AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

Paper Reprinted from Conference Pre-Print No.196 on Avionic Cooling and Power supplies for Advanced Aircraft

NORTH ATLANTIC TREATY ORGANIZATION

DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF.		SECURITY CLASS.
	NLR-MP-76006-U		Unclassified

ORIGINATOR National Aerospace Laboratory (NLR)
Amsterdam. The Netherlands

TITLE The cooling of a pod-mounted avionic system

PRESENTED AT the AGARD Avionics Panel Specialists' Meeting held in The Hague, Netherlands, 1[illegible]-10 June 1976

AUTHORS	DATE	pp	ref
I. de Boer	22-III-1976	6	-

DESCRIPTORS

Optical equipment
Cooling systems
Aerial reconnaissance
Pods (external stores)
Cameras
Infrared scanners
Air cooling
Intake systems
Evaporative cooling

22 Mar 76

ABSTRACT

The paper describes the principles and testing of the air cooling of the pod-mounted Orpheus day and night aerial reconnaissance system, since 1974 operational with the Royal Netherlands Air Force.

At ram air temperatures up to 44° C, cooling is provided by ambient air entering the pod through a flush air intake in the nose, and leaving it through slots in the pod belly. In low level flight at high subsonic speeds, with ram air temperatures up to 79° C, the cooling air temperature is kept below 50° C by spraying an automatically controlled amount of water into the airflow near the intake.

During the flight testing unexpected cooling problems were encountered, that could be shown to originate in the NACA flush air intake. By changing to a flush air intake with parallel side walls the cooling system could be made to perform to entire satisfaction.

THE COOLING OF A POD-MOUNTED AVIONIC SYSTEM

I. de Boer
National Aerospace Laboratory NLR
Anthony Fokkerweg 2
Amsterdam 1017
Netherlands

SUMMARY

The paper describes the principles and testing of the air cooling of the pod-mounted Orpheus day and night aerial reconnaissance system, since 1974 operational with the Royal Netherlands Air Force. The pod airconditioning system was developed by the pod manufacturer Fokker-VFW and flight-tested by the National Aerospace Laboratory NLR.

At moderate airspeeds (e.g. 400 kts), with ram air temperatures up to 44° C, cooling is provided by ambient air entering the pod through a flush air intake in the nose, and leaving it through slots in the pod belly. In low level flight at high subsonic speeds (e.g. 600 kts), with ram air temperatures up to 79° C, the cooling air temperature is kept below 50° C by spraying an automatically controlled amount of water into the airflow near the intake.

During the flight testing of a pre-production reconnaissance system, unexpected cooling problems were encountered. These problems, which had not been experienced during previous prototype tests, could be shown to originate in the NACA flush air intake. By changing to a flush air intake with parallel side walls the cooling system could be made to perform to entire satisfaction in the series.

1. INTRODUCTION

In the first half of 1975 the original aerial reconnaissance equipment of the Lockheed RF-104 G aircraft of a Royal Netherlands Air Force squadron, comprising 3 day-light cameras, was replaced by an advanced pod-mounted day and night reconnaissance system. This so-called Orpheus-system had been designed, in co-operation by the "Old Delft" Optical Industry and Fokker-VFW, to meet air force requirements for a tactical reconnaissance system, providing aerial reconnaissance capability during day and night, at high subsonic speeds and at low to medium altitudes.

The requirement for a pod-mounted system originated from the fact that the space available inside the RF-104 G aircraft was clearly insufficient for the considerable enlargement of the reconnaissance equipment and also from the condition that the aircraft had to remain serviceable and therefore could not be grounded for substantial modifications. A detachable pod provides a solution for these problems and offers the additional advantages of easy maintenance and repair of the pod equipment and, by replacement of the reconnaissance pod by another external store, of mission versatility.

2. ORPHEUS AERIAL RECONNAISSANCE SYSTEM

The Orpheus reconnaissance equipment was developed by the "Old Delft" Optical Industry and the pod structure and aircraft installation by Fokker-VFW. Figure 1 shows the Orpheus pod attached to the standard centre-line bomb rack of a RF-104 G. The only other connection with the aircraft is by way of an electrical connector for power supply lines and remote control by the pilot. This connector has been designed to permit jettison of the pod in case of emergency. Figure 2 gives an impression of the rather densely packed pod interior. It contains from nose to tail:

- a forward looking camera(1) , mounted in a fixed position
- two sideways looking cameras (2 and 4), also in a fixed position
- two more lateral looking cameras (5 and 6) that can be placed in high-oblique or split-vertical positions. In the split-vertical position these cameras, together with the sideways looking cameras, mentioned before, provide complete horizon-to-horizon coverage.
- an infrared linescanner (7) with interchangeable detector package and a total field of view of 120°, roll-stabilised in the vertical and 30° oblique positions
- a control-coupler unit (10) that houses the system interface equipment and the automatic control of camera frame rate, linescanner film speed and airconditioning
- a vertical gyro (12) providing a reference for scanner stabilization
- a static frequency converter (13) that converts the aircraft power supply of variable frequency into fixed frequency power
- a water-tank (14) for the air cooling system
- provisions (3 and 9) for the installation of a radar altimeter, if a true height signal cannot be obtained from the aircraft (not needed for the Netherlands RF-104 G).

In order to benefit fully from the pod configuration, the system should be as self-contained as possible. This implies that the aircraft airconditioning system cannot be used for the pod interior and consequently, in most cases, a separate pod system will be required. Depending on the operational flight envelope, the pod airconditioning system may have to provide cooling at high temperature conditions as experienced in high speed, low level flight, as well as heating during cruising flight at high altitude. Only the Orpheus cooling system will be discussed hereafter.

3. COOLING SYSTEM CONCEPT

According to the environmental specification the Orpheus-system had to be capable of continuous operation at sea level, with sustained true air [illegible] to 600 KTAS (knots true air speed) and ambient temperatures up to 30° C. Due to compression and friction of the air flowing past the pod, the temperature of most of its skin rises according to the relation $\Delta T(^{\circ}C) = 0.00012\,(KTAS)^2$. From this formula, which could be verified during flight testing, it follows that the temperature rise at the maximum speed of 600 KTAS is 43° C. At an atmospheric temperature of 30° C, this corresponds to a pod skin temperature of 73° C. From these figures and a maximum air temperature of 50° C for cooling the infrared scanner and cameras, as demanded by the manufacturer, it follows that a pod cooling system was called for.

The pod manufacturer Fokker-VFW undertook to develop an airconditioning system providing cooling air with a maximum initial temperature of 50° C and a minimum mass flow at this temperature of 0.125 kg/sec. The minimum airflow requirement was based upon a total heat dissipation of the reconnaissance system equivalent to 2.500 W and a maximum final air temperature after cooling of 70° C. During extensive ground tests it could be shown that at these temperatures this airflow was just sufficient to warrant proper continuous functioning of the reconnaissance equipment.

With the intention to provide a simple cooling system, needing as little pod volume as possible, Fokker-VFW chose to design an open airflow cooling system, using atmospheric air routed through the pod and kept below 50° C initially by evaporating an automatically controlled amount of water near the air intake. This method of cooling the ventilating air is made possible by the temperature rise due to compression at the intake, which causes the air to achieve a very low relative humidity permitting sufficient water evaporation for the desired cooling effect.

4. COOLING AIR FLOW

Figure 3 shows the general lay-out of the pod air cooling system. Ambient air enters the system through a flush air intake (1), located at the top of the pod nose and subsequently passes through a primary filter (2). This so-called fly-filter is intended to stop insects and coarse particles. It can be easily removed for inspection or replacement through the camera compartment. Downstream of the fly-filter, two water spray nozzles (3) are installed in the air duct. Evaporation of the water takes place in an evaporator unit (4) consisting of two light alloy honey comb parts with a secondary filter in between. This secondary, or main filter collects fine dust and small particles that passed the primary filter (2). These fine particles are largely washed out during flight in rain and during operation of the water spray nozzles. A water separator (5), with drain to the pod skin, is located downstream and partly below the evaporator. It serves to remove rain and the small quantity of water which may not have evaporated at this point of the air cooling process. Beyond the water separator the air passes over a cluster of 4 temperature sensors (6), two of which are used for the cooling process control and the other two for pod heating control and ground measurements. Downstream of the temperature sensors the airflow is divided into 3 directions to provide cooling in the separate compartments of cameras, infrared scanner and frequency converter. After passing the cameras the air is routed backward to the common exhaust through the scanner port, if open, or to the outlet slots in the converter compartment. Distilled water for the cooling system is stored in a 7.6-liter water-tank in the pod tail cone.

