	Min	Range	Mean	Max	Min	Range	Mean	Max	Min	Range	Mean	Max	Min	Range	Mean
I A	Top center carton: Air	109	92	17	100	104	91	13	98	119	96	23	108	98	90	8	94
I C	Top center carton: Food (can)	107	92	15	100	104	91	13	98	118	97	21	108	98	90	8	94
II A	Second layer, carton below I: Air	101	93	8	97	100	93	7	96	--	--	--	--	97	91	6	94
III A	Diametric center of stack, carton: Air	98	93	5	96	99	93	6	96	98*	93	5	96*	96	91	5	94
IV A	Center of bottom layer of stack, carton: Air	98	93	5	96	99	92	7	96	96	92	4	94	97	91	6	94
V A	Center of west face of stack, carton: Air	111	93	18	102	103	92	11	98	117	98	19	108	98	91	7	94
V C	Center of west face of stack: Food (can)	107	94	13	100	101	92	9	96	115	98	17	106	98	91	7	94
VI A	Top center carton: Air outside ration package	--	--	--	--	106	92	14	99	128	95	33	112	98	91	7	94
VII A	Top layer, southwest, carton: Air	112	91	21	102	105	92	13	98	125	92	33	108	104	90	14	97
VIII S	Lower paulin surface temperature (west-facing if raised fly)	--	--	--	--	--	--	--	--	159**	78	81	118	152	77	75	114
IX S	Below foil surface on stack 4	--	--	--	--	--	--	--	--	--	--	--	--	106	88	18	97
X S	Below first V-board surface of top carton	--	--	--	--	114	86	28	100	--	--	--	--	106	87	19	96
	Free air temperature (Yuma Test Sta.)	112	88	24	100	112	88	24	100	112	88	24	100	112	88	24	100

* Atypical values. Maximum and mean in this position were generally 5F° higher than in the other stacks.

**A paulin surface temperature of 171°F was recorded on 27 June, a day of high total radiation and low windspeed.

It is apparent that the tight paulin stack showed surface carton temperatures appreciably higher than ambient air temperatures, while the other stacks at most equalled the ambient air values. Since Position IC has been shown above to be representative of the most critical exposure, it may be generally concluded (as supported by the records for all days in the period) that on the most critical days in dump storage, ambient high temperature maxima and means are limiting values for all forms of stack exposure studied, except that of the tight paulin stack, in which the temperatures may reach figures well in excess of ambient values.*

c. Temperatures at interior ("buried") cartons (III-A & IV-A)

Within the deep interior, however, no such striking differences among the stacks is observed. Temperatures at Position III-A, carton air temperatures at the diametric center of stack, were as follows:

	Maximum	Means
Tight paulin stack	98	96
Open stack	98	96
Raised paulin stack	99	96
Raised paulin & foil	96	94

Position IV-A, carton air temperature in the center of the bottom layer of the stack, showed values almost identical to those for Position III-A.

It might be therefore presumed that there is little difference in temperature behavior from stack to stack within the interior, in contrast to the surface layer. This is indeed true for all stacks except the tight paulin stack, as is evident from inspection of Table IX; this table gives daily mean temperature and range of temperature for carton air in the center of the stacks on 9 representative days. This table shows, moreover, that the interior of the tight paulin stack experiences daily mean and maximum temperatures about 5F° higher than those for the other stacks on the average day, and that therefore interior temperatures observed in the tight paulin stack on 15 July are atypically low.

It may be concluded from the data of Tables II and IX that on very hot days, the tight paulin stack shows surface carton mean and maximum temperatures at least 10F° higher than the other stacks and interior temperatures at least 5F° higher. It also follows from the foregoing discussion that the gradient of temperature from the surface to the interior, based on either maximum or mean temperature, is greatest in the

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* Isolated instances occur in which carton air mean temperatures in stacks other than tight paulin exceed ambient air means, but these excesses are infrequent and of the order of 2-3 F°.

tight paulin stack (in which the temperature difference is approximately 15F° at time of maximum surface temperature), and diminishes progressively to the raised-fly-with-foil stack, which is virtually isothermal.

d. Ranges and minimum temperatures

As is apparent in Table II, temperature ranges throughout the daily cycle in the surface layer of cartons diminish in the same order as maximum and mean temperatures, from the tight paulin stack (21F°), through the open stack (15F°) and the raised-fly stack (13F°), to the raised fly-with-foil stack (8F°). Table II shows that these differences in ranges are largely due to differences in maximum temperatures; the minima are essentially the same in all stacks except for a slight elevation in the tight paulin stack.

There is a great reduction in temperature range from the surface (e.g., top center carton I-C) to the interior cartons (e.g., III-A) in all stacks except raised-fly-with-foil, whose range is low at the surface. Within the interior, ranges are essentially the same (5F°) in the four stacks (Tables II and IX).

Minima are similar in the three stacks except the tight paulin stack, which is generally warmer by 5F° at the temperature minimum (although atypically cool on 15 July). No stack temperature measured went below ambient temperature, and in general the ambient temperature was 5F° or more below minimum for stack temperatures.

Although at the time of minimum ambient temperature the stacks (as on 15 July) generally approached an isothermal condition throughout their bulk, two stacks - the open stack and the raised-fly stack - may show interior temperatures more than 5F° higher than the surface temperatures.* In these two stacks, surface carton temperatures oscillate about the relatively conservative temperature regime of the interior.

e. Comparison with extreme temperatures observed in other studies

Dump storage maximum temperatures on 15 July are compared below with peak figures for boxcar temperatures (Porter, 1956).

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* This tendency to an inversion of the temperature gradient from that prevailing at time of maximum may be found at times in all stacks, but is most pronounced in the two stacks cited in the text, the reversal often being as great at minimum as the normal gradient at maximum.

Position	Maximum Temperature (°F) Dump Storage Tight Paulin 15 July 1955	 Boxcar 15 August 1953
Top Layer Center Carton Air (similar location and identical carton in dump and car)	119	119
Temperature of underside of radiating surface (roof for boxcar, paulin for dump)	159	155
Ambient Air	112	111
[Total Radiation on Horizontal Surface (langleys)]	[766]	[697]

The close agreement is partly fortuitous, but certainly suggests near-absolute maxima in such situations.

In addition, temperature data (°F) from previous dump studies are compared below with data for hottest day in the current study (see Table III).

TABLE III. MAXIMUM STORAGE TEMPERATURE DATA FROM VARIOUS STUDIES (°F)

Date	Test Description	Free Air	Paulin Surface*	Absolute max. temp. carton air outside pkge	Max. food temp. in carton
1943	Blythe, California (conducted by QM in Sonoran Desert of California)	113	150	126	115
1944	Indian Bay, Florida (QM study of monsoon area dump storage)	94	150-160	125	**
1945	Marianas Islands, S.W. Pacific (Questionnaires sent to 20 QM storage dumps in operational theaters)	89***	**	125	110
1955	Yuma Dump Storage, <u>15 July</u> [<u>Tightly-covered stack</u>]	112	159	128	118

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* Or air immediately below paulin.

** Data missing.

***The low <u>ambient</u> temperature at this maximum <u>storage</u> temperature should be noted.

The concurrence of these data suggests that absolute maximum carton air temperatures in storage will rarely exceed 125 to 130°F, and that within overseas carton and ration packages, food and air temperatures will rarely exceed 115 to 120°F.

f. Duration of high temperatures on hottest day

One may estimate the length of time temperatures remained higher than selected critical levels in the tight paulin stack on 15 July (hottest day) by an inspection of Fig. 8. (For the other stacks, see Figs. 9, 10, 11.) A table comparing the duration of high temperatures in this most extreme type of dump exposure with the other three stacks and with that at comparable positions in boxcars is shown below:

TABLE IV. DURATION OF HIGH TEMPERATURES (°F) ON HOTTEST DAY FOR VARIOUS TYPES OF STORAGE (in hours per day)

Position	Duration (hours per day) of temperature (°F) above:					
	90	95	100	110	120	130
Tight Paulin (dump)						
Under surface of paulin (VIII-S)	16		12	10	9	7
Top center carton air (I-A)	24		20	10	--	--
Top center carton food (I-C)	24		22	11	--	--
Boxcar						
Air 6" below roof	15		12	10	8	7
Top center carton air	24		17	8	--	--
Top center carton food	24		21	5	--	--
Open stack (dump)						
Top center carton air	--	20	13	--	--	--
Top center carton food	--	21	13	--	--	--
Raised fly stack (dump)						
Top center carton air	--	19	9	--	--	--
Top center carton food	--	20	10	--	--	--
Raised fly stack &foil						
Top center carton air	--	11	--	--	--	--
Top center carton food	--	11	--	--	--	--

It is obvious from the above tables that cartons in the other three stacks are much less exposed to temperatures over 100°F than are cartons in the tight paulin stack. The effect of the addition of foil to the raised fly (which will be discussed in more detail below) is shown to reduce by about half the hours of exposure to carton temperatures over 95°F.

8. Frequency of daily maximum temperatures in top center carton food

The cumulative percentage frequency distribution of daily maximum temperatures observed in the top center carton food in the several stacks is shown in Figure 12 and Table V. All daily maxima in the period of record fell in the range 85 to 118°F. Maxima in the tight paulin stack clustered in the class 110 to 114°F; maxima in the other three stacks clustered between 90 and 99°F.

The effect of the foil is again shown in the concentration of daily maxima in the range 85 to 94°F for the raised-fly-with-foil stack. Range of daily maxima was reduced; no maxima exceeded 100°F.

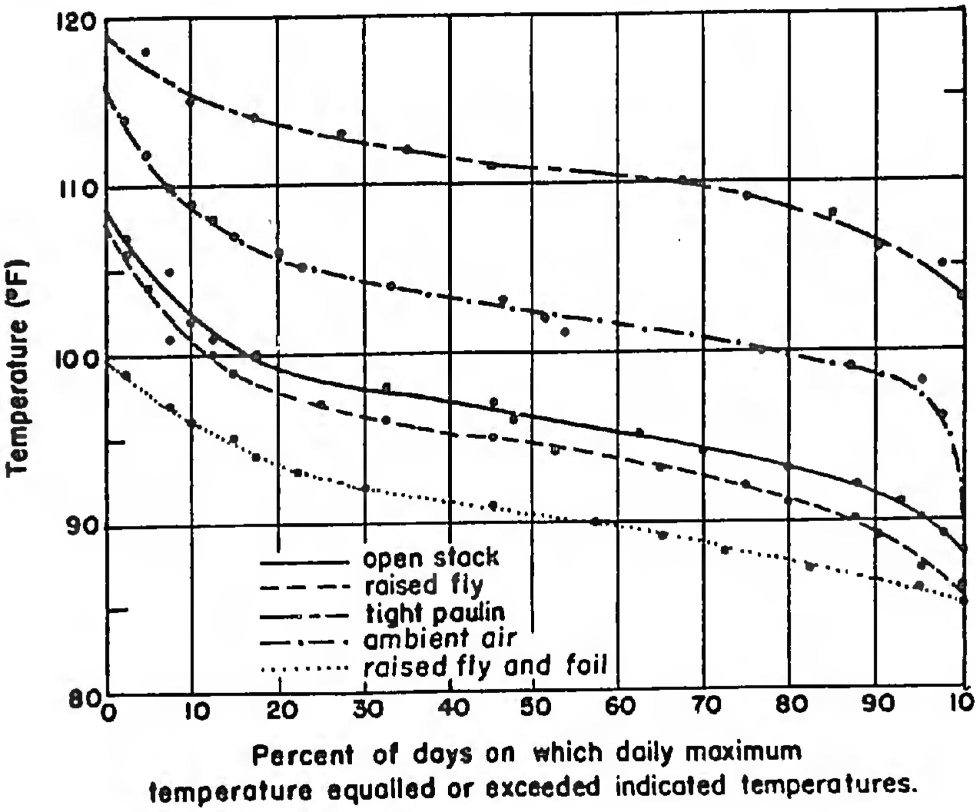

Figure 12. Cumulative frequency distribution of daily maximum temperatures for position I-C (top center carton, food).

TABLE V. PERCENTAGE FREQUENCY OF DAILY MAXIMUM TEMPERATURES IN FOOD IN TOP CENTER CARTON (I-C)*

(Period: 43 days, 22 June - 3 August 1955)

Type of Stack	85-89°	90-94°	95-99°	100-104°	105-109°	110-114°	115-119°
Tight Paulin Stack				3 (100)	25 (97)	57 (72)	15 (15)
Open Stack	3 (100)	30 (97)	48 (67)	13 (19)	6 (6)		
Raised Fly Stack	11 (100)	39 (89)	37 (50)	9 (13)	4 (4)		
Raised Fly Stack with Foil	38 (100)	46 (62)	16 (16)				
Ambient Temperature		1 (100)	18 (99)	52 (81)	20 (29)	9 (9)	

* Figures in parentheses show cumulative percent of all days with maximum temperature above lowest figure of interval.

9. Frequency of all half-hourly food temperatures top center carton food

a. Method of estimating: "normalizing" daily cycle

To obtain a frequency distribution of all half-hourly food temperature readings, a method of estimation has been developed which practically eliminates the time-consuming tabulation of all readings throughout the research period. This method, developed in the earlier boxcar study, depends upon the general uniformity in the shape of the daily temperature cycle in carton air or food. It has been found to give dependable though approximate results in both studies.

The method is as follows: The cumulative daily temperature cycle* on each of several sample days for the stack position (e.g., I-C) being studied is normalized, i.e., reduced to unit range. By averaging these curves, a usable "standard day" normalized cumulative daily temperature cycle is developed. This can be divided into deciles of unit range, and one can read off the number of hours per day during which the temperature may be expected to be below daily maximum by no more than a given decile of the range. Cumulative frequency distributions for all half-hourly temperatures may then be derived from the individual daily maximum

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*A plot of the number of hours of the day experiencing temperatures at or below a given number of degrees below maximum.

and daily range. By use of the standard normalized cycle, one may apportion the number of hours of the day the temperature remained within each of the designated class intervals of the frequency distribution.*

In the relatively homogeneous boxcar environment, the standard normalized daily cycle so derived was found to approach closely a cumulative sine curve. However, in dump storage, the standard cycle in the various stacks departs more or less widely from a cumulative sine curve (Fig. 13).

Four standard normalized cumulative daily curves were derived, based on food temperature in top center carton in each of the four stacks observed for the entire research period (Fig. 13).

b. Distributions derived: for entire period, hottest 5-day period and hottest day

Estimated cumulative frequency distributions for half-hourly food temperatures in the top center carton of each stack were derived from standard cycles as described above. Distributions were prepared for data 1) from the entire period, 2) from the hottest 5-day period (13-17 July), and 3) from the hottest day (15 July). The last two (5-day and hottest day) were based on actual tabulations of all half-hourly readings in these periods. Tables VI, VII, and VIII and Figures 14, 15, and 16 give these distributions.

