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SECRET

FOREST FIRE RESEARCH

Requirements for a Means of Destroying

Forest/Jungle Growth by Fire

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Volume I

Final Report - Phase I

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INDEX - VOLUME I

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Many of the photographs used in this report were supplied by the 600th Photo Squadron, USAF.

SUMMARY

The research described in this report was conducted in Pleiku Province, Republic of Vietnam in January-March, 1966 by the Forest Service, Department of Agriculture under the sponsorship of the Advanced Research Projects Agency, Department of Defense. The objective of the research is to determine the techniques and conditions required to destroy large areas of forest or jungle growth by fire.

Factors Affecting Forest Fire Behavior.

Because there is little thermal feedback in a forest fire, its combustion behavior is greatly affected by relatively minor changes in weather, fuel moisture or structure, and the pattern of ignition. Each of these fire behavior controls was studied specifically for the central highlands of South Vietnam.

Forest Fire Climate of Indochina.

With the exception of the eastern half of North Vietnam, the climate of Indochina is such that successful forest incendiary operations can be conducted anywhere in the area for at least a short period during each year. The possible burning season may be as short as five weeks (Feb. 1 - March 7 in the delta region of South Vietnam), or as long as eighteen weeks (Nov. 7 - March 21 in central Laos and northeastern Thailand). In the central highlands of South Vietnam the normal season for burning extends from mid December to mid March.

Forest Fire Weather in South Vietnam.

Favorable burning conditions occur in South Vietnam during the northeast monsoon period. The most favorable weather occurs one or two days after a surge of cool, dry air moves over the Republic from the semi-permanent high pressure system in northern China. The surge usually follows the formation of a cold front moving from the south China coast to the Philippines.

During these favorable periods, relative humidities in the Central Highlands can be expected to reach minimum values below 40% (occasionally below 30%) with maximum air

temperatures near or exceeding 100°F. Such hot, cloudless, relatively dry conditions are necessary for successful burning operations.

Vegetation of South Vietnam.

Because of the mixture of sites and species, combined with the effects of shifting agriculture on the original forest stands, the vegetation of South Vietnam is extremely heterogenous and complex. About the only generalizations possible in relation to burning are that: (1) Dwarf mangrove is unsuitable for incendiary operations; (2) Woodlands with a high proportion of deciduous species should be either burned early in the dry season or avoided; (3) Dense, multistoried forests have only marginal amounts of ground fuels unless small openings are present to provide "edge" effects; (4) Bamboo sites burn poorly; (5) Intermediate forests with mixed tree sizes and a high proportion of evergreen species are optimum sites for forest incendiary operations.

Fuel Treatment.

Intensive observations were made on two forest sites sprayed with Orange defoliant. Both sites were immediately adjacent to the Duc Co Special Forces Camp. One was sprayed in late November (before the onset of the dry season) and the other in late January (in the middle of the dry season). The November spray resulted in: (1) 95% mortality of leaves within 8 weeks of spraying; (2) 80% leaf fall from the upper and middle canopies and 50% leaf fall from the understory. (Leaf mortality is absolutely necessary for successful burning, leaf fall is highly undesirable.) In contrast, the January spray resulted in: (1) Only 60% leaf mortality within 6 weeks of spraying, but (2) only 20% overall leaf fall.

On a 21 square kilometer area at Chu Pong Mountain, 17 kilometers south of Duc Co, a late January - early February spray operation also resulted in about 60% leaf mortality within six weeks. There is insufficient data to establish whether these poor results were due to season of application, species of vegetation, or mechanical application difficulties due to rough topography.

Fuel Moisture.

Two hundred forty two fuel moisture samples were collected at the Duc Co sites in order to determine the effects of weather, fuel treatment and time of day. We found that: (1) The moisture content of green, unsprayed foliage averaged 185% (dry weight basis), much too high for burning to be possible; (2) The drying rate of successfully sprayed foliage is extremely rapid. Leaves which were killed lost 95% of their moisture within 10 days of spraying; (3) Drying rates following rain were also unexpectedly rapid. Leaf litter redried in less than 24 hours following a 0.04 inch shower, and in less than 48 hours after a 0.27 inch rain; (4) Fine twigs, which make up two thirds or more of the available fuel, were not sufficiently dessicated by the Orange spray treatment. A month after spraying, twig moisture was 90%, too wet for acceptable burning.

Fuel Flammability.

Samples of Vietnamese fuels were collected at Duc Co and sent to the Northern Forest Fire Laboratory for analysis. Heat content and ignition times were similar to those for standard forest fuels of the U.S. However the heat release rate of the Vietnamese fuels was only 75% of the standard, and flame heights only 60%.

Ignition Pattern and Fire Behavior.

The 21 square kilometer test site at Chu Pong was burned, starting at 1400 on March 11, 1966. Fourteen thousand five hundred thirty five ignition points were laid down in a 20 minute period. This calculated spacing proved to be too low. Later analysis showed that fire interaction occurred only when ignitions occurred within 90 feet of each other. Twice as many incendiaries were needed as were used.

Fires did merge in areas with exceptional concentrations of incendiaries. The resulting fire buildup progressed as predicted with peak burning reached in approximately 35 minutes. The resulting convection column reached 22,000 feet.

Although a total of 39,000 tons of vegetation were burned within the first hour, crown removal was not satisfactory. The fire burned about 25% of the total available fuel, but only about 10% of the overstory crown cover. The combination of too widely spaced ignitions, high twig moistures, and only a 60% effective defoliation effort kept the fires on the ground.

Recommendations.

Forest incendiary operations planned for the Republic of Vietnam in 1967 should essentially follow the same guidelines used in 1966 except that:

1) Spray operations using Orange should be performed before the onset of the dry season.

2) Whenever possible, areas treated with Orange should be resprayed with Blue or Black about 10 days before the planned burning date.

3) Ordnance requirements should be based on obtaining at least one ignition per 8000 square feet of forest area.

4) The number of drying days needed between the last rain and TOT can be reduced to 3 days following rains of 0.2 inches or more and 1 day following rains less than 0.2 inch.

INTRODUCTION

In September, 1965, CINCPAC requested that the Joint Chiefs of Staff take action to expedite the development of a device capable of destroying large areas of jungle or forest growth by fire.

In December, 1965, the Joint Chiefs of Staff, by JCSM-862-65, requested the Secretary of Defense to initiate programs to determine the feasibility of dehydrating jungle growth to the point where such material would support combustion, and to initiate development of operational means for determining the specific jungle conditions under which there is the greatest probability of destroying jungle or forest growth by fire.

The Branch of Forest Fire Research, Forest Service, offered to assist in the conduct of research designed to answer the questions posed by JCSM-862. The Forest Service suggested a two-phase program.

Phase I would be centered around an operational field test to be conducted by the armed forces in South Vietnam. The objectives would be:

> To provide technical advisory service to the military units responsible for conducting the operational test,
>
> To upgrade existing information on fuel and weather potential for area incendiary operations in South Vietnam, and
>
> To determine by instrumented field trials the rate of dehydration of jungle growth following desiccant application and other characteristics of fuels and microclimate that affect the buildup and behavior of fire under South Vietnamese jungle conditions.

Phase II would be a three-to-five-year research program designed to specify criteria that will insure operationally useful techniques for forest incendiary operations, applicable to major forested areas of the world.

The Advanced Research Projects Agency initiated Phase I of the proposed Forest Service program on December 20, 1965, under ARPA order No. 818 (Project EMOTE).

A five-man team of forest fire research specialists moved to South Vietnam on January 15, 1966, and returned on March 13, 1966. This report summarizes the findings and conclusions of Project EMOTE, Phase I.

FACTORS AFFECTING FOREST FIRE BEHAVIOR

Essentially, a forest fire is merely the free space combustion of several cellulosic solids.

Forest fires differ from more familiar combustion reactions such as those in furnaces, engines, or even fireplaces, in that they occur in free space without confining walls. This means that most of the radiative and convective energy is lost to the combustion system. With little thermal feedback, a forest fire is always in a delicate state of balance, capable of being greatly accelerated or greatly retarded by relatively minor changes in combustion conditions.

Forest fires also differ from most common combustion phenomena because they originate as a fuel controlled process, grow into an oxygen controlled phase, and then often alternate between the two sets of controls. The effect of a change in any particular variable, such as fuel moisture, depends on which regime the fire is burning in at the time.

These characteristics of forest fires make it difficult to present a simplified discussion of the factors that govern forest fire behavior. Instead, the process is described stepwise--from ignition of an individual fuel element to development of a mass fire occupying a volume of several cubic miles (see Appendix A, Volume II).

This description of the fundamental process shows the importance of minor changes in several factors. The volume of fine fuel, its ratio of surface area to volume, and its structural arrangement in the fuel bed are critical in ignition and in buildup of the fire. Moisture content of the fine fuel greatly affects the production of volatiles at ignition, the heat loss during burning, the flammability limits for the combustible gases, and flame temperatures attained when the gases are ignited. Relative humidity largely determines moisture content of fine fuel. Solar radiation reduces the fuel moisture content by increasing temperature of the fuel surface; radiation also is an important heat source that adds to combustion efficiency. Wind changes the oxygen supply and flame angle, thus greatly affecting buildup and spread of fire.

Information on certain of these factors was obtained during Phase I in Vietnam. The comprehensive research program proposed for Phase II will develop better criteria for evaluating the factors that determine burning characteristics of jungle fuels.

RESULTS AND CONCLUSIONS--PHASE I

FOREST FIRE CLIMATE OF INDOCHINA

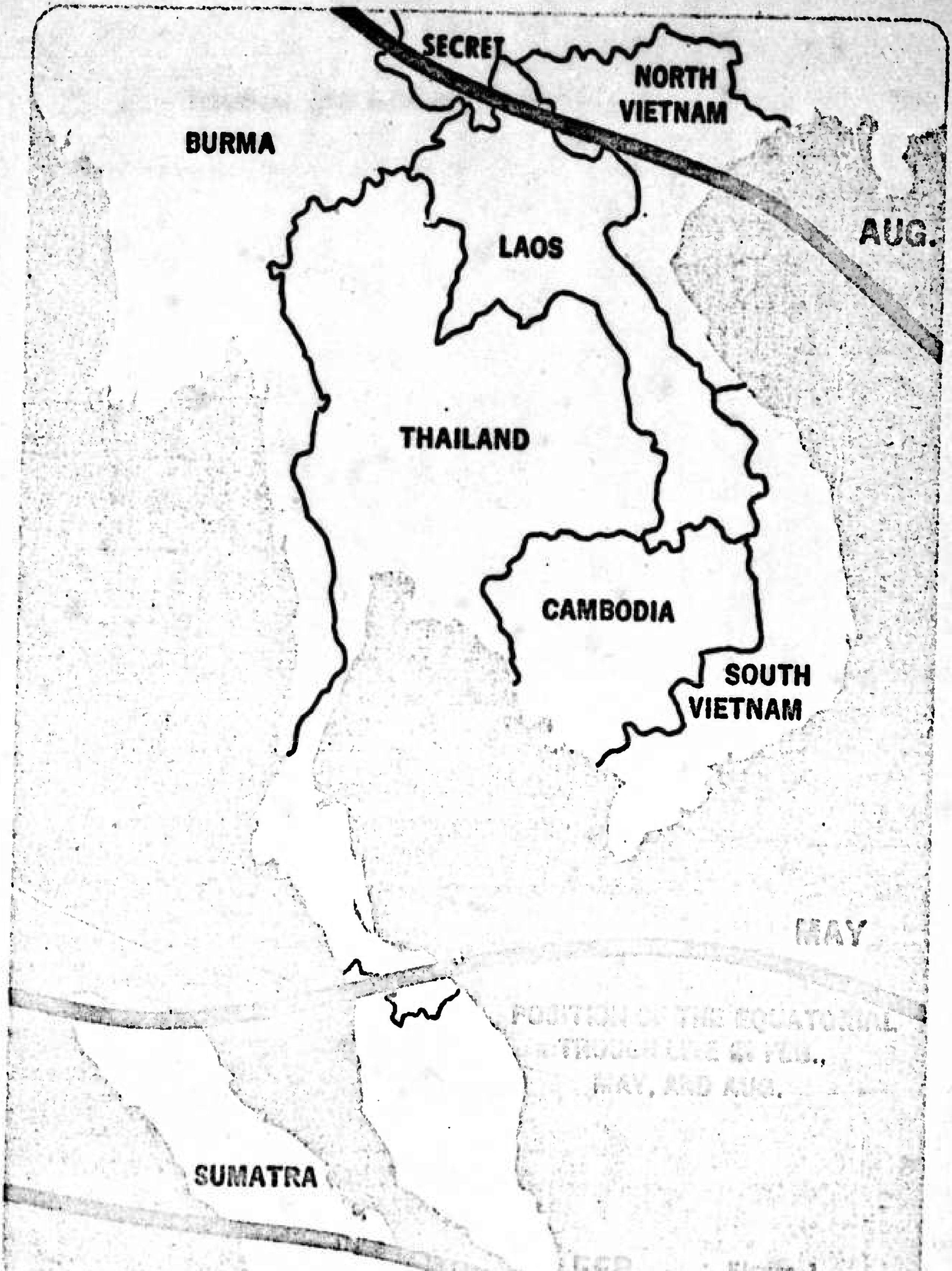
For most of Indochina (Thailand, South Vietnam, Cambodia, the southern portions of Laos and North Vietnam except for the northern interior regions) the climate is monsoonal in nature (Tropical Savannah or Köppen Type Aw). It is characterized by two major seasons: the wet southwest monsoon from May through September, and the dry northeast monsoon from November through early March (Fig. 1). The climate during the transition periods (March-April and September-October) varies with distance from the coast.

In the northern interior of Laos and North Vietnam the climate is more continental in character (Köppen Type C Wa or Warm Temperate-Winter Dry). Here the changes are less abrupt and rainfall is more evenly distributed throughout the year.

Excellent detailed coverage of climatic patterns for Southeast Asia in general and South Vietnam in particular have been prepared by the U.S. Air Force.

Using these climatic data, it is possible to calculate the number of days in any month at any location when forest incendiary operations are possible under stated weather conditions. This was done for 15 stations in Thailand, Laos, Cambodia and Vietnam. The results are shown in figures 2 to 11. Using the same criteria, it is also possible to determine the probability for success of an incendiary mission conducted against a randomly selected target on a randomly selected day of the month. These data are listed in Table 1. Using a modified Markov chain matrix, we have also calculated the probability that at least one of "x" selected targets will be suitable for burning within "y" days of any given date. A sample of the computer print out is shown in figure 12. The criteria and methodology used for these analyses and a complete listing of data are presented in appendix E, in Volume II.

As improved criteria are developed, the programs will be rerun to provide more accurate assessment of the forest incendiary potential of particular areas of interest. Extension of this work will be accomplished early in Phase II of Project EMOTE.



POSITION OF THE EQUATORIAL TROUGH LINE IN FEB., MAY, AND AUG.

