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ROLE OF VISIBLE TRAILS IN MID-AIR COLLISION PREVENTION

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prepared for

FEDERAL AVIATION AGENCY
SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

This report has been approved for general distribution.
by

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FINAL REPORT NO. 3
Contract FAA/BRD-127
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THE ROLE OF VISIBLE TRAILS
IN
MID-AIR COLLISION PREVENTION

Prepared for
Federal Aviation Agency
Systems Research and Development Service
Washington 25, D. C.

Project No. 110-512R

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August 1962

Applied Psychology Corporation

Arlington, Virginia

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ABSTRACT

This report summarizes that portion of a research program on visual mid-air collision avoidance techniques which deals with the use of intentionally generated visible trails. The aim was to determine the effectiveness of such trails as conspicuity aids under daytime VFR conditions. Analytical review of the literature covers detection of various clouds, dusts, smokes and mists, their capability of indicating flight path, and their possible use with information-coding techniques. Technical and operational considerations in using trails are also considered.

The evidence provides both favorable and unfavorable indications of the merit of trails as aids for lessening the likelihood of collisions. In good weather and with crossing flight paths, detection range is increased. Also, trails can aid determination of relative motion, and can provide coded information. However, some of these advantages are negligible for certain conditions, such as head-on courses, or they are of limited feasibility. Technical and operational disadvantages are: (a) high cost of installation and maintenance; (b) toxicity and other hazards to aircraft and communities; (c) severe weight requirements; and (d) unreliability of the visible signal. These disadvantages are great enough to preclude recommending a requirement that trails be generated for use in preventing mid-air collisions.

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THE ROLE OF VISIBLE TRAILS IN MID-AIR COLLISION PREVENTION

I. INTRODUCTION

The fact that one frequently can see the developing condensation trail ("contrail") of an aircraft when he cannot see the aircraft at all has led to the suggestion that such contrails may prove suitable in preventing mid-air collisions in Visual Flight Rules (VFR) weather. It has often been suggested that methods be devised to generate trails intentionally, using either vapor- or smoke-producing techniques.

The fact is that generating and controlling a dependable, operationally satisfactory vapor trail or smoke trail poses difficulties. Nevertheless, analysis of pertinent research on generating trails was warranted, to determine the possible usefulness of such visual signals in preventing collisions. This report presents such an analysis.¹

There is some disagreement in scientific and other circles as to the precise meaning of a number of the terms used to classify types of trails and their manner of generation. This report deals with visible trails (or more briefly "trails") which are naturally or artificially produced particulate clouds, more or less visually detectable. Invisible trails such as heat trails and ionized cloud trails are not included. All of the processes described in this report produce particulate clouds, which consist of any type of suspension of particles in a gaseous medium regardless of the nature of the suspended material, but excluding particles of such size that they settle very rapidly (Green & Lane, 1957). The main categories of particulate clouds are dusts, smokes, and mists. Smokes include a wide variety of gaseous disperse systems of particles of low vapor pressure which settle slowly. At one time, this term was used only to describe clouds formed by combustion or destructive distillation. However, as it is now used, the term "smokes" includes many other gaseous suspensions which cannot be classified as dusts or mists. Smokes may be formed by volatilization and condensation, chemical and photochemical reaction, and electrical and mechanical pulverization (Green & Lane, 1957). Dusts consist of solid particles dispersed in

¹ The Federal Aviation Agency has sponsored a comprehensive research program (contract FAA/BRD-127) to examine all visual aids--lights, paints, optical devices, etc.--that may have collision prevention value. This report covers one portion of that research.

a gaseous medium as the result of mechanical pulverization of matter. They may be distinguished from smokes in that the number of particles is usually lower (Green & Lane, 1957). Mists consist of droplets formed by the condensation of vapor, or the atomization of liquid (Green & Lane, 1957). Condensation trails (also called contrails and vapor trails) are visible trails of water droplets or ice crystals which sometimes form in the wake of an aircraft (Heflin, 1956).

II. TECHNICAL BACKGROUND

Why Natural Contrails Occur

An aircraft traveling in the upper atmosphere may leave behind it a visible trail of ice particles. These condensation trails (contrails) can result from (a) aerodynamic cooling or (b) the presence of moisture in the engine exhaust. In either case, the air in the wake of the aircraft becomes supersaturated.

Aerodynamic contrails are caused by the rapid reduction in air pressure behind the airfoils of high-speed aircraft, resulting in adiabatic cooling of the air. If in this cooling process the relative humidity rises above 100%, condensation will occur and a visible contrail be formed.

Exhaust contrails occur when water vapor from the aircraft exhaust (produced by combustion of hydrocarbons) locally saturates the atmosphere with respect to water. Since the atmospheric temperature at high altitudes is very low, the water droplets are supercooled and freeze immediately. The trail which was at 100% humidity with respect to water now becomes supersaturated with respect to ice. The excess water droplets freeze on the ice crystals, producing larger and larger crystals, thus forming a visible trail.

Generally speaking, the minimum conditions for contrails to form are (a) temperatures of the order of -45°C , (b) relative humidity of 50%, (c) altitude of 25,000 feet, and (d) ice crystal concentration of .01 gram per cubic millimeter (Air Weather Service, undated).

How visible the resulting trail will be and how long it will persist depend on many factors and on relationships among factors, including the size, number, and stability of the droplets; vapor pressure; surface tension; wind; turbulence; temperature; humidity; altitude; and equilibrium (or lack of it) between the processes of condensation and evaporation. One cannot obtain at will the special environment required for a visible vapor trail.