TABLE VI. PERCENTAGE FREQUENCY OF FOOD TEMPERATURES IN TOP CENTER CARTON FOR ENTIRE TEST PERIOD*

Type of Stack	Temperature classes (°F) 70-74	75-79	80-84	85-89	90-94	95-99	100-104	105-109	110-114	115-119
Tight Paulin				6 (100)	15 (94)	23 (79)	23 (56)	21 (33)	11 (12)	1 (1)
Open		5 (100)	15 (95)	26 (80)	29 (54)	19 (25)	4 (6)	2 (2)		
Raised fly		4 (100)	16 (96)	31 (80)	32 (49)	13 (17)	3.6 (4)	0.4 (0.4)		
Raised fly &foil			17 (100)	46 (83)	30 (37)	7 (7)				
Ambient air	6 (100)	8 (94)	11 (86)	17 (75)	17 (58)	21 (41)	15 (20)	4 (5)	1 (1)	

*Figures in parentheses are cumulative percentages.

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*The degree interval between maximum temperature and the lower class limit of each class interval concerned in the temperature of that day, is expressed as a fraction of the daily range. The standard cycle then permits conversion of this fraction into number of hours spent within the class.

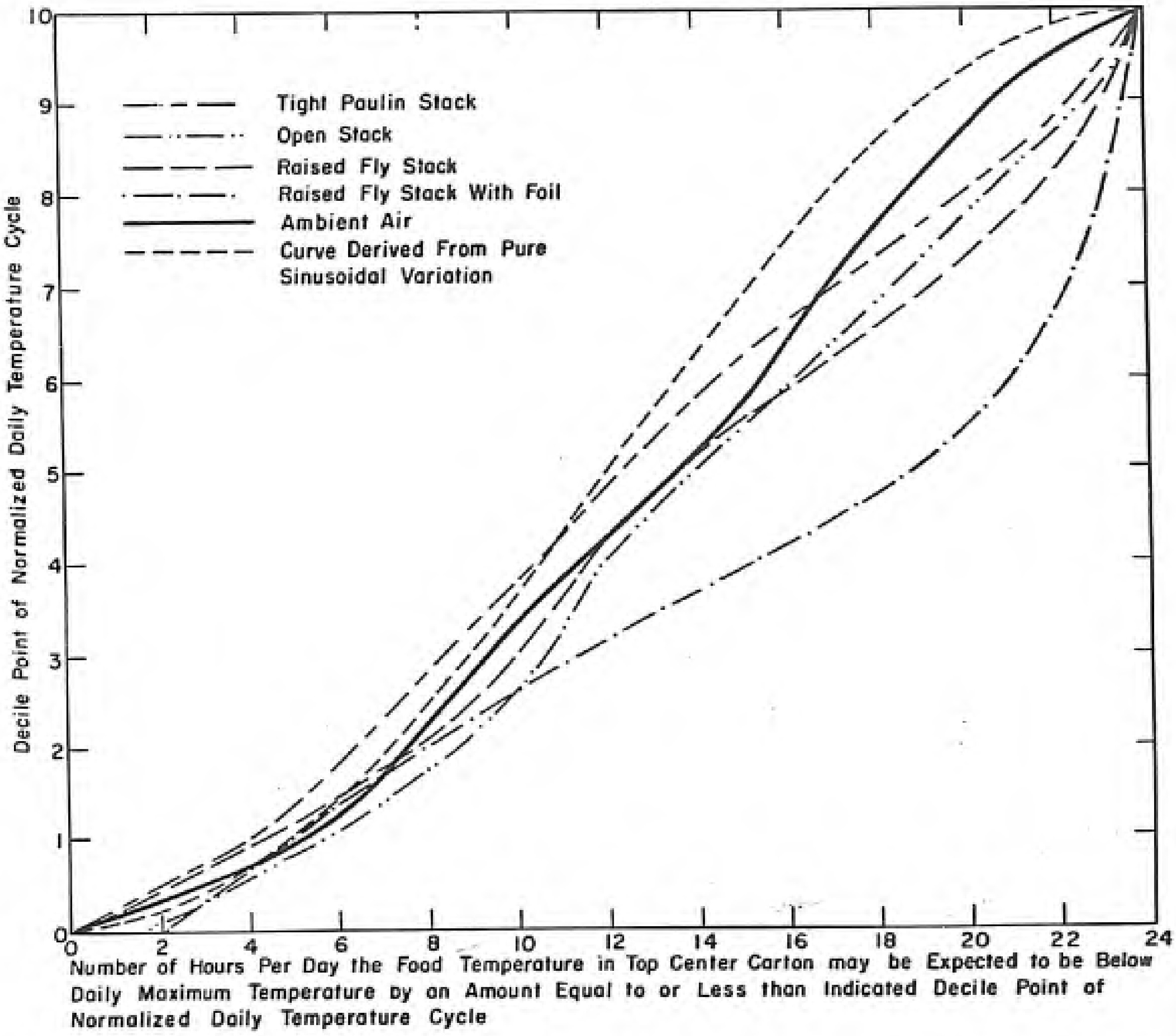

Figure 13. Normalized cumulative frequency temperature distributions for standard day for top center carton food and ambient air temperatures.

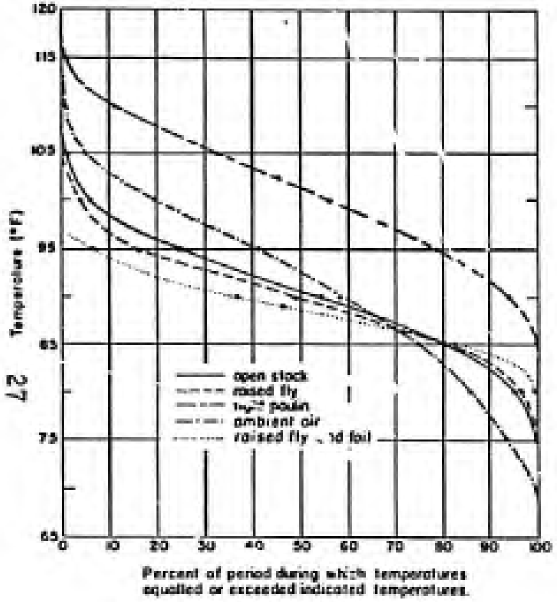

Figure 14. Cumulative frequency distribution of all temperatures for top center carton food (I-C) for total research period.

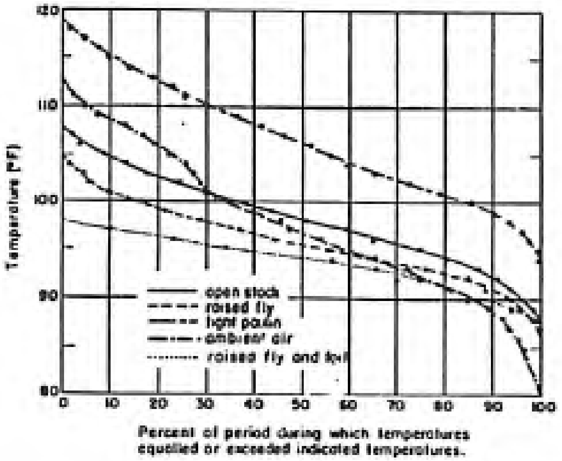

Figure 15. Cumulative frequency distribution of all half-hourly temperatures for top center carton food (I-C) for hottest 5 days.

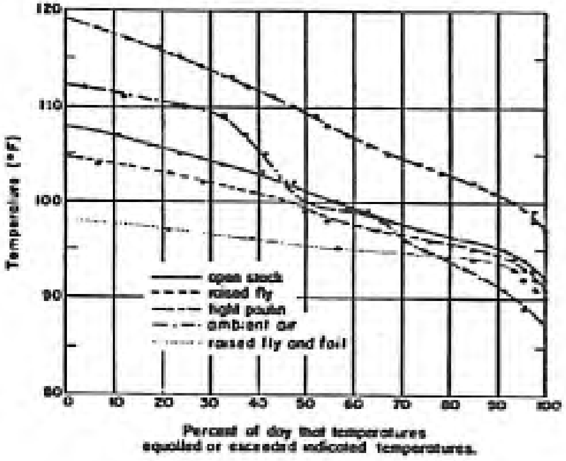

Figure 16. Cumulative frequency distribution of all half-hourly temperatures for top center carton (I-C) for hottest day.

TABLE VII. PERCENTAGE FREQUENCY OF FOOD TEMPERATURES IN TOP CENTER CARTON FOR HOTTEST 5-DAY PERIOD (13-17 JULY)*

Type of Stack	Temperature Classes (°F)							
	80-84	85-89	90-94	95-99	100-104	105-109	110-114	115-119
Tight Paulin				14 (100)	30 (86)	26 (56)	20 (30)	10 (10)
Open		3 (100)	22 (97)	41 (75)	26 (34)	8 (8)		
Raised fly		6 (100)	36 (94)	42 (58)	16 (16)			
Raised fly & foil		13 (100)	53 (87)	34 (34)				
Ambient air	3 (100)	12 (97)	26 (85)	24 (59)	13 (35)	17 (22)	5 (5)	

*Figures in parentheses are cumulative percentages.

TABLE VIII. PERCENTAGE FREQUENCY OF FOOD TEMPERATURES IN TOP CENTER CARTON FOR HOTTEST DAY (15 JULY)*

Type of Stack	Temperature Classes (°F)						
	85-89	90-94	95-99	100-104	105-109	110-114	115-119
Tight paulin			6 (100)	27 (94)	19 (67)	24 (48)	24 (24)
Open		9 (100)	34 (91)	33 (57)	24 (24)		
Raised fly		15 (100)	37 (85)	48 (48)			
Raised fly & foil		44 (100)	56 (56)				
Ambient air	6 (100)	19 (94)	25 (75)	8 (50)	17 (42)	25 (25)	

*Figures in parentheses are cumulative percentages.

Curves for each of the 3 periods (Figs. 14, 15, 16) show the relative heat stress imposed by the various stack exposures, from tight paulin (by far the worst) to raised-fly-with-foil (the best). Little difference in protection is shown among the open stack, the raised-fly, and the raised-fly-with-foil on most of the 39 days. Only in the hottest 10 to 20 percent of the period (i.e., the 5-day period) does the protection of the raised fly, and especially of the added foil, become apparent. This is illustrated in the frequency distributions for the hottest 5-day period (Table VII and Fig. 15) and the hottest day (Table VIII and Figure 16) where the traces for the three stacks are more widely separated from each other. It will be recalled that correlative evidence for the special value of the foil in reducing peak temperatures was found in Table V, in which the reduced frequency of occurrence of high daily maxima is shown.

Relative stack storage stress shown by the frequency distributions may be summarized by the following tabulations for food temperature top center carton:

	80% of the time	
Tight paulin	above	95°
Open stack	below (or at)	
Raised paulin		
Raised fly with foil		

	Temperature below 90°F Time (%)
Tight paulin	6
Open stack	45
Raised paulin	50
Raised paulin with foil	65

10. Temperature regimes of buried cartons

The buried or interior cartons (those with no face exposed to solar or paulin radiation) represented 16 percent of the stack volume in this study. This ratio of interior to exterior (surface) volume would, of course, increase with stack size. However, in food degradation problems, for any practical stack size, the temperature reached in surface layers will always be the determining factor in storage stress, since these layers constitute a proportion of the total stack large enough to be the final criterion of storage safety.*

The long-term temperature behavior of these cartons may be studied by considering the air temperature in the carton located at the diametric center of each stack (III-A). Table IX and Figures 17 and 18 show the daily means and ranges for 9 representative days, taken at 5-day intervals throughout the period.

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*The east and west stack faces are nearly as severe an environment as the top surface of the stack. Compare positions IA and VA, Table II.

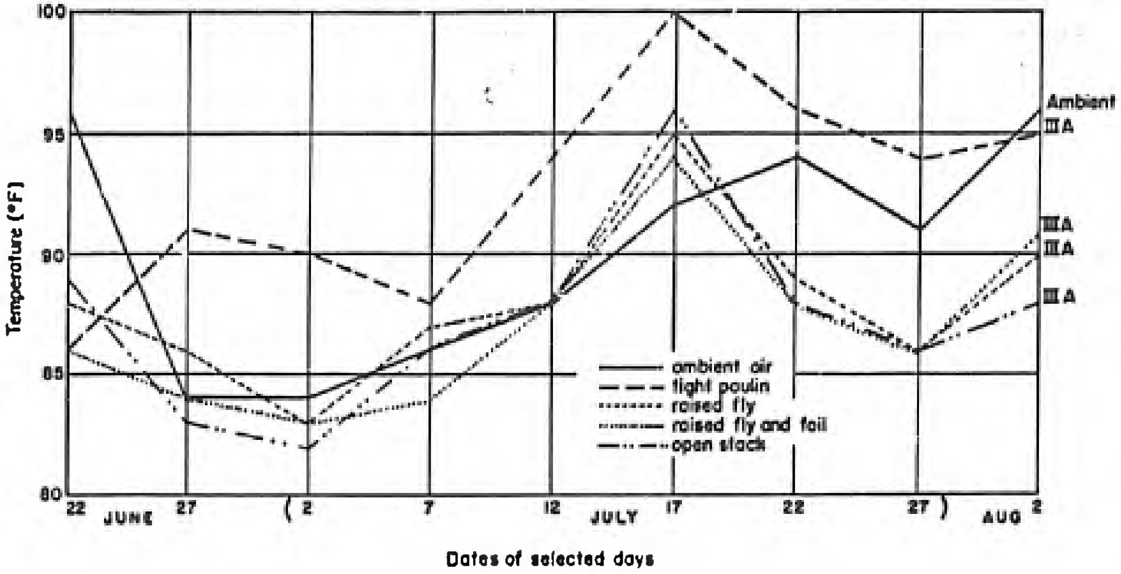

Figure 17. Mean temperature of "buried" carton air (III-A) for 4 stacks (mean of daily temperatures for 9 representative days).

Since the outer cartons partially insulate the buried cartons from ambient temperature and radiation variations, one would expect the range of temperature in the center of the stack to be much smaller than that in surface cartons because of the damping of temperature fluctuations. The range is actually reduced to about 5F° in each stack. The rather low thermal diffusivity of the compartmentalized stack produces another effect, less evident in Figure 17:* a lag in the adjustment of interior to ambient and surface conditions, varying from 3 days to a week in these small stacks. The lag and the reduction of interior range would, of course, be greater in a larger stack.

The temperature regimes at the center of the open stack, the raised-fly stack, and the raised-fly-with-foil stack are similar. Means and ranges for these three stack centers are within 3F° of each other on each of the representative days, and means of the separate daily means are almost identical, as Figure 18 shows.

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*The ambient temperatures in Figure 17 are those for the selected days at 5-day intervals. The variability of such arbitrarily selected ambient temperatures masks the long-term trends, which are revealed in the 5-day period mean ambient temperatures of Figure 19. Comparison of Figures 17 and 19 will reveal the lag.

Perhaps the most important conclusion about the three above-mentioned stacks is that, in mean temperature (and also effective storage temperature for food), they are very nearly the same throughout their volume (Fig. 18). That is, for mean temperature, the surface differs little from interior, and food degradation would be approximately similar in rate throughout the volume of each stack and would differ only slightly from stack to stack.