Figure 1

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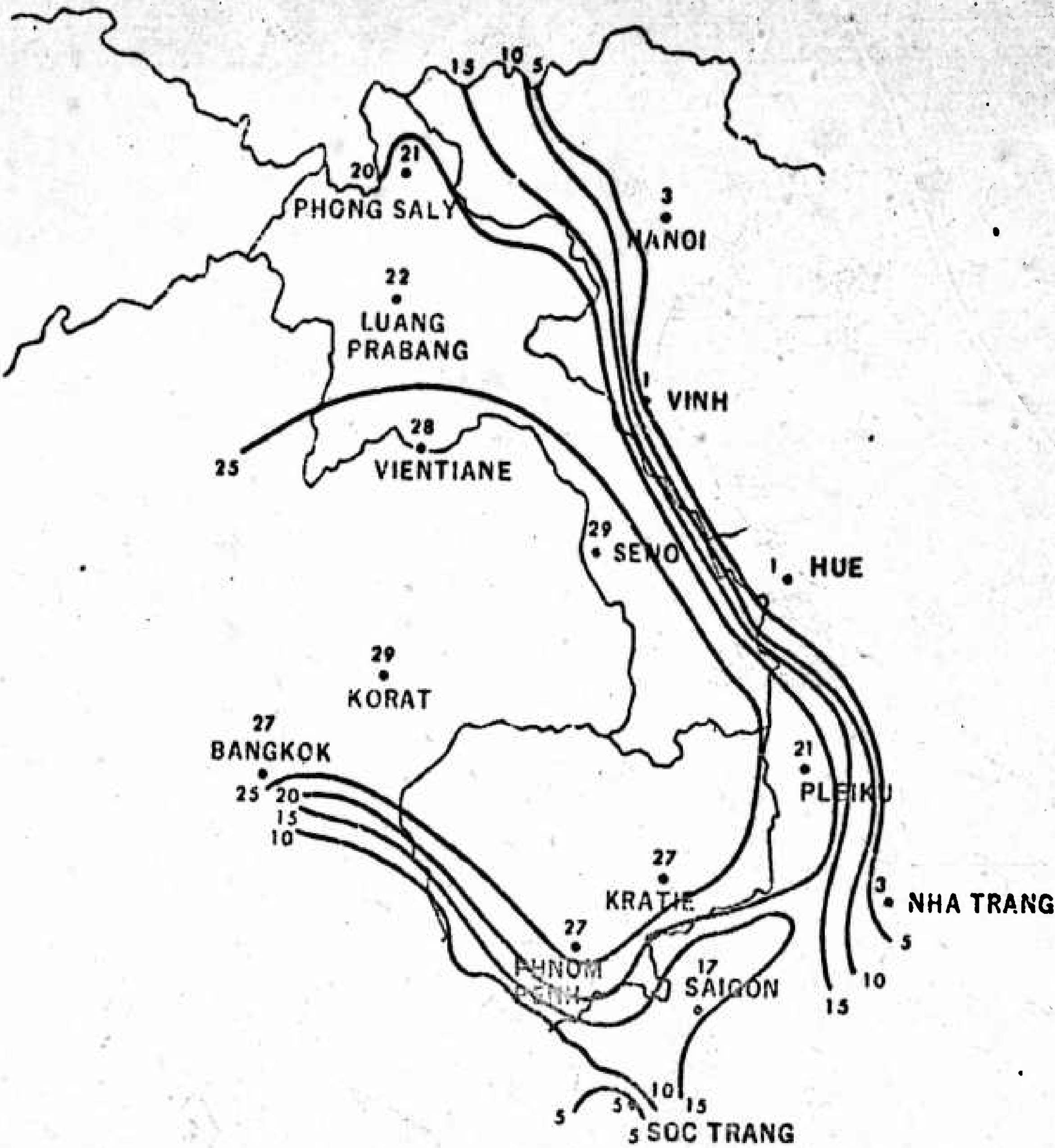
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KRATIE
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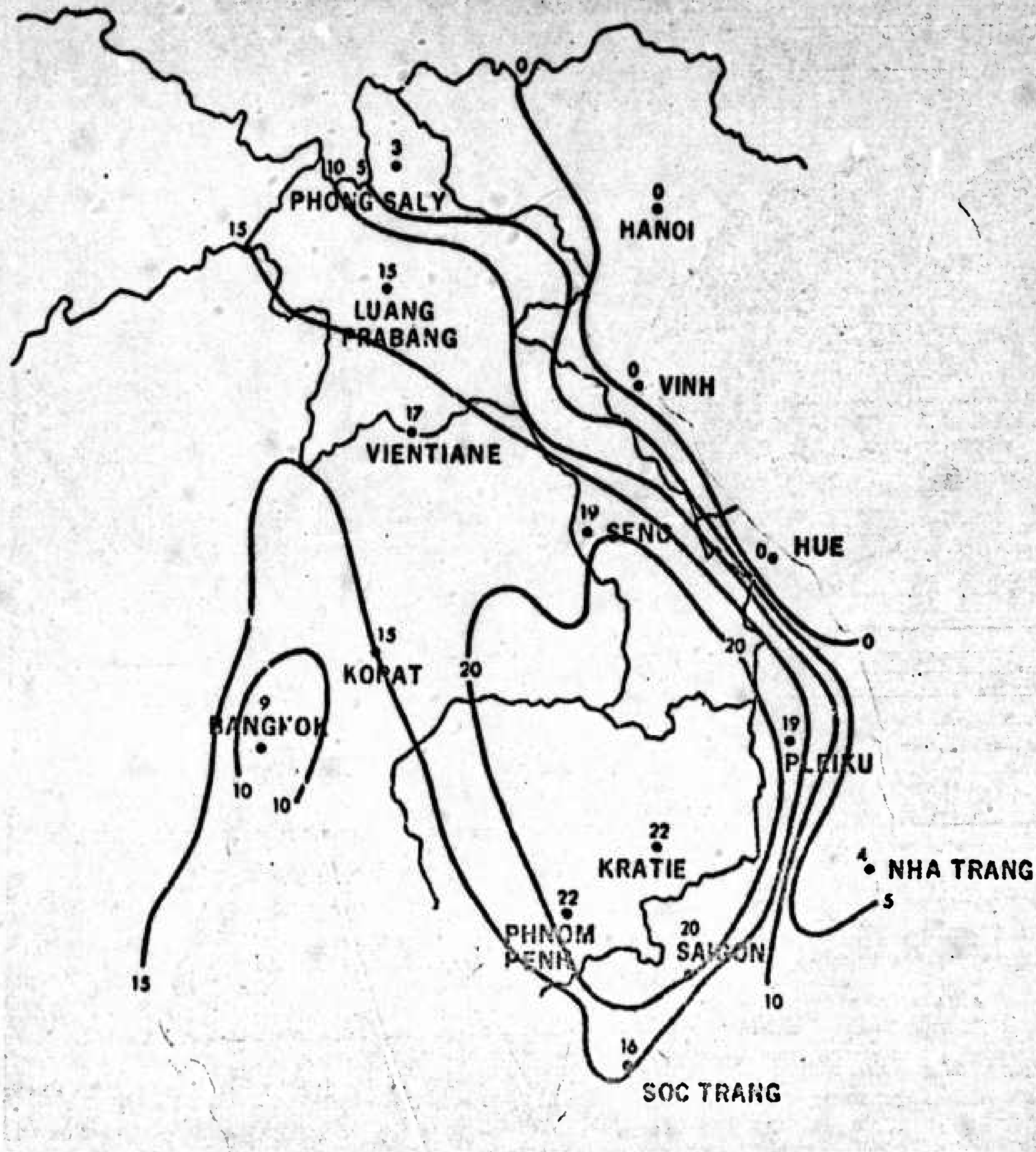
January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SOC TRANG

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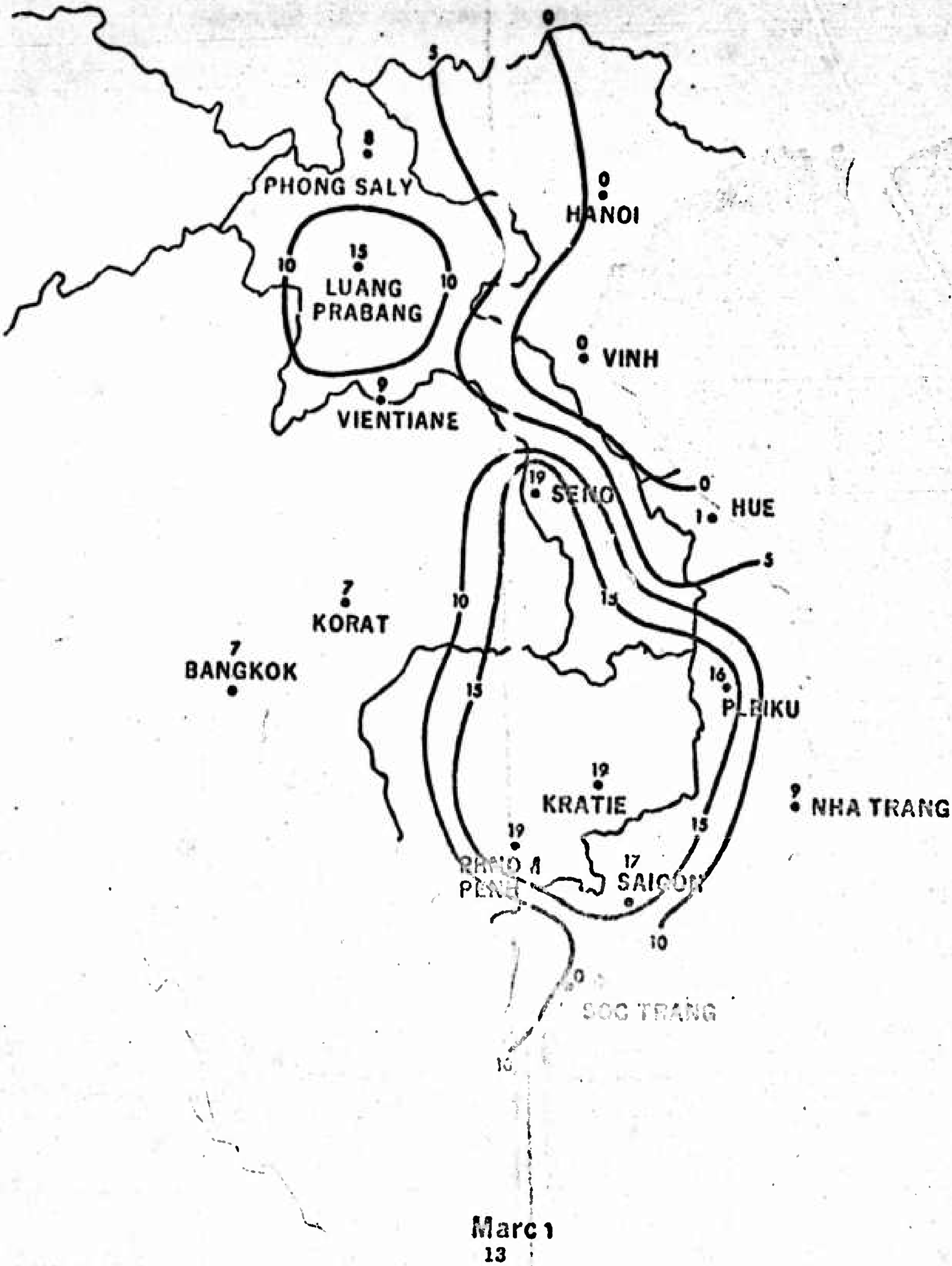

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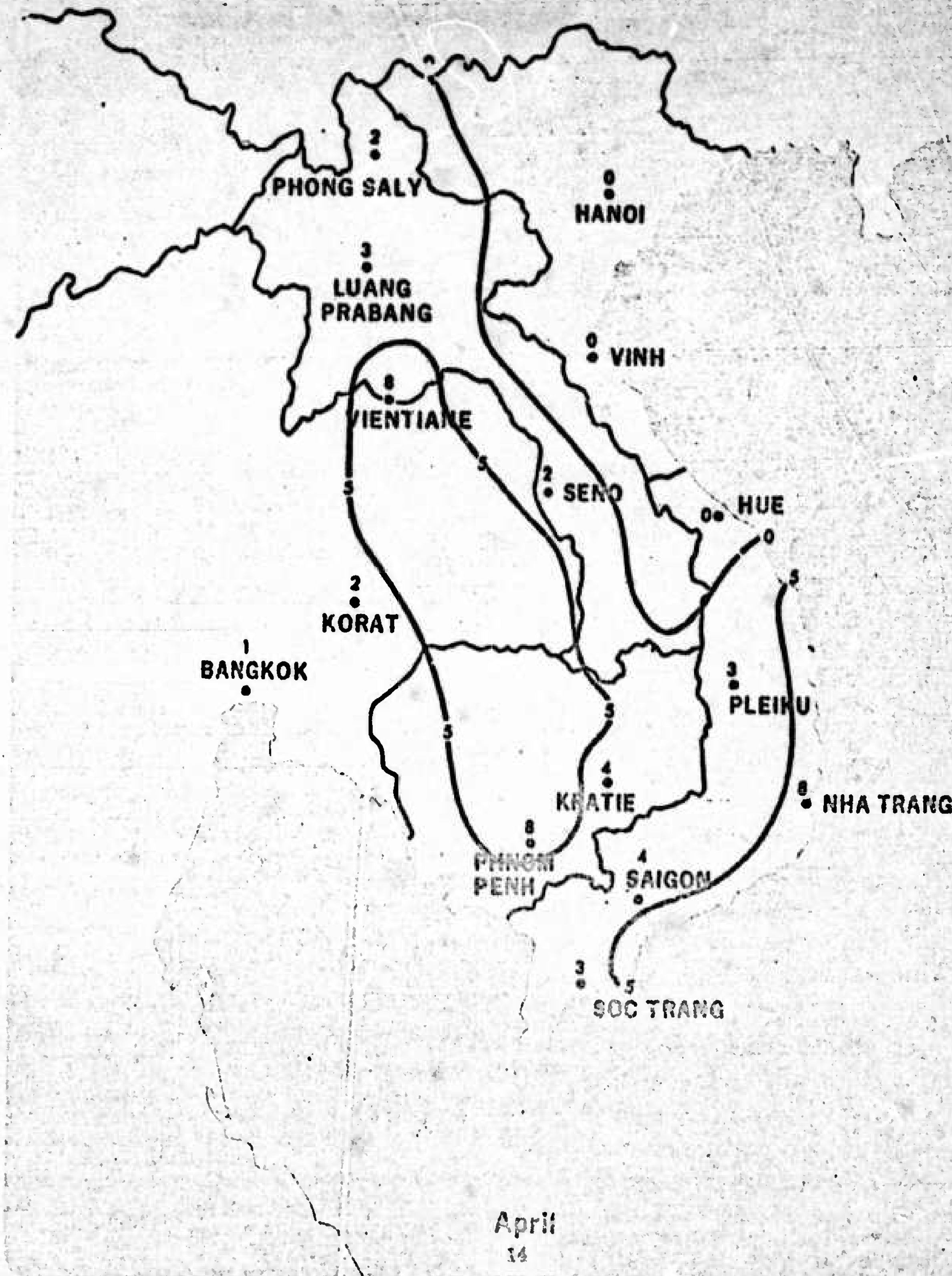

