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GUIDANCE AND HOMING OF MISSILES AND PILOTLESS AIRCRAFT

A Report of the AAF Scientific Advisory Group

by

H. L. DRYDEN G. A. MORTON
I. A. GETTING

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A REPORT PREPARED FOR THE AAF SCIENTIFIC ADVISORY GROUP

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The AAF Scientific Advisory Group was activated late in 1944 by General of the Army H. H. Arnold. He secured the services of Dr. Theodore von Karman, renowned scientist and consultant in aeronautics, who agreed to organize and direct the group.

Dr. von Karman gathered about him a group of American scientists from every field of research having a bearing on air power. These men then analyzed important developments in the basic sciences, both here and abroad, and attempted to evaluate the effects of their application to air power.

This volume is one of a group of reports made to the Army Air Forces by the Scientific Advisory Group.

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By

HUGH L. DRYDEN

PART I

SELECTED GUIDED MISSILES NOW DEVELOPED OR UNDER DEVELOPMENT

30 NOVEMBER 1945

INTRODUCTION

In order to give a general picture of accomplishments and plans for the design and development of guided missiles and pilotless aircraft, a description will be given of selected missiles now developed or under development. The descriptions are brief and intended solely to give a general picture. No attempt is made to list all the variations in design which occur in missiles actually manufactured in large numbers as well as in design studies.

The missiles included are:

AIR-TO-GROUND

- PC-1400-FX (German)
- Hs-293 (German)
- GB Series (Army Air Forces)
- VB Series (Army Air Forces)
- Glomb (Navy, Bureau of Aeronautics)
- Gargoyle (Navy, Bureau of Aeronautics)
- Pelican (Navy, Bureau of Ordnance)
- Bat Series (Navy, Bureau of Ordnance)
- Dove (Navy, Bureau of Ordnance)

GROUND-TO-GROUND

- V-1 (German)
- V-2, A-4 (German)
- A-9 and A-10 (German)
- JB Series (Army Air Forces)
- BQ and Willie (Army Air Forces)
- Ord-Cit (Army Ordnance)
- Hermes (Army Ordnance)
- TDR (Navy, Bureau of Aeronautics)

AIR-TO-AIR

Hs-298 (German)
X-4 (German)
Gorgon (Navy, Bureau of Aeronautics)
Lark (Navy, Bureau of Aeronautics)

GROUND-TO-AIR

Enzian (German)
Rheintochter (German)
Wasserfall (German)
Schmetterling (German)
Feuerlilie (German)
Boeing Study (Army Air Forces)
Nike (Army Ordnance)
Bumblebee (Navy, Bureau of Ordnance)

AIR TO GROUND MISSILES

PC-1400-FX (GERMAN)

This air-to-ground missile, the first guided missile to be used operationally during the war, is a high-angle bomb provided with a special tail and with rudimentary wings for control purposes. It is remotely controlled by radio by an operator in the releasing aircraft who watches the bomb visually. It was developed by the Germans during the period 1939-1943 and first used in August, 1943. Between August and October, 1943, there were some 14 attacks. Between August, 1943 and February, 1944, 28 bombs were dropped, of which five were hits resulting in one ship sunk and four damaged.

The pay load is a standard German armor-piercing bomb weighing 1400 kg (3080 lb), of which 600 lb is the explosive filling. The bomb is 75.5 in. long, 22.5 in. in diameter and the complete missile is 130 in long. The fins, provided to give a greater lateral area for more effective control, have a span of 5 ft and the tail has a span of 4 ft. The missile is stabilized against roll by a free- and rate-gyro combination controlling lift spoilers on the two fixed airfoils in the tail structure. The steering is by remote radio control, also actuating solenoids which operate spoilers on airfoils in the tail structure. A flare on the tail assists the operator in following the missile.

The missile is dropped from altitudes between 12,000 and 21,000 ft. For the first 15 sec there is no control. From an altitude of 21,000 ft it is estimated that the point of impact can be moved 500 ft to the right or left, and from 500 ft over to 1000 ft short. The dispersion was estimated to be about 100 ft from the development tests, and claims were made that 80% hits could be obtained. This precision was not obtained under combat conditions. Air superiority is necessary if accurate results are to be obtained.

HS-293 (GERMAN)

The Hs-293 is a glide bomb, accelerated by a liquid-fuel rocket for 12 to 15 sec just after release. It is remotely controlled by radio by an operator in the releasing aircraft who observes the bomb visually. It was first used on 4 October 1943, in the Mediterranean against a convoy. Between this date and February, 1944, 159 of these missiles were dropped against warships and convoys, resulting in five vessels sunk and two damaged, according to one summary. Minor damage was done to a number of other ships by four near misses. Other attacks on harbors sank three ships and damaged three. Between February, 1944 and July, 1944, there were 11 additional attacks resulting in one sinking.

The missile is a monoplane glider of 10-ft span and 13-ft over-all length. The total weight is 2000 lb, of which 1322 lb is accounted for by the bomb. The tail span

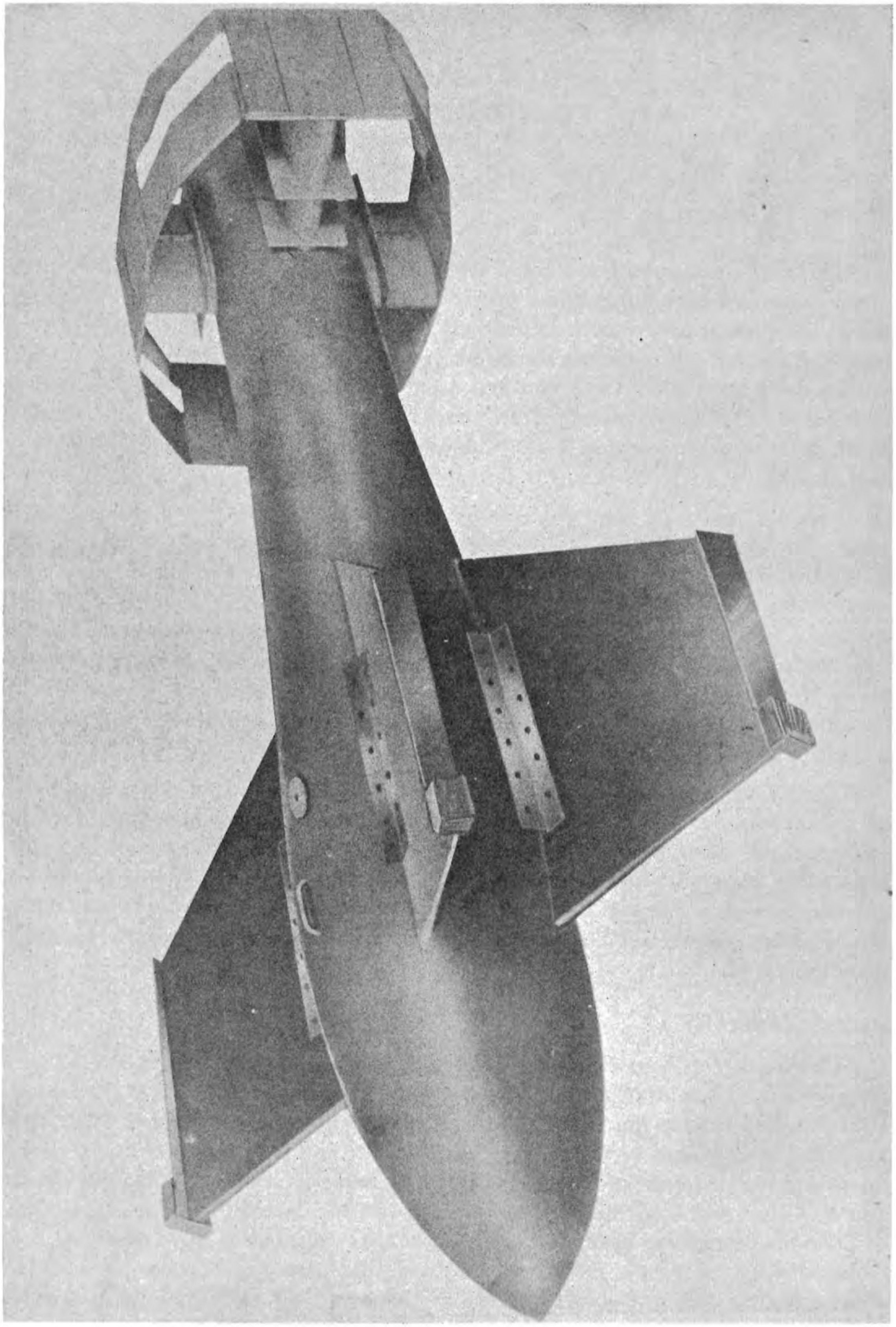


Figure 1 — PC-1400-FX

is 3-1/2 ft. The missile is stabilized in roll. The radio control operates ailerons and elevators. The minimum radius of turn is estimated to be greater than 1500 ft. About 50% of the missiles failed to function properly. The missile is accelerated from the release speed of about 225 to 400 mph by a liquid-fuel jet operating from 12 to 15 sec. The purpose of the acceleration is to get the missile ahead of the launching aircraft so that direct-sight control is more readily usable. The missile carries a flare to assist the operator. The range is from 10 to 11 miles when released from 11,000 ft. Air superiority is required for its successful use.

GB SERIES (ARMY AIR FORCES)

The Air Materiel Command at Wright Field has designed some dozen or more glide bombs, all with a standard 2000-lb bomb as pay load (except for one which carries a torpedo) but with different methods of control. The first of the series, GB-1, is a glider with rectangular wings of 12-ft span carrying a conventional tail structure on two booms. The bomb is fastened to this glider frame by two straps. A Hammond autopilot is used to maintain the original direction of flight and the elevator is preset to give the best glide path. The glide bomb is launched from an aircraft. From 15,000 ft the range is about 20 miles. The estimated probable error is from 3000 to 5000 ft in range and from 700 to 1000 ft in azimuth. A limited number have been used in combat. The same vehicle and control were used with a torpedo as pay load in the GT-1.

The GB-4 is a somewhat similar glider with additional housing for the Block III (AN/AXT-2) television equipment and remote radio control with which it is equipped. Evaluation tests have been made of this weapon by the Air Forces Board and a few have been tried in combat. The gross weight is 2500 lb and the air speed is 240 mph. In the evaluation tests unreliable operation of equipment (not the television equipment in all cases) was experienced in 20% of the drops. The average circular probable error for the test was 200 ft.

The GB-6A is a heat-homing bomb using the Offner heat seeker. Numerous development tests have been made with encouraging results.

The GB-8 is a direct-sight radio-controlled glide bomb similar to GB-1 in external appearance. Evaluation tests by the Air Forces Board show a mean circular probable error of 1084 ft.

The GB-12 is a marine light-contrast-homing glide bomb and GB-13 is a flare seeker. Experimental drops have been made with a number of these missiles with varying results.

The GB-14 is a radar-homing bomb in which both transmitter and receiver are in the missile. The radar equipment is that developed by Division 5 NDRC and Bell Telephone Laboratories for this project and for the Bat Project (SWOD Mark 9), Navy Bureau of Ordnance. No drop tests have yet been made.

VB SERIES (ARMY AIR FORCES)

The VB series comprises a group of guided high-angle bombs sponsored by the Air Material Command at Wright Field, the development being carried out by Division 5 of the National Defense Research Committee. The VB-1 and VB-2 are 1000-lb

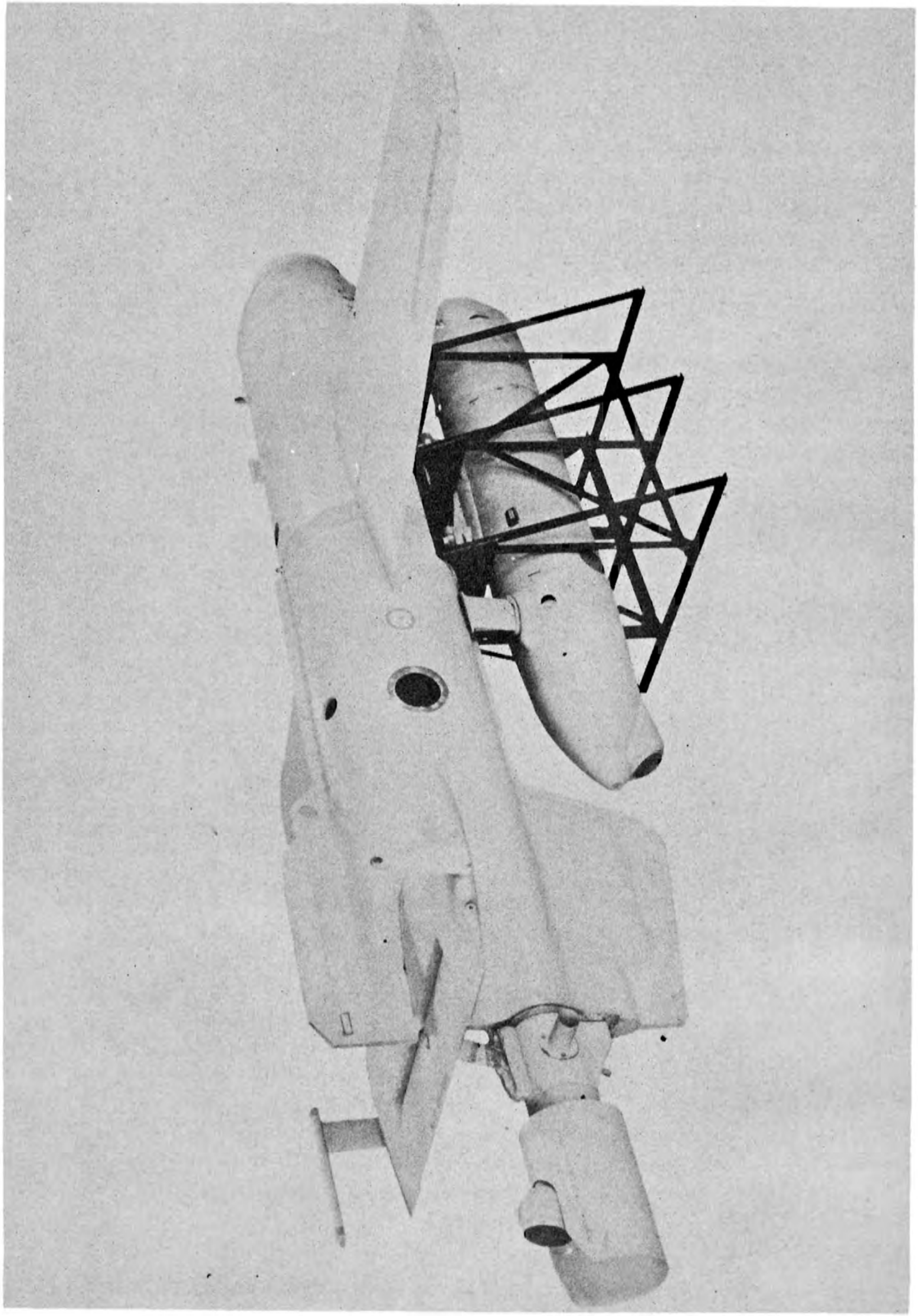


Figure 2 — Hs-293

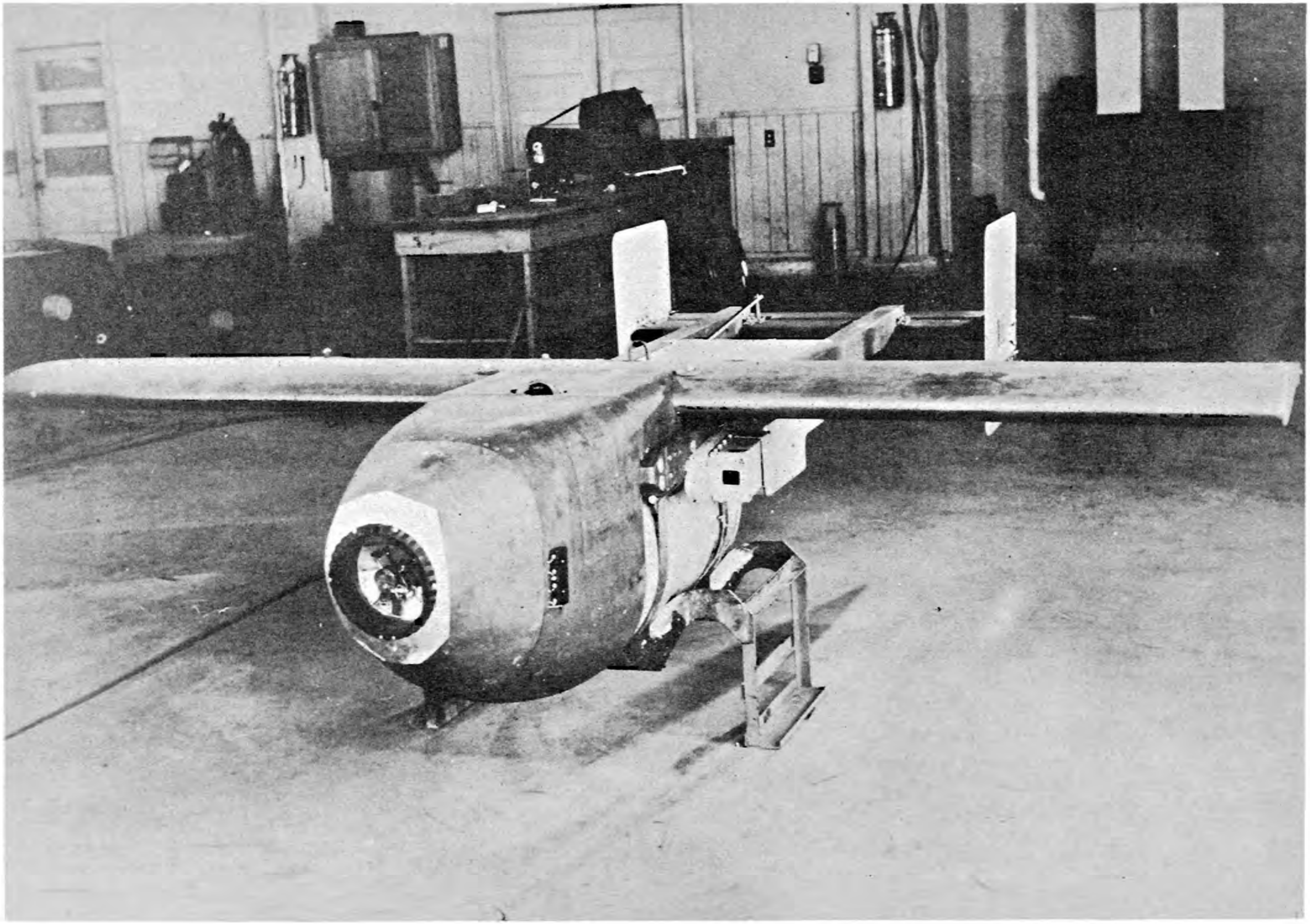


Figure 3 — GB-6A

and 2000-lb bombs capable of being steered by remote radio control in azimuth only and hence called "Azon" by Division 5. The VB-3 and VB-4 are 1000-lb and 2000-lb bombs capable of being steered in both range and azimuth and hence called "Razon" by Division 5. In all four cases the complete mechanism is in a tail assembly which is attached to standard general-purpose bombs by the existing fin mounting threads. The VB-5 is a 1000-lb bomb equipped with a light-seeker. The VB-6 is a 1000-lb bomb equipped with the Bemis heat-seeker and designated as "Felix" by Division 5. The VB-7 and VB-8 are 1000-lb and 2000-lb bombs equipped with television and controlled remotely by radio. The VB-9, VB-10, VB-11, and VB-12 use the NDRC "Roc" vehicle, with radar-homing, television, heat-homing, and direct visual control respectively.

The Azon tail assembly consists of a tail with four fins, each of which contains a control flap. The horizontal pair are controlled by displacement and rate gyros to prevent rolling, while the vertical pair are operated remotely by radio as rudders to steer the bomb from right to left. The Razon assembly consists of an octagonal tail. Flaps on the supporting struts are gyro-controlled, as in Azon, to prevent rolling. Flaps on the horizontal and vertical surfaces constitute elevators and rudders, remotely controlled by radio. An additional octagonal shroud about eight inches long has been mounted forward of the octagonal tail in order to increase maneuverability. The Razon-type tail is also used on the VB-5, VB-6, VB-7, and VB-8.

The 1000-lb Azon VB-1 has been used in combat. The ideal targets are bridges, railways, roads, etc., where range errors are unimportant. The point of impact can be moved from 2000 to 3000 ft by the operator who observes the bomb visually. A flare on the tail of the bomb enables the operator to follow the bomb all the way to the ground. The standard bombsight is used for range. An accuracy of a few feet is obtained by well-trained operators. The combat experience has been good when the weapon was used as intended and when enemy opposition has not been severe.

Good use has been made of the VB-1 in the Burma theater. Some 1357 were dropped against communication targets between 27 December 1944 and 24 August 1945, with 12% direct hits. The average errors were 131 ft in azimuth and 201 ft in range. Forty-one bridges were destroyed and 12 damaged.

The VB-2 has been engineered for production and tested. The VB-3 completed development tests, showing a maneuverability of 2650 ft and was about to be used operationally when the war ended. Special sighting devices have been found desirable for the VB-3. A probable error of 50 ft in range and 20 ft in azimuth is expected. Design of the VB-4 was postponed pending completion of the VB-3 development.

The VB-5 has been used only for experimental purposes.

A "crash" program was instituted on the heat-seeker, VB-6, to secure 1000 missiles. In 12 experimental drops on an artificial target a mean circular probable error of 85 ft was obtained.

The VB-7 and VB-8 did not reach the test stage.

Tests by Division 5 of the National Defense Research Committee have shown that radar homing is inoperative in high-angle bombs because of fundamental charac-

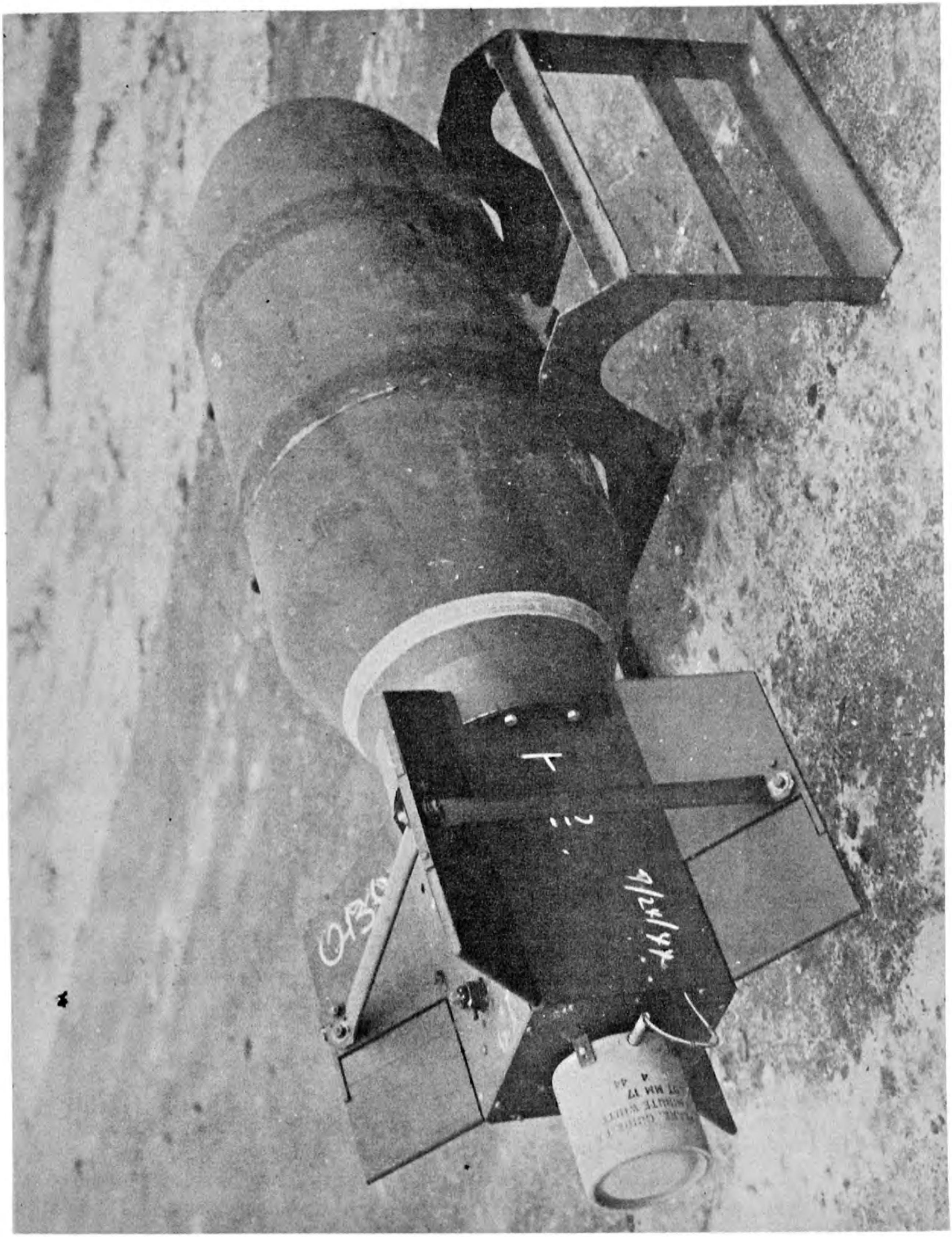


Figure 4 — VB-1

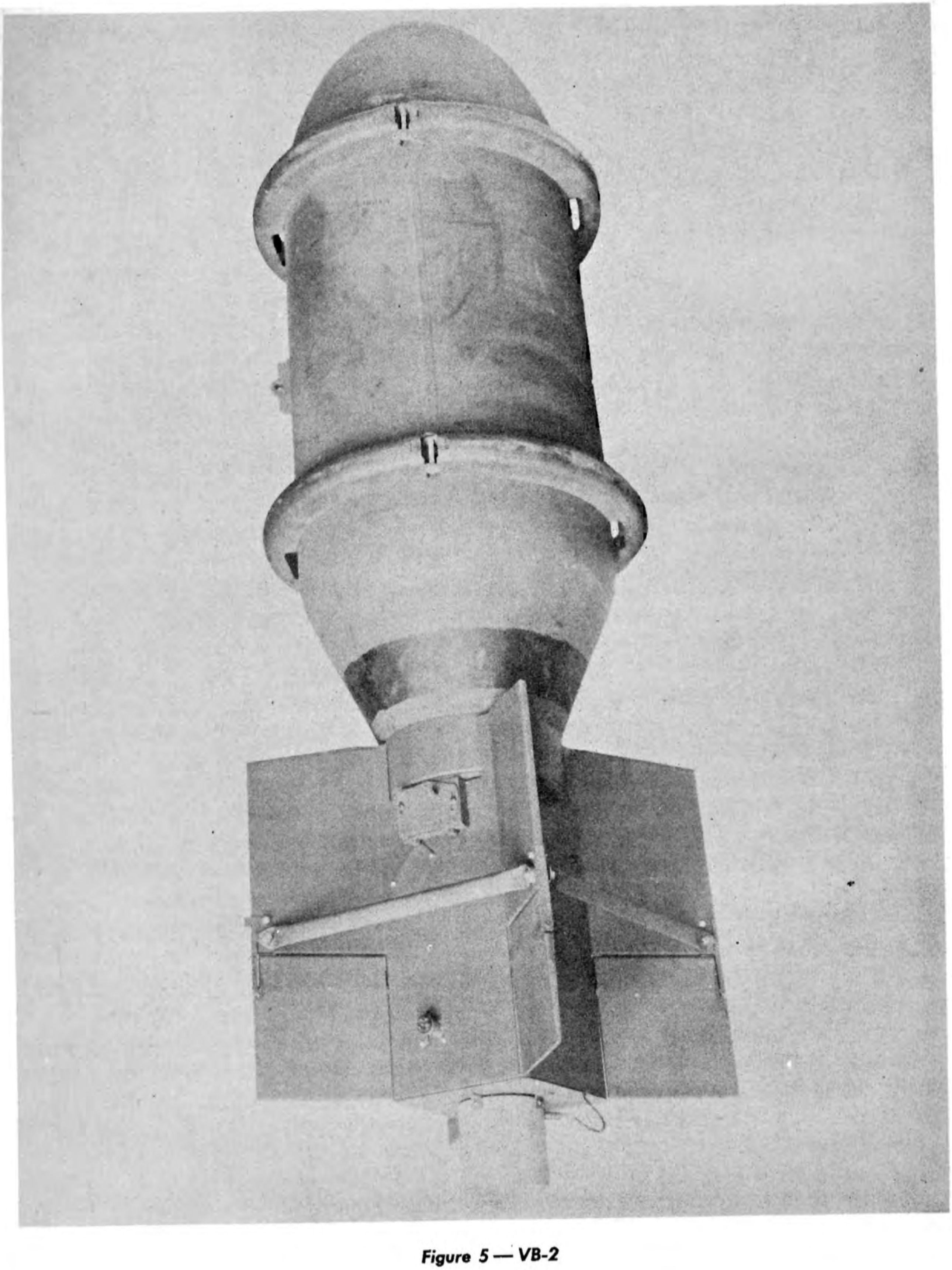


Figure 5 — VB-2

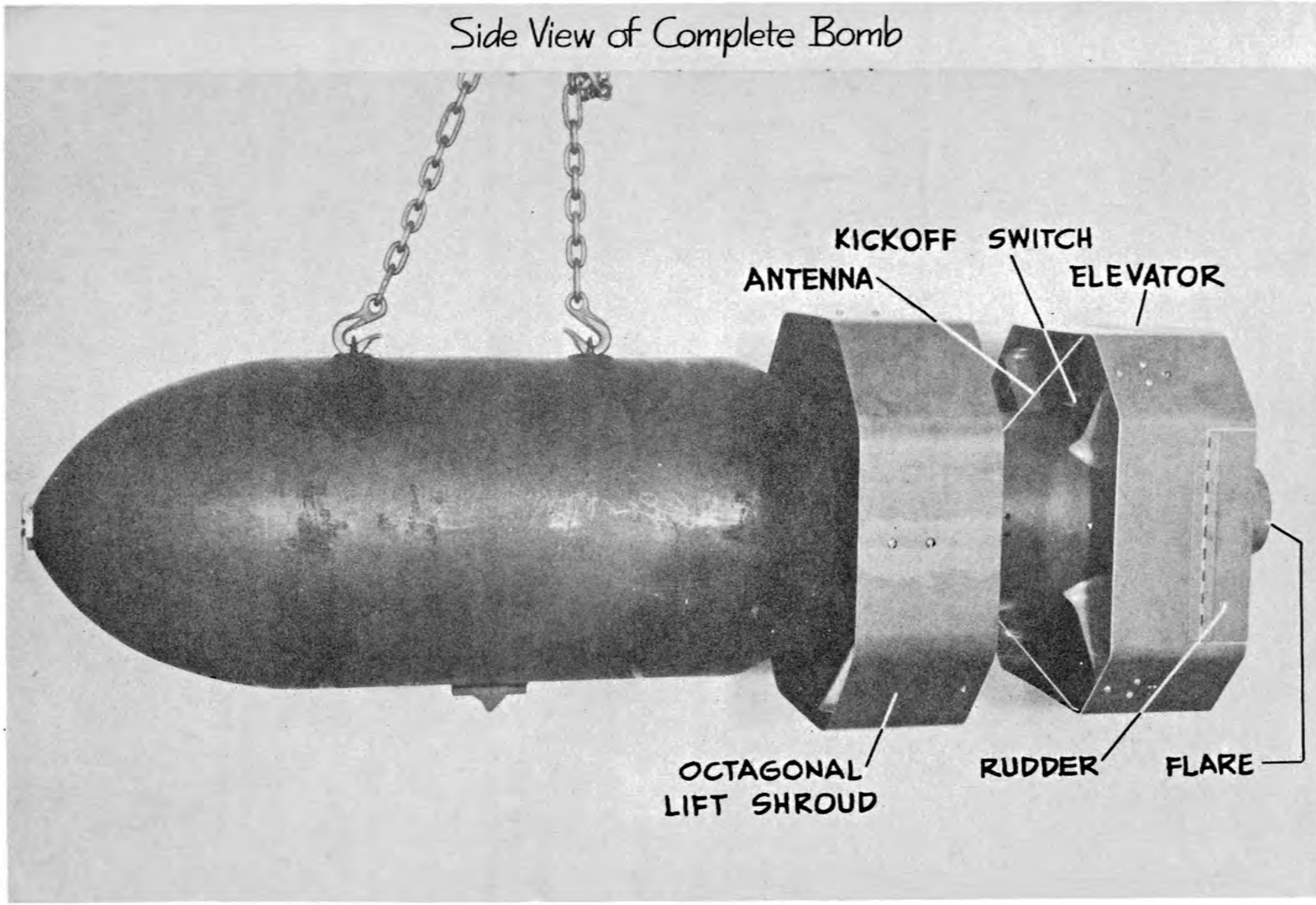


Figure 6 — VB-3 — Mark IV

teristics of radar reflections from target and background at high angles. Hence the VB-9 would be inoperative.

The newest model of the Roc vehicle, VB-12, has been drop-tested and its use has been explored to some extent. Some VB-10 tests have been made. Work on the VB-11 was suspended until a heat-homing device with suitable output is available.

The Rox vehicle is a bomb of symmetrical design with a cylindrical wing or shroud of airfoil section which can be rocked about the yaw or pitch axis for control. The tail is fixed and the missile is so proportioned that the change in angle of attack with application of control is negligible. The missile is stabilized in roll by four ailerons located in the tail structure.

GLOMB (NAVY, BUREAU OF AERONAUTICS)

These missiles are towed gliders fitted with television repeat-back and remote radio control. The pay load is a 2000-lb general-purpose or a 4000-lb light-case bomb. Characteristics of three experimental designs are as follows:

Designation	*Gross Weight lb*	*Span ft*	*Over-all ft*	*Length in.*	*Wing Area sq ft*	*Speed mile/hr*
LBT	3930	35	25	2	181	314
LBP	6900	33	28	9	173	300
LBE	7138	32-1 2	29	1-1 2	202	300

(Results of evaluation tests were not available when this document was prepared.)

GARGOYLE (NAVY, BUREAU OF AERONATUCIS)

This missile is a rocket-accelerated, air-to-ground winged missile remotely controlled by radio by an operator following the missile visually from the aircraft. The missile is 10 ft long and has wings of 8 ft, 6 in. span and 17 sq ft area. The gross weight is 1517 lb, the pay load a 1000-lb SAP or GP bomb. The rocket is a solid-fuel 8AS 1000 ATO unit giving a thrust of 1000 lb for 8 sec. The terminal speed of the missile is 690 mph. When dropped from 16,000 ft in a 30° glide path, the range is 27,000 ft. Drop tests of this missile are now in progress.

PELICAN SERIES (NAVY, BUREAU OR ORDNANCE)

This series of missiles consists of glide bombs of three sizes with RHB radar homing. In this type of control the target is illuminated by radar impulse from an ASG search radar forming part of the standard equipment of the carrying aircraft. The missile carries a radar receiver which picks up echoes from the target and homes on their source. Provision is made for range discrimination so that any one of several targets may be selected if they are separated by more than from 500 to 1000 ft.

The glider is controlled by elevons, i.e., wing flaps, which are moved together to control the path in a vertical plane and differentially to give banked turns. The aerodynamic design is such that the angle of attack is practically constant, independent of control position. This is accomplished by suitable tail and center of gravity location which give moments on the tail due to downwash changes which counterbalance the moments produced by the wing flaps.

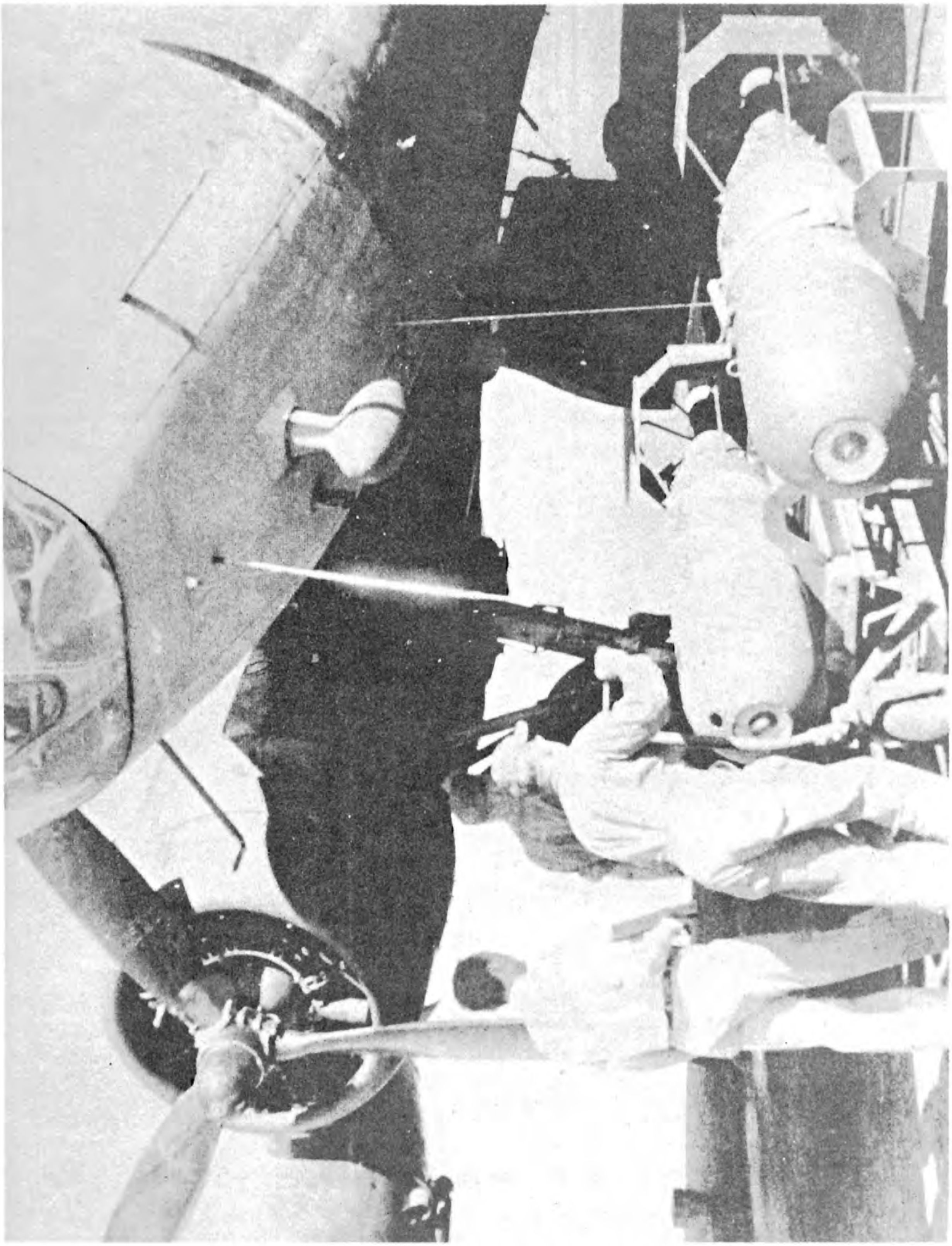


Figure 7 — VB-6 Felix Ready to Load in a B-17 Bomber

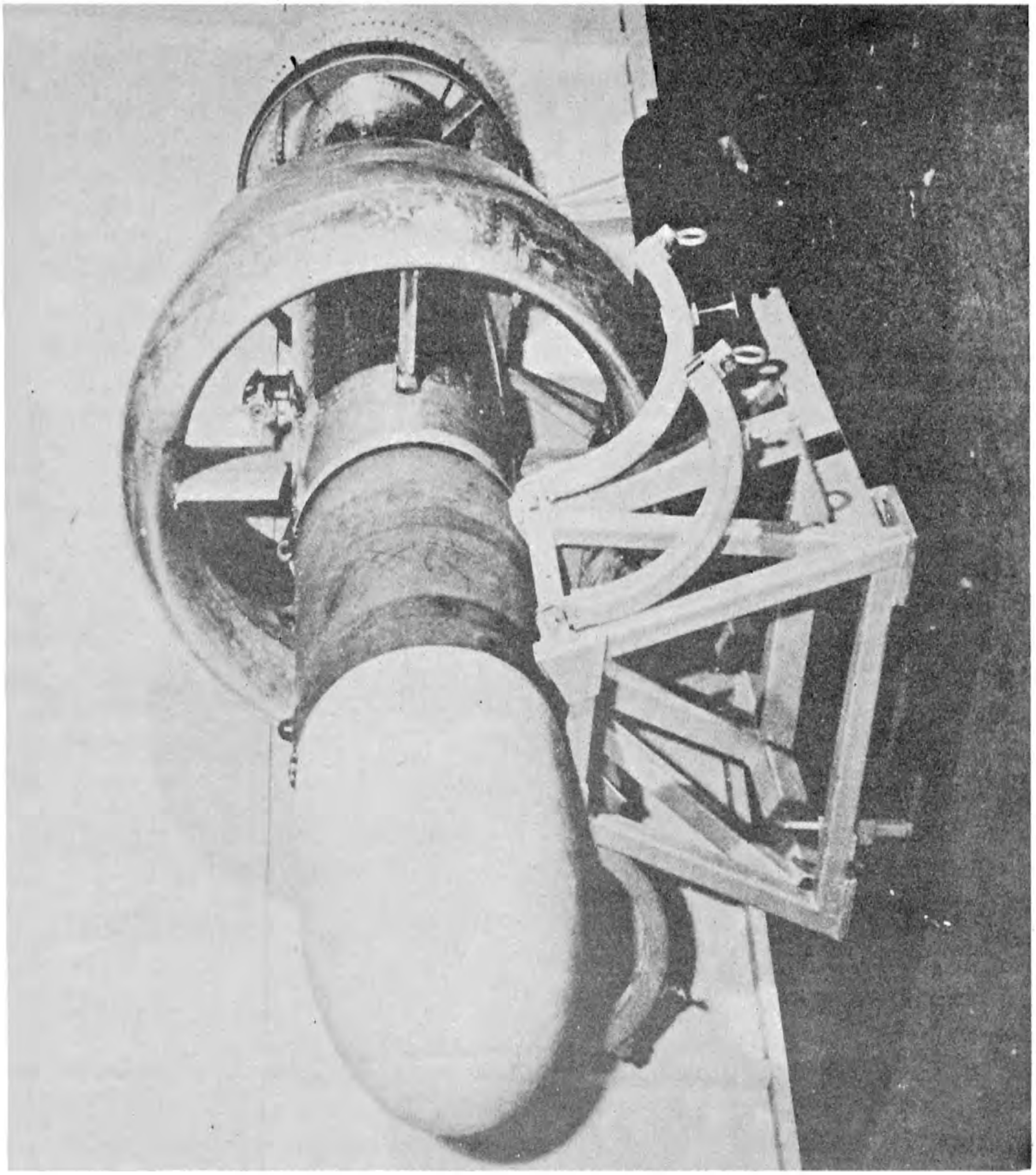


Figure 8 — Cylindrical Wing Roc — Wing in Neutral Position

The following missiles have been developed:

Designation	*Wing Span*		*Total Weight*	*Pay Load*
	ft	*in.*	*lb*	
SWOD Mark 7 Mod 0	8	5	725	325-lb depth charge
SWOD Mark 7 Mod 1	8	5	900	500-lb bomb
SWOD Mark 8 Mod 0	10		1500	1000-lb bomb

A 12-ft glider has also been developed to carry a 2000-lb bomb.

