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MUSAC II: A Method for Modeling Passive Sonar Classification in a Multiple Target Environment

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A Method for Modeling Passive Sonar Classification in a Multiple Target Environment

By: J. R. OLMSTEAD and T. R. ELFERS

Prepared for:

FLEET ANALYSIS AND SUPPORT DIVISION (CODE 230)
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MUSAC II is a mathematical representation of passive sonar classification. The principle attribute of MUSAC II is its multiple target capability. The methodology is based on the detection of Lofar lines, Demon lines, and broadband noise. MUSAC II uses a sequential, Bayesian decision-making approach. The methodology is designed for use in a Monte Carlo, time step simulation of acoustic warfare engagements.

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PREFACE

The MUSAC II methodology described in this technical note is a revision of the original MUSAC model described in the draft report: "MUSAC--A Representation of the Passive Sonar Classification Process," SRI Project 1318-240, November 1973. The major revisions to the methodology include a new formulation of a multifeature sonar detection model, different likelihood calculations, and a more generalized decision making procedure. This technical note provides a concise theoretical description of the MUSAC II methodology; the new concepts have not, as yet, been tested by a computer implementation of the methodology.

The purpose of the research was to create a methodology that mathematically represents the passive sonar classification process in a multiple target environment. The MUSAC II methodology is not intended to be a software package for real classification hardware; instead, MUSAC II is intended to be used by analysts to study passive sonar systems. The primary application of the MUSAC II methodology will be for detailed Monte Carlo simulation modeling of acoustic warfare engagements. The methodology will provide classification decisions that can be used to initiate tactics in an engagement model. The MUSAC II methodology uses the standard acoustic parameters of classical sonar detection theory. By using a physical-based approach, the methodology can represent the inherent classification capability of a sonar system, particularly the sensitivity to signal-to-noise ratios. The alternative approach would try to duplicate the man/machine classification process by simulating the human perception of classification clues. MUSAC II does not try to duplicate the man/machine classification process, instead MUSAC II determines classification decisions from the fundamental information

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content of the acoustics. MUSAC II represents an ideal sonar classifier in the same sense that classical theory represents an ideal sonar detector. The detection capability of detection models can be adjusted to simulate real systems; in the same way, the classification capability of MUSAC II can be adjusted to simulate real passive sonar systems.

The MUSAC II project was conceived as a continuation of a classification model development effort under the sponsorship of James G. Smith, Code 431, Office of Naval Research. As part of an ONR reorganization, the MUSAC II project was transferred to Code 230. After evaluating the potential application and merit of the methodology relative to Code 230 program objectives, the project was redirected to tasks involving tactical development and evaluation research. This technical note reports on the partially completed research of the original tasking.

The authors are indebted to G. W. Black and W. F. Frye who were the originators of the basic ideas of the MUSAC methodology.

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I INTRODUCTION

The Multiple Source Acoustic Classification (MUSAC) methodology is a mathematical representation of passive sonar classification. The principal attribute of the MUSAC II methodology is its multiple-target capability. Almost without exception, other models allow for only one target at a time. The methodology is based on the detection of acoustic features. In this way, spectral and spatial acoustic information is included so that the sonar systems' bearing and frequency resolution can be related to the classification outcome. The acoustic features are defined by the analyst; the features can be narrowband, broadband, or modulated broadband classification clues (for example, Lofar or Demon lines). The acoustic features are represented by Bernoulli random variables. The stochastic structure of the model provides for realistic random variations of acoustic data. A dynamic encounter is represented by a time-step simulation. The MUSAC II methodology is structured for sequential decision-making by the update of classification information and the change in kinematic variables over time. From Monte Carlo replications, the probability of making selected tactical and classification decisions can be estimated.

The MUSAC II methodology uses a Bayesian decision-making approach. Figure 1 shows the model flow. The analyst first formulates a set of multiple-target hypotheses that will be used in the engagement simulation. The probability of detecting specified acoustic features is calculated at each time step, for each sonar look angle, and for each hypothesis (the true target configuration is usually one of the hypotheses). These detection probabilities are then used, in conjunction with the observed random features, to calculate the likelihood that the data would be observed if the hypothesis were true. The likelihoods and the prior probabilities are then combined to produce the posterior probability that the ith hypothesis is true, given the observed data. The analyst defines tactical or classification decisions that are to be simulated, he defines the value of making the decision when each hypothesis is true, and he defines value thresholds. With this decision structure, MUSAC II determines if a decision is to be made at the present time step; if not, another time-step is simulated and more data collected. If a decision is made, the decision with the largest average value is chosen. The above brief outline of the MUSAC II methodology is discussed in detail in the four following chapters, as indicated on Figure 1.

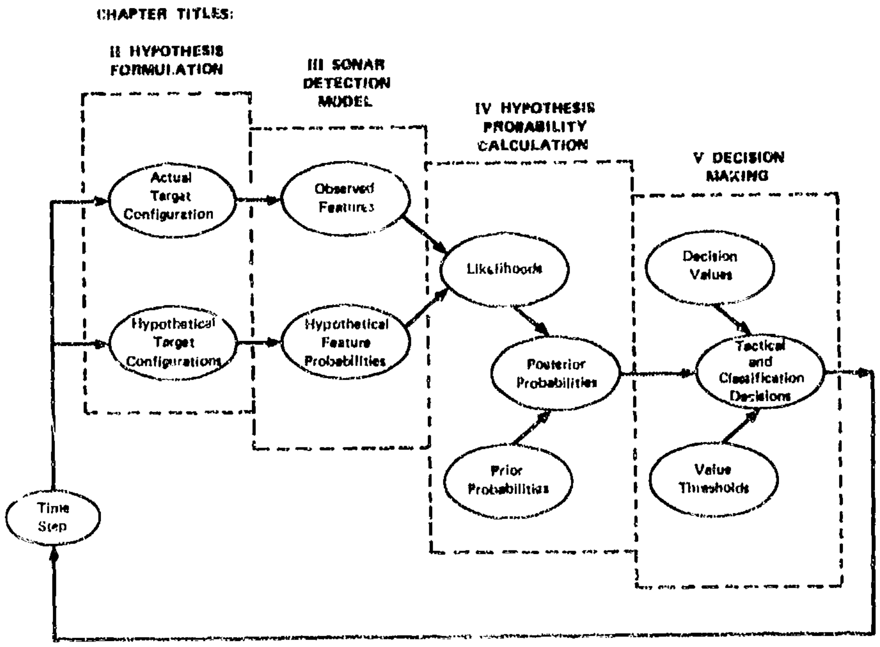

FIGURE 1 MUSAC II MODEL FLOW

II HYPOTHESIS FORMULATION

Hypothesis formulation is the most critical part of the methodology because the hypothesis set directly determines the possible target group configurations under consideration, and because the size of the hypothesis set determines the computational burden required to execute the model. The formulation of multitarget hypotheses are unique to MUSAC II and are very powerful in that they allow the multitarget classification problem to be addressed.

The multitarget hypothesis set consists of ordered arrangements of two components: single-target classes and target tracks.

A. Single-Target Classes

The set of single-target classes is a list of target types that the observer expects to encounter. For any particular application of MUSAC II, the set of single-target classes is defined by the analyst. Depending on the problem at hand, the single-target classes can be very general (submarine, high value warship, low value warship, merchant) or quite detailed (688 class submarine, Nimitz class aircraft carrier). The level of detail of the set of single-target classes dictates the complexity of the acoustic functions that define the uniqueness of a single-target class within the model.

Each single-target class is defined by a set of functions that describe its acoustic characteristics. These functions are like a library of acoustic signatures that an observer would compare to his observations to make classification decisions. In MUSAC II, however, the acoustic functions are in terms of average source levels instead of received signal levels, as would be the case with real signatures. There are three types of functions that describe a single-target class: narrowband, broadband, and modulated broadband functions.

The narrowband characteristics are described by a set of functions that define the average Lofar line level at specified frequencies. The narrowband functions have parameters of target speed and aspect angle. Different single-target classes may have different numbers of Lofar lines or different line levels. The total number of narrowband features in the model is determined by the total number of different line frequencies. If a target does not generate a Lofar line at a particular frequency in the set, then that narrowband function associated with the target is assigned zero power at that frequency.

The broadband characteristics are described by a set of functions that define the average source spectrum level of the target classes. These functions have parameters of frequency, target speed, and aspect angle. The broadband spectrum can be filtered into a set of broadband features. Thus rough classification clues can be derived from the presence or absence of low, medium, or high frequency broadband radiation. The broadband spectrum also acts as noise when detecting Lofar and Demon lines.

The modulated broadband characteristics are described by a set of functions that define the average modulation levels for a defined set of Demon lines. The parameters for these functions include broadband frequency, target speed, and aspect angle. To each Demon line, a modulation-level function is assigned; whereas, to each Lofar line, a line-level value is assigned. Thus the description of Demon features is more complicated than Lofar features.

Besides the user-defined single target classes there is a special target class, designated "nontarget," that will usually be included in the set of single-target classes. The nontarget is characterized by zero power for all the acoustic characteristics. This special target class is required to model the detection of the targets. If at a particular time step the observer has not detected one or more of the actual targets, then a hypothesis that contains the class of nontarget at the appropriate bearings will receive a high likelihood value.

B. Target Tracks

The second component in formulating multitarget hypotheses is a set of target tracks. A track is defined by the target's initial position and its course and speed as a function of time. From these functions the parameters of range, bearing, speed, and aspect angle of the target on a particular track can be calculated. It is important to note that the tracks are not limited to straight lines, and that only the target positions at the current time step need to be known. That is, if MUSAC II is formulated as an engagement model, then the decisions at one time step can affect the position of the observer and targets in later time steps.

Target tracks are thought of as having an existence independent of the target that is moving on them. The reason for this point of view is that hypothetical target configurations are constructed by assigning single-target classes to the tracks. The set of tracks will always include the tracks of the one true target configuration. In some applications of MUSAC II, hypothetical tracks may be defined in addition to the true tracks.

For most applications, only the tracks of the true targets will be defined. This assumes that the observer knows the range and bearing to the actual targets during the engagement. The primary purpose of defining the target tracks in MUSAC II is to provide the necessary kinematic parameters for use in the acoustic characteristic functions.

The acoustic functions and the track parameters are a representation of an acoustic signature library that the observer would compare to his observations for classification decision making. The perfect tracking assumption implies that the observer selects from the library only those signatures that correspond to the range, speed, and aspect of the true targets.

Hypothetical tracks can be defined for the purpose of modeling target position uncertainty. When additional tracks are defined, the MUSAC II methodology also performs a localization function in the sense that a hypothesis with target position close to the true target position will receive a higher likelihood value than a hypothesis that places targets away from the observed position. The addition of hypothetical tracks will result in more hypotheses. The most limiting feature of the MUSAC II methodology is the potential large size of the hypothesis set. For any particular application of the model, the analyst should try to minimize the number of hypotheses to save unnecessary calculations.

C. Multitarget Hypotheses

The complete multitarget hypothesis consists of an ordered arrangement of the possible single-target classes assigned to particular tracks. The formulation is usually done by combinatorial methods for combining the single-target classes with the target tracks. The hypothesis set is under the control of the analyst and should reflect the assumptions about the classification problem that is being studied.

To formulate the hypothesis set by the combinatorial method, all possible n-tuples of the single-target classes are enumerated. For this type of hypothesis structuring there will be k^n multitarget hypotheses generated, where k is the number of single target classes and n is the total number of tracks. For example, let (HVU, LVU, NON) be a set of single-target classes, where HVU is a high value unit, LVU is a low value unit, and NON is the special target class nontarget. Also assume that two tracks have been defined. Then the set of hypotheses is the set of 2-tuples, in which the first element is the target class assigned to track #1 and the second element of the target class assigned to track #2:

$$H_1 = \{HVU, HVU\}, \quad H_4 = \{LVU, HVU\}, \quad H_7 = \{NON, HVU\}$$
$$H_2 = \{HVU, LVU\}, \quad H_5 = \{LVU, LVU\}, \quad H_8 = \{NON, LVU\}$$
$$H_3 = \{HVU, NON\}, \quad H_6 = \{LVU, NON\}, \quad H_9 = \{NON, NON\}$$

This hypothesis formulation might represent a scenario in which there are two real targets, an HVU on track #1, and an LVU on track #2. Thus the second hypothesis is the true hypothesis: $H_0 = H_2$. The observer expects to encounter one or two ships that are HVUs or LVUs. The single-target class, nontarget, is required to model the detection of one or both of the targets.

A hypothesis set that is generated by combinatorial means should be reviewed by the analyst, and unreasonable hypotheses be deleted to avoid unnecessary calculation. In forming the multitarget hypothesis the analyst should consider the maximum number of targets that the observer expects to encounter and the maximum number of occurrences of a particular single-target class within a hypothesis. In the previous example, if it is unlikely to encounter two HVUs, then the first hypothesis should be deleted. For each hypothesis there must be a single-target class assignment to each track. When the number of hypothesized targets is less than the number of defined tracks, then the special class of nontarget is assigned to the remaining tracks.

III SONAR DETECTION MODEL

The sonar detection model is based on a two-channel comparison of time-averaged power. The inputs to the model are source levels, noise levels, propagation loss, etc.; the input levels are allowed to vary randomly in time to simulate signal fade and jump. The outputs of the model are the probabilities of detection of acoustic features such as Lofar lines. The model is a fairly simple representation of a sonar system. The MUSAC II user may replace this model with one of his own creation, so long as the outputs of the new model are also feature detection probabilities.

A. Input Parameters

1. Subscript Definitions

The subscripts i, j, k, m, n are used in the sonar model. As an aid to understanding the subscripted functions given later, the subscripts are first discussed:

i = Hypothesis identifier; i = 0 designates the true target configuration and i = 1,2,... designates the hypothetical target configurations.

j = Feature identifier; features are associated with frequency bands on sonar array/display combinations. As an example, features j = 1,2,...,20 can be associated with 20 possible Lofar lines from an omnidirectional array; features j = 21,...,40 can be associated with the same 20 possible Lofar lines from a towed array; features j = 41,42 can be associated with the low and high bands of the BTR from a spherical array; features j = 43,...,47 can be associated with five possible Demon lines in the 1-2 kHz band; features j = 48,...,52 can be associated with the same five Demon lines in the 2-4 kHz band; and features j = 53,...,57 can be associated with the same five

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Demon lines in the 4-8 kHz band, where the multiband Demon information is from a spherical array. Aural classification from headphone information can be simulated by Lofar features and multiband Demon features.

k = Look angle identifier. The sonar associated with a feature is pointed in various directions. The maximum value of k is indexed on j so that a different number of look angles can be specified for different sonar arrays. For example, only one "look angle" is needed for an omnidirectional array, whereas many angles are needed for a preformed beam array.

m = Target track identifier. A set of tracks (time varying positions) is defined for the model. The real target configuration is constructed by assigning the real targets to their tracks. The hypothetical target configurations are constructed by assigning hypothetical targets to the tracks; nontargets (zero power) may be included in the hypothetical configurations also. The m-index identifies a track; however, a track may be assigned many different target types. The m-index, by itself, is not a target type identifier; but the combination (i,m) does identify a target type at a position in space and time.

n = Noise type identifier; different kinds of noise can be specified. For example, n = 1 can be sea state noise; n = 2 can be shipping noise; and n = 3 can be self noise.

2. Target Characteristics

The input functions that describe the single target class characteristics are the average values of the narrowband, broadband, and modulation levels.

$\overline{P}_{ijm}(v,\alpha)$ = Average narrowband source level (dB relative to 1 μPa^2 at 1 yd); mean squared pressure of the Lofar line associated with the jth feature one yard from the (i,m) target. The line level may be a function of target speed v and aspect angle α. The input to a computer program would not be indexed on i and m, but instead on a single target class ℓ. An additional vector, subscripted with "im" and composed of integer components ℓ, would designate the target class ℓ that is associated with the (i,m) target. Therefore, the computer input functions would be subscripted with "ℓj"; however, the equivalent subscripts "ijm" are used to describe the model.

$\bar{P}'_{im}(f,v,\alpha)$ = Average broadband source spectrum level (dB relative to 1 $\mu Pa^2/Hz$ at 1 yd); mean square pressure per unit frequency at one yard from the (i,m) target. The spectrum level is a function of frequency f, target speed v, and aspect angle α.

$\bar{M}_{ijm}(f,v,\alpha)$ = Average broadband modulation level (dB relative to 1.0); defined as the dB level of the square of the modulation index. The modulation index is the maximum amplitude minus the minimum amplitude divided by twice the average amplitude. The modulation level is a function of frequency, speed, and aspect; and it is indexed on the Demon line associated with the jth feature for the (i,m) target.

3. Track Input

The tracks are calculated from input values of initial positions and time-varying courses and speeds for the observer and targets. The target range r, relative bearing θ, and aspect angle α are then derived from the x,y positions of the units.

$x(t_0)$, $y(t_0)$ = Position of the observer at time $t = t_0$.

$x_m(t_0)$, $y_m(t_0)$ = Position of the mth target at time $t = t_0$.

$\beta(t)$, $u(t)$ = Course and speed (deg, kt) of the observer as a function of time.

$\varphi_m(t)$, $v_m(t)$ = Course and speed (deg, kt) of the mth target track as a function of time.

4. Environment and Sonar System Characteristics

The input parameters that characterize the environment are the average propagation loss and the array output average noise function. The sonar system is characterized by the array output average noise function, the beam pattern, the frequency response, the processor averaging time, the detection threshold, the data rate, and the sonar look angles.

$\overline{A}_i(f,r)$ = Average propagation loss (dB); mean squared pressure at one yard from the target divided by mean squared pressure at a range of r nmi from the target. Propagation loss is a function of frequency and range and is subscripted with i to denote that two propagation functions could be used: one function for the true conditions, and another function for the hypothesized propagation conditions.

$\overline{N}'_{0jn}(f,u,\lambda)$ = Average broadband output noise spectrum level (dB relative to 1 $\mu Pa^2/Hz$); mean square pressure per unit frequency of the nth noise source at the output of the sonar array associated with the jth feature. It is a function of frequency f, observer speed u, and look angle λ. If the noise is isotropic, then $\overline{N}'$ is the noise outside the array minus the directivity index. In the nonisotropic case, the value of $\overline{N}'$ may be a function of look angle λ. The i = 0 index indicates that the true output noise spectrum level is used for both the real and hypothetical configurations.

$B_j(f,\lambda,\theta)$ = Beam pattern ratio ($0 \le B \le 1$); mean square voltage when the sonar is looking at angle λ and a single point-source target is on bearing θ, divided by the mean square voltage when the sonar is looking at the target. The beam pattern depends on the array associated with the jth feature, and the pattern is a function of frequency.

$B^*_j(f)$ = Side lobe ratio ($0 \le B^* \le 1$); the nominal value of $B_j(f,\lambda,\theta)$ when λ and θ are well separated.

$G_j(f)$ = Normalized frequency response ratio ($0 \le G \le 1$); output mean square pressure (voltage) divided by input mean square pressure for the frequency band associated with the jth feature. The function can include effects of hydrophone response, band filtering, or psychoacoustic frequency response.

f_j = Center frequency (Hz) associated with the jth feature (geometrical mean of lower and upper frequency limits).

W_j = Bandwidth (Hz) associated with the jth feature. If the frequency response is a unit rectangular function, then f_j and W_j completely define $G_j(f)$.

T_j = Averaging time (sec) of the signal processor associated with the jth feature.

d_j = Detection threshold ($d > 0$); the number of reference-channel standard deviations by which the data channel output must exceed the reference channel mean so that the jth feature is detected.

n_j = Number of independent observation opportunities on the jth feature during the computer time step ($1 \leq n_j \leq$ computer time step divided by the signal processor averaging time).

λ_{jk} = Value of the kth look angle (degrees from observer's heading) for the array associated with the jth feature. One model design would be to let the sonar look at only the target bearings: $\lambda_{jk} = \theta_m(t)$. An alternative model design would be to let the sonar look at bearings at equal increments; for example, 6° apart with $k = 1,\ldots,60$ to cover 360°.

5. Random Process Parameters

Five input functions for the real target configuration are calculated from a random process that is correlated in time. The input parameters that characterize the random process are the standard deviation, relaxation time, and mixing constant.

σ_r = Standard deviation (dB) of the random process on the rth input function ($r = 1,2,3,4,5$).

τ_r = Relaxation time (min) of the rth random process.

c_r = Mixing constant ($0 \leq c \leq 1$) for the random process; $c = 0$ indicates a pure Gauss-Markov process; $c = 1$ indicates a pure lambda-sigma jump process.

B. Input Parameter Random Process

Real sonar signals fade in and out and make sudden jumps. A mixed random process that was originally proposed by Wagner* is used to model this phenomenon; the process is a combination of a Gauss-Markov and lambda-sigma jump random process. The Gauss-Markov process represents smooth changes in signal level, and the lambda-sigma jump process represents sudden changes in signal level.

1. General Equations

For each engagement run of the model, a different time history of an input parameter can be generated. The input parameter used at a given time step is calculated by drawing three independent random numbers x, y, z. With these random numbers, two zero-mean random values are computed and then mixed together:

$$J_n = J_{n-1}(1-x) + s\,x\,y$$

$$K_n = \rho K_{n-1} + s\sqrt{1-\rho^2}\,z$$

$$L_n = cJ_n + \sqrt{1-c^2}\,K_n$$

where

J_n = lambda-sigma jump random increment at nth time step.

K_n = Gauss-Markov random increment at nth time step.

L_n = mixed random increment at nth time step; L_n is added to the average value of the parameter to calculate value of the parameter at the nth time step.

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*"A Comparison of Detection Models Used in ASW Operations Analysis (U)," D. H. Wagner Associates (October 1973).

c = mixing constant ($0 \le c \le 1$); $c = 0$ indicates a pure Gauss-Markov process, $c = 1$ indicates a pure lambda-sigma jump process.

s = standard deviation of the input parameter (dB).

ρ = $e^{-\Delta t/\tau}$; Gauss-Markov step-to-step correlation; and lambda-sigma jump probability that a jump did not occur during the last time step.

Δt = time step duration (min).

τ = Gauss-Markov relaxation time (min), and lambda-sigma jump mean time between jumps.

x = random number from a Bernoulli distribution with parameter $E(x) = 1 - \rho$. The $x = 0$ case means that no jumps occurred in the last time step; the $x = 1$ case means that at least one jump occurred in the last time step.

y, z = random numbers from a normal distribution with zero mean and unit variance.

The mixed random process, as defined above, has the statistics: $E(L_n) = 0$, $E(L_n^2) = s^2$, and $E(L_n L_{n-1}) = s^2 \rho$.

2. Generation of Input Functions

The equation that generates one of the five input functions is given below. The other four equations are omitted because they are similar and add nothing new to the description of the model. The randomization is applied only to the input functions for the true target configuration because the hypothetical signals must be based on engagement-to-engagement average values, not on detailed knowledge of a particular engagement. The randomly generated input function is denoted by the same symbol that is used in the input list, but omitting the average sign. Notice that the generated input function is defined in units of power ratios, not dB.

$$P_{ijm}(v,\alpha) = \begin{cases} 10^{\,.1[\overline{P}_{0jm}(v,\alpha) + \Delta P_{0jm}]} & \text{for } i = 0 \\ 10^{\,.1[\overline{P}_{ijm}(v,\alpha) + \delta_1]} & \text{for } i = 1,2,3,\ldots \end{cases}$$

where

$\overline{P}_{ijm}(v,\alpha)$ = Average narrowband source level (dB)

ΔP_{0jm} = Random increment (dB); computed from the mixed random process using the parameters s_1, τ_1, and c_1. ΔP is the same as I_m in the previous section.