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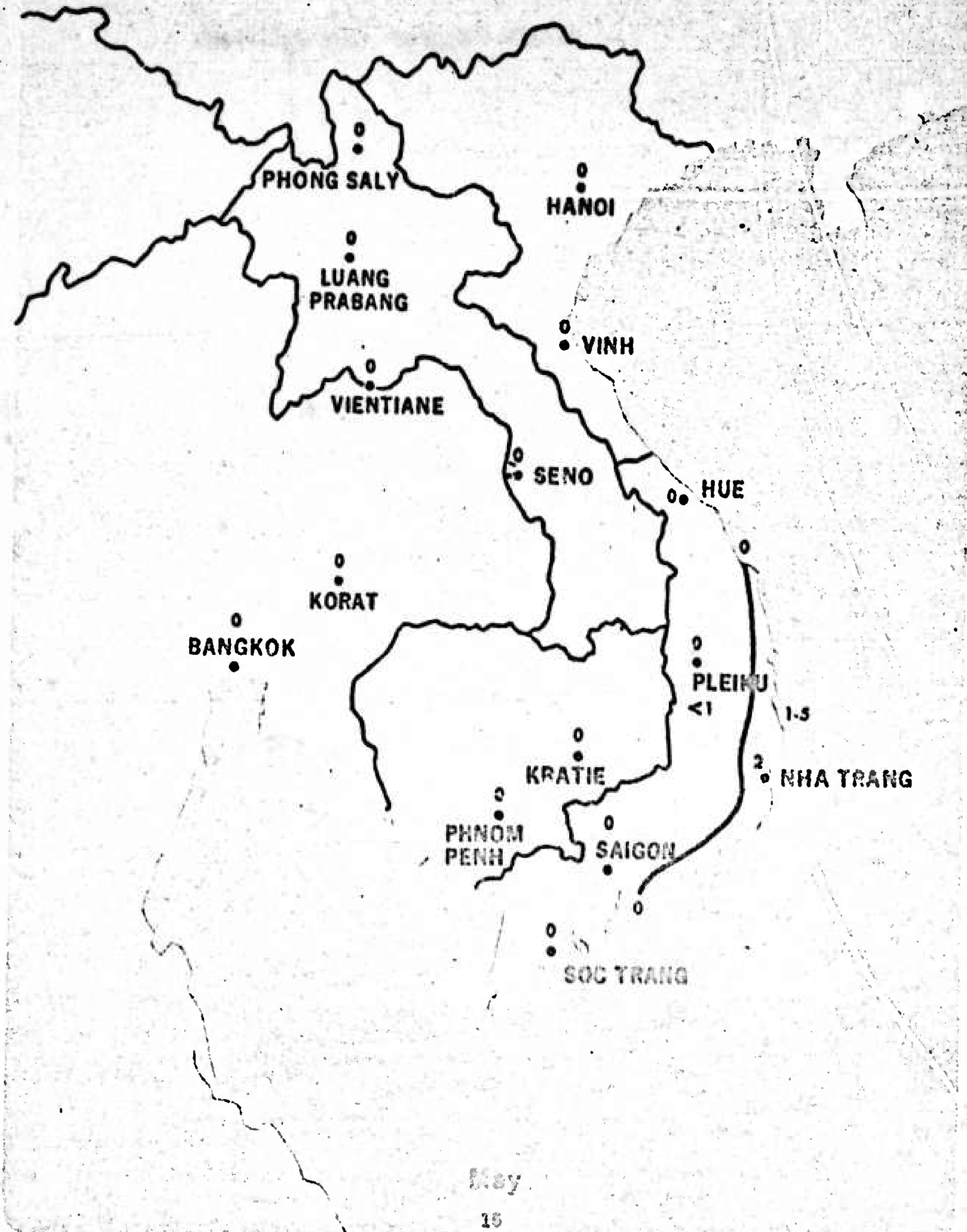
April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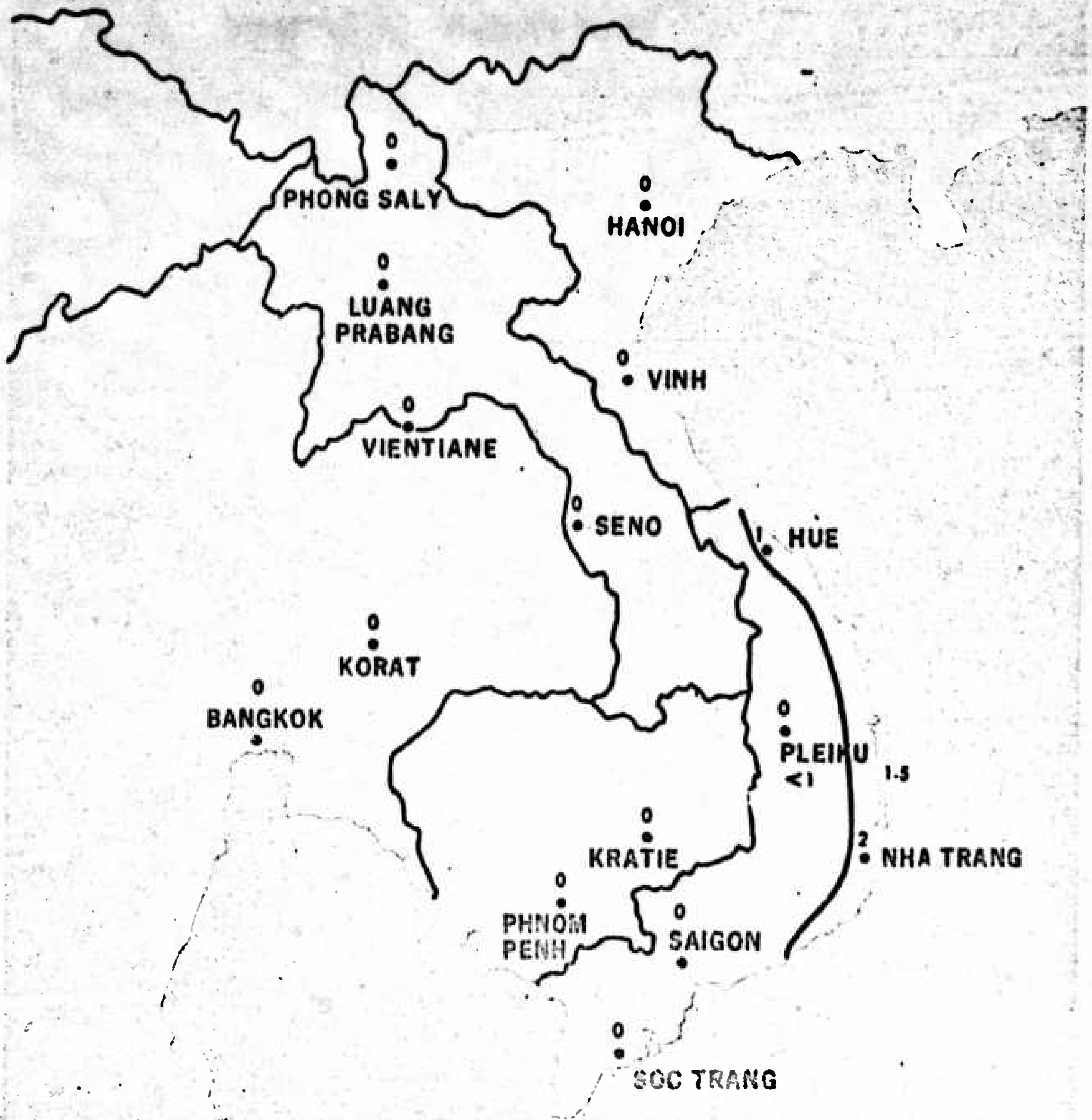
May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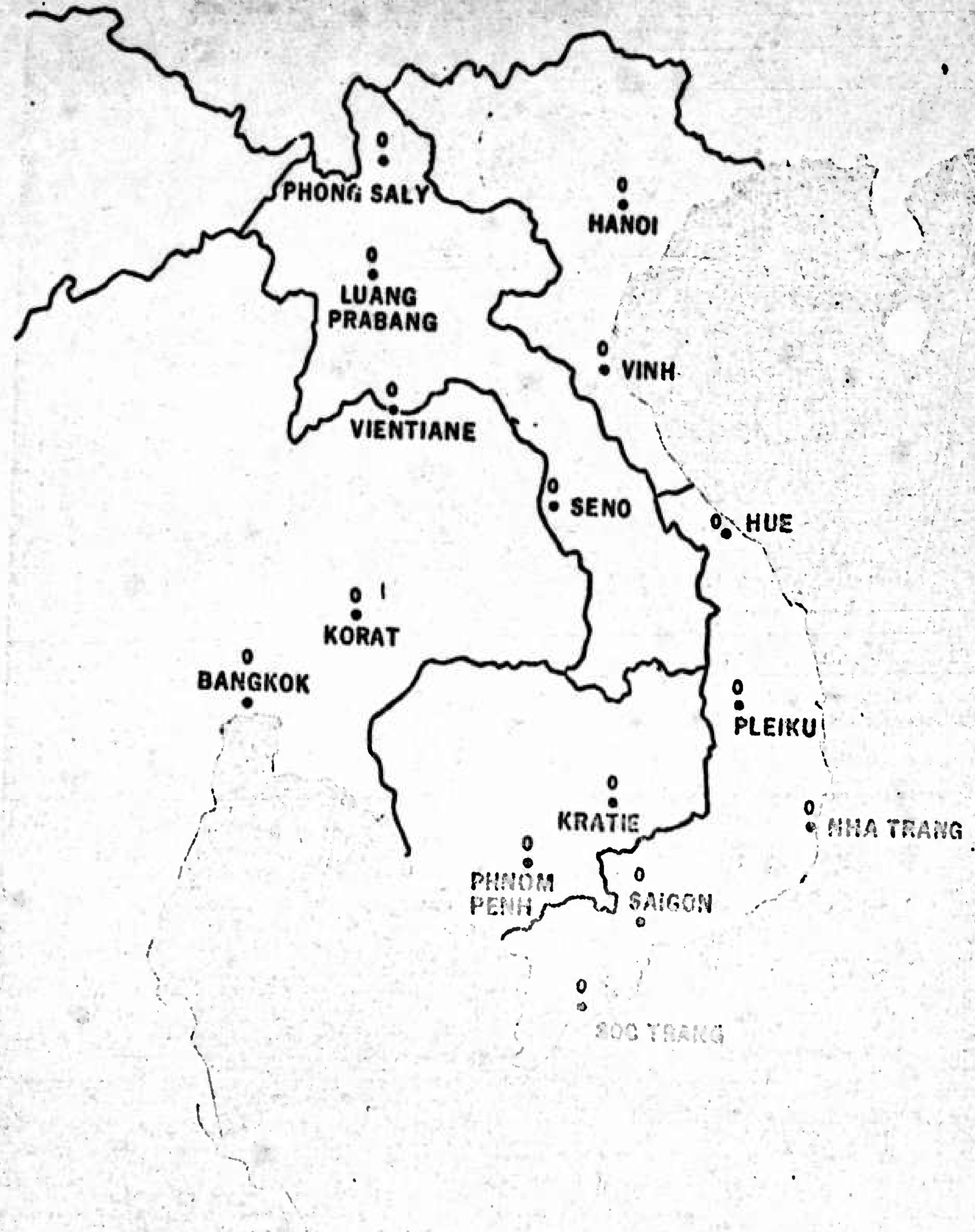
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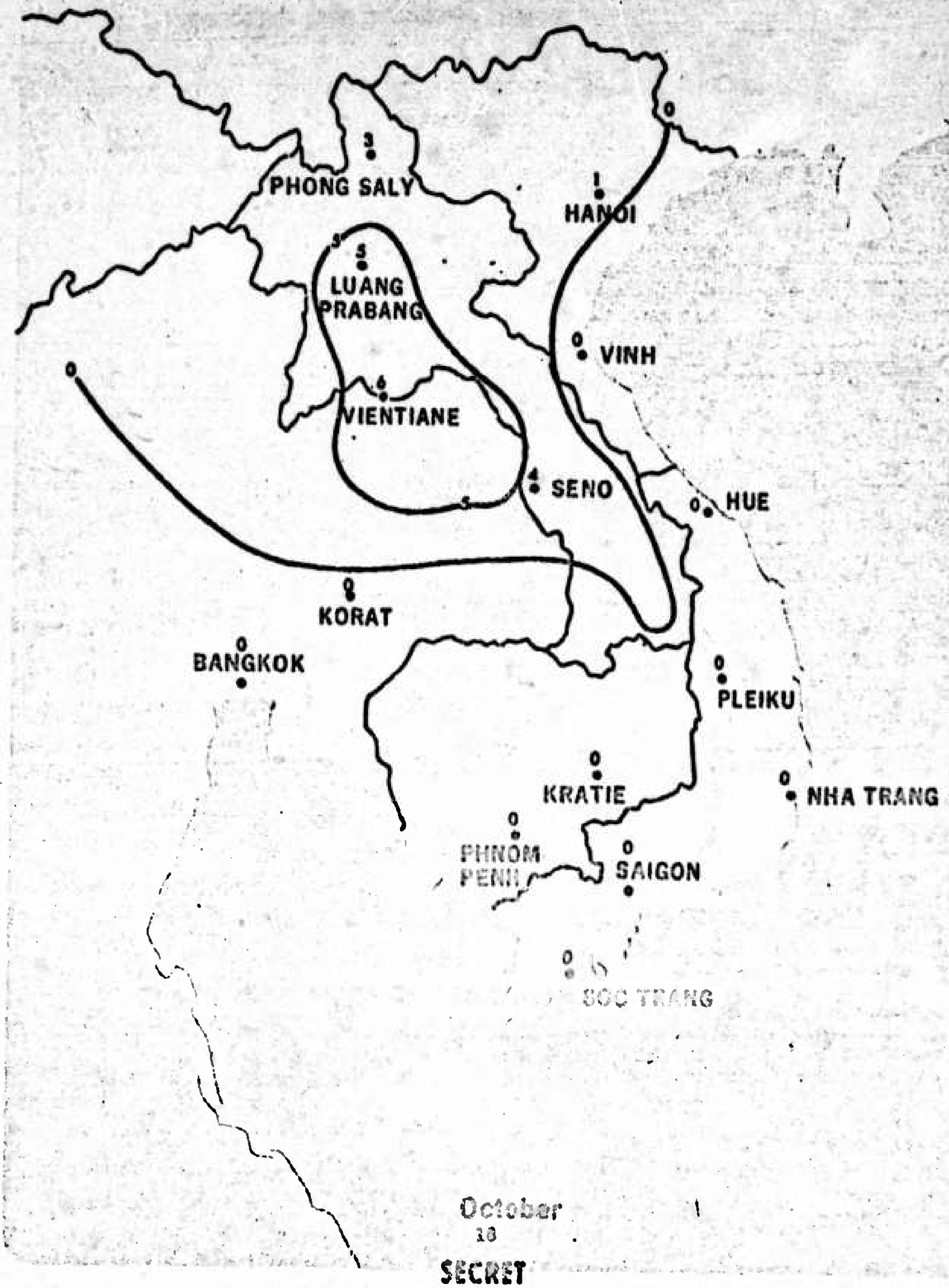
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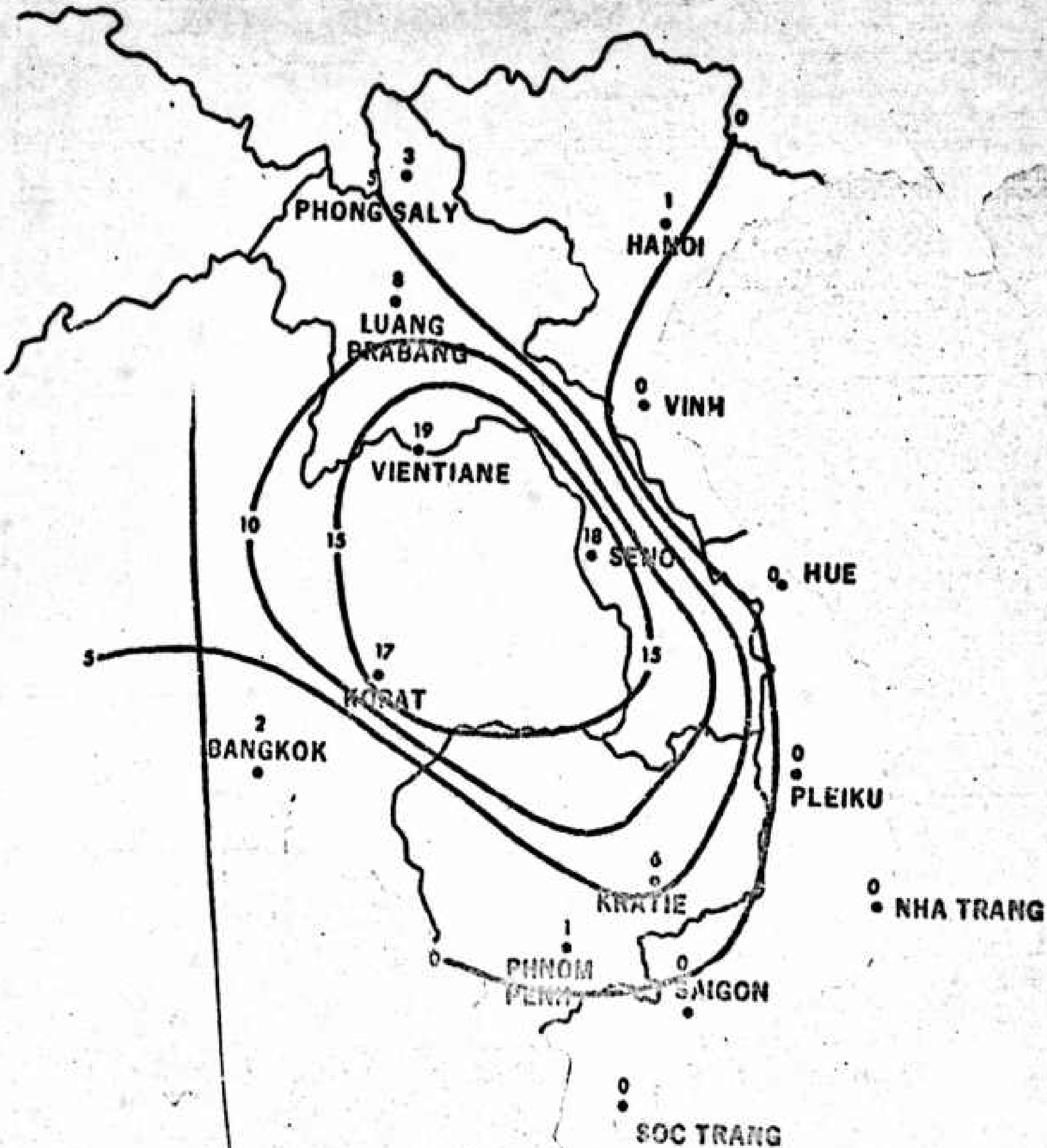
October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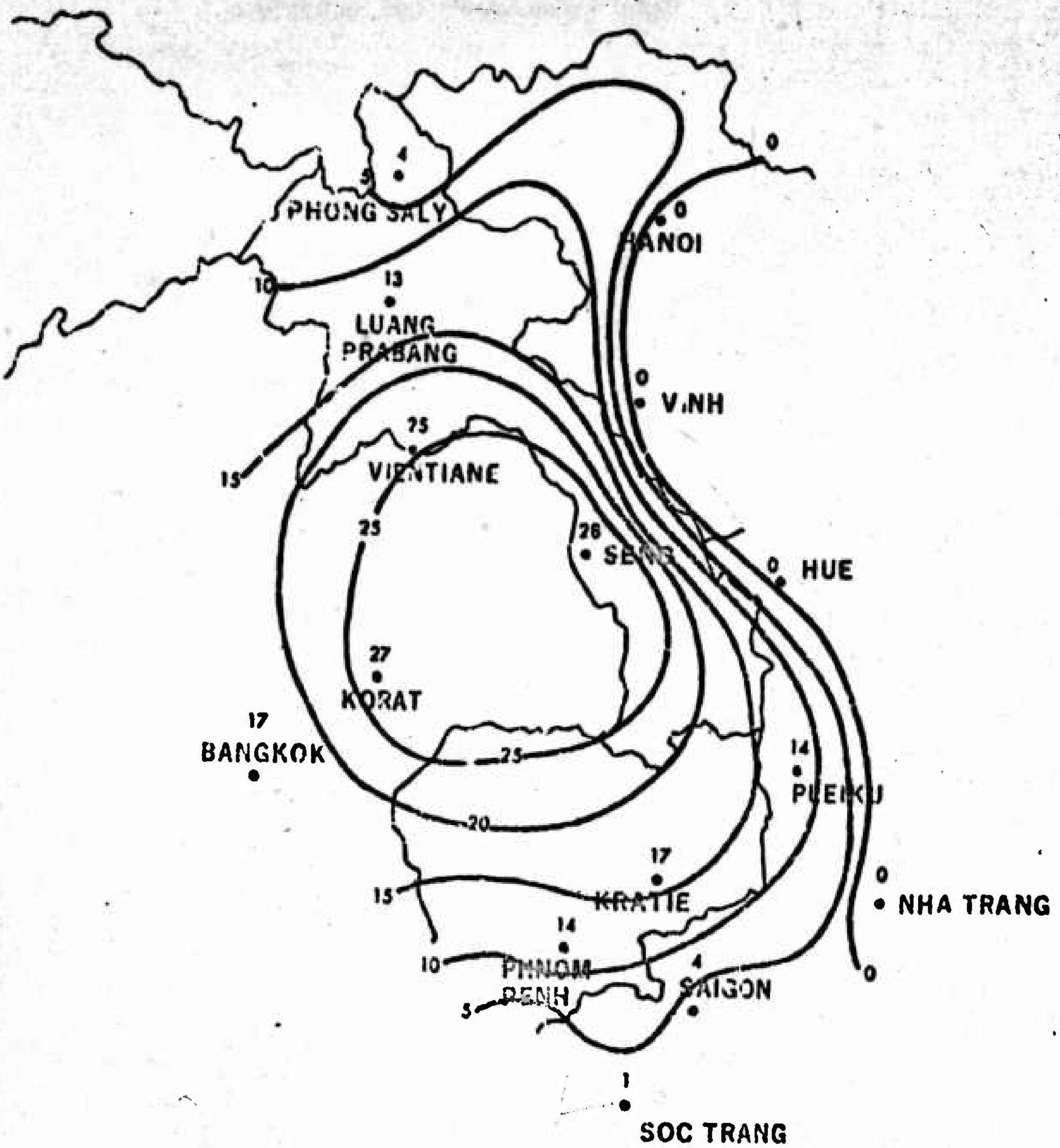
November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KRATIE
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NHA TRANG
14
PHNOM PENH
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5
4
SAIGON
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1
SOC TRANG