5. WATER COOLING SYSTEM

Figure 4 schematically presents the operation of the water cooling system. An electrically-driven pump is fitted to the water-tank. The discharge of this pump is connected to two solenoid operated liquid valves, commanded by temperature sensors in the air duct downstream of the water separator. The solenoid valves pass the water to the spray nozzles upstream of the secondary filter. The pump discharge also has a return to the tank by way of a pressure relief valve, which permits adjustment of the water supply pressure. When the pump is operating, while both solenoid valves are closed, full pump delivery is returned to the tank. The pump circuit is energized when the air temperature reaches the setting of either of the two sensors of the temperature control channels. A time delay relay keeps the pump running for one minute after both temperature control channels have reverted to the de-energized condition, thus preventing unnecessary pump switching.

The primary temperature control channel energizes the pump and opens the primary solenoid valve at a sensor temperature of 44° C, and closes the valve at a temperature which is 1 to 2° C lower. If the air temperature at the intake is only slightly above 44° C the water cooling will function intermittently. As temperature and airflow increase, for instance due to increasing flight Mach number, the spraying of water will continue for a greater percentage of time till the point where the water evaporation cannot any longer lower the temperature below the de-activation temperature of approximately 42° C. The primary nozzle then is spraying continuously. The secondary temperature control channel opens the secondary solenoid valve when the temperature at the corresponding sensor rises to 48° C, and closes the valve at a sensor temperature which is 1 to 2° C lower. Operation is similar to that of the primary channel. During intermittent operation of the secondary channel, the primary channel remains continuously activated.

6. PROTOTYPE TESTING

For the development of the cooling system, a closely interrelated series of ground and flight tests had to be carried out. The flight testing started with a dummy pod, without reconnaissance equipment, to locate the best position and dimensions of the air intake for meeting the minimum cooling airflow requirements. The dummy pod contained an air-duct with resistances to simulate the cooling unit and reconnaissance equipment and was instrumented to measure airflow as a function of flight Mach number. The range of measured airflows, corresponding with the range of airspeeds for reconnaissance missions, was then used in test rig experiments for the detail design of the water cooling system.

The test rig consisted of a complete cooling unit assembled in a representative duct with flush air intake and provisions for pressure and temperature measurements at several points in the airflow. Aft of the cooling unit, the underside of the duct was constructed of a transparent material to enable detection of possible free water in the airstream. A temperature controlled air supply to the flush intake of the duct was provided by a Roots blower and electric heating elements. The airflow was measured with a calibrated nozzle.

During the test rig experiments it proved to be rather difficult to find the right solution for the handling of the large range of possible airflows (0.10 to 0.18 kg/sec) and temperatures (40-72° C). For instance, with a nozzle configuration providing adequate cooling capacity at maximum flow and temperature, sometimes small amounts of free water were detected at minimum flow and at switch-over from operation with one to two nozzles. Eventually, however, the correct combination of waterpump pressure, nozzle size and switching temperatures was attained and employed in the cooling system of the Orpheus prototype. In order to achieve the same cooling performance in flight as on the ground, the airflow in the prototype had to be adjusted to equal the rig test values. During the first few flights with the complete reconnaissance equipment installed and operating, this was accomplished by adaptation of the resistance of a grating (perforated steel plate) fitted for that purpose in the air intake.

After extensive flight testing in the Netherlands and some small adjustments to the cooling system, final testing took place in central Italy, where high ambient temperatures allowed flight tests up to the limits as stated in the environmental specification. Final proof of the maximum cooling capacity was obtained during a flight at 600 KTAS continuous, a height of about 500 ft and an ambient temperature of nearly 30° C. During this flight, which lasted 50 minutes, all temperatures in the pod remained within limits, and the reconnaissance equipment functioned satisfactorily.

7. AIR INTAKE PROBLEMS

In summer 1973 a pre-production Orpheus system, with modified camera configuration but essentially the same pod structure and airconditioning as the prototype, became available for flight testing. During the first few flights the water cooling system turned out not to be working properly. Although repeated ground tests did not show any deficiencies, and the water consumption in flight was exactly as it should be, the cooling effect, if any, was negligible and during short runs at 600 KTAS, air temperatures up to 70° C were recorded downstream of the evaporator. When, after having checked everything without finding anything wrong, in a last effort the air intake of the pre-production pod was replaced by the one of the prototype, the water cooling resumed normal operation! A careful comparison of the air intakes only showed a slightly different location of the grating used for airflow trimming. Evidently small alterations to the intake configuration could be of great influence on the evaporation process.