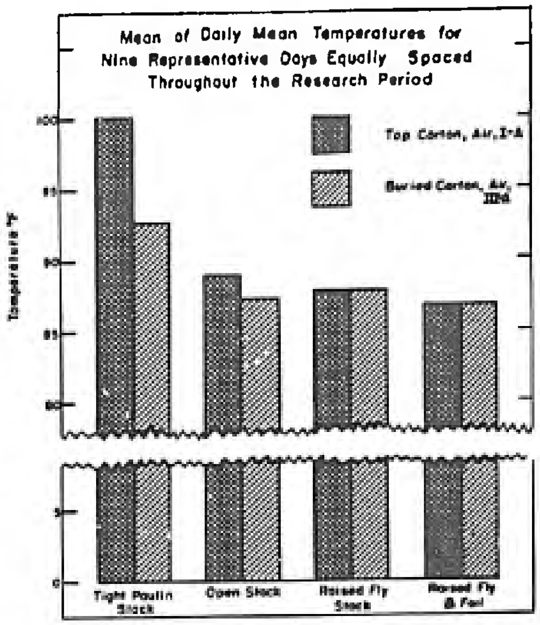

Figure 18. Air temperature in top carton (I-A) compared with that of "buried" carton (III-A) for 4 stacks.

In the tight paulin stack, on the other hand, interior air (and hence food) temperature means are elevated 5 to 8F° above those in the other stacks, emphasizing again the greater heat stress in this form of storage in desert climates. As in the boxcar, mean temperatures in the interior of the load differ markedly from those of surface layers: the gradient of mean temperature in the tight paulin stack is 7F°. Under these conditions, the surface layers are a more severe storage environment; thus, at typical degradation rates in the interior, storage life would be about 30 percent greater.

TABLE IX. MEANS AND RANGES OF AIR TEMPERATURES IN DIAMETRIC CENTER OF STACK (III-A) (INTERIOR CARTONS), AS COMPARED WITH THOSE OF FOOD TEMPERATURES IN TOP CENTER CARTON (I-C) FOR 9 REPRESENTATIVE DAYS

Date	Tight Paulin				Open Stack				Raised Fly				Raised Fly & Foil			
	Interior		Top Carton		Interior		Top Carton		Interior		Top Carton		Interior		Top Carton	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
22 June	86	5	100	25	89	6	92	19	88	8	89	16	86	7	86	9
27	91	6	98	27	83	6	84	19	86	5	85	14	82	5	82	9
2 July	90	3	95	20	82	5	82	14	83	4	81	10	83	4	82	5
7	88	5	99	28	86	5	88	18	87	4	87	16	84	5	86	7
12	94	4	101	24	88	5	88	19	88	4	88	15	88	4	87	6
17	100	1	104	11	96	4	96	6	95	4	93	4	94	3	94	1
22	96	5	104	21	88	6	91	14	89	6	90	13	88	5	89	7
27	94	5	99	22	86	8	88	15	86	6	86	14	86	7	84	7
2 Aug.	95	4	102	17	88	4	92	11	90	2	92	7	91	2	92	3
Average	92.7	4.2	100.1	21.6	87.3	5.4	89.0	15.0	87.6	4.8	87.8	12.1	86.8	4.7	86.8	6.0

PART III. COMPUTING AND USING EFFECTIVE TEMPERATURES TO SIMULATE FIELD STORAGE STRESS IN THE LABORATORY

11. The use of effective temperature index

It has been the aim of Quartermaster food storage research to reduce the observed complicated cycles of temperature at various locations to simple quantitative descriptions, preferably a single index, and to predict storage temperature effects under other conditions where only climatic data (e.g., ambient temperature) are available.

Such indices are called "effective temperatures" and are used for constant temperature laboratory simulation of field storage stress.

12. The arithmetic mean as an approximate effective temperature

Effective temperatures are always higher than the arithmetic mean of cyclically fluctuating temperatures, because the rate of "ageing" (sterile chemical degradation) of canned foods approximates an exponential function of temperature in the ranges concerned,* and high-temperature portions of the range result in disproportionately great reaction rates. For accurate work, a cumulative degradation curve (as in Fig. 23, shown later) should be plotted from the cumulative temperature frequency curve, and the mean degradation rate determined by graphical integration.** The temperature corresponding to this degradation rate is the "effective" temperature for the period.

However, for the purposes of these studies, it has been found in the boxcar research and in the present study that daily arithmetic mean temperatures in either carton air or food may be justifiably used to represent effective degradation temperatures if daily ranges of food temperature are less than 15F°, since the increments to be added to obtain effective temperatures are less than 1 F° when "ageing" proceeds at a Q_{10} rating of 2;*** a common rate.

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* A so-called Q_{10} rating of 2 is common, where reaction rate doubles for every 10C° (18F°) increase in temperature.

** It is presupposed that there is available an empirically observed curve or mathematical degradation function with temperature. Graphical integration is unnecessary if both the degradation-temperature relation and the temperature-time relation may be combined into an integrable function, as when temperature follows a generally sinusoidal curve.

*** (See footnote (*) above.) It should be noted that the assumptions made above concerning substitution of arithmetic mean for effective mean, are not valid with ranges above 20F°, or with Q_{10} ratings much greater than 2. Effective temperature excess over arithmetic mean for range of 30F° and Q_{10} of 3, is over 3 degrees, representing a 20 percent drop in storage life.

Food storage history in the most critical representative top cartons of the four dumps may be duplicated therefore by exposure for 6 weeks at the constant effective temperatures (°F), shown in Table X, measured within the food concerned (or within an oven surrounding these foods):

TABLE X. EFFECTIVE TEMPERATURES FOR VARIOUS TYPES OF STORAGE

Type of Stack	Arith. Mean Temp.*	Effective Food Storage Temperature* (Period 22 June-3Aug)	Difference between Arith. Mean & Effective Temperature
Tight paulin stack	100.8	102.2	1.4
[Boxcar**	102.4	102.7	0.3]
Open Stack	90.7	91.3	0.6
Raised Fly Stack	89.9	90.4	0.5
Raised Fly Stack with Foil	88.7	89.0	0.3
Ambient Air Temperature	92.1	--	--

* The "mean" temperatures were computed by graphical integration of the cumulative temperature frequency curve. The "effective" temperatures were computed by graphical integration of a cumulative curve of relative rates of degradation corresponding to each temperature of the cumulative temperature frequency curve. The incremental difference, shown in the last column is obviously insignificant.

**Month of July 1953.

In a similar manner, we may with reservations extend prediction to similar dump storage situations in other hot, dry areas where there is infrequent airmass change and relatively great solar control of ambient temperature.

13. Predicting weighted mean food storage temperatures from ambient air temperature

a. Comparison of mean food storage temperature with ambient air temperature

To describe by a series of effective temperatures the expected storage stress on food in a critically exposed carton in the field, one must first be able to predict mean food temperatures and ranges from available climatic data.*

As Figure 19 shows, ambient air temperatures and food temperatures (top center carton, I-C) vary similarly in response to net energy gains and losses from the radiation, conduction, and convection balance, when considered over long periods in relatively static airmass situations. Pearson product-moment coefficients of correlation of food temperature in the top center carton of each stack with ambient air temperature were therefore computed.

b. Predictive equations for obtaining mean food storage temperature from ambient air temperature

Daily means and 5-day means were correlated (Table XI and Fig. 20). Correlation coefficients computed for the whole period (22 June to 3 August) ranged from .80 to .95, and all are significant at the 1% level (i.e., the probability of getting such a coefficient by chance fluctuation in the sample size used is .01).

TABLE XI. CORRELATION OF FOOD TEMPERATURE (TOP CENTER CARTON) (I-C) WITH AMBIENT TEMPERATURE

Stack Protection	Regression Equation	Correlation Coefficient
	Daily Means*	
Tight Paulin	47.0 + .59A ± 1.9	.83
Open Stack	8.4 + .90A ± 2.0	.91
Raised Fly	18.6 + .77A ± 2.0	.88
Raised Fly & Foil	31.6 + .62A ± 2.2	.80
	5-day Means**	
Tight Paulin	34.2 + .74A ± 1.5	.89
Open Stack	-4.4 + 1.04A ± 1.4	.95
Raised Fly	5.0 + .92A ± 1.4	.94
Raised Fly & Foil	17.8 + .77A ± 1.5	.90

* 35 days; 4 days (31 July - 3 Aug) omitted, since raised flies were struck during 2 days from 31 July to 1 Aug. because of wind and rain.

**8 periods; last period (1-3 Aug) and last day of 8th period (31 July) omitted for reason shown in footnote above.

Higher coefficients were gained from the 5-day means than from the daily means (See Table XI), confirming the previous observation of a lag

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*See paragraph 12 for derivation of "effective temperature" from mean temperature.

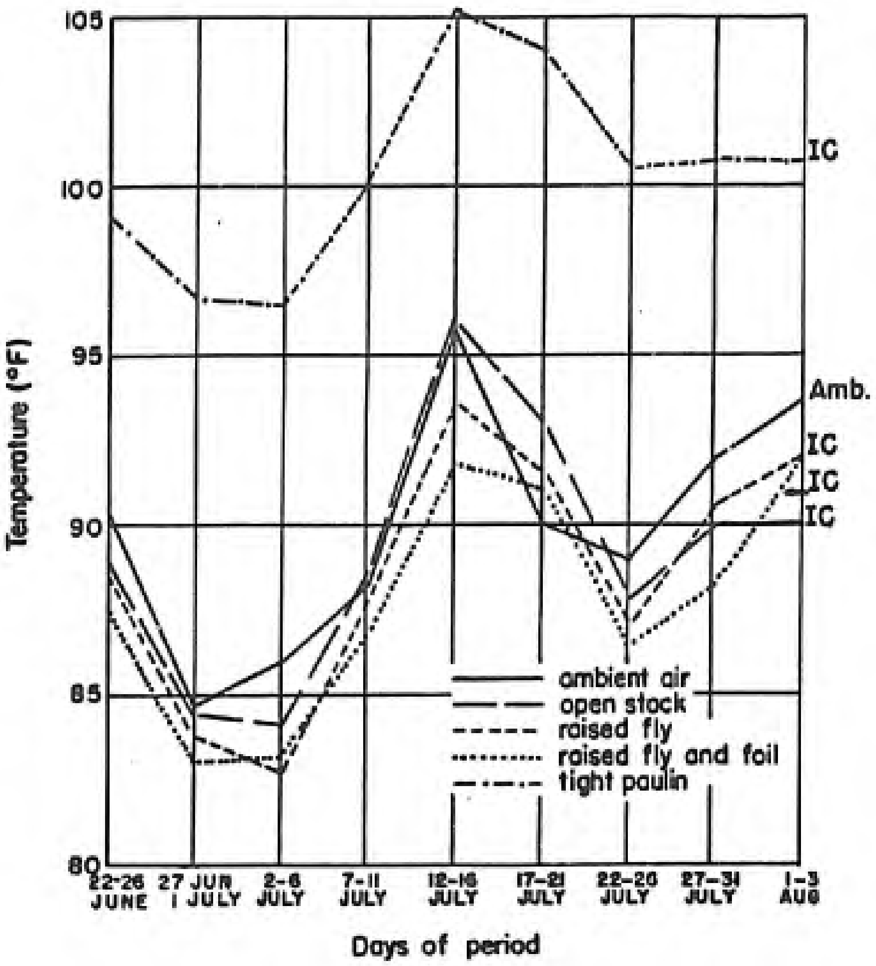

Figure 19. Temperature of food in top carton (I-C) compared with that of ambient air temperature for 4 stacks (mean of nine 5-day periods).

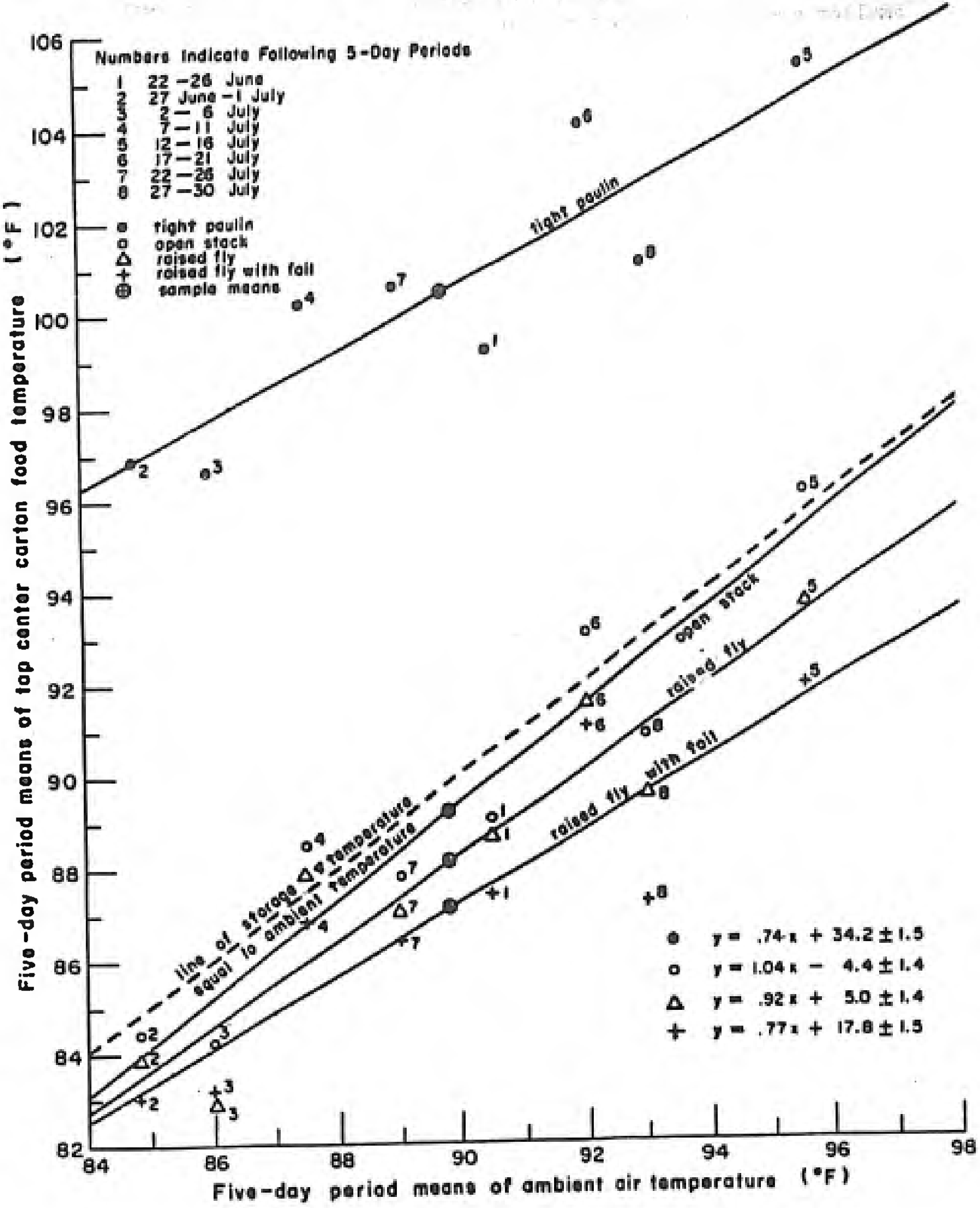

Figure 20. Regression of food temperatures top carton (I-C) on ambient air temperature (means of eight 5-day periods).

in adjustment of food temperature to external conditions. Considering the smaller sample, however, the significance of the coefficient is not greatly changed.