December

TABLE 1

UNCONDITIONAL PROBABILITY OF SUCCESSFUL BURNING

STATION	MONTH											
	JAN	FEB	MAR	APR	MAY	JUNE	JUL	AUG	SEPT	OCT	NOV	DEC
SOC TRANG	.16	.56	.31	.09	.00	.00	.00	.00	.00	.00	.00	.04
SAIGON	.54	.70	.56	.14	.00	.00	.00	.00	.00	.00	.01	.13
NHA TRANG	.11	.15	.30	.27	.06	.03	.03	.02	.00	.00	.00	.00
PLEIKU	.68	.66	.52	.11	.00	.00	.00	.00	.00	.00	.01	.45
HUE	.02	.01	.02	.01	.01	.05	.01	.00	.00	.00	.00	.00
VINH	.03	.01	.01	.02	.02	.01	.00	.00	.00	.01	.00	.01
HANOI	.10	.00	.00	.00	.00	.00	.00	.00	.00	.04	.03	.08
PHNOM PENH	.87	.79	.61	.26	.01	.01	.01	.01	.00	.00	.04	.47
KRATIE	.87	.79	.60	.10	.01	.00	.00	.00	.00	.01	.19	.55
SENO	.93	.69	.60	.07	.00	.00	.00	.00	.00	.13	.61	.89
BANKOK	.87	.32	.22	.04	.00	.00	.00	.00	.00	.00	.07	.55
KORAT	.93	.54	.22	.06	.00	.00	.00	.00	.00	.01	.56	.87
VIENTIANE	.89	.61	.29	.26	.01	.00	.00	.00	.00	.19	.62	.80
LUANG PRABANG	.71	.55	.50	.11	.00	.00	.00	.00	.00	.16	.25	.43
PHONG SALY	.69	.11	.26	.06	.00	.00	.00	.00	.00	.10	.10	.14

STATION A FEB

INPUT DATA
.029
.007
.571
.250
.143

PROBABILITY THAT AT LEAST ONE SITE BECOMES
READY AFTER WEATHER WATCH IS INSTITUTED

ROW HEADS ARE DAYS SINCE WEATHER WATCH BEGAN
COLUMN HEADS ARE NUMBER OF SITES AVAILABLE

	1	2	3	4	5	6	7	8	9	10	XX
1	.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	.020	0.040	0.060	0.079	0.098	0.117	0.135	0.152	0.170	0.187	0.
3	.031	0.155	0.224	0.287	0.344	0.398	0.446	0.491	0.532	0.570	0.
4	.171	0.313	0.431	0.528	0.609	0.676	0.731	0.777	0.815	0.847	0.
5	.274	0.473	0.617	0.722	0.798	0.854	0.894	0.923	0.944	0.959	0.000
6	.376	0.610	0.757	0.848	0.905	0.941	0.963	0.977	0.986	0.991	0.001
7	.467	0.716	0.849	0.920	0.957	0.977	0.988	0.994	0.997	0.998	0.003
8	.545	0.793	0.906	0.957	0.981	0.991	0.996	0.998	0.999	1.000	0.009
9	.609	0.847	0.940	0.977	0.991	0.996	0.999	0.999	1.000	1.000	0.021
10	.659	0.884	0.960	0.986	0.995	0.998	0.999	1.000	1.000	1.000	0.040
11	.698	0.909	0.972	0.992	0.997	0.999	1.000	1.000	1.000	1.000	0.066
12	.728	0.925	0.980	0.995	0.999	1.000	1.000	1.000	1.000	1.000	0.100
13	.752	0.938	0.985	0.996	0.999	1.000	1.000	1.000	1.000	1.000	0.141
14	.771	0.948	0.988	0.997	0.999	1.000	1.000	1.000	1.000	1.000	0.187
15	.787	0.954	0.990	0.998	1.000	1.000	1.000	1.000	1.000	1.000	0.236

COLUMN XX IS SINGLE SITE STARTING DAY AFTER HEAVY RAIN

UNCONDITIONAL PROBABILITY = .557

Figure 12

FOREST FIRE WEATHER IN SOUTH VIETNAM

The climatic analyses showed that many days having the weather conditions prescribed for successful forest incendiary operations occur in much of South Vietnam during the period from December 1 to March 15. Inspection of daily weather records showed that these favorable burning days often occur in groups, usually preceded by short periods of drying weather.

A synoptic scale study was made to determine whether certain weather influences of the northeast monsoon season are associated with short periods of high potential fuel flammability. Knowing that hot, dry, relatively cloud-free days provide optimum burning conditions, we searched selected past and current synoptic records for general weather patterns that provided this type of day. We found that the most desirable synoptic situations are those that produce subsidence over the areas concerned. One such weather pattern, which occurred several times in January and February, 1966, is described briefly below. Its drying effect is usually limited to the Central Highlands, Transition, and Delta regions.

1. A surge (outbreak) of cool air moves south or southeastward from the semi-permanent high pressure system located in or near northern China. This surge usually occurs behind a cold front that moves from the South China coast to the Philippines. A pressure ridge oriented north-south or northeast-southwest follows the front. The front usually becomes diffuse and usually disappears before reaching Saigon and the Delta region.

2. A northeast flow usually precedes and follows the surge, with directional divergence over the Republic. An elongated high pressure ridge at the surface, with its center line oriented NE-SW or N-S along the coast, accompanies the streamline flow.

3. The desired drying conditions occur one or two days after a surge.

4. Two to four days after a surge the desired positive wind speed divergence occurs over the Delta and occasionally affects Saigon.

5. The fourth or fifth day after a surge may or may not have favorable weather conditions for burning. This depends on gradient wind speed and direction.

6. By the sixth day the surface ridge begins to break down or move eastward. This results in a southeasterly flow over Vietnam. Sufficient moisture is then advected inland to produce cloudiness and scattered showers. The period then ends as a new surge begins to form on the seventh day.

This example illustrates the necessity of considering weather patterns when scheduling burning operations. It also serves to point out the need for further research of synoptic patterns affecting RVN throughout the year. Weather radar appears to us to be a valuable research tool in this connection.

In addition to the synoptic study above, we made measurements of the microclimate inside and outside the jungle canopy. This work was done at Duc Co in the Central Highlands. Of greatest interest here are the air temperature and relative humidity values measured under jungle canopy within six inches of the ground surface. We found that, while relative humidity values occasionally reached minima near 25%, the most common low daily values fell between 34 and 39%. The minimum values usually occurred between the hours of 1330 and 1430 L.S.T. The maximum air temperature here always exceeded 96°F and occasionally exceeded 110°F. The maximum temperature values occurred at about the same time of day as the minimum relative humidity.

A graphic illustration of diurnal variation in relative humidity and temperature shows why incendiary operations should commence as close to 1400 as possible (Fig. 13). Before that time, temperature is rising and relative humidity is falling rapidly. On or about 1400 both are at their optimal point for good burning. Shortly after, a reverse situation occurs and chances for an effective burn are reduced rapidly.

VEGETATION OF SOUTH VIETNAM

The vegetation of Vietnam is far from a homogeneous fuel type. It includes several broad vegetation types, each being a complex mixture of many species in associations that are adapted to specific site conditions. Adding to this complexity are the effects of man's activity--principally the temporary clearing of jungle for shifting agricultural use--which has left the vegetative cover on many areas in a secondary stage of development ranging from open savannah to dense woodland scrub.

A detailed forest map of Vietnam would give the best overall picture of the vegetative cover. Such a map shows the locations of broad vegetation types, such as moist forest, secondary forest, mixtures of the two types, dry Dipterocarpus forest, semi-deciduous forest, pine forest, and tree or shrub savannah. But the burning potentials of forest areas are most variable within a broad type. From aerial reconnaissance in Central Vietnam, it was not possible to assign a single fuel rating to the vegetation on any large block of land within any of these broad forest types.

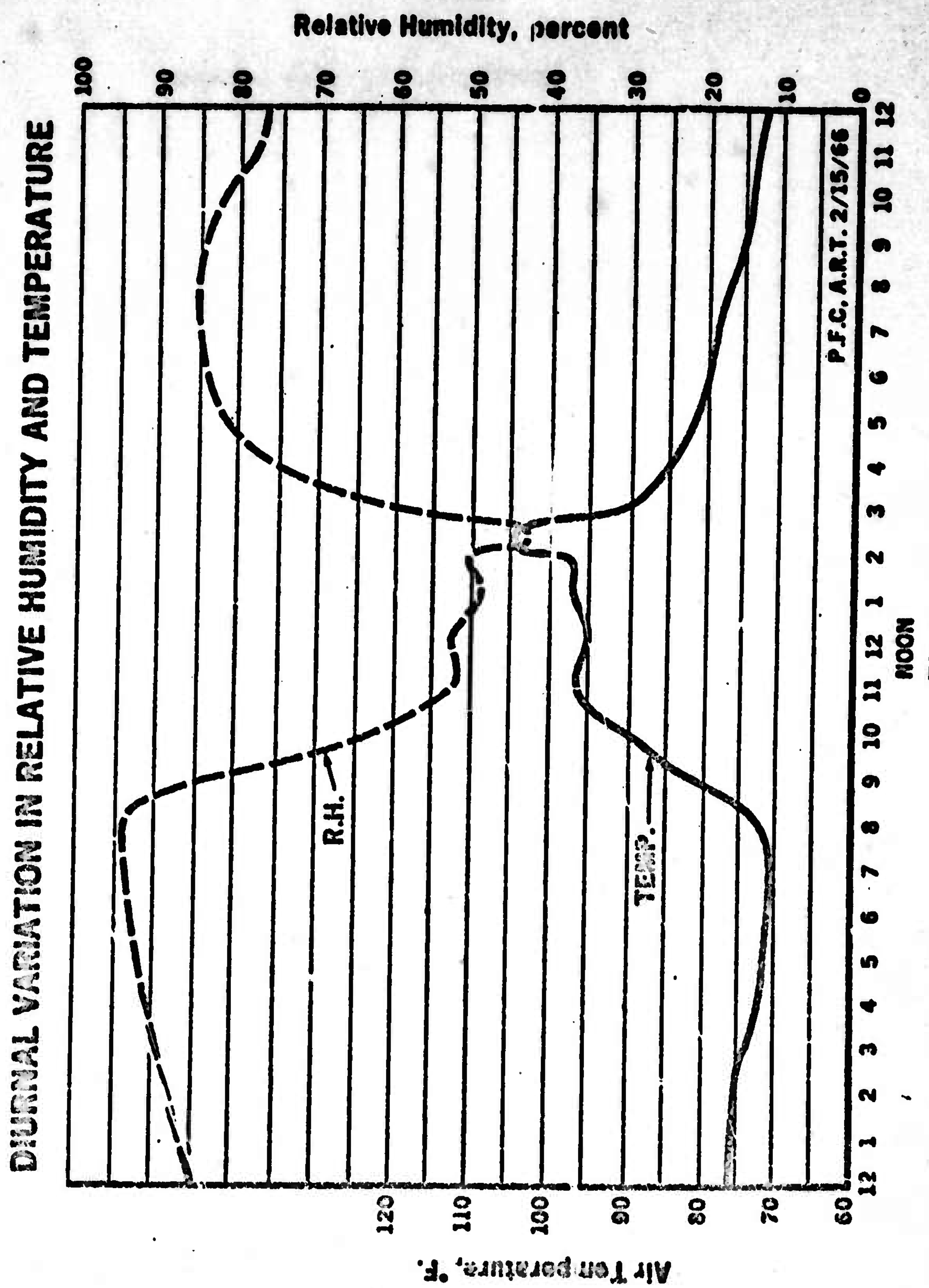

DIURNAL VARIATION IN RELATIVE HUMIDITY AND TEMPERATURE
Relative Humidity, percent
100
90
80
70
60
50
40
30
20
10
0
Air Temperature, °F.
120
110
100
90
80
70
60
12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
NOON
Time
R.H.
TEMP.
P.F.C. A.R.T. 2/15/66

Figure 13

A simplified classification should be used tentatively to describe the vegetative cover on any area considered for burning. The classes are:

1. Dense forest--Typically has a multi-storied canopy dominated by evergreen species.
2. Woodland--Usually has single canopy structure dominated by deciduous species.
3. Intermediate forest--Often is degraded dense forest, but also includes complex mixtures of dense forest and woodland.
4. Woodland scrub--Is an early successional stage after temporary clearing of jungle, with dense shrubby vegatation and varying amounts of tree canopy.
5. Savannah (tree or shrub)--Refers to jungle areas that have been repeatedly cleared, with an herbaceous cover and scattered trees or shrubs.

These general types have been combined as shown in Figure 14.

Classification and evaluation of these broad forest types can best be done from aerial photography, using techniques specially developed for this purpose. But aerial photographs do not provide information on fuel distribution beneath the top canopy. During Phase I we relied on ground observations to obtain this information. In Phase II, remote sensing techniques such as side-looking radar and multi-band sensors will be investigated since opportunities for ground observation in hostile territory are limited.

Possibilities for ground observations in Vietnam during Phase I were too limited for good evaluation of the lower story vegetation--the critical fuel for building and sustaining an effective forest fire. Aerial observation indicated that certain degraded jungle types contain adequate volume of low-growing vegetation to support a fire, and that this vegetation has good horizontal and vertical continuity. The dense, often multi-storied jungle has good horizontal continuity of crowns, but a few ground observations indicate that volume and continuity of burnable ground fuel may be borderline.

Because ground fuel conditions may be marginal, research during Phase II should be concentrated on the lower story vegetation rather than on the upper canopy layers which were of more importance in defoliation studies. Development of the most effective desiccation treatment for these understory shrubs is imperative. The treatment may involve application of more than one herbicide, perhaps in combination, to obtain maximum desiccation of all the plants in the ground cover.


SECRET
PRIMARILY MOIST, DENSE FOREST
MISC. FOREST TYPES
PRIMARILY PINE FORESTS
LOW TREE AND SHRUB TYPES

Aerial observation indicates that one forest type--scrub mangrove--is a poor species for burning. Ground vegetation is lacking, or the trees actually grow in water, and fuel continuity is poor. Fortunately, however, this type can usually be removed adequately by herbicide treatment alone.

FUELS AT DUC CO

Fuel studies were made at a site selected in the Central Highlands about 17 kilometers from the large scale operational trials (Fig. 15). The study site was near the Special Forces A team camp at Duc Co, located on gently rolling terrain at an elevation of approximately 1300 feet.

The jungle vegetation was a degraded moist forest classified as "intermediate forest". It was similar to the cover on parts of the large operational trial area. Structurally, the vegetation resembled a dense hardwood thicket. The overstory (dominant trees) ranged from 20 to 30 meters in height and consisted mainly of species in the Lauraceae family. Litsea lancilimba was a common species. Vines and tree stems with few branches occupied the 10 to 20 meter level. The entire crowns of a few species occurred within this level. The lower level, particularly from the ground to 2 meters, was heavily populated with saplings, shrubs, and vines, but foliage was not exceedingly dense (Fig. 16). Ground litter was composed almost entirely of dead leaves that had dropped during the dry season.