Tests of these models were quite successful, about 40% hits being secured on a Liberty ship from a range of 10 miles. The mean circular probable error for a point target is about 150 ft. However, in view of the Bat Development, which was nearly ready, decision was made not to use this type of missile in combat at that time. The RHB missiles require the releasing aircraft to make a steady 360° turn, while the radar operator keeps the target illuminated until the missile has struck. The Bat missile is entirely self-contained and the releasing aircraft may take evasive action immediately after release. The range of the Pelican is somewhat greater and it may eventually be demanded if radar-homing missiles are found tactically useful.

BAT SERIES (NAVY, BUREAU OF ORDNANCE)

This series of missiles consists of glide bombs with SRB radar homing. The missile carries a radar transmitter and receiver and functions in the same manner as the Pelican except that the missile is entirely self-contained. The equipment is too large to be accommodated with a useful pay load in the 8-ft, 5-in. glider. The first one developed was SWOD Mark 9 Mod 0, of 10-ft span, total weight 1600 lb, pay load 1000-lb bomb. The accuracy is about the same as that of the Pelican, the mean circular probable error being about 150 ft. Extensive tests have been made against ship targets and combat evaluation tests are in progress.

The second member of the series, with a 2000-lb bomb as pay load, has been designed and drop tests will soon be made.

It is expected that with further development the accuracy will be substantially improved.

DOVE (NAVY, BUREAU OF ORDNANCE)

This missile is a heat-homing high-angle bomb. The equipment is contained entirely in a nose assembly attached to a standard 1000-lb bomb. Since the presence of this assembly impairs the stability of the standard bomb, the standard fin assembly is replaced by a somewhat larger fixed fin assembly.

The nose assembly is attached to the body in a manner to permit rotation about the longitudinal axis of the bomb so that the nose may be gyrostabilized to prevent its rotation. The aerodynamic controls are four spoilers which are projected outward from the nose to direct the axis of the bomb to right or left and up or down.

The thermal detector is gyro-mounted and its output precesses the gyro until the target is in the center of the field. The aerodynamic controls are actuated by the current supplied to the precession motors and hence change the course only if the target moves away from the center of the field of view. The missile would accord-

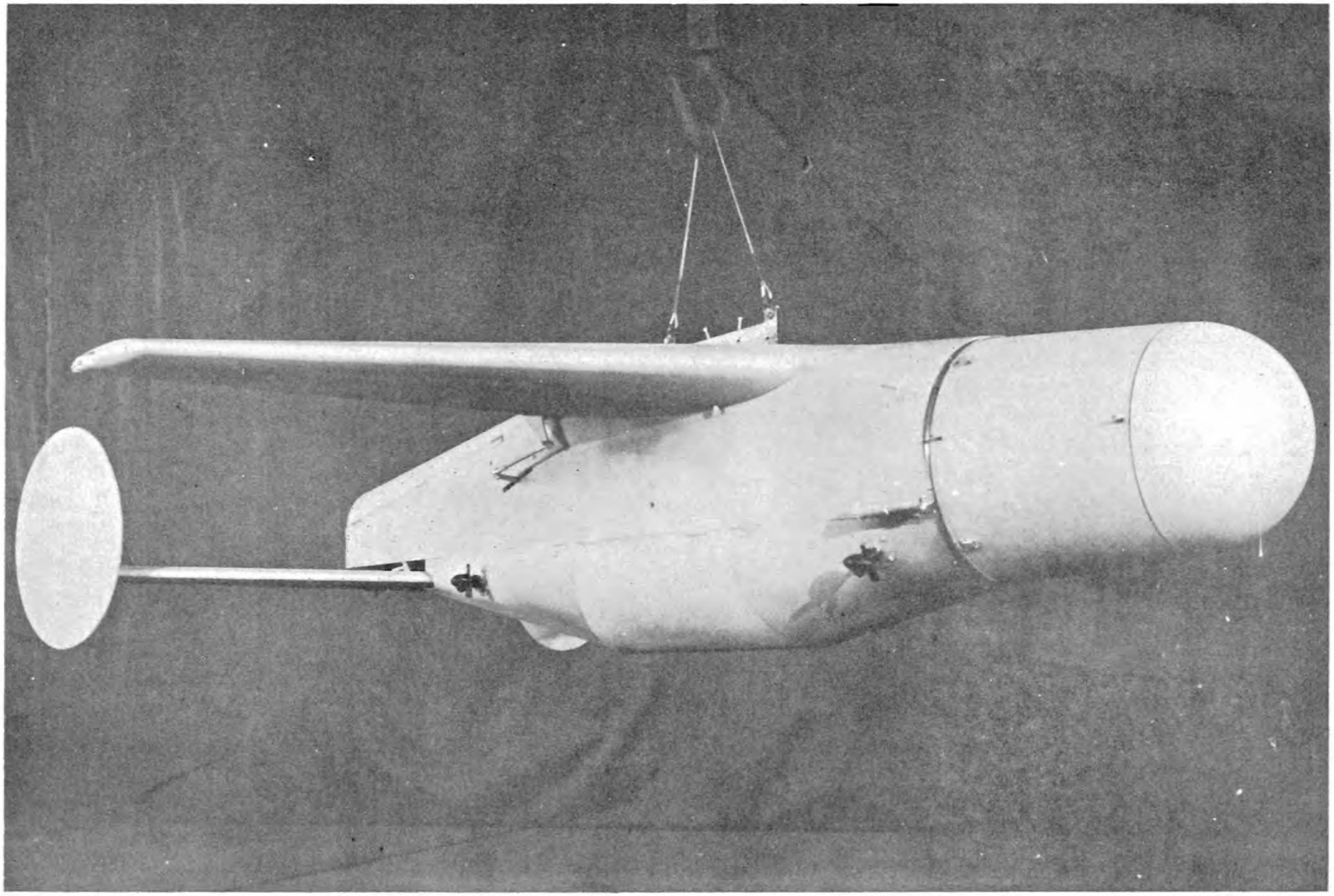


Figure 10 — Bat SWOD Mark 19 Mod O

ingly follow a collision course. Compensation for the effect of gravity is made by a special signal-generating device wich precesses the gyro in the vertical plane.

Drops have not yet been made with the complete assembly. Aerodynamic test drops have shown that the point of impact can be moved about 1500 ft for drops from an altitude of 10,000 ft, which is the point at which the thermal control is designed to take over.

GROUND TO GROUND MISSILES

V-1 (GERMAN)

This well-known missile is a winged missile propelled by a new form of motor usually termed an "aeropulse" motor. It is launched either from the ground or from an aircraft. Ground launching as practiced by the Germans utilizes a long gun in which the working substance is the steam resulting from the catalytic action of calcium permanganate on a concentrated solution of hydrogen peroxide. The length of the special gun and ramp varies from 140 to 170 ft at different sites.

The pay load is 1870 lb of explosive, the range from 120 to 160 miles, and the circular probable error is about five miles at a range of 130 miles when ground-launched. The error is five times as great for air-launching. The over-all weight is about 5000 lb. Attacks on London with this weapon began in the early morning of 13 June 1944. Between this date and 3 September 1944, 8205 missiles were launched. Some 5471 crossed the coast, of which 3750 were destroyed, and 2354 landed within the area. The casulaties were 5476 killed, 15,918 seriously wounded, 29,812 slightly wounded. About 23,000 houses were destroyed and 1,104,000 damaged. In attacks on launching sites, 26,000 aircraft dropped 73,000 T of bombs; 197 aircraft and 1462 men were lost. During the last week the effectiveness of countermeasures had increased to the point where only 9% landed within the area as compared to an average of 29% for the entire period.

The missile flies at an approximately constant altitude of about 2000 ft at speeds varying for individual missiles from 288 to 425 mph. Control is by means of an autopilot monitored by a compass and an altimeter. Fuel supply is controlled by means of an altitude- and speed-sensitive valve. The range is determined by an air log which shuts off the fuel and sets a dive flap to dive the missile at a steep angle to the ground.

The motor is a new development. It consists of a tube with an ingenious grid of bent strips of metal at the front end forming a spring-loaded valve. Following an explosion of a fuel-air mixture within the tube, the reduced pressure combined with the pressure against the front of the grid produced by the forward speed of the missile opens the valve and permits air to enter. Fuel is simultaneously injected. The following explosion closes the valve and discharges the products of combustion through a nozzle at the rear. The explosion frequency is of the order of from 45 to 50 cps. The life of the motor is just sufficient for the flight of the missile.

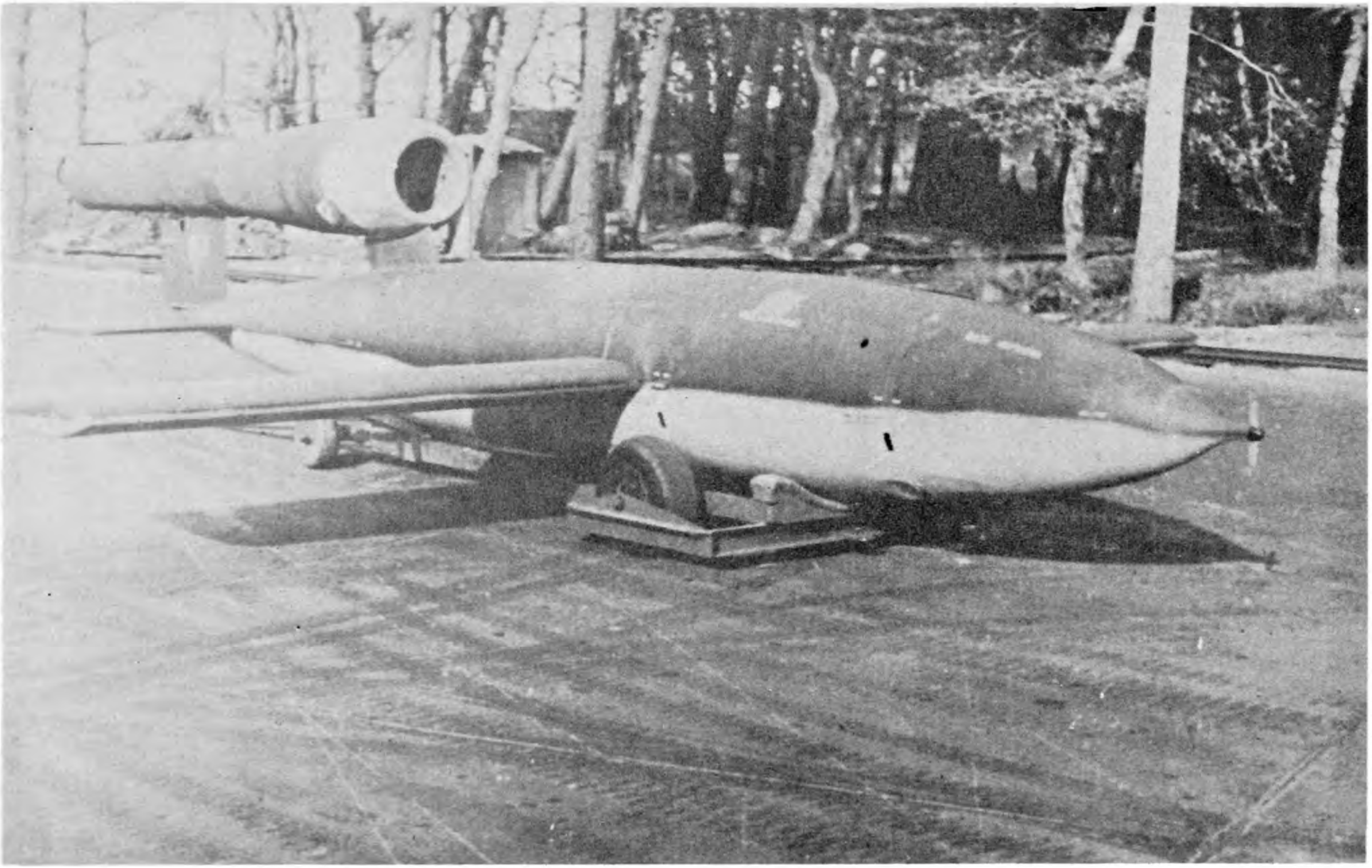


Figure 11 — Buzz Bomb V-1

The missile itself has an over-all length of 25 ft 4-1/2 in. including a 3-ft 6-in. overhang of the propulsion unit which is above the main structure of the missile. The wing span is 17 ft 8 in. and the wing area 60 sq ft. The aspect ratio is 5.2. The propulsion unit is 11 ft 5-1/4 in. long and 1 ft 9-3/4 in. in maximum diameter. The fuel capacity is from 150 to 160 gallons.

V-2, A-4 (GERMAN)

The German missile V-2, originally designated as A-4, is a large fin-stabilized rocket 5-1/2 ft in diam and 45 ft, 10 in. long, weighing at launching 12.2 T. The pay load is 1620 lb of explosive and the range about 200 miles. The rocket was first used on 8 September 1944. Between 8 September and 23 December 380 rockets fell in England and 1120 on the continent. At 200-mile range the circular probable error is of the order of 10 miles.

The rocket is launched under its own power. Connected with a bypass, the rocket motor delivers a thrust of 30,000 lb, without the bypass 68,500 lb of thrust for 65 sec. The motor uses alcohol and liquid oxgyen, the fuel capacity being 7610 lb of alcohol and 10,930 lb of liquid oxygen. The rocket takes off at reduced thrust, travels vertically upward for a short time, after which the thrust is increased to its full amount. A gyroscope then operates control vanes in the rocket jet and on the stabilizing fins until the trajectory makes an angle of from 33° to 39° to the horizontal about a minute after launching. The fuel supply is shut off when the speed reaches about 5100 ft/sec. There is no control of the path after burning stops. The rocket rises about 50 to 60 miles above the surface of the earth. Its speed falls to about 2500 ft/sec in its descent through the earth's atmosphere. Impact occurs about five minutes after launching. Since the speed is supersonic, nothing is heard until the rocket has landed and exploded. There are no effective countermeasures other than attack on the launching parties.

A-9 AND A-10 (GERMAN)

The A-9 was essentially the same rocket as the A-4 or V-2 provided with four small wings. It was computed that the use of wings would increase the range of the A-4 to about 400 miles. The A-10 was a design study of a launching rocket to be used with the A-9 to secure a range of 3000 miles. The total weight of the A-10 was 190,000 lb of which about 140,000 lb was fuel. Its thrust was 440,000 lb for 50 sec. It was nearly 12 ft in diameter and 25 ft long. The 29,000-lb A-9 was to be accelerated to a speed of 3600 ft/sec by the use of the 190,000-lb A-10 as launching rocket. The rocket motor of the A-9 would then be turned on and increase the speed to 8600 ft/sec. The explosive load would be about 1% of the starting weight.

JB SERIES (ARMY AIR FORCES)

Wright Field is developing a series of self-propelled missiles for various applications under the designation JB, denoting jet bombs. The JB-2 is a Chinese copy of the German V-1. Various alternate launching methods are under investigation. A large number of successful flights have been made. The total weight is 5000 lb, the weight of explosive is 1860 lb, the range is 150 miles, and the speed is about 400 mph. The bomb is equipped with a radar beacon so that it can be tracked up to 100 miles and is also fitted with remote radio control. The estimated accuracy which can finally be obtained is one-fourth mile at 80 miles.

All other members of this series are in the design stage or early experimental stage. JB-3, also called Tiamat, is an air-to-air radar-seeker, total weight 625 lb, carrying a 150-lb fragmentation bomb, design speed 600 mph, range 10 miles.

The JB-10 is an aircraft of the flying-wing type propelled by an intermittent jet engine. The gross weight is 7213 lb of which 3209 lb is explosive. The design speed is 400 mph and the range 200 miles. This project is in the early experimental stage.

BQ AND WILLIE SERIES (ARMY AIR FORCES)

The BQ series of missiles are pilotless aircraft especially designed as power-driven bombs while the Willie series is old war-weary aircraft, B-17's and B-24's, fitted with remote-control devices.

A number of experimental pilotless aircraft have been constructed as shown in the following table:

Designation	*Pay Load, lb*	*Speed, mph*	*Range miles*
XBQ-1	2000	230	3200
XBQ-2A	2000	179	1725
XBQ-3	4000	220	1500
XBQ-4 (Navy XTDR-1)	2000	140	425
XBQ-4 (Navy XTD2R-1)	2000	230	1470

This type of missile has been abandoned because of production and procurement difficulties, expense, difficulty of tactical use, and vulnerability.

The Willie project involves loading up war-weary bombers with 20,000 lb of explosive, and taking them off with a pilot who bails out at a suitable time. The aircraft is then remotely controlled into the target. Various methods are under trial including remote radio control with television repeat-back and remote radar control from a ground station using a radar beacon on the aircraft, and an SC584 or similar tracking set with mapping attachment and other modifications. So far as flight performance is concerned, extreme ranges up to 3000 miles could be secured but the control methods now available are limited to about 200 miles from the control station, which may, of course, be another aircraft. The number of missiles which can be handled at one time is limited. Combat evaluation has not been completed. The speed is comparatively low and the missile is undefended.

ORD-CIT (ARMY ORDNANCE, CALIFORNIA INSTITUTE OF TECHNOLOGY) PRIVATE, WAC PRIVATE, AND CORPORAL

The Ord-Cit program looks toward the development of a large rocket, accelerated in the early part of its flight but traveling as a free projectile thereafter, i.e., similar in general performance to the V-2 German missile. Experiments have already been made on the "Private," the name given to Ord-Cit missile XF10S1,000, with a firing weight of 550 lb and a nitric acid - aniline rocket motor giving a thrust of 1100 lb for 30 sec. The missile is launched with four 4-1/2 in. Army rockets giving a thrust of 2800 lb for 0.2 sec. The launching velocity is about 230 ft/sec, the maximum velocity 1100 ft/sec and the range 11 miles. The specific impulse of the fuel is 180 lb/lb/sec. The impulse weight ratio of the rocket motor alone is 89 lb/lb/sec.

Design and construction are in progress on the "Corporal," Ord-Cit missile XF30L20,000. The firing weight is 10,000 lb and the rocket motor gives a thrust of 20,000 lb for 60 sec. It is to be launched vertically under the power of the main motor as in the case of the V-2. It is expected to have a maximum speed of 3300 ft/sec and a range of 80 miles

There has also been designed and constructed an 0.4 scale model of the "Corporal," called "Wac Corporal," Ord-Cit missile XF12L1,000, which could attain an altitude of about 110,000 ft if launched vertically with 25-lb pay load. This missile is intended for meteorological studies. The firing weight is 700 lb and the motor gives a thrust of 1500 lb for 44 sec. The launching velocity is about 400 ft/sec.

All of the Ord-Cit missiles are of the same general form consisting of a 20° conical head, a cylindrical body with 6° boat-tail at the rear end for a length equal to one-half the diameter. The over-all length is about 14 times the diameter. The missile is provided with three or four fins. It is expected to use a simple autopilot to maintain the azimuth of the trajectory in the earlier experiments.

Wind-tunnel experiments at supersonic speeds are in progress at the supersonic wind tunnel of the Ballistics Research Laboratory at Aberdeen Proving Ground.

HERMES (ARMY ORDNANCE, GENERAL ELECTRIC COMPANY)

This project covers the general development of long-range guided missiles suitable for use against ground targets and high-altitude aircraft. The missiles are to be propelled by rockets or ramjets. The project includes work on propulsion, remote-control equipment, stabilization equipment, ground-station and launching equipment, fire-control devices, and target-seeking devices. The plan of operation contemplates three phases: (1) the collection and evaluation of information on guided missiles and associated apparatus; (2) a scientific mission to Germany to survey German developments and obtain samples of weapons and components; and (3) the submission of designs for ground and antiaircraft missiles having military characteristics desired by the Army, and, when approved, the building of prototypes for test firing, and, if requested, preparation of manufacturing plans. The first and second phases are now practically completed.

TDR SERIES (NAVY, BUREAU OF AERONAUTICS)

These missiles are pilotless aircraft, or drones, identical in purpose with the Army BQ series. The first of the series, TDR1, was powered by two Lycoming, 6-cylinder, 220-hp engines. Its gross weight was 6300 lb, speed 155 mph, ceiling 10,000 ft, rate of climb 800 ft/min, range 470 miles, pay load 2000-lb bomb. A later model, TD3R, is powered by two Wright 4-cylinder 450-hp engines, has a gross weight of 10,500 lb, speed 185 mph, ceiling 10,500 ft, rate of climb 750 ft/min, range 900 miles, pay load 2000-lb bomb. The span of this model is 48 ft and its over-all length 39 ft 4-1/2 in. The missiles are fitted with television repeat-back and remote radio control. Extensive evaluation tests have been made. The general feeling appears to be that missiles of this type are not tactically useful.

AIR TO AIR MISSILES

Hs-298 (GERMAN)

Hs-298 is an air-to-air rocket-propelled winged missile designed by the Henschel Company under the direction of Herbert Wagner. About 100 missiles were built and tested. The gross weight is 264 lb of which 106 is war head. Propulsion is by a dry-powder rocket weighing 73 lb and giving a thrust of 110 lb for 31 sec. The missile is approximately 15 in. in diameter, 129 in. long, with wing span of 51 in. The speed is about 790 ft/sec, the vertical range about 0.8 mile, the horizontal range about two miles.

The missile was to be controlled by direct sight using a radio-control link or a direct-wire connection as described for X-4.

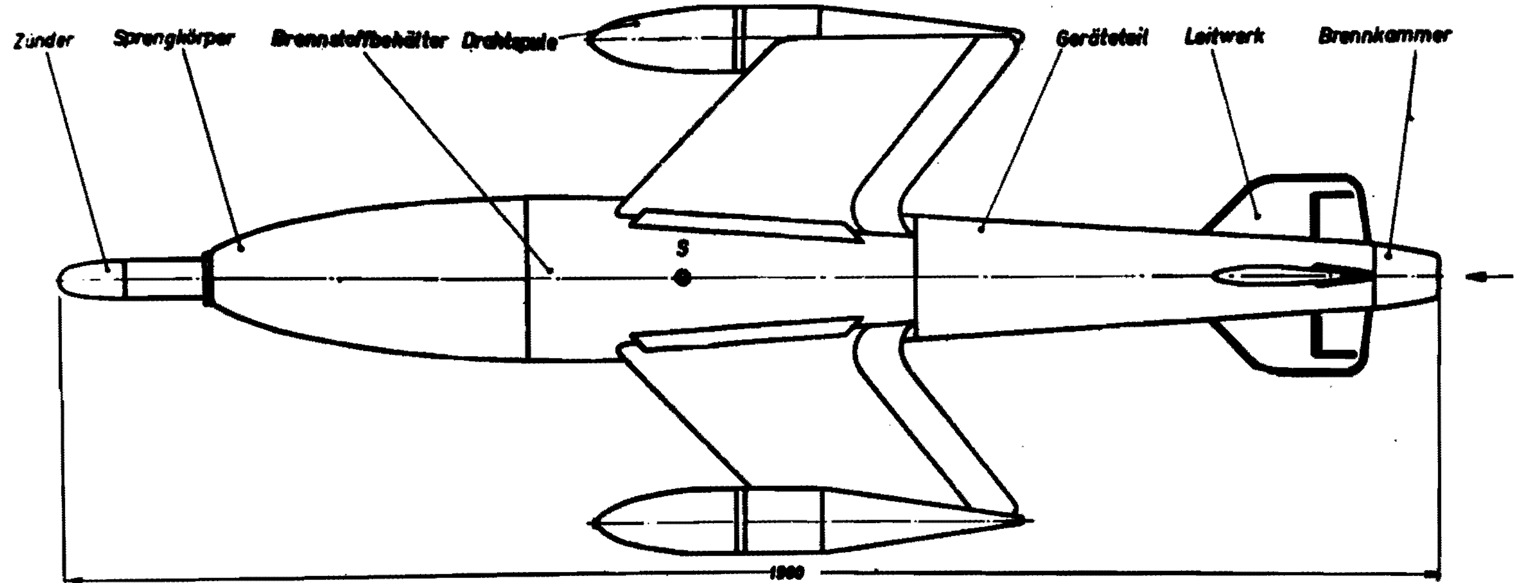
X-4 (GERMAN)

The air-to-air rocket-propelled winged missile X-4 was designed by Max Kramer beginning in June, 1943. About 250 missiles were built and about 150 tested. The gross weight is 132 lb of which 44 lb is war head. Propulsion is by means of a liquid-fuel rocket weighing 31 lb (empty) and giving a thrust of 242 lb for 17 sec. About 19 lb of fuel were provided. The missile is approximately 75 in. long, 8.7 in. in diameter, with wing span of 23 in. The speed is about 790 ft/sec, the horizontal range about 1.2 miles.

The missile has four sharply swept-back wings near the center of gravity and four tail fins. Aerodynamic control is by means of spoilers on the tail fins. Tabs on the wings cause the missile to spin. Two of the wings carry at the tips spools of fine wire 0.009 in. in diameter and long enough to permit a range of about three miles while maintaining direct-wire connection to the control aircraft. A gyrostabilized commutator in the missile and a suitable filter system permit direct electrical transmission of the control from the operator to the spoilers on the control surfaces of the missiles by means of the connecting wires which can feed out at speeds of more than 650 ft/sec.

A document dated 11 January 1945 stated that 130 trials had been made. It was stated that the missile was in the early testing stage to prove its fundamental correctness of functioning. At one time the Air Ministry had a requirement for 5000 missiles by the middle of 1945 but this was later reduced. In February, 1945, SS leader Kammler ordered a lower priority and the closing out of the project at the end of the development period.

Kramer designed an acoustic proximity fuse for this missile known as "Kranich." About 30 were built and some preliminary fly-over and fly-by tests were made. The effective range was expected to be 45 ft. The tests which had been completed were promising. Work was also under way to develop an acoustic homing device with a hoped for range of from 1650 to 3300 ft.



Ansicht in Richtung „A"

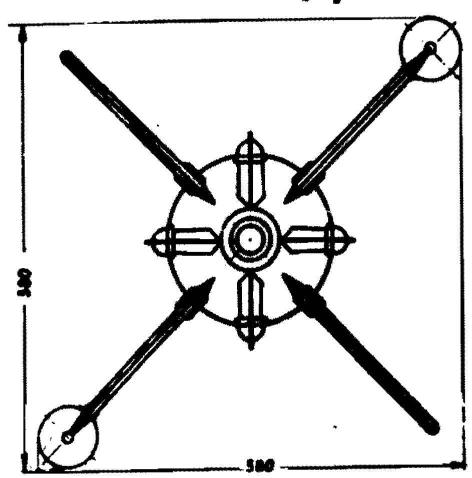


Abb.1: Gesamtansicht des Gerätes „X 4"
M.1:5

Figure 12 — X-4

GORGON (NAVY, BUREAU OF AERONAUTICS)

Gorgon is an air-to-air self-propelled winged missile remotely controlled by radio either on the basis of direct-sight visual information or television repeat-back. The power plant is either a liquid-fuel nitric acid - aniline rocket giving a 340-lb thrust for 118 sec or a Westinghouse 9-1/2 in. turbojet motor. The wing span is 11 ft, the over-all length 14 ft, 4-1/2 in., the wing area 20 sq ft, the total weight 971 lb, the explosive load 100 lb of torpex, the speed 490 mph, and the range 20-25 miles. Two designs are being studied, one a canard or tail-first design, the other a conventional design. The first tests are now being made.

LARK (NAVY, BUREAU OF AERONAUTICS)

This missile is an air-to-air or ground-to-air antiaircraft rocket, under development. According to the information available ground launching would be made by a catapult. Radio control and radar homing are contemplated. The weight will be about 1200 lb and the speed about 600 mph.

GROUND TO AIR MISSILES

ENZIAN (GERMAN)

Enzian was one of several ground-to-air rocket-propelled winged missiles under development as a defense against bomber formations. It was designed by Dr. Wurster, chief test pilot of Messerschmitt. There were several designs and 60 missiles of all types had been built of which 38 had been tested. The E-4 had a launching weight of about 4000 lb of which 1100 lb was in the war head. The missile was launched with the aid of four solid-fuel rockets weighing 700 lb and giving a thrust of 13,200 lb for 4 sec. The main propulsion unit was a Conrad liquid-fuel rocket weighing 200 lb (empty) and giving a thrust decreasing from 4400 to 2200 lb over a time interval of 73 sec. About 2000 lb of fuel was provided for this motor. The missile is about 35 in. in diameter, 143 in. long and had a wing span of about 158 in. The maximum speed is about 1000 ft/sec, the vertical range about 10 miles, and the horizontal range about 15 miles.

The design is similar to that of the Me-163 airplane which has no horizontal tail surface. In the tests a conventional radio control was used. It was intended to use an acoustic or infrared-homing device. A supersonic version E-5 had been designed but not built or tested. The work on this development as well as other guided rockets was stopped early in 1945 in favor of concentration on small unguided rockets because of the critical condition of manpower and materials caused by the successful bombing raids of the Allies.

RHEINTOCHTER (GERMAN)

Rheintochter was an antiaircraft rocket developed by Rheinmetall-Borsig, also for defense against Allied bombers. There were several versions. The Rheintochter 1

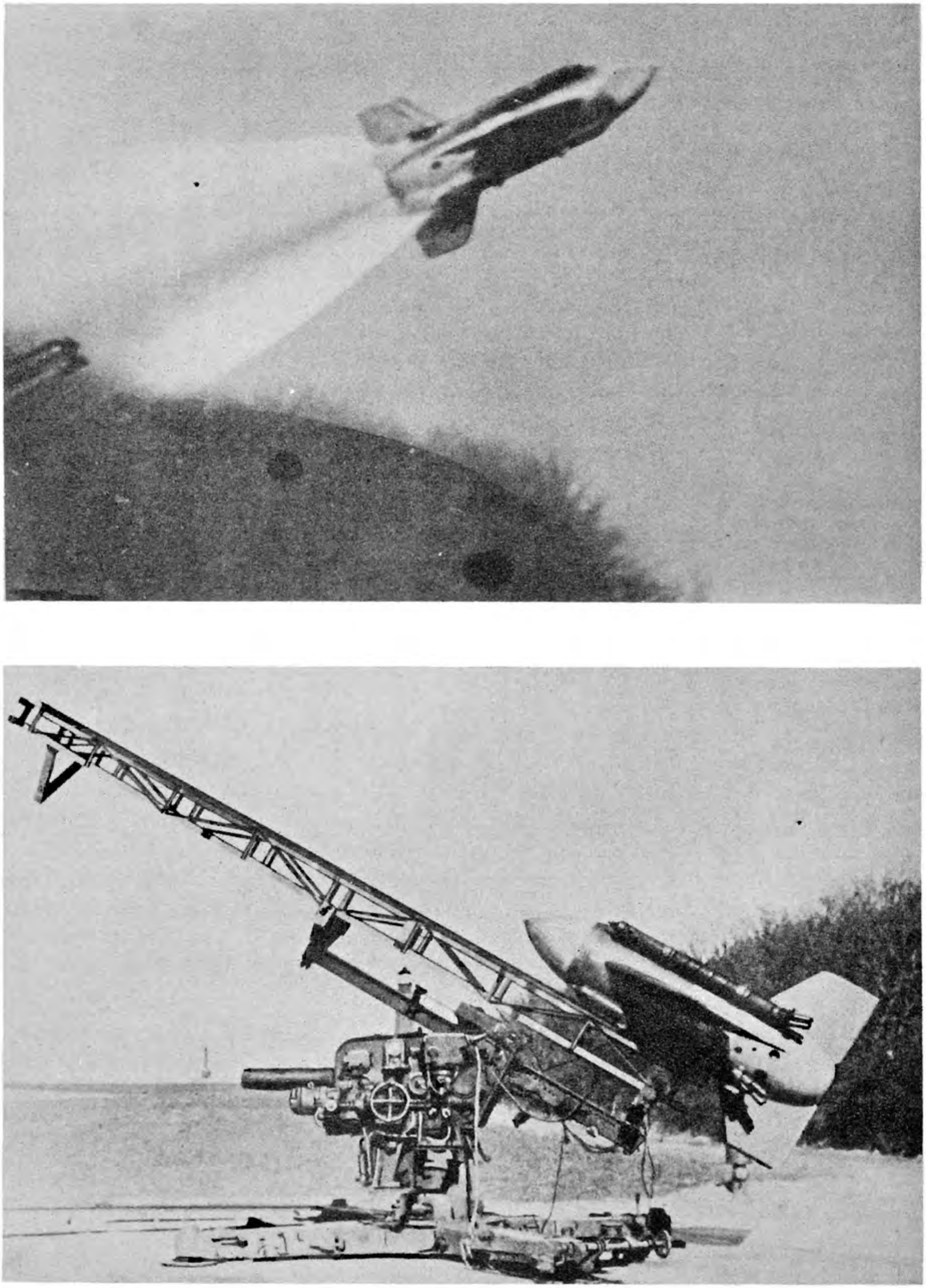


Figure 13 — Enzian

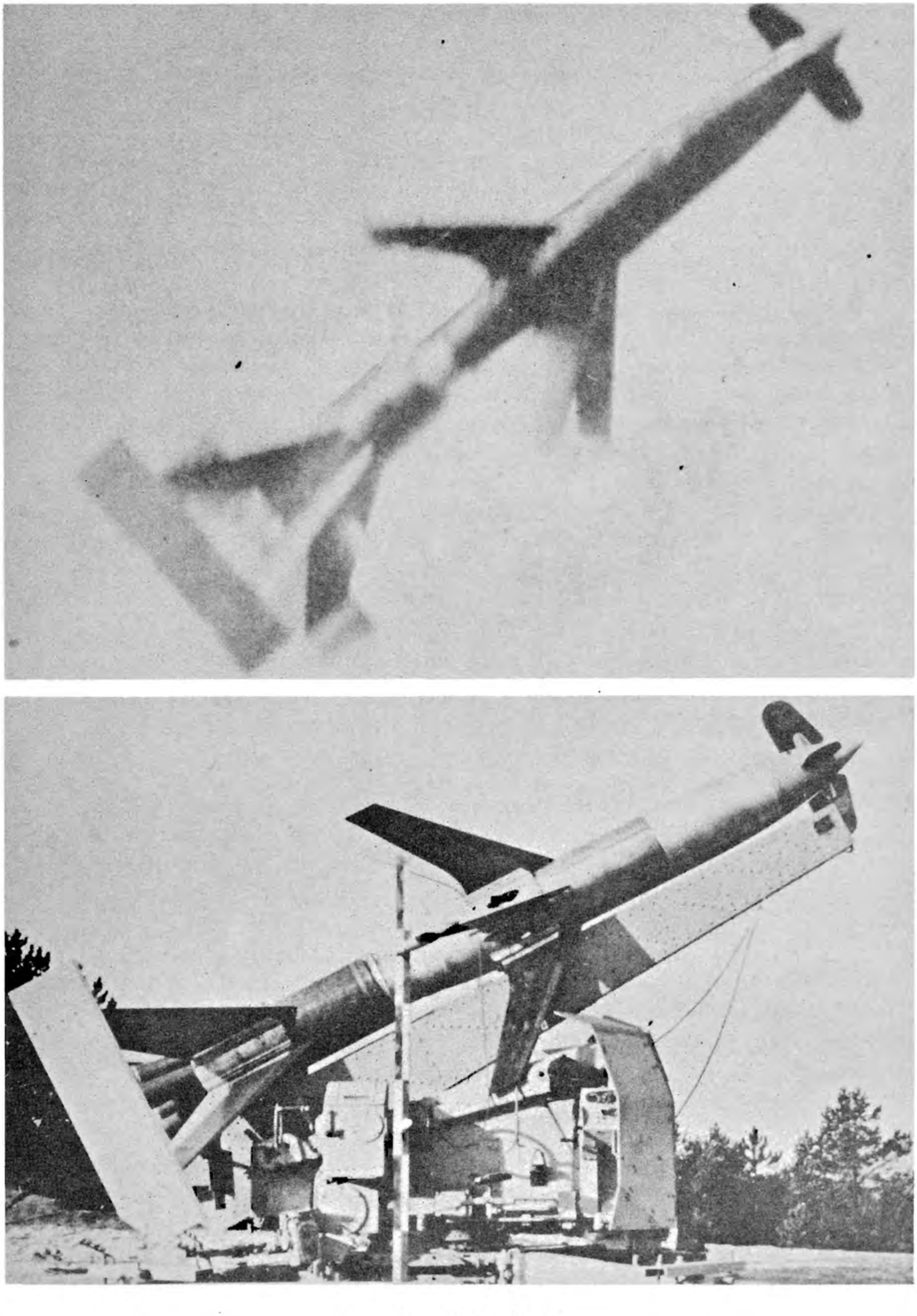


Figure 14 — Rheintochter I

had a launching weight of 3850 lb of which only 330 lb was in the war head. The missile was launched with the aid of a solid-fuel rocket weighing about 1400 lb giving a thrust of 165,000 lb for 0.6 sec. The main propulsion unit was also a solid-fuel rocket weighing 484 lb giving a thrust of 8800 lb for 10 sec. The missile was about 21 in. in diameter, 158 in. long without launcher, 248 in. long with the launcher which was a pusher body with four fins containing the take-off rocket. The missile had six sharply swept-back wings. It attained a speed of about 1200 ft/sec (i.e., supersonic), a vertical range of 3.6 miles and a horizontal range of 7.2 miles. The aerodynamic controls were located at the nose. About 88 missiles were tested, but the design was considered unsuitable for production.

The Rheintochter 3 had a launching weight of 3450 lb with 350 lb in the war head. The pusher launching rocket of Rheintochter 1 was replaced by two solid-fuel rockets mounted alongside the body, the two together weighing 970 lb and giving a thrust of 61,500 lb for 0.9 sec. The main propulsion unit was a Conrad liquid-fuel rocket weighing 220 lb (empty) and giving a thrust of 3900 lb for 45 sec. About 930 lb of fuel was provided. The exterior dimensions were approximately the same as for Rheintochter 1. The speed attained was about 1350 ft/sec, the vertical range about five miles, the horizontal range about nine miles. Some 260 experimental units were built and 40 were tested up to September, 1944. According to one report this missile was abandoned in favor of Schmetterling after a demonstration to Goering and Speer at Karlshagen in October, 1944.

The control method actually used in tests was either a preset program or radio control with visual observation. In common with other missiles of this type, homing devices, proximity fuses, and beam control were considered, but none of these developments was completed in time.

WASSERFALL (GERMAN)

Beginning in early 1943 the entire resources of the Peenemünde Group, which had developed the V-2 rocket, were concentrated on the development of the anti-aircraft rocket Wasserfall. Three hundred were built and about 40 tested before the development was stopped. The first experimental firing was made on 28 February 1944.

This missile is about 35 in. in diameter and 309 in. long. The launching weight is about 7800 lb with war head of 670 lb. The missile is launched vertically by means of the liquid-fuel rocket motor which furnishes a thrust of about 17,000 lb for 42 sec. The fuel weight is about 4300 lb. The maximum speed is about 2500 ft/sec, the vertical range about 11 miles, the horizontal range about 16 miles.