As it was the intention for the production series to dispense with the intake grating and to introduce instead a readily replaceable fly-filter further downstream, it was decided to interrupt the flight testing in order to first introduce this comparatively large modification.

Flight testing with the proposed series intake configuration was resumed in autumn 1973. The water cooling thereby proved to perform normally without, however, attaining the same low temperatures as during prototype measurements. This soon turned out to be caused by substantially higher air intake temperatures than could be accounted for by flying speed and atmospheric temperature.

If all kinetic energy of flowing air is transformed into heat by reducing its speed to zero, the temperature rise due to adiabatic compression amounts to $\Delta T(^{\circ}C) = 0.000132\ (KTAS)^2$. The fraction of this maximum temperature rise, that actually occurs at a certain location is called the local recovery factor. During the prototype flight testing the recovery factor r of the air, downstream of the intake, just before reaching the spraying nozzles, was measured several times and consistently proved to be r=0.85. Now, however, with the series intake configuration, using a fly-filter instead of a grating, a recovery factor r=1.1 was found! At the maximum speed of 600 KTAS the increase of recovery factor meant that the water cooling system was called upon to handle a 12° C higher temperature than expected and designed for.

Since a recovery factor above 1.0 at first seemed to be highly improbable, quite a number of flight tests were made, even using independent measuring systems, which, however, confirmed the first results. The explanation for this unusual phenomenon most probably is to be found in the complicated flow pattern inside the so-called NACA air intake as chosen for the Orpheus prototype. This type of air intake, shown in figure 5, was selected because of its ability to produce relatively high intake pressures, and its immunity from icing up. The efficiency of the NACA air intake is based on the generation of rather strong vortices, which, in certain circumstances, are known to be capable of producing abnormal temperature distributions (Ranque - Hilsch effect). Also, an unsteadiness in the airflow of the resonance type could be responsible for the temperature build-up.

In order not to be forced to redesign the water cooling system, the testing of the Orpheus preproduction system was concentrated upon the retrieval of a low recovery factor. Several intake configurations, with and without different types of grating and filter, were tested in flight as well as at full scale in a high speed wind tunnel of the NLR. Within the limits set by time and budget, however, a recovery factor r=0.85 could not be regained consistently.

As both the total loss of cooling at the start of the flight testing, and the excessive recovery factor experienced later on, were clearly connected with the NACA air intake, it was finally decided to change over to a simple straight air intake as shown in figure 6. This type of air intake with parallel side walls generates no vortices and is known to produce a steady recovery factor r=1.0 under all conditions, which was confirmed during Orpheus flight and wind tunnel tests. As a consequence the cooling capacity had to be increased to cope with the higher recovery factor, and the filter resistance had to be decreased to keep up the minimum cooling airflow. Eventually, however, a satisfactory configuration could be attained.

8. SERIES PERFORMANCE

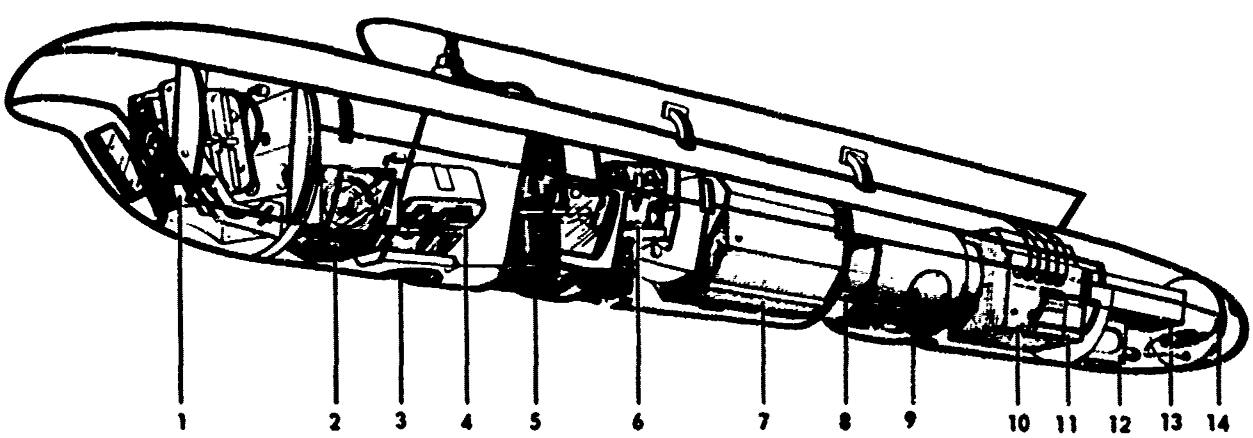
In the final series configuration the limiting condition for the cooling system occurs at sea level with a sustained flight Mach number M=0.90 (610 KTAS) and an ambient temperature of 30° C. The total cooling airflow under these conditions is 0.167 kg/sec with an intake temperature of 79° C. Both spray nozzles are operating continuously, with a total water consumption of approximately 2.5 cm^3/sec, permitting 50 minutes of flight under these conditions at the given tank capacity of 7.6 liters. By evaporating 2.5 cm^3 of water in 0.167 kg of air the humidity is increased by 15 g/kg. Consequently, even while flying in a saturated atmosphere at 30° C (containing 27 g/kg) the humidity downstream of the cooling unit will not exceed 42 g/kg, that is 49 % relative humidity at 50° C. Since in theory the cooling of 0.167 kg of air from 79° C down to 50° C could be achieved by complete evaporation of 2.1 cm^3 of water, the cooling process can be said to have an efficiency, under these conditions, of 84 %.