Correlations were also computed for the daily range of food temperature (top center carton) with the daily ambient range. Results are shown in Table XII.

TABLE XII. CORRELATION OF DAILY FOOD TEMPERATURE RANGE (F°) (TOP CENTER CARTON I-C) WITH DAILY AMBIENT TEMPERATURE RANGE FOR 4 STACKS

Stack	Average daily temperature range		Correlation coefficient
	Food (I-C)	Ambient	
Tight paulin	20.7	25	.88
Open stack	14.1		.86
Raised fly	11.7		.67
Raised fly and foil	6.2		.53

The high range of food temperature in the tight paulin stack shows the influence of the paulin wrapped about the stack, making the stack approach a black body (i.e., a good absorber and emitter of radiant energy). The comparatively average ranges of the other three stacks, as expected, show a decrease as stack protection from radiation is improved. The damping of temperature fluctuations and the increased lag in the temperature cycles which result from increased protection, also lower the temperature range correlation coefficients in the last two stacks.*

c. Application to other climatic and storage conditions

The predictive equations developed above apply strictly only within the range of climatic and storage conditions analogous to those observed at Yuma. However, since situations of extreme heat stress very often occur under similar static hot-dry airmass conditions, relatively good predictions may be made of the temperature extremes and means to which food will be subjected in dump storage if 5-day or monthly ambient mean temperatures are available.

That is, the monthly free air temperature means in a given area may be used to predict approximate effective storage temperatures in the area and for the period concerned, if the range of prediction is restricted

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*Some of the change in correlation coefficient may be more apparent than real, since with reduced range, errors of precision due to instrument sensitivity and rounding-off become more important.

to the range of this study (Figs. 19 and 20). The arithmetic mean of several monthly effective temperatures (or the logarithmically averaged effective mean of these effective temperatures, when inter-month range is greater than 20F°) will serve as an effective temperature for a period of several months. Storage life predictions may then be made using the degradation-temperature function if an arbitrary percentage degradation standard is set up corresponding to maximum safe storage life.*

Extrapolation of prediction to other types of climate, other types of stored goods, different histories of storage exposure, and different stack orientation would be less dependable. However, as in the boxcar study, the conditions and stored goods represented in these data approach the extremes of short-period, summer storage heat stress.

14. Effect of moist airmasses on effective temperature predictions

a. Subperiod of increased effective temperature, at time of decreased solar radiation

The change in climatic regime which divided the research period into two subperiods (see par. 4, Part I) produced a noticeable increase in ambient mean temperatures and in storage mean temperatures. This is clearly shown by the use of 5-day means in Figure 19 and Table XIII. A comparison of mean temperatures for the whole period and for the two subperiods (Table XIV) also illustrates this.

The ambient and storage means for the second subperiod are elevated above the corresponding means for the first subperiod by two factors: substantial increase in the daily minima and small increase in the daily maxima (thus decreasing the daily range). The increase in minimum temperatures is most abrupt after 13 July, the beginning of the second subperiod.

The contrasting climatic conditions of the two subperiods are shown in Figure 21. Total solar radiation (direct and indirect) received on a horizontal surface per day, number of hours of cloudiness, days with precipitation, and daily mean mixing ratio (grams of water vapor in a kilogram of dry air) are shown, together with 5-day mean ambient and food storage temperatures (I-C) in the open stack.

Total radiation falls sharply in the second subperiod, largely because of the increase in cloudiness. Mean mixing ratio begins to rise on 10 July.

Since the daily input of solar radiation is lower during the second subperiod, the substantial increase in daily minima during this subperiod must be attributed to a reduction of net outgoing nighttime long-wave radiation. Other possible contributory climatic variables (such as vertical distribution of temperature and the mean temperature between the surface and 10,000-foot levels and nocturnal windspeed) are essentially

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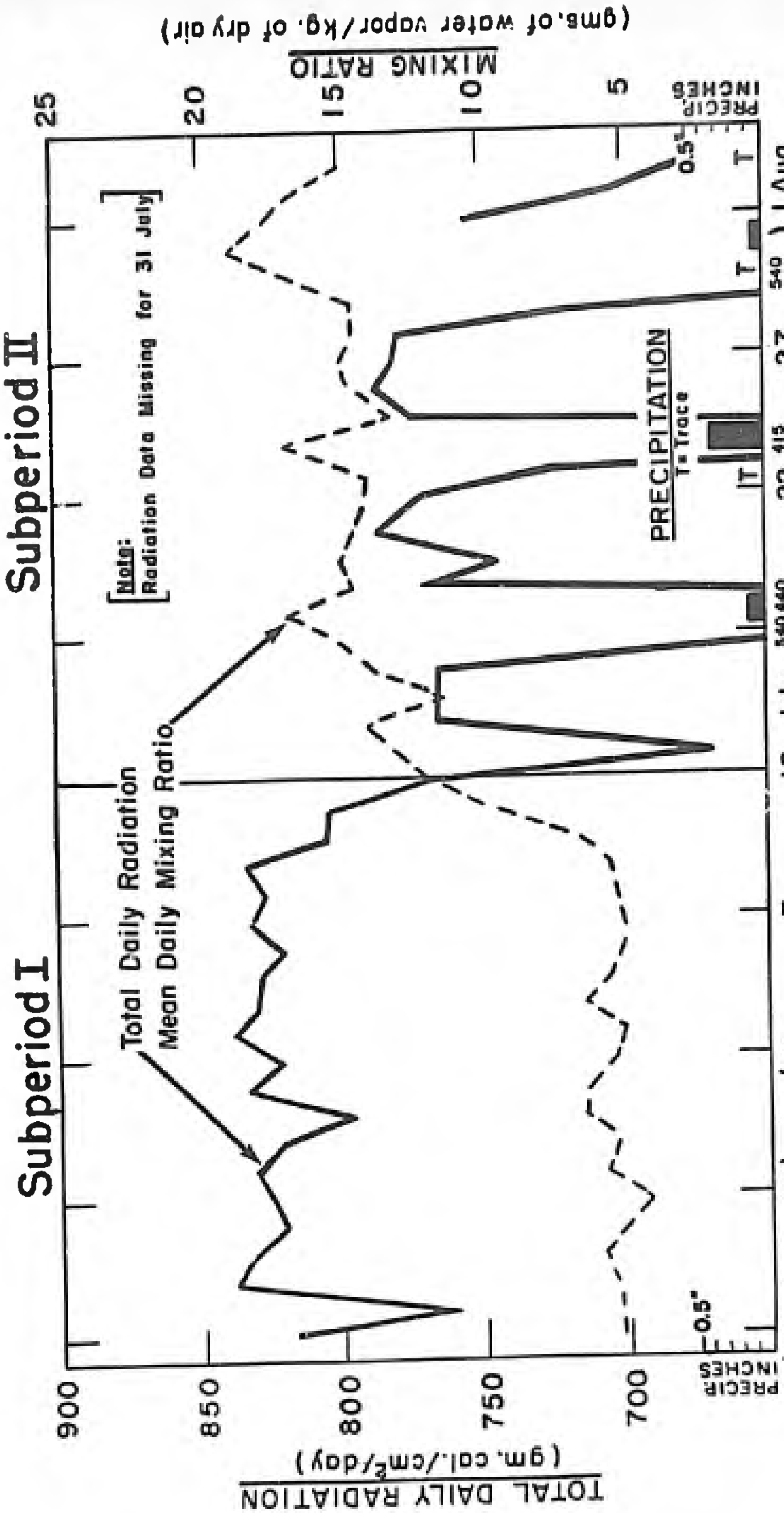
*In other words, if the storage life corresponding to maximum permissible degradation is known at one temperature.


Subperiod I
Subperiod II
Total Daily Radiation
Mean Daily Mixing Ratio
Note: Radiation Data Missing for 31 July
PRECIPITATION
T= Trace
TOTAL DAILY RADIATION
(gm. cal./cm²/day)
900
850
800
750
700
PRECIP. INCHES
0.5"
MIXING RATIO
(gms. of water vapor / kg. of dry air)
25
20
15
10
5
PRECIP. INCHES
0.5"
(22
June
27)
(2
7
12
July
22
27
) 1 Aug
540
440
415
540
T
T
T

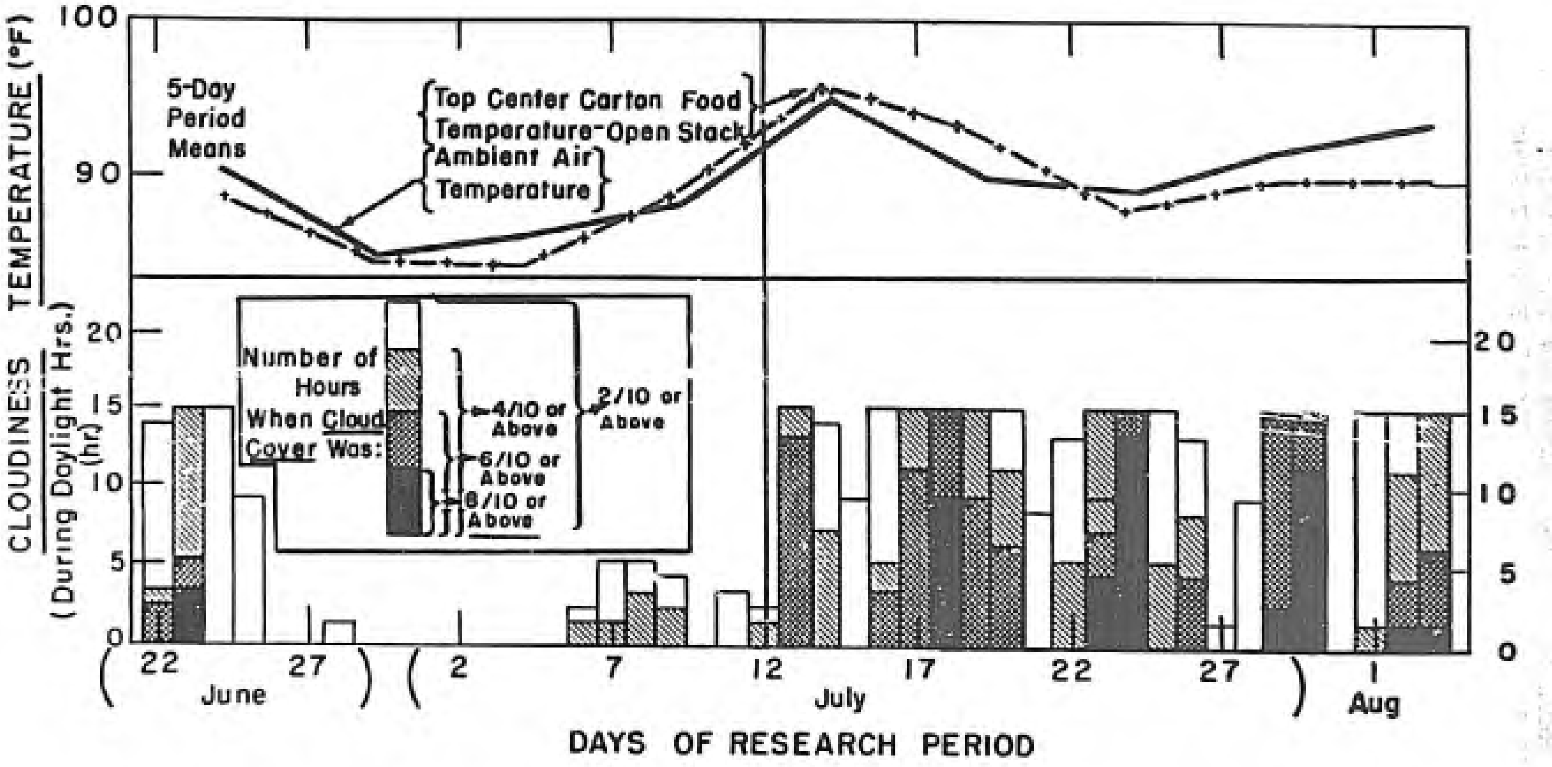


Figure 21. Storage and ambient conditions in contrasting climatic subperiods.

TABLE XIII. MEANS OF FOOD TEMPERATURE TOP CENTER CARTON FOOD (I-C) AND AMBIENT TEMPERATURE, 5-DAY PERIODS, DURING 2 SUBPERIODS
(°F)

Period	Mean ambient temperature	Mean temperature top center carton food			
		Open stack	Raised fly stack	Tight Paulin	Raised fly with foil
			Subperiod I		
22-26 June	90.4	89.0	88.6	99.2	87.4
27 June-1 Jul	84.8	84.4	83.8	96.8	83.0
2-6 July	86.0	84.2	82.8	96.6	83.2
7-11 July	87.5	88.5	87.8	100.2	86.8
			Subperiod II		
12-16 July	95.6	96.0	93.6	105.2	91.8
17,21 July*	92.0	93.0	91.5	104.0	91.0
22-26 July	89.0	87.8	87.0	100.6	86.4
27-31 July	92.0	90.0	90.6	100.8	88.2
1-3 Aug**	93.7	90.0	92.0	100.7	92.0

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* 3 days storage temperature data missing: 18, 19, 20 July.
**Period 3 days in duration only.

TABLE XIV. MEAN STORAGE TEMPERATURES ALL LOCATIONS FOR TWO CLIMATIC SUBPERIODS
(°F)

Time	Mean ambient temperature	Mean storage temperature			
		Open stack	Raised fly stack	Tight Paulin	Raised fly with foil
			All days of period		
22 Jun-3 Aug	89.9	89.0	88.2	100.1	87.3
			Subperiod I*		
22 Jun-12 Jul	87.1	86.5	85.8	98.1	85.1
			Subperiod II		
13 Jul-3 Aug	92.6	91.3	90.9	102.2	89.6

---

*Division point between the two periods for this table is one day later than that for Table XIII, since the 5-day periods used in Table XIII overlap slightly the climatic subperiod division point.

similar in the two subperiods.* It seems probable from the data that the reduction in radiative loss can be ascribed to back radiation from both the increased water-vapor content of the airmass and from cloudiness at high altitudes (Hubley, Richard C., 1957). The small increases in daily maxima are not unexpected in spite of reduced solar radiation, since minimum temperatures are high.

b. <u>Use of soil temperature data to indicate relative contribution of moisture content and cloud cover to increased temperature</u>

A similar behavior in the two subperiods is exhibited by soil surface temperature (Table XV). Daily minima rise about 14F° in the second subperiod, maxima increasing only 4F°, with a resultant mean temperature increase of nearly 10F°.

TABLE XV. SOIL SURFACE TEMPERATURES (°F) YUMA TEST STATION

July	Max.	Min.	Mean	Range	Subperiod Means
			Subperiod I		
7	143	66	104	77	105.2
8	146	66	106	80	
9	141	68	104	73	
10	146	66	106	80	
11	136	69	102	67	
12	147	69	108	78	
			Subperiod II		
13	147	83	115	64	114.4
14	150	84	117	66	
15	149	84	116	65	
16	142	87	114	55	
17	135	84	110	51	

It is difficult to separate the contribution to the back radiation that is due to water vapor in the airmass from that due to nighttime cloudiness, because high moisture content and cloud cover at a high altitude often occur together. Soil temperature behavior on nights before and after the climatic change (Fig. 22, Table XVI) may be used for a rough empirical estimate of these relative contributions, because it is a good index of energy balance at a horizontal surface (and indeed shows high correlation with mean storage temperatures, particularly in the open stack).