δ_1 = Increment (dB) that must be added to the mean level (dB) so that the mean power (ratio) is correctly converted. The input power is assumed to be lognormally distributed, therefore the increment is:

$$\delta_1 = s_1^2/8.68 \quad ,$$

where s_1 is the standard deviation (dB) of the random process on the narrowband source level.

A new random increment is computed at each time step (not explicitly denoted), for each feature (j), and for each target (o,m). Thus, if there are 10 time steps, 5 features, and 2 targets, then 100 random increments will be calculated to generate the input values of narrowband source power. The value of random increment is assumed to be independent of the underlying values of speed, aspect, frequency, etc.

The generation of input functions from the five mixed random processes produces the following functions:

$P_{ijm}(v,\alpha)$ = Narrowband source power (μPa^2 at 1 yd)

$P'_{im}(f,v,\alpha)$ = Broadband source spectrum ($\mu Pa^2/Hz$ at 1 yd)

$M_{ijm}(f,v,\alpha)$ = Broadband modulation ratio ($0 \le M \le 1$)

$A_i(f,r)$ = Propagation loss ratio ($A \ge 1$) from one yard

$N'_{0jn}(f,u,\lambda)$ = Broadband, array output, noise spectrum ($\mu Pa^2/Hz$).

C. Array Output Signal and Noise

The power at the output of the sonar array is calculated for the narrowband, broadband, and modulated broadband cases.

1. Narrowband

The target signal that is outside the array is calculated by reducing the source power by the propagation loss:

$$Q_{ijm} = \frac{P_{ijm}(v_m, \alpha_m)}{A_i(f_j, r_m)} \quad .$$

The mean square pressure from all targets at the output of the array is then calculated by reducing the signal with the beam pattern ratio and summing over all target sources:

$$S_{ijk} = \sum_m Q_{ijm} \; B_j(f_j, \lambda_{jk}, \theta_m) \quad .$$

In addition to the narrowband signal, the following function is needed in later calculations:

$$V_{ijk} = \sum_m [Q_{ijm} \; B_j(f_j, \lambda_{jk}, \theta_m)]^2 \quad .$$

2. Broadband

The target spectrum that is outside the array is calculated by reducing the source spectrum by the propagation loss:

$$Q'_{im}(f) = \frac{P'_{im}(f, v_m, \alpha_m)}{A_i(f, r_m)} \quad .$$

The mean square pressure per unit frequency due to all targets at the output of the array is then calculated by reducing the individual signals with the beam pattern ratio, summing over all target sources, and multiplying by the frequency response:

$$S'_{ijk}(f) = G_j(f) \sum_m Q'_{im}(f) \; B_j(f, \lambda_{jk}, \theta_m) \quad .$$

The side lobe interference spectrum is also needed:

$$S_{O_j}'^{*}(f) = G_j(f)\, B_j^{*}(f) \sum_m Q_{Om}'(f) \quad .$$

Finally, the noise spectrum at the output of the array is the sum from all noise sources:

$$N_{Ojk}'(f) = G_j(f) \sum_n N_{Ojn}'(f,u,\lambda_{jk}) \quad .$$

3. Modulated Broadband

The additional increment of broadband signal power (mean squared pressure per unit frequency) due to the modulation is calculated by multiplying the modulation function times the output broadband signal, summing over all targets, and multiplying by one half the frequency response:

$$\Delta S_{ijk}'(f) = \frac{1}{2} G_j(f) \sum_m Q_{im}'(f)\ B_j(f,\lambda_{jk},\theta_m)\ M_{ijm}(f,v_m,\alpha_m) \quad .$$

D. Signal Processor Statistics

The mean and variance of the output of the signal processor are required to calculate the probability of detection. The sonar model assumes that the signal processor has two channels: (1) a data channel that produces a random value from a normal distribution of mean μ and variance σ^2; and (2) a reference channel that produces two deterministic parameters μ^* and σ^{*2} that are measures of the background noise in which the data signal is to be detected. The equations for the signal processor statistics are not obvious. In the interest of a short description of the sonar model, the derivation of the equations is deferred to Appendix A.

1. Narrowband

The broadband power in a narrowband of width W_j is:

$$R_{ijk} = [S_{ijk}'(f_j) + N_{Ojk}'(f_j)]W_j \quad .$$

With this definition, the channel statistics for the narrowband case are written:

Data Channel

$$\mu_{ijk} = S_{ijk} + R_{ijk} \qquad \text{for } i = 0,1,2,\ldots$$

$$\sigma^2_{ijk} = S^2_{ijk} - V_{ijk} + \frac{2}{W_j T_j} S_{ijk} R_{ijk} + \frac{1}{W_j T_j} R^2_{ijk}$$

Reference Channel

$$\mu^*_{0jk} = R_{0jk}$$

$$\sigma^{*2}_{0jk} = \frac{1}{W_j T_j} R^2_{0jk}$$

2. Broadband

The broadband power is calculated by integrating over frequency. Since the frequency response function $G_j(f)$ is defined as including the band cutoffs, the integration is theoretically from zero to infinity. The signal and noise spectra are combined into a data spectrum and a background spectrum:

$$R'_{ijk}(f) = S'_{ijk}(f) + N'_{0jk}(f)$$

$$R'^*_{0jk}(f) = S'^*_{0j}(f) + N'_{0jk}(f) \quad .$$

With these two definitions the channel statistics for the broadband case are written:

Data Channel

$$\mu_{ijk} = \int R'_{ijk}(f)\, df \qquad \text{for } i = 0,1,2,\ldots$$

$$\sigma^2_{ijk} = \frac{1}{T_j} \int [R'_{ijk}(f)]^2\, df$$

Reference Channel

$$\mu^{*}_{0jk} = \int R'^{*}_{0jk}(f)\, df$$

$$\sigma^{*2}_{0jk} = \frac{1}{T_j} \int [R'^{*}_{0jk}(f)]^2\, df$$

3. **Modulated Broadband**

The squared average of a modulated broadband signal contains more power than the signal without modulation. The statistics for detection of modulated features uses this idea:

Data Channel

$$\mu_{ijk} = \int [\Delta S'_{ijk}(f) + R'_{ijk}(f)]\, df$$

for $i = 0,1,2,\ldots$

$$\sigma^2_{ijk} = \frac{1}{T_j} \int [\Delta S'_{ijk}(f) + R'_{ijk}(f)]^2\, df$$

Reference Channel

$$\mu^{*}_{0jk} = \int R'_{0jk}(f)\, df$$

$$\sigma^{*2}_{0jk} = \frac{1}{T_j} \int [R'_{0jk}(f)]^2\, df \quad .$$

E. Feature Detection

1. Observed Data

The output of the data channel is compared to a threshold value a_{jk} that is a function of the reference channel parameters:

$$a_{jk} = \mu^{*}_{0jk} + d_j\, \sigma^{*}_{0jk} \quad .$$

If the data channel output is larger than the threshold, then the feature is assigned a value one; if the output is less than the threshold, then the feature is assigned a value zero.

The term "feature" is used here to mean feature "j" (for example a Lofar line) on look angle "k" produced by the real target configuration (i = 0). Features, whether they are of value one or zero, are observed data; they are used to classify the target configuration.

The data channel output is assumed to be normally distributed with mean μ_{0jk} and variance σ^2_{0jk}. A random number z_{jk} is drawn from a normal distribution with zero mean and unit variance. The random output of the data channel can be written:

$$y_{jk} = \mu_{0jk} + \sigma_{0jk} z_{jk} \quad .$$

The Bernoulli distributed random feature x_{jk} is then determined by:

$$x_{jk} = \begin{cases} 1 & \text{if} \quad y_{jk} \geq a_{jk} \qquad \text{(detection)} \\ 0 & \text{if} \quad y_{jk} < a_{jk} \qquad \text{(no detection)} \end{cases} \quad .$$

The time required to produce a feature is the processor averaging time T_j. Thus a new feature, of value zero or one, can be produced at a maximum rate of once every T_j seconds. Due to sonar system design, the rate may be less than the maximum. The input parameter that controls the rate is n_j: the number of times the feature x_{jk} is produced in one computer time step.

2. Hypothesized Feature Detection Probabilities

Feature detection probabilities are calculated for each hypothetical target configuration. The probability of detection is the probability that the normally distributed output of the hypothetical data channel is greater than the detection threshold:

$$p_{ijk} = \frac{1}{\sqrt{2\pi}\,\sigma_{ijk}} \int_{a_{jk}}^{\infty} e^{-\frac{1}{2}\left(\frac{y - \mu_{ijk}}{\sigma_{ijk}}\right)^2} dy \quad .$$

The feature detection probability is the probability that the jth feature on the kth look angle would be detected if the ith hypothesis were true. These hypothesized probabilities of detection are used in conjunction with the observed data to calculate the likelihood of the data under each hypothetical configuration.

IV HYPOTHESIS PROBABILITY CALCULATION

The multitarget hypotheses are assigned probabilities called posteriors. The posterior probability is the probability that a particular hypothesis is true, given the observed data. The posteriors are random variables because they are computed from random observed data: the random x_{jk}'s derived in the previous chapter. To calculate the posteriors, the likelihoods are first computed and then Bayes' rule is applied.

A. Likelihood Calculation

The likelihood is the probability that all the data collected through the nth time step would occur if the ith hypothesis were true: $\text{Prob}[D_n | H_i]$. Before the likelihood equations can be derived the x and p symbols of the sonar model must be altered somewhat to include a time step index n and an observation index ℓ:

$x_{jkn\ell}$ = Bernoulli random variable; x = 0 means no detection, and x = 1 means detection of the jth feature on the kth look angle for the ℓth observation during the nth time step.

p_{ijkn} = Probability that the jth feature on the kth look angle would be detected during the nth time step if the ith hypothesis were true. The value of p is the same for all observations during a given time step.

A new random variable ξ_{jkn} is defined as the number of detections of the jth feature on the kth look angle during the nth time step:

$$\xi_{jkn} = \sum_{\ell} x_{jkn\ell} \qquad \ell = 1,2,\ldots,n_j$$

The x-variables are assumed to be independent Bernoulli random variables, and therefore the ξ-variable is binomially distributed with parameters p_{ijkn} and n_j. The probability mass function of a binomial distribution is:

$$L_{ijkn} = \binom{n_j}{\xi_{jkn}} (p_{ijkn})^{\xi_{jkn}} (1 - p_{ijkn})^{n_j - \xi_{jkn}}$$

where

L_{ijkn} = Probability of exactly ξ_{jkn} detections in n_j observations. The equation can also be interpreted as the likelihood (probability) that the observed pattern of detections (of the jth feature on the kth look angle) would occur during the nth time step if the ith hypothesis were true.

$\binom{n}{\xi}$ = $\frac{n!}{\xi!(n-\xi)!}$ binomial coefficient

n_j = Number of observations of the jth feature during a time step.

ξ_{jkn} = Number of detections (of the jth feature on the kth look angle) during the nth time step.

The ξ-variables are assumed to be independent random variables over the index set (j,k,n). Therefore, the joint probability is a product of the individual probabilities:

$$\text{Prob}[D_n | H_i] = \prod_m \prod_k \prod_j L_{ijkn}$$

where

$\text{Prob}[D_n | H_i]$ = Likelihood that observed pattern of detections (of all features on all look angles over all memorable time steps, including the nth step) would occur if the ith hypothesis were true.

j = $1, 2, \ldots, jmax$

k = $1, 2, \ldots, kmax_j$

m = $n, n-1, n-2, \ldots, n-r+1$

r = Number of time steps for which patterns can be remembered; r is the length of memory of the classification process.

The ratio of two likelihoods is a measure of the diagonistic impact of the data on one hypothesis relative to another hypothesis. For example, if the likelihood ratio $L_1/L_2 = 10$, then the data is ten times more favorable to hypothesis H_1 than it is to H_2.

B. Posterior Calculation

Once the likelihoods are calculated, the posteriors are easily determined from Bayes' rule:

$$\text{Prob}[H_i \mid D_n] = \frac{\text{Prob}[D_n \mid H_i]\ \text{Prob}[H_i]}{\sum_i \text{Prob}[D_n \mid H_i]\ \text{Prob}[H_i]}$$

where

$\text{Prob}[H_i]$ = The a priori probability that the ith hypothesis is true. The priors are input constants that quantify intelligence data on the targets before any sonar data is gathered.

$\text{Prob}[H_i \mid D_n]$ = The posterior probability that the ith hypothesis is true after observing memorable sonar data through the nth time step.

The posterior probabilities are random, at-the-moment, probability estimates that are assigned to the hypotheses. The posteriors are not themselves decision probabilities, although the meaning of the phrase "probability of classification" could be defined as the posterior probability. Decision probabilities, such as probability of classification, are defined in the next section on decision making.

V DECISION MAKING

The decision making element of the MUSAC II methodology represents that portion of the classification process that determines the target classes and directs tactical action. A Bayesian decision criterion that uses the posterior probabilities and conditional values of decision outcomes is the basis of the decision making model.

A. Decisions and Values

The analyst must define a set of possible decisions, $B_1,\ldots,B_k$. Next a set of values $Val[B_k|H_i]$, of the kth decision, conditioned on the ith hypothesis being true, must be defined. The values are relative measures, in that they may represent the conditional monetary value, economic value, or utility value of the decision outcome. The exact formulation of the decision set and the value functions will depend on the particular application of the MUSAC II methodology. There are two general categories of decisions: tactical decisions and classification decisions.

1. Tactical Decisions

At some point in the engagement the observer must make tactical decisions based on his estimate of the composition of the target group. An example is the decision to launch a weapon at a particular target. Consider the example described in Chapter II where the hypothesis set consists of three possible target types HVU, LVU, and NON and two possible tracks. Assuming the objective of the observer is to attack the HVU, a possible decision set for tactical action is:

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B_1: attack the target on track #1

B_2: attack the target on track #2

B_3: disengage and search for other targets.

Next a set of conditional values of the decision, assuming the ith hypothesis is true, must be defined. For example, the value for action B_1 for hypotheses that identify the HVU as being on track #1 would be greater than the value for the hypotheses that identify the LVU or non-target as being on track #1. The values for decision B_3 (disengage) would reflect missed opportunity values (costs) for hypotheses that identify the HVU being present. In general, the value set must reflect the objectives of the observer, and the internal consistency of the value set is of importance and not their absolute value. Although the values are somewhat loosely defined, the sensitivity of the decisions to the value structure can easily be determined. For a given set of replications of the MUSAC II model, the values of the posteriors can be saved and then different value structures can be tested with little additional computational effort.

2. Classification Decisions

The classification decisions can vary from determining the presence of one or more targets (detection) to completely describing the target group (designate a single hypothesis as true). As with the tactical decisions, the observer must define his classification decision set. Depending on the context of the problem at hand, the decision set can vary from a very gross description of the target group to a very detailed description. In the previous example, a possible decision set is:

B_1: HVU on track #1

B_2: HVU on track #2

B_3: HVU not present.

If it is assumed that the observer thinks that each decision has equal importance, then a simple value structure can be defined:

$$\mathrm{Val}[B_1|H_i] = \begin{cases} 1 & \text{if } H_i \text{ identifies HVU on track \#1} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{Val}[B_2|H_i] = \begin{cases} 1 & \text{if } H_i \text{ identifies HVU on track \#2} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathrm{Val}[B_3|H_i] = \begin{cases} 1 & \text{if } H_i \text{ does not contain an HVU} \\ 0 & \text{otherwise} \end{cases} \quad .$$

B. Bayes Decision Criterion

Bayes decision criterion is a rule that defines the best decision by calculating the average (expected) value of each decision given the observed data:

$$\mathrm{EVal}[B_k|D_n] = \sum_i \mathrm{Val}[B_k|H_i]\ \mathrm{Prob}[H_i|D_n] \quad ,$$

where $\mathrm{Prob}[H_i|D_n]$ is the posterior probability of the ith hypothesis, given the data D_n through the nth time step. The Bayes criterion selects the decision that has the maximum expected value:

$$\text{select decision } B^* \text{ such that}$$
$$\mathrm{EVal}[B^*|D_n] = \max_k\{\mathrm{EVal}[B_k|D_n]\} \quad .$$

In the classification decision example, the expected value of each decision is simply the summation of posterior probabilities for hypotheses related to the decision. The classification decision B^* is then the decision with the highest aggregated probability.

C. Deferred Decision Making

The decision maker may have the option to make the decision B^* as indicated by the Bayes criterion, or to defer the decision and collect additional information. To model this process, a new function is defined. The expected value of perfect information given the data, $EVal[PI|D_n]$, is defined as the expected value of the best decision (sum of the values of the best decision for each hypothesis times the posterior probability of the hypothesis) minus the expected value of the Bayes decision:

$$EVal[PI|D_n] = \sum_i \max_k\{Val[B_k|H_i]\}\ Prob[H_i|D_n] - EVal[B^*|D_n] \quad .$$

In the limit as the posterior probability of a particular hypothesis approaches unity, the expected value of perfect information approaches zero.

The decision maker selects decision B^* at the first time step that the expected value of perfect information drops below an input threshold V_0:

if $\quad EVal[PI|D_n] \leq V_0 \quad ,$

then $\quad$ select decision $B^* \quad .$

If, however, the expected value of perfect information is greater than the threshold, then the decision maker will defer making a decision and will collect more information.

The idea behind this procedure is that if the expected value of the best decision is considerably higher than the current Bayes decision, then it pays to continue gathering information to make a better decision in the future. On the other hand, if the expected value of the best decision is only a little higher than the current Bayes decision, then it is better to select decision B^* because the gain, in expected value $EVal[PI|D_k]$, is not worth the risk V_0. For example, if a submariner thought he were closing an ASW capable target group, V_0 would reflect the risk associated with counterdetection and might be a relatively large value. Conversely, if the submariner did not expect a high ASW threat, V_0 would be a relatively low value. In the modeling sense V_0 is a control parameter--high values cause quick decisions with higher chances of selecting the wrong decision, and low values delay the decision until very conclusive acoustic information is incorporated in the posterior probabilities. V_0 need not be a constant over the engagement. For example, in the initial stages of the engagement V_0 might be a low value because there is little risk to the observer because the targets are at long range. As the observer closes the targets, the risks of counter-detection increase and the value of V_0 should be increased accordingly.

In the classification decision example, the threshold parameter V_0 can be interpreted as a probability threshold, or a measure of acceptable uncertainty. If V_0 is a low value, say 0.05, then the expected value of a decision must exceed 0.95 for the decision to be made, otherwise it will be deferred.

D. Decision Probabilities

From Monte Carlo replications of the MUSAC II model the probability of making each decision can be estimated. To calculate the probability of making a specified decision at a particular time step, a new random variable is defined:

$$x_{knr} = \begin{cases} 1 & \text{if} \quad B_k = B_r^* \text{ at } t = t_{nr} \\ 0 & \text{otherwise} \end{cases} \quad .$$

That is, if the kth decision is made at the nth time step on the rth replication, x_{knr} is set to 1, and is 0 otherwise. The probability of making the kth decision at the nth time step can then be estimated by:

$$\text{Prob}[B_k D_n] = \frac{1}{R} \sum_{r=1}^{R} x_{knr}$$

where R is the total number of replications. These probabilities can be summed over the time steps to estimate the probability of making decision B_k at any time in the engagement; or the $\text{Prob}[B_k D_n]$ can be summed over the decisions to estimate the probability of making some decision at a particular time step. The probability of some decision at some time is the double sum over time and decisions.

Correct and incorrect classification probabilities are examples of decision probabilities. In the classification decision example, if the HVU were truly on track #1, then the probability of correct classification is:

$$\text{Prob}[CC] = \sum_{n} \text{Prob}[B_1 D_n] \quad .$$

The probability of incorrect classification is:

$$\text{Prob}[IC] = \sum_{n} \left(\text{Prob}[B_2 D_n] + \text{Prob}[B_3 D_n] \right) \quad ,$$

and the probability of no classification is:

$$\text{Prob}[NC] = 1 - \sum_{n} \sum_{k} \text{Prob}[B_k D_n] \quad .$$

E. Engagement MOE

The expected value of the engagement can be used as an overall measure of effectiveness (MOE) to study the effects of parameter variations. To compute the MOE, the actual value of the decision is recorded and averaged over the replications:

$$\text{MOE} = \frac{1}{R} \sum_{r} \text{Val}[B_r^* | H_o] \quad ,$$

where B_r^* is the decision on the rth replication, H_o is the true hypothesis, and R is the total number of replications. In the classification decision example, the engagement MOE is identical to the probability of correct classification.

Appendix A

DERIVATION OF SIGNAL PROCESSOR STATISTICS

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Appendix A

DERIVATION OF SIGNAL PROCESSOR STATISTICS

A rationale for the channel output statistics is presented in this appendix. The first section derives general equations for the statistics of the squared magnitude of a sum of independent random vectors. These equations are used in various ways in the next three sections; the sections present the assumptions and derivations for the narrowband, broadband, and modulated broadband equations.

A. Statistics of the Squared Magnitude of a Sum of Independent Random Vectors

The random variable P is defined as:

$$P = \left|\sum_i \vec{A}_i\right|^2$$

where the $\vec{A}_i$'s are vectors. If the magnitude of $\vec{A}_i$ is the rms pressure from the ith source, then P represents the power from all sources at a given frequency.

The above equation can be rewritten as a double sum of dot products between the vectors:

$$P = \left(\sum_i \vec{A}_i\right) \cdot \left(\sum_j \vec{A}_j\right)$$

$$P = \sum_i \sum_j A_i \; A_j \; \cos(\theta_i - \theta_j)$$

where A_i is the magnitude and θ_i is the phase angle of the ith vector.

Two assumptions are made: the A_i's and θ_i's are all independent random variables; and the θ_i's are uniformly distributed from 0 to 2π radians. Under the independence assumptions, the expected value of P is:

$$E(P) = \sum_i E(A_i^2) + \sum_{i \neq j}\sum E(A_i)\, E(A_j)\, E(\cos\, \theta_{ij}) \quad ,$$

where $\theta_{ij} = \theta_i - \theta_j$. Under the uniform angle assumption, the expected values of the cosine terms are zero. Therefore, the expected value of P is:

$$E(P) = \sum_i E(A_i^2) \quad .$$

In other words, the average total power from many independent sources is the sum of average power from each source.

The expected value of the square of P is:

$$E(P^2) = \sum_i \sum_j \sum_m \sum_n E(A_i A_j A_m A_n \cos\, \theta_{ij}\, \cos\, \theta_{mn}) \quad .$$

When none of the indices are equal, the expected value of the argument is zero because the expected values of both cosine terms are zero. Likewise, when any three of the indices are equal but the fourth index is not, the expected value of the argument is zero because the expected value of one of the cosine terms is zero (the other cosine term has value one). When all indices are equal, the expected value of the argument is:

$$E(A_i^4) \quad .$$

When $i = j$ and $m = n$ and $i \neq m$, the expected value of the argument is:

$$E(A_i^2)\, E(A_m^2) \quad .$$

And finally, when $i = m$ and $j = n$ and $i \neq j$, and when $i = n$ and $j = m$ and $i \neq j$, the expected values of the argument are:

$$E(A_i^2)\, E(A_j^2)\, E(\cos^2\, \theta_{ij})$$

and

$$E(A_i^2)\, E(A_j^2)\, E(\cos\, \theta_{ij}\, \cos\, \theta_{ji}) \quad .$$

The expected value of the square of the cosine is 1/2.