At a flight Mach number M=0.60 (405 KTAS) at sea level and an ambient temperature of 30° C, the cooling airflow with the straight air intake was measured to be 0.094 kg/sec with an intake temperature of 52° C. Intermittent operation of the primary nozzle reduces this temperature to 44° C, thus providing just sufficient cooling capacity.

9. CONCLUDING REMARKS

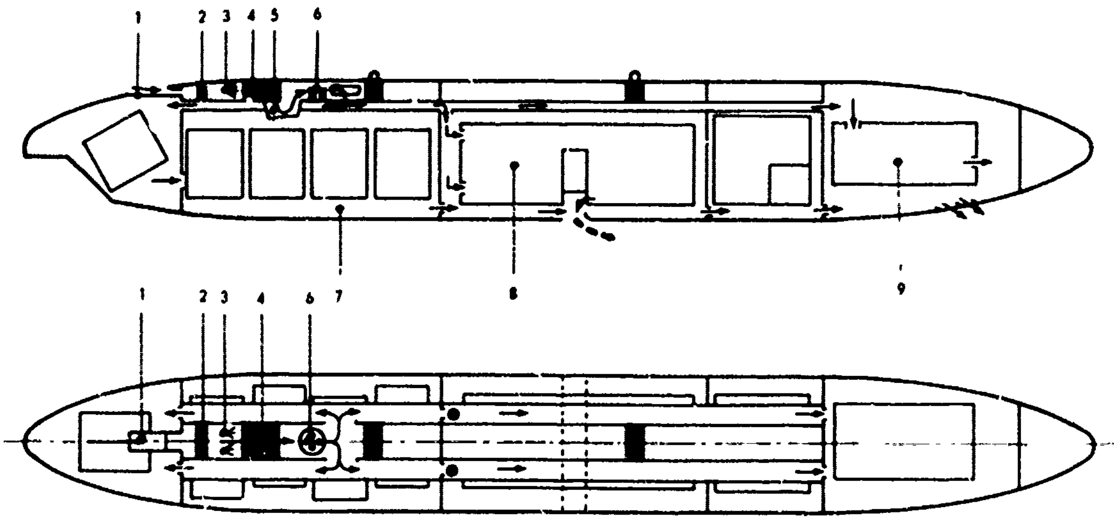
For one and a half years now, the Orpheus reconnaissance system has been fully operational. During a considerable number of sorties, in all kinds of weather, the airconditioning system worked as it was required to do. From a practical point of view, the final configuration therefore can be said to be satisfactory. From the experiences during the flight testing of the Orpheus prototypes, it can be learned, however, that the temperature behaviour of cooling air intakes should be checked carefully, since small alterations of the flush NACA intake turned out to be capable of producing rather surprising results. A closelyreasoned explanation for this behaviour is still missing. Therefore, the inquisitive mind of the research-worker is not satisfied. He still hopes, of course, to be given the opportunity some time to solve this problem.