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*Bryson, R. A. and Lowry, W. P., 1955, p. 329, show mean soundings at Phoenix, Arizona, for a 5-year period. Moisture at all levels is greatly increased after 1 July, but the dry-bulb temperature distribution below 700 millibars is shifted very little, the warming amounting to only 2F°.

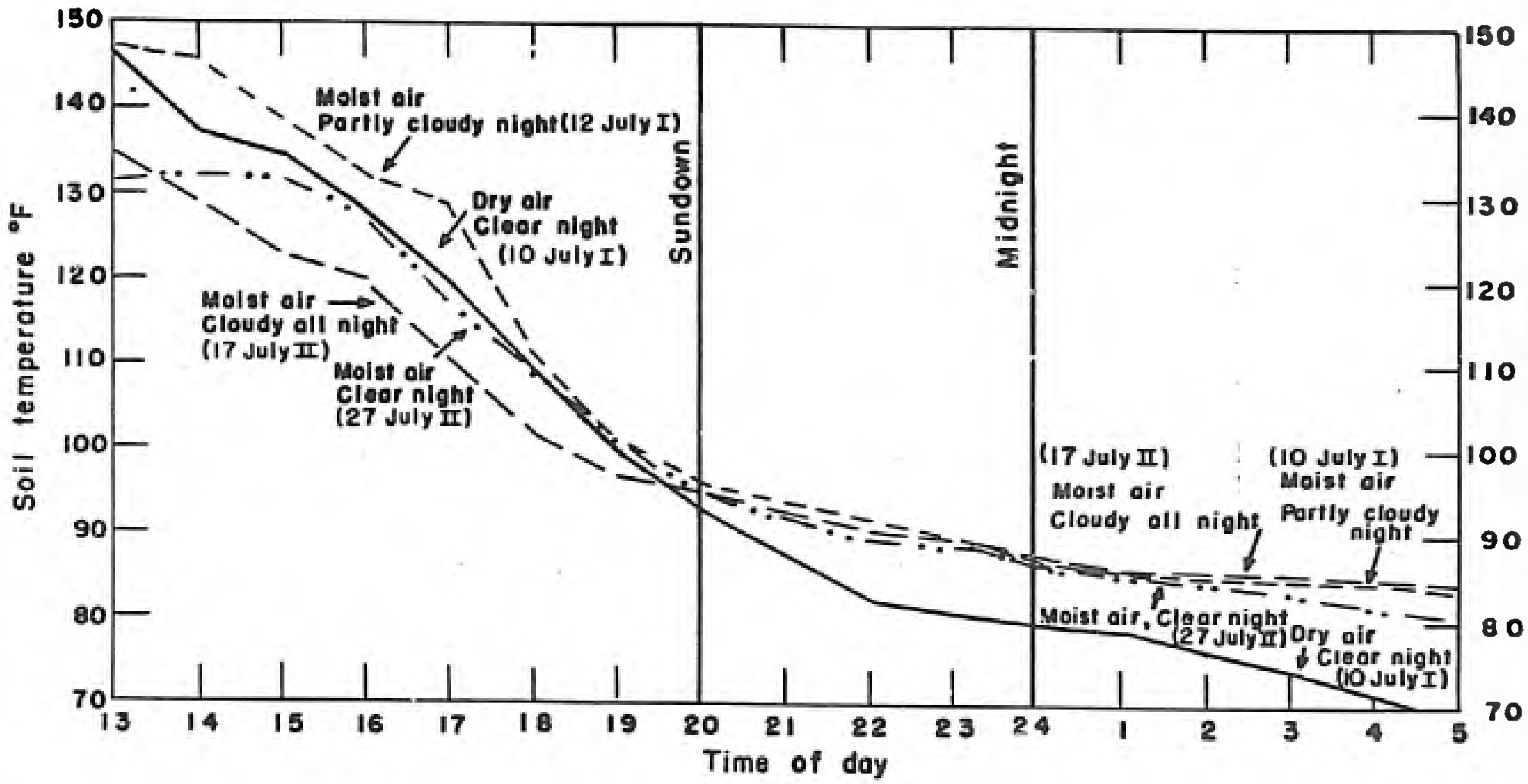

Figure 22. Soil surface temperature decrease and attendant conditions on selected days in two climatic subperiods.
["Nighttime" of July 10, 12, 17 or 27 includes the after-midnight hours, i.e., early morning of July 11, 13, 18 or 28.]

TABLE XVI. NIGHTTIME SOIL TEMPERATURE DECREASE (°F) RELATED TO CLOUD COVER AND AIR MOISTURE FOR 2 DAYS IN 2 SUBPERIODS (2030 to 0530 HOURS)

Soil Temp Fall (°F)	Mean Mix. Ratio* (g/kg)	Mean Wind-speed (mph)	Mean Cloud cover (tenths)	Soil Temp Fall (°F)	Mean Mix. Ratio* (g/kg)	Mean Wind-speed (mph)	Mean Cloud cover (tenths)
Subperiod I							
10 July				12 July			
23.4	6.9	11.7	0	12.8	11.4	3.4	0 to 7
(Dry air - clear night)				(Moist air - partly cloudy night)			
Subperiod II							
17 July				27 July			
11.6	14.4	7.9	7	14.0	14.8	7.9	<2
(Moist air - cloudy night)				(Moist air - clear night)			

*Mean mixing ratio = absolute water vapor content of air.
NOTE: "Nighttime" of July 10, 12, 17, 27 is here presumed to include the after-midnight hours, i.e., the early morning hours of July 11, 13, 18 or 28.

The drop from daily maximum soil temperature to nighttime minima depends largely on net long-wave radiation loss from the soil surface on nights with little wind (i.e., when there is little additional loss of heat caused by mechanical convection). The soil temperature decrease from sundown to time of daily minimum roughly measures this loss (since solar radiation effects are eliminated if days with similar soil temperatures at sundown are chosen). Four nights are illustrated in Figure 22 and Table XVI: one dry, clear night and one moist cloudy night from the first subperiod, and a moist, cloudy and a moist, clear night in the second.

On the night of 10 July (first subperiod), sky conditions were generally clear and absolute water-vapor content of the air (mean mixing ratio) was low; the nighttime soil temperature drop was nearly 24F°. On the night of 17 July (second subperiod), sky conditions were cloudy (thin, high altocumulus clouds) and water-vapor content had risen to more than twice its former value; the soil temperature drop was reduced to about 12F°. The back radiation responsible for this reduction came from both water vapor and cloud cover. However, on 27 July, deep in the second subperiod, there was a similarly reduced temperature fall of only 14F° (only about 2F° greater than on 17 July) when the sky was nearly clear, but moisture content of the air was high. This suggests that back radiation from high water vapor alone is nearly as effective in raising minima as the combined back radiation from water vapor and a cloud cover of thin, high clouds* (Ohman and Pratt, 1956).

The increase in effective storage temperatures during periods of decreased solar radiation but at the same time greater moisture content and nighttime cloud in the atmosphere has widespread implications. In an area where moisture content of air or nighttime cloudiness or both are high, and daytime solar radiation is equal to that at Yuma, it would be possible to observe even higher effective summer storage temperatures than those found in this research.

c. Examples: Marianas and Bahrein Island

As an example, a reliable report of a top carton air temperature of 125°F in a tight paulin stack, when maximum ambient air temperature was only 89°F, was received from a depot in the Mariana Islands (S.W. Pacific, 15° N) (in a reply to a Quartermaster Corps questionnaire-survey of storage dumps in 1945).** Dewpoints were 68 to 70°F, varying little throughout the day or season. Effective storage temperature for the day would be 108°F, 27F° above ambient mean temperature, as contrasted with the Yuma

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* The above interpretation of the data omits: (1) the effect of windspeed, and (2) the requirement for moisture at all levels besides that at ground level to give effective back radiation. With regard to the first, however, the mean windspeed during the dry, clear night (great temperature fall to low minimum) was substantially higher than that on the moist nights (reduced temperature fall). On the nights of 17 and 27 July, mean moisture contents and mean windspeeds were similar. Although one night was cloudy and the other clear, temperature drops were roughly equal. Air temperatures were similar throughout both nights and were 1 to 2F° above soil surface temperatures.

In answer to the second objection, it must be admitted that moisture content of surface air is not necessarily an index of moisture content aloft and that a relatively thick layer of moist air is necessary for appreciable back radiation from water vapor. However, upper air soundings taken during a comparable period of increased surface dew points at Yuma (8 August 1954) (Ohman and Pratt, 1956) and at Phoenix (Bryson and Lowry, 1955) reveal increased moisture at all levels up to 16,000 feet, as might be expected if the main moisture source is modified air whose origin was the Gulf of Mexico (see above under Climatic Summary, par. 4). The moisture in such air, which has been transported across Texas, New Mexico, and Arizona, is distributed to high levels by convection along the unstable lapse rates due to surface heating in the deserts traversed. Thunderstorms along the desert and mountain trajectory of such air greatly reduce its original moisture content, but a substantial amount remains to high levels. The present writers conclude that this moisture content is adequate to account for much of the observed raising of daily minima discussed above.

**See Table III. Substantially similar results were obtained at the same time from a depot on an island 1,000 miles southwest (Pelelieu of the Caroline Islands), but in the same climatic regime.

tight paulin stack, which had an effective temperature only 10F° in excess of ambient mean. This effective temperature, nearly the same as those at Yuma on the hottest day would, unlike the Yuma value, be sustained near this level for much of the summer half of the year. (Mean ambient temperature in the Marianas fluctuates only about 2F° in the year; solar altitude and length of day differ little during 6 months.) In fact, during the so-called "winter" 6 months at these low-latitude stations, solar radiation, and more important, the net daily energy balance from both short-wave and long-wave radiation, would be relatively little changed, since solar altitude at noon is still above 50° , the length of day is little changed, and daytime cloud cover is reduced. The nighttime temperature minima are sustained at high levels by the maritime reduction of daily temperature range and by back radiation from the very moist airmass and partly cloudy conditions which still prevail.

To cite another example: Bahrein Island in the Persian Gulf (27° N) has high solar radiation, relatively long summer days, dewpoints which consistently average 10 to 15F° above those of the moist period at Yuma, and mean temperature in the summer comparable to Yuma.

d. General implications

In view of the effects of high airmass moisture content on storage temperatures as suggested above, it seems probable that summer storage stresses at stations influenced by the Red Sea, Persian Gulf, Gulf of Aden, or northern Indian Ocean and other similarly situated tropical, quasi-maritime stations, might be more severe than those at Yuma, provided that moisture content at upper levels is large.

If one considers the total year-round effective storage temperature, stations within about 20 degrees of the equator that have: 1) high airmass moisture content but 2) limited daytime cloudiness and 3) a high mean annual temperature, must be considered to have the severest longterm high temperature storage stress on the globe. These stations undoubtedly surpass in this regard such areas as the southwestern U. S., the Sahara, or inland Iran, commonly regarded as the "hot poles" of the earth.

PART IV. COMPARISON OF EFFECTIVENESS OF 4 TYPES OF STACKS

15. Mean and maximum temperatures and ranges of temperature

In much of the foregoing discussion, there has been implicit a comparison of the relative temperature stress in the four types of stack exposure. It has been shown that both on the most extreme days and over the entire period, the tight paulin stack experiences higher temperatures and more prolonged high temperatures than any of the other stacks. The other 3 stacks are quite similar to each other in the lower storage hazard they present. In addition, the storage conditions in these other 3 stacks are roughly homogeneous from surface to interior, whereas the surface cartons in the tight paulin stack are more extreme in all storage temperature indices than the interior cartons.

Table XVII sums up the data for the various forms of exposure in four categories: absolute extremes, mean extremes, ranges and means of temperature.

TABLE XVII. COMPARISON OF MEAN AND MAXIMUM TEMPERATURES (°F) FOR 4 STACKS FOR TOP CENTER CARTON FOOD (I-C)

Stack	Absolute		Mean		Range*			Mean of Daily Means	Mean by Graph. Integ**	Effective Temp***
	Max.	Min.	Max.	Min.	Lrg.	Sml.	Mean			
Tight paulin	118	84	110	90	28	8	21	100	101	102
Open stack	107	74	96	82	19	4	14	89	91	91
Raised fly	104	74	94	82	16	1	12	88	90	90
Raised fly with foil	97	77	90	84	11	1	6	87	89	89
Ambient air	114	67	102	77	36	12	25	90	92	--

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* Range: Largest, Smallest & Mean.
** Mean by graphical integration for entire period.
***Effective storage temperature for entire period.

In general, it may be said that the effect of the increased protection ranging from the most severe exposure (tight paulin) to the least severe (raised-fly-with-foil) is to decrease both mean and range, by markedly decreasing maximum temperatures from the levels of the tight paulin stack and moderately decreasing minimum temperatures. As a rough rule, it may be stated that both on critical days and for the entire period, the tight paulin stack surface cartons are at least 10F° higher in maximum and mean temperatures, and the interior cartons at least 5F° higher. Effective storage temperatures in the most critical cartons are at least 11F° higher in the tight paulin stack than in the other stacks. If one assumes a doubled food degradation rate for every 18F° temperature rise, food in any of the less severe stacks would last at least 50 percent longer. There is little difference in storage life under conditions of maximal protection (raised-fly-with-foil) from that in the raised-fly or open stack, assuming that no critical food temperature* is exceeded.

16. Relative frequency of high temperatures

Table XVIII (and Figure 14, from which it was derived) show the food temperatures below which 50% and 80%, respectively, of the research period was spent in the top center carton (I-C) in each of the stacks.

TABLE XVIII. FREQUENCY OF TOP CARTON FOOD TEMPERATURES (I-C)
(for 4 stacks)

Type of stack	During 50% of period, temp was below	During 80% of period temp was above	and	below
Tight Paulin	101	95		108
Open stack	91	85		96
Raised Fly	90	85		94
Raised fly with foil	89	85		92

It is evident that for a major portion (80 percent) of the research period, temperatures were above 95°F in the tight paulin stack and that for an equal percentage of the period they were below approximately 95°F in the other stacks. Comparison of Figures 14 and 23 shows also that the relative storage severity, and conversely the amount of protection afforded in the less severe forms of exposure, increases noticeably at higher temperatures.

The relative severity of the storage environment created by conventional tight-paulin coverings for dump storage has been amply

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* As, for example, a melting point.

documented by this research. However, the threat of thorough wetting by rainstorms, which are sporadic in the desert, but often occur daily in the wet tropics, requires that some form of shelter be provided for the exposed stack. Two such improved forms of shelter (raised paulin, raised paulin with foil) were investigated in this research. Effective temperature was satisfactorily reduced and shelter from precipitation would be adequate in most situations, but it should be reported that some wind damage to the shelters occurred and it was necessary to collapse them during two storm periods. For a description of their performance and suggested types of more durable shelters, the reader is referred to manuscript reports available from Natick QM R&E Command (Porter, 1955).