Smoke Trails

Chemical firms and military organizations have experimented with a number of ways to produce vapor or smoke artificially. Petroleum oils can be fed into engine exhausts; dry salt solids can be produced by vaporizing certain acids which recombine on entering the cooler atmosphere (where they

may or may not react further with the moisture in the air), finely ground solids can be dispersed directly into the air. In all cases the purpose is to produce a suspension of solid particles or liquid droplets in the atmosphere so as to reflect and scatter light in a manner that can be seen.

Important Signal and Environmental Factors

As mentioned above, one widely used method is vaporizing a smoke-producing agent during flight, then utilizing the resulting condensation of the vapors. To accomplish this, the agent, usually a hydrocarbon or derivative, is ejected under pressure from a simple orifice into the engine exhaust stream. The hot exhaust gases vaporize the agent, and when the vapors mix with the relatively cold atmosphere, condensation occurs and a visible trail exists.

Condensation may occur by (a) self-nucleation of a supersaturated vapor or (b) nucleation on foreign particles. The condensation nuclei for smoke trails usually are particles already present in the air or particles of combustion present in the exhaust. However, under certain flight conditions where there may be a scarcity of naturally occurring particles (at high altitudes, for example), condensation nuclei may have to be added to the smoke-producing agent in order to produce an artificial contrail.

The viscosity and freezing point of a smoke-producing substance have little direct effect on either quality or quantity of the smoke produced, but they do impose practical limitations on effectiveness. Unless special heaters and insulated tubings are used, many liquids will freeze or become too viscous on the way from the storage tank to the discharge orifice.

In addition, flash and flame points of the smoke-producing substance must be such as to prevent complete combustion at the temperatures prevailing at the point of generation. If complete combustion does occur (as when jet engine afterburners are operated), no smoke will be produced. If smoke were necessary under such operating conditions, certain special and expensive silicone oils would have to be used.

The stability or persistence of a smoke trail is greatly affected by static and dynamic meteorological factors and by physical properties of the particles as aggregates. Static meteorological factors include temperature, relative humidity, and the number and kind of condensation nuclei present in the atmosphere. Dynamic meteorological factors consist of the various atmospheric motions, such as wind and turbulence. The physical properties of particles which directly affect the stability of a smoke trail are size, density, electrostatic

force, surface tension, and vapor pressure.

High temperatures affect the persistence of a smoke trail by increasing the rate of evaporation or by increasing molecular bombardment, which results in more rapid dispersion of the smoke particles. Humidity usually affects only hygroscopic smoke, high humidity tending to aid stability, low humidity to hinder it. Generally, the effect of wind and thermal turbulence is to disperse or dilute the concentration of smoke particles.

Two important effects for smoke-cloud stability are agglomeration and dispersion. Agglomeration, the coalescence of particles after they have dispersed in the form of a cloud, is caused by electrostatic attraction and condensation. It is essential in smoke formation because particles are produced which become large enough for effective light scattering. However, unrestricted continuation of this process produces particles of such size that they "fall out" and cause smoke cloud instability. Dispersion is a process whereby particles are subdivided upon atomization of the smoke agent. After initial atomization, additional reduction of particle size occurs from evaporation. This reduction can be detrimental to cloud stability whenever particle subdivision reaches a point that particle sizes become too small for effective light scattering.

Depending upon their physical characteristics, the particles comprising a smoke trail affect incident light in several ways: (a) they may simply reflect the light at angles determined by their shape and opacity; (b) they may refract the light, deflecting it from the straight path it has traveled from its source; (c) they may diffract the light as it passes near their edges; or (d) they may absorb most of the light.

The light-scattering capability of a smoke trail is greatly affected by the size of the particles comprising the trail. Since the wavelength range for visible light is .4 micron to .7 micron, a trail consisting of particles within that size range will generally give optimum light scattering in the visible spectrum.

The result of all these complex conditions will be a visible trail, if either brightness contrast or color contrast, or both exist with respect to the perceived background or the field of view. If the trail appears bright against a dark background, the contrast is called positive; if the trail appears dark against a light background, the contrast is called negative. The basic equation for brightness contrast, C , is:

$$C = \frac{B_T - B_0}{B_0}$$

where B_T is the target (trail) brightness and B_0 is the background brightness.

For a perfectly black trail, the value of B_T would be zero, and the brightness contrast, C , would be -1; this is maximum negative contrast. Positive contrast is theoretically limitless; if the trail is very bright and the background very dark, extremely high contrast values are possible. In normal daytime flight, however, positive contrasts having numerical values higher than 5 are unusual, unless the trail is brilliantly lighted by sunlight and the background is a very deep blue sky or very dark terrain.

The interplay of brightness and color contrast is complex, and important to conspicuity. A dark or black trail viewed against a light background of snow or white clouds may be visible primarily because of negative brightness contrast. Conversely, a light or white trail seen against a dark background may be visible primarily because of positive brightness contrast. A colored trail viewed against a dark background may be visible primarily because of positive brightness contrast. A colored trail viewed against a background of different color but equal brightness may be visible because of color contrast alone. Under different circumstances, a colored trail may be visible because of both color contrast and brightness contrast.

These and other technical considerations present serious difficulties to anyone who hopes to arrive at a trail-generating process applicable to various aircraft, at the same time having effective conspicuity under the variety of environmental conditions encountered in VFR operations. On a winter day, white smoke might be effective against the brown terrain of the Southwest with the clear sky, yet markedly less effective over the snow-covered North Central plains under a middle-altitude overcast. On a summer day when turbulence and low humidity would quickly dissipate a trail in the Midwest, it might be almost impossible to "get rid" of trails generated in a stationary air mass (having a temperature inversion) in certain coastal areas.