Combining the above results, the expected value of P^2 is:

$$E(P^2) = \sum_i E(A_i^4) + 2\sum\sum_{i \neq j} E(A_i^2)\, E(A_j^2) \quad .$$

The square of the expected value of P is:

$$E^2(P) = \left[\sum_i E(A_i^2)\right]^2 = \sum_i \sum_j E(A_i^2)\, E(A_j^2)$$

$$E^2(P) = \sum_i E^2(A_i^2) + \sum\sum_{i \neq j} E(A_i^2)\, E(A_j^2) \quad .$$

And therefore the variance of P is:

$$Var(P) = E(P^2) - E^2(P)$$

$$Var(P) = \sum_i Var(A_i^2) + \sum\sum_{i \neq j} E(A_i^2)\, E(A_j^2) \quad .$$

In other words, the variance of the total power from many independent sources is <u>larger</u> than the sum of the variances of the power from each source.

The next task is to calculate the covariance between two squared magnitudes of sums of independent random vectors:

$$P = \sum_i \sum_j A_i\ A_j\ \cos(\theta_i - \theta_j)$$

$$Q = \sum_m \sum_n B_m\ B_n\ \cos(\varphi_m - \varphi_n)$$

where A_i θ_i B_m φ_m are all independent random variables except that A_i is not independent of B_i, and θ_i is not independent of φ_i (however, A_i is independent of θ_i, etc.). The angles θ_i and φ_m are assumed to be uniformly distributed from 0 to 2π radians.

The expected value of the product is:

$$E(PQ) = \sum_i \sum_j \sum_m \sum_n E(A_i\ A_j\ B_m\ B_n\ \cos\theta_{ij}\ \cos\varphi_{mn})$$

where $\theta_{ij} = \theta_i - \theta_j$ and $\varphi_{mn} = \varphi_m - \varphi_n$. When none of the indices are equal, or when any three indices are equal but the fourth is not equal, the expected value of the argument is zero. When all indices are equal, the expected value of the argument is:

$$E(A_i^2 B_i^2) \quad .$$

When $i = j$ and $m = n$ and $i \neq m$, the expected value of the argument is:

$$E(A_i^2)\ E(B_m^2) \quad .$$

When $i = m$ and $j = n$ and $i \neq j$, and when $i = n$ and $j = m$ and $i \neq j$, the expected values of the argument are:

$$E(A_i B_i)\ E(A_j B_j)\ E(\cos\theta_{ij}\ \cos\varphi_{ij})$$

$$E(A_i B_i)\ E(A_j B_j)\ E(\cos\theta_{ji}\ \cos\varphi_{ji})$$

Combining the above results, the expected value of PQ is:

$$E(PQ) = \sum_i E(A_i^2 B_i^2) + \sum_{i \neq j}\sum E(A_i^2)\ E(B_j^2)$$

$$+ 2 \sum_{i \neq j}\sum E(A_i B_i)\ E(A_j B_j)\ E(\cos\theta_{ij}\ \cos\varphi_{ij}) \quad .$$

The product of expected values is:

$$E(P)\ E(Q) = \sum_i E(A_i^2) \sum_j E(B_j^2)$$

$$E(P)\ E(Q) = \sum_i E(A_i^2)\ E(B_i^2) + \sum_{i \neq j}\sum E(A_i^2)\ E(B_j^2) \quad .$$

Therefore, the covariance between P and Q is:

$$\mathrm{Cov}(P,Q) = E(PQ) - E(P)\ E(Q)$$

$$\mathrm{Cov}(P,Q) = \sum_i \mathrm{Cov}(A_i^2, B_i^2)$$

$$+ 2 \sum_{i \neq j}\sum E(A_i B_i)\ E(A_j B_j)\ E(\cos\theta_{ij}\ \cos\varphi_{ij}) \quad .$$

Note that Cov(P,Q) reduces to the previously derived Var(P) when $A_i = B_i$ and $\theta_i = \varphi_i$.

B. Narrowband Statistics

The equations for μ and σ^2 for the narrowband case are derived by assuming that the amplitude A_{in} and phase θ_{in} from the ith source in the nth frequency bin have the statistics as defined in Table 1. The symbols A_{in} A_{im} θ_{in} θ_{im} are being used in the same sense as the symbols A_i B_i θ_i φ_i in the previous section.

The assumptions are discussed below by equation number:

(1) The signal power and the noise power are assumed to be equally distributed over the narrowband of width W.

(2) The variance of the signal is zero; this means that the Lofar line amplitude is assumed to be constant. The variance of the noise power is the square of the mean noise power, this is a Gaussian noise assumption.

(3) The bin-to-bin covariance of the signal power is zero because the amplitude is constant. The covariance of the noise power is zero because the noise is assumed to be independent from bin-to-bin.

(4) The expected value of the signal amplitude product is equal to the expected signal power because the signal amplitude is constant. By assuming that the bin-to-bin covariance of the noise amplitude is zero, the expected value of the product of noise amplitude is equal to the square of the expected value of the noise amplitude. The noise amplitude A is Rayleigh distributed with mean $(\pi E(A^2)/4)^{\frac{1}{2}}$.

(5) The bin-to-bin covariance of the product of the signal cosines is 1/2 because the phase angle from a given source is assumed to be completely correlated from bin to bin. The covariance is zero for noise phase because it is assumed to be independent from bin to bin. The covariances involving signal phase with noise phase are also zero because they are assumed independent.

The mean power from all sources over all frequency bins is:

$$E(P) = \sum_n \sum_i E(A_{in}^2) \qquad i = 1,2,\ldots,s+r \quad n = 1,2,\ldots,WT$$

$$E(P) = WT\left[\sum \frac{S_i}{WT} + \sum \frac{R_k}{WT}\right]$$

Table 1

SIGNAL AND NOISE STATISTICS

		Signal $i = 1,2,\ldots,s$	Noise $i = s+1,\ldots,s+r$ $k = i-s$		
(1)	$E(A_{im}^2) =$	$\frac{S_i}{WT}$	$\frac{N_k}{WT}$		
(2)	$Var(A_{im}^2) =$	0	$\left(\frac{N_k}{WT}\right)^2$		
(3)	$Cov(A_{im}^2, A_{in}^2) =$	0	0		$m \neq n$
(4)	$E(A_{im} A_{in}) =$	$\frac{S_i}{WT}$	$\frac{\pi}{4} \frac{N_k}{WT}$		$m \neq n$
(5)	$E(\cos \theta_{ijm} \cos \theta_{ijn}) =$	$\frac{1}{2}$	0	for $j = 1,\ldots,s$	$m \neq n$
		0	0	for $j = s+1,\ldots,s+r$	

Note: $\theta_{ijm} = \theta_{im} - \theta_{jm}$; the difference of the ith and jth phase angles.

WT = Number of frequency bins; bandwidth times averaging time ($n = 1,2,\ldots, WT$).

therefore, $\mu = S + R$

where $S = \sum S_i \qquad i = 1,2,\ldots,s$

$R = \sum R_k \qquad k = 1,2,\ldots,r$

The variance of the power is computed from the formulae derived in the previous section. The variance of the power in the nth bin is:

$$\mathrm{Var}(P_n) = \sum_i \mathrm{Var}(A_{in}^2) + \sum_{i \neq j}\sum E(A_{in}^2)E(A_{jn}^2)$$

$$\mathrm{Var}(P_n) = \sum \left(\frac{R_k}{WT}\right)^2 + \left[\sum \frac{S_i}{WT} + \sum \frac{R_k}{WT}\right]^2 - \left[\sum \left(\frac{S_i}{WT}\right)^2 + \sum \left(\frac{R_k}{WT}\right)^2\right]$$

$$\mathrm{Var}(P_n) = \left(\frac{1}{WT}\right)^2 \left[(S+R)^2 - V\right] \quad ,$$

where $V = \sum S_i^2 \qquad i = 1,\ldots,s \quad .$

The covariance of the power in the nth bin with the power in the mth bin is:

$$\mathrm{Cov}(P_n, P_m) = \sum_i \mathrm{Cov}(A_{in}^2, A_{im}^2)$$

$$+ 2\sum_{i \neq j}\sum E(A_{in}A_{im})\, E(A_{jn}A_{jm})\, E(\cos\theta_{ijn} \cos\theta_{ijm})$$

$$\mathrm{Cov}(P_n, P_m) = \sum_{i \neq j}\sum E(A_{in}A_{im})\, E(A_{jn}A_{jm}) \qquad \begin{matrix} i = 1,\ldots,s \\ j = 1,\ldots,s \end{matrix}$$

$$\mathrm{Cov}(P_n, P_m) = \left[\sum \frac{S_i}{WT}\right]^2 - \sum \left(\frac{S_i}{WT}\right)^2$$

$$\mathrm{Cov}(P_n, P_m) = \left(\frac{1}{WT}\right)^2 \left[S^2 - V\right] \quad .$$

The variance of the power from all bins is:

$$\mathrm{Var}(P) = \sum_n \mathrm{Var}(P_n) + \sum_{n \neq m}\sum \mathrm{Cov}(P_n, P_m) \qquad \begin{matrix} n = 1,\ldots,WT \\ m = 1,\ldots,WT \end{matrix}$$

$$\mathrm{Var}(P) = \frac{1}{WT}\left[(S+R)^2 - V\right] + \left(1 - \frac{1}{WT}\right)\left[S^2 - V\right]$$

therefore,

$$\sigma^2 = S^2 - V + \frac{2}{WT} SR + \frac{1}{WT} R^2 \quad .$$

As an example, assume just one signal of power S_1 and no noise ($R = 0$), then the variance is:

$$\sigma^2 = S_1^2 - S_1^2 = 0 \quad ,$$

as it should be since the amplitude of the signal is assumed to be constant. If, however, there are two signals of power S_1 and S_2 and no noise, then the variance is:

$$\sigma^2 = (S_1 + S_2)^2 - (S_1^2 + S_2^2) = 2 S_1 S_2 \quad .$$

In this case the two signals have interfered randomly with each other because of their random values of phase angle. If $S_1 = A_1^2$ and $S_2 = A_2^2$, then the minimum power is $(A_1 - A_2)^2$, the maximum power is $(A_1 + A_2)^2$, and the variance due to random values inbetween is $2\,A_1^2 A_2^2$.

The distribution of power caused by random interference is not normally distributed. If, however, there are many independent signals, then the total power is approximately normally distributed (usually) with mean μ and variance σ^2 as derived above. The normal distribution assumption is not very good when there are only a few sources, as will be the case with a MUSAC II application. There is, however, a compensating effect that will tend to reduce the errors involved by assuming a normal distribution. The most critical time for having an accurate detection model occurs when the lines are just being detected. In this case the signals are all small and the variance is approximately R^2/WT. A normal distribution for the small signal case is reasonable because the power is averaged over WT bins.

In addition to the question of the shape of the distribution, there is also the question of observation-to-observation independence. It is reasonable to assume that the noise is independent from one observation to another, but the source signals may not be independent. This is because the random phase angle may not change fast enough compared to the averaging time. The argument for assuming independence uses the same point as raised in assuming a normal distribution: for the cases of interest, the Lofar signal will be small; thus the noise terms in the variance will dominate, and therefore the observation-to-observation independence of noise will also dominate.

The mean and variance of the data channel were derived as:

$$\mu = S + R$$

$$\sigma^2 = S^2 - V + \frac{2}{WT} SR + \frac{1}{WT} R^2 \quad .$$

The equations for the mean and variance of the reference channel are found by simply setting th.. signal terms to zero:

$$\mu^* = R$$

$$\sigma^{*2} = \frac{1}{WT} R^2 \quad .$$

Detection of a Lofar line is performed by comparing the narrowband in question to an average background that is near the narrowband frequency. The μ^*-equation assumes that the average background is caused entirely by broadband noise: there may be broadband target noise in the background but no Lofar lines. This is a reasonable assumption if the various lines are spread out enough on the display for there to be area visible on either side of any line. The value of σ^{*2} is not the variance of the average background. It is, instead, the variance of just one sample of background;

there may be many samples of background, all of them used to compute the average background value. The idea behind the σ^{*2}-equation is that if the signal sources were removed, then the data channel would have the same variance as the reference channel.

The detection threshold is assumed to be adequately described by:

$$a = \mu^* + d\,\sigma^* \quad .$$

The threshold is not a random variable in the sense that the output of data channel is a random variable; however, the threshold does change in response to the changing geometry and to the random process that generates the input values of source level, propagation loss, and noise level. The above definition of the detection threshold is equivalent to assuming a constant false alarm threshold. This means that if there is no Lofar line, then the random output from the data channel will exceed the threshold at a constant rate of:

$$f = \frac{n}{\Delta t}\frac{1}{\sqrt{2\pi}}\int_d^\infty e^{-\frac{1}{2}x^2}dx$$

where

f	=	false alarm rate (number/min)
Δt	=	time step duration (min)
n	=	number of observations in a time step
d	=	number of reference channel standard deviations the threshold is set above the reference channel mean.

C. Broadband Statistics

The equations for μ and σ^* for the broadband case are derived by assuming that the amplitude A_{in} and phase θ_{in} from ith source in the nth frequency bin has the following statistics:

(1) $$E(A_{in}^2) = R'_{in}\ \Delta f$$

(2) $$Var(A_{in}^2) = [R'_{in}\ \Delta f]^2$$

(3) $$Cov(A_{in}^2,\ A_{im}^2) = 0 \qquad n \neq m$$

(4) $$E(\cos\theta_{ijn}\ \cos\theta_{ijm}) = 0 \qquad n \neq m,\ i \neq j$$

where θ_{ijn} = $\theta_{in} - \theta_{jn}$; the difference of the ith and jth phase angles in the nth frequency bin.

Δf = 1/T; width of the frequency bin (Hz).

T = averaging time (sec).

R'_{in} = mean square power from the ith source in the nth frequency bin of width Δf.

The first equation is a definition of symbols. The second equation is a Gaussian noise assumption. The third equation assumes that the noise power in one frequency bin is independent of the noise in another bin. The final equation assumes that the difference in phase angles between two sources is also independent from bin to bin.

The mean power from all frequency bins is:

$$E(P) = \sum_n \sum_i E(A_{in}^2)$$

$$E(P) = \sum_n \sum_i R'_{in}\ \Delta f$$

therefore

$$\mu = \int R'(f)\ df$$

where

$$R'(f) = \sum_i R'_i(f) \quad .$$

The sum over small frequency bins has been approximated by the integral over a power density function: $R'_i(f_n) \cong R'_{in}$, where f_n is the center frequency of the nth frequency bin.

The variance of the power is computed from the formulae derived in Section A. The variance of the power in the nth frequency bin is:

$$\mathrm{Var}(P_n) = \sum_i \mathrm{Var}(A_{in}^2) + \sum_{i \neq j}\sum E(A_{in}^2)\, E(A_{jn}^2)$$

$$\mathrm{Var}(P_n) = \sum_i [R'_{in}\ \Delta f]^2 + \sum_{i \neq j}\sum R'_{in}\ R'_{jn}\ \Delta f^2$$

$$\mathrm{Var}(P_n) = \left[\sum_i R'_{in}\right]^2 \frac{\Delta f}{T} \quad .$$

The covariance of the power in the nth bin with the power in the mth bin is zero because of the independence assumptions. Therefore, the variance of the total power is:

$$\mathrm{Var}(P) = \sum_i \mathrm{Var}(P_n)$$

$$\mathrm{Var}(P) = \frac{1}{T}\sum_n \left[\sum_i R'_{in}\right]^2 \Delta f$$

therefore $$\sigma^2 = \frac{1}{T}\int [R'(f)]^2\, df$$

where $$R'(f) = \sum_i R'_i(f) \quad .$$

The sum over small frequency bins has been approximated by the integration over a squared power density.

The equations for the broadband statistics for the data channel are:

$$\mu = \int R'\, df$$

$$\sigma^2 = \frac{1}{T}\int [R']^2\, df$$

where $R' = S' + N'$; and where S' is a sum of target spectra and N' is a sum of noise spectra. The equations for the broadband statistics for the reference channel are derived by assuming that the target spectra are reduced by a side lobe factor; the target spectra are not set to zero.

Thus, if S'^* is the sum of target spectra when all targets are in the side lobes, then the reference spectrum is:

$$R'^* = S'^* + N'$$

and the mean and variance of the reference channel is:

$$\mu = \int R'^* \, df$$

$$\sigma^2 = \frac{1}{T} \int [R'^*]^2 \, df \quad .$$

The reference channel statistics are defined this way so that the phenomenon of side lobe masking will be properly represented. The presence of a nearby target will drive the reference channel mean up and therefore the data channel output will have to satisfy a higher detection threshold. The net effect will be a low probability of detection when strong side lobe interference is present.

D. Modulated Broadband Statistics

The mean and variance of the data channel are derived by first assuming that the modulated voltage waveform from the array is given by:

$$x(t) = a(1 + m \cos \beta t) \cos \omega t \quad ,$$

where a is the amplitude of the carrier wave of angular frequency ω, and m is the modulation index of the modulating wave of angular frequency β. The modulated voltage can also be written as:

$$x(t) = \frac{ma}{2} \cos (\omega-\beta)t + a \cos \omega t + \frac{ma}{2} \cos (\omega+\beta)t \quad .$$

Since there is a band of waves with approximately the same amplitude a, the wave of amplitude ma/2 and angular frequency $\omega + \beta$ (the third term in the above equation) will interfere with a carrier wave of amplitude a and frequency $\omega + \beta$. The average power in the interference pattern is the sum of powers: $\frac{1}{2}a^2 + \frac{1}{2}\left(\frac{ma}{2}\right)^2$, because the two waves are incoherent. Another modulated wave of carrier frequency $\omega' = \omega + 2\beta$ will have a low side component of amplitude ma/2 and angular frequency $\omega' - \beta = \omega + \beta$. Thus the total power at frequency $f = (\omega+\beta)/2\pi$ is:

$$P'\,df = \frac{1}{2}a^2 + \frac{1}{2}\left(\frac{ma}{2}\right)^2 + \frac{1}{2}\left(\frac{ma}{2}\right)^2 \quad .$$

If the definitions: $M = m^2$ and $S'\,df = a^2/2$ are used, then the average signal power density at frequency f is:

$$P' = S' + \frac{1}{2}M\,S' \quad .$$

By assuming that the value of M changes slowly with frequency and that β is small compared with ω, the expression for the average power density can be integrated over a frequency band:

$$P = \int_{f_1}^{f_2} P'\,df \quad .$$

The integration limits, f_1 and f_2, must be large compared to $\beta/2\pi$.

The noise spectrum N' can be included in the integrand of the above equation because the noise is assumed to be independent of the signal. With the addition of noise, the mean power in the data channel is:

$$\mu = \int \left[S' + \frac{1}{2}MS' + N'\right] df \quad ,$$

and the mean of the reference channel is found by setting the modulation signal to zero:

$$\mu^* = \int [S' + N']\,df \quad .$$

The variances for the two channels are similar to the broadband case:

$$\sigma^2 = \frac{1}{T}\int \left[S' + \frac{1}{2}MS' + N'\right]^2 df$$

$$\sigma^{*2} = \frac{1}{T}\int [S' + N']^2\,df$$

where T is the averaging time.

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The report lists and describes all of the items furnished to the Modern Army Selected Systems Test, Evaluation and Review (MASSTER) for the Phase II Camouflage Test begun in June 1975. Also included is a concept of testing personal camouflage items by emphasizing that they are components of an integrated system of clothing and personal equipment. All experimentally developed items are described with photographs, reflectance data, pertinent associated computational data, and colorant composition formulations. Standard items furnished for reference in the test are included in the listing.

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PREFACE

This report covers the work performed by US Army Natick Research and Development Command during FY 75 in support of the camouflage testing program of MASSTER. This work was performed by NARADCOM under a transfer of funds from US Army Mobility Equipment Research and Engineering Command. These funds were used for the purchase of materials and outside processing and services for fabrication of items.

The report also covers work performed by contract under technical guidance by NARADCOM. The contract on camouflage of tents with Franklin Institute Research Laboratory was equally funded by MERADCOM and NARADCOM with Dr. C. J. Monego of NARADCOM as Project Officer. The contract on camouflage of packaging materials with Battelle Columbus Laboratories was funded by MERADCOM with technical guidance provided by Mr. Raymond Mansur of NARADCOM.

All technical guidance by the above and by the authors of this report was supported by NARADCOM mission funds.

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SUPPORT TO MASSTER PHASE II CAMOUFLAGE TEST

1. Introduction

The US Army Natick Research and Development Command (NARADCOM) US Army Mobility Equipment Research and Development Command (MERADCOM), and Modern Army Selected Systems Test, Evaluation, and Review (MASSTER) have been engaged in a cooperative assessment of developments in personal camouflage for the past several years. The results of the earlier, somewhat limited efforts, clulminated in the Phase I Camouflage Test which was performed during FY 1973. The following statement from the Phase I report[1] summarises the basis for MASSTER's participation in the Army-wide camouflage program.

"An evaluation, conducted during MASSTER combined test ACCB II and TRICAP I,[2] indicated the camouflage posture of participating Army units required considerable improvement. The VCofSA indicated a desire that MASSTER take a leading role in developing innovative camouflage techniques. As a result, MASSTER developed a camouflage evaluation program, and this report documents Phase I of that program."

Before Phase I was completed it became apparent that a second exercise would be necessary, mainly to compensate for the rather low level of emphasis on camouflage of the individual soldier. This is stressed in plans for Phase II Camouflage Test, that began in the summer of 1975.

To allow for proper emphasis on personal camouflage in the Phase II Test, it was necessary that extnesive support in material be given by NARADCOM and MERADCOM. The Lead Laboratory for Camouflage Technology at MERADCOM transferred $52,000 to NARADCOM to supply the many items listed in Section 3. These funds were used exclusively for purchases of materials and services from outside sources, both governmental and commercial. In addition NARADCOM supplied approximately $100,000 of mission funds, largely for technical and managerial support by NARADCOM.

Some of the items furnished were suggested by MERADCOM and MASSTER, and others by NARADCOM. The list of items was subsequently agreed upon at meetings of personnel of all three agencies. The basic intent was to furnish those items needed to permit a camouflage evaluation of the complete system of clothing and person equipment as used by a soldier in combat rather than on the item-by-item basis.

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1. Marrero-Camacho, G. and R.B. McDermott, Camouflage Evaluation Report (Phase I), MASSTER Test Report No. FM 153, Hq MASSTER, Ft. Hood, Texas 76544 (21 January 1974).

2. Humphreys, Adolph H., Camouflage Team Report of MASSTER ACCB II/TRICAP I, Report 2028, US Army Mobility Equipment Research and Development Center, Fort Belvoir, VA 22060 (April 1972).

2. Concepts of Testing Clothing for Camouflage Effectiveness

In 1962 a joint exercise[3] on effectiveness of personal camouflage was conducted under the auspices of the Infantry Board, the Engineer Research and Development Laboratories and the Quartermaster Research and Development Command. This exercise was conducted at Fort Benning and utilized troops wearing different uniforms, both patterned and monotone. The subjects were viewed by a group of trained observers from elevated booths that provided each with a clear line of sight to the targets in the test area. Six uniforms were considered in a detailed, quantitative field test:

a. British monotone similar to Olive Green 107

b. U.S. Army Olive Green 107 without load-carrying equipment

c. U.S. Army Olive Green 107 with load-carrying equipment

d. U.S. Army 1948 four-color camouflage pattern

e. U.S. Marine Corps Mitchell pattern

f. U.S. Army Khaki 1 uniform similar in design to b and d.