Fuel Treatment

Fuel measurements and critical observations were made on two study areas treated at different times:

1. November area--Sprayed in late November, 1965.
2. January area--Sprayed on January 24, 1966.

The desiccation treatment, which is essential before burning jungle fuels, was the standard "Orange" defoliant applied by aerial spraying. Visual effects of the spraying were:

November area--Most of the vegetation was brown in color when first observed on January 21. When fuel sampling started on February 2, leaf mortality was estimated to be in excess of 95 percent. Approximately 80 percent of the leaves in the upper and middle canopy

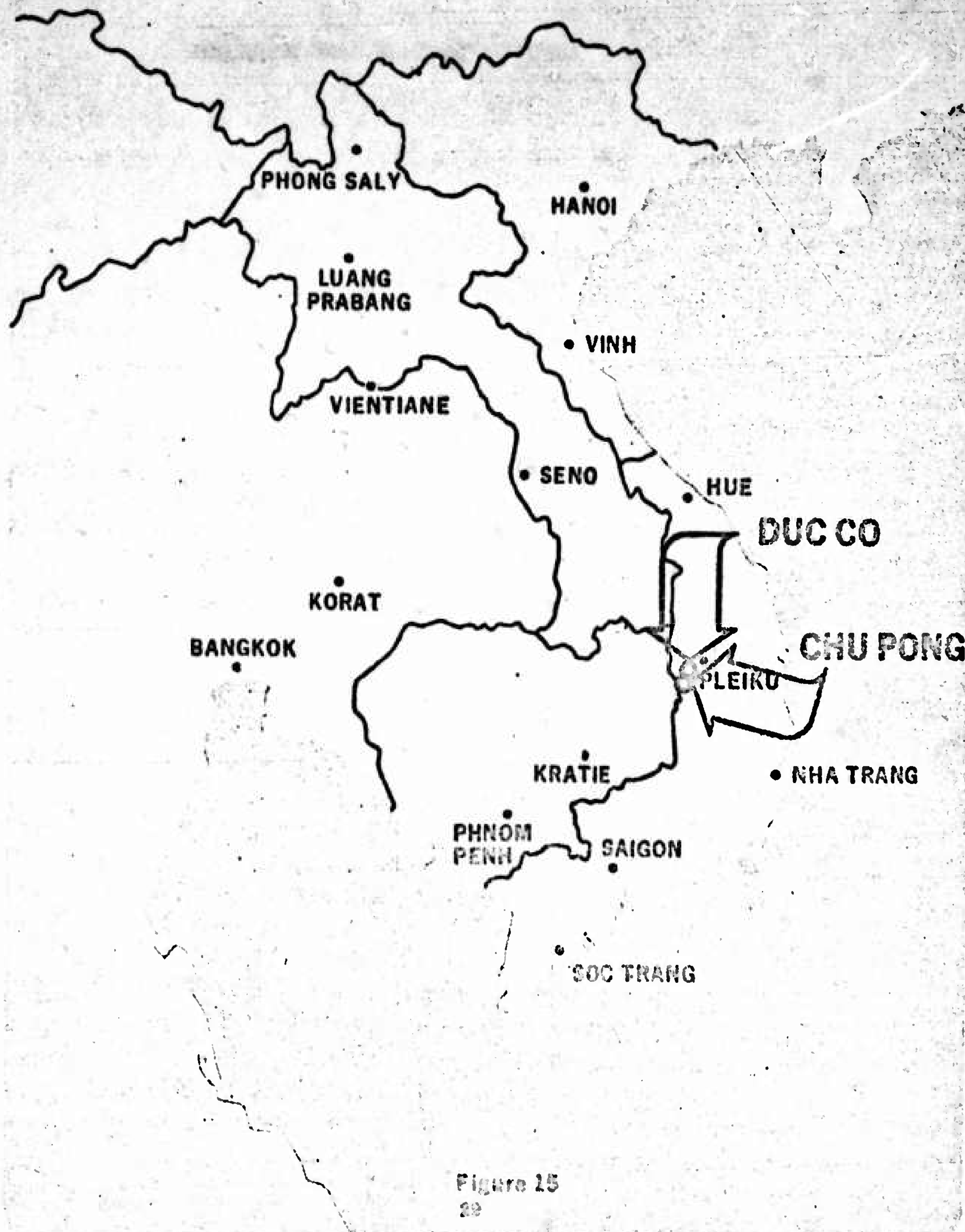

PHONG SALY
HANOI
LUANG
PRABANG
VINH
VIENTIANE
SENO
HUE
DUC CO
KORAT
BANGKOK
CHU PONG
PLEIKU
KRATIE
NHA TRANG
PHNOM
PENH
SAIGON
SOC TRANG

Figure 15

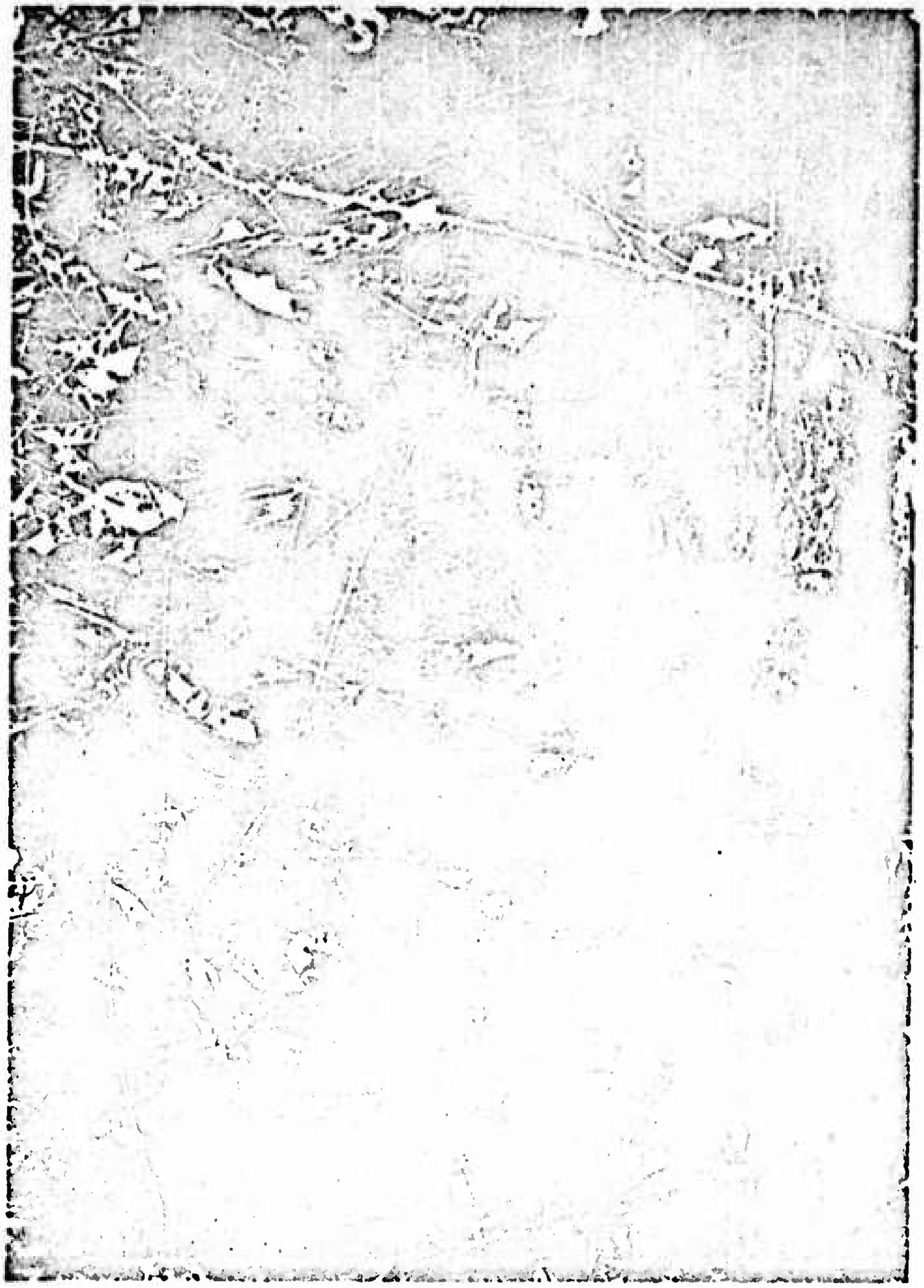


Figure 16

LOWER VEGETATION-DUC CO TEST SITE

layers had fallen. The lower vegetation still held 50 percent of its leafage, which was brown. Only an occasional woody plant remained green and apparently unaffected by the spray treatment (Fig. 17).

The appearance of the vegetation on this area remained about the same until the end of the sampling period, February 25.

January area--Vegetation reaction to the spray treatment was much more limited on this area. The apparent reason was that the treatment was applied after most plant growth had ceased; leaves of deciduous species on nearby areas were already turning brown at the time this area was sprayed.

By February 2, the leaf mortality was estimated at about 40 percent throughout the canopy, with about 10 percent overall leaf fall. By February 25, the estimated leaf mortality increased to 60 percent, and the leaf fall to 20 percent. Many plants in the upper and lower canopy layers remained green and apparently unaffected by the spray treatment (Fig. 17)

Fuel Moisture Content

Measurements of fuel moisture during February provided basic information for better understanding of fuel characteristics in Vietnam jungles.

Moisture samples were taken on 13 days during the period February 2-25. On each sampling sortie, a sample of fuel components was taken at each of two sampling plots in the two treatment areas. Vegetation on sampling plots was selected as being typical of the area as a whole. The components selected for sampling in each plot also were typical for the plot.

Fuel components sampled on each plot were:

1. Dry leaf litter--This litter included the full depth of the leaf layer made up by brown leaves from the current leaf crop.
2. Dead attached leaves--These were the current brown leaves still attached to the stems within easy reach.
3. "Dead" twigs--These twigs, approximately 1/2 inch in diameter, were the twigs with dead leaves or from which the leaves had recently dropped.

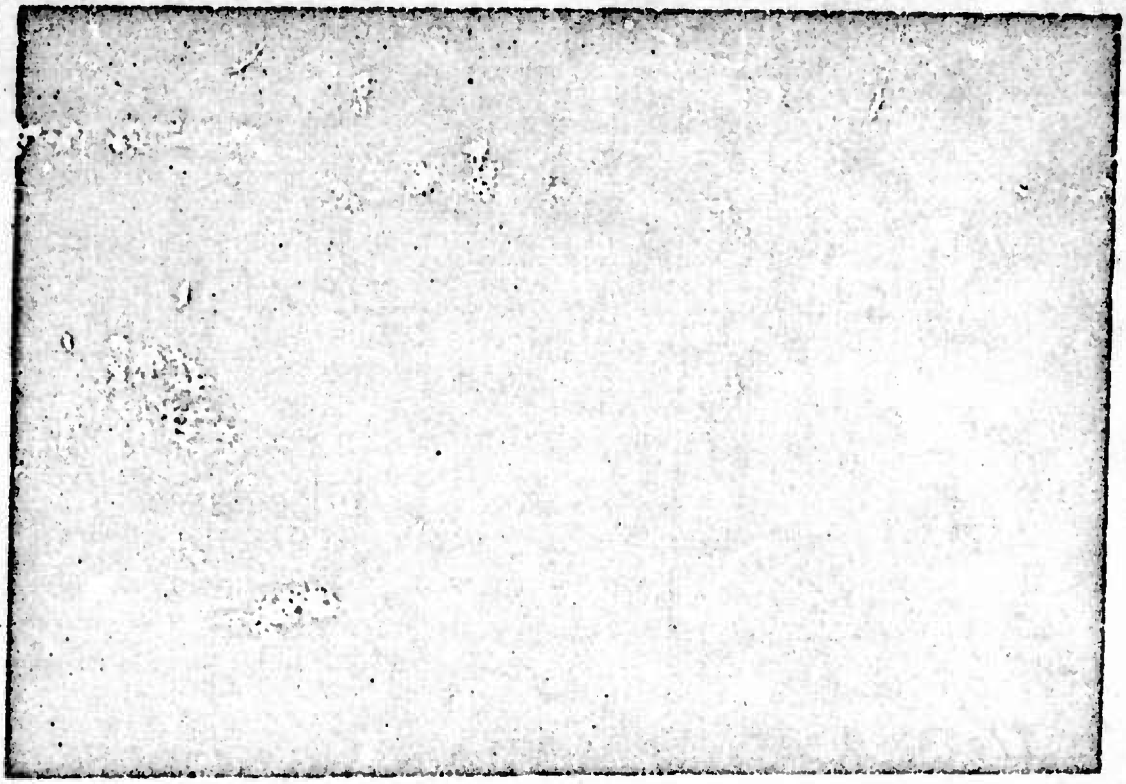


Figure 17

NOVEMBER AND JANUARY SPRAY AREAS
DUC CO TEST SITE

4. Green attached leaves (sampled only on the March-sprayed area)--These green leaves were apparently unaffected by the spray treatment.

5. "Live" twigs (only on March area)--These twigs of 1/2-inch diameter were from branches apparently unaffected by the spray.

A few samples were taken from the outer tissues of the stems of both "dead" and "live" trees.

Most samples (210 out of 242) were collected between the hours of 1200-1430 to tie down the range in moisture content during the part of the day recommended for conducting incendiary operations. The other samples were taken at approximately 0900 and 1700 on February 21 to determine the rate of drying after a thunder shower during the previous evening. A total of 242 bags of samples were collected to provide, as far as possible, the necessary data on fuel moisture content (Fig. 18).

Each sample was weighed soon after collection in the field. Later it was dried in an oven at 100°C until it reached constant weight. The moisture content was calculated as a percentage of oven dry weight (ODW). For example, a sample with a field weight of 50 grams and an ODW of 25 grams was considered to have a 100 percent moisture content in the field $\left\{\frac{50-25}{25} \times 100 = 100\%\right\}$. Checks of sample weights by xylene distillation showed that satisfactory determinations were obtained by the oven drying technique.

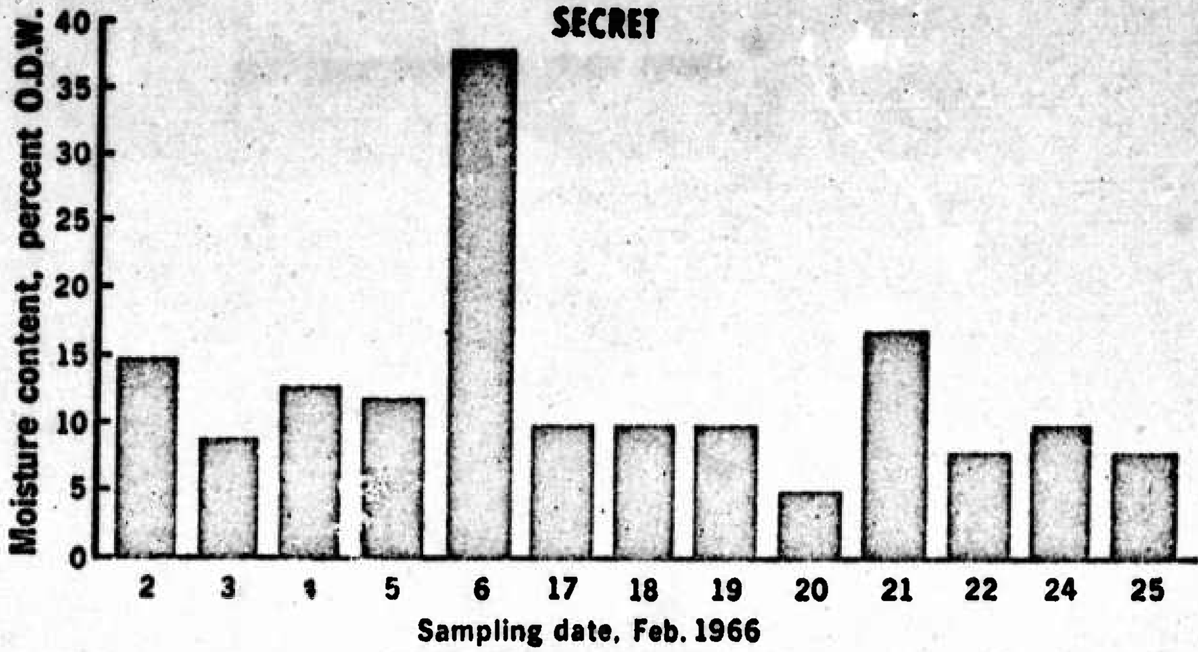
Litter and Dead Attached Leaves

The data show no marked trends in moisture content of the dead leaf litter and the dead attached leaves (figs 19 and 20). During the middle of the day, for all rain-free days preceded by a dry day, the moisture contents of most samples were between 7 and 15 percent. For days preceded by light rains the moisture contents ranged from 17 to 37 percent. The leaf litter averaged 10.0 percent for the November area and 12.7 for the January area. For the attached dead leaves the figures were 12.2 percent for the November area and 10.0 percent for the January area. Differences between areas may have been caused by sampling error, although observations indicated that moisture content of litter on the January area could well have been higher because of greater shading from green tree canopy.