Conclusions

Observations of high temperatures in a typical Quartermaster storage dump under conditions of extreme heat accumulation lead to the following conclusions:

a. The tight paulin stack (complete enclosure of a storage stack by a paulin lashed tightly about the base) creates a storage environment appreciably more severe than other forms of

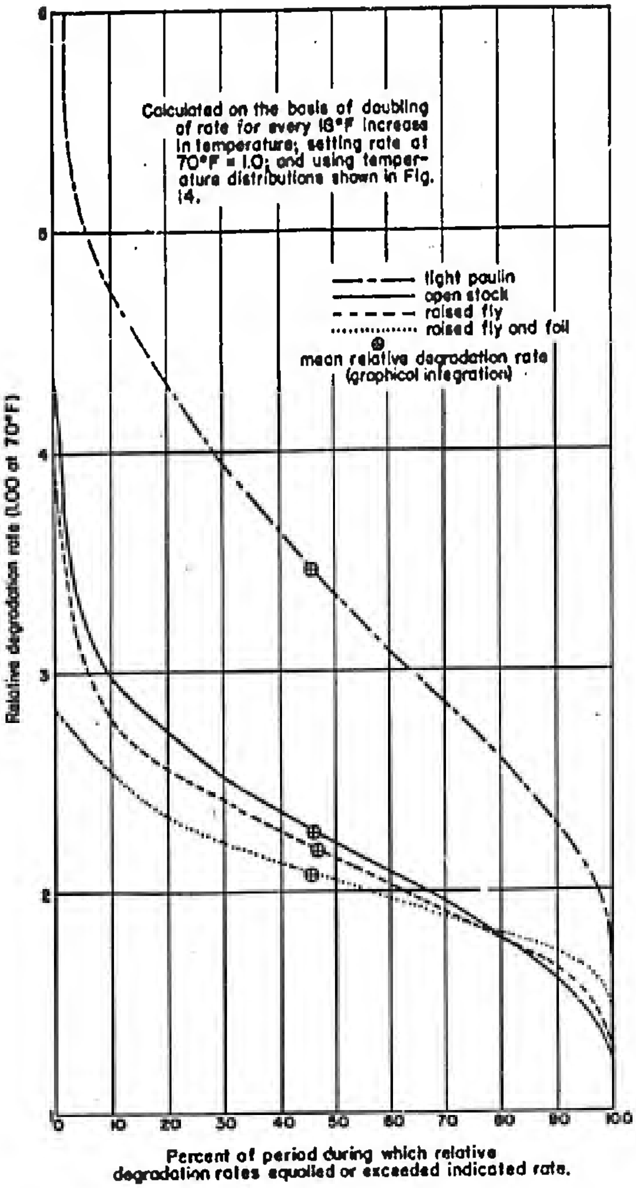

Figure 23. Cumulative frequency distribution of relative degradation rates.

stack exposure, which differ little among themselves in the long-term stress imposed on stored items. Daily maximum, minimum, and daily mean temperatures and range of temperature are increased at all positions in the stack by the tight paulin covering. Maximum and mean temperatures are usually well above corresponding ambient air temperatures. The top center carton food in the tight paulin stack has an effective summer storage temperature 11F° above that of the other forms of stack exposure, although the interior cartons (16 percent of total) of this stack are only 5F° higher in this index than the other stacks. Stated in other terms, summer storage life is increased (in 84 percent of the stack) about 50 percent by removal of the tight paulin covering, at the food ageing rate assumed.

b. Among the three other forms of stack exposure observed (open stack, raised-fly, and raised-fly-with-foil) there is little difference in storage severity except at peak values of temperature, which are noticeably lowered by increased protection. The lowered maxima are partly counteracted by slight increases in minima with increased protection, so that effective storage temperatures for these three stacks differ by less than 2F°. On critical days, temperature maxima and means in these stacks are seldom higher than corresponding ambient air values.

c. Absolute maximum temperature of top center carton air in the tight paulin stack was 128°F, the highest carton temperature observed. The highest food temperature, 118°F, was also observed here. The paulin under-surface in this stack has been observed to reach 171°F. In other types of stack exposure, no carton air maxima were observed above 112°F.

d. Daily maxima in top center carton food in the tight paulin stack were 115°F or over on 15 percent of the days observed and all maxima in this stack were over 100°F. In the raised-fly-with-foil stack (maximum protection) on the other hand, maxima were over 95°F on 16 percent of the days, but never over 100°F.

e. Standard daily cumulative temperature cycles derived for top center carton food temperature in each stack are somewhat less dependable in preparation of cumulative temperature frequency distributions than in the boxcar study, because curves for individual days have greater deviation from the standard. In the cumulative frequency distributions thus prepared, 56 percent of all half-hourly temperatures in top center carton food in the tight paulin stack were over 100°F and 12 percent were over 110°F for the whole period. No readings over 100°F occurred at the comparable position in the raised-fly-with-foil stack.

f. In the interior cartons of the tight paulin stack, the mean food temperature for the period (here identical with "effective" mean) is 7F° lower than the surface carton mean food temperature and 9F° lower than surface carton effective food temperature. However, in the other three stacks, surface differs little from interior and one stack differs little from another stack in effective food temperatures.

g. Significant correlations were found between food temperature means (daily and 5-day) in the top center cartons and ambient air temperature means. Linear regression equations permit limited extrapolation and prediction of food temperature means and effective food temperatures in other subtropical, hot-dry areas with static airmass conditions, similar temperature ranges and dump types.

h. Effective food storage temperatures may be derived by graphical integration of cumulative degradation curves, or by addition of effective temperature increments, from tables based on food temperature range, to food mean temperature. Effective monthly storage temperatures may be effectively averaged (i.e., logarithmically) to give effective seasonal or yearly storage temperatures. In the research reported here, effective storage temperatures differ by at most 2F° from arithmetic mean food temperature. They range from 102°F in the tight paulin stack to about 90°F in the other three stacks. The tight paulin stack temperature is almost identical with that found for the comparable period and carton in boxcar storage. The temperature in the other stacks indicates a much less severe environment than the boxcar, and is similar to those observed for a corresponding month at the top of a stack within a Quartermaster warehouse in the midwestern and southwestern continental interior of the United States (Sissenwine, 1951).

i. Mean storage temperatures and ambient mean temperatures rose noticeably during the second climatic subperiod of the research, when daily radiation was reduced as thin cloudiness and water vapor content of air increased. Increase in mean temperature results from a rise in daily minimum temperatures due to back radiation from airmass water vapor and nighttime cloudiness. This finding implies that greatest long-term storage temperature stress will probably be found at stations below about 20° latitude with high airmass moisture, high mean annual temperature and limited daytime cloudiness, and not, in general, in subtropical deserts.

j. Both in severity and in the difference between surface and interior of storage, the tight paulin stack resembles the boxcar; these are two of the most extreme storage environments yet observed. Any other form of dump exposure is highly preferable from a temperature stress point of view, and would seem mandatory for long-term storage in continuously hot climates, providing logistics requirements of weather protection, wind resistance, tactical convenience, cost, and camouflage may be met.

Recommendations for food testing temperatures

As in the boxcar research, temperatures suggested for oven-testing of food stability will be given in two forms: (1) cycle of temperature for most critical day and (2) effective storage temperatures to duplicate the hottest month and hottest 4 months of the Yuma summer.

It is proposed that for oven simulation, 130°F be considered the extreme carton air temperature to be expected in the most critical carton of food on any day anywhere, if there is a chance that a paulin will be tightly wrapped around the stored food. It is further proposed that 6 hours of sustained carton air temperature at or above 120°F accompany this maximum. The recommended carton air (or oven) temperature cycle for this extreme day (which at Yuma may be expected to occur once in the average month of July) is as follows: (1) 5 hours steady rise from 95°F to 120°F, (2) 3 hours steady slow rise from 120°F to a peak of 130°F, (3) 5 hours steady fall from 130°F to 107°F, (4) 11 hours steady slow fall to 95°F. Effective temperature for constant-temperature duplication of this 1-day cycle is 114°F (Q_{10} rating of 2). However, if there is assurance that a form of stack protection will be used that allows circulation of air (raised fly or raised-fly-with-foil), the peak of the model cycle can be reduced to 105°F, with 8 hours of sustained temperature above 100°F and a minimum of 90°F. Effective temperature for constant-temperature simulation is 98°F. (Radiation load need not be considered in oven simulation.)

The effective storage (oven) temperatures recommended to simulate for food in the hottest carton the hottest month and hottest 4 months of a normal summer at Yuma are shown in Table XIX.*

TABLE XIX. RECOMMENDED EFFECTIVE FOOD STORAGE TEMPERATURES (°F) FOR SIMULATION OF THE HOTTEST MONTH (JULY) AND FOUR HOTTEST MONTHS OF THE NORMAL YUMA SUMMER*
(Top center carton food, I-C)

Stack	June	July**	August	Sept.	4 Months
Tight paulin	98	103	102	98	100.3
Open stack	84	91	90	84	88.0
Raised fly	84	90	89	84	86.8
Raised-fly-with-foil	83	88	88	83	86.0
Ambient air	84.7	91.3	90.5	84.8	(87.8)***

* Based on ambient air monthly mean temperature normals for 70-year record at Yuma (city).
** Hottest month.
***Arithmetic, not effective mean.

The effective storage temperatures derived above for the 4 summer months at Yuma give added justification** for the continued use of a

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* The method of deriving these temperatures from climatic data is explained in Appendix B.

**Comparable recommendations for effective storage temperatures from the Yuma boxcar research were 103°F for the hottest month and 98°F for the hottest 4 months.

constant oven-testing temperature of 6 months at 100°F as a stability criterion for foods having cumulative degradation reactions of Q_{10} rating of 2.

Acknowledgements

The cooperation of many individuals was essential in the planning and prosecution of this study. Mention is made herein only of those most directly concerned, but the authors are indebted to many other persons who helped in the work.

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Subsistence items for use in the research stacks were procured through the efforts of Mr. George W. Kitzmiller, Chief, Care and Preservation Section, Storage Branch, Installations Division, OQMG, and the personnel of Sharpe General Depot, Lathrop, California. Modified paulins for use on stacks were furnished by Mr. Ernest W. Downs, Tentage and Equipage Branch, Textile, Clothing and Footwear Division. Ground anchors for experimental use on paulins were provided by Mr. C. V. Horrigan, Mechanical Engineering Division. Thermocouples were installed in certain food containers and advice on the food deterioration aspects of the project was obtained through the assistance of Dr. Jack H. Mitchell, Chief, Chemistry and Microbiology Branch, Quartermaster Food and Container Institute for the Armed Forces, Chicago.

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Most of the data analysis was carried out by Sp-3 Nico H. Roos, Environmental Analysis Branch, the junior author, under the direction of the senior author. Sp-3 Roos is also the author of substantial portions of the manuscript. The criticism of Dr. David H. Miller, Environmental Analysis Branch, was invaluable in analysis and critical reading of the manuscript for which the authors are also indebted to Dr. William B. Brierly and Mr. Llewelyn Williams of the same Branch. Machine processing of data was carried out by the Data Processing Section, EPRD, under the direction of Mr. James J. Dillon. Figures for the report were executed by Miss Gertrude Barry and Miss Rebecca Brockelbank, Cartographic Draftsmen, Environmental Protection Research Division.

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APPENDIX A

SURFACE TEMPERATURES AT CRITICAL POSITIONS

OUTSIDE OF CARTONS

It may be of interest to compare the absolute maximum temperatures attained during the research period according to the various surfaces transmitting radiant energy and energy in the form of sensible heat to the stack proper. These surfaces include the outer carton surfaces, the paulin flies, and the reflective foil used on one stack. Data for the positions observed (Positions VIIIS, IXS, and XS) are presented in Table II of the text.

On 15 July (the hottest day), the under-surface of the paulin lashed to the tight paulin stack attained maximum and mean temperatures of 159°F and 118°F, respectively, as recorded by a thermocouple threaded into an under-surface seam. However, this is one of the few temperatures measured that was not at peak on 15 July; the absolute maximum for this position was 171°F, on 27 June. This latter temperature is undoubtedly related to high hourly and daily total radiation (826 langleys) and low windspeed (calm to 2 mph before the time of maximum). In general, temperatures on such upper surfaces and in air immediately beneath them in both dumps and boxcars show a quick response to changes in radiation and windspeed. Temperatures within the cartons, on the other hand, respond more slowly to outside conditions, as might be expected, and are often more related to a high morning minimum temperature within the carton and to the temperature history of the rest of the storage stack than to the particular radiation and wind conditions of the day concerned.

Data given in Table III of this report, comparing the results of this study with those of other storage studies, show that there is a good agreement as to peak maximum and mean temperatures reached by such surfaces, or the immediately subjacent air, in various forms and locations of storage. In general, the excess of paulin surface maximum temperature over ambient air maximum is 45 to 55F° in the tight paulin stack. Air immediately below the paulin would show the same excess caused by a net flux of radiant energy into the surface and the space, with resultant heat accumulation.

Paulin surface temperatures reach minima about 10F° below ambient temperature minima. This phenomenon was also observed in boxcar air 6 inches below the roof at minimum temperature. At this time the net flux of radiation is out of the surface to the sky. The energy loss results in sharper drops of paulin surface temperature than soil surface temperatures. On 27 June, the day when the paulin surface maximum of 171°F was recorded, the paulin surface minimum was 10F° below the ambient minimum of 67°F (i.e., it was 57°F) while the soil surface was only 5F° below it (i.e., 62°F). The resultant paulin surface temperature range of 114F° is rather startling when compared to the soil surface range of 78F°.

The raised fly over the fly-with-foil stack also showed high surface temperature maxima, reaching a maximum of 152°F on 15 July (Table II), a value approaching that observed on the tight paulin surface. It may be inferred that, in spite of the greater ventilation it receives from beneath, it also responds strongly to solar radiation received. At the resulting high temperature, it constitutes a large source of radiant energy for the stack below. It was for this reason that reflective foil was used to cover the surface of the fourth research stack below the raised fly.

The protective effect of the foil on extremely hot days is convincingly shown by the comparison of the temperatures at Position X-S, the lower surface of the outer protective sleeve of the surface carton in the raised-fly and raised-fly-with-foil stacks (Table II). There is a difference of 8F° at maximum and 4F° in mean temperature between these two stacks at this position.

APPENDIX B

METHOD OF COMPUTING EFFECTIVE STORAGE TEMPERATURES FROM CLIMATIC DATA

Effective storage temperatures as used in this report may be easily derived from climatic data which include monthly mean temperature normals, if these are a good measure of the true mean (arithmetic mean of 24 hourly observations). They may be calculated by the methods of this report whenever the dump type, the rate of food degradation as a function of temperature, and the climatic situation are analogous to the conditions described in this report.

Mean food temperatures for each month desired are predicted from ambient air monthly mean temperature normals by use of the appropriate relation from Figure 20. An increment to compensate for daily fluctuation is obtained from the following table and added to the food temperature monthly mean to yield the effective temperature for the month concerned:

TABLE XX. EFFECTIVE TEMPERATURE INCREMENTS* TO COMPENSATE FOR DAILY FLUCTUATIONS (°F)

Corresponding dump type	Daily range of food temp	Increment**
Raised-fly-with-foil	10	0.2
Open stack & raised-fly stack	15	0.5
Tight Paulin	20	0.9
Can in single isolated carton covered with paulin	25	1.5
	30	2.2
	40	3.8

---

* The table is based on the assumption of a sinusoidal food temperature daily cycle and a doubling of degradation rate for every 18F° rise in temperature (Q_{10} of 2). If there is good reason to suppose that the daily mean has a considerable range during the month concerned, an additional increment corresponding to the best estimate of that range should be read from the above table and added to the increment for daily range. For this purpose, the monthly range of ambient daily mean temperature may be used, since it is approximately equal to the corresponding range of food daily mean temperature.