The control method was to have been developed in four stages. In the first stage the rocket was to be steered by direct radio control with the aid of optical two-axis tracking apparatus, and the tests completed were made with this system. The second stage was to use radar tracking of missile and target with a suitable visual presentation. A human operator transmitted the control information by radio. The third stage was to make the control automatic by coupling the radar tracking devices through a suitable computer to the radio transmitter. The fourth stage was to be beam guiding with infrared-homing device and proximity fuse. The tests made were not against targets and gave no information on probable accuracy.

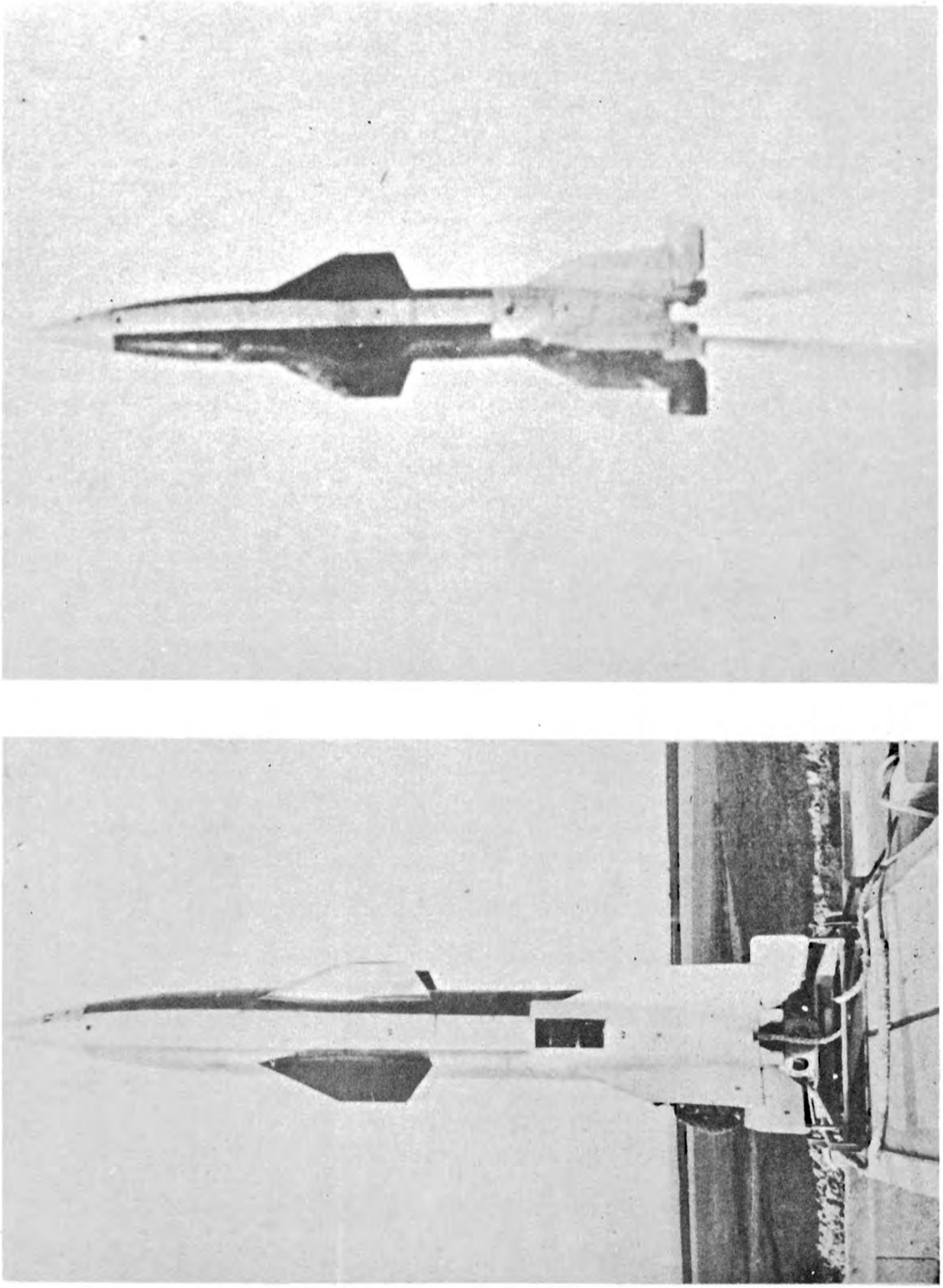


Figure 15 — Wasserfall

SCHMETTERLING (GERMAN)

The ground-to-air rocket-propelled missile known at various times as 8-117, Hs-297, SI, and Schmetterling was proposed by Herbert Wagner in May, 1941, but work was not started on it until May, 1943. About 140 missiles of Hs-117 A-1 type were built and 80 tested. The launching weight is about 950 lb, the war head 55 lb. The missile is launched with the aid of two solid-fuel rockets weighing about 200 lb and giving a thrust of 7700 lb for 4 sec. The main propulsion unit is a BMW liquid-fuel rocket weighing 176 lb and giving a thrust of about 500 lb for 57 sec. The missile is about 14 in. in diameter, 109 in. long, and the span of the two swept-back wings is about 80 in. The speed is about 800 ft/sec (i.e., subsonic), the vertical range about 6 miles, the horizontal range about 13 miles.

Control was to be by radio according to visual observation. A scheme for control with tracking and a computer was under development. It was also planned to use some form of proximity fuse. Large-scale production of the missile was started early in 1945, but in common with the other antiaircraft rocket projects, the development was stopped by the SS leader Kammler in March, 1945.

FEUERLILIE (GERMAN)

Feuerlilie was the research ground-to-air supersonic missile of the LFA, Braunschweig, the largest aeronautical research laboratory of the Germans. Only a few tests were actually made. The launching weight of the F-55 was 2200 lb. No war head was provided. The missile was launched with solid-fuel rockets weighing 800 lb and giving a thrust of 22,000 lb for 2.7 sec. The main propulsion unit was a Conrad liquid-fuel rocket giving a thrust of 14,000 lb for 7 sec, using 460 lb of fuel. The speed at-attained was about 1300 ft/sec, the vertical range was about three miles, the horizontal range about 4.5 miles.

The missile has a large swept-back tail surface of about 100-in. span with tail disks at the ends. The diameter of the body is about 22 in., the length about 190 in. Guiding was to be by means of a radio beam.

BOEING STUDY (ARMY AIR FORCES, BOEING AIRCRAFT COMPANY)

A study was carried out by Boeing Aircraft of the design of a supersonic ground-to-air pilotless aircraft. The report recommends an extensive and detailed program for the "design, development, tests, and construction of such components and combinations of these components, as may be required to furnish the basic engineering data necessary for the preparation of a specification and design of a tactically satisfactory supersonic pilotless aircraft." The conclusion was reached that guidance by a beam with a target-seeking device for the final stage of the trajectory was probably the best system. The ramjet was selected as the most suitable power plant.

NIKE (ARMY ORDNANCE, ARMY AIR FORCES, BELL TELEPHONE LABORATORIES)

This project was a study of a guided antiaircraft missile, with its associated control and launching equipment, carried out jointly for Army Ordnance and Army Air Forces by Bell Telephone Laboratories. The study has been completed. The missile contemplated is 19 ft long, 16 in. in diameter and weighs 1000 lb. The effective range

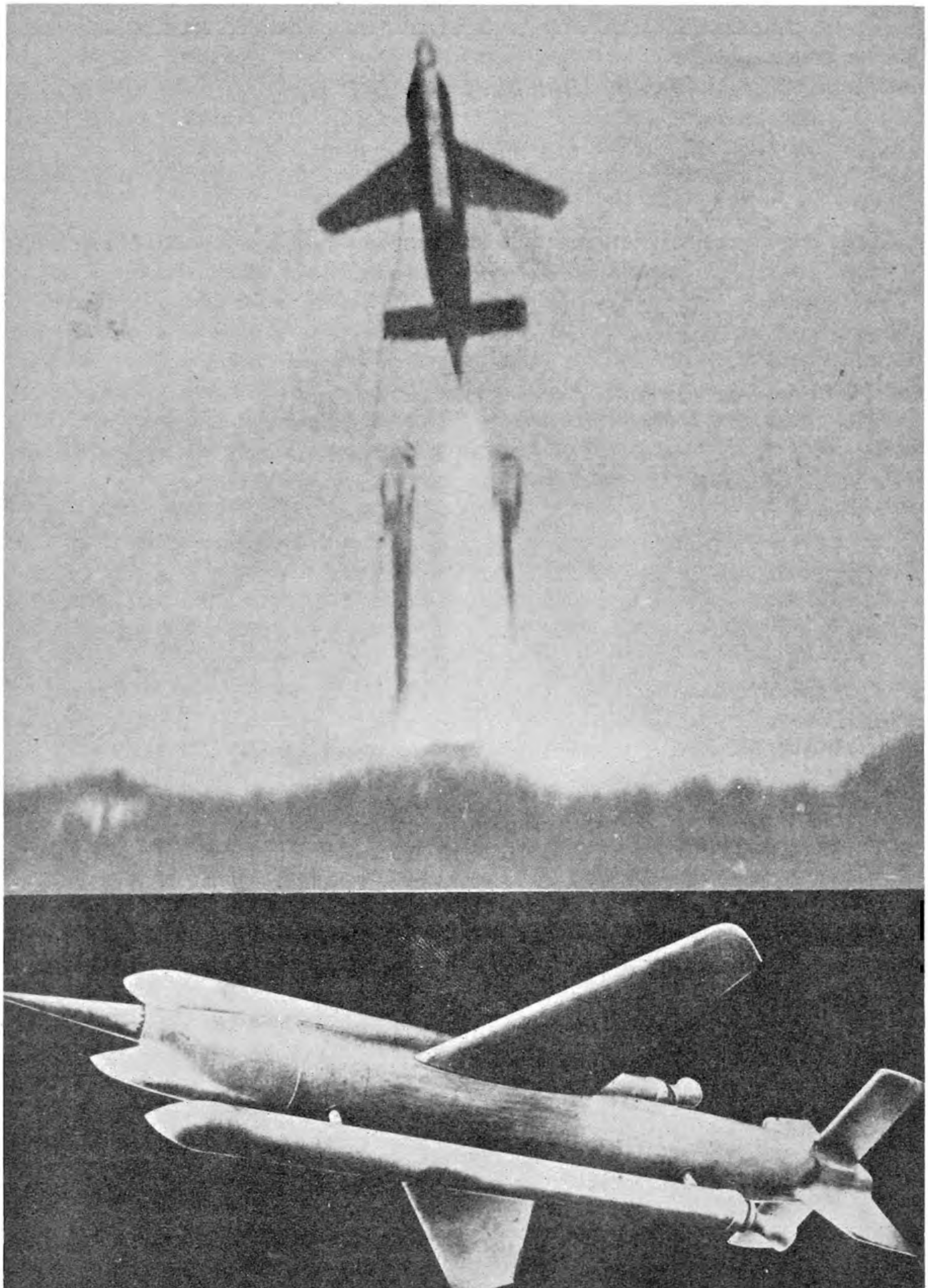


Figure 16 — Hs-117 (Schmetterling)

is about 11 miles at an effective altitude of about 11 miles. Propulsion is by a liquid-fuel rocket motor. Eight solid-fuel rockets are to be used for vertical launching The maximum speed is to be 2300 ft/sec.

The control system will contain two radars, one tracking the target, the other tracking the missile; a computer, and a means for sending guiding signals to the missile by frequency modulation of the missile-tracking radar.

BUMBLEBEE (NAVY, BUREAU OF ORDNANCE)

The missile under development by the Applied Physics Laboratory of the Johns Hopkins University under the direction of Dr. Merle Tuve for the Bureau of Ordnance, Navy Department, is a supersonic ground-to-air missile. So far as can be learned at the present time, the plans contemplate a missile of 2000 lb, total weight, with a pay load of 600 lb to travel at 1800 mph to a range of 20 miles. Propulsion is to be either by a ramjet or liquid-fuel rocket. Guiding is to be by a radar beam, whose position is determined by a computer deriving information from a ground radar set which tracks the target. This development is being prosecuted vigorously, so perhaps the design will change somewhat as the experimental work develops.

PART II

HEAT AND TELEVISION GUIDED MISSILES

By

G. A. MORTON

PART II

HEAT AND TELEVISION GUIDED MISSILES

12 DECEMBER 1945

INTRODUCTION

Guided missiles were used to some extent in the recent war and will inevitably become increasingly important. In planning a military system which has sufficient strength to discourge the outbreak of future wars, guided missiles will unquestionably assume an outstanding role. The present report is concerned with controlled missiles of the class which are self-guided by the thermal radiation from the target, by special light signals or flares, and also those containing television equipment which transmits a picture of the scene before it, back to an operator who can control the trajectory of the missile by means of a radio link. Principal emphasis is placed on the detecting and controlling equipment and, in particular, upon the radiation-sensitive element which picks up the signal from the target, rather than upon the aerodynamics of the missile itself. The latter is considered only where it is necessary for an understanding of the application of a particular controlled system.

The thermal-guided missile contains an element which is sensitive to the heat radiation or long-wavelength infrared radiation that is emitted by all bodies whose temperatures are in the range of those normally encountered in nature. The control element is so coupled to the aerodynamic guiding fins that the missile is directed toward the hottest point in the field of view of the detector. For example, if such a missile is released in the general direction of a ship, it will be guided toward the ship because this object will be the warmest object in the field of view of the detecting element. Similarly, it will home on land targets which are large heat sources, e.g., large industrial buildings, plutonian production plants, steel mills or oil refineries. As will be brought out later, when used against land targets, it will frequently be necessary to make a thermal reconnaissance survey of the area being attacked in order to determine whether or not the desired targets represent the warmest areas in their immediate vicinity.

When the thermal guiding head is used in a dropped bomb, the bomb will be carried to the target area by bomber and released with the aid of a conventional bombsight. The guiding head will serve to correct errors made in aiming the bomb.

When used in long-range, self-propelled missiles, the thermal element will simply control the terminal portion of the trajectory. For the major portion of its path, some other means must be employed to guide the missile. This is made necessary by the relatively short range over which these detectors can be relied upon for either land or marine targets. The means for guiding the missile over the main part of its flight may take any one of a number of forms. For example: a Loran-type system may be employed; the missile may use automatic celestial navigation; or some form of radar-following and radio control may be found best. Any of these forms of guiding will serve to bring the bomb to the target area but will not have the accuracy necessary to hit a relatively small target. The thermal guiding element can make up for this deficiency in accuracy, if the target is a good heat source. Large ships and industrial plants have, in general, been shown to make good targets. The factor determining whether or not a target is a suitable object for the homing system is not, in general, the sensitivity of the thermal detector, but the distribution of other heat sources in the vicinity. This point will be discussed in greater detail in "Thermal Environmet," p 37.

Another important application of thermal guiding systems is in antiaircraft missiles. Here the missile will be aimed by the best predictor techniques, and the heat-homing mechanism will serve to correct for aiming errors, changes in course of the target, etc. In this application, the sensitivity of the element establishes the limiting performance. However, a large or fast plane is a fairly effective thermal source. Jet-propelled planes in particular may be very vulnerable targets.

The television bomb is not a self-guided missile, but rather the television system picks up the scene in front of the bomb and transmits this information back to an operator. The operator, with the aid of the scene transmitted back to him, guides the missile by remote radio control. Although subject to many obvious limitations, this type of missile has the enormous advantage of allowing the operator to use judgment in selecting the target toward which the missile is directed.

Like the thermal guiding element, the television control should be considered as a means for obtaining a final correction in aim rather than the long-range aiming unit. Again, the missile may be a dropped bomb, where the long-range aiming is done by the bomber pilot, bombadier, etc., or it may be a self-propelled pilotless flying projectile. In this case, it is guided to the target area by other means and television control is only used in the terminal portion of its path. Because a servoloop which includes a human being as one of its elements is relatively slow in response, it may be necessary to brake the missile during the final portion of its flight.

The possibility of using a television head in an antiaircraft projectile might be mentioned. However, because long reaction time of the human operator delays the response, it would necessarily have to approach the airplane being attacked rather slowly. This means that it would have to chase the plane and be very vulnerable to being shot down during the approach. Therefore, while such means might be successful as a temporary expedient, countermeasures are so easy that it would probably be of doubtful permanent value.

A final type of missile to be considered is the "light seeker." One form of this bomb is so designed that it seeks out the region of maximum contrast in the field of view. A second somewhat simpler missile homes on a bright point of light, such as a flare. While somewhat more limited in their application than the television or heat-homing missile, they nevertheless may play an important part in military thinking.

Two types of operation for which they appear to be well suited might be mentioned. Ships against a water background in daylight almost always present a region of maximum contrast. Contrast-seeking missiles are, therefore, effective against ships which are not obscured by fog, low clouds, or smoke screen. The flare-seeking missile is designed primarily for attacking a target which has been marked by a flare. This flare may be dropped by low flying, fast fighter planes which can place the flare accurately on the target, or the flare may be dropped in an elaborate guided missile of a more general type. After the flare or flares have been placed, heavy bombers can, from a distance of comparative safety, release flare-seeking bombs in large numbers.

HEAT AND LIGHT HOMING MISSILES

PRINCIPLES AND TECHNIQUES OF THERMAL-GUIDED MISSILES

Thermal Environment

As a result of reasearch extending over a long period of time, it has been possible to develop thermal radiation detectors which are extremely sensitive. There are several types of these detectors (as will be described in "Heat Detectors," p 43) which in combination with appropriate electrical circuits have sufficient sensitivity to detect radiation energy of the order of 10^{-7} watts or less. When combined with suitable optical systems, these detectors can be made sensitive to radiation fields of considerably less than 0.1 erg/cm^2/sec. The application of infrared-sensitive elements to relatively long-range detecting devices, is made possible by two natural phenomena. The first is that the atmosphere with its normal moisture content, while relatively opaque to radiation in the spectral regions extending from wavelengths of a fraction of a millimeter up to a few microns, has a transmission band of low absorption in the region from 8-1/2 to 13-1/2 microns. Furthermore, all objects with temperatures of -50°C and above are "incandescent" in this region of the spectrum. Figure 1 shows the percentage of absorption in 650 ft of air (dew point 15°C) over the spectral regions from 4 to 17 microns. Superimposed on the absorption curve are curves of the radiation emission spectra of objects at $-50°$, $0°$ and $+50$°C (Ref. 1). It will be observed that the emission maxima for these temperatures occur in regions of minimum absorption, a condition favorable to obtaining maximum radiation at a distance. In order to give a quantitative indication of the intensity of radiation from objects in this temperature range, Fig. 2 is presented, showing the radiation intensity in the spectral region from 8-1/2 to 13-1/2 microns for various temperatures from $-50°$ to $+50$°C (Ref. 2). It might be pointed out that this radiation intensity is exactly analogous to brightness in the case of objects which are incandescent in the visible portion of the spectra. Therefore, the term "infrared brightness" is apropos and will be used in the course of the discussion.

The radiation power received by an infrared detector from a given object will, of course, vary inversely with the square of the distance from the object, and will furthermore be decreased by atmospheric absorption. The extent of this absorption can be determined by curves similar to those given in Fig. 3 (Ref. 3). If the infrared

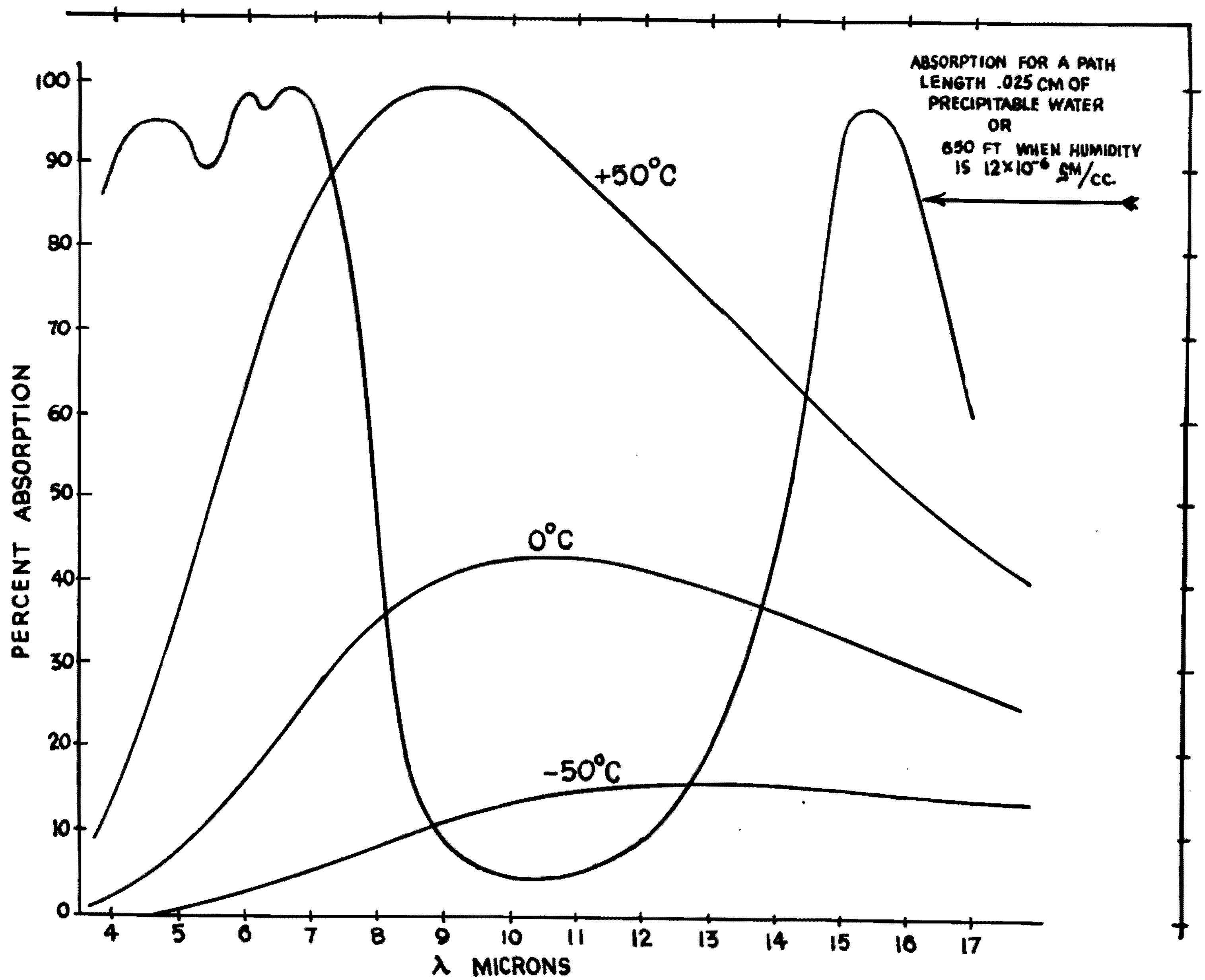

ABSORPTION FOR A PATH LENGTH .025 CM OF PRECIPITABLE WATER OR 650 FT WHEN HUMIDITY IS 12×10⁻⁶ GM/CC.
+50°C
0°C
-50°C
PERCENT ABSORPTION
0
10
20
30
40
50
60
70
80
90
100
λ MICRONS
4
5
6
7
8
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Figure 1

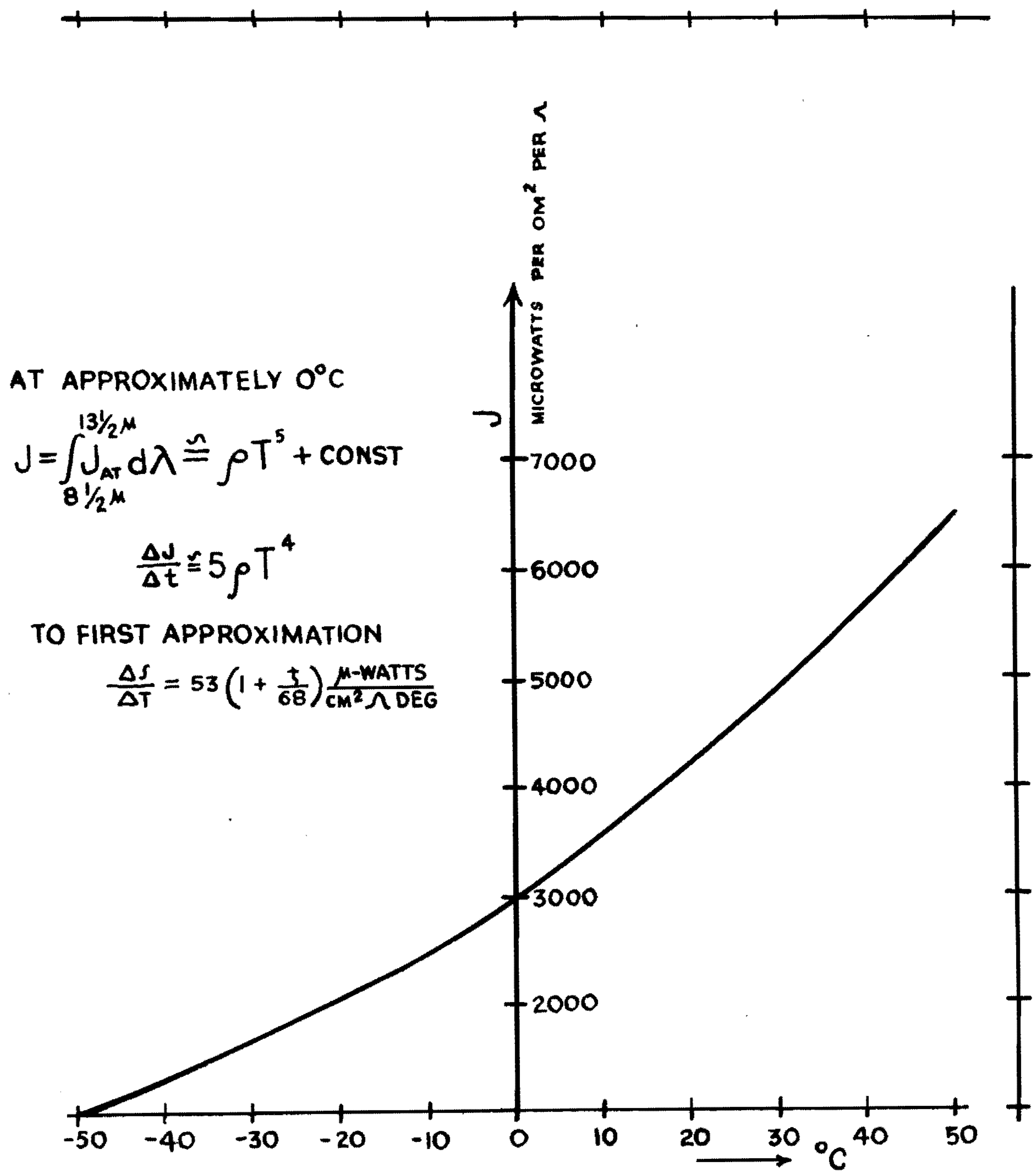

AT APPROXIMATELY 0°C
$J = \int_{8\frac{1}{2}\mu}^{13\frac{1}{2}\mu} J_{\lambda T}\, d\lambda \cong \rho T^5 + \text{CONST}$
$\frac{\Delta J}{\Delta t} \cong 5 \rho T^4$
TO FIRST APPROXIMATION
$\frac{\Delta J}{\Delta T} = 53 \left(1 + \frac{t}{68}\right) \frac{\mu\text{-WATTS}}{\text{CM}^2\, \lambda\ \text{DEG}}$
J
MICROWATTS PER CM^2 PER λ
7000
6000
5000
4000
3000
2000
-50
-40
-30
-20
-10
0
10
20
30
40
50
°C

Figure 2

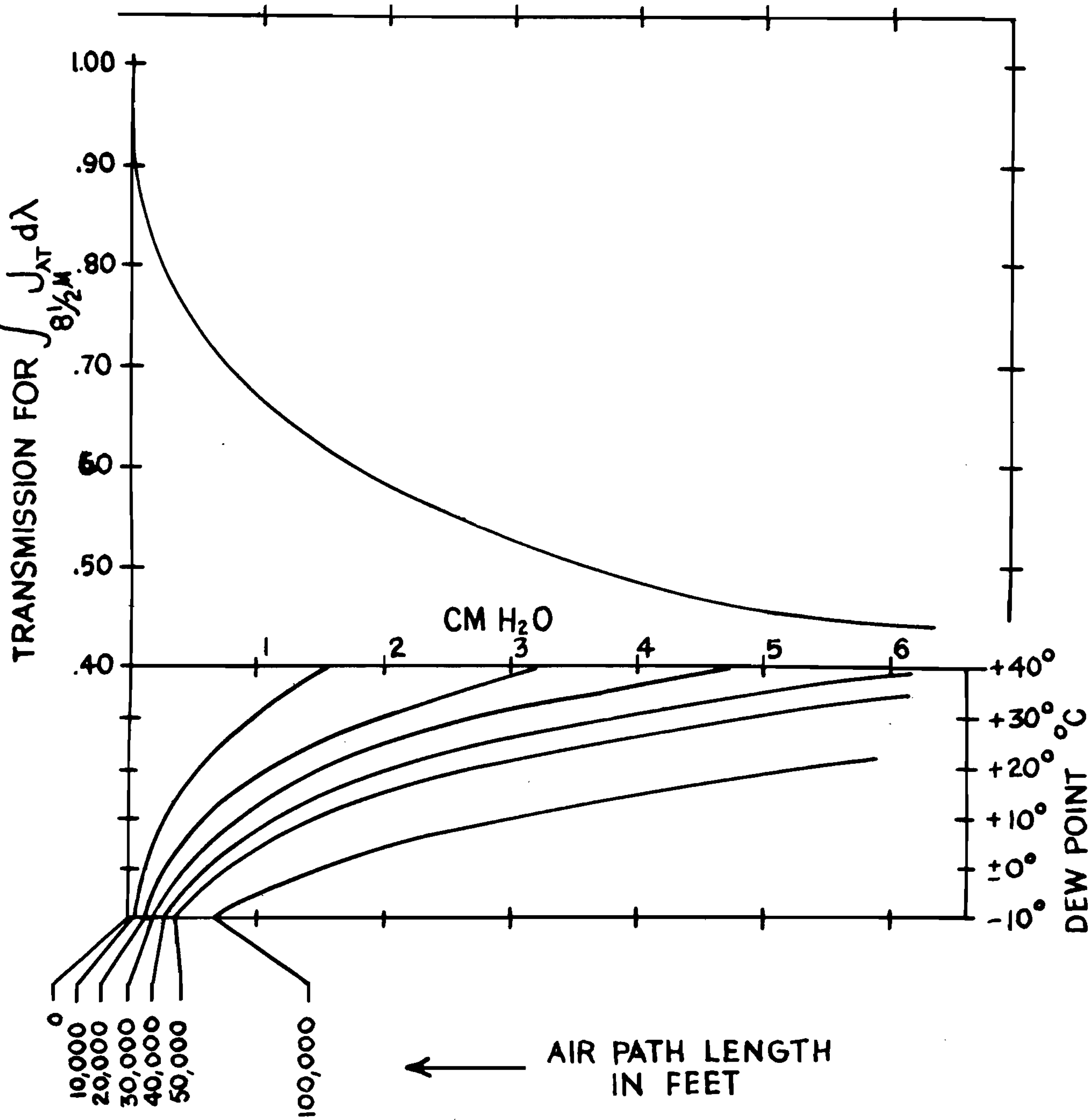

TRANSMISSION FOR $\int_{8\frac{1}{2}\mu}^{13\frac{1}{2}\mu} J_{\lambda T}\, d\lambda$
1.00
.90
.80
.70
.60
.50
.40
CM H_2O
1
2
3
4
5
6
+40°
+30°
+20°
+10°
±0°
-10°
DEW POINT °C
0
10,000
20,000
30,000
40,000
50,000
100,000
AIR PATH LENGTH
IN FEET

Figure 3

detector is considered as consisting of an optical system which forms an infrared image of objects within its field of view, and a sensitive element lying in the image plane of this optical system, the following conclusion can be drawn:

If all of the objects in the field of view of the detector are at the same effective temperature, all points in the image plane of the detector will have equal infrared brightness and, therefore, the sensitive element will be unable to distinguish between different objects or between objects and background. If, however, a particular object has a slightly higher temperature than the rest of the field, it will appear in the image plane of the detector as a region having slightly higher radiation intensity and, therefore, when the sensitive element is in the vicinity of this region, it will giave a greater signal than given for the rest of the field. Thus it is the difference in temperature between an object and its background that determines whether or not it can be detected. Furthermore, if the background against which the object appears is non-uniform, as will be the case in most practical applications of the detector, it will only be possible to identify the object in question if its infrared brightness is greater than the variations in brightness of the background.

Studies have been made (1) of the radiation expected from various types of targets, (2) of background intensities, and (3) of the fluctuation that may be expected in the background. Because of their greater simplicity, marine backgrounds and marine targets have been more extensively examined. While these studies are far from complete, they will nevertheless allow certain conclusions to be drawn, particularly in connection with marine objects. A survey (made by the Bureau of Ordnance, Ref. 4) of the signal from a number of different types of ships, when converted to correspond to an altitude of 10,000 ft, gives the following values of radiation intensity expressed in ergs/cm^2/sec: destroyer, 0.3; freighter, 0.5 to 2.5; battleship, 1.9. Background-fluctuation measurements made at the same time indicate an rms value of 0.025 ergs/cm^2/sec over an angular field of 64 sq mils. With these data, it can be shown that even relatively simple detectors which integrate the radiation in the four quadrants, corresponding to up-down, right-left, will give a positive signal for all of these ships from a 5000-ft altitude and the larger class, yielding radiation fields of one or more ergs/cm^2/sec, from 10,000 ft. Detectors of greater complexity and incorporating various refinements can be expected to have a much greater range. These figures should be considered only as a guide to expected performance, inasmuch as under actual operating conditions, circumstances may be complicated by weather, cloud reflection, position of the sun and seasonal variations in temperature.

Land targets and land backgrounds are much more complex than those involved in marine operations, and the data available at present does not warrant generalization. Surveys have been made over a number of industrial areas using the actual controlling heads from guided missiles and recording the signals obtained from them. These show that large industrial plants where considerable power is used, such as steel mills, oil refineries, etc., can be quite regularly relied upon to give signals far in excess of those of the background. One survey (Ref. 5) of over 30 such targets, although not yet completely analyzed, permits the following generalization to be made. In daytime all but two of these land targets gave positive control up to an altitude of 10,000 ft. Many large factories, railroad yards, railroad crossings, highway intersections, the center portions of long bridges, shore installations, docks, navy yards, etc., are all good thermal targets on sunny days provided there is not a greater heat source within the field of view of the missile. At night any factory with sufficient internal heat source is a good target. Surroundings at night are generally much more uniform. The greatest source of trouble observed so far has been that large bodies of water tend to be relatively warm at night, particularly in late summer and early fall.

An important point, considering present-day trends, is the question of the detectability of underground plants by this means. If heat-sensitive cells can be used to detect and direct bombs against underground factories their value becomes very great.

Before this question can be unequivocally answered, a good deal of experimental work will be required. Obviously, the answer depends upon whether or not the heat generated in the plant can be gotten rid of without raising the temperature of the ground over the plant or some exhaust point more than 1/2 to 1°, i.e., less than the expected natural variation in effective temperature of the earth's surface. It has been shown* that the heat conductivity of the earth is so small that the temperature rise of the earth's surface over a factory which is buried more than a few feet underground is entirely negligible if the temperature within the plant is kept within reasonable limits. Based on figures from the U.S. Industrial Census of 1939, an average manufacturing plant (exclusive of power generating plants, steel mills and chemical industries for which the figure would be much higher) employing 1000 workers, would consume about 5000 kw of power. The resulting heat would have to be dissipated by some form of ventilating system. If the ventilating air were allowed to rise 20°C in temperature, about 16,000 cu ft/sec of air would have to be moved. A 14-20-ft duct can easily carry this much air. It probably would be very difficult if not impossible to hide the exhaust point of this duct from thermal detection, but the exhaust point could be at a considerable distance from the factory itself. Therefore, an average underground factory may be made relatively secure against thermal detection.

Power plants and certain chemical industries which involve much larger amounts of heat probably cannot be protected against thermal detection and will have to be defended by direct military action.

Prior to operations against land targets, it will be necessary to obtain thermal maps of the target areas, as has been already mentioned. These maps will indicate the relative strength of heat emission of the target as compared to its background. It is interesting to note that camouflage under these circumstances is very difficult, particularly in the case of industrial plants which are in themselves enormous heat sources. Even where the plant is underground, it is not free from detection by thermal means as it is difficult if not impossible to dissipate the heat generated without warming up the area in the immediate vicinity of the target. Airborne equipment for heat-mapping is being developed as will be described later. This equipment is in such form that a single excursion over the terrain by a reconnaissance airplane is sufficient to obtain an accurate map of the thermal variations of the region. A few thermal maps of a given area made on different days and under different weather conditions will suffice to indicate the effectiveness of thermal-guided missiles against any particular

*See G. E. Valley, "The Thermal Detectability of Underground Factories."

target in this area. In addition to their value as a preliminary to bombing with thermal-guided missiles, heat-mapping and thermal surveys are a very practical means of detecting certain types of targets. Heat detectors mounted on ships in such a way that they sweep out the horizon can be used as a means of detecting even relatively small vessels at ranges of several miles, under conditions where these vessels are entirely invisible. Tanks, locomotives, industrial plants and even personnel can be found by these thermal detectors. Special detectors, designed for this purpose, have now been developed to the point where they are going into production.

Aircraft, particularly high-flying fast jet planes, are very suitable targets for heat-homing missiles. In the first place, high temperatures are unavoidable in jets, exhaust pipes, etc. Second, due to their high velocity, the skin of the plane is appreciably warmed. Finally, the background against which they are seen is uniform, and, if the missile and plane are in the stratosphere, has a low effective temperature.

For a propeller-driven airplane the exhaust stubs and supports have an effective temperature of about 700°K. While some shielding may reduce the radiation in some directions, complete shielding of thermal radiation is impossible without intolerably large losses in efficiency. There will be even more radiation from jet-propelled aircraft since the radiating areas are larger and the effective temperatures higher.

The temperature of the aircraft skin above its surroundings is given approximately by $0.47\left(\frac{V}{100}\right)^2$ where V is the airspeed in ft/sec. Thus an airplane at 800 ft/sec will experience a skin temperature rise of 30°C, while at 1500 ft/sec the rise becomes 105°C.

The effective sky temperature as far as thermal radiation is concerned is around 215°K at low altitudes (depending, of course, on conditions of clouds, etc.) and lower at high altitudes. Above the clouds, the effective temperature distribution is quite uniform.

For the above reasons thermal and far-infrared guiding mechanisms may become very important for self-propelled antiaircraft missiles. Based on these data, the range of control will be at least three to five miles and may be considerably greater.

Heat Detectors

The two most widely used types of thermal-sensitive elements are the bolometer and the thermopile. However, a number of other types of detectors have been investigated and among them the Golay sensitive element, in particular, has been developed to a point where it is quite practical for use in thermal-mapping and detecting devices.

The bolometer depends for its action upon the change of resistance of a material with termperature. Energy in the form of infrared radiation is supplied to a small strip of bolometer material. The temperature of the strip then rises until an energy equilibrium is reached, that is, until the rate of energy supplied to the strip equals the rate of energy leaving it. This rise in temperature causes a change of resistance in the material which is detected by the change in voltage which occurs when current from an auxiliary source flows through the bolometer strip. Factors such as the thermal coefficient of resistance, heat capacity, the thermal conductivity of the element, and the way in which it is supported determine the sensitivity and speed of response.

Three different types of bolometers are most commonly used in heat-detecting devices. The first of these is the metal strip bolometer. Here the metal (nickel being a frequently used material) is deposited by evaporation or electrolysis to form a thin film. After being stripped from the surface upon which it was deposited and cut to the required shape, the film is mounted in a suitable holder, either backed or self-supporting, depending on the application for which the bolometer is being designed. Because metals in general are good reflectors of radiation, the surface of the materials must be blackened in order to increase the coefficient of absorption of the surface. The metal bolometer is characterized by a low resistance which makes it necessary to use a transformer with a high step-up ratio if the output is to be amplified with a conventional thermionic amplifier. The thermistor bolometer which is the second type is similar in principle but the material used for it is a specially prepared metal oxide. It is characterized by an extremely high resistance which introduces a number of problems in connection with the associated electrical circuit. The third bolometer employs a semimetal in the form of an evaporated film. This type of bolometer has an intermediate resistance which simplifies coupling it into a conventional thermionic amplifier.

A potentially important bolometer has been investigated by Dr. Andrews of Johns Hopkins University. The element is of columbium nitride which becomes superconducting at between 14° and 16°K. It is maintained at the transition temperature by means of a special cryostat containing liquid hydrogen. At this temperature, the change of resistance is very high and the noise level low; therefore the cell is extremely sensitive. Tests indicate that its sensitivity is from 10 to 100 times greater than any of the other types studied. The fact that liquid hydrogen is required is a serious drawback, but in view of the tremendous sensitivity may not be insurmountable.