Observation ranges varied from 500 to 1800 meters. It was reported[3] that at none of the ranges could any of the patterns be visually resolved into their individual components. Also, the average, integrated colors were nearly the same for the first five colors listed. If it is assumed that a subject was uniformly illuminated and the brown, dark green and black areas of the 4-color pattern are visually equivalent at the observation ranges, a dark-light pattern should be discernible at some range. Under the conditions of the test the contrast between the dark and light areas was about 1.0. For an average area of about 60 cm^2 for parts of the light green portion of this 4-color pattern, Tiffany data[4,5] suggest the dark-light pattern could not have been resolved beyond about 200 meters. Thus, both by expectation and observation, the contrast of each of the first five uniforms (listed above) with the background against which it was viewed was approximately the same. Unfortunately, extremely hot and dry weather seared the grass that comprised most of the viewing background and, therefore, the contrast with the terrain for these five uniforms was high, probably equivalent to about 0.8. The Tiffany data also suggest that all five of these target uniforms with a perceived area of about 0.75 m^2 should be visible at all ranges, under the good viewing conditions that generally prevailed during the test.

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3. Gee, D. L., and A. H. Humphreys, User Review of Camouflage for the Individual Combat Soldier in the Field, ERDL Report No. 1834, Mobility Equipment R&D Command, Ft. Belvoir, VA. 22060, Oct 1965.

4. Blackwell, H. R., Contrast Thresholds of the Human Eye, J. Opt. Soc. Amer., 36, 624-643 (1946).

5. Middleton, W.E.K., Vision Through the Atmosphere, U. Toronto Press, 1952.

The same data suggest that the detection range for the Khaki 1 uniform, with a lower contrast with the background (probably about 0.2), should be about half that of the other uniforms. The results of the test, indeed, supported the conclusion that the Khaki 1 uniform was substantially less conspicuous than the other five, which were indistinguishable from one another.

The color of the terrain, its near absence of perceptual clutter, and the extreme observation ranges combined to preclude any quantitative comparison of patterned uniforms and their monotone equivalents. Moreover, as the test progressed, the observers became familiar with the test area. This may have biased the results. Some of these unfortunate factors were avoided in the design of MASSTER test FM 204b: the grass was greener, observation ranges were shorter; observers were frequently rotated. Yet the contrast with the immediately surrounding terrain against which targets were viewed was still rather high, probably near 0.5.

The qualitative visual portions of the 1962 test yielded some interesting observations. An ambush and an infiltration test were conducted at shorter ranges and in more cluttered terrains, where patterns could be resolved. It was generally agreed that patterned uniforms were more effective than monotone uniforms under these conditions. It was also observed, however, that additional measures need to be taken beyond a camouflaged uniform and helmet cover to achieve camouflage effectiveness. In none of the 1962 testing was a specific attempt made to disrupt the soldier's silhouette beyond modest use of indigenous materials such as foliage or long grass. One of the most conspicuous clues was the black, shiny boots that were worn. At long ranges they were generally obscured, but at the short ranges used in the informal, qualitative observations, the boots were often visible. Another conspicuous clue to recognition of a man at all ranges was the characteristic head-neck-shoulder outline. These subjective observations were generally borne out in the later Vietnam experience.

MASSTER FM 204b was partly intended as a prelude to a more definitive test of camouflage effectiveness. Improving on the design of the 1962 test, it was also hoped that quantitative data on probability of detection as a function of range would be generated that could be useful in various computer models. From FM 204b it was hoped that one of the patterned uniforms could be identified as being less conspicuous than the others. This uniform could then be augmented with other patterned or otherwise camouflaged items to provide the soldier with a full complement of camouflage within the state of the art. It was planned that this augmented, patterned, camouflage clothing and equipment system would be compared later with a similar system consisting only of standard items in the monotone olive green color in competitive unit exercises. The rational for this type of test was that a quantitative measure of camouflage effectiveness should be in realistic operational terms that relate to a tactical environment.

Such an exercise involves pitting one fully camouflaged force against an equivalent force equipped only with standard, authorized olive green monotone equipment in a field setting. At the time FM 204b was being formulated, it was planned that the follow-up exercise would be squad-on-squad scale using an appropriate, available scenario. The basis of effectiveness would have included scoring probable casualties by available techniques.

It was not necessarily expected that the squad-on-squad exercise would, by itself, provide a total basis for a cost/effectiveness analysis, but that it would at least have pointed the direction that future, definitive testing should take. It is anticipated that implementing personal camouflage to the full extent now possible within the current state of the artmight add about 15 per cent to the cost of a complete clothing and personal equipment system for the combat soldier. Proper analysis requires that the effectiveness data also be quantitative and realistic. It is within this context that the many items listed and described in the following sections were produced and made available for the MASSTER test.

3. <u>Summary of Items to be Tested</u>

The list below tabulates the items furnished to MASSTER for test beginning the summer of 1975. The items were not intended to be evaluated separately, but to be used as components of experimental ensembles that represent total clothing and personal equipment systems, typical of those that might be seen by soldiers in combat stations. Although some items will be subjected to individual evaluation, and some screening of similar items is under way, the more rigorously conducted tests will deal with comparisons among systems of personal equipment.

a. Standard Combat Tropical Uniforms, Olive Green 107

b. Standard Combat Tropical Uniforms, US Army 1948 4-color pattern

c. Experimental Desert Uniform, 6-color pattern

d. Experimental Uniforms for Verdant Terrains with four levels of expansion of the US Army 1948 4-color pattern

e. Experimental Uniforms with Experimental Disruptive Camouflage for Verdant Terrains

f. Experimental Uniforms with "Tiger" pattern oriented horizontally

g. Standard Helmet Covers, Reversible

h. Standard Helmet Covers, 1948 4-color pattern

i. Experimental Helmet Covers, Coarse Net

j. Experimental Body Net, Coarse Net

k. Standard Ballistic Vests, Olive Green 106

l. Ballistic Vests, Standard 4-color pattern

m. Ballistic Vest, Experimental 4-color pattern expanded by 60 per cent

n. Experimental Poncho, Experimental 4-color pattern

o. Experimental Watch Covers

p. Experimental Weapon Covers

q. Standard Load Carrying Equipment

r. Load Carrying Equipment with Experimental 4-color Camouflage Pattern

s. Experimental Pack Covers, 4-color

t. Experimental Pack Covers, 6-color

u. Experimental Overcoloring Compound, Removable

v. Experimental Overcoloring Compound, Durable

w. Experimental Combat Boots, Green

x. Experimental Combat Boots, Tan

y. Experimental Face Paints, Desert Colors

z. Experimental Face Paints, Verdant Colors

aa. Experimental Face Veil

bb. Experimental Dye Packets for Field Dyeing of Personal Items (Handkerchiefs, Underwear, etc.)

cc. Standard Leather Gloves, Tan

dd. Experimental Leather Gloves, Tan

ee. Experimentally Patterned General Purpose Small Tent, Nature Pattern

ff. Experimentally Patterned General Purpose Small Tent, MERDC Pattern

gg. Experimentally Patterned General Purpose Medium Tent, Nature Pattern

hh. Experimentally Patterned General Purpose Medium Tent, MERDC Pattern

ii. Experimental Recoloring Compound for Tentage

jj. Experimentally Camouflaged Packaging Materials

kk. Experimentally Camouflaged Mobile Field Kitchen

Descriptions of each item furnished by Natick Research and Development Command for testing by MASSTER in the Phase II Camouflage Test are given in Section 4 of this report.

4. Development of Items for Test

As indicated in the tabulation in Section 3, many of the items furnished to MASSTER are standard and available from stock. For that reason no developmental data are furnished for these items.

a. Standard Combat Tropical Uniforms, Olive Green 107

Thirty-five coats and trousers, combat tropical, have been furnished in a variety of sizes. The fabric used in these garments is cotton poplin with a 6.35 mm nylon rip-stop, vat dyed to an Olive Green 107 shade.

The Olive Green 107 shade is vat dyed and was developed in 1950 by the Quartermaster Research and Development Command directed to sniperscope detection. It was type classified in 1952. Figure B.1 is the reflectance curve from 400 to 1000 nm for this uniform. Included are C.I.E. tristimulus coordinates, visual reflectance and the ratio of infrared to red reflectances integrated with respect to the sensitivity functions of CD film. Figure A.1 includes a photograph of this uniform.

b. Standard Combat Tropical Uniforms, 1948 4-color Pattern

Fifty coats and trousers in the same fabric as 4.a. have been furnished in a variety of sizes. The four colors were vat printed over a vat-dyed ground shade in a regular procurement.

The pattern was originally designed in 1948 at the Engineer Research and Development Center. Subsequently, it was translated to fabric under guidance by the QM Research and Development Command and type classified in 1966 as the US Army 1948 camouflage pattern, also directed toward minimizing sniperscope detection.

Figure B.2 gives reflectance curves and computational data for each of the four colors of the camouflage pattern of this uniform. Figure A.1 is a photograph of the 1948 4-color pattern with the standard Olive Green 107 uniform described in 4.a.

c. Experimental Desert Uniforms, 6-color Pattern

Fifty experimentally developed desert uniforms were furnished for the Phase II test in the same tariff of sizes as in 4.a. This camouflage pattern was designed at MERADCOM. Subsequently, the pattern was printed under NARADCOM technical guidance on a fabric that was designed for use in combat clothing for desert terrains. This is the pattern design evaluated by MASSTER in Phase I, of which it was said, "the desert uniform was the most effective in breaking up the silhouette at the longer ranges".[1]

This [illegible] was based on subjective visual observation alone. Simultaneous laboratory investigation at NARADCOM demonstrated that some alteration in visual color and substantial changes in infrared reflectance should be made. To make the indicated corrections a total reformulation of the vat dyed printing was required. Guidance for the reformulation was provided by application of the Kubelka-Munk analysis of colorant layers.[6] Figures A.2. and A.3 are photographs with conventional and infrared color film, respectively, of the original and corrected 6-color desert uniforms, those sent for Phase I and Phase II, respectively. Figures B.3 and B.4 are reflectance curves for each of the five major colors of each of the two uniforms. The dye formulations used for the base color and the colorant components of the print paste for each of the six colors are given in Appendix C.1. The fifty uniforms provided to MASSTER were produced using these corrected formulations.

In fabricating the experimental uniforms a nylon/cotton sateen, approximately 290 g/m^2, was used. The design of the jacket and trousers is similar to the combat tropical uniforms, a design agreed upon jointly for all uniforms in the test in the interest of consistency to eliminate the factor of garment design and outline.

d. Four-Color Pattern Expansion

The MASSTER report of Phase I[1] indicated a definite subjective preference for camouflage patterned uniforms. It also suggested that a larger pattern might be more effective at longer observation ranges. Accordingly, a series of four uniforms was made in which four sizes of camouflage pattern were used. The colorant formulations, shown in Appendix C.2., were identical in each of the levels of expansion and all printing was done by the same mill at the same time on the same base fabric.

The fabric used was also a nylon/cotton sateen approximately 290 g/m^2 and fabricated into the combat tropical design. Figure A.4. is a photograph that illustrates the appearance of the four sizes of patterns used. The smallest pattern size is the same as the standard US Army 1948 4-color verdant pattern; the others are of the same geometry and color but linearly expanded by 30, 60 and 100 per cent. Area expansions are therefore, approximately 70, 250 and 400 per cent, respectively,. Figure B.5. presents reflectance and associated computed data for each of the four colors used in all the patterns.

e. Disruptive Patterned Camouflage

Based on observations in Phase I of certain foreign uniforms, it was agreed by participants in the test that a variation in pattern design from the 4-color pattern should also be considered. The pattern selected was one made by printing the black portion of the "Tiger" pattern (see 4.f.) oriented in a vertical direction over the standard 4-color 1948 pattern. This resulted in a darker total effect than other uniforms, as is shown in Figure A.5. The 4-color patterned fabric, all cotton sateen approximately 290 g/m^2, was withdrawn from general st[illegible] and over printed with the same black formulation used in the expansion series described in 4.d. (see Appendix C.2).

6. Judd, Deane B., Color in Business, Science and Industry, Wiley, New York, 1952.

f. <u>Tiger Patterned Uniforms</u>

This pattern, with one variation is that which was widely used by the ARVN in Vietnam. This uniform is also illustrated in Figure A.5. with the reflectance data given in Figure B.6. The dye formulations used for the various colors are given in Appendix C.3.

g. <u>Standard Reversible Helmet Covers</u>

Two hundred (200) standard reversible helmet covers, FSN 8415-00-261-6833, were sent to MASSTER to be used with a variety of uniforms. One side of the helmet cover is predominantly greenish, the other tan. The green side of the helmet cover is illustrated with the Standard Olive Green 107 and the Standard 1948 4-color patterned uniform in Figure A.1. The tan colored side is illustrated with the 6-color Desert uniform in Figures A.2 and A.3.

h. <u>Standard 4-color Patterned Helmet Cover</u>

One hundred (100) standard helmet covers made of the US Army 1948 4-color pattern, FSN 8415-105-0605 were sent to MASSTER. These are illustrated in Figure A.4. with the expansion series of uniforms.

i. <u>Experimental Helmet Covers, Coarse Netting</u>

A coarsely woven net was vat printed with formulations described in Appendix C.4. in the 4-color verdant pattern. When fully stretched, the net has a mesh of about 15 mm with strands about 3 mm thick. Helmet covers made of this are illustrated in Figure A.4. To prevent hang-up in view of the tendency to snag, the fabric was tenderised by soaking for 2 minutes in a one-per cent solution of hydrochloric acid, dried at 105° C, and neutralised with soda ash.

To form the helmet cover the fabric was cut into 50 cm squares, draped over the helmet and held in place with an elastic tape. It is intended that the excess fabric be raised above the tape to enhance the gross texture and be formed into an uneven surface with paper covered wire.

j. <u>Experimental Body Net, Coarse Netting</u>

The experimental body nets were made of the same fabric as the helmet cover in 4.i. Each net measures about three meters long when stretched longitudinally, and about two meters wide when stretched laterally. The large size was chosen to permit troops to use the net experimentally for camouflage purposes in addition to a close fitting body net as was illustrated in the Phase I report[1]. Figure A.6 illustrates one use of the experimental netting as a personal camouflage net. The individual body nets weigh about 900 grams and folds easily into a package 40 cm by 18 cm by 5 cm.

k. <u>Standard Ballistic Vest</u>

Fifty (50) standard ballistic vests were withdrawn from stock and sent to MASSTER for Phase II. The outer layer is nylon and was commercially dyed Olive Green 106 in a regular procurement. The vest is shown in Figure A.1. by the subject wearing the standard Olive Green 107 coat and trousers.

l. Ballistic Vests, Standard Si · 4-color Pattern

Nylon duck was dyed and printed with formulations also given in Appendix C.4 to produce the standard size 4-color pattern. The fabric was then used to produce (50) otherwise standard ballistic vests that were sent to MASSTER for Phase II. This item is ullustrated in Figure A.1 by the subject wearing the standard 1948 4-color patterned uniform. Reflectance and related data are given in Figure B.7.

m. Ballistic Vest, Experimental Pattern

The same formulations (C.4.) and fabric were used to print a 4-color pattern linearly expanded 60 per cent compared with the standard 1948 4-color pattern. This was used to make fifty (50) armored vests that also were sent to MASSTER for Phase II. This vest is illustrated in Figure A.4. by the subject wearing the uniform with the camouflage pattern also expanded 60 per cent. Reflectance curves and associated computed data for each of the four areas of the camouflage pattern are the same as those that appear in Figure B.7.

n. Experimental Poncho

Figure A.6 also illustrates an experimental 4-color patterned poncho, fifty (50) of which have been sent to MASSTER for Phase II. Nylon rip-stop (approx. 55 g/m^2) was printed with a 4-color pattern using formulations also listed in Appendix C.4. This camouflage pattern was then coated with clear polyurethane film to render the item water repellent. Reflectance curves and related computed data are given in Figure B.8.

o. Experimental Watch Covers

It was pointed out by MERADCOM personnel that the highly directional reflection from a watch crystal may provide an early clue to detection of an infantry soldier. They requested that a few experimental fabric watch covers be furnished to MASSTER for evaluation. These were fabricated from the same fabric as the uniform in 4.b., with a 4-color pattern. The watch cover is illustrated in Figure A.1 by the subject wearing the uniform with the standard size 4-color camouflage pattern.

p. Experimental Weapon Covers

MERADCOM also recommended that MASSTER evaluate the usefulness of devices to disrupt the distinctive outline of individual weapons. NARADCOM fabricated such items from fabric for fifty (50) M-16 rifles and forwarded them to MASSTER. These items are illustrated in Figure A.4., by one of the subjects. The fabric used was a standard sized 4-color patterned poplin, as in 4.d., incised by hand, and provided with Velcro fasteners to hold the cover in place. The items were designed so as to minimize interference with the weapon's function.

q. Standard Load Carrying Equipment

Fifty (50) sets of the new nylon sets of the latest standard load-carrying equipment were sent to MASSTER to be worn with the standard Olive Green 107 in the Phase II test. This is illustrated in Figure A.1.

r. Patterned Load Carrying Equipment

Fifty sets of load carrying equipment were patterned in a manner similar to the US Army 4-color pattern by brushing, using the durable experimental overcoloring compound (see 4.v). These are intended to be worn with the 4-color patterned uniforms as illustrated in Figure A.4. The items of the load carrying equipment are the same as in 4.q.

s. Experimental Pack Covers, US Army 4-Color Pattern

As an alternative to field patterning of load carrying equipment, pack covers of cotton sateen, approximately 290 g/m^2, with a 4-color pattern the same as 4.b., were fabricated. The design was the same as the standard white pack cover for snow camouflage. This is illustrated in Figure A.4.

t. Experimental Pack Covers, 6-Color Desert Pattern

Pack covers, similar to those in 4.s., were fabricated of a nylon/cotton, approximately 290 g/m^2, with the 6-color desert pattern described in 4.c. The pack covers are illustrated in Figures A.2 and A.3 with the comparable uniform.

u. Experimental Overcoloring Compound, Removable

Five gallons in each of four colors of a removable overcoloring compound for textiles were sent to MASSTER. The compound is water based and is intended to be applied to textiles that are not water repellent. Compositions of the four colors are given in Appendix C.5. Although the colorant system resists water (e.g.rain), it is readily removed in an alkaline laundry. Reflectance curves for each of the four colors and computed associated data are given in Figure 9. Reflectance curves of specimens after removal of the compound are shown in Figure B.10.

v. Experimental Overcoloring Compound, Durable

For those applications that demand a more permanent overcoloring, a durable formulation has been developed. Five (5) gallons of each of four colors have been furnished MASSTER for their consideration. This formulation also is intended for application to textile items, including those that are water repellent. To illustrate one use for this overcolorant compound, load carrying equipment was colored with the four colors in a pattern resembling the US Army 1948 4-color pattern (4.b.) The formulation is given in Appendix C.6.

Reflectance and colorimetric data are shown in Figure B.11., while the patterned load carrying equipment is illustrated in Figure A.4.

w. Experimental Combat Boots, Green

One clue to detection that often has been cited is the shined, black combat boot. Only recently NARADCOM has found ways to overcome problems of water resistance of a flesh-out boot. Accordingly, fifty (50) pairs of combat boots were made with the flesh side outward. These were tanned and dyed green, as outlined in Appendix C.7., and were sent to MASSTER for testing in verdant terrains.

Figure A.4 shows one of the subjects wearing a pair of the green flesh-out boots; reflectance and colorimetric data are shown in Figure B.12.

x. Experimental Combat Boots, Tan

Fifty pairs of tan flesh-out boots were also made and sent to MASSTER for testing in an arid terrain. The color of these boots is due entirely to the tanning process as described in Appendix C.7. The tan boots are illustrated in Figures A.2 and A.3; reflectance and colorimetric data are also given in Figure B.12.

y. Experimental Face Paint, Desert Colors

Camouflage face paints have long been used to tone down the highlights and color of the face and hand, particularly of Caucasians. In recent years an insect repellent was incorporated to provide a dual function for the face paint stick. One hundred (100) sticks of the loam and sand colored face paints were sent to MASSTER for testing in an arid terrain. The composition varied from standard only in respect to the colorants for the sand color and was done to improve the infrared reflectance properties. The formulation is described in Appendix C.8., and illustrated in Figures A.2 and A.3. Reflectance curves and computed data are given in Figure B.13 for the compound as a mass tone.

z. Experimental Face Paints, Verdant Terrains

In a manner similar to the face paint for arid terrains, the green color was reformulated as a camouflage face paint color for verdant terrains. The second color in the stick is the same loam color as in the stick for arid terrains. The reason for change in the colorant of the green stick was its poor reflectivity in the infrared spectrum. The difference between the old and new formulation is shown in the reflectance curves of Figure B.14. The appearance of the new face paint is illustrated in several figures of Appendix A. Appendix C.9., contains information on the composition of formulations used.

aa. Experimental Face Veil

A camouflage problem that often has been cited is that of glare from spectacles. Since approximately one-third of the Army wear corrective lenses and many more use sun glasses, the problem is wide spread. One approach to mitigate the problem is by the use of a netting to cover the face. To minimize impairment of vision, a face veil must have a large mesh size and be dark in color to minimize light scattering by the grid. Fifty (50) items were fabricated from the same netting as used in the body net (see 4.j.). To minimize scattering of light, the inner surface was colored with the black durable over-coloring compound (see 4.v.). The face veil is mounted on an elastic band and attached to the helmet as illustrated in Figure A.4.

bb. Field Dyeing Packets

Another camouflage problem arises from the fact that many personal items, e.g., towels, underwear, and handkerchiefs, are issued in a white state. When troops wash such items in the field, they may spread them on bushes or the ground to dry, in obvious conflict with good camouflage practice. A field dyeing packet has been developed to permit troops in the field to dye such personal items to appropriate camouflage colors to minimize their adverse contribution to battlefield litter.

Standard field dyeing packets, Olive Green 109, FSN 6820-782-2682 were withdrawn from stock and sent to MASSTER for evaluation. Preliminary trials showed that the color produced was far from an Olive Green 107 shade and that adjustments in the dye formulation were indicated. A packet was developed such that when it was added to the stock item, the proper shade was obtained. Sufficient dye has been sent to MASSTER, and personnel at the base laundry at Fort Hood were instructed by NARADCOM personnel in the appropriate dyeing procedure. The formulation for the supplementary package are given in Appendix C.10. Figure A.8 is a photograph of several items that have been dyed with the revised formula and displayed as they might be in a field situation.

cc. Leather Gloves, Standard Black Color

Leather gloves have been furnished to MASSTER for the Phase II test as an alternative means of camouflaging the hands. The black color is that of the standard item and is illustrated in Figure A.1.

dd. Leather Gloves, Tan

Gloves, similar to those in 4.bb., have been sent to MASSTER in a tan color. These are furnished as an alternative to the face paint for camouflaging the hands and are to be worn with the 6-color desert uniform. Figures A.3 and A.4., show the gloves being worn by one of the subjects. The reflectance and associated data are included in Figure B.15. The color was attained by use of a vegetable tanning process alone.

ee. Tents, General Purpose, Small and Medium, Nature Pattern

One each of subject tents were camouflage patterned in a configuration referred to as the Nature Pattern. This is a pattern designed by Franklin Institute Research Laboratories under contract to NARADCOM[7] and was intended to resemble foliated terrains that likely would serve as a background to a properly sited tent in a foliated region. Four colors were used to produce the pattern using a formulation described in 4.gg. Figure A.9 is a photograph of the GP Medium tent sited in a manner to illustrate the pattern, not its camouflage effectiveness. The patterns for these two tents were applied by spraying techniques suggested by the contractor.