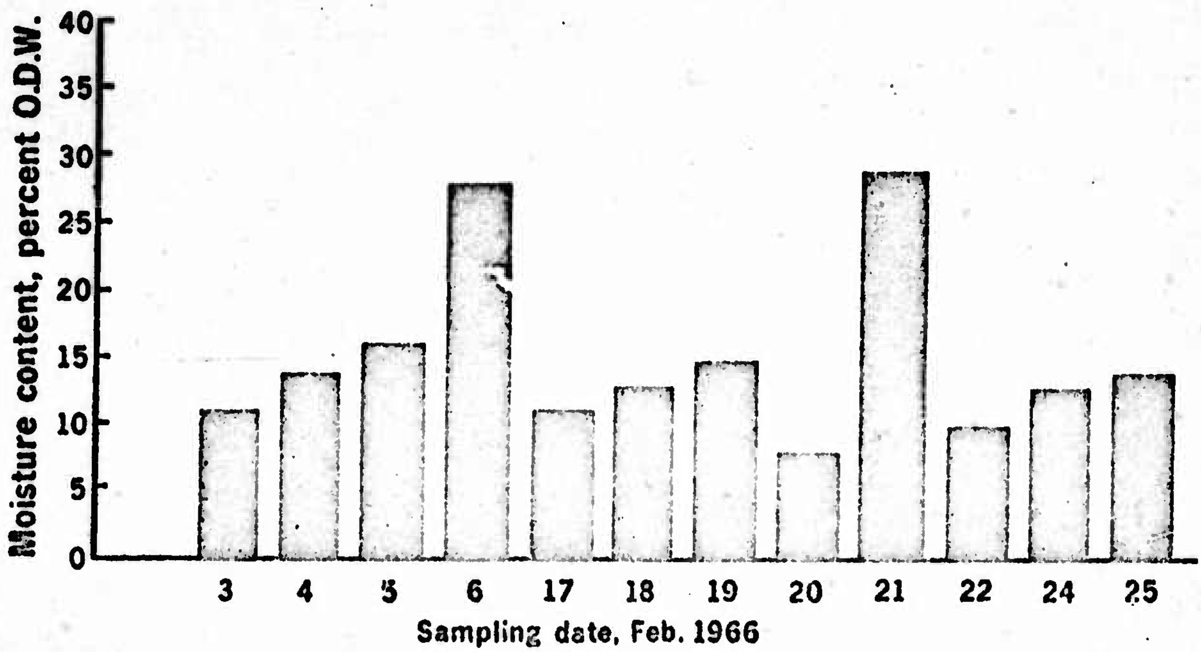
The above results have important implications in conducting incendiary operations in the Central Highlands. They show that dead leaf fuel, either attached to the trees or in the ground litter, reached a low moisture content soon after they turned brown. Extending the drying

Figure 18

LITTER COLLECTION FOR MOISTURE CONTENT DETERMINATION



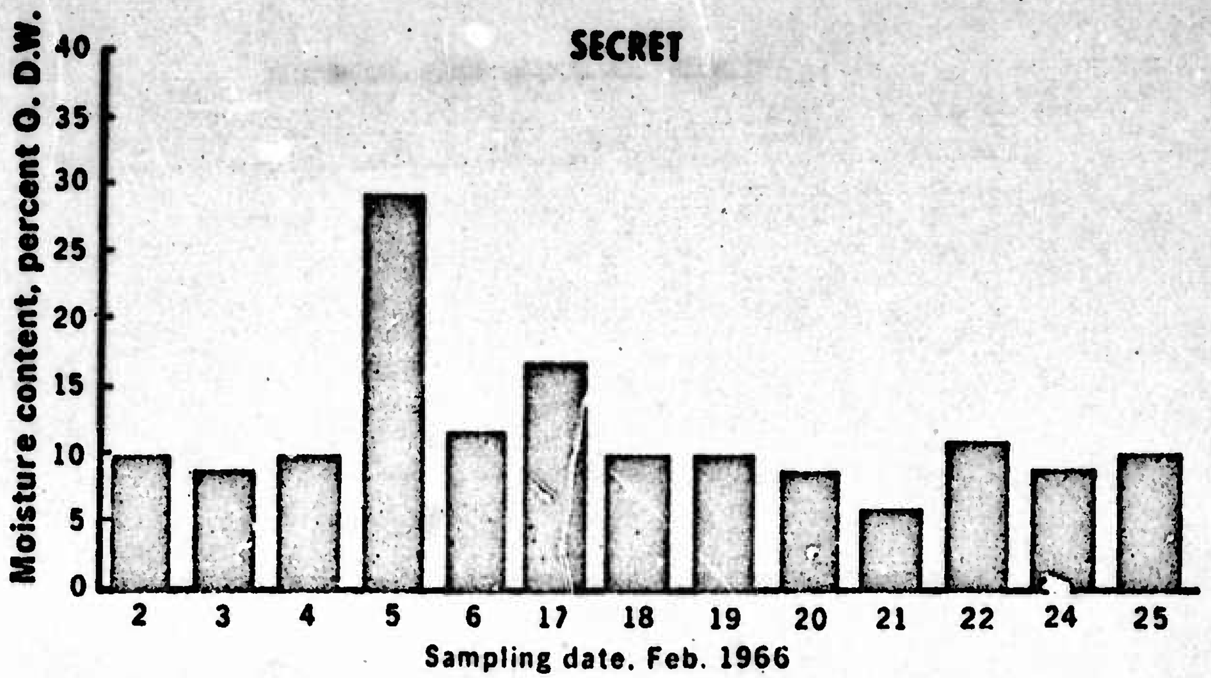
NOVEMBER TREATMENT



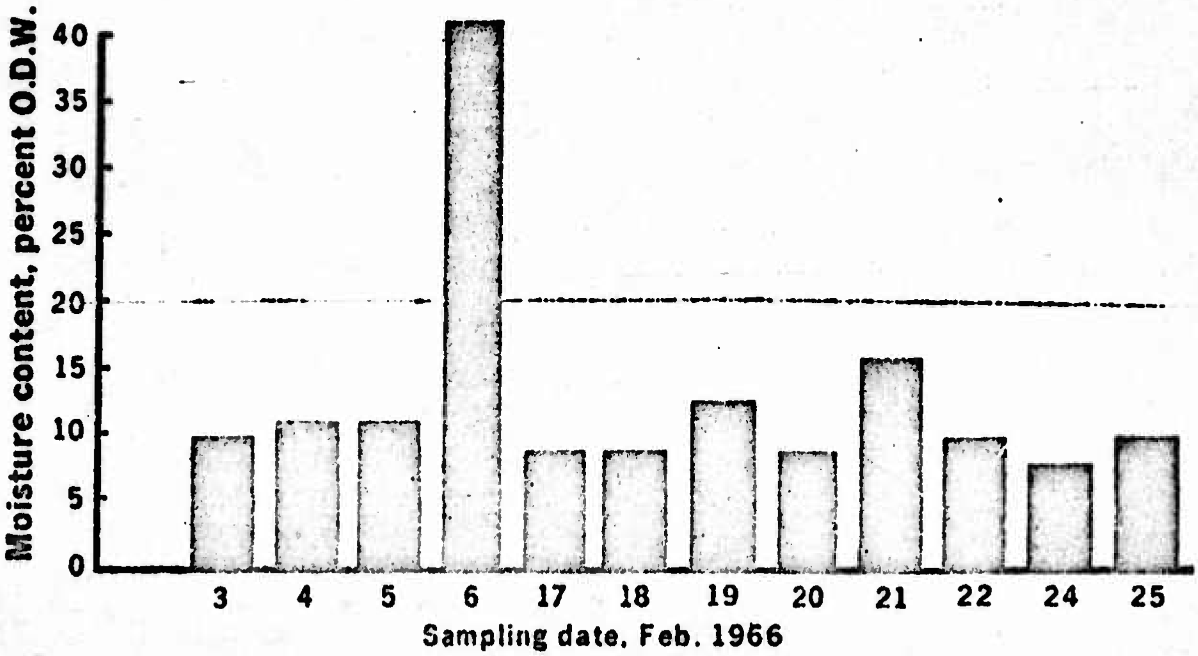
JANUARY TREATMENT

Figure 19

MOISTURE CONTENT OF DEAD LEAF LITTER ON TWO TREATED AREAS



NOVEMBER TREATMENT



JANUARY TREATMENT

Figure 20

MOISTURE CONTENT OF DE... TTACHED LEAVES ON TWO TREATED AREAS

period through February did not materially lower their moisture content. This indicates, as far as leaf fuel is concerned, that an incendiary operation can be carried on early in the dry season, provided that a prior desiccation treatment has effectively deadened the leafage.

Samples taken on days following a rain shower showed a much quicker drying of leaf litter and attached dead leaves than was expected. After a heavy shower of .27 inch, the moisture content dropped rapidly the next day between the hours of 0900 and 1700 and down to normal by the second day (fig. 21).

These results have important application in modifying the specifications for burning jungle fuels. For example, the 1966 requirements, which specified 2 drying days as being required after a light rain and 5 days after a heavy rain, can now be lowered to 1 and 3 drying days, respectively. A light rain can be redefined as one with less than .20 inch of rain instead of .10 inch as defined in 1966. These changes in specifications will add materially to the number of days considered favorable for burning at any given location.

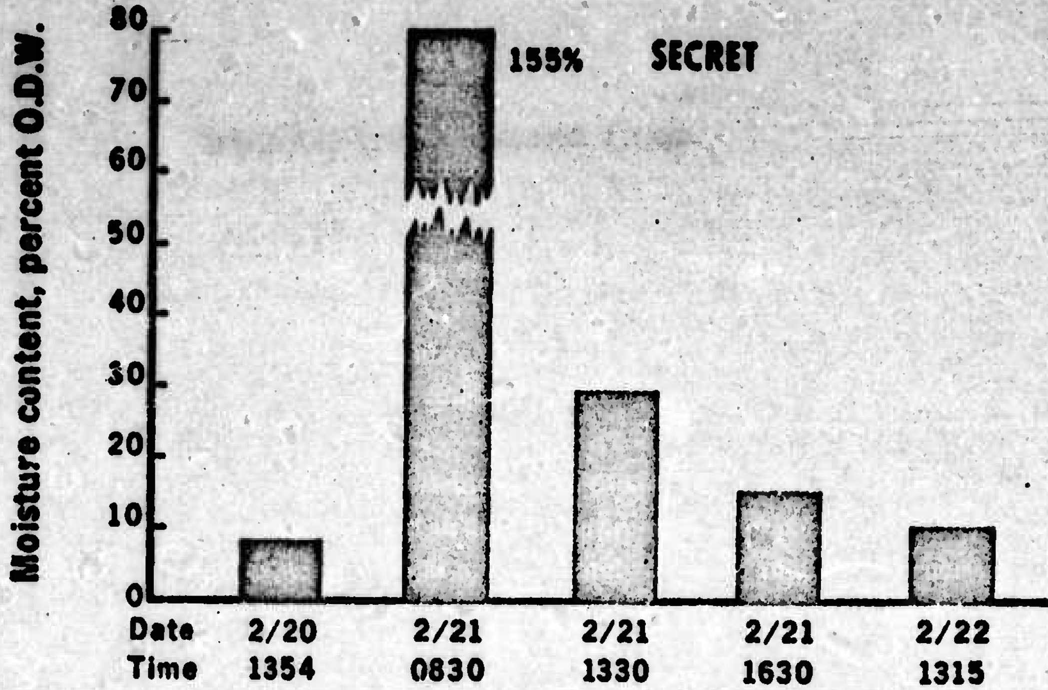
"Dead" Twigs

The level of moisture content in so-called dead twigs and the trend in moisture through the sampling period were not so clear cut as for leaf litter and dead attached leaves. Moisture contents of individual twig samples differed greatly throughout the sampling period. This variation occurred in both the November-treated area and the January-treated area.

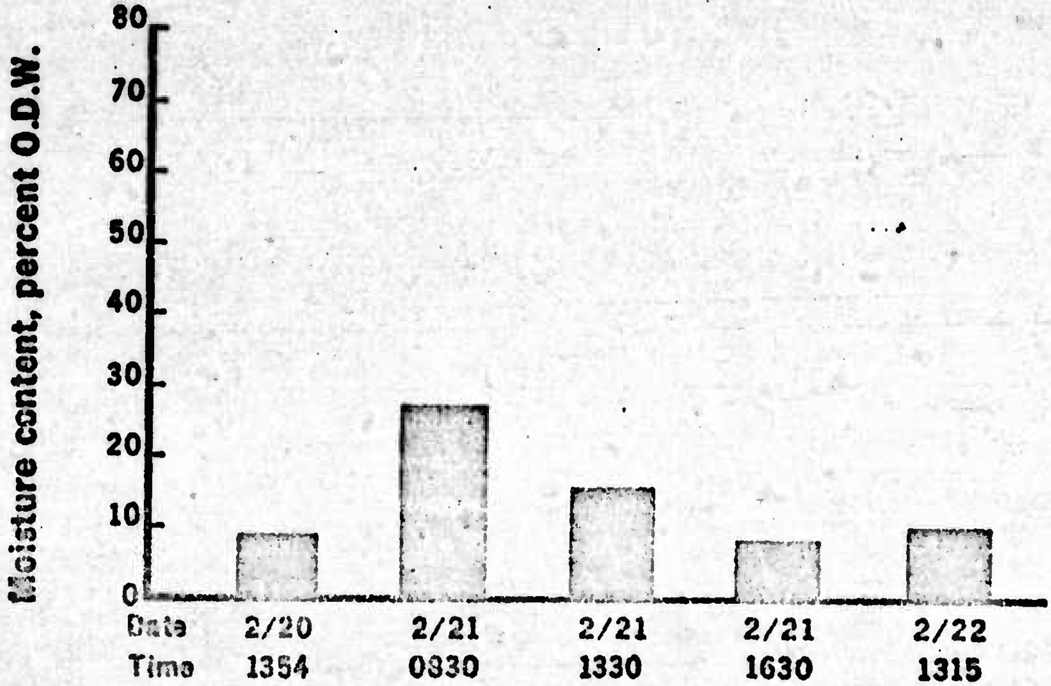
Most samples showed a high moisture content for the 1/2-inch twigs that had dead leaves. The average of all samples on rain-free days in the November area was 85.9 percent moisture content; in the January area the average was 81.4 percent. These moisture contents indicate that most of the twigs were not actually dead even though the leaves had turned brown and may have dropped from the twigs.

However, many of the "dead" twig samples on both areas showed low moisture contents. Out of a total of 50 samples, 11 samples had moisture contents of only 13 to 30 percent. The reason for these low moisture levels was not determined; the samples may have been collected from plants that were killed by the spray treatment. The study was not designed to determine the proportion of total twig volume with low moisture content.

Regardless of the apparent great variation in twig moisture, the results show conclusively that average moisture content of this important fine fuel constituent is well above



LITTER



ATTACHED LEAVES (DEAD)

Figure 21

MOISTURE CONTENT CHANGES OF DEAD LEAF MATERIAL FOLLOWING A RAIN SHOWER

January Spray Area-Duc Co Test Site

the 20 to 40 percent level required for ignition and efficient combustion. This is particularly important since twigs comprise the bulk of the fine fuel in the understory shrub layer where forest fire ignition takes place (Fig. 22). Obviously, one of the most pressing research problems in Phase II is development of desiccation treatments that will bring the moisture content of twigs down to the lowest possible level.

The trend in moisture content of twigs during February on each area was confused by the variations between samples. Using all samples in each area, the results do not show definite trends in twig moisture through the sampling period. If the samples with low moisture content (13 to 30 percent) are removed from the data, the remaining samples in both areas show increases through the entire sampling period for moisture content of "dead" twigs (fig. 23). The reasons for such an increase in moisture content are not apparent. But the data do present one more reason for intensification of research on the problem of twig desiccation.

Green Leaves and Twigs

All the samples taken from living green trees in the area sprayed in March had high moisture content throughout the entire sampling period (fig. 24). These data show that all the vegetation on any forest area to be burned must be effectively desiccated ahead of burning. If appreciable green vegetation remains, it will add excess moisture to the combustion system and will materially lower the intensity of any fire occurring in the area.

Fuel Structure and Flammability

The lower level vegetation at Duc Co did not have the desired vertical continuity at the end of February (fig. 25). Dry leaves, the most combustible of the fine fuels, mainly had dropped from the branches. This thin layer of new leaf litter provided the bulk of the dry fuel, with only sparse dry leafage remaining in the lower level vegetation. The nearly bare stems of vines, shrubs, and saplings, which were not readily ignited, were also too widely spaced for ready burning.

Working conditions did not allow the intensive sampling required to determine volume of dry fuel at each vegetation level. Collection of a few square-foot samples indicated that the litter averaged about 3 tons dry weight per acre.