The action of the thermopile is based upon the potential difference developed between two junctions of dissimilar metals which are at different temperatures. The voltage developed by one pair of junctions per degree temperature difference is quite small but by using a number of such junctions in series, together with an appropriate circuit arrangement, sufficient sensitivity can be obtained to make this system a very useful detector.

The Golay detector is a nonelectrical device. It is based on the expansion of gas as a result of the heat developed when infrared radiation falls on the detector. This gas is enclosed in a small chamber closed at one end by a membrane which acts also as a mirror. The expanding gas distorts this mirror, which in turn alters the amount of light falling on a phototube. The output from the phototube is then amplified up to the level required for the particular application of the sensitive element.

In order to indicate the degree of sensitivity that can be expected from these types of detectors, the following table is given:

Bolometers	*Sensitivity*
1. Metallic (Low resistance)	.01 to .03
2. Semimetal (Intermediate resistance)	.01 to .03
3. Thermistor (High resistance)	.005 to .01
4. Andrews' (Low temperature)	.0005 and less
Thermopile	
1. Helger	.05
2. Schwartz	.04 to .02
3. Eppley	.05
Mechanical	
1. Golay	.0025 to .0015

The sensitivity here given is in terms of the number of microwatts required to produce a signal equal to the RMS noise over a frequency band of 1 cps peaking at 15 c. These values should be considered as approximate only.

Another type of far-infrared detector has been the subject of considerable investigation, in particular by the Germans. This detector depends for its action upon the photoconductivity of certain compounds. The effect differs from that in the cells previously discussed in that there is no heating of the sensitive element, but rather the incident radiation produces an internal photoelectric effect which makes the cell become conducting. Some of the materials exhibiting this effect are lead sulphide, lead selenide and lead teluride. As with all photoelectric effects, there is a long wavelength limit beyond which the cell is not sensitive. For the materials investigated so far, this limit is 3.5 microns wavelength. It will be noted that this wavelength is too short to make use of the transmission band at 8-1/2 to 13-1/2 microns, but instead must depend upon the transmission band near 4 microns. At 4 microns these cells are from 1000 to 10,000 times more sensitive than a bolometer when considered on an energy basis. However, unless the object temperature is above 50°C, very little radiation is emitted with wavelengths as short as 4 microns. Consequently, bolometer detectors will probably continue to be more suitable for the detection of objects whose temperature is only slightly above their background, such as industrial plants, most ships, etc., while photoconductive cells will find application for aircraft and other objects having exposed surfaces which are at a high temperature.

With each of these detector elements, there are many amplifier and circuit problems. These problems cannot be generalized inasmuch as they are intimately related to the specific element used, and the application in question. In all cases, care must be exercised in design in order to obtain the maximum ratio of useful signal to spurious effect.

Associated with the application of thermosensitive elements as detectors is the problem of focusing infrared radiation on the element. In general, this problem is closely related to the corresponding problem of visible imagery, except that the selection of materials which can be used for the optical elements is greatly limited by the fact that most materials, even though transparent to visible light, are opaque to the long wavelengths of this region of the spectrum. However, there are a few materials which are suitable for this purpose, such as sodium chloride, silver chloride, and thallium bromide - iodide mixtures.

Almost all practical heat detectors designed so far employ reflective optics rather than refractive optical focusing systems. Where the sensitive element is small and located on the optical axis of the system, a parabolic mirror can be used to form the image. In this type of system, transmitting materials are only required for protective coverings over the sensitive element. However, some heat-detecting devices are so designed that the sensitive element covers a relatively large angular field. In this case, a parabolic mirror will not suffice. Instead a spherical mirror is generally employed with a Schmidt corrector plate to reduce spherical aberration, the corrector plate being formed of rock salt. Both of these systems are well-suited to heat-detector work inasmuch as the image definition is usually not critical and a high aperture optical system is required.

Associated with the detecting head (consisting of the optical system, a sensitive element and some form of amplifier) are a number of electrical and mechanical auxiliaries. Obviously, these cannot be generalized because they are intimately associated with the particular application and the particular way in which the design problems of that application are met in a given unit.

Heat-Seeking Missile Control

As was pointed out in the introduction, thermal-guided missiles may be divided into three classes: (1) dropped bombs with thermal-homing heads; (2) self-propelled missiles, guided over most of their path by some long-range navigational system and controlled over the last portion of their flight by means of a thermal detector; and (3) antiaircraft missiles which are predictor-aimed but which employ a thermal-guiding element to control them in flight.

The thermal-detection problems of the first two classes of missiles are very similar. Such missiles may be employed against either marine or land targets. It is probable that the controlling heads for either types of target would be nearly the same.

Determination of the expected performance of a thermal-guiding element cannot be made until specific scanning and controlling mechanism is specified and the nature of the target is known. However, by assuming a simple guiding mechanism and using the available data for marine targets, it is possible to estimate at least the order of magnitude of range and area of search.

The simplest guiding mechanism divides the area of search into four quadrants corresponding to up-down and right-left directions. The signals from opposite quadrants are compared and the aerodynamic control surfaces moved in such a way as to direct the missile towards the area giving the greater signal.

This type of search can be effected in the following way. A circular bolometer is located at the focal point of a parabolic reflector. The bolometer therefore "sees" a circular area the size of which depends upon the angle which the bolometer subtends from the vertex of the paraboloid, and the distance to the seach area. The paraboloid is moved in such a way that the area seen by the bolometer rotates about a point on its circumference. Thus the total area of search is a circle whose diameter is twice the diameter of the instantaneous field of view of the bolometer.

The bolometer signal is commutated by four electronic switches corresponding to the up-down, right-left quadrants and the output from the commutator actuates the appropriate aerodynamic control elements.

When the target is in the field of view, the rate W at which energy falls on the cell is

$$W = \frac{JT(X,H)}{X^2} \frac{\pi D^2}{4} \tag{1}$$

where J is the difference in radiation rate between target and surroundings per unit solid angle, X the distance from the target and D the diameter of the optical system. T(X, H) is the transmission function which depends upon the amount of precipitatable water in the transmission path. The signal S is proportional to the energy W and can be written $S = aW$. The rms value of the component of the signal at scanning frequency can readily be shown to be $\frac{\pi}{S^2}$ where the following two conditions are satisfied: (1) The output is commutated into four quadrants and opposite quadrants compared. (2) The average DC signal over any quadrant is maintained at its DC level while the other three quadrants are searched.

In order to control the missile successfully, the rms target signal must be greater than the rms random fluctuation signal or noise. The probability that erroneous differences due to these fluctuations will not deflect the missile depends upon the signal-to-noise ratio. Reasonably reliable control will probably begin when the signal-to-noise ratio R has a value even as low as one.

As has been already mentioned, in the case of marine or land targets, the fluctuation in background is greater than the instrumental fluctuations of a bolometer by a fairly large factor. Therefore, the latter can be ignored in the present computation.

The noise or background fluctuations may be taken as random in space. The rms value of this noise intensity can be shown to be proportional to the square root of the area of view. Hence, the rms noise signal N will be

$$N = a \cdot K_1 \frac{\sqrt{AS}}{X^2} \cdot T(S,H) \times \frac{\pi D^2}{4} \qquad (2)$$

where K_1 is the noise constant which depends upon meteorological conditions, time of day, etc.

The signal-to-noise ratio upon which control depends is therefore

$$R = \frac{2}{\pi}\frac{S}{N} = \frac{2}{\pi} \frac{\frac{aJT(X,H)}{X^2} \quad \frac{\pi D^2}{4}}{aK_1 \frac{\sqrt{A_s}}{X^2} \; T(X,H) \; \frac{\pi D^2}{4}} \qquad (3)$$

$$= \frac{J}{K_1 \sqrt{A_s}} .$$

It will be noticed that for a given signal-to-noise ratio the useful area of search depends only on the radiation from the target and the noise constant, and *not* upon the distance from the target. This is, of course, only true when instrumental noise is neglected.

On the basis of the marine data discussed on page 41, assuming a target producing a radiation of 1 x 10^{-7} w/cm^2 at 1000 ft and a signal-to-noise ratio of 1, the radius of search is 2400 ft, and with a signal-to-noise ratio of 2, about 1500 ft.

With present-day control units, the inherent fluctuation noise of the overall system limits the reliable maximum range of detection to 15,000-20,000 ft. However, it is quite certain that this range could be considerably increased with further research.

Against land targets it is not at present possible to estimate the area of search or the maximum range because too little data are available. The surveys which have been made indicate that the larger heat sources, such as steel mills and power plants, will permit at least as great an area of search as do marine targets, in spite of the greater variability of background. Ranges of three to six miles at least can be expected.

When used against aircraft the internal noise of the thermal control system rather than background fluctuations limit both range and area of search. Measurements on the heat radiation from aircraft are not as yet sufficiently reliable or numerous to permit an accurate estimate of the performance that ben be expected. German sources give the following figures for the thermal readiation from three types of aircraft: Mosquito, 2.5 kw; Fortress, 250 kw; and Me-262 (jet-propelled), 2000 kw.

On this basis the radiation intensity at 1 mile is 0.08 x 10^{-7}, 8 x 10^{-7} and 70 x 10^{-7} w/cm^2. With a detector based upon the thermistor bolometer, ranges of from three to five miles might be expected, at least for the two larger types of airplanes. This range is great enough to make this general means of control of antiaircraft missiles very important. The application of photoconductive detecting elements in place of bolometer cells may further increase the range of action by a factor of two or three, adding still more to the value of the method.

To date the only thermally controlled missiles which have been developed to any extent are of the dropped-bomb type. These developments are discussed in some detail in the following section of this report, "Development in the Field of Heat and Light-Controlled Devices During World War II."

DEVELOPMENT IN THE FIELD OF HEAT AND LIGHT CONTROLLED DEVICES DURING WORLD WAR II

Heat-Controlled Missiles

The first missile to be described is that developed under "Project Felix." This work is being done by NDRC, Section 5.2, through contract NDC-rc-180, at the Massachusetts Institute of Technology, and contract NDC-rc-183, Gulf Research and Development Company. The control mechanism is designed around the standard 1000-lb bomb, and consists of a head which contains the heat-sensitive control element and a tail structure with the movable fins which guide the missile. The control heat is attached to the nose of a standard bomb and the tail assembly is placed in the normal tail fitting. The tail assembly contains the motor for operating the rudders and elevators and also the gyroscope required for stabilizing the bomb in rotation. The motors are driven through wires in a cable passing along the outside of the bomb to batteries and relays located in the control head. This cable also contains two flexible metal cords which transfer the mechanical motion of the rudders to the head end, thus coupling the heat-sensitive eye with the motion of the tail members. The heat detector is mounted in a window at the extreme forward position of the control head. The detector consists of a thermal element mounted at the focal point of a parabolic mirror. This mirror is rotated by a small motor so that it turns about an axis which makes an angle of 5° to its optical axis. The thermal element, parabolic reflector and driving motor are mounted in a frame supported on gimbal bearings and the flexible cords coming from the tail are attached to this frame through appropriate linkages. As the rudders turn, the whole assembly turns also in such a way as to bring the axis of rotation of the system into the line of flight of the missile. Similarly, when the elevators move to readjust the pitch of the missile, the detector again turns in the direction of flight.

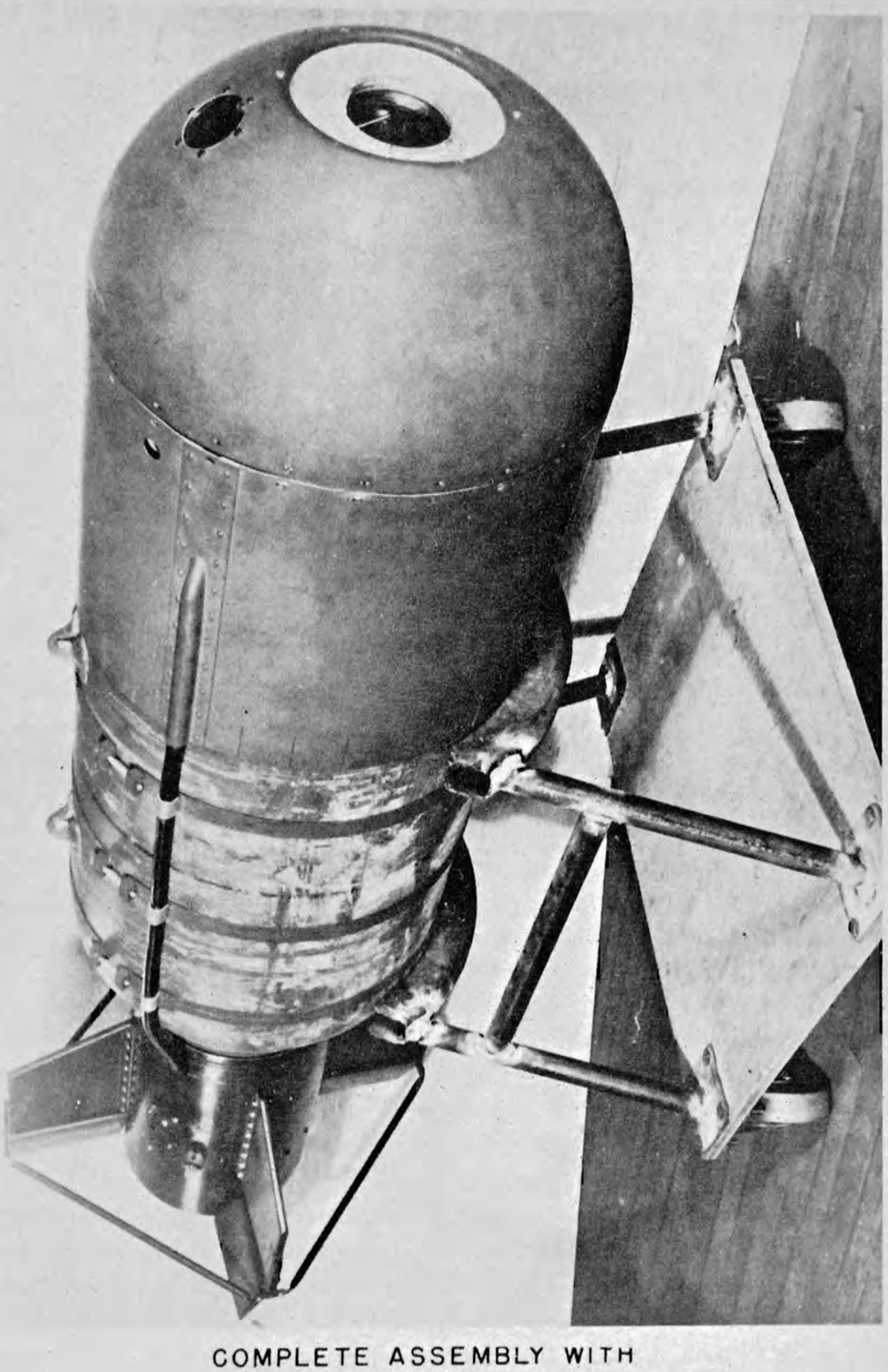
The thermal element itself is a nickel strip bolometer. Four very thick nickel ribbons laid side by side form a sensitive area which is about .2 in. in diameter. Because the nickel bolometer is a low-impedance device, as has heretofore been pointed out, it is connected to the amplifier through a transformer. In order not to saturate the transformer with direct current, the bolometer forms one arm of a bridge.

The parabolic reflector in which this element is mounted has a focal length of one inch and an effective aperture of approximately 2-3/8 in. The sensitive area subtends an angle of about 5° and as the parabola rotates, the sensitive area sweeps out a field about 20° in diameter. The action of this arrangement can best be visualized when considering the thermal element as projected on the field of view of the head. If the center of rotation is taken as the center of this area, the image of the thermal element moves in a circle about this center. For the sake of illustration, assume that there is a heat source to the right of the center of rotation; the thermal element will only receive energy when it is located so that its image falls in the right-hand quadrant of the total field. Thus an electrical pulse will be generated each time it rotates. The phase of this pulse is determined by the quadrant in which the heat source is located. Four electronic switches following the output from the amplifier are actuated by a commutator which connects the up-down, right-left relays in synchronism with the rotation of the sensitive area. Thus the relay corresponding to the quadrant seen by the element is always connected to the amplifier. Delay circuits with time constants about one-fourth second serve to integrate the signals from the four quadrants. These relays in turn control the appropriate motor in the tail.

The motion of the missile is quite complicated because of the couplings between the rudder and the eye. When the bomb is following the correct trajectory towards the target, it does not simply fly a straight course but oscillates at a forced frequency related to the constants of the servoloop formed by mechanical and electrical coupling between the eye and the tail. Under these conditions, the aerodynamic control surfaces will move by equal amounts alternately up-down, right-left. If the target is slightly to the right of the trajectory, the rudder will still oscillate but it will be in the right position for a longer period than in the left position. If the target is far to the right of the trajectory of the missile, the rudder will move to the maximum right turn position and will not oscillate.

In use, the bomb is dropped as a vertical bomb from an altitude of from 15,000 to 20,000 ft. A time switch keeps the control at "off" until the bomb has fallen to about 10,000 ft. At this point, the control element is turned on. The initial portion of the trajectory when the bomb is not being controlled by the thermal detector must be such as to bring the target in sight of the bomb at 10,000 ft. In order to accomplish this, a standard bombsight is used for the release of the missile. At 10,000 ft the area seen by the sensitive "eye" is approximately 2000 ft in diameter and the control radius of the missile is approximately 1500 ft.

The project for the development of the bomb is well advanced and a number of preproduction models have been built. Figure 4 is a photograph of one of these missiles. A large number of drops have been made to determine their characteristics and behavior. Except for a number of failures due to obvious electrical or mechanical defects, the performance of the bomb is quite saitsfactory. Figure 5 shows the results of one series of these drop tests. The impact points of 12 bombs are shown, together with the point where they would have fallen had there been no control. Eleven of these bombs fell within a circle of 200-ft radius. The twelfth bomb had full control during its entire flight but due to faulty release the target was beyond the effective radius of the bomb. It will be seen that in this case the missile had moved about 1500 ft in the direction of the target.



COMPLETE ASSEMBLY WITH
CRUCIFORM TAIL

Figure 4 — Photograph of Combat Model

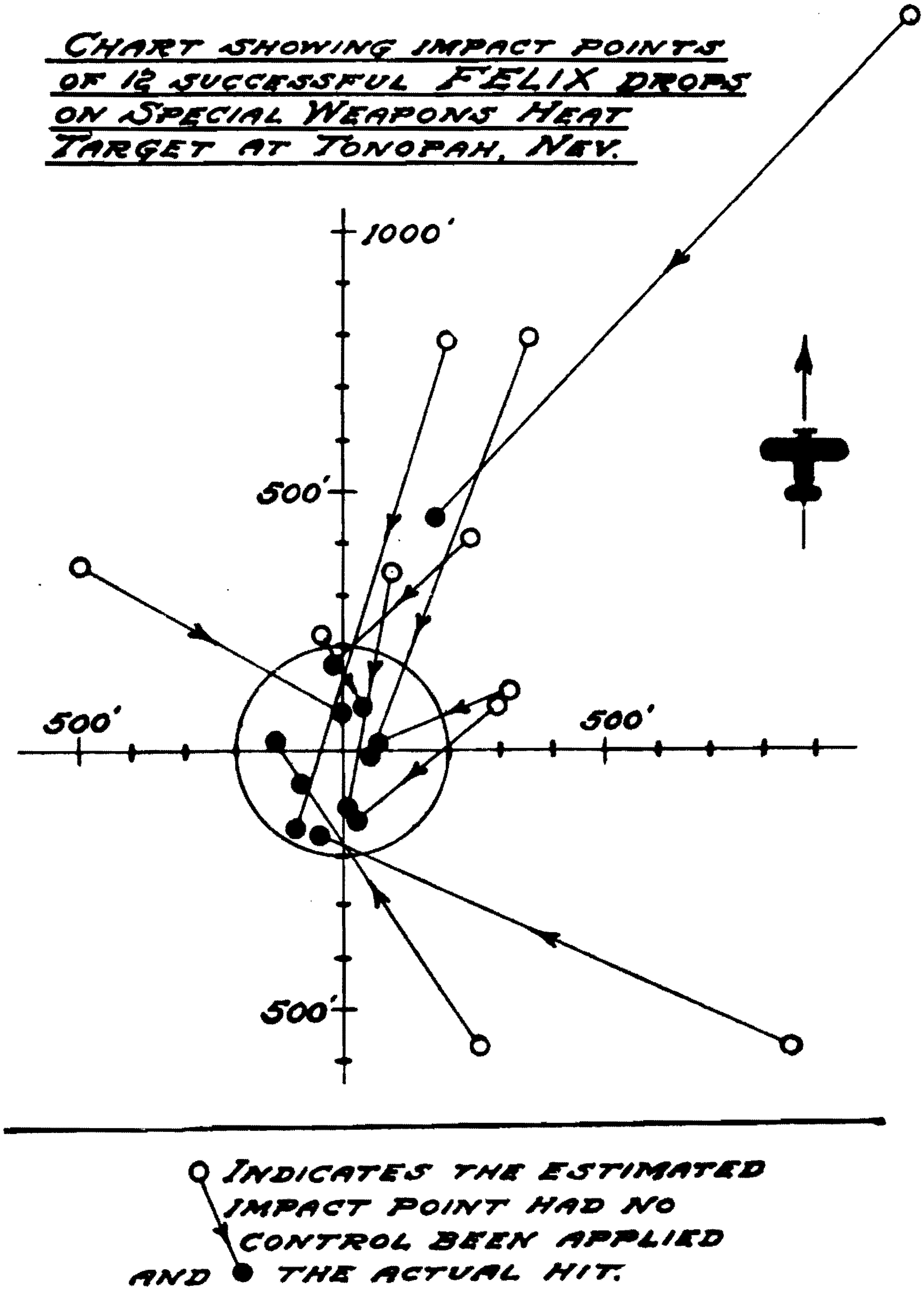


CHART SHOWING IMPACT POINTS
OF 12 SUCCESSFUL FELIX DROPS
ON SPECIAL WEAPONS HEAT
TARGET AT TONOPAH, NEV.
1000'
500'
500'
500'
500'
INDICATES THE ESTIMATED
IMPACT POINT HAD NO
CONTROL BEEN APPLIED
AND THE ACTUAL HIT.

Figure 5

The sensitivity of the thermal control mechanism appears to be adequate for both land and sea targets. Laboratory measurements of the sensitivity indicate that a radiation intensity of about .4 $ergs/cm^2/sec$ is required. In actual flight, the energy required to actuate the unit is probably somewhat greater, and is estimated to be about 1 $erg/cm^2/sec$.

The second heat-seeking missile to be discussed is being developed at Polaroid Corporation under the direction of the Bureau of Ordnance and under NDRC contract OEM-sr-1317. This missile is a vertical bomb but differs from that discussed above in two important essentials: (1) The aerodynamic control is in the nose of the bomb. (2) The guiding element is arranged so that it flies a collision course rather than the homing or pursuit course followed by the missile developed under Project Felix. The equipment, in the form of a tail assembly and a control eye, attaches directly to a standard 1000-lb bomb, and is so designed that the bomb may be carried in a carrier-borne bomber. In this missile, the tail serves merely as a stabilizer and none of the aerodynamic controls are contained in it, thus eliminating any connection between the head end and the tail. The fuse mechanism, however, is carried in the tail.

The heat element (or eye) and control mechanism attaches to the nose plug of the standard bomb. It is so joined that the body of the bomb and tail can rotate about its long axis while the nose is held stationary, being stabilized by a gyroscope. The aerodynamic control fins are located around the center of the nose, and consist of four segments of a cylinder. These fins are retracted or pushed forward according to whether the bomb is to be directed in one direction or the other. If, for example, the target is to the left of the bomb trajectory, the left-hand fin is pushed forward while the right-hand fin is retracted, thus making the bomb turn towards the left. These fins are controlled by the electrical output from the heat-sensitive detector.

The thermal element used in this missile is a thermistor bolometer. The thermistor is in the form of a cross, mounted at the focal point of a parabolic mirror. This mirror rotates about an axis which is displaced by an angle of about 5° from its optical axis. As the parabola rotates, the cross sweeps out the area of the field view of the detector. A heat source in the field of the detector produces a pulse signal whose phase depends upon which quadrant it is in. By the use of a suitable commutator, this signal can be arranged to operate up-down, right-left relays. The rotating optical system is supported on gimbal bearings and acts as a gyroscope. The output signal is supplied to precession motors which move the gyroscope in such a way that the image of a heat source tends to be moved towards the axis of rotation. The aerodynamic control elements are actuated by the current which is supplied to the precession motors so that they only tend to change the course of the missile when the heat source moves away from the center of the optical system. Thus if the angle between the trajectory of the missile and a line to the heat source or target remains constant, the control fins will not be moved. This constancy of angle is characteristic of a collision course. Since the normal trajectory of the bomb is a parabola, a special signal generator supplies the vertical precession motor with the necessary compensation for the path. Thus, if the bomb is dropped so that the uncontrolled parabolic path would intercept the path of the target at the point of impact, no control is required to keep the eye pointed at the target and the bomb will fall as an ordinary dropped bomb.

Test drops have been made to determine the aerodynamic performance of the nose control system described above. Sensitivity and performance tests have been made on the thermal-detecting system. The two components independently perform very satisfactorily. Some tests have been made on the complete missile but not under conditions which permit evaluation of the performance which can be expected.

Released from an altitude of from 15,000 to 20,000 ft, the bomb is designed to fall as an undirected missile to 10,000 ft; at this point the control takes over. Dropping tests have shown that from 10,000 ft, the range of control is approximately 1500 ft. Sensitivity tests of the thermal control element indicates that the system is capable of a sensitivity of between 1-1/2 ergs/cm²/sec.

A third project for the development of a heat-seeker bomb is being carried on under the Army Air Forces Materiel Command at Wright Field (Ref. 7). This missile is a glide bomb using an Aeronca airframe, an Offner heat-sensitive unit and a Hammond gyrocontrol, and is designated GB6.

Figure 6 is a photograph illustrating one of these missiles. The heat-sensitive element and reflector can be seen in the nose of the bomb. Directly behind the detecting head arc the amplifiers and relays. A standard 2000-lb demolition bomb is strapped to the frame behind the control head, and in back of this, attached to the spars which support the tail surfaces, is the case containing the Hammond gyrocontrol and stabilizer.

The thermal element used in this missile is an Eppley thermopile. This thermopile is an array of junctions arranged to cover the entire image area of the field of view. It consists of two rectangular areas, one containing the "cold" junctions, the other, "hot" junctions. The two areas together make up the entire field. The sensitive area is so mounted that it is at the focal plane of a parabolic mirror, which rotates about its optical axis, being driven by a small motor.

In order to avoid having to commutate the electrical signal at an extremely low power level, the transformer which is supplied from the thermal element and two stages of the amplifier rotate with the parabola and thermopile. After the two stages of amplification, the signal level is high enough so that it can be commutated without the introduction of additional spurious effects.

The operation of the Offner heat-seeker is as follows: The sensitive element forms a square on the image plane of the parabolic reflector. Half of the square is occupied by the "hot" junctions (a) and the other half by the "cold" junctions (b). As was mentioned previously, the entire structure including the sensitive element rotates, and a commutator synchronized with this rotation switches the output signals to relays corresponding to the up-down and right-left quadrants. Assume that the image of the heat source lies above the center of the sensitive area. As the junctions (a) turn so that the heat image falls on them, they are warmed, producing a current. This current builds up in the highly inductive primary of the transformer which couples the element to the amplifier. The primary current is then broken abruptly and a relatively large inductive surge is produced. This in turn produces a still larger voltage in the secondary. The turn ratio between primary and secondary is about 30, and furthermore, the voltage gain as a result of the inductive kick is about 30 times the voltage induced in the thermal junction, so that the net gain of the transformer

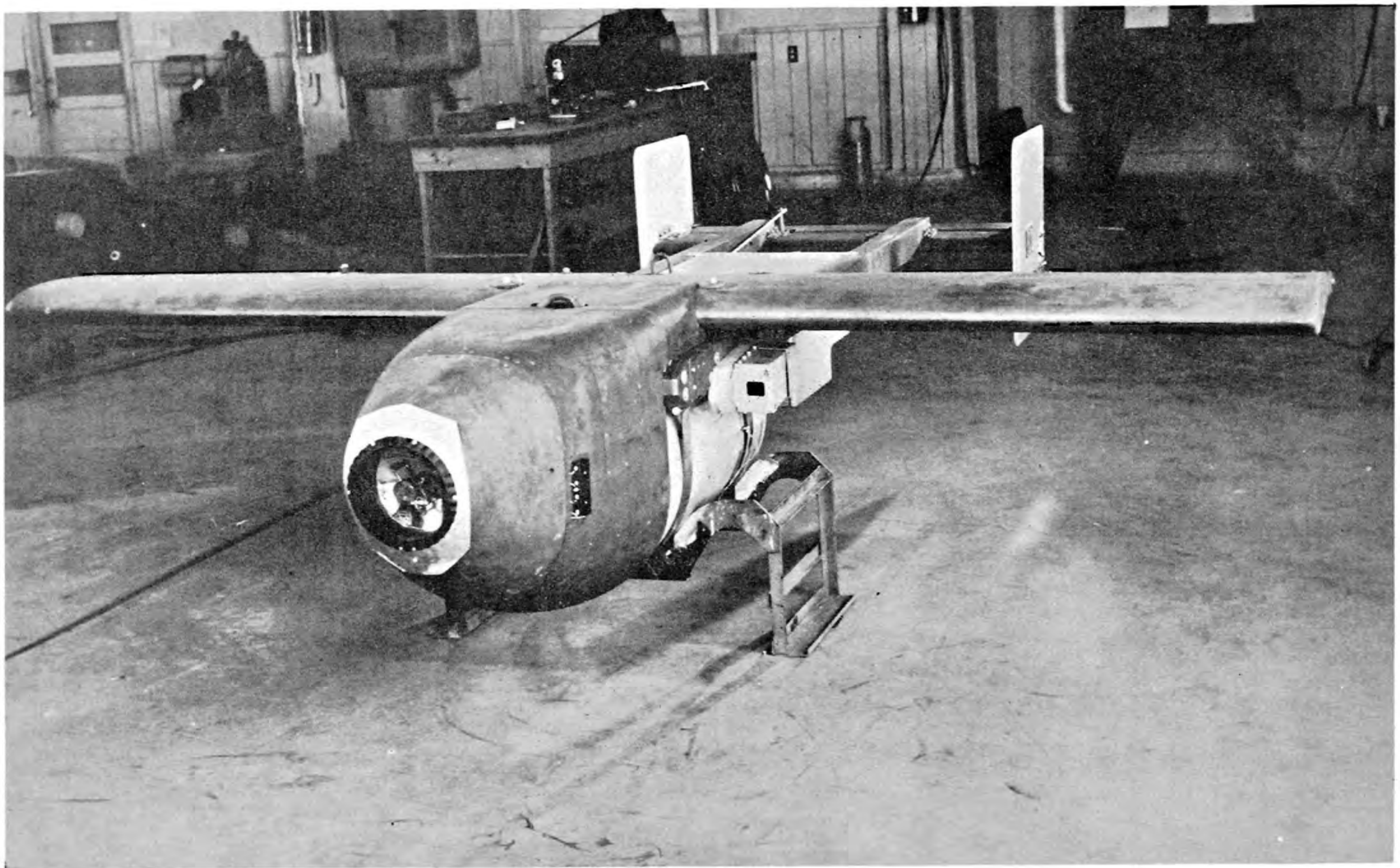


Figure 6

combination is nealy 1000. This voltage is supplied to the first stage of the amplifier and appears as a voltage rise in the output. At the time of the occurrence of the break, the commutator will be in a position corresponding to the "up" position of the image and consequently, by means of appropriate trigger circuits and relays, the proper control signal will be supplied to the elevator. When the head has rotated through 180° bringing the junction (b) into the region occupied by the image of the heat source, the commutator will have reversed the polarity of the output so that the voltage rise now produced, which is in the opposite direction from the previous one, still produces a signal of the same sense to the elevators. The method of obtaining the right-left signal is the same except that it occurs when the head is rotated 90° with respect to the up-down position. The control signals from the four relays in the heat seeker are supplied to the Hammond gyrostabilizer and from thence to the appropriate control element.

These bombs fly with a glide-to-fall ratio of 5:1. Therefore, when released at 6000 ft they will have a range of some 5 or 6 miles. They are arranged so that the first 20 sec of their flight is preset. At the end of this time, an automatic timing switch turns on the heat seeker. A large number of tests have been made to determine the performance of the airframe and stabilizer. Other tests have been made with the heat seeker mounted in an airplane to determine the performance of the Offner detector and control. Finally, tests have been made of the entire heat seeker bomb. Except for certain failures due to easily corrected mechanical defects and due to poor adjustment, the performance has come up to expectation. Figure 7 is a photograph made with a camera mounted on the wing of such a missile showing its approach to the target. Included also, are the photographs of the missile in flight, a flare being mounted on it so that its path could be followed.

A series of surveys were made with an airborne Offner unit to determine the ranges which can be expected from various targets. The result of these range tests, although not complete, indicates the following: On a clear day with an air temperature above the water of 30°, satisfactory homing can be expected from 3 to 4 miles on ships of the 6500-T class. For land targets, such as steel mills, oil refineries, etc., when the targets are isolated from large built-up areas, homing was found possible from three to five miles on relatively clear days. When such targets are part of a large city, satisfactory homing has been accomplished from distances as great as 15 miles. The whole city area serves as a target at the beginning of such a run. As the range decreases, industrial installations become the main target because of their relatively greater heat dissipation.

One difficulty has been encountered in the case of glide bombs which may limit the applications for which this particular type of heat seeker can be used. This is a spurious signal which is very frequently encountered and which is produced by the heat gradient toward the horizon. The effect of this vertical gradient near the horizon is to limit the use of this type heat seeker to operations where angles of not less than about 8° to the horizontal are involved. Work is already in progress on an alternative type of heat seeker for these bombs which will be insensitive to this form of gradient.

The work that has been done on the glide bomb so far indicates that it is potentially a very powerful weapon. Technically, it has been brought to a point where

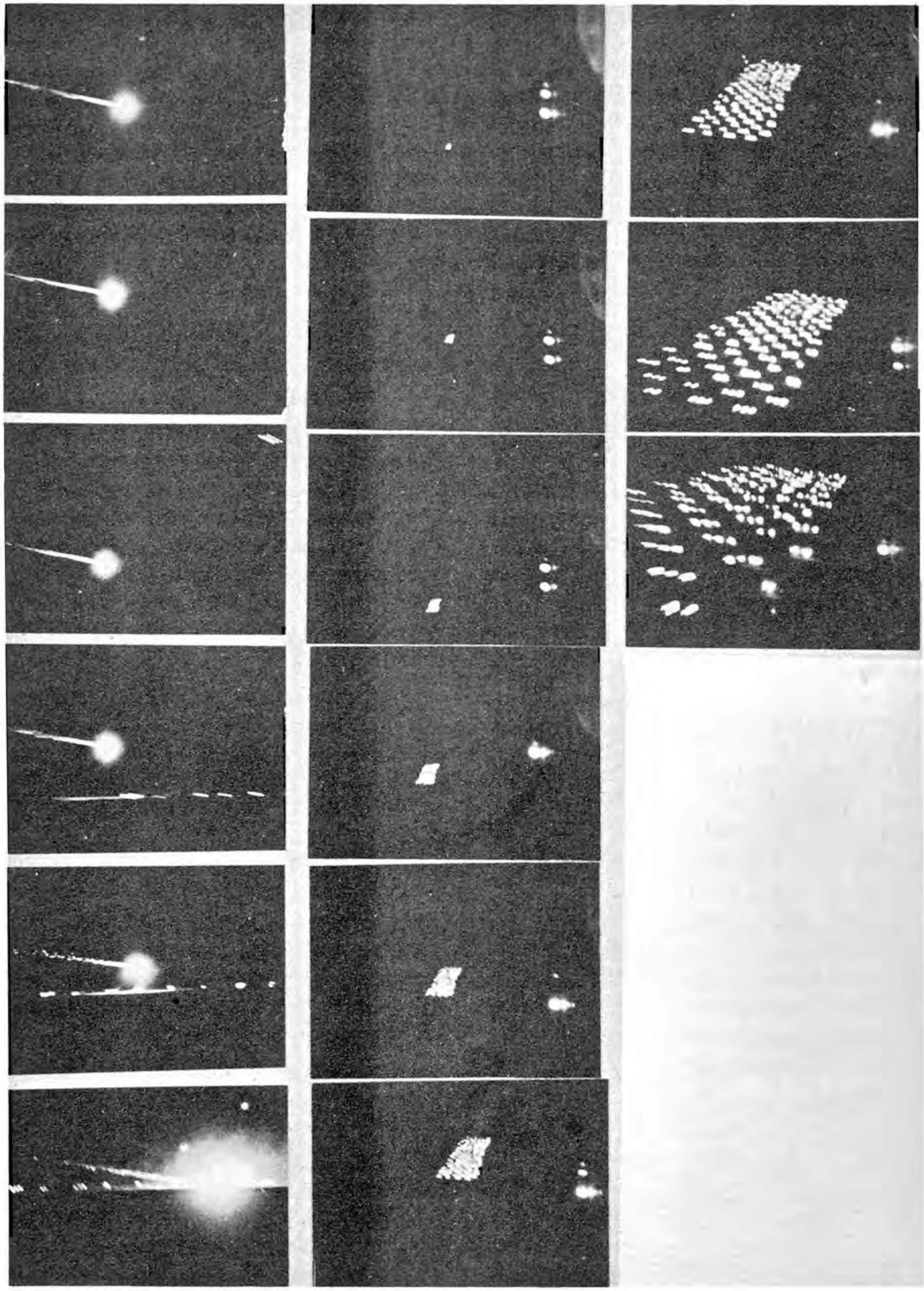


Figure 7

heat-seeking missile of this type could be produced which would be effective against a variety of important targets. Future developments will eliminate a number of the difficulties which are now encountered.

The application of heat-control equipment is not limited to unpowered missiles. Several projects are actively engaged in determining the value of the present type heat seekers as a means of guiding automatically piloted airplanes to useful military targets. Both the direct control of the airplane by the thermal signal, and the indirect method where the airplane is radio controlled and the information from the heat seeker is radio relayed to the operator who is guiding the plane, are being investigated.

Heat Detectors and Mappers

In addition to their application in controlled missiles, heat-detecting elements are destined to play an important role in the detection of objects such as ships, tanks, etc., which differ in their temperature from their normal environment, and also in the location of camouflaged manufacturing plants, underground production units, and hidden industrial areas. This method of detection is important not only as a preliminary to bombings with heat-controlled missiles but also as a supplement to radar in various detection problems, in particular, where radio silence must be maintained.

For marine operations, the horizon scanner appears to be the most useful. Here the thermal-sensitive element is in the form of a narrow strip, subtending a few tenths of a degree in the horizontal direction and somewhat more in the vertical direction. This strip is mounted at the focus of a parabolic mirror. The mirror and strip are made to oscillate about a vertical axis so that the sensitive element scans the horizon. As the image of the horizon scans across the thermal element, any discontinuity will be recorded as an electrical signal. After amplification, this signal can be shown on a long persistence radar cathode-ray tube or it can be recorded on a facsimile strip with the stylus which moves across the strip in synchronism with the scanning of the head. The latter method greatly increases the effective sensitivity of the instrument because any external object is recorded in the form of a straight line on this strip after a number of successive scans, and this line can easily be distinguished from the random fluctuation which appears merely as scattered marks or dots on the paper.

The heat mapper is very similar to the recording scanner described. The detecting head is mounted in an airplane so that it points downward and forward in the direction of the motion. The scanning motion of the head is at right angles to the line of flight. As the airplane proceeds, the scanning element sweeps out a series of straight, parallel lines along the ground. If the recorder paper is moved at a speed which bears the proper relationship to the motion of the plane and the scanning of the head, a map will be recorded representing the thermal distribution over the terrain covered. A heat-mapping instrument of this type has been developed and is in use at Wright Field. This instrument employs the Golay heat detector. A second heat mapper employing a thermistor bolometer is being developed by NDRC, Section 16.4, at the Bell Telephone Laboratories. In addition to these heat-mapping equipments, a number of marine ship detectors are also being developed by NDRC and others.

Light-Controlled Missiles

As was pointed out in the introduction, there are at least two important applications of light-seeking missiles. One of these is the guiding of bombs against marine targets in daytime. The Hammond-Crosley contrast-seeking bomb was developed expressly to meet this problem. The control head contains a photoelectric device which will detect the presence of objects radiating or reflecting light energy with an intensity differing from that of the surrounding field. The marine head has a duel optical system, each element of which consists of a lens forming an image of the scene before it on a slit. Back of this slit is a wedge mirror which divides the light into two branches leading to two photocells. The two slits are vertical, each subtending an angle of about five degrees in height and so arranged that one is in the upper half of the field and the other in the lower, with an overlap of a half degree. The entire head is scanned about a vertical axis so that the image moves horizontally across the slit. As any discontinuity in the light in the field of view crosses either the upper or lower slit, a signal is produced. This signal actuates the rudders or elevators and thus guides the missile. Tests on this contrast seeker show it to be quite satisfactory. On normally clear days ranges of from three to four miles can be obtained against medium-sized ships.