If artificial trails were to be used as a visual aid in collision prevention, compromises would obviously be necessary. The primary consideration in choosing among alternative visual aids must be the signal's usefulness to the pilot in terms of conspicuity and correct evaluation of collision threats.

III. HOW TRAILS MIGHT HELP PREVENT MID-AIR COLLISIONS

For two aircraft to collide, their flight paths must intersect, and they must reach the point of intersection at the same instant. Considering the smallness of the cross-section of aircraft in relation to the vastness of the three-dimensional space they fly in, it seems evident that the probability of collision is extremely small. In fact, if a pilot tried to collide with an airplane he had sighted, he would have extreme difficulty doing so.

This "reverse" consideration points up the real problem in the VFR safety picture: anxiety aroused by the difficulty of knowing exactly whether two converging courses will result in a collision. Consequently, in trying to avoid collision, pilots can rarely be certain that they are making the right maneuver.

The value of any device or technique for collision avoidance is often difficult to assess. Some pilots appear to be convinced that they have developed useful techniques for avoiding collisions. It may be, however, that a pilot comes through safely not because of any intrinsic value in his individual collision avoidance "system," but mainly because of the extremely low probability of collision. A careful evaluation of collision-avoidance aids must cover such questions as these:

1. Does the technique demonstrably reduce the probability of collision?
2. Does it reduce the uncertainty that inheres in the solutions attempted by pilots?
3. Does it reduce the occasions for unnecessary avoidance maneuvers?

In practical terms, the first question is difficult to handle: we are not anxious for collisions to occur simply to provide statistical data about avoidance techniques, yet we cannot be satisfied with mathematical demonstrations of collision-probability reduction, because each demonstration depends heavily on the assumptions employed at the start of the probability computation. It appears that practical advances are more likely to be evident in reduced anxiety and reduced numbers of unnecessary avoidance maneuvers.

Aviation literature mentions at least eight items of

information about an "intruder" aircraft which might have some value to a pilot in his collision-avoidance efforts: (a) presence and location (sight-line bearing), (b) distance, (c) speed, (d) altitude, (e) attitude (pitch or roll), (f) heading, (g) type of aircraft, and (h) intended maneuver.

It would seem that trails might help with a number of these items. Provided there is brightness and/or color contrast in a favorable air mass, under certain conditions a trail unquestionably aids early detection of an aircraft (often before the aircraft itself can be seen); it may trace the aircraft's flight path for the other pilot, giving him some indication of heading, altitude, and speed. Many of the enthusiastic reports about contrails deal with situations in which this appears to have been the case. Also, it is possible that intermittent release of artificial trails might be accomplished to provide visually coded information.

On the other hand, it must be asked whether distant trails might not take a pilot's attention away from more important nearby stimuli. Also, it must be determined how accurately the visible flight path can be interpreted, since the pilot is not seeing two flight paths from some distance as a developing vector problem in space and time geometry; rather he is in the "nose" of one trail, looking out at the other, and this can produce various kinds of apparent slippings, skiddings, and other unorthodox motions in the target.

IV. SUMMARY OF EVIDENCE

Detection

Since natural contrails usually occur at high altitudes, they are often detectable at extremely long ranges. Pilots have reported seeing contrails produced by aircraft which, upon checking with Traffic Control Centers, turn out to be nearly 100 miles away (Miller, 1959). These long-range detections almost always involve at least the following factors: (a) the contrail is composed of ice crystals and has high efficiency in scattering incident light; (b) there is a high ratio of brightness and color contrast between the contrail and the blue sky; (c) the upper-altitude air is generally clearer than that closer to the earth's surface; and (d) it is possible to achieve greater visual range as the observer's height above the earth's surface and the size of the contrail increase. Thus, long-range detectability of natural contrails occurs when circumstances are ideal.

In conducting tests on missiles, aircraft, and other vehicles, the Air Force uses cameras and other optical instruments along with electronic equipment to obtain test-performance data. Frequently with high-speed and high-altitude vehicles the optical instrument operator failed to find the test vehicle, lost it during its flight, or was unable to distinguish it from other vehicles. As a consequence, the Air Force initiated a program to investigate the feasibility of using artificially generated trails as a tracking aid (Grundemeier, 1957; Ekstedt, 1958). A variety of smoke agents and smoke generating systems has been tried, some successful, some not. No single smoke agent or generating system appears to satisfy all testing requirements.

One of the more satisfactory methods, developed especially for photographic purposes, is the ejection at half-second intervals of explosive photoflash shells.¹ As customarily used from high-performance aircraft, detonation occurs a half-second after ejection, producing a brilliant flash and a persisting spherical white smoke puff. An aircraft firing a "stick" of these shells leaves a trail of regularly spaced dots. But although the visibility of these trails is generally very good, the technique is undoubtedly too hazardous and requires hardware too complex to be seriously recommended for air transport and general aviation aircraft.

¹ Information supplied by Kirtland AFB, February 1960.

Military and civilian acrobatic flights, to improve their visibility to spectators, have often utilized oil-exhaust, vapor-dumping, or chemical-ejecting devices. They provide detection advantage in favorable weather circumstances, but because of economic and aerodynamic factors do not appear to be appropriate for transport or general aviation.

Two experiments point up important issues in detecting trails. Buck (1938) measured the discovery time of standard smoke columns of experimental forest fires viewed under different sun-angle conditions and found that discovery time decreased as the angle of the column away from the sun increased (Fig. 1). Since the smoke columns were presented in forest terrain, the actual detection times shown may be larger than would generally be encountered in aircraft detection. Nevertheless, the relative detectability of smokes viewed into the sun as opposed to those viewed with side sunlighting or with the sun behind the observer is relevant to the flight situation.