7. De Benedictis, John A., Camouflage Study of the GP Small and GP Medium Tents, US Army Natick Research and Development Command, Natick, Mass. 01760, (in preparation).

ff. Tents, GP Small and Medium, MERDC Pattern

One of each of subject tents was camouflage patterned in a design referred to as the MERADCOM Pattern. This pattern is included in a compendium of patterns designed by MERADCOM for the camouflage of a wide variety of vehicles and other field equipment. The same colorant formulations were used for these tents as for those discussed in 4.ee., and are illustrated in Figure A.10. Application was by brush which resulted in somewhat better coverage than in 4.ee.

gg. Recoloring Compound for Tentage

Part of a contract with the Franklin Institute Research Laboratories produced four colors of a compound to be used in recoloring field tents.[6] The composition of the formulations was intended to preserve the resistance of existing tents to mildew, rain, wind and fire. Use of the compounds is illustrated in Figures A.9., and A.10.; reflectance and related data are given in Figure B.16. The composition of each of the four colorant formulations is given in Appendix C.11.

hh. Camouflaged Packaging Materials

Under a MERADCOM-funded contract[8] colorant finishes were developed for camouflage of fiberboard cartons, wooden crates, polyethylene film for food packaging and tin cans. As currently procured none of these items is properly camouflaged; all can easily contribute to battlefield litter in a manner that violates good camouflage practice. Figure A.11. displays the above items with the developed colorants. Reflectance and related data are given in Figure B.17., and the composition of the formulations is reported in the Battelle report.[8]

ii. Camouflaged Mobile Field Kitchen

The mobile field kitchen that has been designed by NARADCOM was patterned using two formulations, one for the metal parts, and one for the fabric components. For the surfaces of ranges and ovens that face outward a commercial stove blacking was used. All other metal parts, the storage containers, floor, trailer chassis and roof were painted with the alkyd enamel (Mil-E-52798). The fabric components were patterned with the tentage recoloring compound discussed in paragraph 4.gg.

Two patterns were used, the MERADCOM Pattern (4.ff) for those areas exposed when the unit is configured as a trailer. This includes the roof and the nylon tarpaulins. The Nature Pattern was applied to those areas that are exposed when the unit is deployed as a kitchen. The garbage cans and lids were painted with the alkyd enamel with a free-hand version of the Nature Pattern. Figure A.12 illustrates the unit deployed as a kitchen with the side curtains down. In this configuration the Nature Pattern predominates.

8. Kowacki, Louis J., Camouflaged Packaging Materials, Battelle Columbus Laboratories, US Army Mobility Equipment Research and Development Center, Fort Belvoir, VA 22060 (27 December 1974).

APPENDIX A

Appendix A contains photographs of the items that were produced during the FY 75 program and sent to MASSTER for the Phase II test. The items are portrayed by troops in a somewhat realistic manner and in an appropriate terrain. No special effort was made to display the subjects in a tactical situation; emphasis was placed on illustrating the items. Infrared color film (CD) was used for Figure 3; all other photographs were made using Ektachrome (ASA64) film.

LIST OF ILLUSTRATIONS

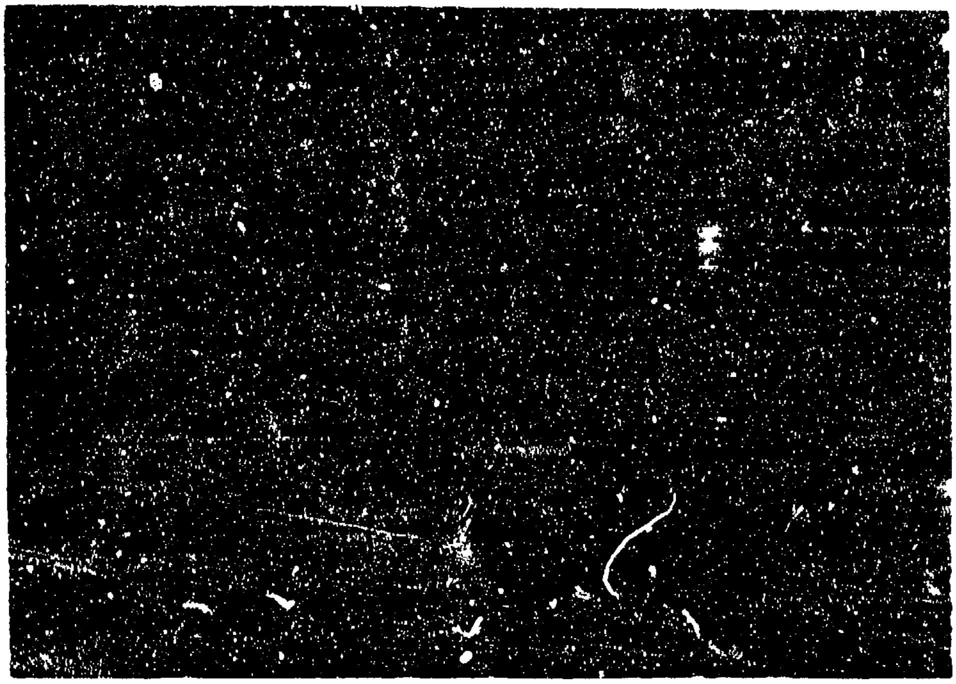


Figure A.1. Left: Standard Olive Green 107 uniform, black gloves, standard reversible helmet cover, standard face paint, standard load-carrying equipment.

Center: Standard US Army 1948 camouflage patterned uniform, standard reversible helmet cover, experimental 4-color patterned armored vest, experimental green and loam face paint.

Right: Standard Olive Green 107 uniform, standard reversible helmet cover, standard Olive Green 106 armored vest, standard face paint.

Figure A.2. Desert Camouflage, 6-Color Pattern

Left: New colorant formulation, 6-color patterned desert uniform and pack cover; experimental tan flesh-out boots; standard reversible helmet cover; experimental face paint.

Right: Old colorant formulation, 6-color patterned desert uniform; standard reversible helmet cover.

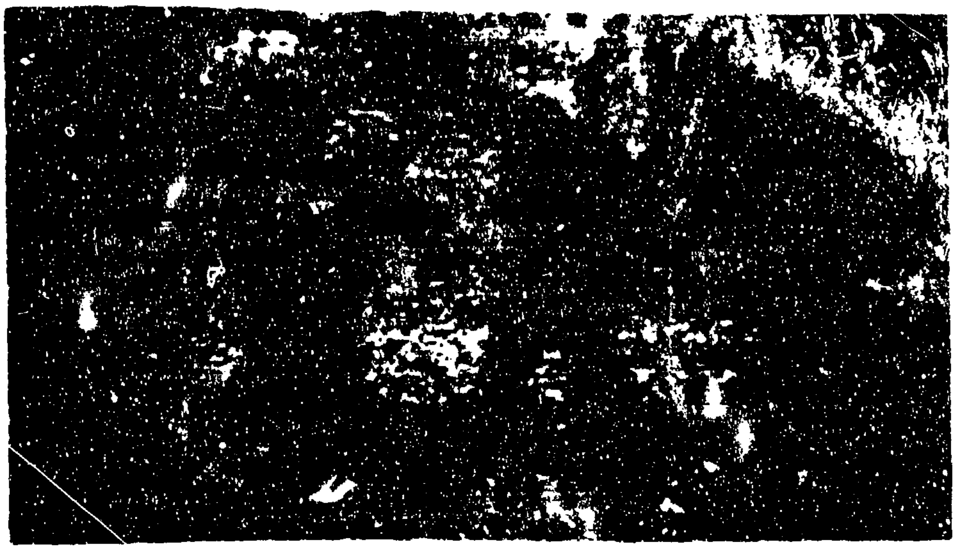


Figure A.3. Desert Camouflage. Sames as Figure A.2. except that Infrared Color film was used.

Figure A.4. Pattern Expansion Series, Experimental.

Left: Standard size patterned uniform, standard size patterned armored vest, standard 4-color helmet cover, experimental watch cover.

Left - center: 1.3 times expansion patterned uniform, standard 4-color helmet cover, weapon cover, camouflage patterned standard load carrying equipment.

Right - center: 1.6 times expansion patterned uniforms, 1.6 times expansion patterned armored vest, experimental helmet cover, weapon cover, experimental green shoes.

Right: 2.0 times expansion patterned uniforms, 4-color pack cover, face veil, 4-color helmet cover, black gloves.

Figure A.5. Disruptive and Tiger Patterns

Left: Disruptive patterned uniform, standard reversible helmet cover, experimental face paint.

Right: Tiger patterned uniform, standard reversible helmet cover, standard face paint.

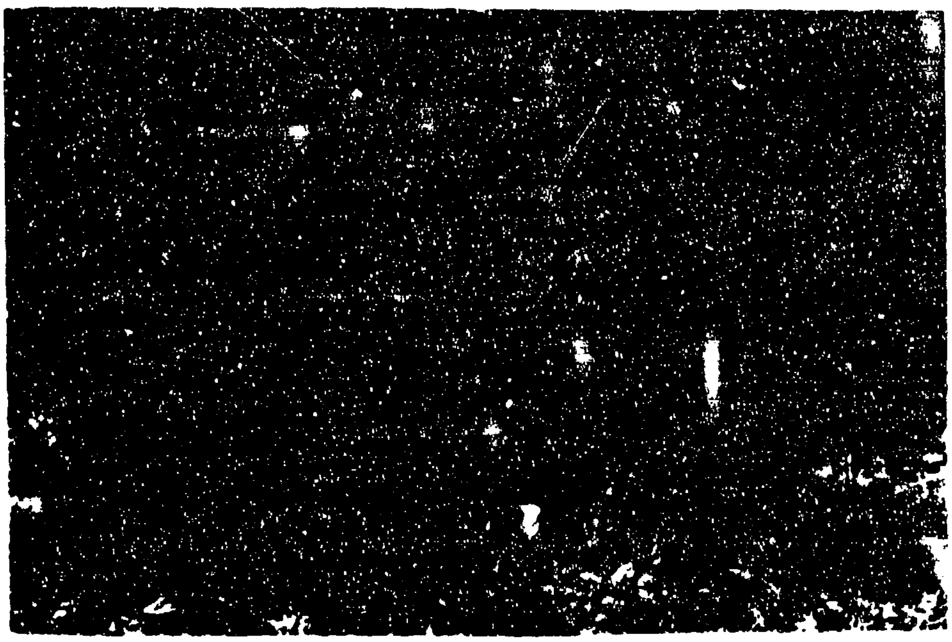


Figure A.6. Body net deployed as a personal camouflage screen.

Figure A.7. Standard and Experimental 4-color Ponchos.

Figure A.8. Field-dyed underwear.

Figure A.9. General Purpose Medium Tent with Nature Pattern.

Figure A.10. General Purpose Medium Tent with MERADCOM Pattern.

Figure A.11. Packaging Materials
Left: Standard items; wood ammunition box, fiberboard carton, tin cans, plastic/aluminum laminates.
Right: Same items coated with camouflage color formulation.

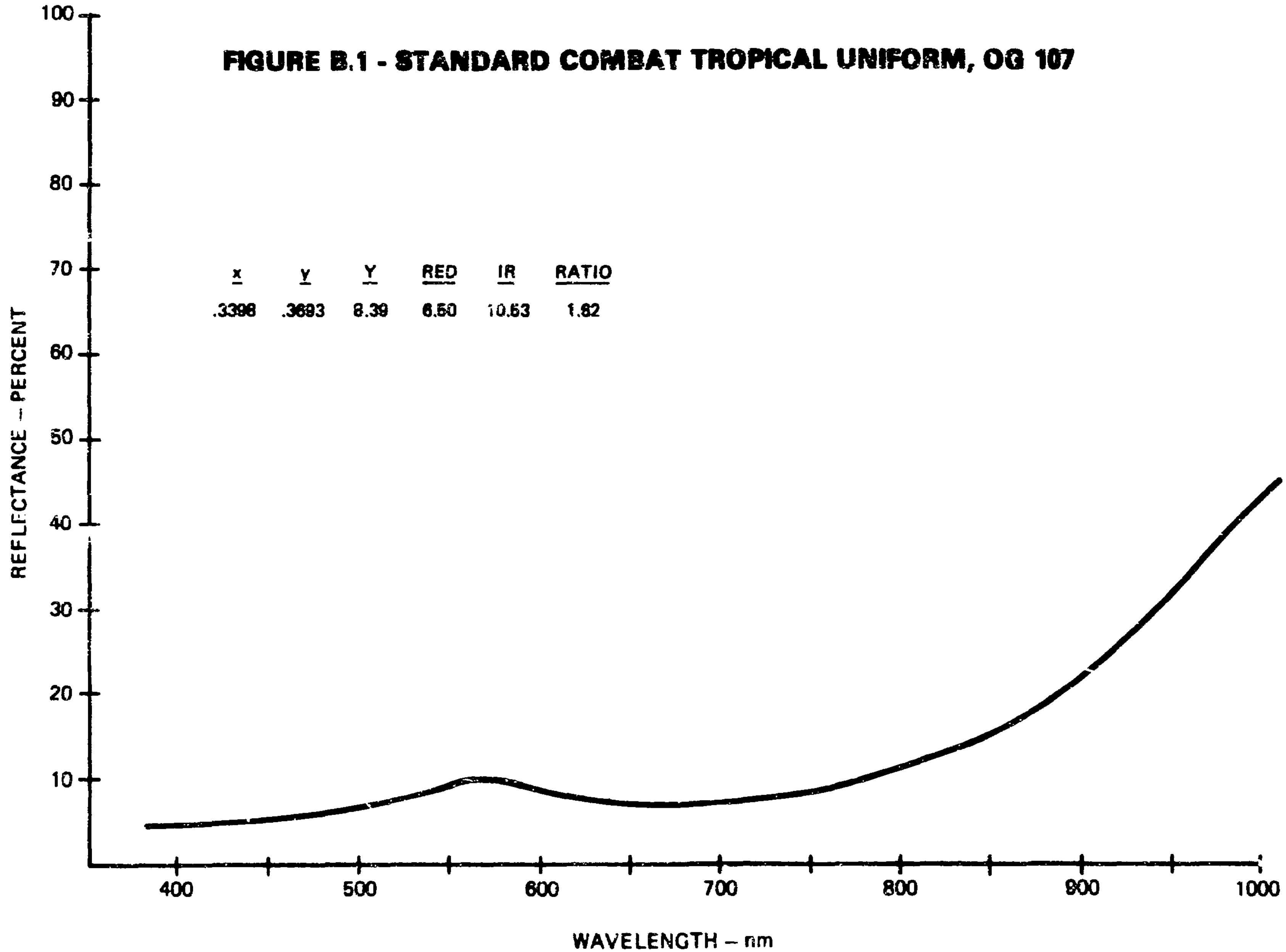
Figure A.12. Mobile field kitchen camouflaged with Nature Pattern.

APPENDIX B

This appendix contains spectral reflectance curves from 380 to 1000 nanometers for all items sent to MASSTER for Phase II. Curves were obtained using the General Electric Recording Spectrophotometer. Tristimulus coordinates (x, y) were calculated from tristimulus values automatically computed with respect to the Standard Observer and Source "C" with a Davidson-Hemmendinger Tristimulus Integrator. Red and Infrared reflectances were computed as defined in Mil-E-52798 (ME) using a Hewlett-Packard programmable calculator and curve tracer.

FIGURE B.1 - STANDARD COMBAT TROPICAL UNIFORM, OG 107

x	y	Y	RED	IR	RATIO
.3398	.3693	8.39	6.50	10.63	1.62



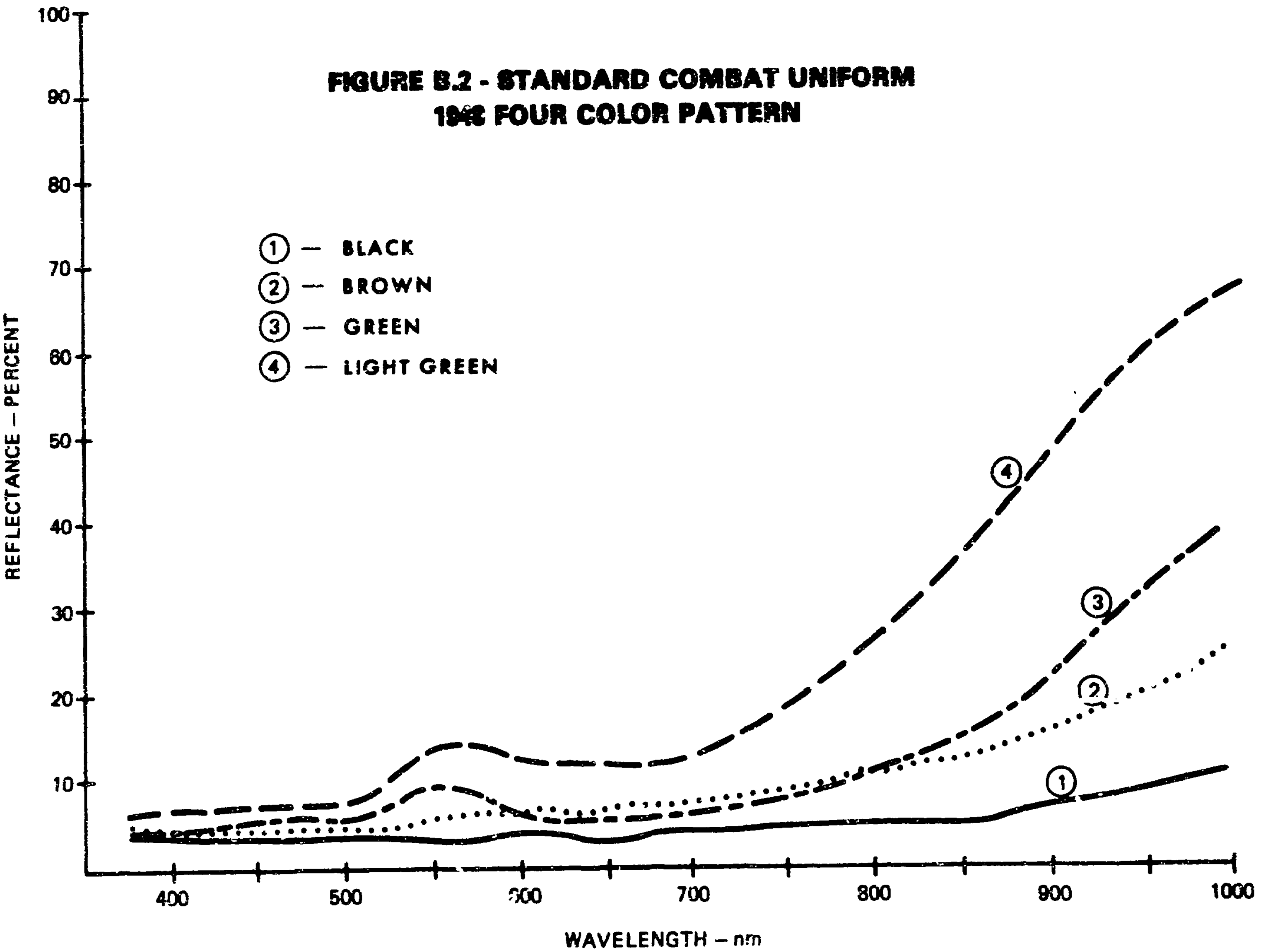


FIGURE B.2 - STANDARD COMBAT UNIFORM
1948 FOUR COLOR PATTERN

TABLE B.2.1. STANDARD COMBAT UNIFORM, 1948 4-COLOR PATTERN

	x	y	Y	RED	IR	RATIO
Black	0.3169	0.3219	3.86	4.12	4.67	1.13
Brown	0.3543	0.3554	6.32	7.52	11.30	1.50
Green	0.3211	0.3701	7.78	5.55	11.37	2.05
Yellow	0.3537	0.3768	12.88	12.26	26.41	2.15

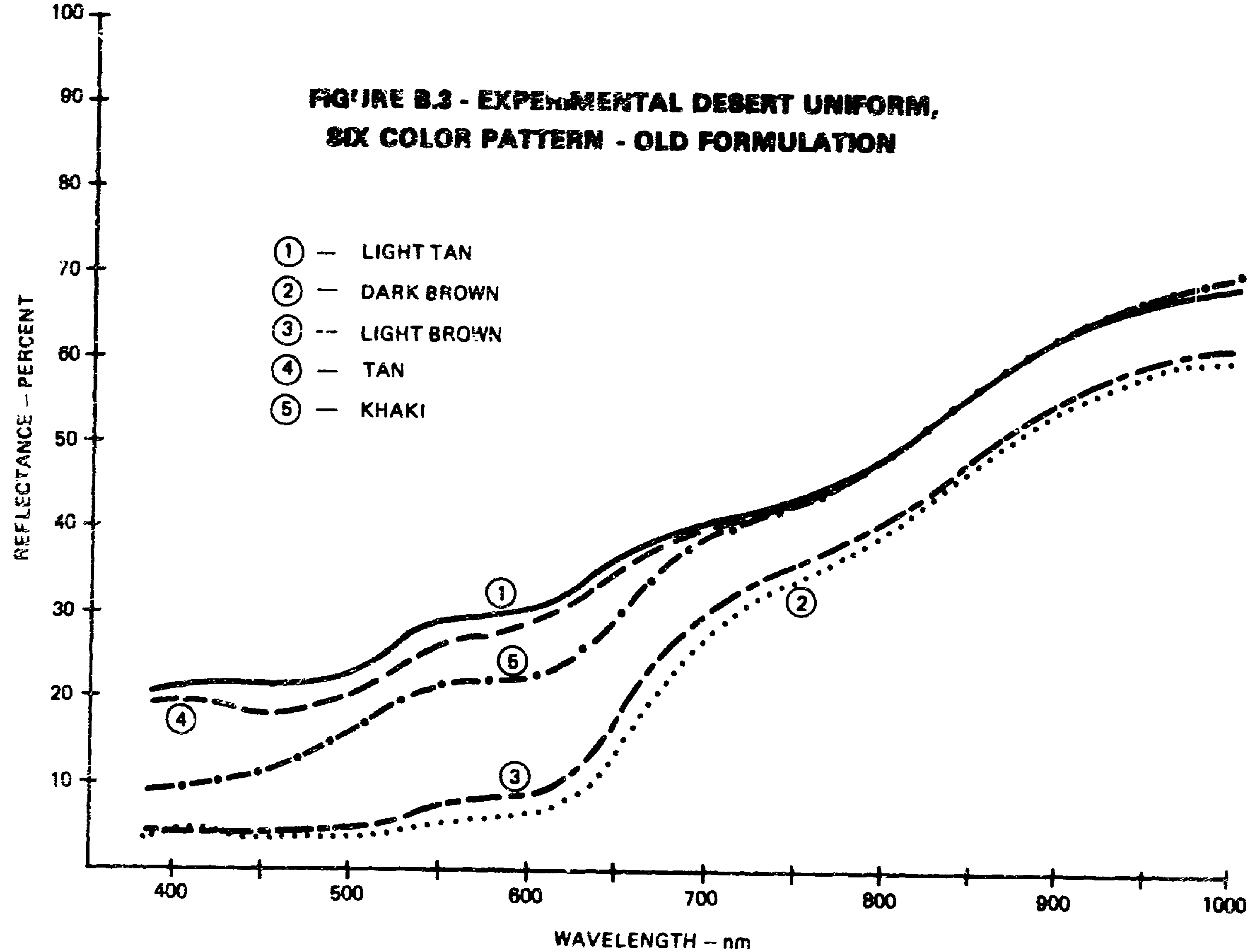


FIGURE B.3 - EXPERIMENTAL DESERT UNIFORM, SIX COLOR PATTERN - OLD FORMULATION

TABLE B.3.1 EXPERIMENTAL DESERT UNIFORM, 6-COLOR PATTERN - OLD FORMULATION

	x	y	Y	RED	IR	RATIO
Light Tan	0.3455	0.3455	29.86	35.21	47.83	1.36
Dark Brown	0.3833	0.3439	6.28	13.80	39.82	2.89
Light Brown	0.3945	0.3567	8.10	17.25	40.63	2.36
Tan	0.3536	0.3487	26.40	34.81	42.28	1.21
Khaki	0.3681	0.3744	21.39	29.63	47.95	1.62