This contrast seeker can be used as a missile whose purpose it is to home on a flare. However, it is possible to devise a much simpler guiding mechanism for this purpose. Such a missile is represented by the GB5-13, using a Fairchild flare seeker.

The optical system consists of a lens which forms an image on a disk covering all but one quadrant of the field. The light which passes through this quadrant is focused, by means of a second lens, onto an RCA 931 Multiplier. If the flare lies in the exposed quadrant, a signal is obtained from the multiplier. If not, no signal is obtained. The entire lens barrel rotates about its axis, carrying with it the sector disk. A commutator, operating in synchronism with the barrel, switches the signal output between the up-down, right-left relays as the exposed quadrant moves into the corresponding portions of the field. This type of control represents a simple and reliable system which is eminently suited for the solution of flare seeking problems of the type outlined in the introduction.

APPLICATION OF TELEVISION TO GUIDED MISSILES

GENERAL DISCUSSION

The television missile is not a homing or self-guided bomb such as described in the preceding section. Instead it is controlled remotely through the means of radio by an operator either in an accompanying plane or at a ground station. The television camera, mounted in the missile, picks up an image of the scene before it and transmits this information back to the operator, where it appears on suitable viewing equipment. By the appearance of the reproduced picture, the operator can determine just how the controls should be moved to correct the aim of the missile. This type of equipment is suitable for self-propelled missiles, glide bombs or vertical bombs, and has been tested in all three of these carriers.

Missiles of this class have a number of serious limitations: (1) It is technically rather complicated. (2) It is fairly susceptible to jamming and interference. (3) It is only satisfactory against targets which are optically visible. However, these disadvantages are more than offset by a number of unique advantages. In the first place, it allows very accurate selection of the target or even the point on the target towards which the bomb is to be directed. Second, inasmuch as the bomb is controlled by an operator, he may use judgment in choosing the target and the path to the target, thus rendering the missile less susceptible to decoy and interception. It should be pointed out that before an operator can be truly effective in controlling such a missile he must learn to interpret correctly and rapidly the picture transmitted back to him. An inexperienced and improperly briefed operator will find the direction of this type of missile a difficult if not impossible task. A number of tests, which have been performed in the past where the operator has not had the necessary skill, have very clearly illustrated that this is the case.

It has been pointed out that the successful operation of this missile requires visibility for the target. This means that the weapon is only operative during daylight hours. With the iconoscope-type camera tube as represented by the Block I and Block III equipment (to be described herein) the missile can only be used between the hours of sunrise and sunset. Even then reliable operation cannot be counted on except between a couple of hours after sunrise and a couple of hours before sunset. Where a more sensitive pick-up tube is used (the image orthicon, such as in the Mimo equipment) operation can continue long after sunset and commence before sunrise. In fact, some pictures have been transmitted by full moonlight. A heavy overcast may render the Block III type equipment relatively ineffectual. However, the Mimo equipment will operate in any degree of overcast as long as the target itself is not in fog or clouds. The intensity of the illumination alone does not determine entirely whether or not the missile may be used. The contrast between the target and its environment is a second determining factor. If, due to haze, lighting conditions, or its own color, the target does not show up against the background, it cannot, of course, be seen in the reproduced picture. Where the missile is used under conditions of haze, etc., it is frequently an advantage if there is ample light to place a color filter before the camera, in particular a yellow or red filter is advantageous in reducing the effect of marine haze.

Television Pick-up and Receiving Equipment.

Several types of television pick-up tubes are suitable for use in television missiles. Two of these will be described in some detail. The first is the iconoscope and the second, the image orthicon.

The iconoscope is an arrangement for converting a light image into television video signals. It consists of a photosensitive mosaic and an electron gun contained in a glass envelope which is highly evacuated. The electron gun produces an extremely fine thread of electrons which by means of a suitable magnetic deflecting yoke is made to sweep back and forth across the mosaic in a series of straight parallel lines forming the scanning pattern. The mosaic which is the photosensitive element or retina of the pick-up tube consists of a thin plate of dielectric (e.g., mica) coated with a conducting metal film on one side and covered on the other with a vast number of tiny photosensitized silver globuals. This mosaic may be thought of as a two-dimensional array of tiny photocells, each shunted by a condenser which connects it to the metallized film on the back and thus to the signal lead. When a light image is focused on the mosaic, each of the tiny globuals emits electrons in proportion to the amount of light falling on it, and becomes positively charged with respect to its equilibrium potential. For any particular element, this charging process continues for the length of time equal to the picture-repetition interval, that is, from the time the beam leaves the element until it returns again in the process of scanning. When the beam does return again, it strikes the element and drives it to its equilibrium potential, releasing the charge accumulated due to photo-emission and inducing an impulse in the signal lead. The train of impulses thus generated constitutes the picture-signal output of the pick-up tube. This signal is amplified by a suitable thermionic amplifier, the output of which is fed to the modulator of a wide-band radio transmitter. In addition, impulses timed to the horizontal and vertical scanning processes are also supplied to the transmitter to be used as synchronizing pulses. The receiver which picks up the transmitted television signal is a superheterodyne similar in principle to the ordinary broadcast receiver but designed to have the much broader bandwidth required by television. The signal from this receiver is supplied to the circuits associated with the viewing tube. The viewing tube or kinescope contains an electron gun, which, like that in the iconoscope, produces a fine electron beam, and the end of the tube is coated with fluorescent material which becomes brightly luminescent at the point where the electron beam strikes it. The beam is made to sweep across the fluorescent screen in a scanning pattern which is synchronized with that at the iconoscope by means of the timing signals sent out by the transmitter. Furthermore, the instantaneous current in the electron beam, and consequently the brightness of the point on the fluorescent screen where the beam strikes, is controlled by the video signal supplied from the receiver. Therefore, there is reproduced on the end of the kinescope an exact replica of the light image projected on the mosaic of the iconoscope.

The second type of pick-up tube finding military application is the image orthicon. Like the iconoscope, the image orthicon integrates the photoelectric current produced by the light image over the picture-repetition period. It differs from it in three respects; namely, it uses a low-velocity electron beam, employs image multiplication, and also employs signal multiplication. The light image is not projected directly onto the mosaic but instead onto a photosensitive cathode where electrons are released in proportion to the geometric distribution of the light intensities. These electrons by means of a suitable electron optical system are reformed into an electron image on the mosaic. Where the electron strikes the mosaic, secondary electrons are emitted and for every electron which strikes the mosaic several electrons are released. This quantity of charge which is stored upon the mosaic is multiplied by the secondary emission ratio. The second point of difference is that the electron beam which scans the mosaic is not a high-velocity beam as in the case of the inconoscope but a low-velocity beam. This, for reasons which are beyond the scope of the present report, results in an increase of sensitivity of several times. The third point of difference is that the signal instead of being taken from signal plate directly, is multiplied by a secondary emission multiplier which leads to a still further increase in sensitivity.

As a result of these differences, the tube is 20 to 100 times more sensitive than the iconoscope and, consequently, can be used over a much wider range of lighting conditions.

Two other types of television pick-up tubes have been tested in connection with the television missiles. These are the dissector tubes and the two-inch orthicon. Neither of these has proved to be very satisfactory; the first, because, although it gives good resolution, its sensitivity is low; the second, because it possesses no advantages for this application over the image orthicon and is lower in sensitivity. Therefore, descriptions of these tubes will be omitted from the discussion.

Two types of television equipment using the iconoscope have been tested in aerial missiles; namely Block I and Block III. These missiles are quite similar in design, differing primarily in that Block I operates with a television transmitter frequency of 100 megacycles, while Block III operates at approximately 300 megacycles.

The camera of both Block I and III used an F/4 lens with about a 20-cm focal length to form the image on the iconoscope mosaic. This gives the camera a field of view of about 24°. The operating range of sensitivity for this equipment is from 2000 or more candles/sq ft down to a minimum of about 5 candles/sq ft. This range of brightness as has been pointed out above is sufficient for most daytime operations.

The weight and power consumption of airborne equipment is, of course, a consideration of maximum importance. The Block III equipment has the following weight distribution: Camera 33-1/4 lb, transmitter 26-3/4 lb, power supply and junction box 22-1/2 lb.

The total weight of equipment including connectors and shock mountings comes to approximately 100 lb. The power required for operation is 28 amp at 24 v.

The Mimo equipment is a much lighter-weight outfit than either the Block I or III equipments. Furthermore, it employs the image orthicon and is consequently much more sensitive. The lens used for this camera is an F/3.5, 8.9-cm focal length lens which gives an angular field of view of about 25° and a sensitivity range of from more than 2000 candles/sq ft down to about .5 candles. The over-all sensitivity of the unit is therefore 10 times as great as that of Block III. The weights of this unit are, camera 20 lb, transmitter 7 lb, power supply 15 lb.

The total weight of equipment including mechanical accessories for support is about 50 lb. The Mimo transmitter operates in the same frequency range as does Block III with a power output of 6 w. The power required to operate the unit is less than half that required for Block III, being 8 amp at 24 v. The total number of vacuum tubes used in the Mimo is only 22, which includes the two type C-43 lighthouse tubes used for power output.

Television Control Techniques.

The television transmitters and receivers discussed in the preceding section are suitable for use in various controlled missiles. As will be covered in the section "Television Missiles Developed During World War II" (page 63) of this report, both the Block and the Mimo equipments have already been used in experimental glide and vertical bombs.

When used as part of the control system of a dropped bomb, the bomb is carried to the target area by some form of aircraft and released by a more or less conventional bombsight. As the bomb falls, it transmits a picture of the area in front of it, to an observer in the aircraft. On the basis of the scene reproduced at the receiver, the observer guides the missile by means of a radio control link.

A number of factors must be considered in the design of such a control system. The angular field must be large enough so that the target, or other landmarks can be seen when allowance is made for the error in release. The speed of approach must be slow enough so that the operator has time to effect control. It is highly desirable that the center of the picture represent the point of impact of the bomb when the control is set in neutral. As an alternative, a moving reticle may serve to indicate the point of impact.

Other considerations relate to the equipment design. The television antennas on the missile and plane must be designed to minimize reflections. The control system, as well as the video, must be protected from jamming and interference.

It is very important that the operator be very familiar with his weapon. He must be able to interpret the picture rapidly and accurately and be able to pick out important features at a glance. The coordination between his movement of the control lever and what he sees on the picture should be trained to the point where his reaction is almost instinctive.

This type of missile obviously has rather special and limited application. It is used to attack small targets which require a high degree of accuracy, and which for one reason or another cannot, or should not, be attacked with a large number of ordinary, less accurate bombs. In releasing the bomb, it will not be necessary for the bomber actually to see the target. He may, for example, fly at such a height that the target cannot be resolved, or he may be hidden by clouds, etc. However, the target must be visible to the bomb in time to allow the bomb pilot to direct it into the target.

Where the missile is in the form of a glide bomb, and the release point is at a considerable distance from the target, the bomb pilot has a much more difficult operation to perform. He must be able to recognize from the picture the location of the bomb and the direction it must fly to bring the target into view. This will require considerable briefing, probably with the aid of relief models of the terrain and television pictures of this model. An improperly briefed pilot will almost inevitably get lost, even though he may have flown over the territory a number of times, because of the necessarily small angle of view of the television camera, etc.

There is also a possibility of using this type of bomb at night, in conjunction with a dropped flare. This might be effective against submarines as well as surface vessels and land targets.

The problem of applying television control to self-propelled missiles is more difficult. The range of optical observation with the television head is obviously limited. Even with telephoto lenses it will not be more than a few miles. Therefore, for most of its flight, the missile must be guided by other means. Furthermore, the range of the television transmitter is limited to the line of sight. Even when the receiver is in an airplane, this will only be the order of a hundred miles because the bomb pilot must be able to follow the missile down to the ground. If greater distances than this are required, relay stations are necessary. This greatly complicates the use of the weapon.

There are other applications of television to military problems, particularly in the highly sensitive, very compact form represented by the Mimo-type equipment. Its use as an auxiliary submarine periscope, the monitory of military production processes, aerial reconnaissance, and the guarding of a number of points around an airbase, outpost, or other military installation are only a few of the many possibilities. These, however, are outside the scope of this report.

The following section (below) of this report describes the television-controlled bombs which were developed as part of the research program of World War II. At the close of the war, a number of these missiles had been brought to the point where they could be field tested, and one or two were essentially in production. Their use in combat, however, has been limited indeed. One or two missions were equipped with these weapons, where certain very special targets were involved. The results obtained under these circumstances should not be considered in an appraisal of the weapons, inasmuch as the attempted uses were few in number and on the whole premature.

TELEVISION MISSILES DEVELOPED DURING WORLD WAR II

The first series of missile tests made with television equipment used a glide bomb designed at the Bureau of Standards. This bomb had a wing span of about 8-1/2 ft and a glide ration of 5 to 1. The television transmitter was of the Block I type. A radio control link with the transmitter at the operator and receiver on the glider was arranged to actuate the aerodynamic controls. In order to direct the missile, the operator moved a miniature stick which simulated the control stick of a normal airplane. The transmitter was arranged to give signals characterizing the direction in which the stick was moved. This signal actuated appropriate relays on the bomb. Variable-length pulses and tones of different frequency were tested for their suitability in selecting the correct relays. Systems using tones for up-down, right-left, and a fifth standby tone have thus far been found the best suited.

Twelve television bombs were built in this series and drop tests were made on them. The results from these tests were rather discouraging. The most outstanding difficulties appear to be the following: (1) Mechanical or electrical failure of some of the components. In this connection, it is interesting to note that television link failed less often than did the radio control link. (2) Difficulty in associating pictures seen with known sections of the terrain over which the bomb is dropped. Several drops were made in which the operator never succeeded in finding the target although during the entire flight of the bomb a good picture of the ground below was presented to him on the screen. (3) Difficulty in recognizing the point on the picture towards which the glider was actually headed. In other words, the center of the picture did not necessarily coincide with the line of trajectory. This is particularly confusing if the angle of attack of the missile changes as the angle of the trajectory is changed.

The first of these difficulties is purely a technical one, and can be overcome by further work on the equipment. The second difficulty is due in part to lack of training of the operator, and in part due to the fact that the exact position and direction of the missile at the time of release was not quite accurately known. The third difficulty could be overcome by experience and training on the part of the operator but it also can be reduced considerably by the use of various electrical or mechanical aids. When the camera is fixed in the bomb, a relatively simple computer at the operating point could be arranged to actuate an index which corrects both for changing angle of attack and the effects of air motion. Preliminary tests have already been made with such an arrangement. An alternative method of reducing this cause of error would be to mount the camera or optical system in such a way that it is movable and by means of a suitable computer to direct the camera so that the center of the picture coincides with the terminal point of the trajectory of the missile, either for a homing course or a collision course. This second method is somewhat more complicated and has not yet been investigated.

Another series of glide-bomb tests were made at Wright Field. These tests were of the GB-4 which employs an Aeronca airplane similar to that illustrated in Fig. 6. Here the television equipment was mounted below the explosive chamber while the radio control receiver and Hammond gyro-stabilizer were mounted on the two spars supporting the tail.

The television equipment used for this was the Block III. The radio control element consisted of a superheterodyne receiver, designed and built for Western Electric, and a selector system based on five tones. Four tones actuated the rudder and elevator through the Hammond stabilizer system the fifth being a standby tone which locked the receiver against interfering signals.

The tests made on these bombs suffered from the same difficulties mentioned in connection with the first series tested. With the GB-4, the third item was perhaps the most serious due to the fact that in the case of this particular airframe, the angle of attack varies widely with the angle of trajectory. Further tests on the glide bombs were suspended, pending tests on television equipment in high-angle bombs.

The first series of tests on high-angle bombs were made on a bomb having a cylindrical shroud or wing near its center and an octagonal tail with movable control surfaces. Both Block I and III equipments were used with this bomb.

The results of these tests were rather unfavorable, primarily due to the fact that the angle of attack varies so greatly with the trajectory. This is particularly serious in this type of bomb because the operator has such a short time in which to direct the missile.

The second type of high-angle bomb to be tested is the Roc, developed under NDRC contract by the Douglas Aircraft Company. It is characterized by having the control element located close to the center of gravity so that the angle of attack remains constant, independent of changes in the trajectory. The wing in the present modification of this bomb is in the form of a cylinder located around the bomb. This cylinder can be rocked about horizontal and vertical axes to guide the missile. The tail is also cylindrical but is stationary and does not include any of the control surfaces except those required to stabilize it in roll. The bomb has a maximum glide angle of about 45° and its maneuverability characteristics have been found to be excellent. Television equipment for this bomb is type Mimo which is suited for the purpose because of its compactness and also its high sensitivity. The control system for this missile was designed and built by Philco and consists of a superheterodyne receiver which by means of interchangeable RF heads can be adjusted to operate in carrier frequency bands from 80 to 88 megacycles and 53-1/3 to 58-2/3 megacycles. The output is in

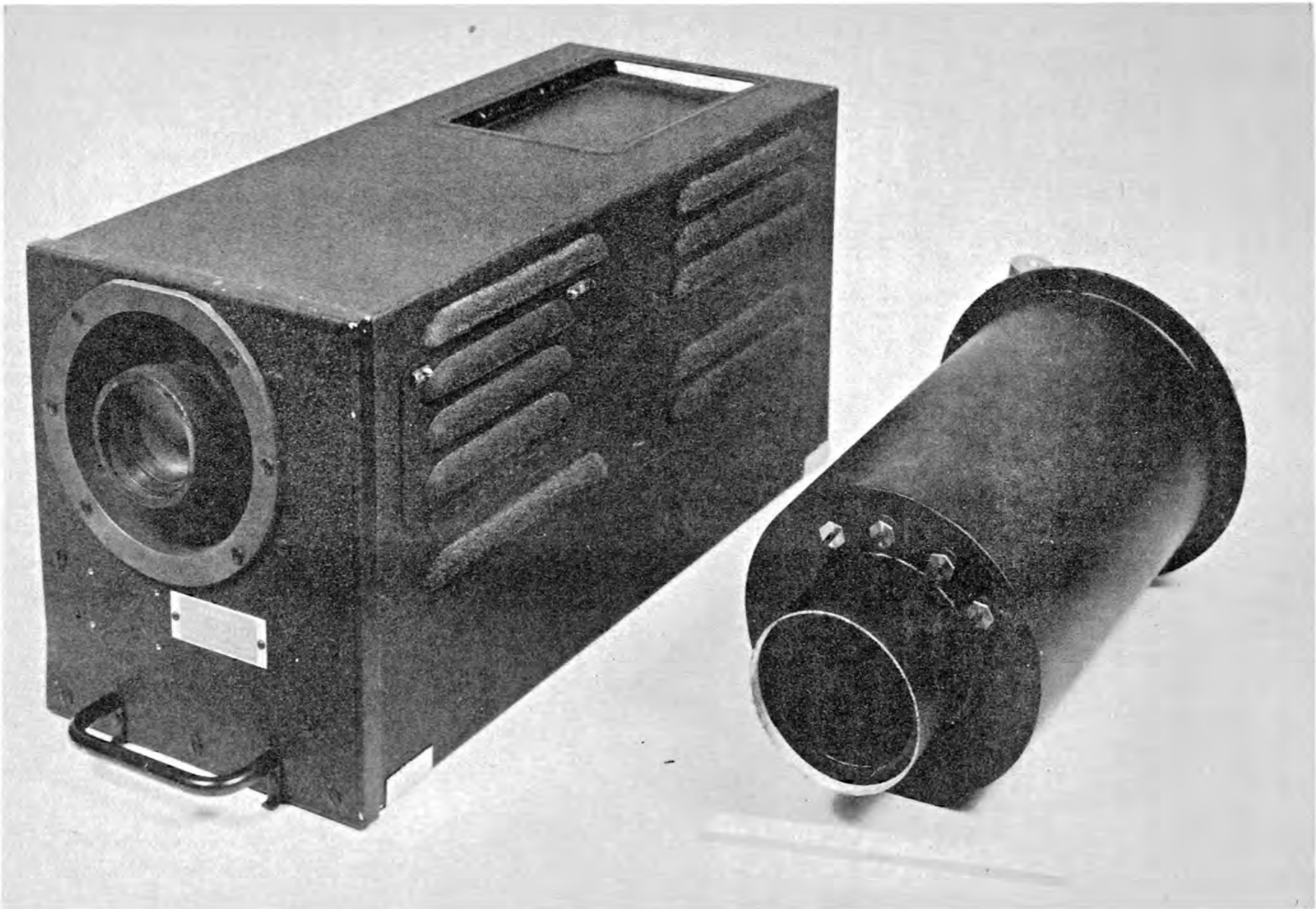


Figure 8 — Mimo Television Equipment

the form of four audio frequencies, namely, 300, 475, 755, and 1195 cycles for the four positions of the operator's control stick. Tuned circuits caused these frequencies to actuate the appropriate relay. Tests on the various components of this missile have been very satisfactory and tests on the complete missiles are in progress at present.

Both the Block and Mimo equipments can be used in powered missiles, such as those for the "Willie" projects. A large number of tests, starting long before the war, have been made on airplane-carried television equipment, and very good results, as far as the technical performance of the apparatus is concerned, have been obtained. The greatest difficulty appears to be that of recognizing the plane's location by the appearance of the picture. This same difficulty exists even when a plane is operated by a pilot, but is here exaggerated because of the rather small field of view of the camera. It can be largely overcome by one or more of the following measures: (1) projecting the instrument readings onto the pickup tube; (2) using an automatic pilot and dead reckoning in the approach to the target; or (3) the use of radar to follow the plane during its journey. The procedure then would be to bring the plane to the target area by instrument and radar, and to use the television equipment only at the end of the flight for locating the target exactly. Of course, the television picture may be of assistance during the flight, showing towns, rivers, etc., but only as an auxiliary.

Where television is used with powered missiles, the transmission range is a serious matter. In general this range is only to visual horizons, so that if the missile is to be used for greater ranges, provisions must be made for relaying the signal.

CONCLUSIONS

As a result of extensive research, missiles based on thermal radiation, light, and television detecting systems have been developed to a point where they are essentially ready for use.

Heat-seeking control equipment has been designed to be attached to a standard vertical bomb. Such a unit, on the basis of thermal surveys which have been made, should be a powerful weapon against marine targets in the immediate future. With the completion of the development of heat mappers, they may become useful against land targets. Glide bombs incorporating heat-detecting equipment are also well advanced.

As part of a long-range program, heat-seeking missiles have considerable importance. Heat-homing heads to guide powered missiles against industrial targets where the missile is brought within a few miles of the target by other means represents one type of application. The difficulty of hiding or disguising plants which are large heat sources is an important consideration in this connection. Vertical heat-seeking bombs dropped from a great height against either ships or land targets, and high-angle bombs to follow up attacks by other missiles are examples of other possible applications. One of the most important applications of thermal- or far-infrared-guided mechanisms may be in connection with antiaircraft missiles.

Light-seeking bombs, because of their simplicity, can be used in large numbers, in follow-up attacks where flares are placed in advance.

The application of television missiles is more complicated and warrants considerable study. The mistake must not be made, as has frequently been made in the past, of assuming that because the missile contains a television head it should be able to solve all problems, supply the answer to all navigational requirements, etc. It is a very powerful weapon, but it has very definite limitations. As a means of obtaining very high accuracy, when fully developed it will probably be without equal. Thus as a high-angle bomb, it can be used in attacks against giant tanks, front line strong points, etc. In a long-range missile, if the missile can be brought by other navigational means within sight of the target, it permits the operator to use judgment in selecting the final point of impact. It is not impossible in this connection that the picture may be of assistance in protecting the missile from destruction during its flight to the target.

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See also:

Bimonthly Reports
Division 5, NDRC

Progress Report Contracts
OEM-sr-441
OEM-sr- 60
OEM-sr-638
OEM-sr-1168

PART III

RADAR AIDS FOR THE GUIDANCE OF MISSILES

By

I. A. GETTING

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NOVEMBER 1945

INTRODUCTION

The development of radar during World War II has stimulated a large amount of consideration of the general problem of guided missiles. The application of radar and radar-type aids to the guidance of various types of missiles is very broad. There is hardly any aspect of warfare which is not included. An exhaustive report would not only be extremely long but would in fact defeat its purpose by omitting any new applications which will continuously arise as new weapons are evolved. The purpose of this memorandum is, therefore, to point out some of the problems which must be considered in the field of radar applications to the guidance of missiles and to indicate the tremendous scope and capabilities of the art.

RADAR AIDS TO GUIDED MISSILES IN WORLD WAR II

Before extrapolating into the future, it is first desirable to review the progress made in the field of application of radar aids to the guidance of missiles during World War II. These include control of antiaircraft fire by means of radar, dropping of bombs by means of radar, the control of glide bombs such as Pelican and Bat, and the remote control of planes such as Willie Orphan and radar control of JB-2 (buzz bomb).

The first two examples, the use of radar in the control of antiaircraft fire and the use of radar in bombing, may at first seem to fall outside of the scope of this report. However, this is not true. In the case of antiaircraft fire, the radar was used to track a target continuously. This automatic operation was followed by a computation also carried out automatically. The output data of the computer was used to position guns automatically. A missile (the projectile) was then ejected by the gun and also guided by the gun at least during the time the missile remained in the barrel. From any pragmatic viewpoint, the antiaircraft problem is, therefore, a radar-guided missile where the guidance is limited to the first part of the flight of the missile.

In the Bat project, a glide bomb was released from a plane and made to home on the ship target using radar data to locate the direction of the target. The homing process continued over a large fraction of the trajectory but was inoperative during the last few hundred yards.

The Willie Orphan project and the controlled JB-2 were intended for use against ground fixed targets whose position was known by map coordinates. The Willie Orphan plane (a special B-17 or a B-24) or the JB-2 (buzz bomb) was tracked by radar. To assist in this tracking, the effective reflectivity of the target was enhanced by putting into the missile a beacon transponder. This transponder received the radar signal from the ground station and immediately replied. The reply signal was many times stronger than the reflection of the plane itself. The course of the missile was automatically plotted at the ground station using the tracking information from the radar. Knowing the direction, the speed, and the position of the missile relative to the target, steering information was computed and transmitted to the missile using the radar beam as the carrier.

As weapons of warfare, the radar-guided missiles met with considerable success. The SCR-584 and the SCR-545, radar sets used with antiaircraft fire, combined with the M-9 director and 90-mm guns proved lethal to all enemy attacks whenever the enemy was in a position to fly in strength. This equipment was largely responsible for the defense of London and Antwerp against enemy buzz-bomb attack. The Bat project showed great potentialities in being able to hit targets with almost 100% efficiency. The guided buzz-bomb development was not completed at the ending of the war. The use of Oboe, Gee, Loran, and H2X in the bombing of Germany and Japan was covered in the report to the AAF Scientific Advisory Committee on radar.

In general, this bombing is not considered as the application of radar to guided missiles. The distinctions are not very clear. For example, in Oboe the sole function of the pilot was to steer the plane according to instructions received from the ground stations as far as 200 miles away. The bombardier released the bomb on a signal from the ground station. It is clear that by proper use of this information, an automatic pilot could have flown the plane, and an automatic release mechanism could have dropped the bomb. The function of the pilot would have been limited to take-off and the landing of the plane. In short, World War II saw the introduction, on a very large scale and in a very successful manner, of radar to guided missiles where a biomechanical link, a man, was used in the missile in place of what might have been fully automatic equipment.

ADVANTAGE OF RADAR GUIDED MISSILES

The use of radar in the guidance of bombers, in the control of antiaircraft fire, and in the control of glide bombs brings forth the major advantages of the radar applications to guided missiles.

NDEPENDENCE OF VISIBILITY

Radar was introduced in bombing to make the air force useful in all conditions of weather. By its ability of "seeing" in the dark, through clouds, rain, and snow, one of radar's chief advantages is its usefulness 24 hours each day.

ACCURACY

In many problems, radar can offer greater accuracy than any other known means. In the case of antiaircraft fire control, radar range has proven to be more accurate than optical, whereas directional tracking in many cases was just as good as optical tracking even under conditions of good visibility. Where location at long ranges was required and range triangulation of one form or another is possible, radar gives greater accuracy than any other known practical method. For example, in Oboe bombing the location of targets and planes could be determined to an accuracy of about five yards at 200 miles. Oboe bombing in World War II was about as accurate as the best optical local bombing in World War II.

AUTOMATICITY

Radar lends itself to fully automatic operation. The removal of personal errors possible through automatic operation has been realized very forcefully as a result of the success of automatic equipment in World War II. The absence of fear and the continuous alertness of automatic equipment are the only hope of making equipment which can be highly efficient from the start. On the SCR-584, the training of operators, so far as getting good data for the control of the missiles was concerned, was a matter of a few minutes. With optical tracking and other hand operations, no matter how simple, efficiency of equipment is very dependent upon the thoroughness of personnel training.

RANGE

Radar has increased the effective distance of vision by a large magnitude. A visual spotter can pick up a plane under extremely good conditions of visibility up to approximately 15 miles. A modern radar set, properly sited, is limited only by the horizon. For example, the MEW could track a plane at 20,000 feet out to 200 miles. In addition, a missile can always be equipped with beacons or beacon transponders so that it, too, regardless of its size, can be located and tracked to long ranges limited again only by the horizon. In certain applications of radar-like equipment such as Loran, missiles can be located to distances as great as 1000 miles. Obviously, by use of proper ground stations and relays, this distance can be made adequate to circumnavigate the globe.

RUGGEDNESS

Radar aids to the guidance of missiles share in common with other methods of guidance the advantages to be derived from ruggedness resulting chiefly from removing the man from the carrier of the missile or from the missile itself. For example, the JB-2 underwent acceleration during launching which could have prevented the use of a pilot. The future use of stratosphere planes and missiles can certainly be assisted by not requiring considerations of the presence therein of human beings.

MORALE

A final major advantage of radar aids to guided missiles is that in removing a man from the carrier or missile the problem of morale does not arise. The evidence gathered from World War II shows that pilots become uneasy if the losses of any one mission seriously exceed five percent; and, in fact, the nervous strain on pilots is so great that after from 25 to 50 strenuous missions, a pilot requires rest. Whether or not an air force can carry home its mission is, therefore, a delicate balance between the effectiveness of enemy action and the morale of the human beings involved. Obviously, the removal of humans from the carriers or from the missiles removes this problem.

DISADVANTAGES OF RADAR GUIDED MISSILES

For the sake of completeness, it is repeated here that guided missiles will probably never entirely replace human-controlled carriers. There are many targets of opportunity and fast-changing situations where human discrimination and processes are required. It is, of course, conceivable that by adequate combination of television, radar, radio, and other technical gadgets even some of these functions may be transferred from the carrier to a ground station. There is, however, in all considerations of this type a balance between complexity, efficiency, and the personal risk.

THE PROBLEM

As stated in the opening remarks, radar aids to guided missiles cover all conceivable types of problems. Guided missiles released from ground may be used against aircraft (Project Niki, Project Bumblebee, etc.). They can be used from ground against targets on the surface of the earth (JB-2). Also, radar aids can be used in the control of missiles fired or dropped from planes against other targets in the air or against targets on the surface of the sea or on land. All these problems have certain general characteristics. A very general case is illustrated in a block diagram, Fig. 1. A target

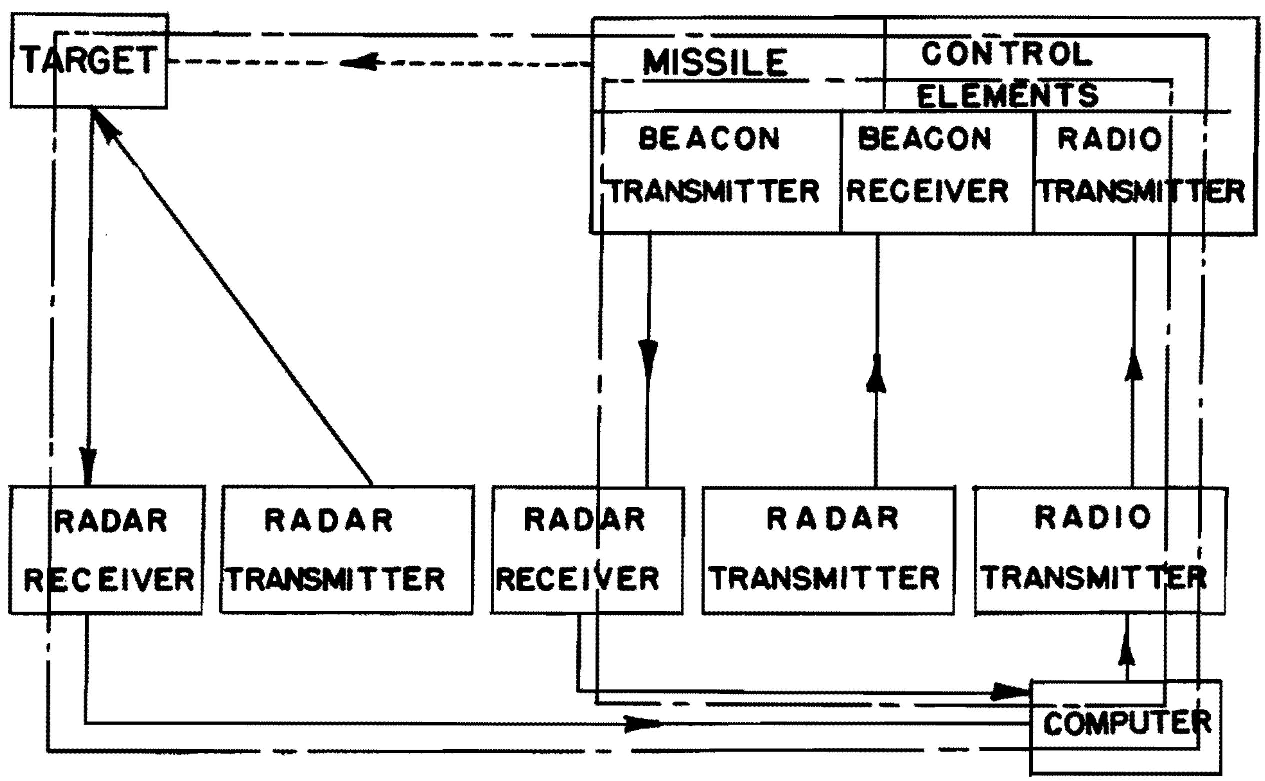


Figure 1 — General Block Diagram of a Radar Guided Missile

is illuminated by a radar transmitter. The reflection from this target is picked up by a radar receiver. The combination of these two elements determines the position of the target. This target information is transmitted to the computer. The computer also requires information on the position of the missile. Hence, a radar is required either to illuminate the missile or to interrogate the beacon on the missile. A receiver is required to measure the position of the missile. The position of the missile is then fed to the computer. The computer, having the information regarding both the target and the missile and being furnished with all the dynamic properties of both the target and the missile, computes the information necessary for the control elements on the missile to bring about the desired collision of the missile and the target. In the general case, the computer and the missile are removed from each other. Hence, a radio transmitter is required to relay the information to the missile where a radio receiver amplifies the information and converts it into motions of the control elements.

Before considering the technical aspects of this problem, it is worth while to consider how this general diagram conforms to certain missiles now under development. In case of the use of the SCR-584 to control the JB-2, the target's positions are known as map coordinates and are inserted directly into the computer. The radar transmitter, the radar receiver, and the radio transmitter are incorporated in the one set using the one beam. A simplified diagram is shown in Fig. 2.

In one form of the Bumblebee Project known as the Beam Rider, Fig. 3, the target is located by a radar-transmitter, radar-receiver combination. The missile carries its radar receiver itself and uses the same transmitter as the target locator. The computer is also carried in the missile, although in this case, the computer is indeed a very simple one. The computer transmits information to the controls directly because in this case they are also in the missile.

As indicated in the radar report to the Scientific Advisory Group Committee, the control of a plane can be done automatically by the use of Loran. Obviously, Loran can be used to control the flight of a pilotless plane to a predetermined point. In this case, as in the case of the JB-2, the target's coordinates are known from a map. The missile is located, however, from radar lighthouses located on the surface of the earth. Its position and steering information are computed at the missile.

It will be seen from the preceding examples that radar-controlled guided missiles possess, in general, closed loops in the form indicated in Fig. 1. There are two major loops as shown by the broken line in Fig. 1. A dynamic problem of this type requires careful consideration because such a system must be, above all, stable, and secondly, must be sufficiently accurate to serve the military mission. *Experience has shown that unless systems of this type are developed and engineered as complete systems, a successful instrument will not result.*

Closed-loop systems are known in feed-back amplifiers and in the field known as servomechanisms. In most practical cases, these problems concern themselves with time constants and delays inherent in the mechanisms themselves. The same class of problems exist in the application of radar to guided missiles; viz., it is necessary to consider the dynamic responses of the missile to its controls; it is neceessary to consider the dynamics of the computer; and finally, it is necessary to take into consideration the dynamic capabilities of the target.

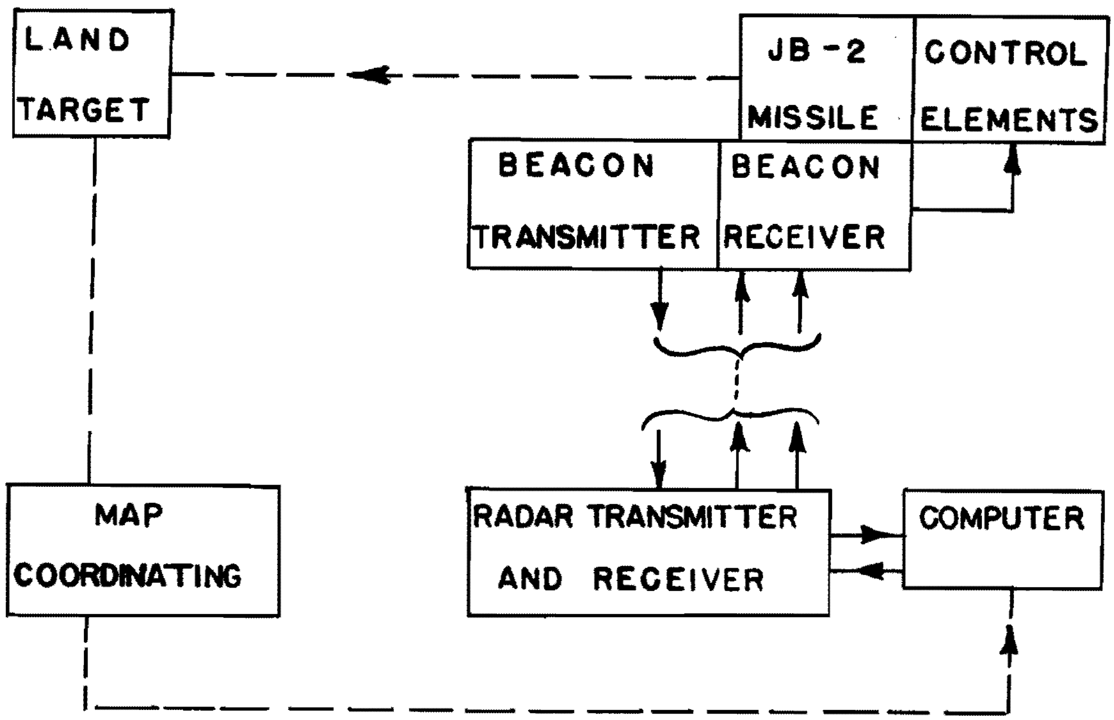


Figure 2 — The Guided Buzz-Bomb (JB-2)

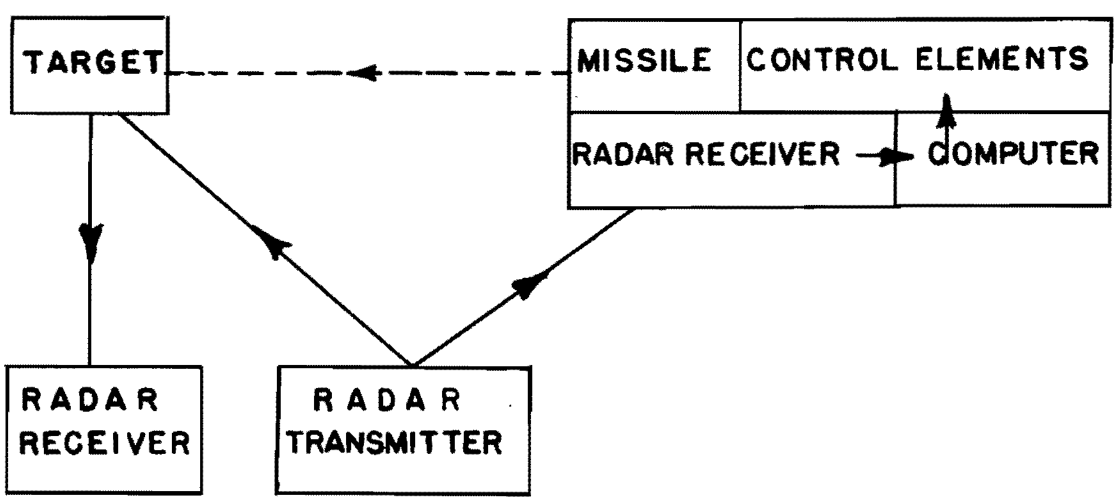


Figure 3 — Beam-Riding Anti-Aircraft Missile

There is, however, present in radar-guided missiles a series of problems generally not present in servomechanisms and feed-back amplifiers. This is the problem arising from poor data. In the present state of the art, it is not possible to track a missile or a target without errors in tracking. These tracking errors are not in themselves very large. However, even the simplest type of computer or control elements in the missile will require a determination of leads or derivatives. Unless proper care is taken to smooth data (thereby introducing time delays), instability can result which would not have been present with a perfect error-detecting system and a perfect data transmission system. In short, future work in the application of radar-guided missiles should include development of better tracking and locating systems where the criteria of "better" is determined by the dynamic requirements of the entire system. Several illustrations of some of these considerations are given in Appendix I, which is a theoretical study on the stability of certain systems made by Dr. Witold Hurewicz of the Radiation Laboratory, MIT. For example, a beam-riding antiaircraft missile possessed with certain specific dynamic properties could attack targets with speeds up to 600 mph with a maximum error not greater than 15 yd at a range of 10,000 yd. If, however, radar equipment such as the SCR-584 in its present embodiment were used, a random error of at least 20 yd at 10,000 yd would result. Even the existence of this small error is contingent on the right choice of constants in the derivative control required to give stability.