A flight test of artificial trail effectiveness was conducted by the Navy (Miller, 1959). The trail, produced by ejecting fuel oil into the jet exhaust of an F11F aircraft, was white, of low density and volume, and dissipated within 30 to 40 seconds. Detection distances are shown in Table 1. When the F11F was flown on a 45° to 50° course relative to the observer aircraft, detection range was increased from approximately 8 miles without the trail to about 20 to 24 miles with the trail. For head-on flights, detection distance was not effectively increased above what was obtained without the trail. On one head-on pass without a trail, the observer did not detect the F11F until it passed directly overhead. Normally, an object the size of this aircraft viewed head-on should be detectable at a distance of 3.6 miles.

It should be noted that some aviation safety experts have cautioned against overvaluing early detection of intruder aircraft. This viewpoint holds that a sky full of trails detectable at long range would constitute a visual field in which most stimuli would be unworthy of serious concern, but would distract and preoccupy the observing pilot. Detection is needed at optimum range, which is not necessarily maximum range.

Indication of Flight Path

Whenever a trail is detectable it will be capable to some degree of indicating an aircraft's flight path. In certain instances the flight-path information will be relatively complete and unequivocal (targets crossing well in

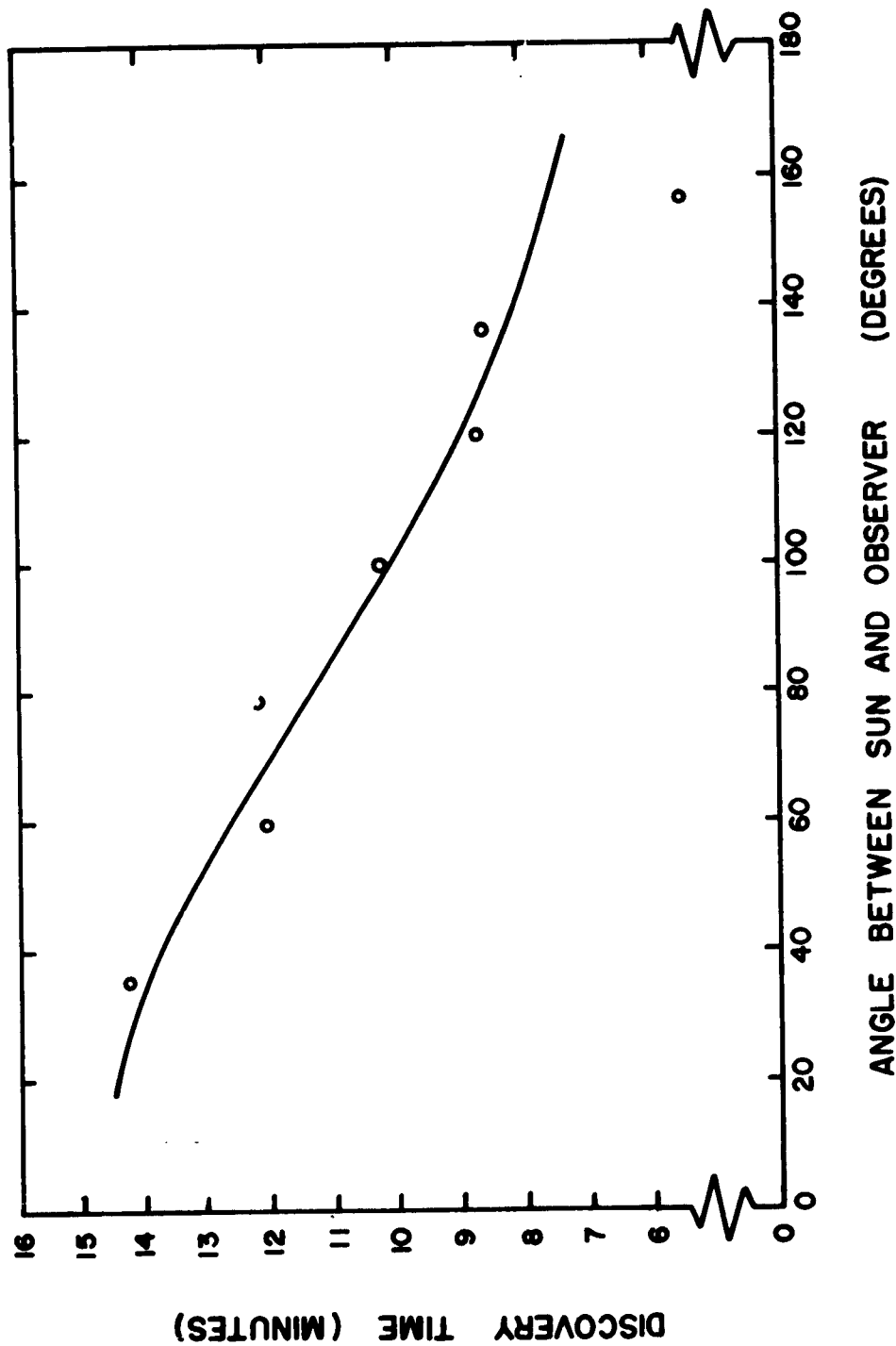


Fig. 1. Effect of relative direction of sun and smoke on time of discovery of experimental forest fires in conditions of great visual range. An angle of 0° means that the smoke is in the direction of the sun (from Middleton, 1958, after Buck, 1938).