Burning of small plots periodically during the fuel sampling period showed low flammability of the litter. Dry leaf litter, loosely stacked to a depth of a few inches on an area of 4

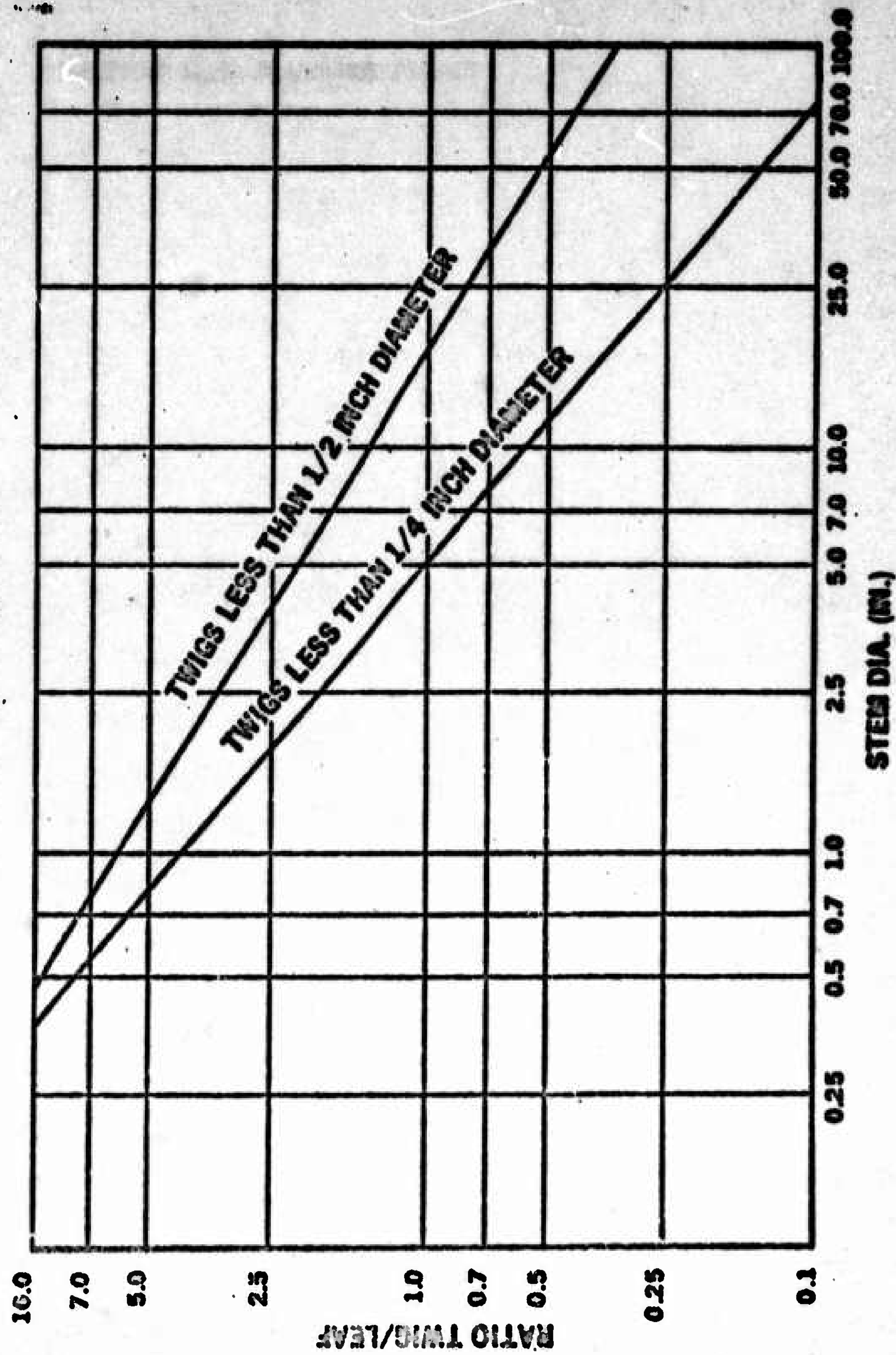
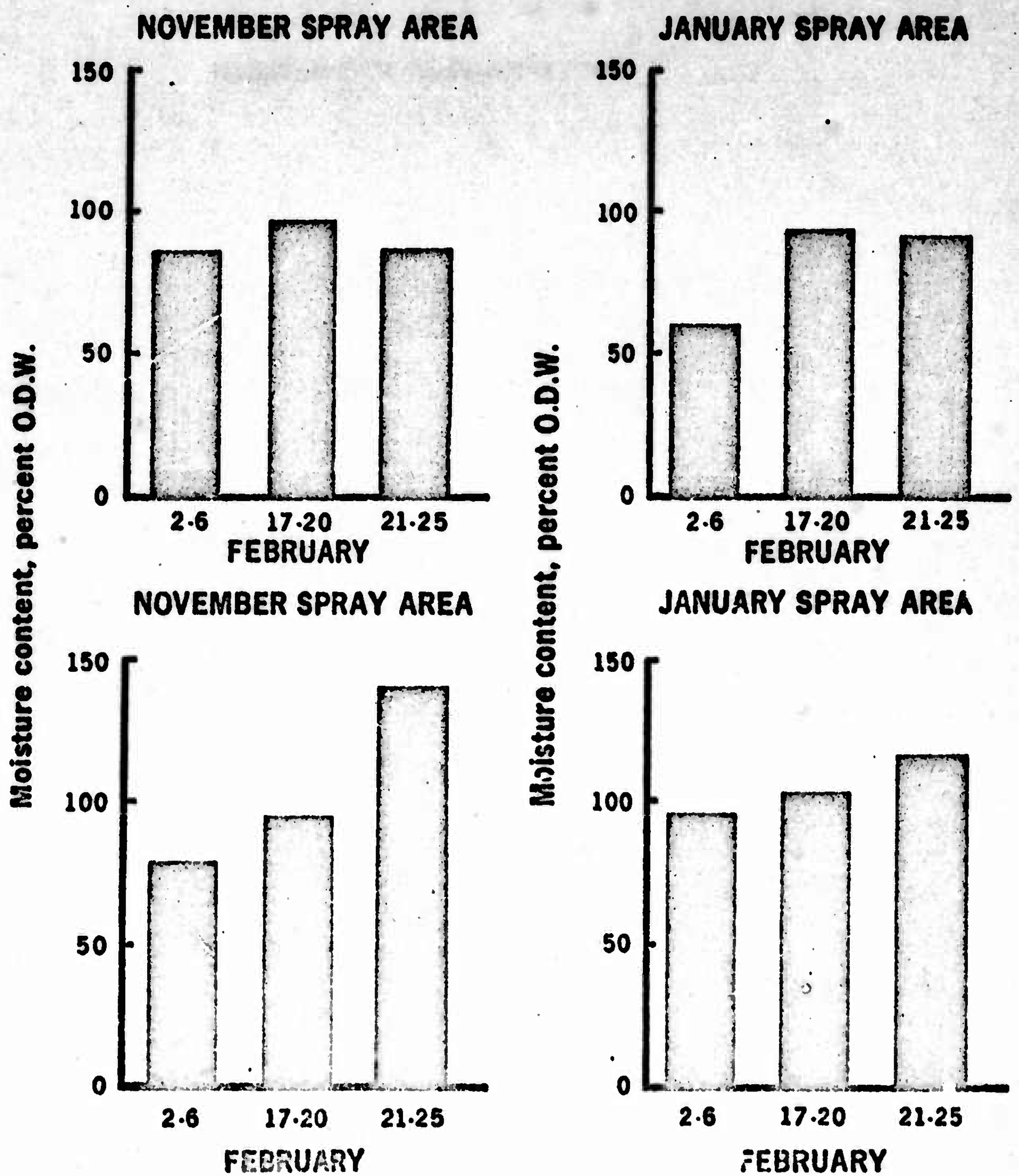


Figure 22
TWIG/LEAF RATIOS

(No Samples Excluded)



(Low Moisture Content Samples Excluded)

Figure 23

MOISTURE CONTENT OF "DEAD" TWIGS

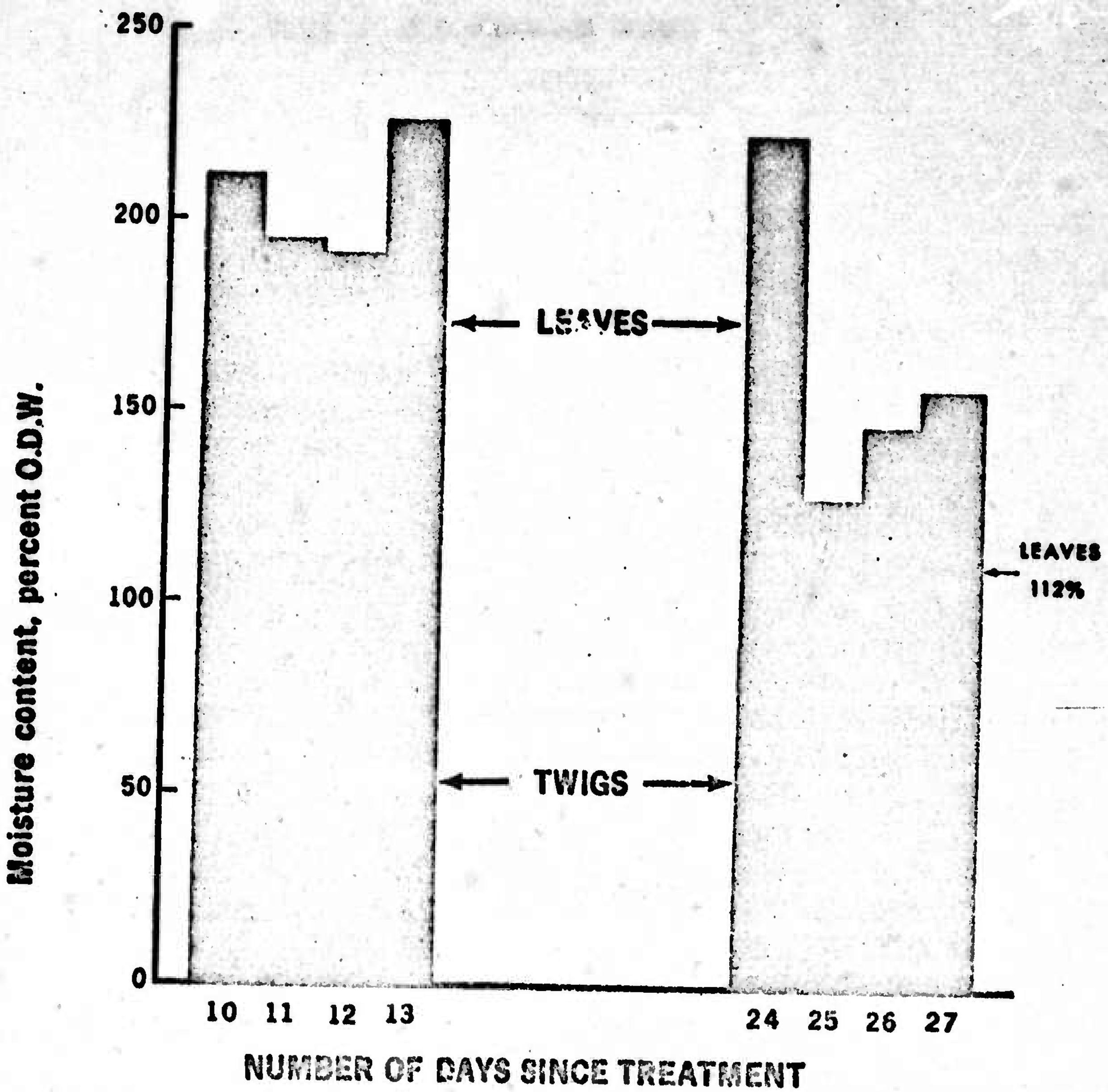


Figure 24

MOISTURE CONTENT OF ATTACHED GREEN LEAVES AND TWIGS

January Spray Area

Figure 25

NOVEMBER SPRAY AREA-DUC CO TEST SITE
POOR VERTICAL CONTINUITY OF LOWER VEGETATION

square feet, failed to produce an intense fire when ignited. Flame height was short, burning rate was slow, and heat release rate was appreciably less than for common forest fuels in the United States. The leaves remained intact after being burned; their black color indicated incomplete combustion.

The same general flammability characteristics were observed during a test of ignition and fire build up on February 26. This test, conducted on the area sprayed in November, involved simultaneous ignition of 32 sets spaced 100 - 200 feet apart. Each set consisted of 1/2 gallon of thickened gasoline spread over a space about 10 feet in diameter (Fig. 26).

Although weather was most favorable, the 32 fires burned slowly and did not reinforce one another during the limited fire build up. After two hours none of the fires had merged with another; many had died after traveling only short distances. The remaining fires traveled slowly and burned the ground litter on several acres during the next few days.

Ignition points in this test were obviously too widely spaced for building an intense fire under the prevailing fuel conditions. Vertical continuity was also inadequate to carry low intensity fire into the tree crowns. But low fuel flammability also appeared to be a major factor in limiting fire behavior.

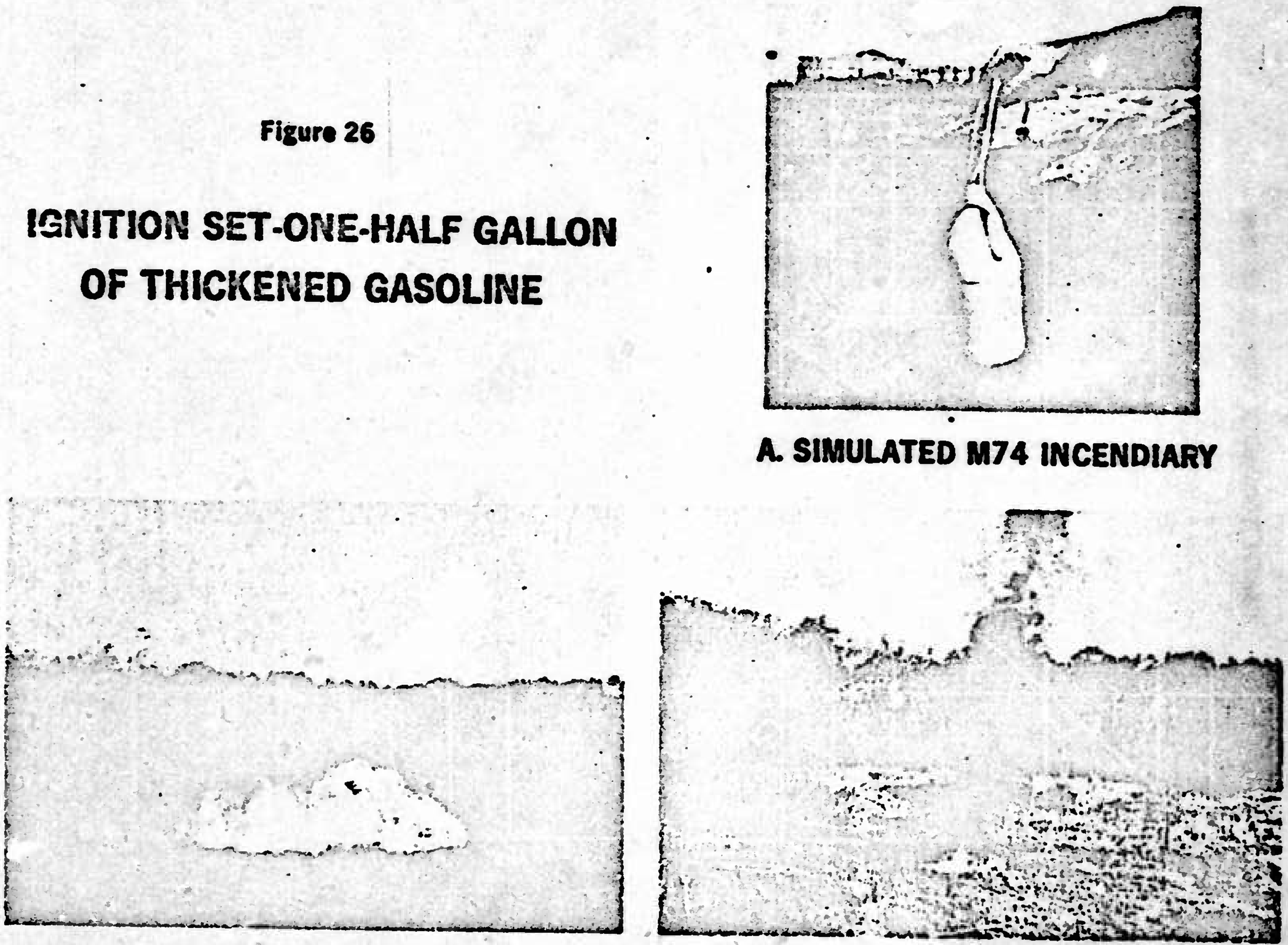
Preliminary tests of certain ignition and combustion characteristics of the Duc Co fuels have been made in the laboratory, using samples that had been oven dried in Saigon. The measurements of leaf samples from Vietnam were compared with concurrent measurements of ponderosa pine needles--a standard laboratory fuel in the United States. The procedures used, and a complete listing of data is shown in Appendix B, Volume II.

The tests did not show that initial ignition time for dried leaves from jungle vegetation was necessarily different than for the pine needles. Inconsistencies occurred in pilot ignition delay between leaves collected while green compared to leaves collected after they had dried. It is likely that the oven drying process resulted in loss of some volatile constituents. These results will be checked with samples that have not been oven dried before ignition.

A laboratory combustion test did show a low energy release rate for the jungle leaves as compared to the pine needles. Leaf fuelbeds paired with needle fuelbeds of comparable density showed relative releases in terms of BTU per square foot per minute as follows:

Figure 26

IGNITION SET-ONE-HALF GALLON OF THICKENED GASOLINE



A. SIMULATED M74 INCENDIARY

B. IGNITION

C. FIRE REMAINING AFTER 3 MINUTES

Leaves collected when dead --

7 out of 8 less than pine needles, with average of 72 percent as great.

Leaves collected while green --

6 out of 7 less than pine needles, with average of 80 percent as great.

Flame heights of leaf samples previously oven dried were in all cases lower than for the paired needle sample, averaging only 58 percent as high.

Ash content of jungle leaves was significantly greater than for pine needles, averaging 6.92 for leaves and 4.01 for pine needles, on an oven dry basis.

Determination of chemical and physical properties and their effects on burning of forest fuels should be greatly expanded in the Phase II research. Basic information on flammability and energy release is needed for specifying ignition patterns and predicting fire behavior in incendiary operations.

IGNITION PATTERN AND FIRE BEHAVIOR

A target of military interest was selected for the operational trial of forest incendiarism. The specified area included 21 square kilometers on the Chu Pong mountain complex in Pleiku Province (fig. 27).

Most of the area was sprayed with Orange defoliant between January 24 and February 6, 1966. Reaction of the herbicide applied at this time of year was greatly delayed. Additional defoliant (Blue) was added on February 22 and 23 in an attempt to obtain maximum possible fuel desiccation. This defoliant covered a critical corner and some of the greenest patches of forest within the original area and included additional area outside the western boundary. Bombing boxes were adjusted to include the newly sprayed area.

The initial date for burning was postponed until March 3 to allow time for desiccation of the fuel. By that time, portions of the area sprayed with Orange had turned brown, but little effect was apparent from the Blue application. Rain forced cancellation of the initial date.

The area was fired on March 11, 1966. Between 1400 and 1420, fifteen B-52 aircraft dropped 255 M-35 incendiary clusters on the target area. This firing was followed after 1430 by 11 napalm sorties (6 F-4 and 5 F-100) along the upwind side of the target area.