It is obvious that military limitations on size and weight may result in restrictions on the goodness of radar systems. This will in turn influence the character of the computer and may even result in fixing the nature of the military missions which the guided missile itself can carry out. If, for example, in controlled missiles for use against enemy cities at extremely long range, it develops that radar can furnish only instantnaeously inaccurate data, the type of the approach of the missile toward that city may be limited by the nature and goodness of the radar itself. From a military standpoint, it may be desirable to have a missile approach the target from an arbitrary direction. However, limitations arising from the radar data itself may require approach to the target along a definitely specified curve.

PRESENT STATUS OF THE TECHNICAL DEVELOPMENT

Present-day techniques in radar development are divided into two broad regions: (1) the short-wave region where the propagation is in straight lines and where range is limited by the curvature of the earth; and (2) the long-wave region in which the rays are trapped by the ionosphere and where ranges in excess of 1,000 miles near the earth's surface are possible.

For use in three-dimensional problems, such as the control of antiaircraft weapons, the control of glide bombs and other type bombs against surface targets, and the control of rocket and high-trajectory weapons of the type similar to V-2, it is desirable to use extremely short waves especially those in the microwave region. The present state of the art in the microwave region permits the tracking of targets and missiles in angle with accuracy better than one angular mil. This corresponds to a lateral error of one one-thousandth of the range. For example, the probable error of a target at range of 20 miles is approximately 34 yd. It is easily possible to locate targets in range with an accuracy of ten yards. This range accuracy can be maintained independent of distance up to any desired range provided only that sufficient power in the radar beam is available. The accuracy of the determination of angular rates is at present such that a probable error of one-tenth of a mil per second can be obtained over an interval of time not greater than ten seconds or a quarter or a mil per second in two seconds. Range rate can be measured with modern military radar equipments to an accuracy of five yards per second by averaging over a period of two seconds. These data are sufficiently good to provide control for rocket-propelled missiles so that when combined with modern fuses and reasonably large explosive charges, any plane can be destroyed out to ranges of 20,000 yards. (Please note that this statement is limited to the fact that the present state of the radar art is adequate. No implication is meant about the missile itself.)

It is obvious from the preceding statements that missiles of the type similar to the JB-2 can be positioned over any desired spot on the map to a high degrees of accuracy even with a single radar station tracking in angle and in range. Briefly, it is possible to place a JB-2 over a given target to an accuracy of approximately one-half mile or better, at a range of 200 miles. It is not implied here that the accuracy of hitting a target would equal this figure because at the present time nothing is known about the "exterior ballistics" of the JB-2, namely, what happens when a JB-2 goes into a dive and is no longer controlled by the radar. On the other hand, it has been calculated that the probable error of a bomb dropped by a JB-2 could be about twice the probable error of the instantaneous location of the JB-2 itself, if 20-second rate smoothing is used. No consideration has been given to possible errors arising from Lloyd's mirror effect or to errors in instrumentation. If greater accuracy is required in attacking map-located ground targets by the use of guided missiles, it is possible to use some modification of Shoran or Oboe in which range tracking only is used, or some equivalent of hyperbolic navigation. While tests of the control of JB-2 have not yet been very conclusive, some tests made at Eglin Field by the Army Air Forces Board on piloted planes using a single SCR-584 as a ground control station have shown that the above percentages are realizable at least at distances of from 35 to 50 miles.

There is available at present no data on the use of radar-controlled missiles from planes against other planes.

FUTURE POSSIBILITIES

As indicated in the opening remarks of this report, radar control can be applied to a variety of problems. Some considerations which enter into the problem of radar control are outlined in Appendix II. It is perhaps profitable to consider in a little more detail the possibilities brought about by the introduction of the atomic bomb. It is recognized that atomic bombs can be delivered in a variety of ways. For the purpose of this study, let use consider the possibilities of radar-controlled unpiloted planes and rockets. Lacking further information, it is assumed that the atomic bomb will require carrying a pay load in the neighborhood of one ton and that a probable error of two miles can be tolerated at the termination of the delivery.

The atomic bomb can obviously be delivered by means of an unpiloted aircraft controlled by radar. The present JB-2 controlled by SCR-584 and automatic plotting board kit MC-627 is able to perform this task out to ranges of 200 miles. Further work is required along these lines, however, to guarantee the impossibility on the part of the enemy to jam the radar link (APW-3). If ranges longer than 200 miles are desired, two broad possibilities are left open: One is the introduction of microwave relays on a system similar to the Oboe; the other is the use of Loran. The present status of Loran is adequate to provide for pilot navigation. However, the hyperbolic navigation scheme at low frequencies can be applied to controlling pilotless aircraft out to ranges of 1500 miles. It is difficult to give a clear presentation of the accuracy of control because of insufficient data. It is plausible that an accuracy of two miles could be obtained if sufficient work is put into development and adequate care is exercised in the controlling process.

Another method of delivering atomic bombs and using radar-controlled missiles is the employment of rocket missiles of the type developed by the Germans and known as V-2. Assuming that some means can be provided for slowly altering the course of the equivalent V-2, a single-base radar station of the type SCR-584 can provide an accurate means of guiding the missile along the trajectory which passes through the target. Since the missile is moving in vacuum, the accuracy to be derived from this type of control depends only on the accuracy with which the missile can be turned. This report proposes to answer only the first part. As stated earlier, the accuracy which is obtainable with present-day radar techniques for determining position is better than one angular mil. There may be errors introduced by atmospheric variations affecting the radar path. If the top of the trajectory is, say, 500 miles from the launching site, and the radar is also near the launching site, the lateral error in the determination of the peak of the trajectory will be less than one-half mile. Consequently, if the angle of turn can be carried out accurately, then the error at the target resulting from the lateral tracking error should be not greater than twice the error of radar location at the peak, or one mile. The angle of fall at the target will not differ appreciably from the angle of firing. Hence, the error along the surface trace of the trajectory will be not more than twice the lateral probable error, or not more than two miles. In general, a missile can be tracked during the rising part of its trajectory (by the use of a beacon if necessary); therefore, so far as the radar is concerned an accuracy of approximately 0.1% of the actual range seems plausible. If the rockets can be made to go 4000 miles and if they can be controlled, then present radar techniques are adequate to provide sufficiently good tracking for a probable error of approximately eight miles. It is possible to increase the angular accuracy of tracking by almost an order of magnitude if the missile and its control elements warrant it.

SUMMARY

Some radar-controlled missiles have been used in World War II. While their use was somewhat limited, they were nevertheless successful as military weapons. Future development should lead towards much greater exploitation of this field. At the present time, it seems that the fundamental radar art is adequate to provide control good to about 0.1% of the distance. Future development on missiles, especially in the way of increased range and dynamic performance, may require an improvement in radar techniques. There is a possibility of improving angular tracking accuracy an order of magnitude. Hence, further development in the radar art should be maintained at least to keep up with the advancement in aerodynamic missiles. In particular, the improvements should go in the direction of (1) compact and rugged transponders for use in missiles, (2) the development of extremely accurate, automatic angular-tracking ground stations, (3) the exploration of long wavelength Loran-type automatic controls for missiles, and (4) exploration of other types of systems.

APPENDIX I

GUIDED MISSILES

W. HUREWICZ

6 June 1945

Two distinct schemes have been suggested for guiding a missile toward a moving target (airplane). (a) Control from the ground. A ground base finds the instantaneous positions of the missile and of the target and transmits steering orders to the missile. The missile is guided along the line of sight in such a way that its distance to the line of sight (from the ground base to the target) decreases constantly. (b) Controls located in the missile. The projectile carries its own tracking equipment which locates the position of the target, and this information is used directly (without being relayed to the ground base) to control the course of the missile. The missile is steered toward the target on a "collision course."

In this report, we discuss the servoloops involved in each of the schemes mentioned above. An attempt is made to evaluate the expected accuracy in guiding on the basis of the available tracking data with SCR-584.

We assume that the projectile maintains a constant speed during the time it is guided toward the target. This implies that the projectile is self-propelled (rocket or buzz bomb) during its entire flight and not only during an initial period after the launching. In the latter case, the instantaneous speed of the projectile would depend on the previously covered trajectory, and the problem of control could not be studied without a detailed knowledge of the aerodynamic characteristics of the projectile.

CONTROL FROM THE GROUND

Assumptions	
Speed of the missile	500 yd/sec
Speed of the target	Maximum 300 yd/sec
Maneuverability of the missile	Maximum turn corresponding to the radial acceleration of 5 g
Maneuverability of the target	Maximum acceleration 4 g
Range of the target	10,000 yd or more

1. *Description of the System.*

In Fig. 4, G denotes the ground base, M the missile, and T the projection of the target onto the vertical plane through G and M. MN is the projection of the velocity vector of M onto the same plane. θ is the angle between MN and the horizontal plane.

The derivative θ is determined by the position of the vertical rudder (which controls the lift).

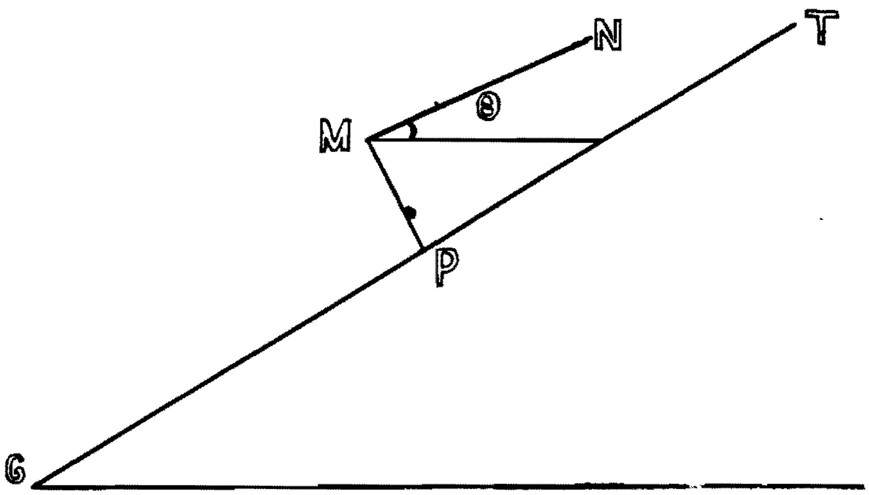


Figure 4

It will suffice to describe the control of the vertical rudder, the hozintal (lateral) control being quite similar.

The distance ϵ = MP, from M to the line of sight GP, is used as the error signal; ϵ is regarded as positive if M is above the line GT, otherwise as negative; ϵ is computed at G from the elevtion and range data (ϵ is simply the product of the range of M by the difference between the elevation angles of M and T). The missile is steered in such a way that the angular rate $\dot{\theta}$ assumes the value

$$K\epsilon + K_1\epsilon$$

when K and K_1 are suitably selected constants. In other terms, we use proportional and derivative control.*

If the controls could be moved instantaneously, we would have the equation

$$\dot{\theta} = -(K\epsilon + K_1\dot{\epsilon}) \qquad (1)$$

Actually it will take a finite period of time, say T sec, to move the controls into the prescribed position, and the previous equation has to be replaced by

$$T\ddot{\theta} + \dot{\theta} = -(K\epsilon + K_1\dot{\epsilon}) \qquad (2)$$

or setting $K = K_1/T_d$ (where T_d has the dimension of time) and using operational symbols

$$p(Tp + 1)\,\theta = -K(T_d p + 1)\,\epsilon. \qquad (3)$$

The relations (2) and (3) are subjected to the restriction that the quantity θ under no circumstances can exceed the value of 6°/sec which corresponds to the acceleration 5 g.

It is estimated that the time constant T has to be at least 0.2 sec. **

* The way the angular rate $\dot{\theta}$ is correlated with the rudder position depends, of course, on the aerodynamic properties of the missile.

** This means that the steering controls cannot be moved at a faster rate. Observe that the time lag T has the effect of smoothing the rough velocity data $\dot{\theta}$.

The constants K and T_d are entirely at our disposal.

a. EVALUATION OF THE CONSTANT K. For the sake of simplicity, we assume that the azimuth of the target remains constant and that the ground base G, the missile, and the target are always in the same vertical plane. In Fig. 4, T coincides with the target, and MN is the complete velocity vector of M. We introduce the following additional notations: ϕ = angle between MN and GT; r = distance GM; R = distance GT; w = the component of target velocity perpendicular to GT (with + sign if the target gains elevation, − sign if it loses elevation); v = the speed of the missile.

We have

$$\dot{\epsilon} = v \sin \phi - \frac{wr}{R} \tag{4}$$

$$\dot{\phi} = \dot{\theta} - \frac{w}{R} \tag{5}$$

$$\dot{r} = v \cos \phi. \tag{6}$$

Let us assume that w and R are constant (i.e., the target moves on a circle with G as a center). From (4) and (6) we obtain

$$\ddot{\epsilon} = (v \cos \phi)\, \dot{\phi} - \frac{wv}{R} \cos \phi. \tag{7}$$

From (3), (4), (5), and (7), one derives

$$\frac{1}{v}(Tp + 1)\, \frac{p^2\epsilon}{\cos\phi} + K(T_d p + 1)\, \epsilon = -\, \frac{2w}{R}. \tag{8}$$

The equation (8) has the "steady state" solution

$$\epsilon_s = \frac{-2w}{KR} \tag{9}$$

Assuming that the servoloop is stable ϵ_s is the limiting value of the error for increasing target range. If the servo is sufficiently fast the error will practically reach the steady state value ϵ_s before r gets larger than R, so that, aside from random errors, which will be discussed later, ϵ_s represents the distance between the missile and the target at the moment they are closest.

According to our previous assumptions, the maximum value of w is 300 yd/sec, and the minimum value of R is 10,000 yd, hence by (9)

$$\text{Maximum } \epsilon_s = \frac{.06}{K} \tag{10}$$

In order to insure the destruction of the target, it is probably necessary to keep ϵ_s = 15 yd.

This will be the case when we choose K as follows:

$$K = .004 \text{ radians/sec-yd} \tag{11}$$

With this value of K, the missile will rotate at the rate of 4 mils/sec, when the error is 1 yd.

We observe that for $\epsilon = 0$ (steady state) according to (5) and (7)

$$\dot{\theta} = \frac{2w}{R} = .06 \text{ radians/sec} \tag{12}$$

which is well below the maximum allowed rate of 6° or .1 radians/sec.

b. CHOICE OF THE TIME CONSTANT T_d. The derivative time constant T_d determines the stability and the fastness of the servoloop. Consider the simplest case $w = 0$; so this means that the line of sight is stationary. When T_d is too small, the path of the missile will have the shape indicated in Fig. 5, with oscillations either increasing (instability case) or decreasing very slowly.

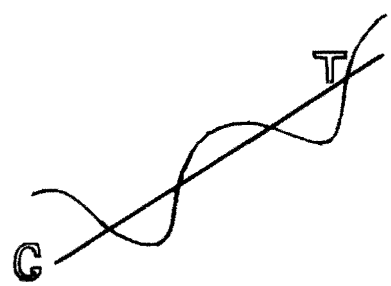


Figure 5

If T_d is too large the system is overdamped and the shape of the path will be as follows:

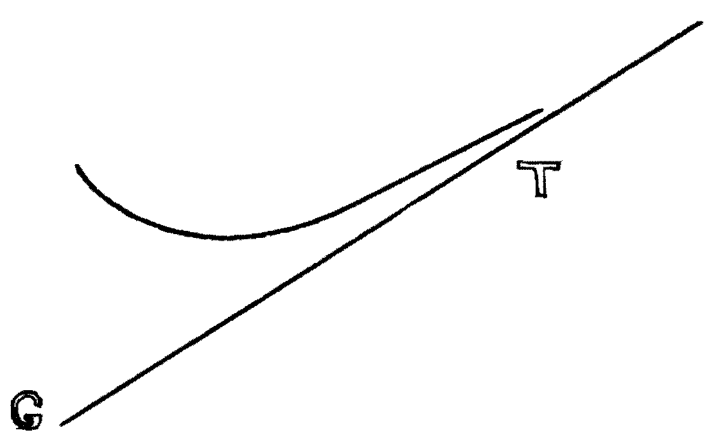


Figure 6

That is, the path will approach the line of sight at a very slow rate. Obviously both cases are undesirable.

In order to get a rough estimate of the desirable value for T_d, we observe that in case of a stationary line of sight GT, we obviously have $\phi = 0$ in the steady state, and we shall assume that in the transient state ϕ is near to zero. (This means that the missile has an approximately correct course at the moment the radar control starts.) Then cos ϕ in the right hand term of (8) may be replaced by 1, and since $w = 0$, we have

$$(Tp^3 + p^2 + KvT_dp + Kv)\,\epsilon = 0 \tag{13}$$

The servo will be stable if the roots of the characteristic equation

$$Tp^3 + p^2 + KvT_dp + Kv = 0 \tag{14}$$

have negative real parts.

This will be the case if and only if

$$T_d > T$$

Suppose

$$T = .2 \text{ sec}, \; v = 500 \text{ yd/sec}, \quad K = .004 \text{ radians/sec-yd.}$$

One finds that the servo will have good stability and fast response when T_d is between 0.7 and 1.5 sec. Take for instance

$$T_d = 1 \text{ sec}$$

The roots of the characteristic equation (14) are approximately

$$-2.5, \; -1.25, \; \pm 1.6\,t$$

and the general solution of (13) is

$$\epsilon(t) = c_1e^{-2.5t} + c_2e^{-1.25t}\sin 1.6t + c_3e^{-1.25t}\cos 1.6t \tag{15}$$

Suppose that at $t = 0$, the missile is at the distance of 150 yd from the line GT, and has at this moment a rectilinear course forming an angle of 15° or less with the direction GT.

The initial conditions at $t = 0$ are $\epsilon(0) = 150$ yd.
$\dot{\epsilon}(0) = -v \sin 15° = -130$ yd/sec, $\ddot{\epsilon}(0) = 0$

One computes easily that in 3 sec the initial error of 150 yd will be reduced to less than 10 yd. It may be assumed that at the time the control starts the missile is at a distance of at least 5000 yd from the target, hence the time of flight from this moment on is at least $\frac{5000}{800} = 6$ sec (assuming that the target moves toward G), compared to 3 sec transient time. This shows that the response of the servo is sufficiently fast.

Although the preceding discussion assumed $w = 0$, the result will not be changed materially if the line of sight is not stationary.

2. *Response to the Maneuvering of the Target.*

Suppose that in order to evade the missile the target changes from the radial course to the crossover course with a 4-g turn, which is the sharpest turn that can be made by a plane with a pilot.

Assuming $K = .004$ radians/sec-yd, a computation which is omitted here shows that the target cannot escape by more than 30 yd, that is, in addition to the steady state error of 15 yd we may have an additional error of not more than 30 yd at the time the targets and the missile are closest.

3. *Accuracy.*

So far, we assumed that the tracking of the missile and of the target is perfect. Actually, however, the position data obtained from the radar are distorted by the noise, and this leads to random errors in the control of the missile, in addition to the systematic errors (steady state errors) discussed previously.

In order to evaluate the effect of the noise we distinguish between the true distance MP (see Fig. 4), which we continue to denote by ϵ, and the observed distance MP which will be denoted by $\hat{\epsilon}$. The discrepancy

$$\eta = \epsilon - \hat{\epsilon}$$

is due to the noise. The control signal is

$$K(T_d p + 1)\hat{\epsilon} = K(T_d p + 1)\epsilon - K(T_d p + 1)\eta \tag{16}$$

Equation (11) has to be replaced by

$$\frac{1}{V\cos\phi}(T_d p + 1)p\epsilon + K(T_d p + 1)\epsilon = -K(T_d p + 1)\eta - \frac{2w}{R} \tag{17}$$

Confirming ourselves to the case $w = 0$ and replacing $\cos\phi$ by 1, we have

$$(Tp^3 + p^2 + KvT_d p + Kv)\epsilon = Kv(T_d p + 1)\eta \tag{18}$$

The noise η is a random variable which can be described only by its statistical properties. Let $C(t)$ be the autocorrelation of η. On the basis of the available tracking data, it is reasonable to assume that $C(t)$ has the form

$$c_o e^{\frac{-t}{t_o}}$$

where the time constant t_o has the approximate value of 3 sec. For the Fourier transform $A(\omega)$ of $C(t)$ (that is, the power spectrum of η), we obtain

$$A(\omega) = \frac{2c_o t_o}{1 + t_o^2\omega^2} \tag{19}$$

Now let

$$F(p) = \frac{Kv(T_d p + 1)}{Tp^3 + p^2 + KvT_d p + Kv} \tag{20}$$

In the steady state the mean square deviation of ϵ from its mean value 0 is given by the formula

$$\overline{\epsilon^2} = \int_{-\infty}^{\infty} \left|F(i\omega)\right|^2 A(\omega)\, d\omega \tag{21}$$

This integral can easily be evaluated (by the method of residus):

$$\overline{\epsilon^2} = c_o t_o \frac{(T + t_o)(KvT_d^2 + 1) + (T_d - T)Kvt_o^2}{(T_d - T)(T + t_o + KvT_d t_o^2 + Kvt_o^3)} \tag{22}$$

setting

$$t_o = 3 \text{ sec}, T = .2 \text{ sec}, T_d = 1 \text{ sec}, v = 500 \text{ yd/sec}$$
$$K = .004 \text{ radian/sec-yd},$$

we obtain

$$\overline{\epsilon^2} = c_o \text{ (approximately)} \tag{23}$$

Since c_o is the mean square value of the input noise, the preceding relation shows that our servo follows the input noise without either amplifying or attenuating it.

According to the available data about radar auto tracking the root mean square angular error in tracking a single object is approximately 1.4 mils. Since, in our problem, two objects (the missile and the target) are tracked independently, the angle between the corresponding line of sight is known up to a root mean square error of

$$1.4\sqrt{2} = 2 \text{ mils (approximately)}$$

This correspond to the linear distance of 20 yd at 10,000-yd range. Hence 20 yd is the value to be substituted for $\sqrt{c_0}$ when the missile is in the distance of 10,000 yd from G, and 20 yd is also the root mean square error in guiding the missile at this range. It should be explained that the error is superimposed on the systematic error, which, as we found above, depends on the speed of the target.

We observe that the constant K can be increased indefinitely, without changing appreciably the random error. The result of increasing K would be a reduction of the steady state error. However, it is not desirable to make K larger than necessary. The higher K is, the greater the danger of the servo becoming unstable due to "parasitic" time lags.

4. *Conclusions.*

The system with the constants

$$K = .004 \text{ radians/sec-yd}, \; T_d = 1 \text{ sec}$$

has the following properties:

Assuming 10,000 yd as the minimum range of the target, the systematic error is no more than 15 yd. The expected random error is 20 yd at the range of 10,000 yd, and 40 yd at the range of 20,000 yd, etc. Assuming an initial error 150 yd the transient time is about 3 sec. The target has little chance to escape by an evasive action.

CONTROLS LOCATED IN THE MISSILE

Let MT be the line of sight joining the missile to the target. Let ψ be the angle between MT and a fixed direction OX in the space.

It is understood that the missile carries its own tracking equipment including gyro whose precession currents measure the rate $\dot{\psi}$.

In order to simplify the exposition, let us assume that the missile and the target are always in a fixed plane (which also contains the direction OX). In other terms, we replace the problem in three dimensions by the one in two dimensions. Let θ be the angle between OX and the instantaneous tangent to the trajectory.

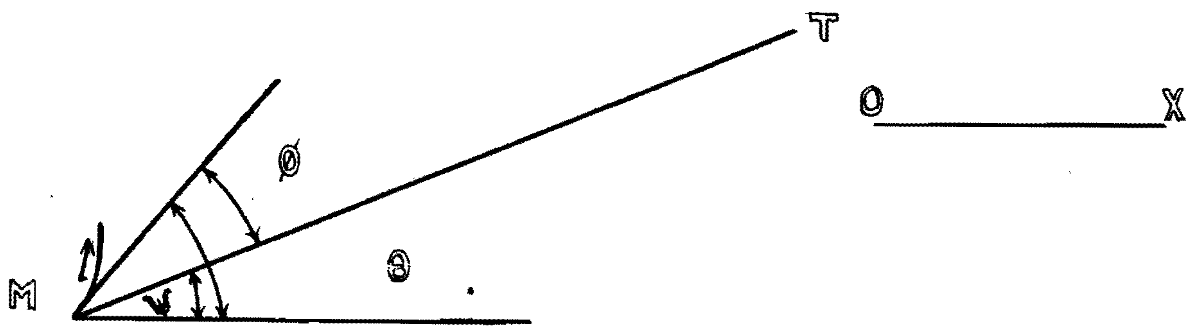


Figure 7

The missile is steered in such a way that (neglecting the time lag in displacing the steering controls) the angular rate θ is proportional to the angular rate $\dot{\psi}$.

$$\theta = K\dot{\psi} \tag{24}$$

where K is the dimensionless proportionality factor. If we take into account a time lag of about .2 sec, we obtain the more rigorous equation

$$.2\ \theta + \theta = K\dot{\psi} \tag{25}$$

It should be stressed that these equations are subject to the restriction that $\dot{\theta}$ can never exceed a certain maximum value, say 6°/sec (corresponding to the maximum acceleration of 5 g).

Let V_1 be the velocity vector of the missile, V_2 the velocity vector of the target. Suppose the motion of the target is uniform and rectilinear, i.e., the vector V_2 is constant. Consider the difference vector.

$$W = V_1 - V_2 \tag{26}$$

If at a given moment W is parallel to the line of sight MT, the missile is on a collision course, this means that the missile would eventually collide with the target, if it would continue on the same course.

In general, let us denote by y the component of the vector W, perpendicular to the line MT. The quantity y can be regarded as measuring the deviation by which the course of the missile fails to be a collision course.

Let r be the distance MT. We obviously have

$$\dot{\psi} = -\frac{y}{r} \tag{27}$$

and consequently

$$.2\ddot{\theta} + \dot{\theta} = -K\frac{y}{r} \tag{28}$$

Setting

$$\phi = \theta - \psi \tag{29}$$

and neglecting the small term $.2\ \ddot{\psi}$, we derive from the two preceding equations

$$.2\ \ddot{\phi} + \dot{\phi} + (K-1)\frac{y}{r} = 0. \tag{30}$$

ϕ is obviously the angle between the course of the missile and the line of sight MT. If v is the speed of the missile, the component of V_1, orthogonal to MT is given by the expression v $\sin\phi$, and the quantity (v $\cos\phi$) $\dot{\phi}$ represents the contribution of the vector V_1 to the linear rate $\dot{y}$. The contribution of the vector V_2 is relatively small and can be neglected; hence we can write approximately

$$\dot{\phi} = \frac{\dot{y}}{v \cos \phi} \tag{31}$$

and in operational rotation

$$\frac{1}{v}\,(.2p + 1)\,\frac{y}{\cos\phi} + (K-1)\,\frac{y}{r} = 0 \tag{32}$$

When M is on a collision course, the component v $\sin\phi$ is equal to the component of V_2 orthogonal to MT. If we assume that 500 yd/sec is the speed of M and 300 yd/sec the maximum speed of T, we get

$$500 \sin\phi \leqq 300 \tag{33}$$

or $\sin\phi = < .6$ and hence $\cos\phi \geqq .8$. it is permissible to assume that during the whole flight of the missile its course never deviates very much from the collision course, so that $\cos\phi$ is always close to 1. Under this assumption, we replace in the last equation $\cos\phi$ by 1. This yields, after substituting v = 500 yd/sec,

$$.2\ddot{y} + \dot{y} + \frac{500\,(K-1)}{r}\,y = 0 \tag{34}$$

This equation shows that the condition

$$K > 1$$

is necessary for stability. If this condition is satisfied, y approaches zero with progressing time, in other terms, the course of M approaches asymptotically a collision course.

The last term in our equation depends on r. This means that the gain of the servo depends on r. For large r the gain is very small, for small r the gain is large. This has the consequence that the servo has poor stability (that is, great sensitivity to random disturbances) when r is small. This fact is, however, of little significance since the final piece of the trajectory of M during the last record before the expected collision, is practically a straight line (due to the limitation on the maximum value of the rate of turn of $\dot{\theta}$); any displacement of the rudder immediately before the expected hit will have very little effect.

It is desirable to select K in such a way that the servo has a good stability for r = 500 yd. The value K = 10 seems to be a reasonable choice.

In order to compute the response to the noise, we go back to the original equation

$$.2\,\ddot{\theta} + \dot{\theta} = K\,\dot{\psi} \tag{25}$$

We may neglect the first term (since the time constant .2 sec is small compared to the time constant in the autocorrelation of the noise).

From the simplified equation

$$\dot{\theta} = K \dot{\psi} \tag{24}$$

it follows easily that the mean root square error in θ is K times the mean root square error in ψ. The latter error being approximately 1.4 mils, the former error is about 14 mils (assuming K = 10). In other terms, when the missile is close to the target (say 500 yd) its course will have a rms deviation from a collision course of about 14 mils, which means a linear deviation of 7 yd at 500-yd range. The actual error (the distance between the missile and the target when they are closest) may be greater due to the fact that even during the last second the missile does not move strictly on a straight line. If we assume the maximum curvature corresponding to the rate of turn of 6°/sec, we obtain about 25 yd, a maximum deviation due to the curvature of the trajectory. This error can be decreased by limiting the maximum rate of turn of the missile.

It should be stressed that the system will work even if the tracking is very poor at long range. Up to the very last moment, the only important thing is that the distance between the missile and the target should decrease, and this will be the case even if the tracking is very rough.

APPENDIX II

REMARKS ON THE "LINE-OF-SIGHT COURSES"

W. HUREWICZ

11 June 1945

Consider a moving target T. Suppose the missile M is steered in such a way that M is always on the line of sight GT (this corresponds to the ideal case of a steering servo with infinite gain). How is the trajectory of M related to that of T?

Let r be the distance GM. Since the azimuth and the elevation of M are the same as the azimuth and the elevation of T, the trajectory of M is described completely if r is expressed as a function of time.

Let R be the distance GT, u the instantaneous speed of T, and ϕ the angle between the line of sight and the course of T. Then

$$\alpha = \frac{u \sin \phi}{R} \tag{1}$$

is the angular speed (in radians/sec) at which the line of sight rotates around G.

The velocity component of M perpendicular to the line of sight is αr. Assuming that M has a constant speed v, the velocity component in the direction of the line of sight, is $\sqrt{v^2 - \alpha^2 r^2}$, hence r satisfies the differential equation

$$\dot{r} = \sqrt{v^2 - \alpha^2 r^2} \tag{2}$$

In the particular case that α is a constant, equation (2) can be solved quite easily. As long as r remains below the value $\frac{v}{\alpha}$, the function

$$r = \frac{v}{\alpha} \sin (\alpha t + \delta) \qquad (\alpha t + \delta \leqq \frac{\pi}{2}) \tag{3}$$

where δ is an integration constant, satisfies the equation (2).

For $t = \frac{1}{\alpha}(\frac{\pi}{2} - \delta)$ r reaches the value $\frac{v}{\alpha}$ and from then on remains constant.

$$r = \frac{v}{\alpha} \qquad (\alpha t + \delta > \frac{\pi}{2}) \tag{3a}$$

Of course this maximum range will be reached only after the collision with the target (assuming that the missile can cross the target without disintegrating), and the part of the trajectory in which we are actually interested is the one described by equation (3).

Suppose in particular that T moves uniformly on a circle whose center is at G (in other terms R = constant). In polar coordinates, with the proper selection of the reference direction, the trajectory of M is described by the equations:

$$\begin{aligned} \theta &= \alpha t \\ r &= \frac{v}{\alpha} \sin (\alpha t + \delta) \end{aligned} \qquad (\alpha t + \delta < \frac{\pi}{2}) \tag{4}$$

and

$$\begin{aligned} \theta &= \alpha t \\ r &= \frac{v}{\alpha} \end{aligned} \qquad (\alpha t + \delta > \frac{\pi}{2}) \tag{4a}$$

Equations (4) represent a family of circles passing through G with the radius $= \frac{v}{2\alpha} = R\frac{v}{2u}$.

Equations (4a) represent, of course, a circle around G as the center, which is incidentally the envelope of the family (4).

A trajectory of M, assuming a circular trajectory for T, and $\frac{v}{\alpha} = 1.6$ is shown in Fig. 8. The arcs of the circles (4) and (4a) are matched together at the point A.

If α is not a constant, equation (3a) will still give an approximate solution of (3) provided the angular acceleration α is small.

Observe that, if the missile is supposed to hit the target at the range $\leqq$ R, it must be capable of radial acceleration at least equal

$$\frac{v^2}{R\frac{v}{2u}} = \frac{2uv}{R} \tag{5}$$

corresponding to the radius of curvature $\frac{v}{2\alpha,}$ where $\alpha = \frac{u}{R}$.

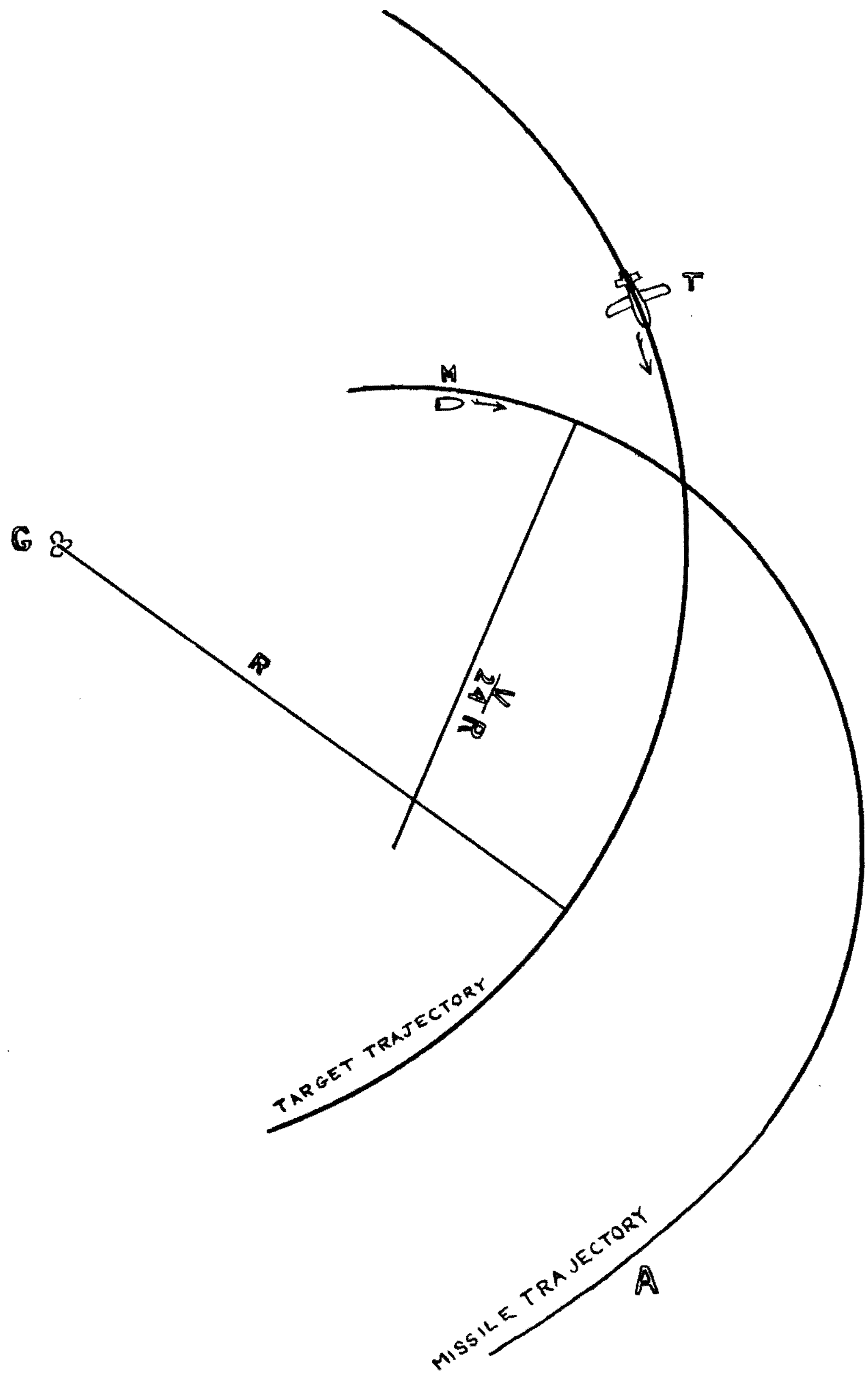


Figure 8

APPENDIX III

SOME CONSIDERATIONS ENTERING INTO THE PROBLEMS OF RADAR-CONTROLLED MISSILES

The problem of radar-controlled missiles requires consideration of all its aspects. In general, such a missile will require:

1. Tracking of the missile and/or target.
2. A computer for producing steering information.
3. A means of transmitting intelligence to the missile.
4. Suitable response mechanisms in the missile.

The problem of homing devices other than by the use of radar will not be considered in this outline.

In order to qualify the words used above, the following terms are defined:

By *tracking* is meant any radar device which enables an operator on the ground or in the air, as the case may be, to determine the position of the missile in relation to himself or some other frame of reference or which enables the missile to locate itself with respect to a beam on the target, or which tracks the target.

A *computer* can be a plotting board or it can be a network in a servoloop. In some instances a computer may degenerate into a simple right, left, or error indicator. On the other hand, the computer may be a very involved device which takes into account motions of target as well as motions of the controlling element.

The means of transmitting intelligence may be CW radar or radio, pulsed radio, or any combination. The means for transmitting information may be, but need not be, the same as the tracking radiation. In the case of homing devices, the intelligence may be transmitted directly from the tracking device to the controlling element.

The *controlling element* is the mechanization on the missile which responds to the intelligence given to it from the computer in such a way as to give response in the missile.

An outline of a preliminary characteris given which lists some of the aspects of the problem. This outline is by no means complete and no attempt is made to qualify each entry.

OUTLINES OF SOME CONSIDERATIONS ENTERING INTO THE PROBLEMS OF RADAR-CONTROLLED MISSILES

I. *Types of Problems*
   A. Ground-to-ground (Willie Orphan, JB-2, etc.)
   B. Ground-to-aircraft (antiaircraft such as GAP)

C. Aircraft-to-aircraft
D. Ship-to-ship
E. Ship-to-aircraft
F. Ship-to-ground
G. Aircraft-to-ship (Pelican, Bat)
H. Aircraft-to-ground
I. Ground to surface moving target
J. Conglomerates (i.e. launched from ground but controlled from air, Willie Mother)

II. *Survival Problem of the Missile* (*these are not all applicable to every missile*)

A. Against fighter planes
B. Against AA
C. Against radar or other detection devices
D. Against jamming of tracking element
E. Against controlling jamming or interference
F. Against destruction of controlling element
G. Against destruction of launching site or base
H. Against other guided missiles
I. Saturation characteristics

III. *Tracking Problems of Missile*

A. Single station at a point remote from the missile

1. Ground station
   a Limited in accuracy to about .1% of range
   b Limited in range by horizon
   c Suited for three-dimensional control
   d Tracking of target or determination of target point

2. Shipborne
   a Similar to (1) above
   b Requires elaborate navigational computers and/or aids

3. Airborne
   a Similar to (1) and (2) above
   b Other radar aids

B. Single-station hermaphrodite (defined as a system which requires tracking both remotely and on the missile, viz., a missile flying down the beam for angle but tracked in range) possible in all combinations as in III-A

C. Single remote station with self-contained tracking in the missile, viz., GAP (possible from ground, ship, or air)

D. Multiple station at remote points (range trangulative from two ground stations or psuedo Loran) (1) reasonable traffic capacity with coding, (2) not useful for three dimensions

E. Multiple station hermaphrodite (viz., time difference for direction, release on given range)

1. Possible larger traffic capacity than III-D

F. Multiple station with tracking self-contained in missile (Loran type)

G. Tracking by missile

1. With retransmission
2. With independent illumination
3. Fully homing

IV. *Dynamic Problems*

A. Tracking characteristics of target or missile or both (autocorrelation functions)
B. Steering characteristics of missile
C. Stability of the closed loop
D. Computing aids for target motion and/or controlling station
E. Maneuverability of the target
F. Computer or plotter for directing the missile (when applicable)
G. Launching

V. *Problems of Transmision of Intelligence when Accomplished by Radio or Radar*

A. Survival (see II)
B. Mutual interference
C. Interference with normal tactical, strategic, and navigational operations

PART IV

RADAR HOMING MISSILES

By

HUGH L. DRYDEN

PART IV

RADAR HOMING MISSILES

INTRODUCTION

Much attention has been devoted during the present war to the development of guided missiles, which are intended automatically to seek out a target or "home" on the target. Such a missile must utilize some physical property of the military target which causes the target to stand out from the background. The most commonly suggested property is the emission or reflection of electromagnetic radiation, and homing systems of control have been developed for the three major divisions of the electromagnetic spectrum, popularly described as light, heat, and radio. The report by Dr. G. A. Morton, entitled "Heat and Television Guided Missiles," page 35, reviews the state of development of the light- and heat-seeking missiles, and the present report describes the general principles, problems, and state of development of radar homing.