Table 1

In-Flight Visibility of Smoke Trails
(After Miller 1959)

Run No.	Initial Separation (miles)	Target Course	Observer & Target Altitude (ft.)	Background	Smoke	Smoke Released at (miles)	Sighted (miles)	Clock Position of Target
1	20	head-on	10-11,000	White clouds	none	---	2½	1200
2	30	45°	10-11,000	Patchy clouds	none	---	8	0900
3	25	head-on	10-11,000	White clouds	15 sec. steady	25,12,5	3	1200
4	40	45°	20-21,000	Patchy clouds	15 sec. steady	40,21		
5	30	45°	32-35,000	Clear blue	ten 1 sec. bursts	39,30,25	21	0900
6	30	45°	32-38,000	White clouds & clear blue	15 sec. steady	30,25,20	20	0830
7	32	head-on	20-21,000	White clouds	15 sec. steady	24,20	20-24	1500
8	30	head-on	20-21,000	White clouds	none	---	5	1215
9	35	50°	20-21,000	Patchy	15 sec. steady	15,10	8,3	1400
10	30	50°	20-21,000	Clear blue	10 sec. steady	25,17,15	15	1430
					10 sec. steady	28,23,20	20-23	1500

Flight 1
12

Flight 2

front of an observer); in other cases the visual cues may be of little value, or may be ambiguous (targets whose flight paths are slightly off parallel, either diverging or approaching, with respect to the observer's flight path).

In favorable situations, the conical shape of the developing trail (small in diameter at the point of generation, expanding gradually with increased distance behind the generating aircraft) usually indicates the direction of movement. Also, relative motion can be easily judged in these situations, enabling the observing pilot to make use of the fixity-of-bearing criterion when it is applicable.¹ Furthermore, changes in flight path become visible almost as soon as they are made, provided the relative courses and visual background are favorable.

In contrast, it must be noted that there will probably be far too many "other" occasions. Adverse weather conditions, such as air turbulence, wind, haze, rain, or even overcast, may nullify or change the informational value of a trail. Within a fairly large approach cone, a trail will have little or no detection or interpretation value: it will not greatly enhance the apparent size of the aircraft; the cone of generation may be obscured by the remainder of the trail; or the trail may appear only as a growing cloud without length, thereby making it hard to verify either the presence or absence of relative motion. Thus, trails have maximum effectiveness only under conditions of fair weather and when the intruder's flight path is within certain bounds.

Estimating a target aircraft's altitude by means of a continuous trail also varies in effectiveness. With a favorable horizon and background for visual reference, and with a substantial difference in absolute altitude, an observer might rarely make a wrong estimate of collision danger. If any or all of the factors involved deteriorate, the ability to read a trail as a safe vertical separation is correspondingly reduced.

Possible Information-Coding Techniques

Intentionally generated trails can have at least two characteristics advantageous for presenting collision-prevention information in coded form: they can be colored, and they can be made up of intermittent puffs (thus overcoming some of the ambiguity of a continuous trail).

¹ If the sight-line bearing of one aircraft remains constant in the field of view of another aircraft's pilot, a collision is impending, provided both aircraft are, and remain on, straight-line, constant speed courses.

Theoretically, smokes of designated hues can be obtained by rigidly controlling the size of their component particles. However, the state-of-the-art is not sufficiently advanced to solve the problem of generating a trail in which the average particle size corresponds exactly to a given wave length of light and in which the standard deviation (a plus and minus value that will include $2/3$ of all the particles) is 0.1 micron above and below that wave length.

Dry dyes and dye solutions have been added to oils or chemicals to produce colored trails. In general they have not behaved consistently, and often have introduced problems with respect to ejection nozzles, aircraft surfaces, and underlying communities (see, for example, Ekstedt, 1958).

As a means of conveying useful coded information to pilots, colored trails suffer from three major difficulties. First, there are only a few colors that can be reliably distinguished, thus limiting the amount of information that can be encoded. For example, if orange trails were to identify military aircraft and red trails transport aircraft, either color, seen above, could be mistaken for the other. The available "noticeably different" colors would be exhausted before one developed a coding to include all major categories of aircraft. Second, color is severely attenuated by the atmosphere, tending to fade toward gray as a function of transmissivity and increasing distance. A third difficulty is the presence of sky coloration during sunrise and sunset. Difficulties of colored trails suggest that they would be of little usefulness.

A series of puffs of smoke appears to be more feasible, at least from the viewpoint of presently available apparatus. Two of the operating equipments encountered during this research are described below.

A trail-generating demonstration which took place at FAA's National Aviation Facilities Experimental Center in July of 1959 provides some excellent insight into operational factors involved in producing intermittent trails. An F9F-8T aircraft was used, with the trail-generating apparatus housed in a drop-tank carried under the left wing. It consisted basically of two cylinders, one containing liquid sulphur dioxide, the other, liquid ammonia, two solenoid valves, two manually operated valves, and a cycling switch, plus the necessary wiring and tubing (Fig. 2). The device was wired so that both solenoid valves opened at the same time, which allowed the two chemicals to mix as gases, and form a white puff. This particular installation weighed