FIG. 1 ORPHEUS RECONNAISSANCE POD ATTACHED TO A LOCKHEED RF-104G



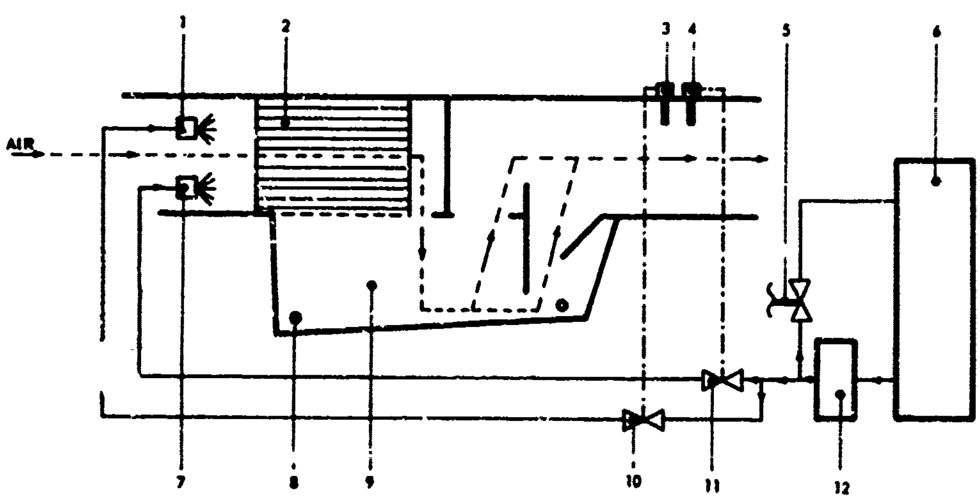
1. FORWARD CAMERA
2. LEFT PRIMARY CAMERA
3. RADAR ALTIMETER Tx ANTENNA
4. RIGHT PRIMARY CAMERA
5. LEFT SECONDARY CAMERA
6. RIGHT SECONDARY CAMERA
7. INFRARED LINESCANNER
8. SCANNING PORT DOOR
9. RADAR ALTIMETER Rx ANTENNA
10. CONTROL-COUPLER UNIT
11. TEMPERATURE CONTROL BOX
12. ROLL REF. GYRO
13. AC/AC CONVERTER
14. WATERTANK AND PUMP

FIG. 2 LAY-OUT OF THE ORPHEUS RECONNAISSANCE SYSTEM



1. FLUSH AIR INTAKE
2. PRIMARY FILTER
3. WATER SPRAY NOZZLES
4. EVAPORATOR WITH SEC. FILTER
5. WATER SEPARATOR
6. TEMPERATURE SENSORS
7. CAMERA COMPARTMENT
8. INFRARED SCANNER
9. FREQUENCY CONVERTER

FIG. 3 COOLING AIR FLOW IN THE ORPHEUS RECONNAISSANCE POD



1. SECONDARY SPRAY NOZZLE
2. EVAPORATOR AND SEC. FILTER
3. TEMPERATURE SENSOR 48° C
4. TEMPERATURE SENSOR 44° C
5. PRESSURE RELIEVE VALVE
6. WATER-TANK
7. PRIMARY SPRAY NOZZLE
8. DRAIN TO POD SKIN
9. WATER SEPARATOR
10. SEC. SOLENOID VALVE
11. PRIMARY SOLENOID VALVE
12. ELECTRIC WATER PUMP

FIG. 4 WATER COOLING SYSTEM

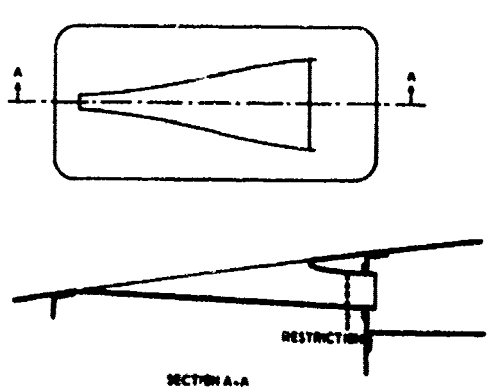


FIG. 5 NACA AIR INTAKE FOR PROTOTYPES

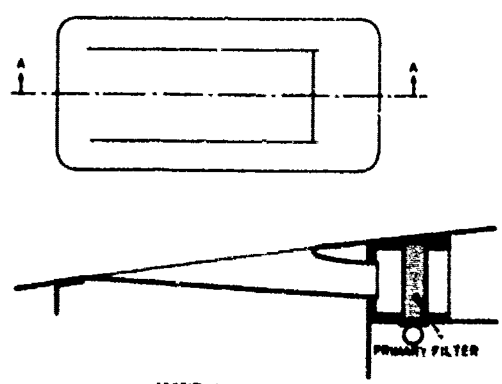


FIG. 6 STRAIGHT AIR INTAKE FOR SERIES