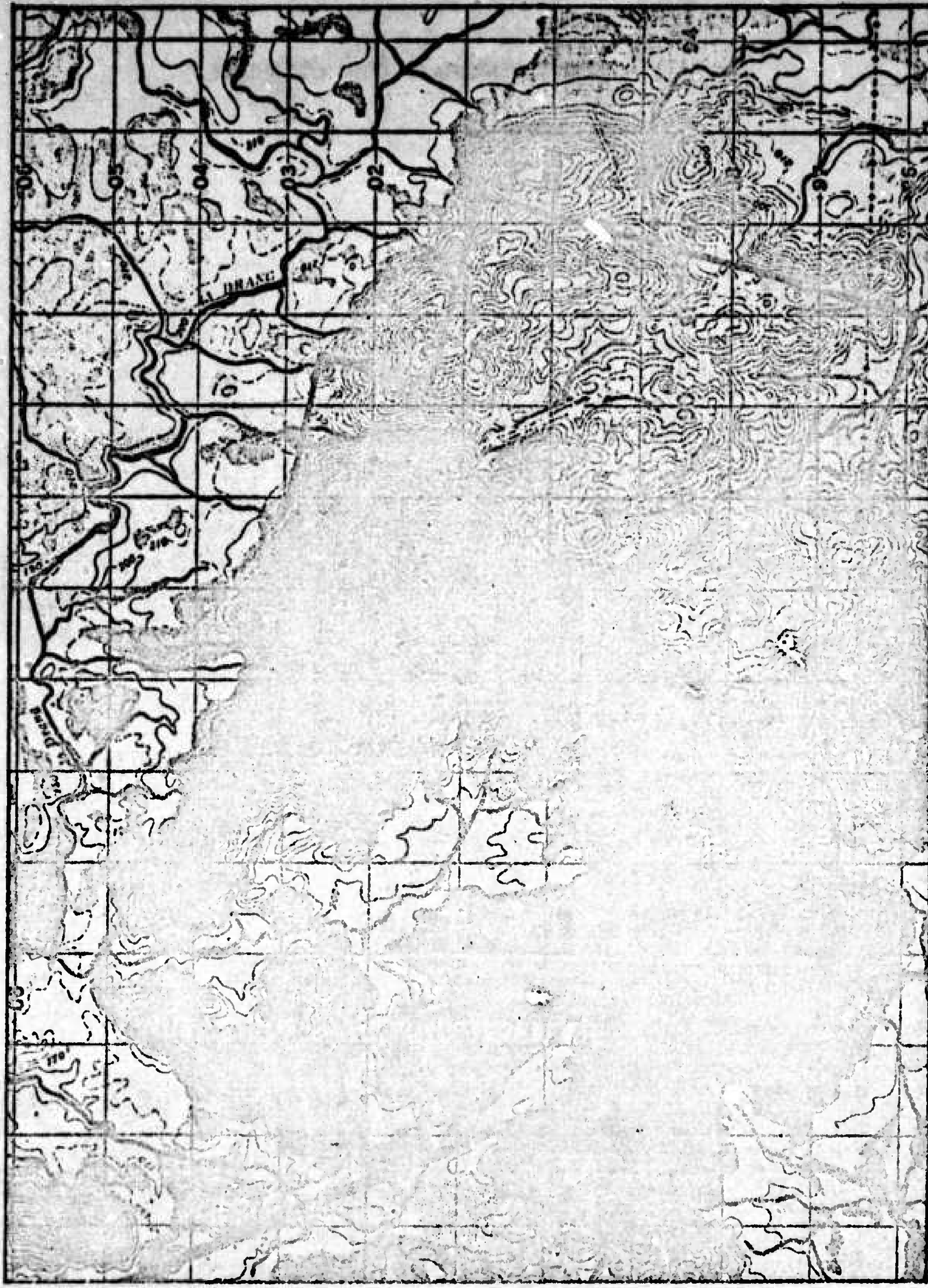


Figure 27

The ordnance requirements for this mission were based on formulas developed by the Dikewood Corporation for predicting firestorm formation in cities. Modifications and technical input data required to adapt the formula to Vietnamese forest conditions were supplied by the Forest Service. Details of the rationale are contained in Appendix C, Volume II.

The calculations predicted that firestorm formation would occur only if coalescense of fires occurred in 60 minutes, or less, and if indraft velocities of 35 m.p.h., or higher, were reached within 30 minutes of ignition. With the fuel conditions assumed for Chu Pong, an average spacing of 145 feet between initial sets would be required for firestorm production on a 65 square kilometer area, using the M-74 bomblet in the M-35 configuration. For the 21 square kilometer area finally selected, the spacing requirement was 125 feet.

But the spacing requirement would be relatively insensitive to bomb size. For example, the required spacing for 65 square kilometers would be 210 feet for 500-pound napalm bombs to get the same firestorm effect. This means that 29 such napalm bombs would be required to equal one M-35 cluster that weighs only 750 pounds.

In the Chu Pong operation, many of the initial fires merged and developed a strong convection column reaching to 22,000 feet, with assumed strong indrafts, within the prescribed length of time (fig. 28). But flames did not carry through the tree canopies to produce the desired firestorm. Even so, the total reaction appeared to be only slightly short of this goal.

It is likely that the input data on volume of fuel and its characteristics were in error, and that the basic formula is still applicable to forest incendiary operations.

For fuel conditions at Chu Pong, which were somewhat less favorable than predicted, the calculated 125 feet for overall average spacing of sets was too great. Examination of the post strike photos, as well as the movies taken during the operation, show that fully effective burning did occur in certain "bombing strips" where concentration of bomblets appeared to be greater than one per 90-foot spacing (fig. 29).

Proper calculations of required ignition patterns are vital in planning incendiary operations. The number of any incendiary ordnance required to ignite an area will vary as the square of the reciprocal of the spacing. In other words, if spacing distance between sets is cut in half, the ordnance requirement will be increased four times. For this reason, investigation of ignition pattern requirements will be intensified during the Phase II research. Included in the study will be a sensitivity analysis of the Dikewood equations.

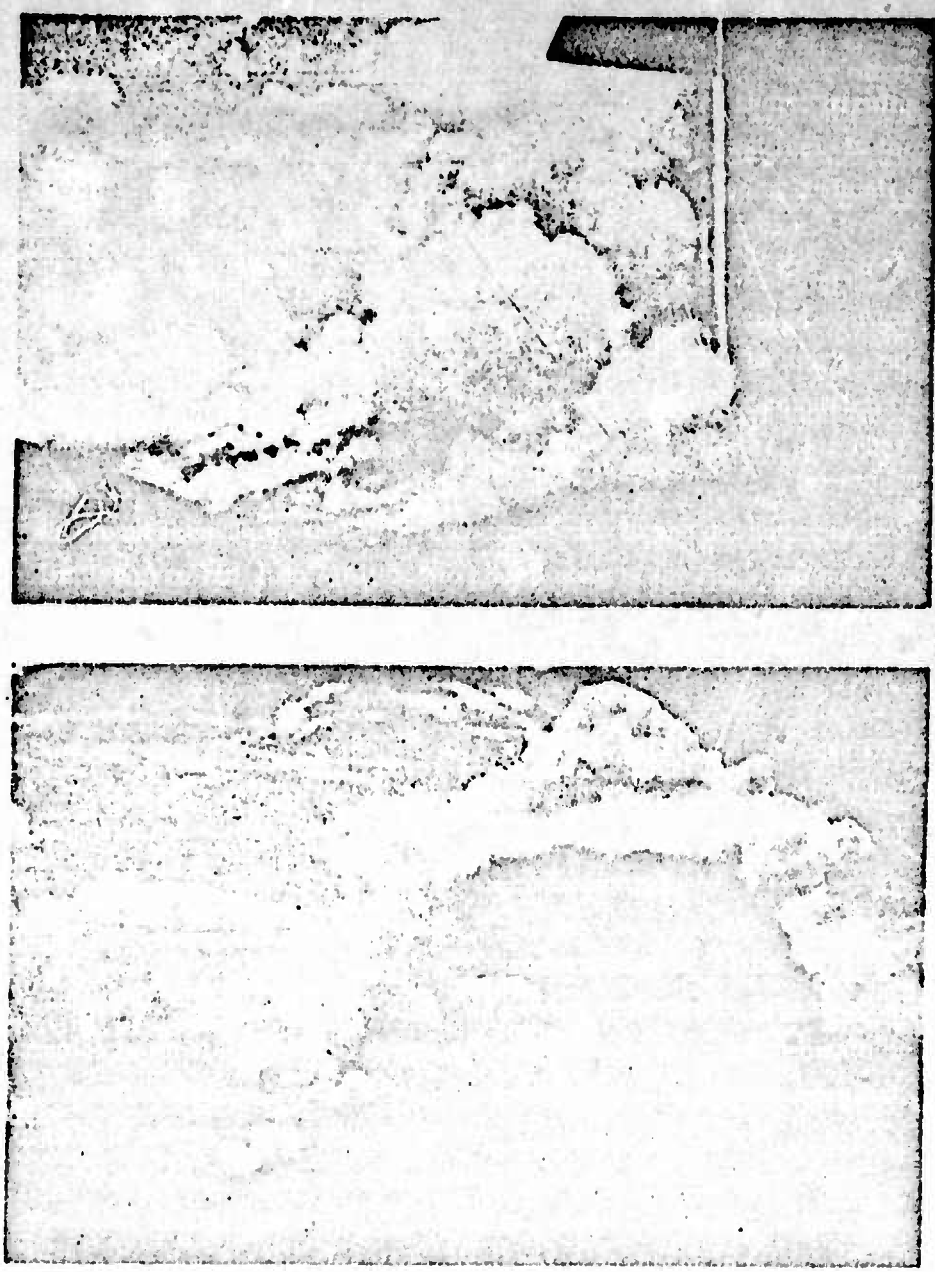


Figure 28

THE CONVECTION COLUMN REACHED 22,000 FEET WITHIN 30 MINUTES

Figure 29

INCENDIARIES TENDED TO CLUSTER IN STRIPS

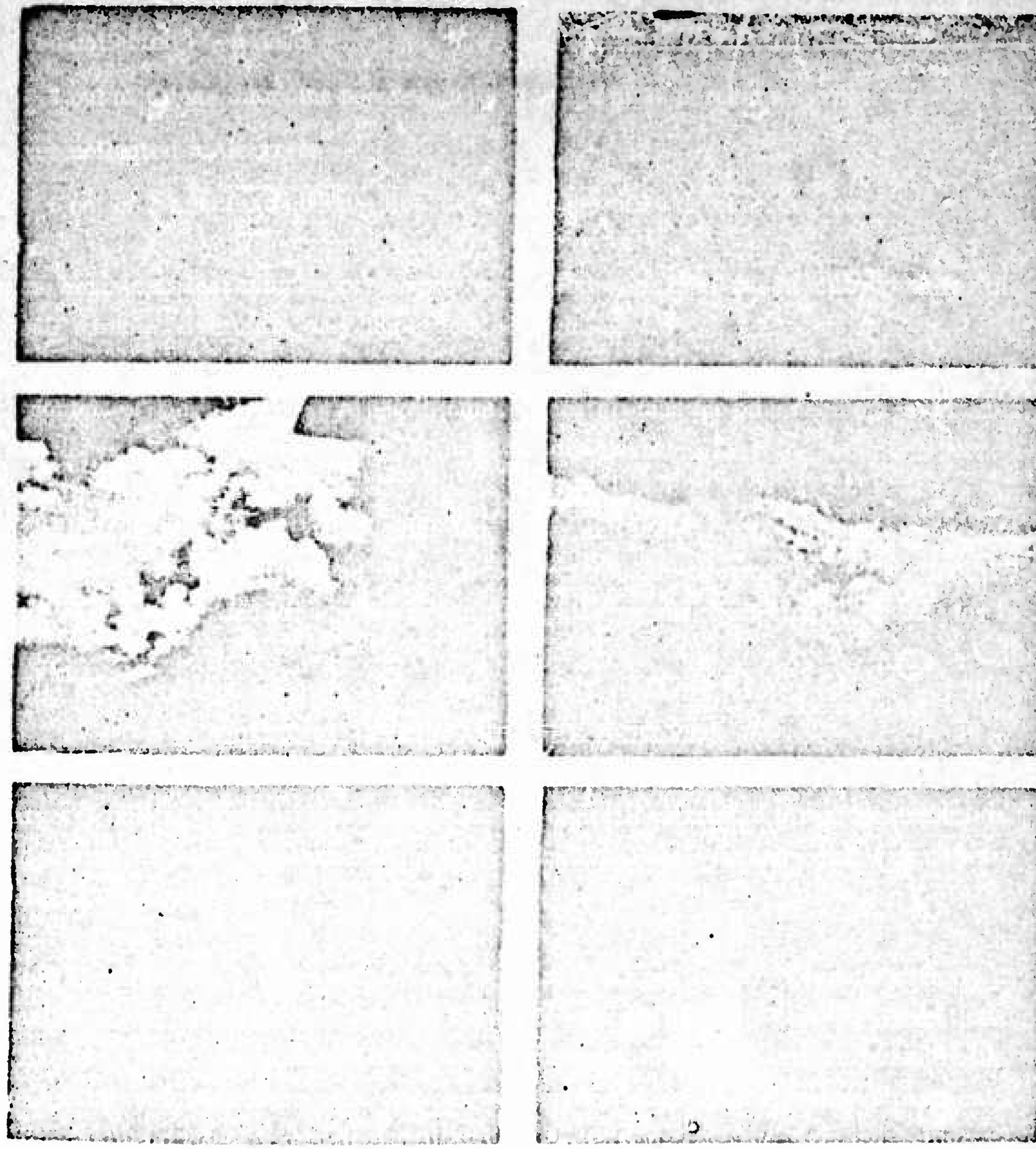


Figure 30

CHU PONG OPERATIONAL TEST
1400-1430 HOURS 11 MARCH, 1966

OPERATIONAL GUIDELINES--1966-67

FOREST INCENDIARY OPERATIONS IN SOUTH VIETNAM

Procedures

1. Conduct the incendiary operations within the portion of Vietnam that has little or no rainfall during the NE monsoon season.

2. Apply herbicidal spray to desiccate the fine fuels before burning.

The standard Orange desiccant is recommended. Apply it after tree leaves are fully formed, but while leaf and twig tissues are still tender. Best spraying date probably is in late October or early November.

3. Make a trial of double spraying on at least one area, or a portion of a large area. On an area already sprayed with Orange, apply a quick-acting herbicide such as Black. The purpose is to desiccate those ground level species that are not susceptible to Orange. Apply the second spray about 10 days before the planned burning date.

4. Select a date and hour for TOT. Burning in early January at hour 1400 is suggested. The date should be at least 4 weeks after the Orange spray has been applied; delay setting the date until all leafage has turned brown. Attempt to burn before natural leaf fall of deciduous plants has started, which probably will be February 1, or earlier.

Attempt to select the planned target date to coincide with favorable burning days within a short-term weather cycle, if such cycles can be identified by the forecasting experts. This will allow firmer 48-hour forecasts, and it will give more assurance that the weather will be favorable on the planned date.

If operationally feasible, make the final selection of target date only 4 to 6 days ahead. This will allow better fit within weather cycles.

Also, if operationally feasible, set up a sliding date that can be changed, if necessary, at 48-hour intervals.

5. Make daily forecasts of the expected weather at 1400 for each target area. Start forecasts a few weeks preceding the expected date of burning.

6. Start both 24-hour and 48-hour forecasts three days before the planned date of burning. If the last 24-hour forecast is favorable, make forecasts at 18, 12, and 8 hours ahead of TOT.

The forecasts should include information on precipitation, air temperature, relative humidity, cloud cover, wind, and stability expected at 1400.

7. Mount an aerial weather watch during daylight hours, starting 4 days before the planned date of burning.

Each watch should report indications of precipitation, or lack of it, since the preceding watch; also report precipitation at the time, cloud cover, and wind.

8. Postpone the date of burning if rains occur on the target area immediately ahead of the planned target date. The new requirements for drying days after a rain are:

Light rain (less than 0.2 inch)-- 1 drying day.

Heavy rain (more than 0.2 inch)-- 3 drying days.

A drying day is defined as one in which fuel moisture content will decrease, finally down to equilibrium level. Specifications for a drying day are:

(1) No rain has fallen in the preceding 24 hours.

(2) Minimum relative humidity drops below 70 percent.

(3) Afternoon cloud cover is less than 3/8.

9. Ignite the fuels overall of the target area by using a mass ignition technique. Many, closely spaced, small fire sets will be required.

Requirements for 1967 can be calculated simply by comparison with actual results from the 1966 operational test. The ignition pattern from M-35 clusters was satisfactory in the relatively narrow strips within which the bomblets from one flight landed. However, the pattern over the area as a whole could have been improved by spacing the strips so that they were contiguous and, thus, saturated all of the target area. A rough estimate from the post strike photos and movies of the operation indicates that between two and three times as many flights would have been required to saturate the entire area. Thus, more than twice as many bomblets were needed.

Another approach is to decrease the required average spacing between sets over an entire area. A calculated average of 125 feet between bomblets was used in planning the 1966 operation. The results indicated that this spacing should be greatly reduced. But additional trials are needed to determine the most effective and efficient spacing. Assuming an arbitrary reduction of 50 percent in spacing is required, the number of bomblet sets that are required will be four times as great as used in 1966.

We recommend that the required number of bomblets per unit of area in 1967 be three times the number used in 1966. They should be dropped in essentially the same manner as in 1966, but without spacing between the bombing strips. Spacing of flight strips, aircraft in a flight, and fusing of bombs can be adjusted to deliver the best overall pattern and intensity of ignition.