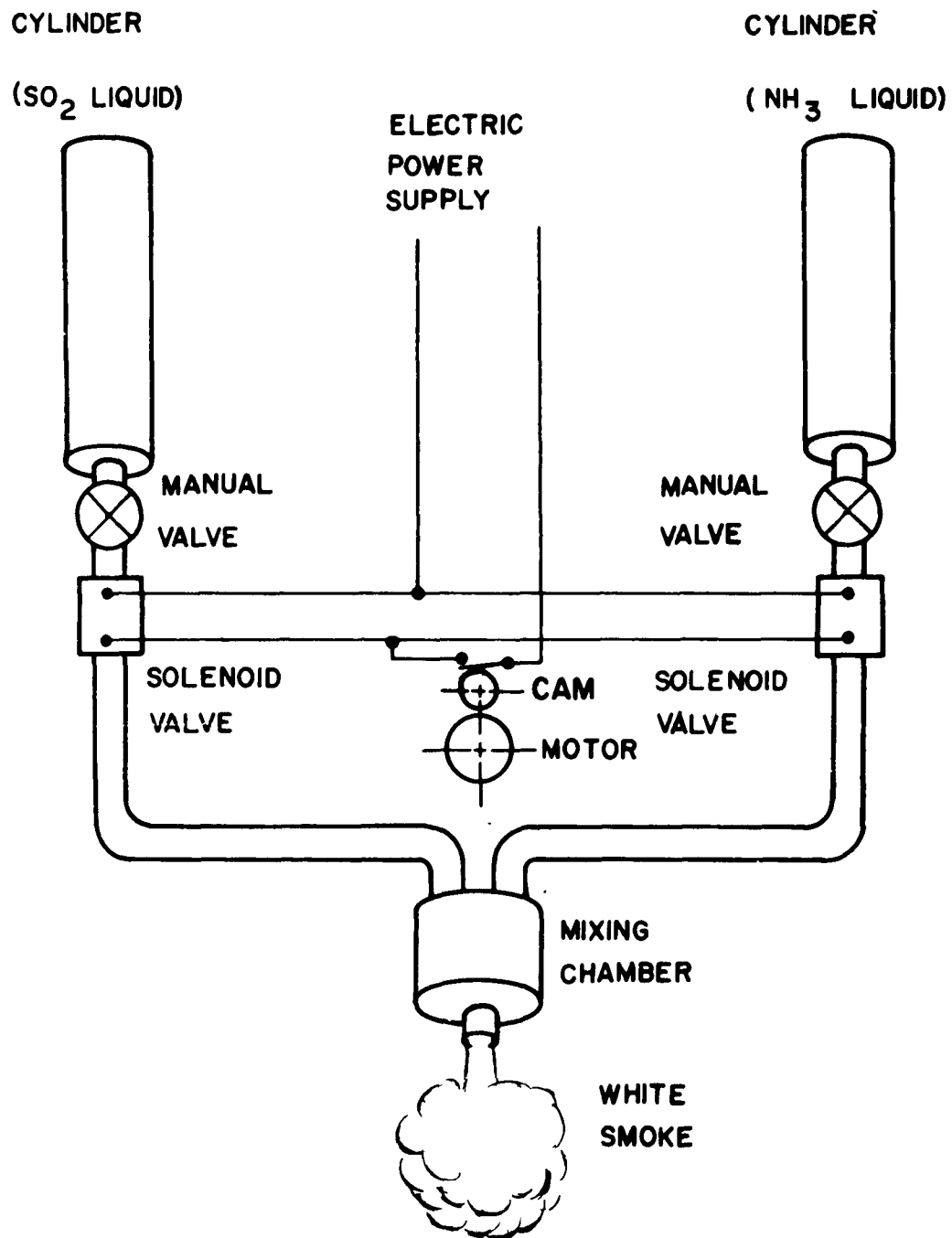


Fig. 2. Diagram of a representative smoke generator.

about 20 pounds and contained enough chemicals to last approximately 20 minutes when cycling at the rate of "on" for one second, "off" for two seconds.

When successfully generated, the trail was white and of a density comparable to the discharge of a carbon dioxide fire extinguisher. Nevertheless, its persistence was very brief; the puffs were rarely visible for more than 5 or 6 seconds. The aircraft and the trail were clearly visible at close range (up to one mile), but the lack of persistence made the signal unsatisfactory at longer ranges.

Two malfunctions marred the demonstration. On one occasion a metal chip in one of the valves prevented the chemicals from mixing properly, and the trail was not produced. On another occasion, one ingredient of a rust-inhibiting substance "froze" during flight and effectively blocked the discharge tubes. These malfunctions illustrate some operating frustrations that might be commonplace.

Another application, in which a paraffin-based hydrocarbon is ejected into the exhaust by means of electronic programming, has been used for advertising purposes. Known as Sky Typing, the process calls for five aircraft to fly abreast along a straight-line path, while an electronic programming device, specific to each airplane, provides precise bursts of smoke at correct intervals so that letters are formed by the puffs. Figure 3 illustrates the resulting message capability. Suggested usages of this coding technique are varied. One proposal, for example, postulates a single trail which would indicate direction of bank by means of its intermittent or continuous generation; a double trail, similarly interrupted or continuous, might indicate ascent or descent.

It is evident that this type of apparatus could produce desired visible codes (of dots, or dots and dashes), and thereby communicate some information. Other research results from the present contract have led to the suggestion that coded altitude information would add significantly to a pilot's ability to make correct collision-avoidance decisions, and experimental studies have been completed using dot-dash light signals to give altitude information during night flight. It is tempting to speculate on the possibility that coded trails could provide a daytime signal whose operation would be compatible with that of the navigation light system.

But some of the difficulties already attributed to trails are particularly troublesome with coded signals. For example, the codes might be clearly visible and readable when viewed broadside (when the other aircraft is

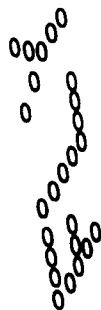
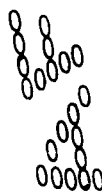
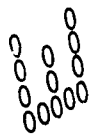
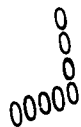
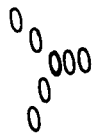


Fig. 3. Smoke production in Sky Typing process.

crossing a pilot's flight path); but when the courses are nearly parallel and one aircraft is overtaking another, the parallax can easily make the code unintelligible. The variability of the coded signals' persistence would also present difficulties. And presenting coded artificial trails at times when continuous contrails are being produced naturally would cause confusion.