FIGURE B.4 - EXPERIMENTAL DESERT UNIFORM, SIX COLOR PATTERN - NEW FORMULATION

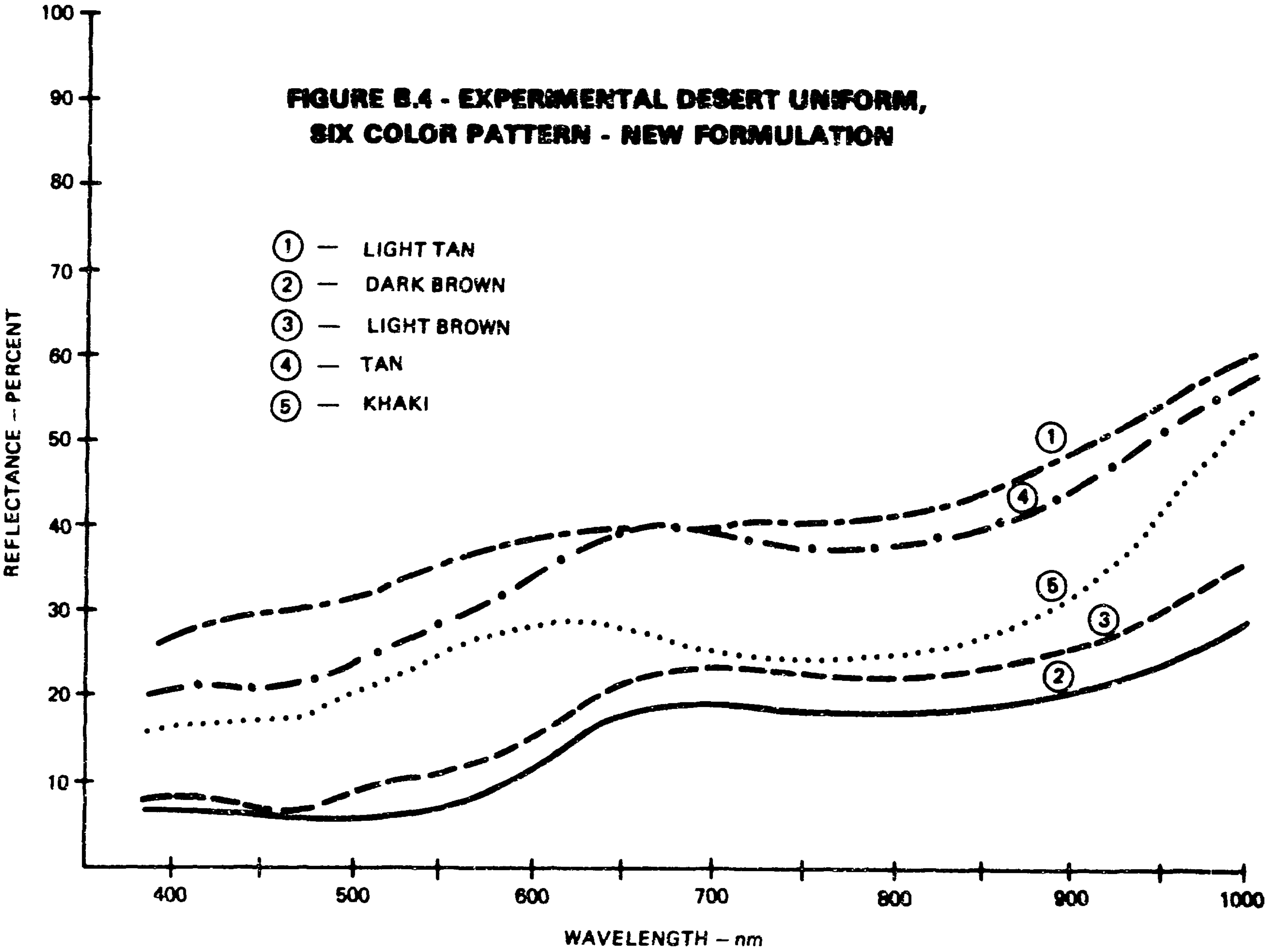


TABLE B.4.1. EXPERIMENTAL DESERT UNIFORM, 6-COLOR PATTERN - NEW FORMULATION

	x	y	Y	RED	IR	RATIO
Dark Brown	0.2741	0.3369	8.74	12.10	18.76	1.55
Khaki	0.3528	0.3557	25.49	28.71	25.98	0.90
Light Tan	0.3345	0.3359	35.96	40.26	42.15	1.05
Light Brown	0.3966	0.3598	11.94	21.30	22.92	1.08
Tan	0.3549	0.3474	30.37	39.32	39.03	0.99

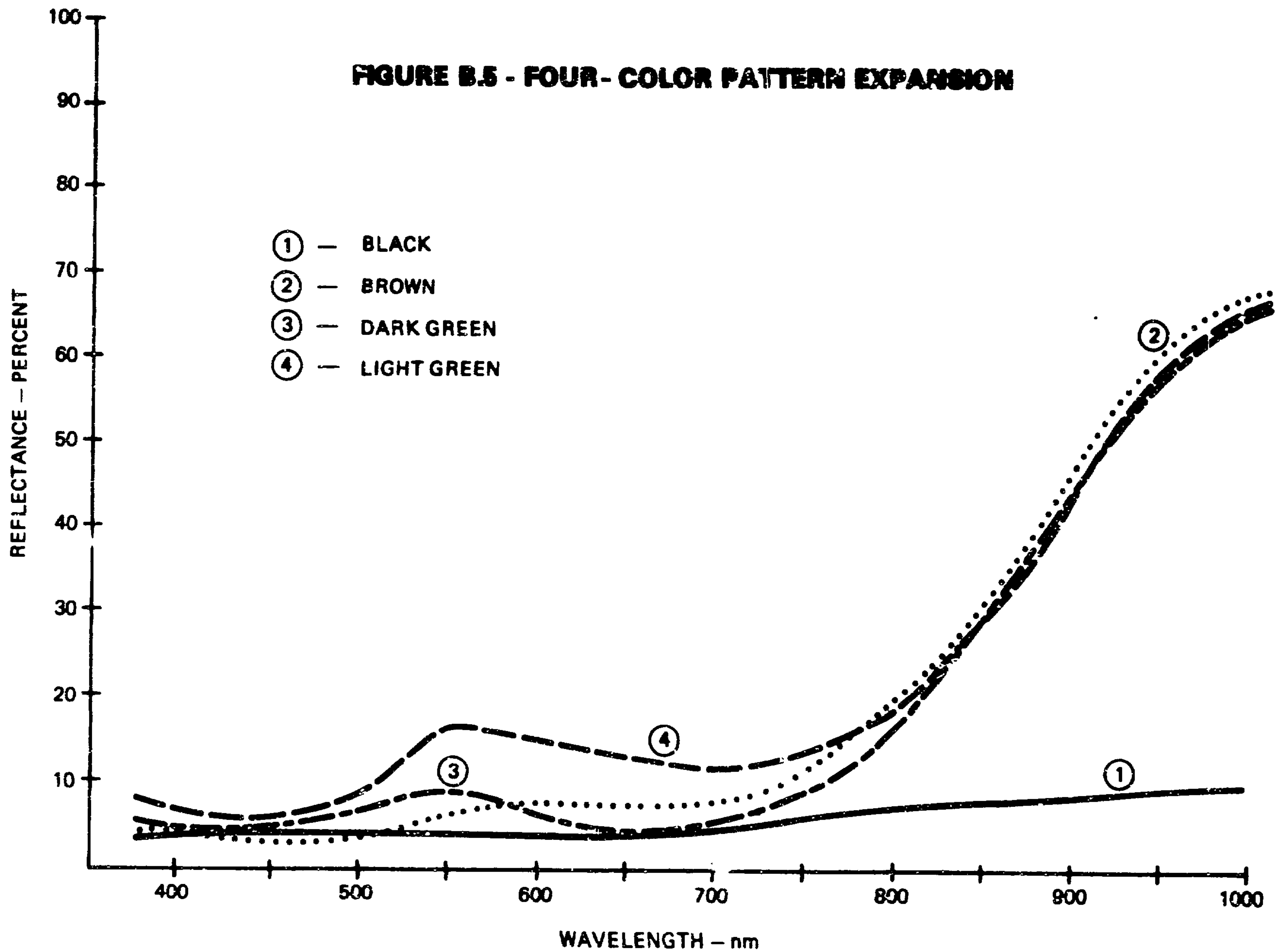


FIGURE B.5 - FOUR-COLOR PATTERN EXPANSION

TABLE B.5.1, FOUR-COLOR PATTERN EXPANSION

	x	y	Y	RED	IR	RATIO
Black	0.3071	0.3197	4.06	3.98	6.99	1.76
Brown	0.3691	0.3644	6.96	8.00	20.08	2.51
Dark Green	0.3170	0.3831	7.42	5.23	17.90	3.42
Light Green	0.3636	0.3984	15.12	13.70	20.61	1.50

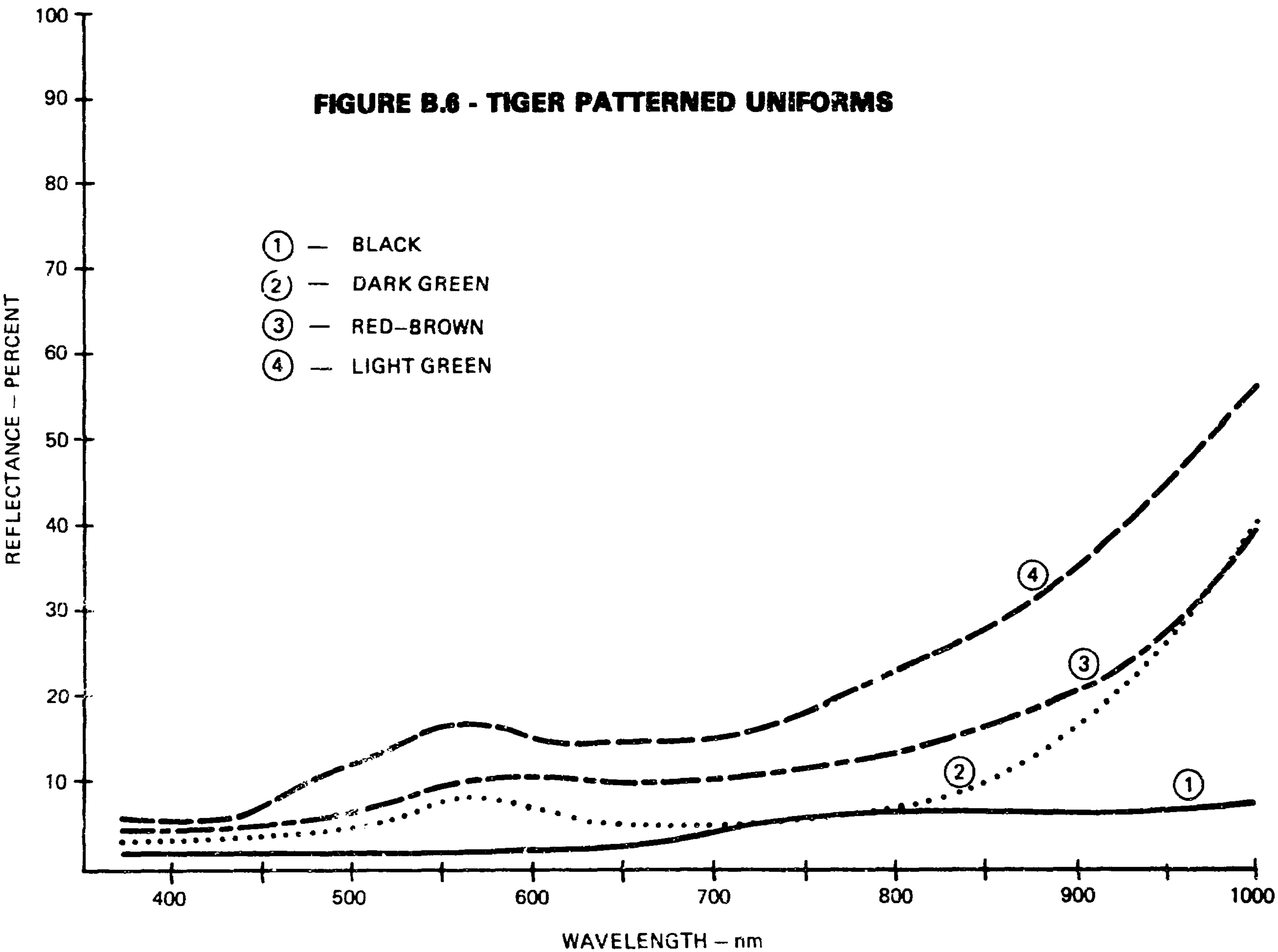


FIGURE B.6 - TIGER PATTERNED UNIFORMS

TABLE B.6.1, TIGER PATTERNED UNIFORMS

	x	y	Y	RED	IR	RATIO
Black	0.3086	0.3062	2.48	3.26	6.35	1.95
Dark Green	0.3417	0.3812	7.25	5.87	8.00	1.36
Red-Brown	0.3609	0.3756	9.22	10.85	13.67	1.26
Light Green	0.3893	0.2565	15.54	15.19	22.75	1.50

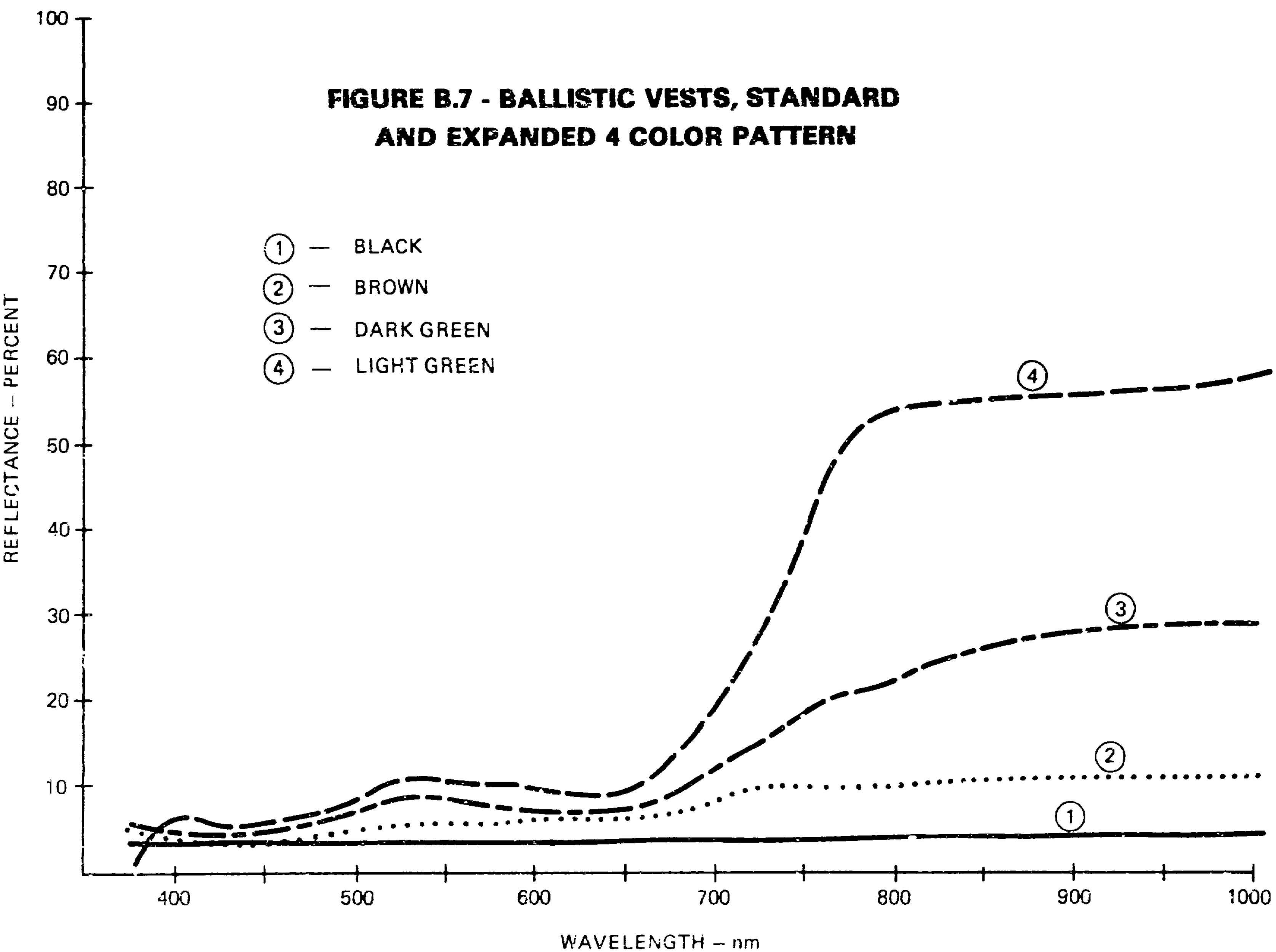


FIGURE B.7 - BALLISTIC VESTS, STANDARD AND EXPANDED 4 COLOR PATTERN
1 — BLACK
2 — BROWN
3 — DARK GREEN
4 — LIGHT GREEN
REFLECTANCE – PERCENT
100
90
80
70
60
50
40
30
20
10
400
500
600
700
800
900
1000
WAVELENGTH – nm
1
2
3
4

TABLE B.7.1. BALLISTIC VESTS, STANDARD AND EXPANDED, 4 COLOR PATTERN

	x	y	Y	RED	IR	RATIO
Black	0.3167	0.3227	3.24	3.21	4.12	1.28
Brown	0.3422	0.3548	5.06	5.39	9.87	1.83
Dark Green	0.3323	0.3861	7.39	6.64	20.82	3.14
Light Green	0.3540	0.3[illegible]45	9.65	9.47	47.42	5.01

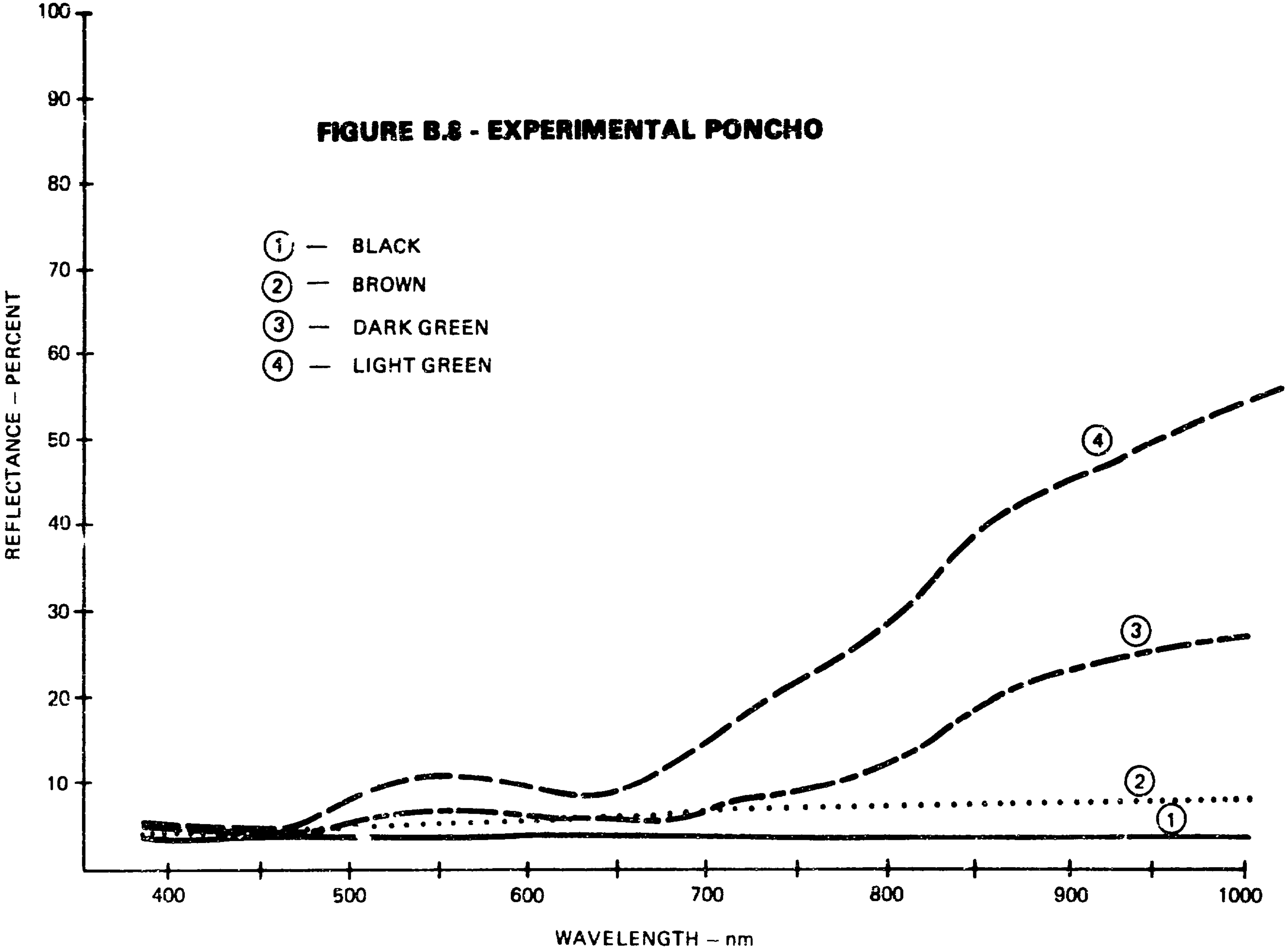


FIGURE B.8 - EXPERIMENTAL PONCHO

TABLE B.8.1. EXPERIMENTAL PONCHO

	x	y	Y	RED	IR	RATIO
Black	0.3159	0.3274	4.26	4.28	4.59	1.07
Brown	0.3318	0.3324	5.01	5.72	7.26	1.27
Dark Green	0.3241	0.3701	6.28	5.23	12.68	2.42
Light Green	0.3493	0.4011	10.06	9.55	29.01	3.04