**Increment: Effective temperature minus food mean temperature.

Several monthly effective temperatures may be effectively averaged to yield an effective temperature for the entire period concerned. The method is as follows: the relative severity of storage corresponding to each effective monthly temperature is obtained by linear interpolation in the table below:

TABLE XXI. RELATIVE SEVERITY OF STORAGE AT DIFFERENT TEMPERATURES

Effective Temperature	Relative Severity* (with respect to storage at 100°F)	Relative Storage Life**
100	1.000	6
95	.823	7.3
90	.677	8.8
85	.559	10.7
80	.462	13.0
75	.376	15.6
70	.312	19.0

---

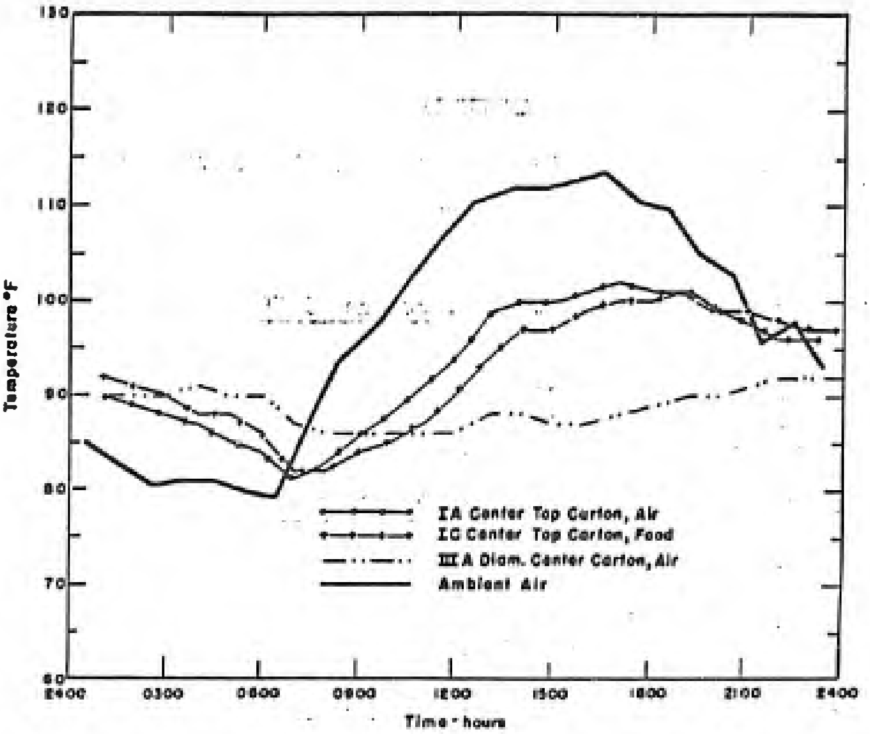
* Based on Q_{10} of 2.

**Based on 6 months at 100°F.

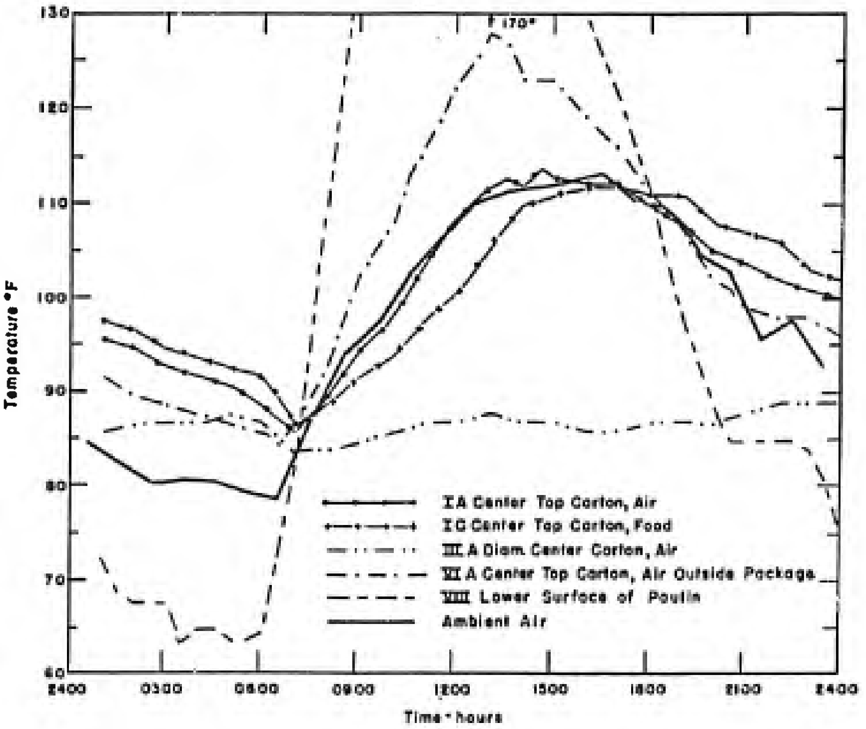
The relative severity indices so obtained are averaged and the temperature corresponding to this effective average relative severity of storage is the effective temperature for the period. The error introduced by linear interpolation in a non-linear relation is not excessive at the intervals shown. If it is desired to eliminate even this error, the values shown may be plotted on logarithmic paper to yield a straight line graph in which interpolation is unnecessary.

APPENDIX C

GRAPHS OF DUMP STORAGE TEMPERATURES ON SELECTED DAYS

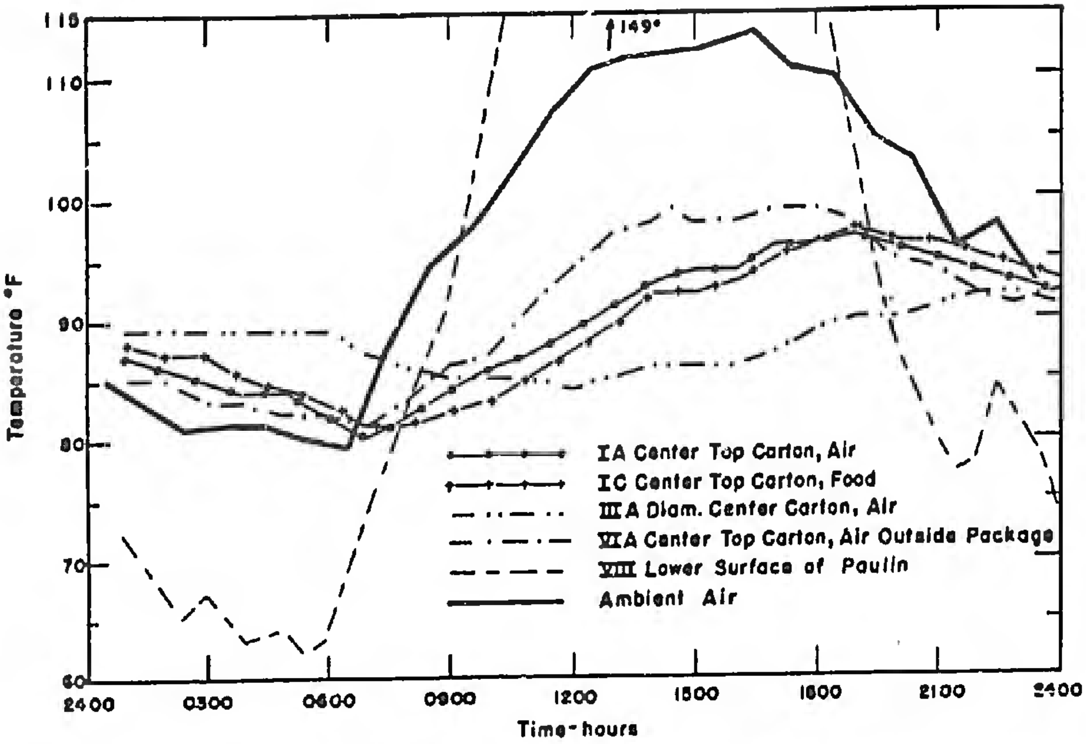


a. Open stack.

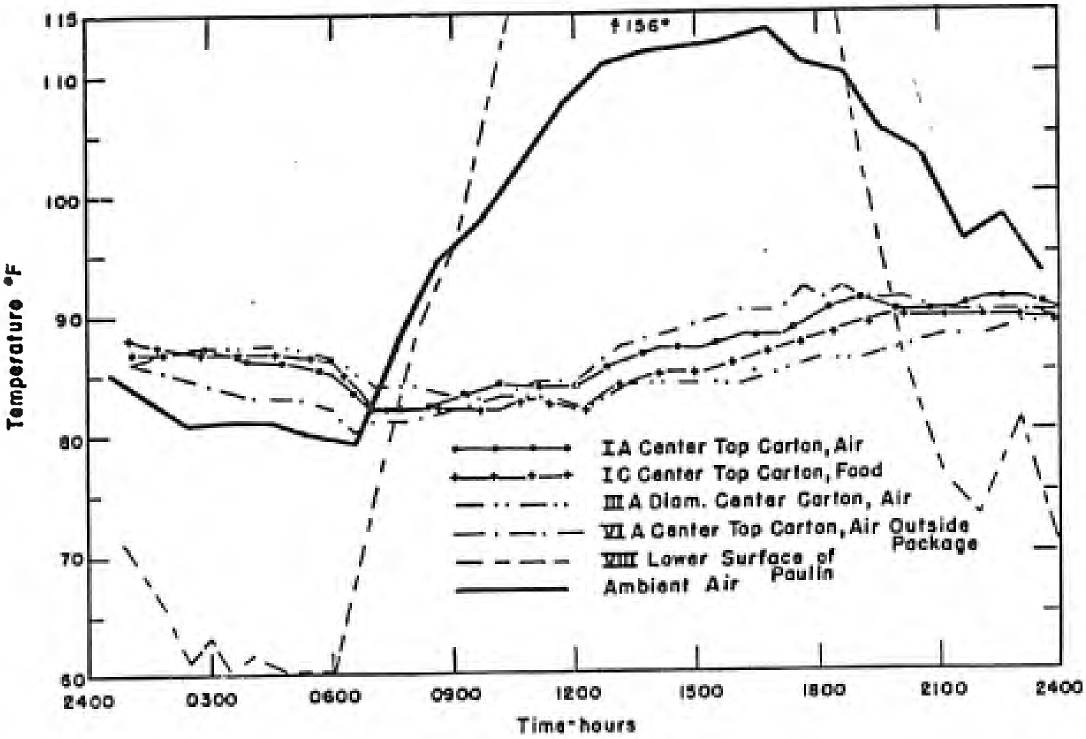


b. Tight paulin stack.

Figure 24. Daily temperature

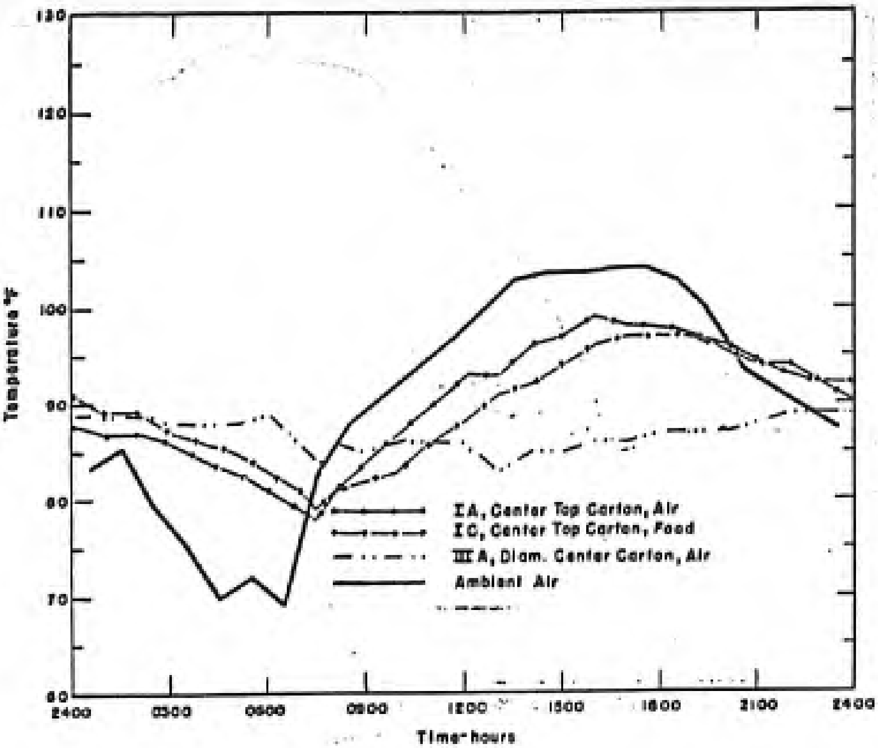


c. Raised fly stack.

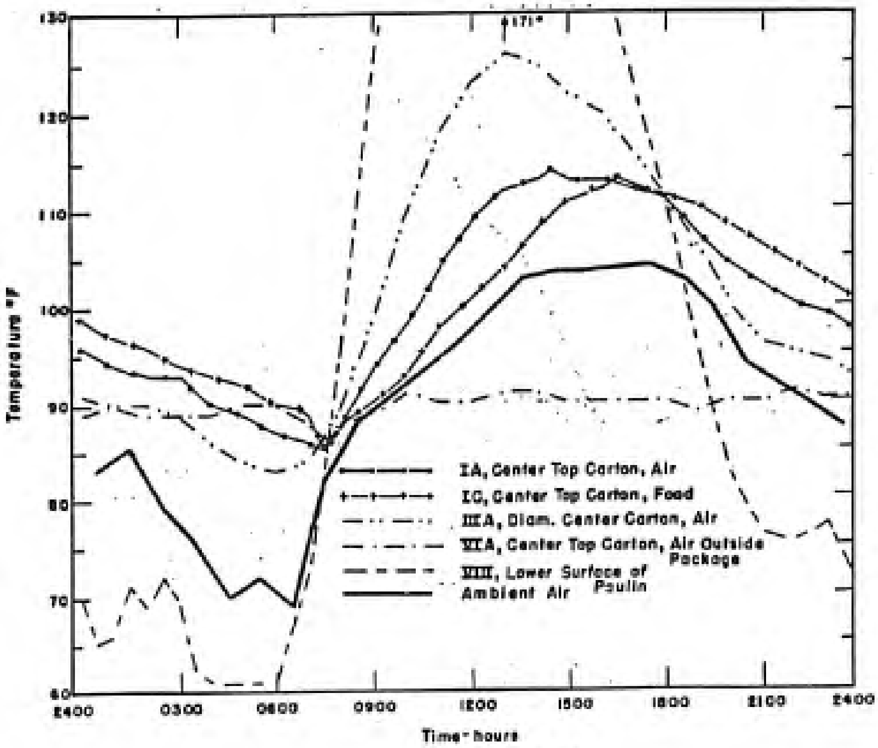


d. Raised fly with foil.

cycles, 22 June 1955.