Technical and Operational Considerations

Methods of generating trails. Laboratory techniques for producing smoke or other aerosols are sophisticated and complex. Techniques for producing trails during flight are categorized in Table 2. Examination of the methods and materials used will reveal some of the practical difficulties associated with using the techniques in each category. Weight, space, corrosion, cost, fire hazard, pollution, and sometimes a combination of several of these make it prohibitive to require all aircraft to carry such equipment.

Problems of measuring smoke characteristics. Various techniques of measuring the size and other characteristics of laboratory-produced smoke particles have been used. Standard sieves, measurement of the light-scattering characteristics of particles, microscopic techniques, and electron-charge methods are among the techniques available (Green & Lane, 1957). The number of particles per unit volume of a smoke can be measured in the laboratory with a photoelectric cell which permits recording the amount of light, from a known source, transmitted through the smoke. The obscuring power of screening-type smokes is measured as "the area in square feet covered by the smoke produced from one pound of material in a layer of thickness and density such that a 40-watt lamp is completely obscured" (Prater & Romine, 1952).

The obvious complexity of these measurement techniques and the ever-present variation of aircraft and atmospheric factors during flight make it clear that adequate measurement of the characteristics of intentionally generated trails is not feasible. While this seriously limits sophisticated experimentation with trails in flight, there might still be some justification for flight tests if one were to strive to control and measure those factors which could be controlled and measured, at the same time acknowledging factors not quantifiable or controllable. But justification even of this type of flight test seems to be nullified by available technical information.

Limitations of specific trail generating techniques. As a case in point, let us examine exhaust vaporization. Military acrobatic teams have ejected hydrocarbons into engine exhaust streams. Consumption rates (and therefore

Table 2
Methods of Generating Trails

Method of Process	Material or Equipment
External Heat Sources (engine exhaust)	1. Aliphatic hydrocarbons (corvis oil, kerosene) 2. Aromatic hydrocarbons (anthracene, naphthalene) 3. Silicone oils
Chemical Reactions	1. Sulphus trioxide 2. Metallic chlorides 3. Ammonia and sulphur dioxide
Mechanical Ejection	1. Talc, powdered clay, ground solids 2. Agricultural substances 3. Fuel or water "dumping"
Internal Heat Sources	1. Additives to fuel-combustion cycle 2. Smoke pots, flares, other pyrotechnics

weight and tankage volume factors) are generally high, approximately 2 to 3 gallons per minute for continuous operation. With jets, care must be exercised to extend the ejection nozzle far enough beyond the tail pipe to prevent the oil from being sucked forward by slipstream eddies.¹

In the case of chemical reactions, the commonly expected difficulties have been realized. Ammonium salts of volatile acids such as hydrochloric acid and nitric acid can be vaporized with heat; on cooling they produce solid white particles of salt. When dry, these salts have no appreciable effect on metals; in the presence of moisture, they cause corrosion. They are generally harmless to personnel and can be safely handled.

The sulphur compounds and metallic chlorides produce smoke by reacting with atmospheric oxygen or water vapor or both. The former corrode metals, and many of them cause slow-healing burns on contact; their smokes are irritating and in some cases toxic. The metallic chlorides, while not very corrosive if kept dry, produce a smoke that is itself corrosive to all materials affected by hydrochloric acid. Aluminum chloride and zinc chloride will burn flesh on contact. Mercuric chloride is extremely poisonous if swallowed. Phosphorus and its sulphur and chlorine compounds are excellent smoke producers, but cause corrosion and tissue damage.

Visible trails of dispersed solids, very finely ground or in the form of precipitated powders, may consist of Bentonite clay, talc, lime, or ground glass or plastic ejected into the atmosphere by gas pressure. The particle size necessary for efficient trail production is difficult to obtain by grinding. Some powders which coalesce readily, are very difficult to store and to disperse uniformly. On the other hand, plastic "mists" have been produced with particles so light and noncombinable that their retrieval has required very sophisticated vacuum cleaning techniques in the laboratory. Other mechanical ejection methods involve releasing small amounts of fuel or other available liquid (most commonly observed when pilots are "dumping" excess liquid), but the resulting trail is misty, generally of poor visibility, and extremely vulnerable to air-mass characteristics.

Although pyrotechnics do not appear consonant with flight safety, a brief note is included for the sake of

¹ At least one jet fighter suffered an explosion in the tail pipe because of insufficient nozzle length (Ekstedt, 1958).

completeness. Basically, a pyrotechnic unit consists of (a) a fuel, such as sulphur or other organic material, (b) an oxygen-producing substance, usually a perchlorate or nitrate, and (c) a cooling substance, such as ammonium chloride or salts of magnesium. Although pyrotechnics generally produce a dense, highly visible smoke, their duration, even when multiple units are used, is so short that their usefulness in aviation appears restricted to special events such as missile firings, fighter-bomber rendezvous, and aerial gunnery practice. Added to this are fire hazard during flight and storage problems on the ground. Furthermore, many pyrotechnic substances are difficult to ignite at the low temperatures frequently encountered in present-day flight.

Selected operational realities. Assuming that exhaust vaporization of a hydrocarbon is the most feasible trail-generating method for widespread use, there are a number of operational considerations.

Standard hardware consists of (a) a "fuel" tank, (b) a pressure device, (c) connecting plumbing, (d) a control valve, and (e) wiring and control switch.

Aircraft used by the Skywriting Corporation of New York City are equipped with 70-gallon storage tanks, drained at about 1-1/2 gallons per minute, generating smoke continuously for approximately 45 minutes, or intermittently for about three hours. The Air Force reports that consumption of two to three gallons per minute produces a trail comparable in width to a natural contrail (about 100 feet).¹ Assuming two gallons per minute, then 16 cubic feet of storage space would be required to obtain continuous smoke generation for one hour. For intermittent generation in a cycle of one second "on" and two seconds "off," approximately five cubic feet of storage would be required to provide a smoke trail for the same length of time.