As indicated by the title, radio waves of very short wavelength (ten centimeters or less) give the most useful technical results in missiles because the scale of the apparatus required to intercept or direct the energy into beams is of the same order as a small multiple of the wavelength. Likewise the techniques used in radar, in particular the transmission in short pulses of energy rather than continuously, are particularly useful in solving the problems of target selection and discrimination. Thus the radio-homing device invariably uses microwaves and usually microwave-radar techniques.

GENERAL PRINCIPLES OF OPERATION

Since military targets, with the exception of enemy radar transmitters, do not emit radio waves, it is necessary to illuminate the target with radio waves if a radio homing method is to be used. In a pulsed radar system the transmitter consists of a high-power oscillator capable of emitting radio waves of the desired wavelength from an antenna system. A modulator or pulser causes the transmitter to emit electromagnetic waves in the form of short pulses or wave trains of high intensity. To give some quantitative idea, one of the systems to be described emits 2000 pulses/sec of waves having a length of about 10 cm. The duration of the emission at each pulse is 0.7 microsec. Since a wavelength of 10 cm corresponds to a frequency of 3000 mcps, each pulse or wave train contains about 2250 waves extending over 22,500 cm or about 740 ft. Since the pulses are 500 microsec apart, the wave trains are separated in space by 93 miles.

The emitted energy is focused into a beam by the directional properties of the antenna system. While the wave train is of constant thickness in the direction of travel, it continually spreads in directions at right angles to the direction of travel. When the emitted energy strikes any object, some of the energy is scattered or reflected and a very small fraction travels back toward the transmitter and can be detected and measured by a sensitive receiver. Since every object returns some reflected or scattered energy, the study of the return of energy from various types of targets is basic for the design of successful radar-homing systems.

The energy returned from the target is detected and measured by a suitable sensitive receiver. In order to be useful in guiding a missile, the information must be in the form of directional data, preferably in quantitative form. To obtain directional data the homing device must be directionally sensitive. Usually the receiving antenna for a missile homing device has axially symmetrical directional characteristics produced by a spherical or parabolic reflector. The response of the receiver is greatest when the axis of the antenna is pointed directly at the target. While this property could be used to determine when the target is on the axis for steady signals, there is no discrimination between right and left or up and down and fluctuations of signal intensity cannot be distinguished from changes in intensity produced by changes in direction. The usual practice is to scan the field of view by moving the antenna axis and to commutate or phase the received signal intensity with the scanning. The on-course indication then becomes an equality of two signals and a directional sense is provided. Furthermore, most of the effects of signal fluctuation are eliminated by scanning at a reasonably rapid rate. The scan rate in present equipment is of the order of from 30 to 40 cps. Conical scanning is used; i. e., the axis rotates in a cone so that the receiver effectively looks up, right, down, left, in succession. The output is switched automatically by a commutator to the up, right, down, and left channels of two differential amplifiers which supply the up-down and right-left control signals.

The use of pulsed radar permits the selection of a definite target which will be described later in greater detail. In principle, if the receiver is kept insensitive at all times except for a brief period of time which begins at a definite time interval following the emission of a pulse, energy will be received only from those objects lying at a fixed range, i. e., those for which the transit time from transmitter to object to receiver equals the interval between the emission of the pulse and the increase of receiver sensitivity. To be specific, if the receiver is increased in sensitivity 50 microsec after the emission of a pulse, only objects where the total distance from transmitter to object to receiver is 9.3 miles will contribute energy to the receiver output. Since the total distance changes as the missile approaches its target, some method of automatically varying the time interval must be used to track the target in range.

In order to be useful a homing control must be operative at a reasonable distance from the targets of interest. As the missile approaches the target, the received energy will vary by as much as a billion fold or more. Hence the receiver must be provided with an automatic gain control to decrease its sensitivity as the received energy increases.

TYPES OF SYSTEMS

Three types of systems have been given attention, differing only in the location of the transmitter, the receiver always being in the missile. The transmitter may be an enemy transmitter, a transmitter illuminating the target but not carried by the missile, or a transmitter carried by the missile. The nomenclature is not standardized. The first type has generally received the code name "Moth," the second "RHB" or "Pelican," the third "SRB" or "Bat." German scientists who conceived but did not complete the development of similar systems referred to them as passive, half-active, and active radio-homing methods. The general locations of missile and target for a glide bomb released from an aircraft are indicated in Figs. 1, 2 and 3.

A simplified block diagram of the RHB or Pelican equipment, as installed in a glide bomb released from an aircraft is shown in Fig. 4. A block diagram for Moth would be identical except that the target selector and rear view antenna would be omitted. Provision is made for supplying external power from the carrying aircraft through the umbilical cord. This cord also carries circuits for supervising the operation of the equipment before release, for remote tuning of the receiver, and for selecting and locking on a target, these circuits terminating at the airplane control and indicator station.

The umbilical cord is connected by a pull-away connector to the missile junction box. Before release the equipment is switched to the internal battery which with the power supply furnishes all the necessary voltage for the receiver and other units. The energy returned from the target passes from antenna to receiver to target selector. The output of the target selector operates the automatic gain control of the receiver and is passed through the commutator to a differential amplifier which furnishes signals to the autopilot.

As the missile approaches the target, the transmitted pulse directly received from the transmitter decreases. The energy received from the target increases and the automatic gain control accordingly decreases the sensitivity of the receiver. Sufficient energy had to be received from the transmitter in the original design of the Pelican equipment to synchornize the target-selector circuit, and it was found necessary to add the auxiliary rear view antenna which is indicated on the block diagram. A later development accomplished synchronization from a special oscillator in the missile and the rear view antenna was eliminated.

A simplified block diagram of the SRB or Bat equipment, as installed in a glide bomb released from an aircraft is shown in Fig. 5. The new elements added are the transmitter, modulator, and the TR tube for switching from transmitter to receiver so that the same antenna can be used for both. Synchornization is accomplished by direct connection from the transmitter. Otherwise the simplified block diagrams are identical.

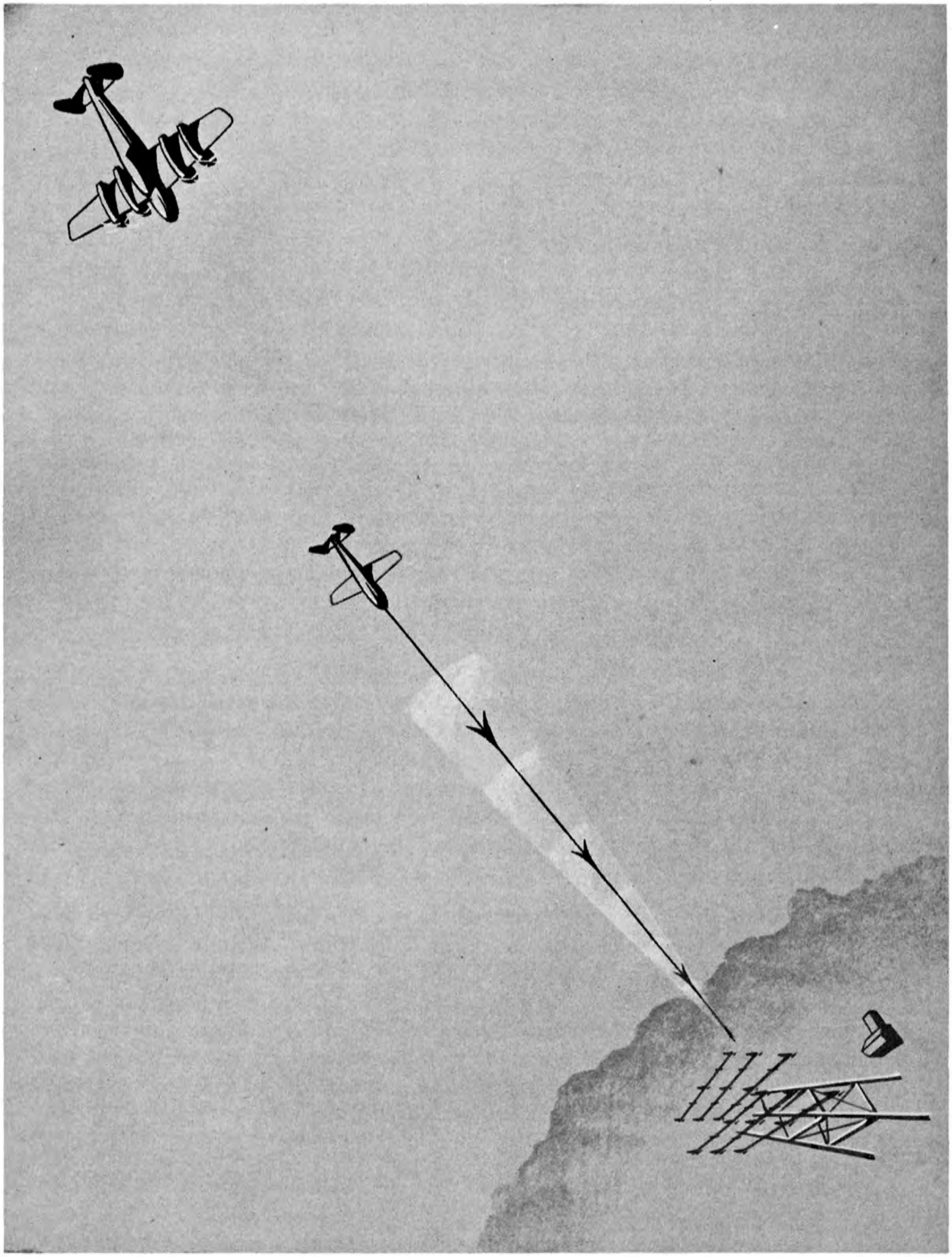


Figure 1 — Moth

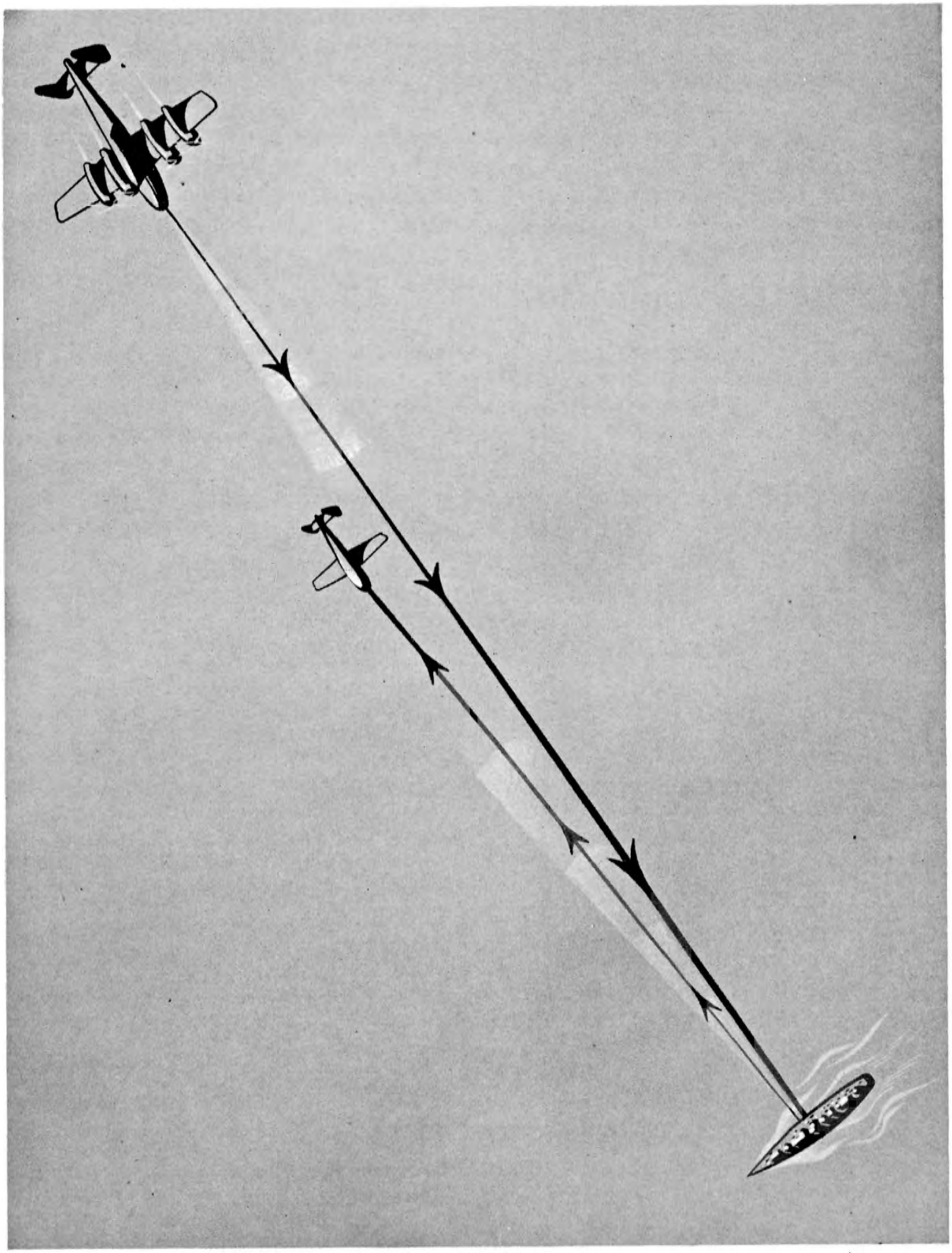


Figure 2 — RHB (Pelican)

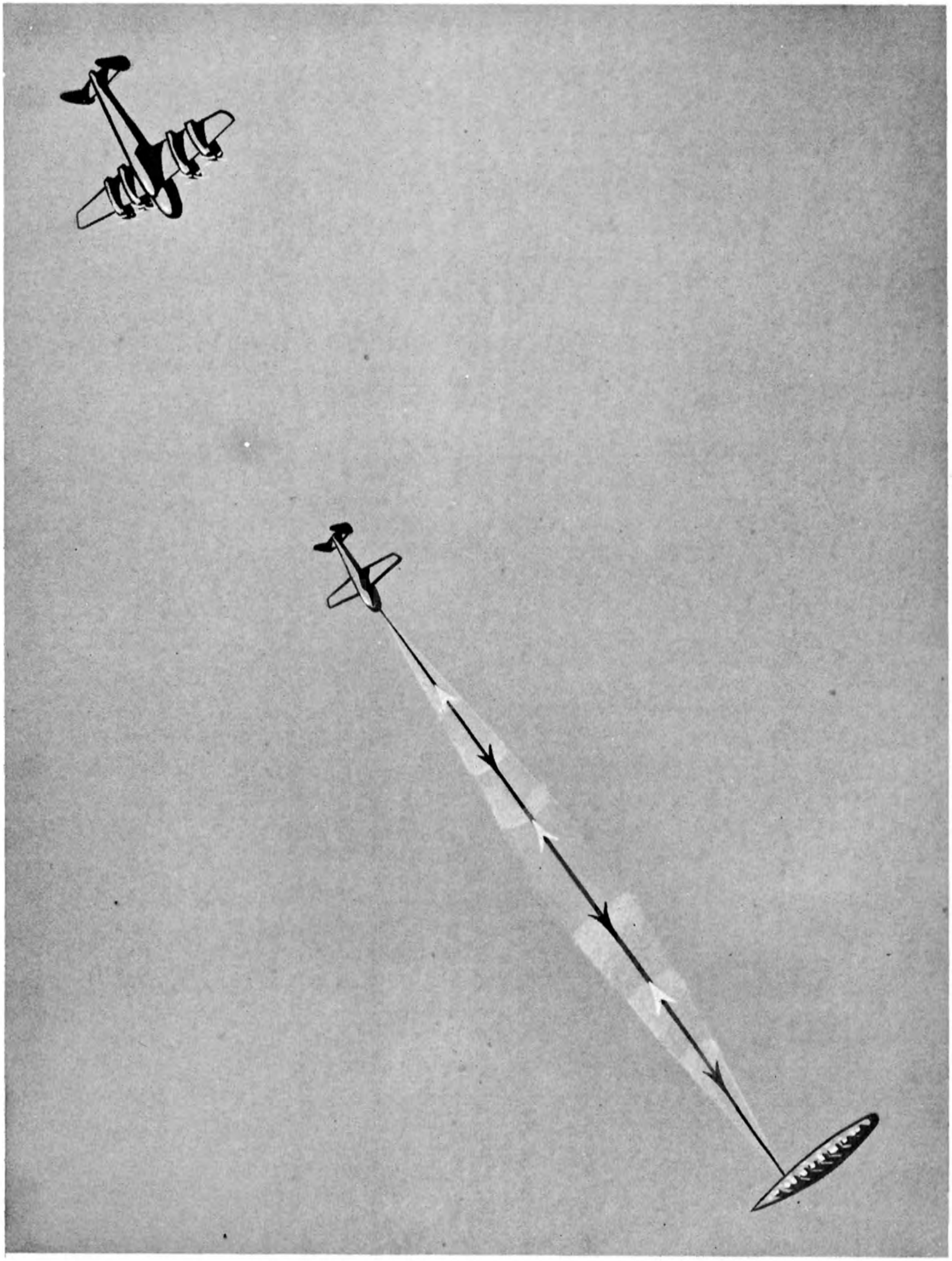


Figure 3 — SRB (Bat)

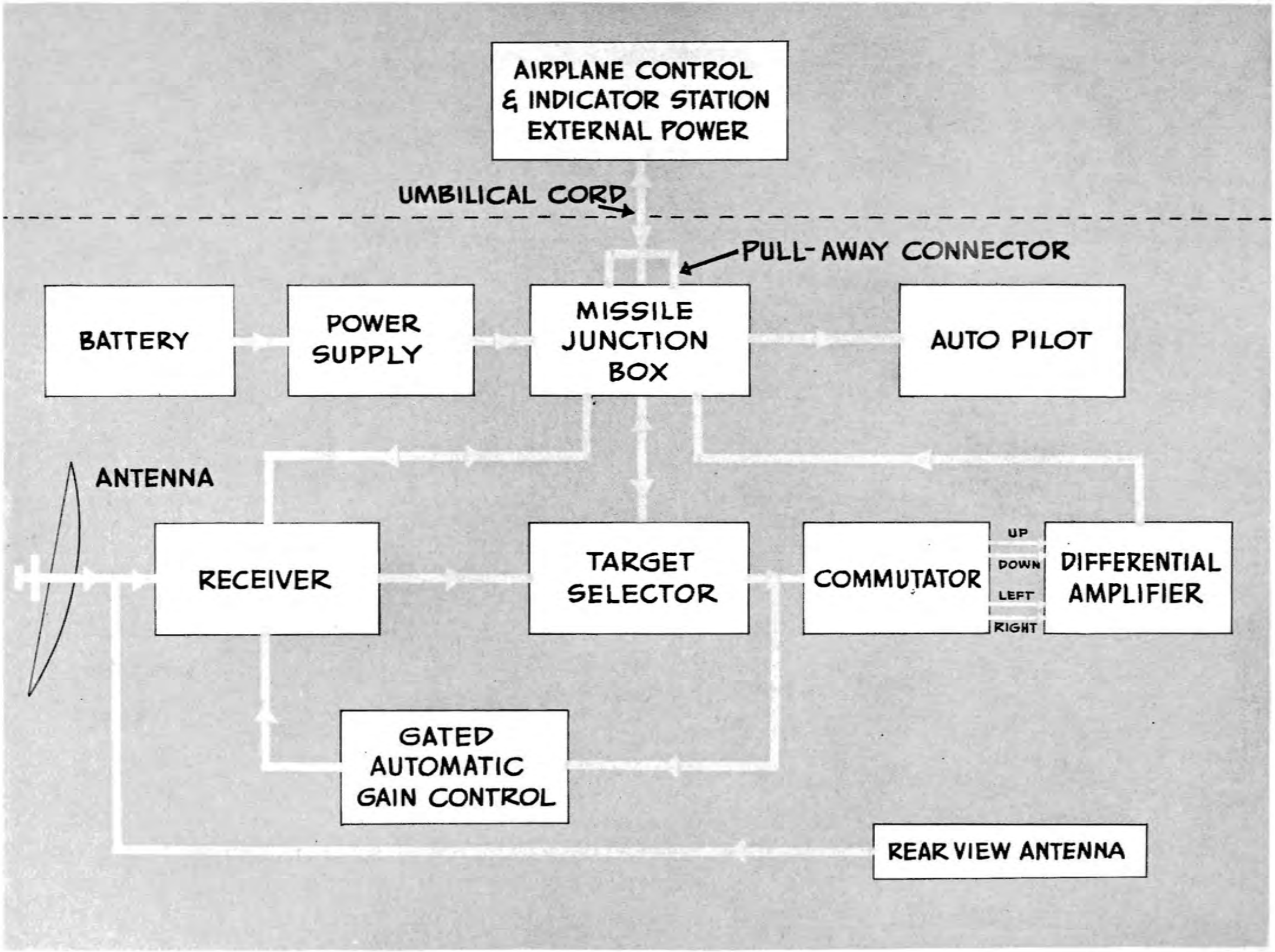


Figure 4 — Block Diagram of RHB (Pelican)

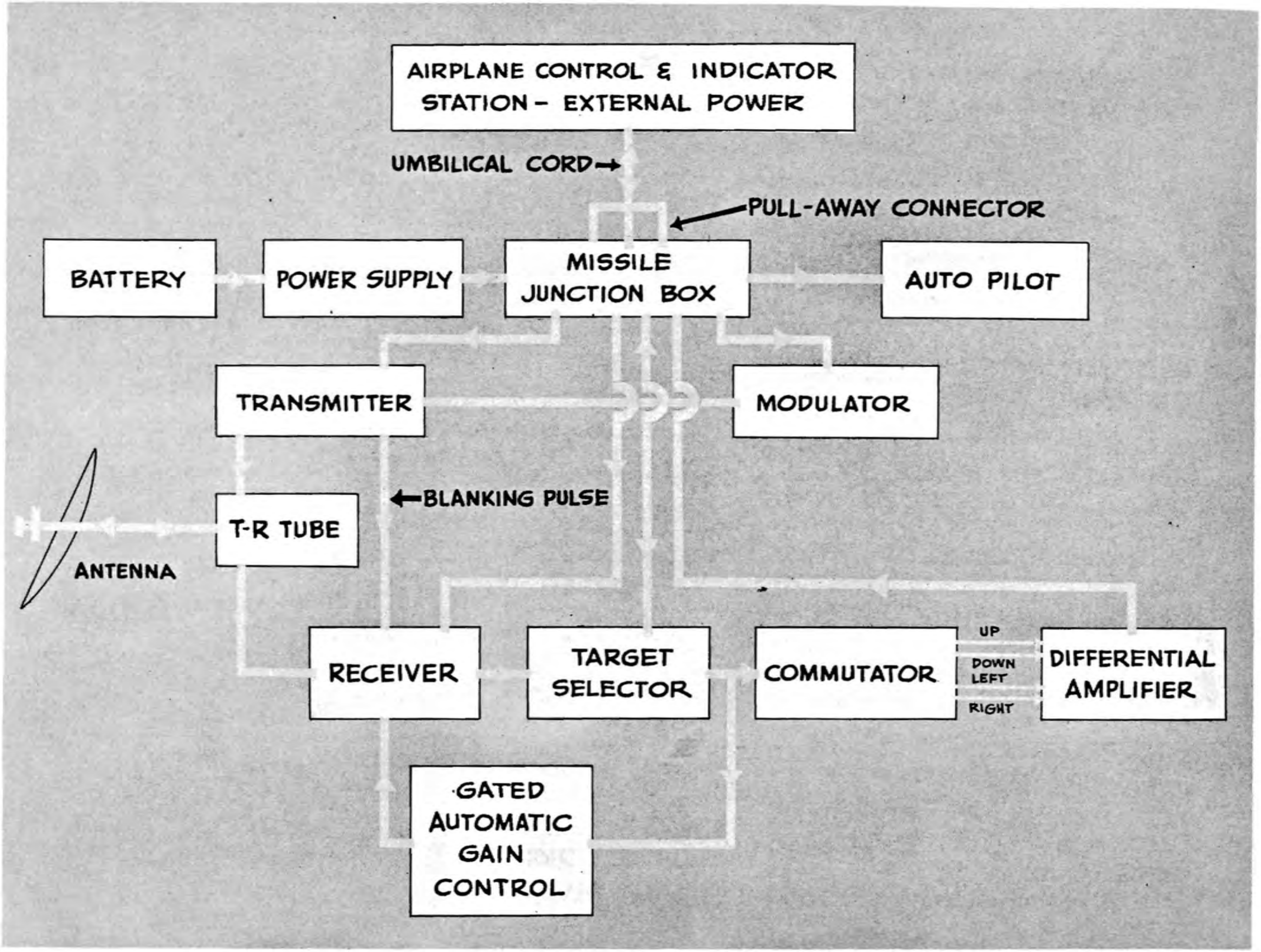


Figure 5 — Block Diagram of SRB (Bat)

PROPAGATION AND TARGET PROPERTIES

Microwaves travel without serious loss of energy through ordinary clouds and fog; hence, radar-homing devices are effective through overcast and at night. The propagation of microwaves is quasi-optical in character. They are not reflected to an appreciable degree by the Kennelly-Heaviside layer, and they do not spread far beyond the horizon by diffraction. Around small obstacles the waves spread appreciably by diffraction and they are usually scattered by rough surfaces such as the ground. The surface of the sea is, however, a good reflector especially near grazing incidence. Water vapor in the atmosphere may produce refraction effects.

Any ordinary solid or liquid substance is capable of returning radio energy. Depending on size and shape of the object in relation to the wavelength, the process may be one of reflection or scattering. No method is known of making an object of complicated shape invisible to radar, although special coatings have been developed which reduce the return from large flat surfaces. Radar reflections from most objects have some of the characteristics of optical reflections of the sun from the earth as observed from aircraft, in that small changes of position of the receiver may produce large changes in energy received corresponding to the kaleidoscopic high lights from window panes, pools of water, etc. Radar reflections from ships and aircraft show similar fluctuations.

Ordinarily there will be many objects at the same range and although a military target reflects radio waves, the reflected energy or echo from the desired target may be lost in a background "clutter" of unwanted echoes. This is especially true for land targets since the usual irregularities of the ground insure the presence of many echoes. Even for sea targets such as ships, the surface of the water, especially in high winds, reflects energy to a receiver. Only in the case of aircraft targets viewed from below is the unwanted background energy negligible.

The distinguishing features of an individual echo are very few. In very special cases there may be a characteristic relation between the polarization of the incident and reflected waves and in some situations moving targets may be isolated from stationary targets. The most favorable situations for the application of radar-homing missiles are those in which there are only a few targets and in which the energy returned from these targets is substantially greater than that from the ground or sea at the same range. Hence, the primary application of radar-homing missiles to date has been against ships.

In connection with the Pelican and Bat projects, numerous studies have been made of the reflection of microwaves from ships. These studies have shown that the energy returned from a given target and from the sea varies within wide limits and is a function of the angle of illumination and surface conditions. The energy returned from the ship targets constantly decreases as the angle of illumination and reception increases, whereas that returned from the sea constantly increases. Comparative tests were made with a Pelican receiver on microwaves of approximately 10-cm wavelength of the energy received at various depression angles when the target was illuminated from a distance at depression angles of from 2° to 11°. These tests showed that nearly all of the energy scattered from the ship appears between the sea and 45° above the incident beam and that the return is fairly uniform over 180° in azimuth on the illuminated side of the target. A receiver which picks up signals at 20 miles and has adequate return for automatic tracking and homing at 10 miles can no longer obtain an adequate signal for tracking or homing at one mile when the depression angle at the receiver is 70°.

A more complete study was made for wavelengths of about 3 cm. The energy returned was expressed in the form of the cross-sectional areas of a sphere which would return the same energy as the target. If the received power at range r is P_r as measured with a receiving antenna of effective area A_r when the peak transmitted power is P_t, the gain of the transmitting antenna is G_t and the transmitter is at range r_2, the cross-sectional area S_a of the equivalent sphere is defined by:

$$S_a = \frac{16\pi^2 r_1^2 r_2^2 P_r}{P_t G_t A_r} \qquad (1)$$

The values of S_a for the return from the sea measured with transmitter and receiver at the same location varied through the ranges indicated below as a function of depression angle:

Depression Angle	*Cross-Sectional Area of Equivalent Sphere in Sq Ft*
40°	7 to 1,500
50°	15 to 1,600
60°	200 to 16,000
70°	4,000 to 64,000
80°	250,000 to 640,000
90°	40,000,000 to 100,000,000

The values of S_a for ships ranging in size from LST to Liberty ships as a function of depression angle were as follows:

Depression Angle	*Cross-Sectional Area of Equivalent Sphere in Sq Ft*
20°	10,000 to 100,000
30°	10,000 to 100,000
40°	10,000 to 65,000
50°	1,000 to 20,000
55°	250 to 10,000

It is seen that the target becomes lost in the sea return at depression angles of 50° to 60°. Because of fading, automatic-tracking circuits may have difficulty at depression angles as low as 35° to 45° even when the average power in the preceding table appears adequate.

Other studies made on microwaves of 10-cm wavelength show cross-sectional areas of the equivalent sphere of the same order of magnitude. For design purposes the value of S_a for a large ship of high gain may be taken as 23,000,000 sq ft, for an average Liberty ship 500,000 sq ft, and for a very small ship 20,000 sq ft if viewed at depression angles of the order of 10°. The average reflected power is found to increase inversely as the fourth power of the range when transmitter and receiver are at the same range as indicated by the formula previously given. This relation was checked experimentally to within 800 ft of large ships. However, the power at a given distance may vary through wide limits, i.e., by a factor of as much as 100 times in some cases for runs on apparently similar targets.

The values of S_a for aircraft targets are naturally much smaller than for ship targets. For a large bomber S_a is of the order of 1000 sq ft. For small aircraft or missiles S_a is considerably smaller.

While studies are known to be in progress on land targets with respect to the practicability of radar-homing missiles, detailed results are not yet available. It is known that there are some target situations in which radar homing is feasible, but more research is needed.

DETECTION

The energy returned from the target is detected and measured by a superheterodyne receiver. The receiver contains a tunable local oscillator in the form of a velocity-modulated or Klystorn tube with associated cavity which generates microwaves whose frequency can be adjusted to differ by a fixed amount, the beat or intermediate frequency, from the frequency of the radio waves to be received. In the Pelican equipment the intermediate frequency is 30 mcps; in the Bat, 60 mcps. The received energy and that from the local oscillator are applied to a crystal mixer the resulting output echo signals being at the intermediate frequency. These signals are amplified by a multistage amplifier tuned to the intermediate frequency but with a sufficient bandwidth to transmit the short pulses without large distortion. A detector tube passes the envelope of the pulses. These signals are designated "video" signals. After amplification and passage through a control gate amplifier, which is made operative at the proper time by the target-selector circuit, the signals pass to the directional control unit. The general operation of these units will be described later.

The amount of energy available to the receiver from an incoming signal is proportional to the effective areas of the receiver antenna. If the antenna is in the form of a dipole or other receptor at the focus of a reflector of diameter D, the effective area of the antenna is $\frac{\pi D^2}{4}$. Thus a large antenna enables the detection of smaller signals better than does a small antenna.

The background of random noise in the receiver sets a lower limit to the intensity of signal which can be detected. If the radar receiver were perfect, the noise would be determined solely by the bandwidth of the receiver and the absolute temperature of the system, being in fact equal to $KT\Delta f$ where K is a universal constant (1.372×10^{-23} joules per degree C). T is the absolute temperature and Δf the receiver bandwidth. For a bandwidth of 10 mcps and an absolute temperature of 325°C the noise intensity in a perfect receiver would be 4.4×10^{-14} w. Any actual receiver gives N times as much noise where N is called the over-all noise figure and is about 10 for modern receivers. The receivers used in radar-homing equipment now available and in production will usually detect signals of 10^{-12} w; but a target giving such small signals will not operate the tracking circuits satisfactorily.

DIRECTIONAL INFORMATION

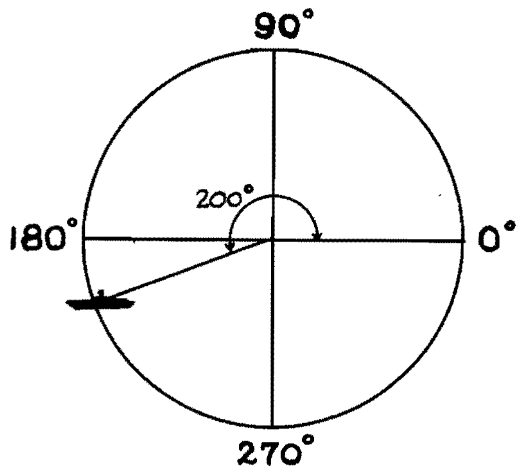
The video signals which pass from the control gate amplifier are extremely short pulses spaced far apart in time as compared with their duration; for example, in the Bat equipment 0.7 microsec pulses 500 microsec apart. As a result of the conical scanning of the antenna, the amplitudes vary unless the target is on the axis of rotation of the antenna. For small angular displacements of the target, the modulation is approximately sinusoidal at the scanning frequency which in present equipment is about 30 cps. Thus there are about 67 pulses for each scanning cycle. As shown in Fig. 6, the amplitude and phase of the modulation measure the amount and direction of the target position with reference to the axis of rotation of the antenna.

The narrow, widely spaced pulses contain insufficient energy to operate controls. They are first passed to a rectifier or demodulator which acts as a pulse stretcher, giving an output consisting of the 30-c envelope on which is superimposed a pulse frequency ripple. The signal is then subdivided by the commutator, as indicated in Fig. 7, into four parts corresponding to the four quadrants of the antenna scan. The up-down and the right-left signals proceed to differential amplifiers which compare the signals from the opposite commutator segments and smooth the result to give an approximately DC output proportional to the angle off course.

The method of obtaining directional information which has been described is that exemplified in available equipment. It is inherently a comparison of the amplitudes of signals obtained successively from two slightly different directions. The results may be falsified by fluctuations in the echo occurring in the 0.017 sec required to move the antenna to the two directions. Future development of this general method will almost certainly use much higher scan rates, probably obtained wholly by electrical means, and will probably use simultaneous lobe-comparison methods. Not only can the effects of fading be reduced, but also the time lags in furnishing directional information to the controls of the missile can be greatly reduced.

TARGET DISCRIMINATION

The first main problem in the design of any homing missile is the determination of the method or methods to be used for discriminating between the desired target and others which may be present. The directional characteristics of the transmitting and receiving antennas permit a certain degree of selection. Within the field of view determined by these directional characteristics, the target giving the greatest echo will normally control.



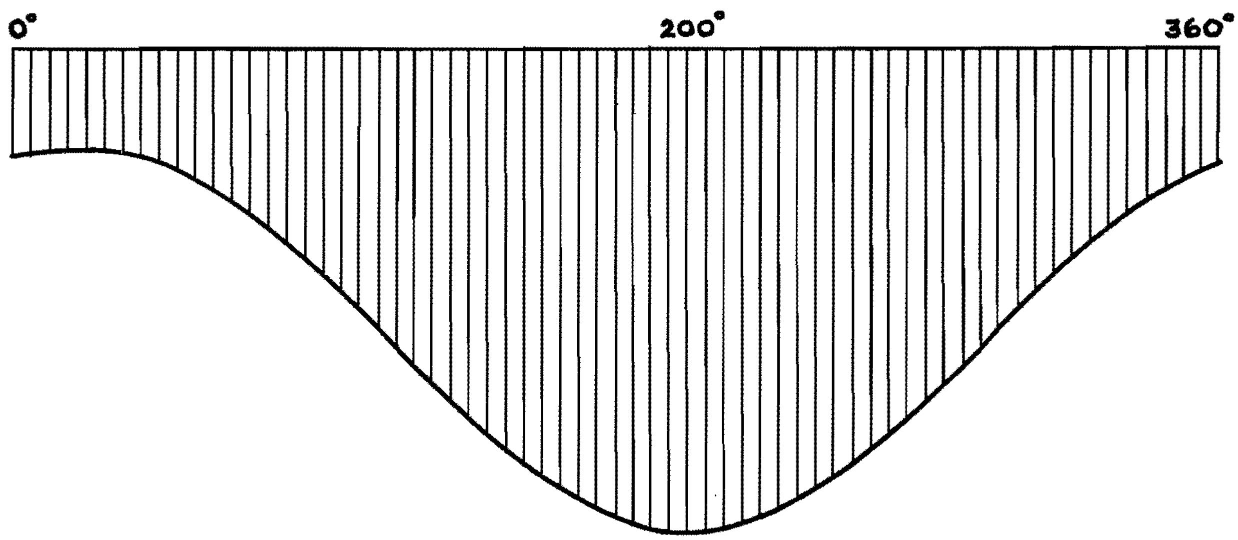


Figure 6 — Conical Scanning Process

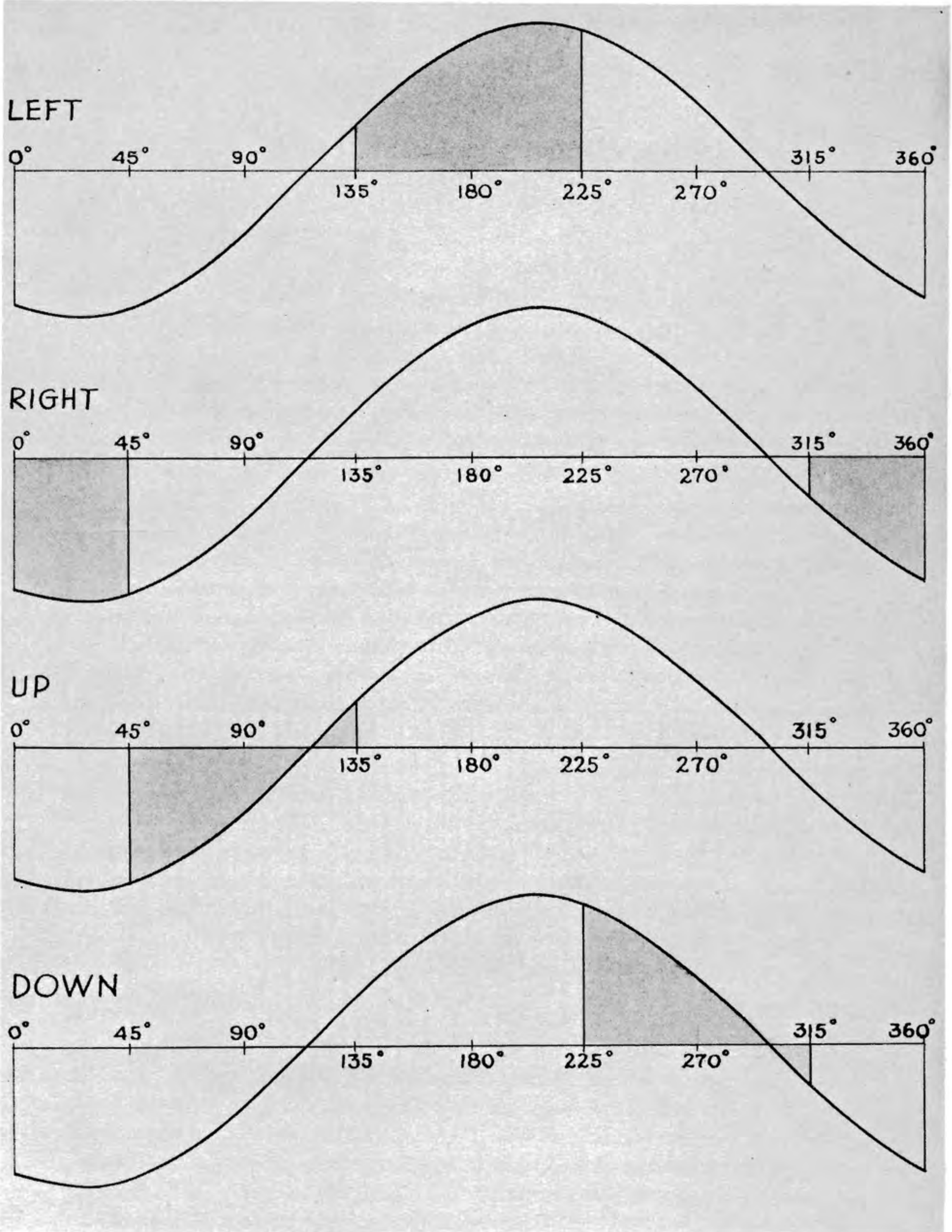


Figure 7 — Commutation of Scanned Signals

However, it is not technically feasible to use extremely narrow beams, first, because the antennas cannot be made sufficiently large in comparison with the wave-length, and second, because a narrow field of view would require the motion of the missile to be controlled to an impractical degree.