FIGURE B.9 - REMOVABLE OVERCOLORING COMPOUND OVER NYLON PACK

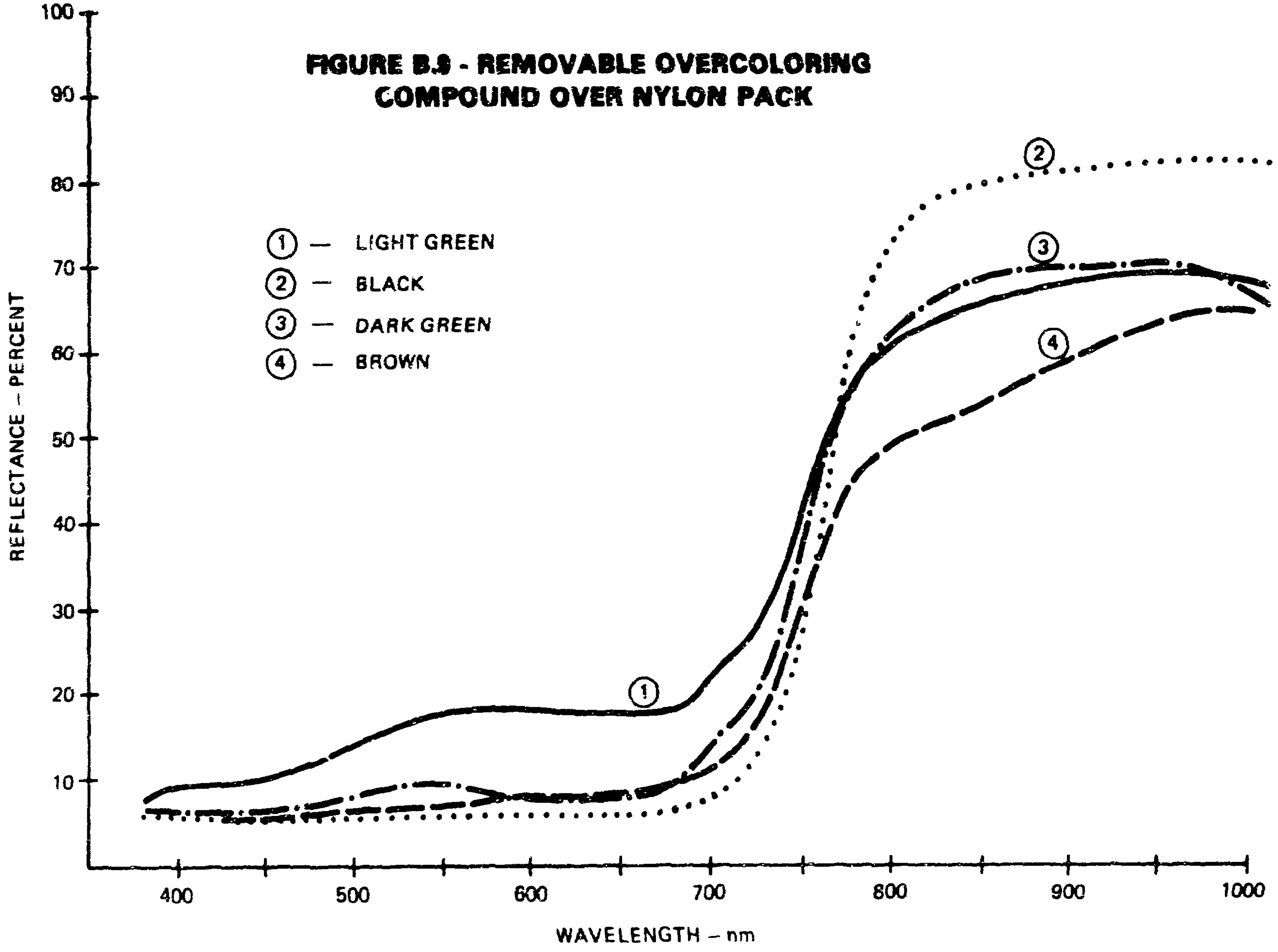


TABLE B.9.1. REMOVABLE OVERCOLORING COMPOUND, OVER NYLON PACK

	x	y	Y	RED	IR	RATIO
Light Green	0.3488	0.3670	16.74	17.52	54.01	3.08
Dark Green	0.3244	0.3597	8.68	8.11	53.07	6.54
Dark Brown	0.3438	0.3461	7.67	9.06	42.36	4.67
Black	0.3055	0.3096	6.14	6.23	57.23	9.20

FIGURE B.10 - NYLON PACK FABRIC AFTER REMOVAL OF OVERCOLORING COMPOUND

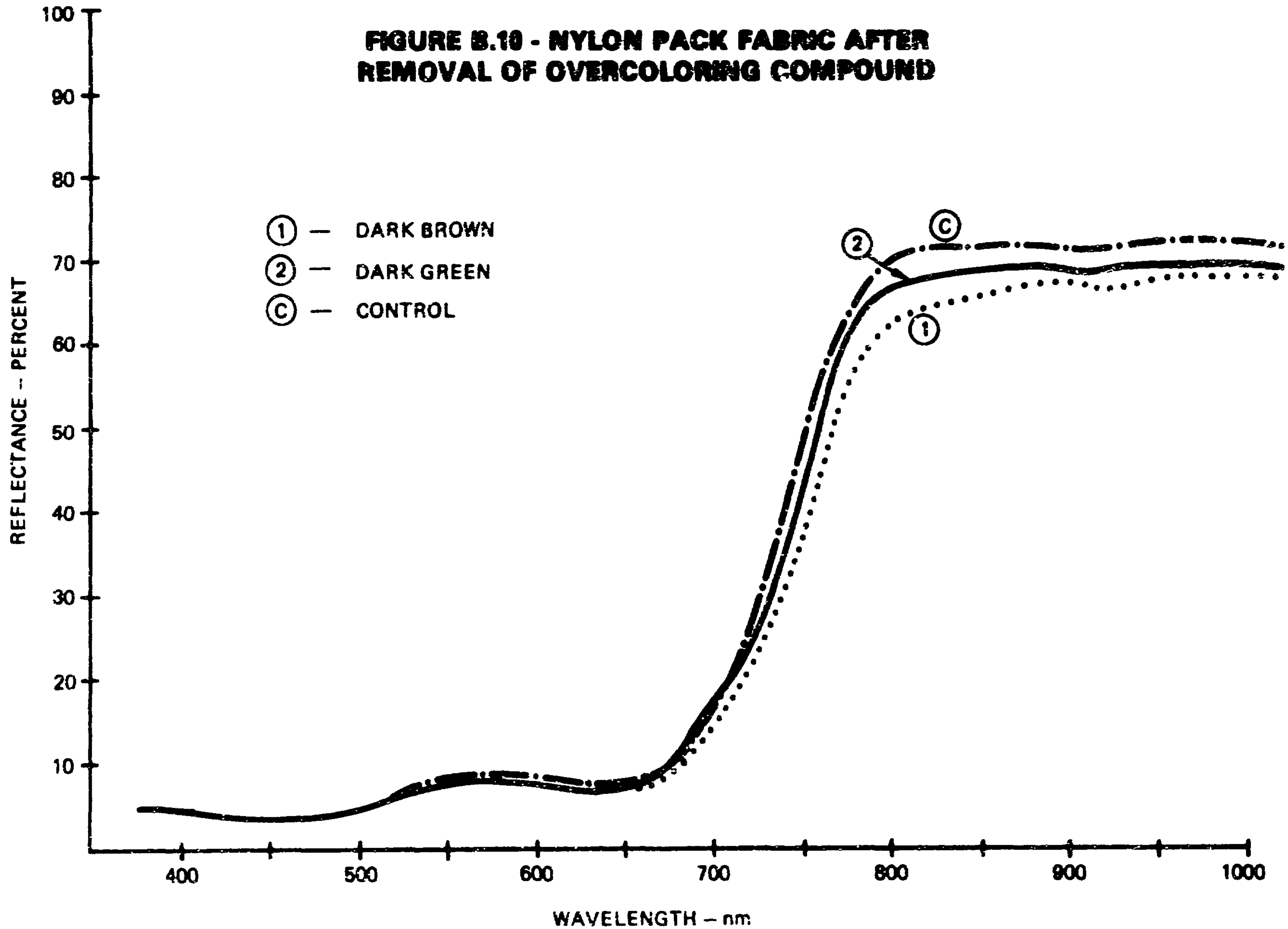


TABLE B.10.1 NYLON PACK FABRIC AFTER REMOVAL OF OVERCOLORING COMPOUND

	x	y	Y	RED	IR	RATIO
Substrate	0.3624	0.3886	8.02	8.53	60.58	7.10
*Light Green	0.3586	0.3789	7.09	7.37	56.40	7.65
Dark Green	0.3551	0.3845	7.14	7.86	56.70	7.21
Dark Brown	0.3564	0.3767	6.85	7.22	54.25	7.51
*Black	0.3507	0.3697	6.40	7.17	58.95	8.22

*Curves for Light Green and Black areas after removal are too close to those illustrated for useful presentation.

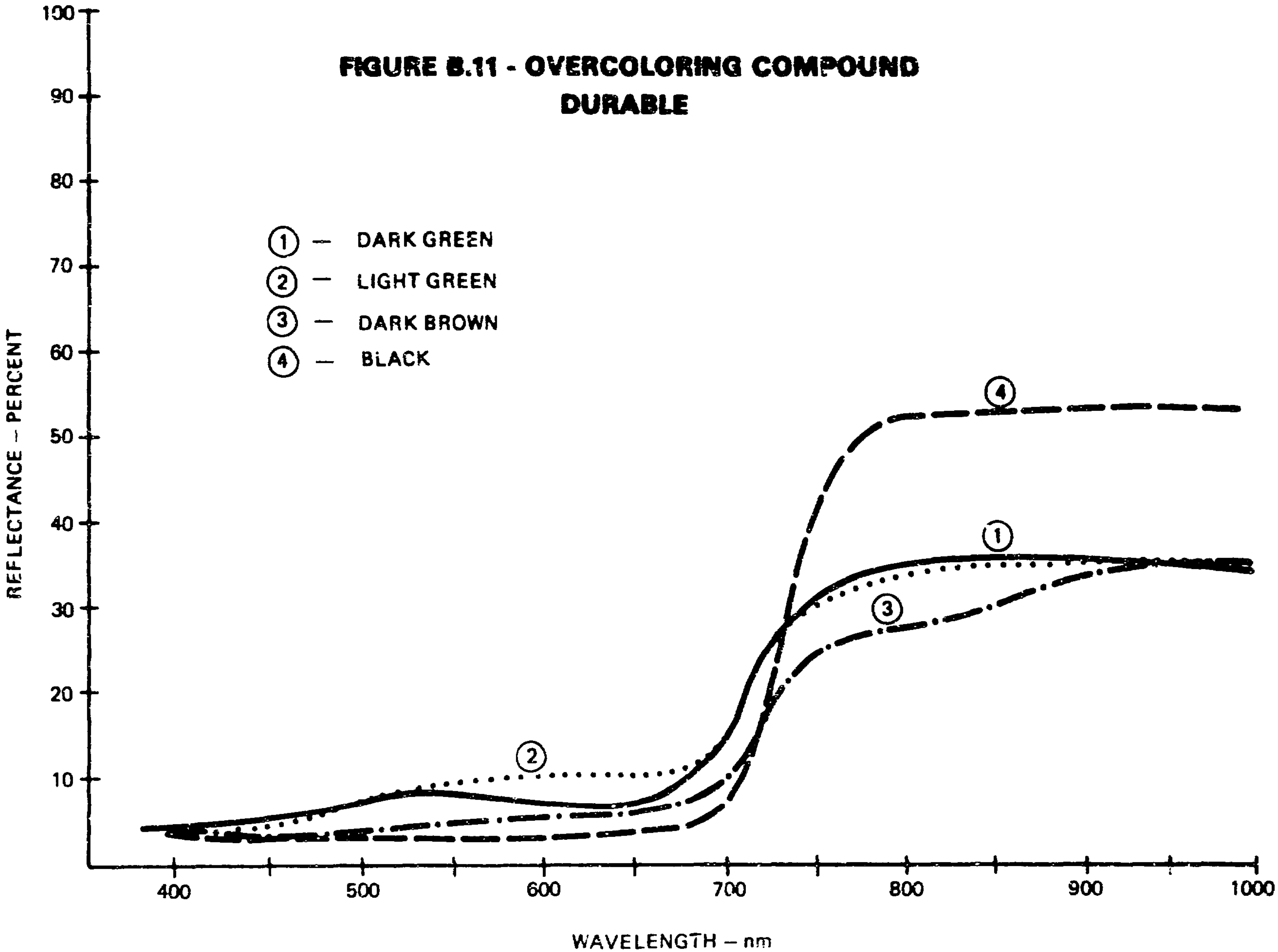


FIGURE B.11 - OVERCOLORING COMPOUND DURABLE

TABLE B.11.1. OVERCOLORING COMPOUND, DURABLE

	x	y	Y	RED	IR	RATIO
Light Green	0.3623	0.3806	9.39	10.97	31.18	2.84
Dark Green	0.3270	0.3673	7.84	7.27	32.12	4.42
Dark Brown	0.3493	0.3499	5.98	7.30	26.71	3.66
Black	0.3052	0.3117	4.29	4.47	45.48	10.17

FIGURE B.12 - GREEN AND TAN BOOTS

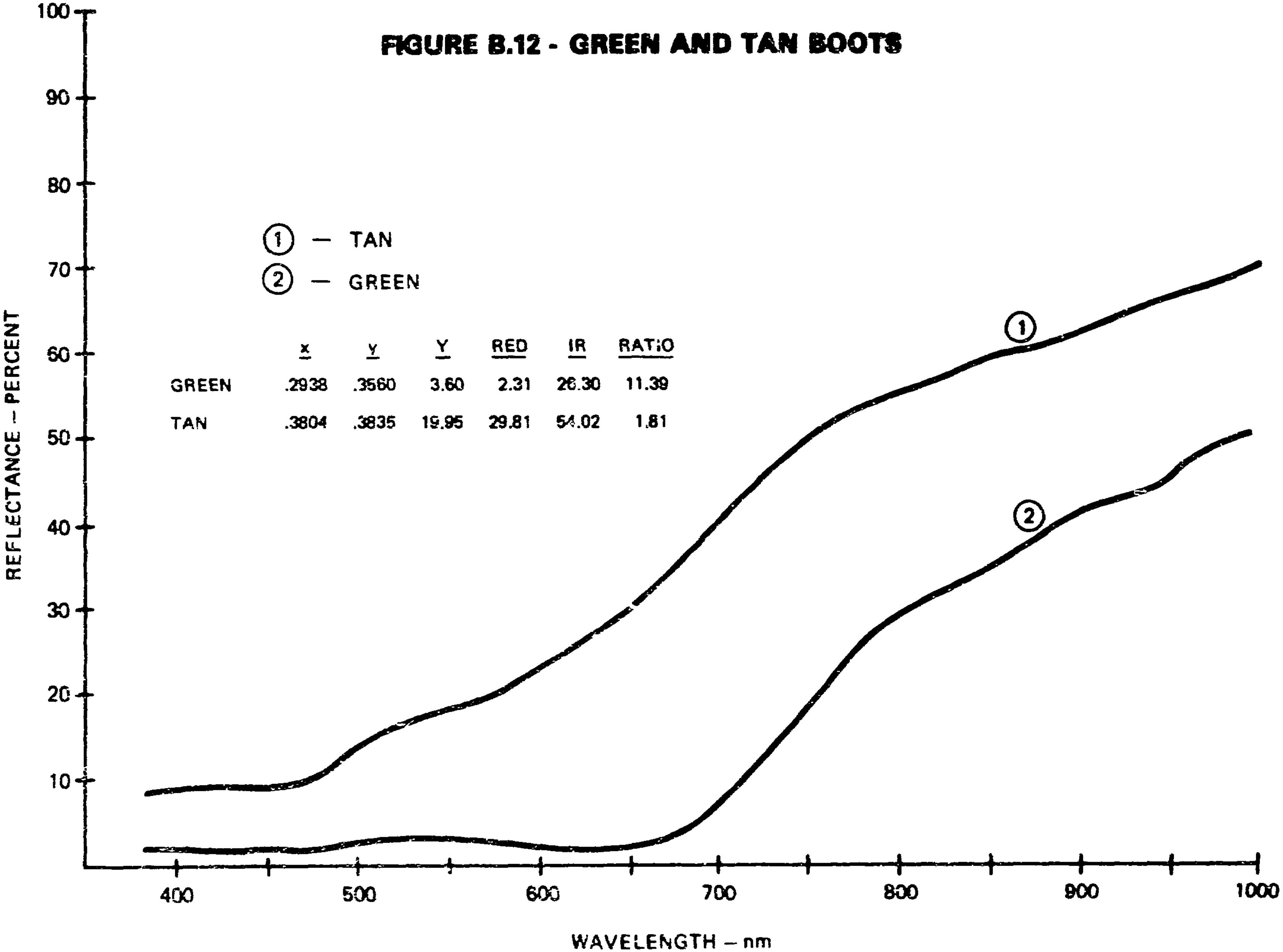
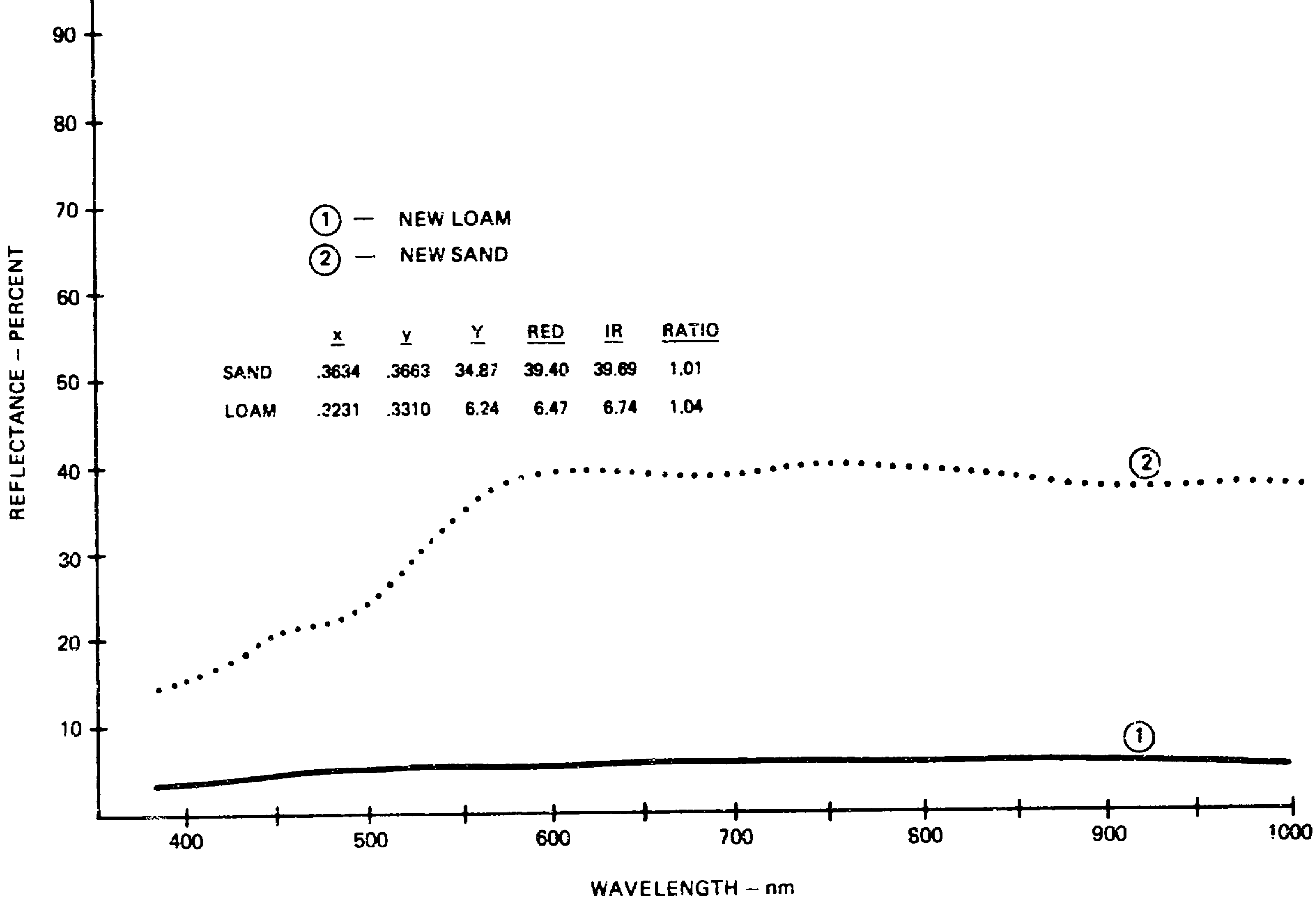
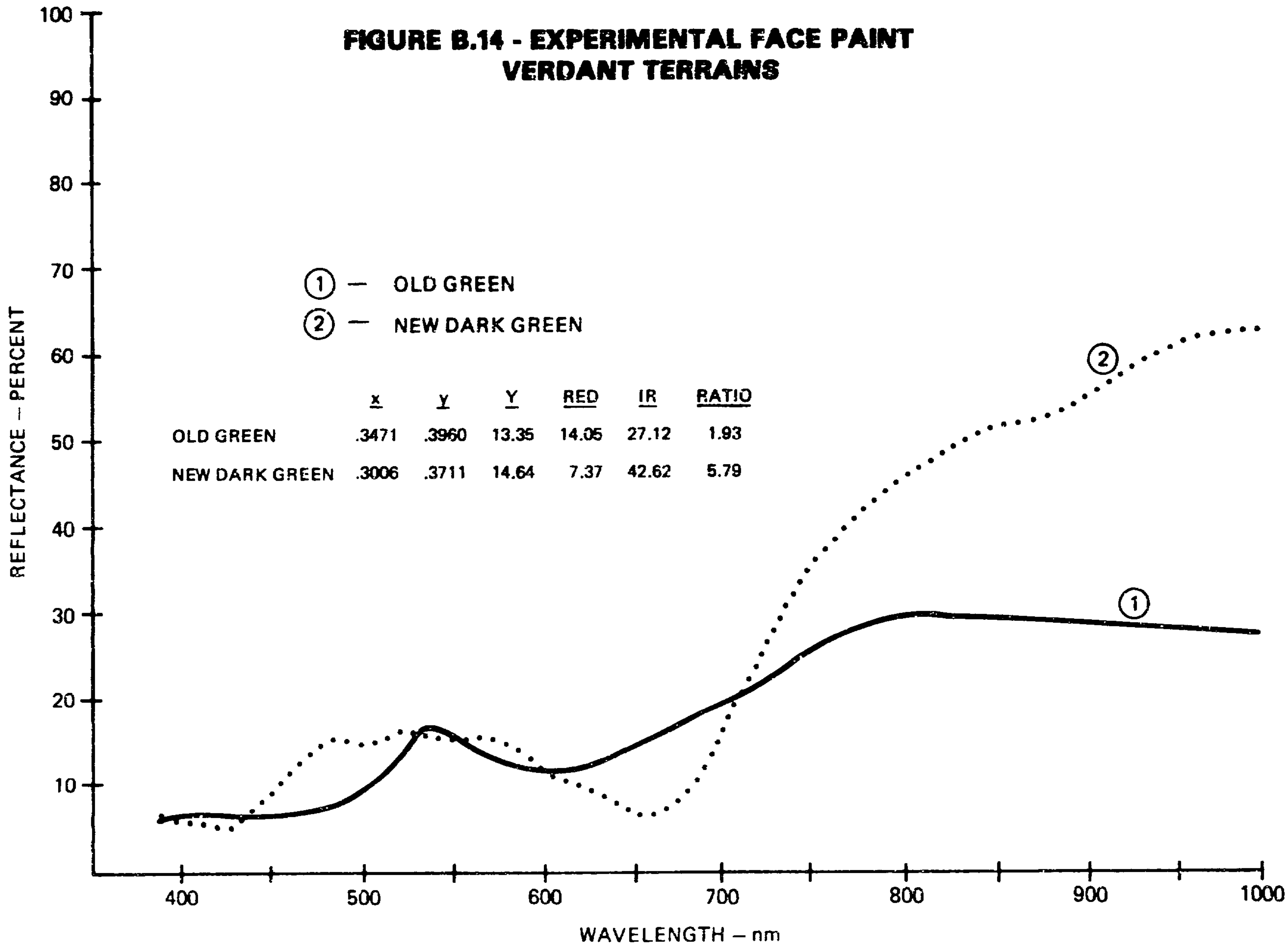