Location of the connecting plumbing presents problems. It may affect the choice of location for the storage tank. If high-altitude flight is contemplated, immersion-type heaters and tubing insulation may be required to keep the smoke agent at proper viscosity for efficient operation. But if the flow lines pass a high-heat location (as in jet aircraft) special insulation may be required to keep the agent from evaporating. Furthermore, it must be impossible for the agent or any fumes resulting from the production of smoke to seep into pilot or passenger areas of the aircraft

¹ According to data supplied by Wright Air Development Center, 1959.

The control-valve portion of the apparatus restricts the usefulness of titanium tetrachloride, a chemical that is otherwise somewhat promising. It has relatively high smoke-producing efficiency and very high apparent brightness, can be used in its liquid state, and is independent of heat sources. But it seriously "gums up" most known pumps and valves, rendering sustained functioning impossible.

Ejecting the trail-producing agent requires some device to exert pressure or to act as a pump. Pressures in reported systems have ranged from 10 to 100 psi, and cartridge units are available which operate from a self-contained compressed air supply (present units are for short-burst operation only). Conventionally the pumps are powered electrically or by direct linkage to the aircraft engine.

Ejection nozzles are generally simple devices consisting of a tube with one or more orifices at the end or along the side. The number and size of orifices required depends on desired rate of flow, viscosity of the smoke agent, and pressure supplied at the nozzle. For a reciprocating engine, the nozzle is located in or near the exhaust manifold, with exact location and extent of projection into the exhaust stream depending on the specific engine. For jet aircraft, placement of the nozzle is more critical: explosions must be avoided and vibration or buffeting eliminated. Coking and burning of most nozzles is commonplace, necessitating periodic replacement.

Control systems for continuous generation of trails usually consist of a solenoid valve, a control switch, and associated wiring. Power requirements for this portion of the system present no special problems beyond those involved in reliability. If intermittent trails are desired, a cycling mechanism of some kind will be needed.

A valveless pulsejet developed by the Navy (Persechino, 1959) to generate screening smokes appeared, on first examination, to have potential usefulness for airborne trails. It operates when air and a regulated amount of fuel are fed simultaneously to a combustion chamber. After the first ignition, resonant intermittent combustion occurs (approximately 100 cps) and automatically maintains itself as long as fuel is supplied under proper pressure. Some advantages claimed for the pulsejet generators are: low cost, no moving parts, little or no carbon deposit in the vaporizing chamber, and ability to operate on a variety of fuels. The major drawback thus far is that wind tunnel tests and aircraft trials have extinguished the generator.

Control of the rate of flow would be desirable, since economies in consumption could be effected when ideal atmospheric conditions exist. Limited control can be accomplished

by changing nozzles (different units having different numbers and sizes of orifices). In-flight control can be obtained either by regulating the speed of the pressure system or by varying the control valve openings. In-flight controls are obviously preferable, since they would allow the pilot to make adjustments as conditions changed.

Most of these problems could perhaps be tolerated. In fact, parallels might easily be found in many airborne systems or components now being used; some navigation equipment, for example, is costly and requires owners to perform substantial retrofitting; other equipment drains horsepower or adds aerodynamic drag points that reduce aircraft performance. The decision to use each equipment system or type of fuel must be made so that flight values outweigh anticipated risks and costs.

V. CONCLUSIONS

In good VFR weather conditions and for flight paths that involve crossing courses, visible trails unquestionably increase detection range. This advantage is less pronounced as the intruder aircraft's course approaches head-on. There is also some question whether detection at extreme range is completely beneficial, since many of the detected targets might be merely powerful distractors unworthy of concern. Optimum detection range, it appears, is not necessarily maximum detection range.

Trails can indicate an aircraft's flight path through noticeable relative motion (or lack of it), and the conical shape of the developing trail. These indications, most useful in crossing courses, tend to lose value as flight paths approach the parallel or head-on, or take place in an empty visual field.

Specific flight-path data (such as altitude) might be coded by means of colored trails or intermittent puffs. Colored trails are difficult to produce, however, and for identification purposes are limited in range and distorted by atmosphere and sunlighting. Intermittent generation (puffs), although feasible with existing equipment, is relatively costly. Its interpretation would be affected by the degree of parallax characterizing the viewing situation, and further difficulty would be encountered if continuous natural contrails were being formed concurrently.

A number of technical and operational problems seem to offset whatever advantages accrue to trails. These problems appear sufficient to recommend against a requirement for trail-generating equipment on aircraft in the foreseeable future. These problems can be summarized conveniently in four categories:

1. Installation and maintenance requirements. The structural changes involved in retrofitting each aircraft would be an excessive burden, and regulations assuring effective functioning would necessarily require frequent maintenance.
2. Hazards to aircraft and communities. It is likely that one or more of the following hazards would exist on every flight utilizing intentionally generated trails: corrosion, fire, explosion, air pollution, and complications in the event of a crash. In the case of certain of the smoke-producing chemicals, ground handling of materials would be dangerous.
3. Weight requirements. Present and foreseeable

equipment demands a relatively heavy combination of apparatus and materials.

4. Unreliable nature of the visible signal. Visibility of trails is seriously affected by atmospheric factors beyond the pilot's control. These factors change from day to day and are usually different in different locations on the same day. Persistence, brightness contrast, size of trail, and color contrast are among the vulnerable characteristics.

Recommendation

For the reasons cited above the contractor believes that a requirement for generating visible trails for the purpose of helping prevent mid-air collisions in VFR weather is not appropriate.

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