In a homing system using a pulsed illuminating beam, another method is most useful, namely, a range-selection method. By making the receiver senstive only for a short period of time at a definite time interval following the emission of a pulse by the transmitter, signals will be received only from targets at a selected range, since the selected time interval is the time of transit from transmitter to target to receiver. As the missile approaches the target, the time interval must be shortened, i.e., the target must be automatically tracked in range. Likewise since the time measurement must start with the emission of a pulse, the transmitter and receiver must be synchronized in some manner.

Range discrimination is essential in radar-homing missiles launched from aircraft because of the large amount of energy returned from the ground or sea, one of which is always the biggest target in the field. At ranges of the order of five miles or more, and with antennas of the smaller sizes required for missiles, as much energy is received from the ground or sea directly below as from an average target. This first signal is known as "altitude" signal and must be excluded from the receiver. In glider missiles the altitude is always less than the range to the target, and hence the range selector makes possible elimination of the altitude signal. In ground-to-air missiles with receiver only (RHB), there is no "altitude" signal but in air-to-air missiles at ranges greater than the altitude or ground-to-air SRB missiles, the range to the target and to the ground will sometimes coincide and special measures will have to be taken to prevent a switch from homing on the target to homing on the altitude signal.

The functions of the target selector are: (1) to "gate" the signal from the desired target, i. e., allow the differential amplifiers to receive information only at the exact time that the signal from the desired target is received; and (2) to adjust the time of operation of the gate circuit to the range of the target, i. e., to track the target in range. The gating operation must be synchronized with the transmitter. The general methods used in present equipment will be briefly discussed.

When the transmitter and receiver are in the missile a synchronizing pulse is obtained very simply by a direct connection to the pulse transformer of the transmitter. When the transmitter and receiver are separated another method must be used. So far two have been developed. The older uses the directly received signal from the transmitter as the synchronizing impulse. Precautions must be taken to insure that sufficient energy is received. When the target is illuminated from an aircraft, the missile may not remain within the beam because of evasive action of the aircraft or because of the difference in the speeds of the missile and aircraft. Hence the transmitter must be equipped with an additional nondirectional or at least a very broad-beam antenna to insure the radiation of some energy in the direction of the missile. Likewise the directional characteristics of the receiver antenna are such that little energy is received from the rear which is the direction of the transmitter. It is necessary, therefore, to provide a rear view antenna on the missile to insure that sufficient energy is received directly from the transmitter to synchronize the range-selection gate.

The second system derives its synchronization from the reflected signal and hence the equipment is termed self-synchronous. Actually a very stable low-frequency oscillator is built into the receiver and an identical oscillator is used to control the pulse rate of the transmitter. The frequency of the receiver oscillator is automatically adjusted to that of the received pulse rate. The self-synchronous RHB was developed primarily because it offered a means of securing homing intelligence all the way into the point of impact with the target. Both the Pelican and the Bat experience difficulties at close ranges because of the coincidence of the initial pulse with the returning echo. The Pelican requires the reception of the direct-transmitted pulse for sychronization, and the Bat cannot make use of the echo when its transmitter is operating. The self-synchronous RHB, however, derives its synchronization from the echo only and it can exclude the initial pulse which is transmitted from many miles behind the receiver. A few experimental models of radar-homing equipment with this method of synchornization have been built and tested.

The gating operation by which the receiver is made receptive to the target echo is accomplished by applying a square-wave negative impulse of about one micro-second duration to the cathode of the control-gate amplifying tube which has its grid normally biased well below cutoff, but which is made operative while the gate is applied. The formation of the gate is initiated by the synchronizing pulse from the transmitter or synchronizing oscillator being applied to the grid of a variable time-delay pulse generator, which is a multivibrator adapted to give only one cycle of operation. The rapid change of voltage at the end of the square wave formed by the multivibrator is used to form the time-delayed pulse. This output pulse is applied to a blocking oscillator which in turn generates the range-selector gate pulse of one microsecond duration. The latter pulse is used to sensitize the control amplifier tubes. The proper time delay required to make the gate from the blocking oscillator coincide with the returning echo is determined by the voltage applied to a control grid of the multivibrator, either by a manual adjustment when initially selecting a target or from the automatic range-tracking circuit.

The final function of the target selector is to track the target in range as the missile approaches the target. The nature of the methods used will be illustrated by that used in the Bat equipment. After leaving the video amplifier, the echo signals are applied to an artificial delay line which has three output taps so that for every echo signal applied to the input three echoes, designated early echo, control echo, and late echo, appear in order separated in time by about 0.27 microsec. The echoes so spaced are fed separately to the grids of three amplifier tubes, all of which are baised below cutoff. These same tubes are gated simultaneously by the range-selector gate pulse. If the range-selector gate is centered on the control echo, the signals passed by the early and late echo amplifiers will be equal. If the gate is early, the early echo signal will be larger than the late echo signal, whereas if the gate is late, the late echo signal will be larger. (See Fig. 8.) These early and late echo signals are used in succeeding stages of the target-tracking circuits to control the variable time-delay pulse generator so that the gate moves at the speed corresponding to the changing range of the target. Circuits are also included which cause the gate to continue to move at nearly the correct speed even if the received signals should fade for a few seconds. If the signal fades for a longer time, it may not be in the gate when it reappears because the gate speed is not

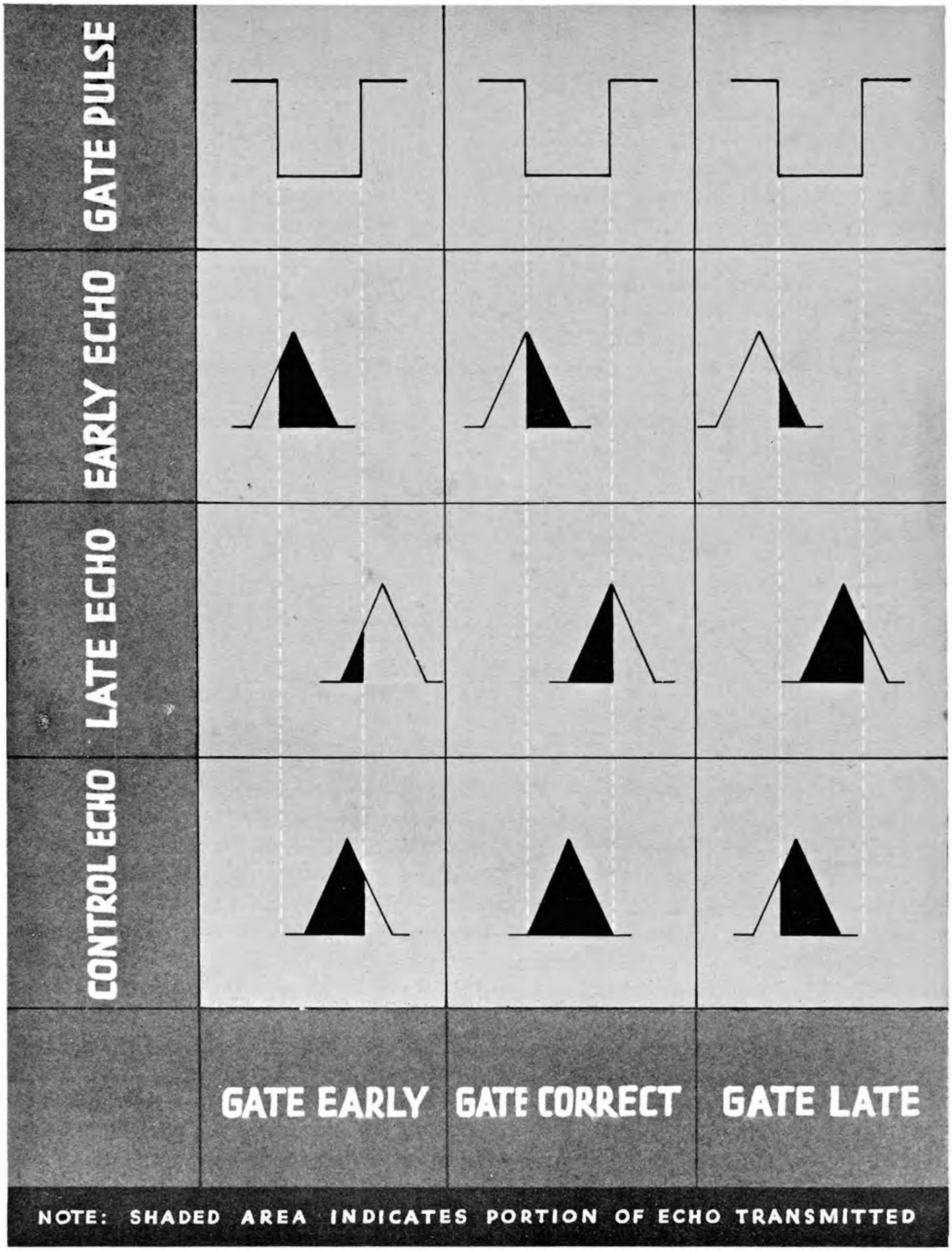


Figure 8 — Principles of Tracking in Range

accurately that of the target. In this case the target is lost and the gate will lock on the next echo entering it. Since the gate is only 0.7 microsec wide, the selector can distinguish between targets within about 750 ft of each other in range.

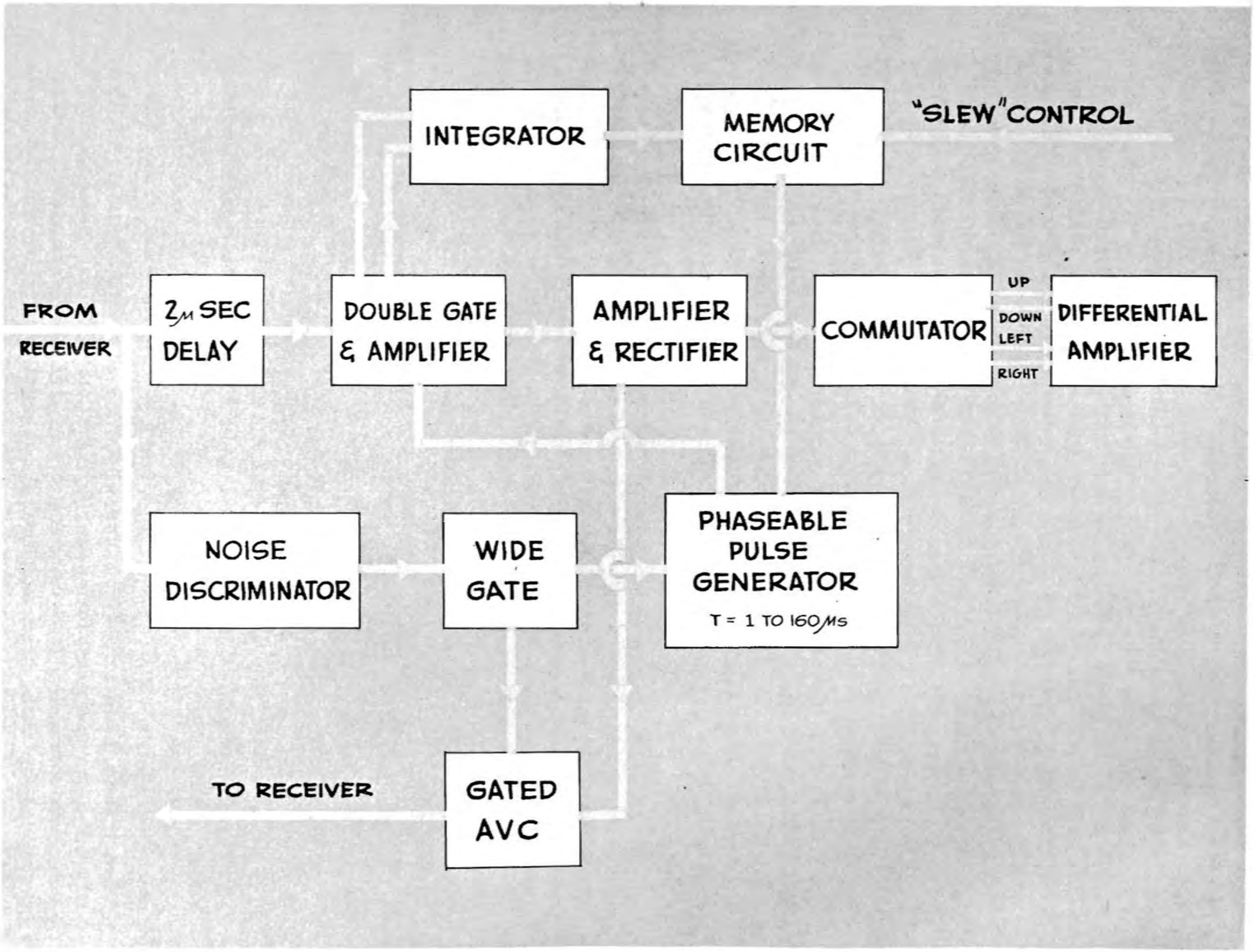
For tracking purposes the Pelican target selector uses one echo and a delay line to form an early and a late gate rather than a single gate and an early and delayed echo, but the general principles are otherwise identical. A simplified block diagram of the Pelican target selector is shown in Fig. 9. The video signals pass through a two-microsec delay line, thence through the double-gated amplifier to an amplifier and rectifier, to commutator, to differential amplifier. The formation of the gating pulse is accomplished in precisely the same way as just described for the Bat, except that it is initiated at the reception of the direct signal from the transmitter which enters a noise discriminator. This is a tube so biased as to prevent initiation of the gates by noise or weak interference but to permit entry of the stronger synchronizing pulse. As soon as the initial pulse is received it operates a single-cycle multivibrator which gates the noise discriminator to prevent any other signals from entering the timing circuits until after the echo has been received. A square gate is taken from this multivibrator to apply the automatic gain control which will be discussed later. As with all the radar-homing equipments the control-gate pulse can be manually adjusted or locked on the desired target before release by application of a "slewing" voltage through the connection indicated which runs through the umbilical cord to the airplane control station.

AUTOMATIC GAIN CONTROL

The energy returned from a target increases by more than a billion fold (10^9) as a missile carrying its transmitter and released at extreme range travels toward a large traget. The average receivers available will just detect a signal of 10^{-12} w. With transmitters of moderate power and fairely wide beams, the maximum observed power return from a large ship on close approach is about 10^{-2} w. Directional information of satisfactory quality must be supplied over this enormous range (90 to 100 decibels), and an automatic control of the sensitivity of the receiver is required. It has in fact proved difficult to provide a range of more than about 70 decibels in the automatic gain control itself, and the problem of a completely satisfactory automatic gain control for homing against targets from long ranges cannot be regarded as solved to complete satisfaction.

The automatic gain control must not be made so fast in action as to obscure the 30-c modulation which gives the directional information. It is so adjusted that a strong signal will be held to half the overload value of the video-output stage and thus the full modulation of the echo due to the scanning will be passed without distortion.

The automatic gain control operates from the output of the control-gate amplifier so that the sensitivity is controlled only by variations in signal from the target on which the gate is locked. The gain control operates by adjusting the grid or plate voltage of certain of the tubes of the intermediate-frequency amplifier.


INTEGRATOR
MEMORY CIRCUIT
"SLEW" CONTROL
FROM RECEIVER
2μ SEC DELAY
DOUBLE GATE & AMPLIFIER
AMPLIFIER & RECTIFIER
COMMUTATOR
UP
DOWN
LEFT
RIGHT
DIFFERENTIAL AMPLIFIER
NOISE DISCRIMINATOR
WIDE GATE
PHASEABLE PULSE GENERATOR
T = 1 TO 160μs
TO RECEIVER
GATED AVC

In the case of the RHB system, receiving its synchronization from the transmitted beam, it is necessary to prevent the operation of the automatic gain control on the direct transmitted pulse. When the transmitter and receiver are together (as in the Bat), however, a synchronizing pulse can be obtained through a direct wire connection. For considerations of range tracking very close to the target the initial pulse is held down as much as possible. Not only is the automatic gain control applied, but a special blanking pulse is added to early stages of the intermediate-frequency amplifier. Since the transmitter is always immediately adjacent to the receiver, the initial pulse can only be blanked out with difficulty. In the case of the Pelican carrying only the receiver, it is necessay to keep the receiver fully sensitive until the initial pulse is received and then to apply the automatic gain-control voltage. A pentode tube gated by the positive square wave of the wide-gate multivibrator, which is shown in Fig. 9, provides the proper gain-control voltage to the grids of the intermediate-frequency amplifier stages. The sensitivity of the receiver is thus reduced by action of the wide gate for a period of approximately 300 microsec to a value determined by the level of the target signal on which the target selector is locked.

Since in the Pelican the transmitter remains nearly at a fixed distance, the energy returned increases inversely as the square of the distance of the missile from the target, whereas in the Bat the energy returned increases inversely as the fourth power. Thus the required range of operation of the automatic gain control is less for the Pelican than for the Bat on the assumption that control must be retained to within the same distance of the target.

The receivers now available begin to show effects of overload when the received energy amounts to about 10^{-5} w. The effect of overloading is to decrease the directional sensitivity, although for some receivers the decrease may be preceded by a region of increased sensitivity as the power level is increased. The directional sensitivity is measured by the output current for a given angle of course. As the power level is increased the directional sensitivity falls to zero. With further increase the receiver begins to give a reversed signal, i.e., in a direction to move the missile away from the target. It is obvious that overloading must be avoided if accuracy is to be obtained.

RANGE

The range of radar-homing equipment can be determined from the standard radar range formula:

$$r_1^2\, r_2^2 = \frac{P_t\, G_t\, A_r\, S_a}{16\pi^2\, P_r} \tag{2}$$

where r_1 is the distance from transmitter to target, r_2 is the distance from receiver to target, P_t is the peak transmitted power, G_t is the gain of the transmitter antenna, A_r is the effective receiver area, S_a is the cross-sectional area of the sphere which reflects the same energy as the target, and P_r is the minimum power required to operate the receiver.

Since $G_t = \frac{\pi^2 D_t^2}{\lambda^2}$ where D_t is the diameter of the "dish" on the transmitting antenna and λ is the wavelength, and $A_r = \frac{\pi D_r^2}{4}$ where D_r is the diameter of the "dish" on the receiving antenna, the range formula may be written

$$r_1^2 r_2^2 = \frac{\pi P_t D_t^2 D_r^2 S_a}{64 P_r \lambda^2} \tag{3}$$

The peak powers of the transmitters used in Pelican and Bat equipment are of the order of 30,000 and 8,000 w respectively. The diameter of the receiver antenna reflector used in the missile is 1 ft and we shall make illustrative computations for $\lambda = 1/3$ ft. The value of receiver power P_r depends on the magnitude of the fluctuations of the target echo and on the factors of safety desired. While a signal of 10^{-12} w can be detected, it is necessary to have a signal of 10^{-10} w for reliable tracking in view of fluctuations of the signal. We shall therefore assume $P_r = 10^{-10}$. In the case of the Pelican, the transmitter is on the launching aircraft and may be equipped with a larger reflector, for example, $D_t = 2.5$ ft. For the Bat, the same anetnna is used for transmitting and receiving, i.e., $D_t = 1$ ft. In both Pelican and Bat, the transmitter and receiver are at the same distance at the release point; hence $r_1 = r_2 = r_o$. Introducing these values, we find

$$\text{for Pelican} \quad r_o^4 = 8.28 \times 10^{14} S_a \tag{4}$$

$$\text{for Bat} \quad r_o^4 = .353 \times 10^{14} S_a \tag{5}$$

Hence, Pelican gives a range of $\sqrt[4]{\frac{8.28}{.353}}$ or 2.2 times that of Bat, due mostly to the larger reflector on the transmitter and to some extent to the somewhat larger transmitted power.

We have previously seen that S_a ranges from 2×10^4 sq ft for small ships to 2×10^7 sq ft for very large ships when viewed at small depression angles. Hence, for these extremes the ranges are as follows: for Pelican, 12 miles and 68 miles; for Bat, 5.5 miles and 31 miles. for a Liberty ship S_a is about 5×10^5 sq ft which corresponds to a range of 27 miles for Pelican and 12 miles for Bat.

COUNTERMEASURES

An important consideration in the use of any automatic homing device is its susceptibility to countermeasures. It will never be possible to claim that any given radar-homing device is proof against jamming. But there are several reasons why this fact does not make radar-homing devices useless.

The most common method of jamming is to fill the receiver with continuous wave radiation of frequency very near the transmitter radar frequency. A beat frequency with the target echo signal is set up in the receiver and directional information is lost. The method requires a knowledge of the frequency and a reasonably accurate adjustment of the jamming transmitter. Unless the jamming transmitter tracks the missile and concentrates its energy in a beam, the power required becomes very high. If the missile contains transmitter and receiver, the target signal increases as the inverse fourth power while the jamming signal increases only as the inverse square of the distance from target to missile. In view of the short time of flight of a missile, and of the possibility of using several missiles simultaneously on different frequencies, the task of the jammer is not simple. Moreover decoy methods could be used by the attacking aircraft, such as illuminating the target with search radar at frequencies not used on the homing missile. If the enemy finds means to counter these tactics, the missile could be equipped with an automatic frequency shifting device to change suddenly the frequencies of the radar transmitter and receiver equally and simultaneously every few seconds. Or more simply, the missile could be equipped with an automatic switching device to cause it to home on the jamming transmitter.

A more effective countermeasure against radar-homing missiles is the use of decoy targets such as corner reflectors towed on barges behind ships which are possible targets. The decoy targets must be close enough so that range distrimination by the radar-homing device is not possible. The use of such decoys would be a great nuisance to ships and the destruction of the decoy targets by an early attack would leave the ship exposed to later missiles.

The use of radar-controlled gunfire might be effective against a few missiles but the simultaneous release of a sufficient number of missiles on different courses would probably saturate the defenses.

Maneuvering of the target is another possible countermeasure, but it is probable that computers will soon be available which will make such a countermeasure ineffective.

EQUIPMENT AVAILABLE AT PRESENT

The radar-homing equipment now available was developed in its essential features by the Radiation Laboratory of the Massachusetts Institute of Technology at the request of the Army and Navy. Further engineering development was directed by a special group recruited from the Radiation Laboratory and set up under contract with Division 5, National Defense Research Committee, as an M.I.T. field station at the National Bureau of Standards, Washington, D. C. Here under one roof a cooperative organization was set up to develop radar-homing missiles, consisting of a National Bureau of Standards civilian group operating as the Washington Project of Division 5, NDRC, the M.I.T. field radar group, and the Bureau of Ordnance Experimental Unit of the Research and Development Division, Bureau of Ordnance, Navy Department, made up of officers and enlisted men of the U. S. Navy. Engineers of the Zenith Radio Corporation, of Bell Telephone Laboratories, and of the Western

Electric Company cooperated in the development of production equipment under contract with the Navy.

A brief description will be given of the Pelican (RHB) equipment of Navy designation SWOD Radio Receiver Mark 1, Mod 3, built by the Zenith Radio Corporation and of the Bat (SRB) equipment of Navy designation SWOD Radar Mark 2, Mod 1, built by the Western Electric Company. Detailed descriptions are given in bulletins prepared by the manufacturers. The reports of the M.I.T. field radar group contain more additional information relative to certain desirable modifications to give improved performance, and to service test equipment.

The SWOD Radio Receiver Mark 1, is shown in Fig. 10. The complete system consists of spinner antenna, receiver unit, blower, junction box, rear antenna, power supply, and battery. Using a 14-v storage battery weighing 37 lb and providing full-load power for approximately 30 min, the total weight is 126 lb. The approximate weights and over-all dimensions of the principal components are as follows:

Component	*Weight (lb)*	*Approximate Dimensions (in.)*
Spinner Antenna	11	19 x 19 x 17
Receiver Unit	28	17 x 16 x 7
Blower	1	
Junction Box	7	19 x 9 x 5
Rear Antenna	3	
Power Supply	34	14 x 9 x 9
Battery	37	11 x 9 x 5
Cables	5	

The spinner antenna consists of a horizontal dipole mounted at the focus of a paraboloid reflector 12 in. in diameter having a focal length of 3.6 in. In front of the dipole is a much smaller flat reflector. The radiation pattern is about 30° wide and the spinning reflector is offset by 5.5° in order to displace the axis of the pattern by 11° from the axis of rotation. As the reflector is rotated the axis of the radiation pattern describes a cone having a vertex angle of 22°.

The receiver unit contains the local oscillator (a 2K28 reflex Klystron tube), the crystal mixer, the 30-mcps intermediate-frequency amplifier of 3-mcps bandwidth, the synchronizing and gate generating circuits, the double gate and amplifier, the target-selector and tracking circuits, the automatic gain control, and the differential amplifiers.

The blower is a thermostatically controlled fan to circulate air in the receiver compartment if the temperature in this compartment rises above 70°F.

The junction box provides a central distributing point and contains the lower half of the breakaway connector between the missile and the carrying aircraft. It also contains a time-delay switch to prevent the application of electrical intelligence for a period of 3 sec to permit the missile to clear the aircraft safely.

The rear antenna consists of three half-wave dipoles arranged circularly around the central coaxial feed line, thus giving nondirectional characteristics.

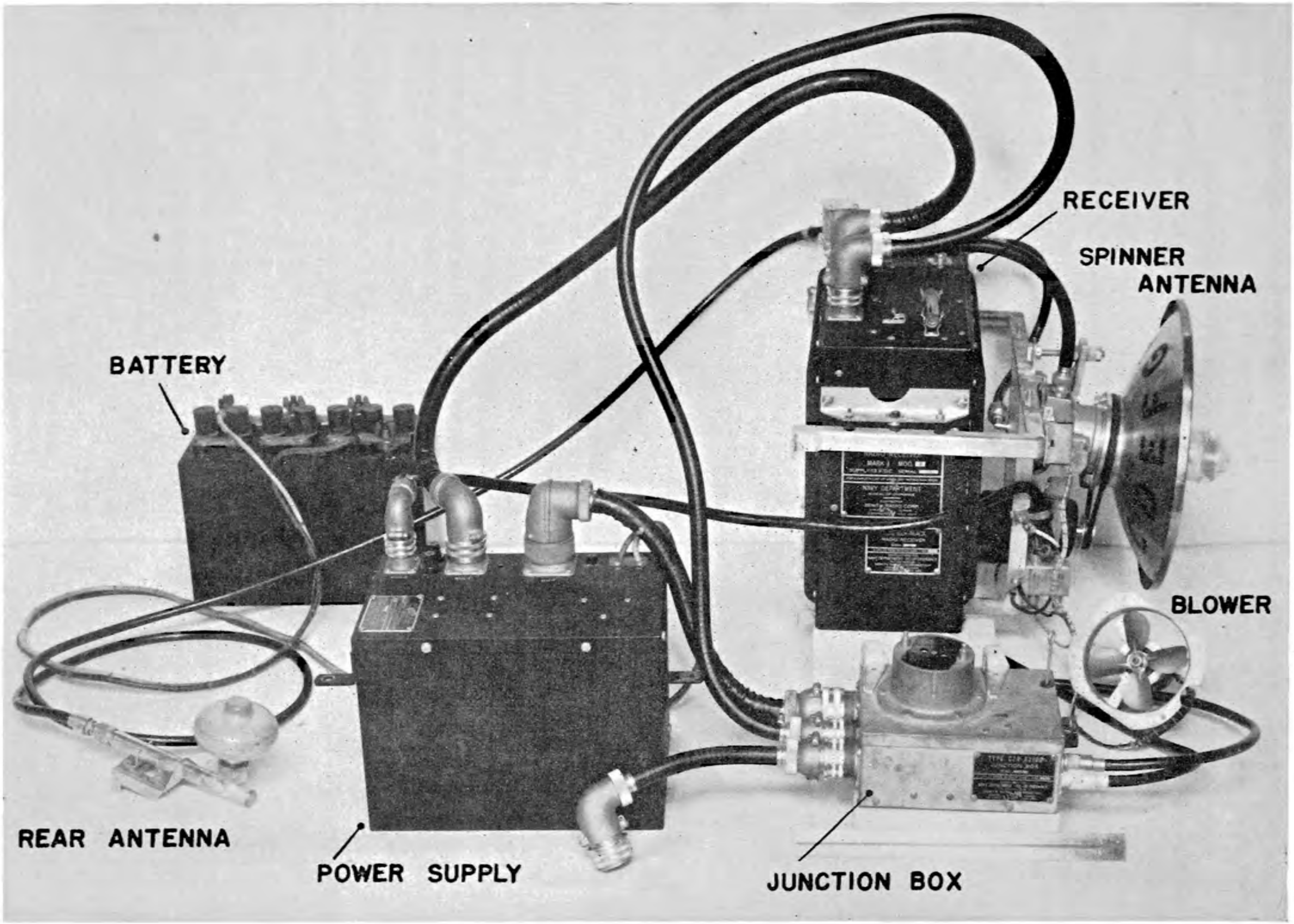


Figure 10 — SWOD Radio Receiver Mark 1

The power supply contains the dynamotor which furnishes the high DC voltages required by the receiver unit. It also contains a motor-driven potentiometer to provide repeller voltage for tuning the local oscillator in the receiver by remote control from the aircraft control station.

The SWOD Radio Receiver Mark 1 is designed to operate with a standard AN/APS-2 search radar. This equipment emits about 800 pulses/sec, each of about 1-microsec duration. The peak power is about 30 kw and the antenna reflector is 30 in. in diameter.

The SWOD Radio Receiver Mark 1 will just detect a signal of 10^{-12} w and saturates at about 10^{-5} w. A signal of 10^{-10} w is required for staisfactory tracking and operation of the automatic gain control. The response begins to drop off at power levels higher than 10^{-4} w. The loss is preceded by an abrupt increase in sensitivity over a small range in power. For moderate overloads the effect of overload is a loss of directional information, but for large overloads the receiver gives error signals of the wrong sign.

The SWOD Radar Mark 2, Mod 1, is shown in Fig. 11. The complete system consists of a nose assembly, power supply unit, inverter, and batteries. The total weight is 216 lb. The approximate weights and over-all dimensions of the principal components are as follows:

Component	*Weight (lb)*	*Approximate Dimensions (in.)*
Nose Assembly (with Plastic covering)	75	36 x 22 x 23
Power Supply Unit	36	22 x 20 x 9
Inverter	26	12 x 9 x 7
Batteries (two 14-v)	74	10 x 11 x 9
Cables	5	

The nose assembly consists of the antenna assembly, the transmitter-receiver, and the target-selector and directional-control assembly. The same antenna is used for transmitting and receiving. It is a half-wave dipole fed by a coaxial line. The dipole is at the focus of a 12-in. paraboloidal reflector. In front of the dipole is a small semicylindrical reflector to intercept the nonfocused forward radiation. The beam is about 21° wide. The offset angle and the method of conical scanning are the same as for the SWOD Radio Receiver Mark 1.

The transmitter is modulated by a free-running blocking oscillator feeding an 807 amplifier which triggers two 1B29 gas tubes. These tubes operate into a pulse-forming line, thence into a 3-1/2 to 1 step-up transformer which excites the 2J39 magnetron. The output of the magnetron is fed by a coaxial line into a 721B TR switching tube in the antenna line. The peak power radiated is from 6 to 10 kw. The pulse width is about 0.7 microsec and the pulse rate is variable from 1900 to 2100 cps. The synchronizing pulse for the target selector is obtained from a third winding on the magnetron coupling transformer.

The receiving system consists of a superhetrodyne receiver using a crystal mixer and Shepard-Pierce 726A local oscillator. The intermediate frequency is 60 megacycles with a bandwidth of about 4 mcps for 6 decibels down. The maximum ampli-

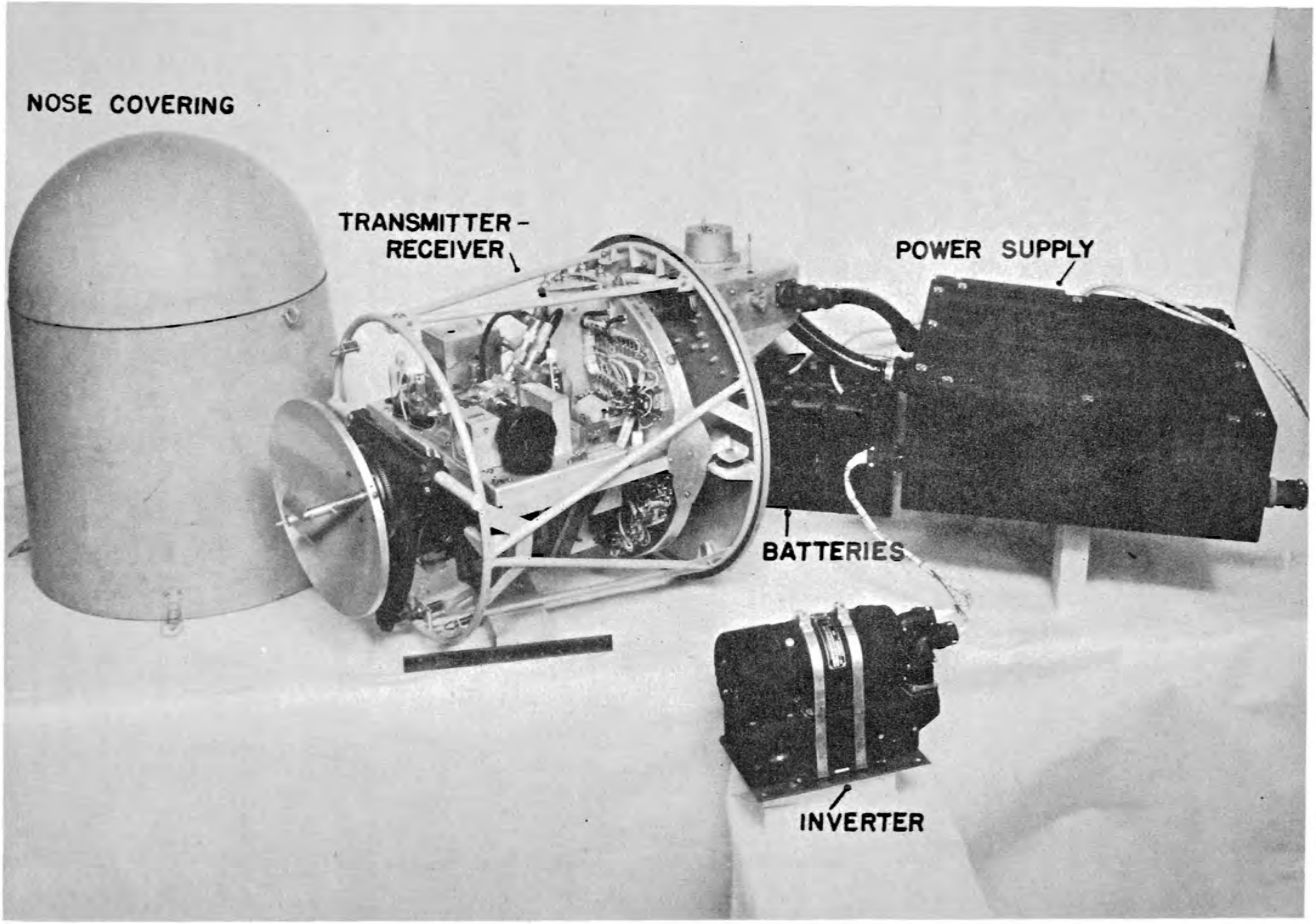


Figure 11 — SWOD Radar Mark 2 Model 1

fication of the 7-stage 1F amplifier is more than 100 decibels. The second detector is followed by a video amplifier whose output is fed into a tapped delay line which is a part of the target-selector circuit. The delay line supplies early, control, and late echoes to operate the target selector as previously described.

The junction box, housing the breakaway connector and time-delay switch, is mounted directly on the nose assembly.

The power is obtained from two 14-v batteries driving a 26.5-v input inverter with selenium disc regulator. The output is 115 v, 800 c, supplying regulated plate and bias voltages for the nose assembly.

The receiver characteristics of the SWOD Radar Mark 2, Mod 1, are substantially the same as those of the SWOD Radio Receiver Mark 1.

The two radar-homing devices just described were manufactured in substantial numbers together with the associated airplane control equipment and test equipment.

RADAR HOMING MISSILES AVAILABLE

Two series of missiles have been developed by the cooperative organization previously mentioned representing Division 5 of the National Defense Research Committee, the Bureau of Ordnance, Navy Department, the Massachusetts Institute of Technology, and the National Bureau of Standards. In addition, two missiles have been developed by the AAF Air Material Command to use the same radar-homing devices.

The Pelican series of missiles consists of glide bombs of three sizes using the SWOD Radio Receiver Mark 1, Mod 3, an RHB system. The gliders are controlled by elevons, i.e., wing flaps, which are moved together to control the path in a vertical plane and differentially to give banked turns. The aerodynamic design is such that the angle of attack is practically constant, independent of control position. This is accomplished by suitable tail and center of gravity locations which give moments on the tail due to changes in downwash from the wings to counter balance the moments produced by displacement of the flaps.

The following missiles have been developed:

Designation	*Wing Span*		*Total Weight*	*Pay Load*
	ft	*in.*	*lb*	
Experimental	8	5	725	325-lb depth charge
SWOD Mark 7	8	5	900	500-lb bomb
SWOD Mark 8	10	—	1500	1000-lb bomb
	12	—	2600	2000-lb bomb

Tests of these missiles were quite successful, about 40% hits being secured on a Liberty ship from a range of 10 miles. The mean circular probable error for a point target is about 150 ft. However, in view of the Bat development, which was nearly ready, decision was made not to use this type of missile in combat. RHB missiles require the releasing aircraft to make a steady 360° turn, while the radar operator keeps the target illuminated until the missile has struck. The Bat missiles are entirely self-contained and the releasing aircraft may take evasive action immediately after release. As previously pointed out, the range of Pelican is about twice that of Bat and hence the Pelican type may eventually be found useful.

The Bat series of missiles have the same airframes as Pelican with the SRB system SWOD Radar Mark 2, Mod 1. However, the SRB cannot be used in the smallest Pelican airframe of 8 ft, 5 in.-span. The following missiles have been developed:

Designation	*Wing Span (ft)*	*Total Weight (lb)*	*Pay Load*
SWOD Mark 9	10	1600	1000-lb bomb
SWOD Mark 10	12	2600	2000-lb bomb

The accuracy of Bat missiles is about the same as that of Pelican, the mean circular probable error being about 150 ft. Only a few of these missiles reached the combat area, but two ships are reported to have been sunk by their use.

The Army Air Forces applied the two devices to glide bombs of their GB series carrying a 2000-lb bomb, the one with RHB being denoted GB-7, and the one with SRB being denoted GB-14. These developments have proceeded with low priority and few tests have been made.

TREND OF FUTURE DEVELOPMENT

Experience with present radar-homing equipment and missiles suggests many directions for future development. Since there is great military interest in propelled missiles of supersonic speed and long range against air and groud targets, the homing device of the future will probably be intended to function only in the final stages of flight; the control during the earlier stages is by autopilot, some form of radar beam, or remote radio control. Present equipment would not function at all under such conditions, since it requires selection and locking on the target before release and continuous tracking in range. Two solutions suggest themselves: (1) radar repeat-back and control channels to permit remote target selection; or (2) an automatic target-seeking and selecting circuit which (a) can be kept inoperative during the early part of the flight, (b) can be made to search automatically in range beginning at any desired range, and (c) can be preset to give first, second, third, fourth, or fifth target in order of increasing range according to decision of the operator made on the basis of the early warning radar reconnaissance. The first solution is probably not applicable to high-speed missiles. Enough work has been done in the laboratory on the second solution to show that the circuits can be developed.

The radar-homing device of the future will probably use high-speed electrical switching rather than mechanical scanning. Thus it will be able to compare the amplitudes of successive pulses, reduce the effects of fading and also reduce the time lag of the system. If of the RHB type, synchronization will be accomplished by means of a stabilized audio-frequency oscillator in the missile. Steps will be incorporated to defeat countermeasures. The SRB type will use a separate antenna for transmitting so that the enemy cannot detect the scanning frequency in the transmitted signals. Automatic frequency shifting of transmitter and local oscillator simultaneously will make jamming exceedingly difficult. The equipment will probably operate at shorter wavelengths, probably in the neighborhood of 3 cm. In order to reduce the size and weight, the tubes and circuit techniques developed in connection with proximity fuses will probably be applied to radar-homing devices.

The servomechanisms will be much more rapid in action and have smaller time lag. Computers will be used to reduce errors arising from wind and target motion. The intelligence device will probably be of the automatically tracking type, its output being used on a servo system to keep its axis pointed at the target. Information for missile control will be derived from the angular displacement and speed of the axis of the intelligence device with reference to the missile axis.

It is important to note that much of this development can be carried out economically on glide bombs or on powered missiles of 500-mph speed. The Air Forces should undertake to see that development of radar-homing devices is continued along the lines indicated.

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