FIGURE B.13 - EXPERIMENTAL FACE PAINT DESERT COLORS



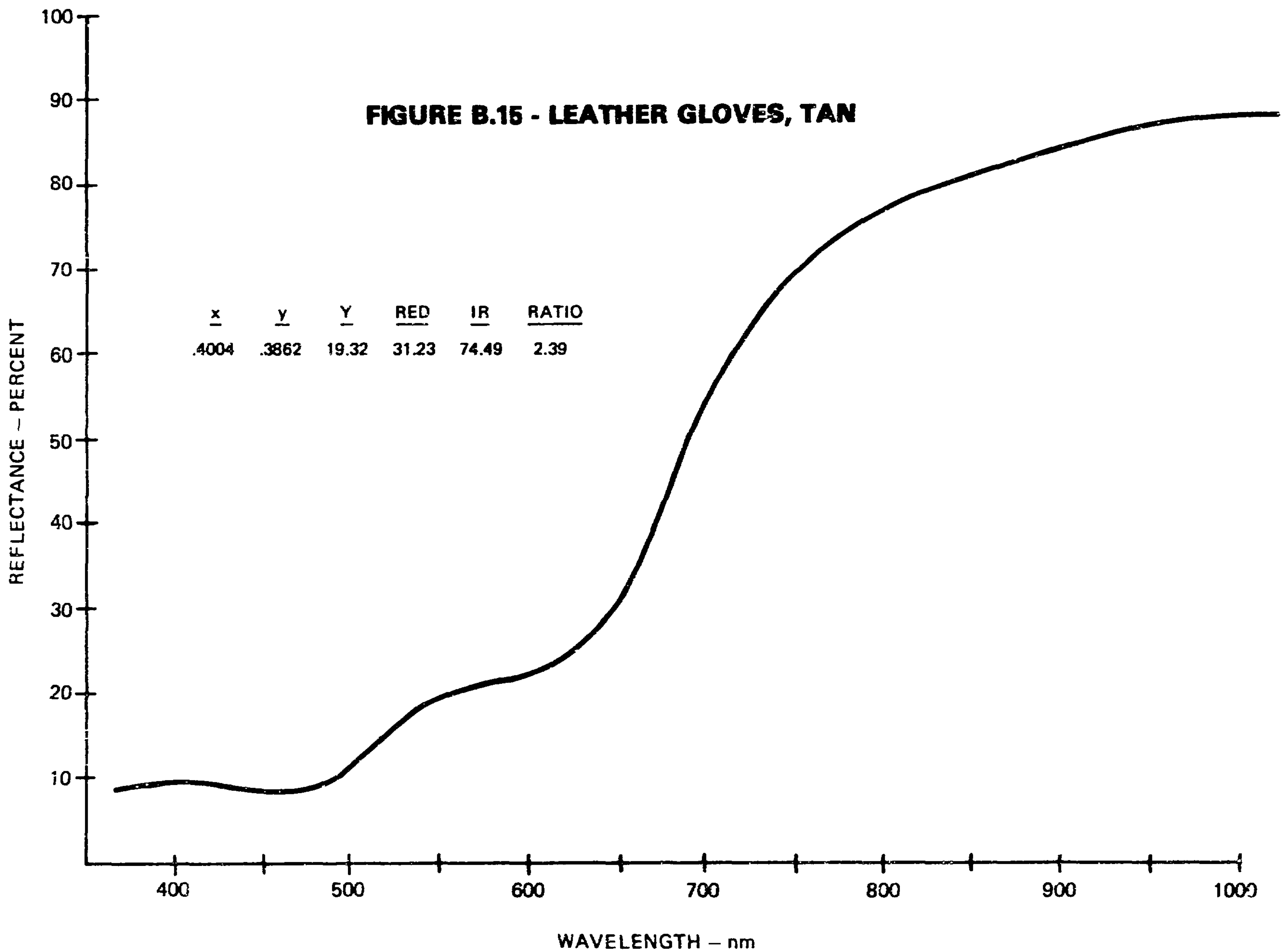
	x	y	Y	RED	IR	RATIO
SAND	.3634	.3663	34.87	39.40	39.89	1.01
LOAM	.3231	.3310	6.24	6.47	6.74	1.04

FIGURE B.14 - EXPERIMENTAL FACE PAINT VERDANT TERRAINS



	x	y	Y	RED	IR	RATIO
OLD GREEN	.3471	.3960	13.35	14.05	27.12	1.93
NEW DARK GREEN	.3006	.3711	14.64	7.37	42.62	5.79

FIGURE B.15 - LEATHER GLOVES, TAN



x	y	Y	RED	IR	RATIO
.4004	.3862	19.32	31.23	74.49	2.39

FIGURE B.16 - RECOLORING COMPOUND FOR TENTAGE

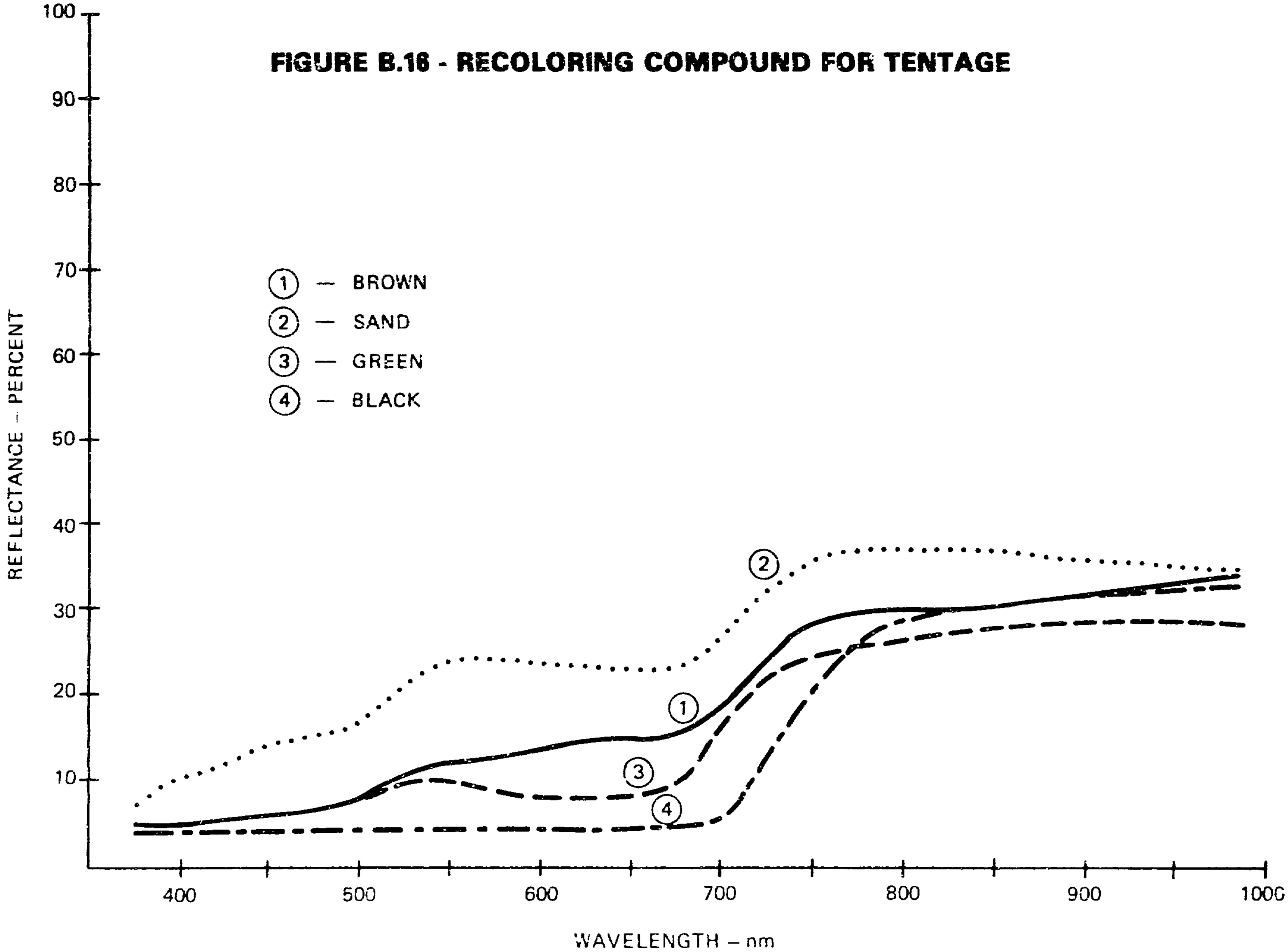


TABLE B.16.1 RECOLORING COMPOUND, FOR TENTAGE

	x	y	Y	RED	IR	IR
Black	0.[illegible]087	0.3163	4.96	4.66	24.94	5.35
Brown	0.3759	0.3701	12.08	14.91	28.74	1.93
Green	0.3295	0.3716	9.71	8.41	25.03	2.98
Sand	0.3545	0.3702	0.2335	23.91	38.86	1.63

FIGURE B.17 - PACKAGING MATERIALS FOREST GREEN

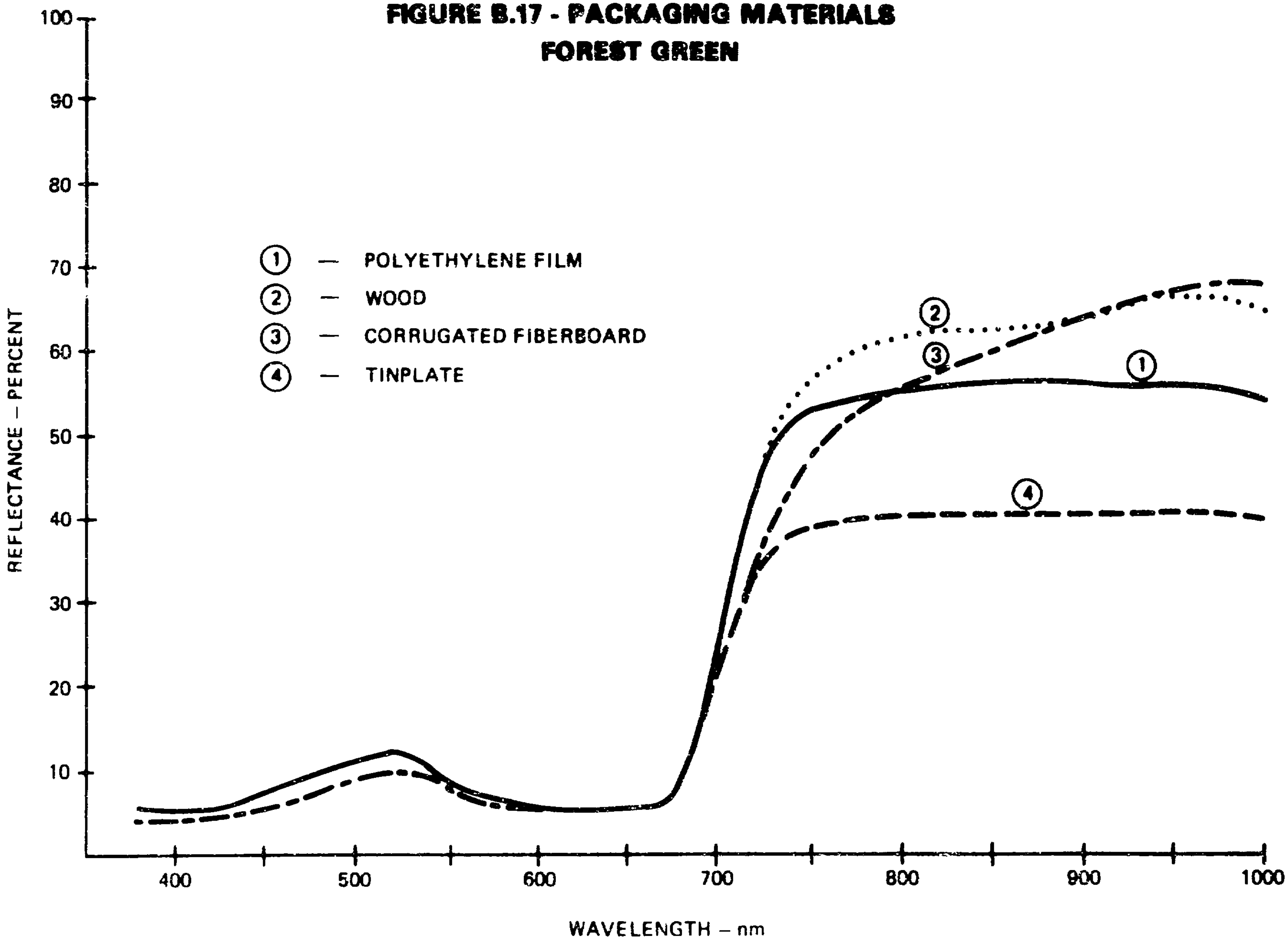


TABLE B.17.1. PACKAGING MATERIALS, FOREST GREEN

	x	y	Y	RED	IR	RATIO
Wood/Spray	0.2954	0.3647	9.68	6.1	58.4	9.6
Corrugated Fiberboard	0.2901	0.3589	8.67	5.6	51.1	9.1
Polyethylene	0.2837	0.3576	9.72	6.1	53.0	8.7
Tinplate	0.2918	0.3625	8.82	5.2	39.3	7.6

APPENDIX C

EXPERIMENTAL COLORANT FORMULATIONS

All experimental colorant formulations used on material furnished to MASSTER are shown. Colorant formulations for items withdrawn from stock are not known, because the relevant specifications under which they were purchased do not require use of specific colorants.

LIST OF TABLES

TABLE C.1. SIX-COLOR PATTERN (NEW)

GROUND SHADE - TAN 379

0.20 Oz/g Intravat Brown 2 BR MD Vat Brown 33
0.26 Oz/g Calcoloid Olive Green 2 GI DP
0.18 Oz/g Intravat Gray 2 GR Paste

TAN 380

0.13% Intravat Brown 2 BR MD Vat Brown 33
0.24% Intravat Brown GR DP Vat Brown 3

BROWN 381
1.6% Intravat Brown 2 BR MD Vat Brown 33
1.9% Intravat Brown GR DP Vat Brown 3

BROWN 382

2.8% Intravat Brown 2 BR MD Vat Brown 33
3.75% Intravat Brown GR DP Vat Brown 3

BLACK 383
Indocarbon CLGS Paste Fine Vat Black 6

KHAKI 384
1.35% Calcoloid Olive Green 2G1 DP
0.25% Intravat Brown GR DP Vat Brown 3

TABLE C.2. FOUR-COLOR PATTERN, EXPANSION SERIES

GROUND SHADE

2.91% Intravat Brown GR DP Vat Brown 3
0.82% Cibanone Green BFD Vat Green 1
1.8 % Algol Yellow GC Vat Yellow 2

LIGHT GREEN 354

0.60% Intravat Brown GR DP Vat Brown 3
0.08% Ponsol Jade Green DP Vat Green 1
0.12% Amanthrene Yellow 10G Paste Vat Yellow 2
99.2 % Vat Reducing Gum

DARK GREEN 355

1.9% Intravat Brown GR DP Vat Brown 3
2.0% Ponsol Jade Green DP Vat Green 1
0.3% Amanthrene Yellow 10 G Paste Vat Yellow 2
95.8% Vat Reducing Gum

BROWN 356

2.43% Hostovat Brown HRR paste Vat Brown 57
0.50% Intravat Brown GR DP Vat Brown 3
0.64% Ponsol Jade Green DP Vat Green 1
0.23% Amanthrene Yellow 10G Paste Vat Yellow 2
96.2 % Vat Reducing Gum

BLACK

7.6% Sodyeco Fast Black FCLG Paste Vat Black 6
1.16% Cibanone Brown F2BR Powder
0.64% Cibanone Blue BO Paste Vat Blue 20
90.6% Vat Reducing Gum

C.3. TIGER PATTERN

DYED GROUND - LIGHT OLIVE GREEN 454

Vat Orange 15	CI #69025
Vat Brown 1	CI #70800
Vat Green 1	CI #59825
Vat Green 3	CI #69500

GREEN 455

Vat Green 3	CI #69500
Vat Green 32	(Veranthrene Khaki E3G)

LIGHT BROWN 456

Vat Green 32	(Veranthrene Khaki E3G)

BLACK 457

Vat Blue 20	CI 59800
Vat Brown 33	
Vat Sulfur Black 6	CI 53295

TABLE C.4
HELMET COVER, BODY NET, BALLISTIC FABRIC, FOUR-COLOR PONCHO

GROUND SHADES

Helmet Cover and Body Net	Ballistic and Poncho Fabrics
Vat Green 1	Irgalan Yellow FGL Acid Yellow 128
Vat Yellow 2	Irgalan Dark Green 2BL Acid Green 58
Vat Brown 3	Irgalan Brill Green 3 GL

PRINT PATTERN FOR ALL FOUR FABRICS

GREEN 354

0.8% Kemprint Yellow 4234
0.6% Kemprint Red 4000 RB60
0.4% Kemprint Blue 4400 RB21
1.8% Binder
96.4% Cut Clear

GREEN 355

5.5% Kemprint Green 4330 RB40
0.4% Kemprint Black 4600 RB10
4.1% Kemprint Yellow 4234
2.8% Kemprint Red 4000 RB60
12.8% Binder
74.4% Cut Clear

BROWN 356

5.0% Sherdye Yellow 4234
2.5% Sherdye Red 4000 RB60
0.9% Sherdye Black 4600 RB10
0.4% Binder
83.2% Cut Clear

BLACK 357
5.0% Sherdye Black 4600 RB10
5.0% Sherdye Brown 4800
10.0% Binder
8.0% Cut Clear

TABLE C.5. TEXTILE OVERCOLORING COMPOUND - REMOVABLE

Vehicle and Binder (total parts)

Polyvinyl Acetate Copolymer (Gelva C-5V-10) (Binder)	7.8
Dispersant (Tamol 850)	0.5
Tricresyl Phosphate (Plasticizer)	3.6
Nonyl Phenyl Ethylene Oxide (Igepal CO-630)	0.1
Hydroxyethyl Cellulose (Cellusize QP-4400)	0.1
Defoamer (Foamkill 639)	0.1
Ammonium Hydroxide (26° Be')	0.5
Water	28.5

Pigments (total parts)

	Dark Green	Light Green	Brown	Black
Green K-639*	7.7	3.3	-	-
Yellow V-9112	1.6	4.2	5.6	-
Brown F-6111	-	trace	2.4	-
Black RM 137	0.8	trace	2.2	10.7
Turquoise K-1607	0.7	-	-	-
Rutile TiO_2	-	1.9	-	-

TABLE C.6. TEXTILE OVERCOLORING COMPOUND - DURABLE

Vehicle and Binder (total parts)

Chlorinated Rubber (Parlon S-10) 10 CPS)(Binder)	6.7
Chlorinated Paraffin (Chlorowax 40) Plasticizer)	9.9
Thixotrope (Thixatrol ST) Thickener	0.7
Epoxy Resin (Epon 828) (Heat Stabilizer)	0.3
n-Butyl Acetate (Solvent)	20.0
Epichlorhydrin (Gelation Stabilizer)	0.1

Pigments (total parts)

	Dark Green	Light Green	Brown	Black
Green K-639*	6.4	6.5	-	-
Yellow V-9112	trace	6.5	4.9	-
Brown F-6111	-	trace	4.8	-
Black RM 137	5.9	-	3.7	13.4
Rutile TiO_2	trace	-	-	-

*Except for the rutile titanium dioxide obtained from DuPont, all pigments were obtained from Ferro Corporation, Cleveland, Ohio whose designations are shown.

TABLE C.7. COLORATION OF GREEN SHOES

This combination of dyes was used to achieve the shade for the green boots by the manufacturer.

Acid Green 2G	Acid Green 3
Derma Green B	
Brill Yellow Conc.	
Xylene Dark Green B	Acid Green 20
Duralan Fast Black WA	Acid Black 52

Both the green and tan shoes were tanned in the same way, first with a conventional chrome tan followed by a vegetable retan. The tan color produced is the result of the tanning process alone. Water repellent was applied after coloration was achieved.

TABLE C.8. COMPOSITION - PAINT, FACE, CAMOUFLAGE, ARID TERRAIN

	#23-6667-Loam (Parts by weight)	#21-6667-Sand (Parts by weight)
Castor Wax	17.5	17.5
Carbauba Wax	2.5	2.5
Mineral Oil, U.S.P. Heavy	22.5	22.5
Lanolin, U.S.P., Anhydrous	8.5	8.5
N,N Diethyl m-toluamide	10.0	10.0
Talc	7.0	7.0
Ochre C1624	16.0	7.8
Titanium Dioxide, Atlas White	-	24.0
Carbon Black A 3278		0.2
Black Iron Oxide	16.0	
Total	100.0	100.0

TABLE C.9. COMPOSITION - PAINT, FACE, CAMOUFLAGE, VERDANT TERRAIN

	#46-6667 - Green (Chlorophyll Type) (Parts by Weight)
Castor Wax	21.6
Carnauba Wax	3.1
Mineral Oil, U.S.P.Heavy	22.5
Lanolin, U.S.P. anhydrous	10.5
N,N Diethyl m-toluamide	12.2
Talc	8.6
Titanium Dioxide	10.0
Chlorophyll, Oil-Soluble	11.5
Total	100.0

TABLE C.10. FIELD DYEING PACKETS Mil-D-2273

TYPE IV

Direct Blue 71	CI-34140
Direct Orange 37	CI-40265
Direct Orange 34	CI-40215

TABLE C.11 TENTAGE RECOLORING FORMULATIONS

Batch Compositions
(Parts by Weight)

1.	Polyvinyl Chloride (Geon 222)	100
2.	Cyclohexanone	300
3.	FMC-Tricresyl Phosphate	15
4.	Synpron 966	10
5.	Chlorinated Parafin (Chlorowax 70)	25
6.	Inorganic TiO_2 (Oncor 75 RA)	5
7.	Diatomaceous Earth (Celite)	30
8.	Pigments	40
	Total	525

Pigments
(Parts by Weight)

	Dark Green	Black	Sand	Field Drab
Ferro Green K639	40	-	4.0	10.1
Ferro Black V6782	-	40	2.3	3.4
Ferro Yellow V6951	-	-	6.2	10.7
Ferro Brown V6111	-	-	0.5	11.8
White TiO_2	-	-	27.0	4.0