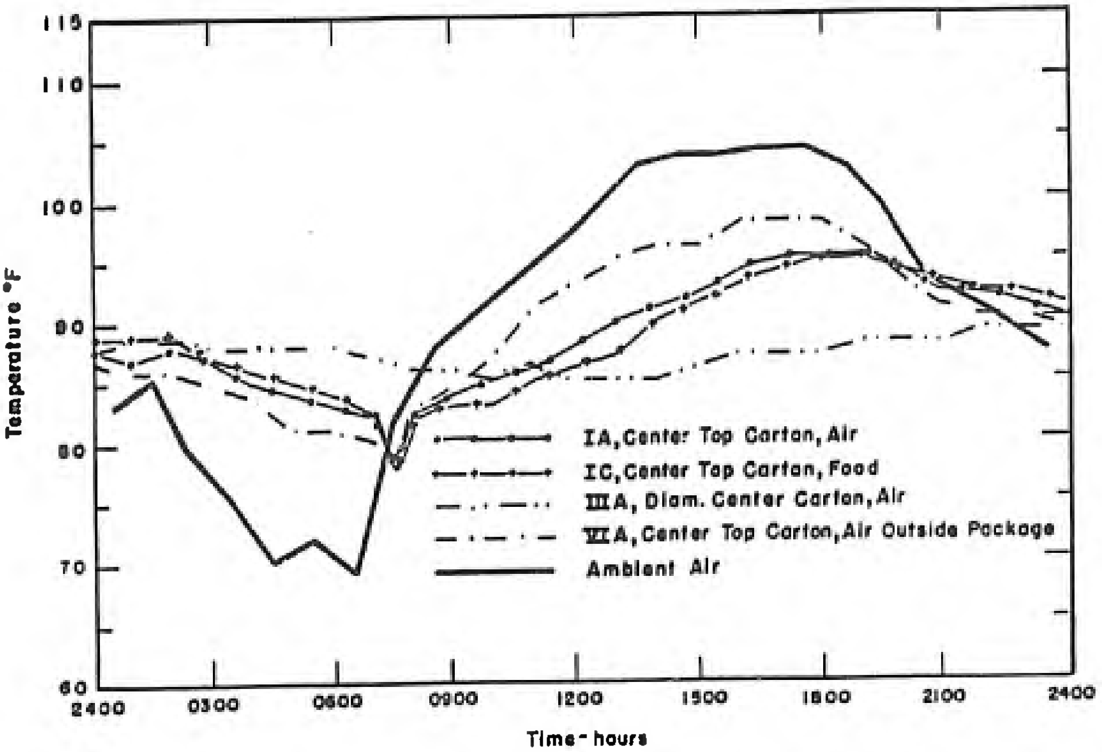


a. Open stack.

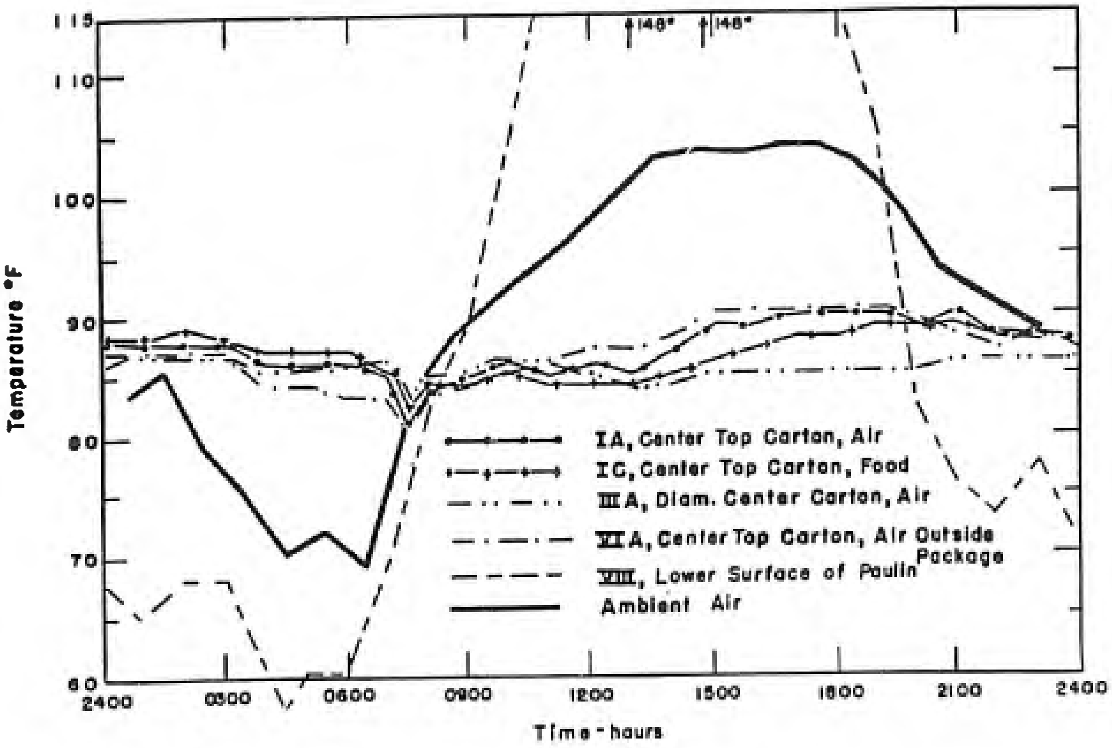


b. Tight paulin stack.

Figure 25. Daily temperature

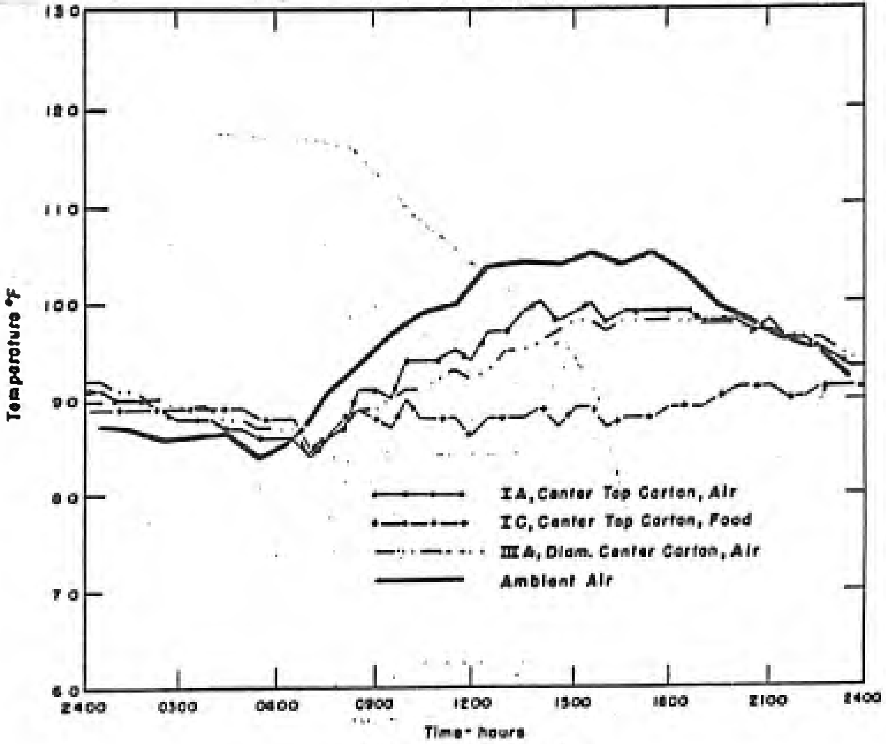


c. Raised fly stack.

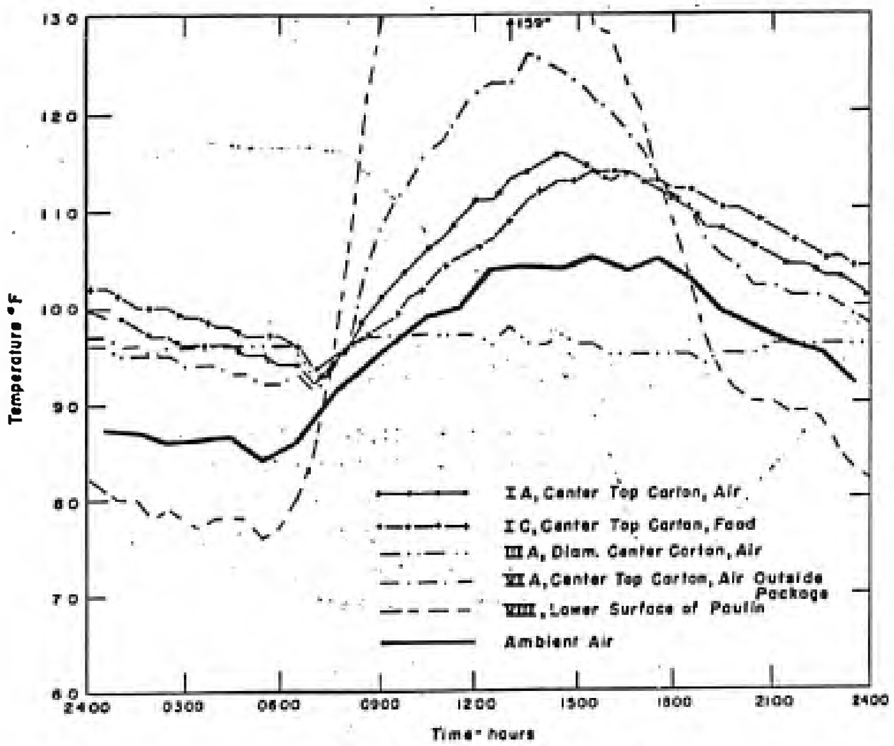


d. Raised fly with foil.

cycles, 7 July 1955

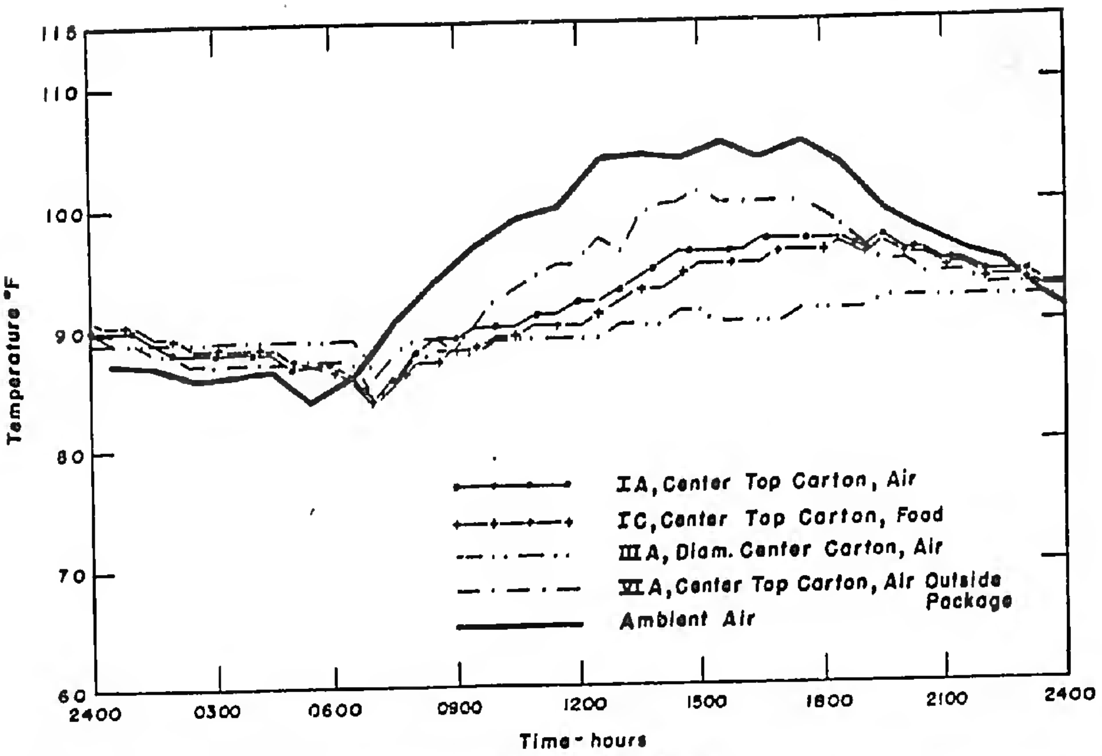


a. Open stack.

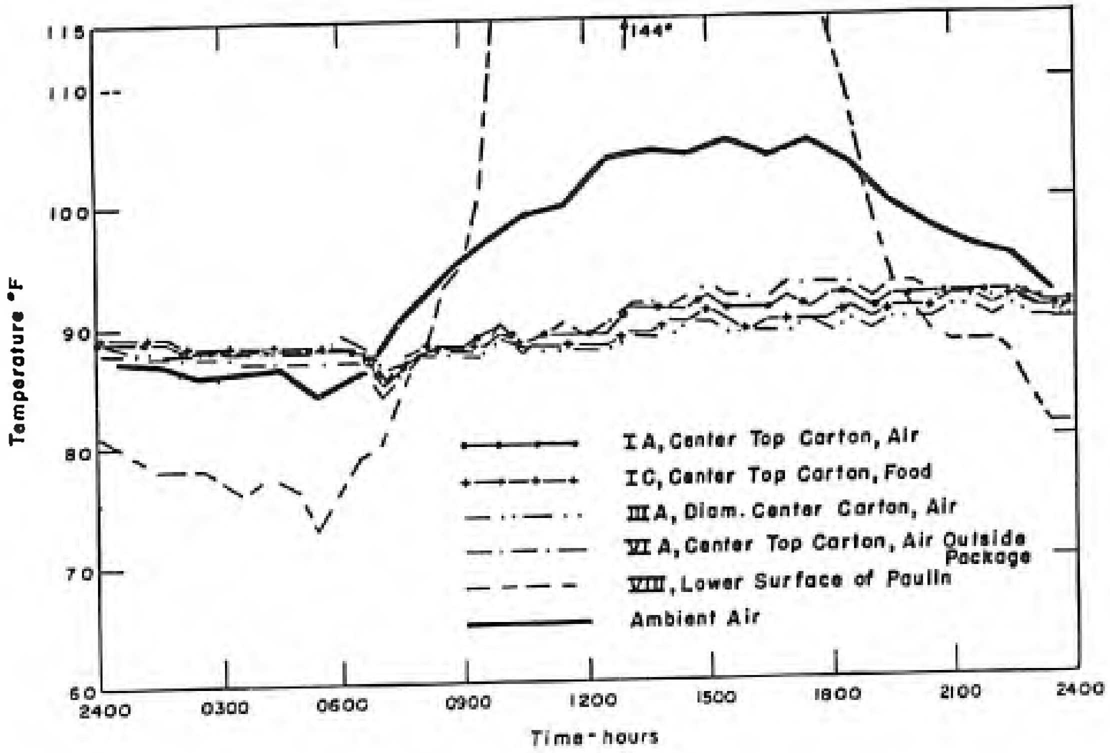


b. Tight paulin stack.

Figure 26. Daily temperature



c. Raised fly stack.



d. Raised fly with foil.

cycles, 22 July 1955.

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