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BLADE ANTI-ICING SYSTEMS FOR MIL HELICOPTERS

By

BORIS S. SIROTINSKY
MIL MOSCOW HELICOPTER PLANT
Design Bureau
MOSCOW, RUSSIA

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Boris S. Sirotinsky

Mil Moscow Helicopter Plant Design Bureau

1. ABSTRACT

Russian climate makes high demands of helicopter operation. The start of operation of the first production Mi-1 helicopter has shown that the lack of anti-icing system limits greatly the possibility to operate them in Russia and in the countries of similar climate.

The problems of development of engine intakes, windshield and aerial ice protection systems are similar to those of the airplanes and are not a subject of the present paper.

The problem of rotor blades anti-icing system development is quite a specific one as the surface to be protected subject to considerable alternative elongation that calls for application of structural elements with fatigue strength. At the same time the surface mentioned should be able to withstand sand and rain erosion.

It is also required to develop specific components to transmit substantial amounts of power available on board to rotating rotor as well as special systems for warning and indication, automatic engagement, control and power distribution over the protected areas.

This paper reflects our experience in development of such a systems.

2. PNEUMATIC ANTI-ICING SYSTEMS.

The surface to be ice-protected must be deformable when compressed air is feeded to the special ducts laid under that surface. The ice made up breaks and is thrown away by the airflow, vibrations and centrifugal force.

Such a systems has been used to protect the wings of low speed airplanes. Application of pneumatic systems on helicopter rotor blades is not feasible because of their low efficiency at low temperatures, possibility of considerable outer surface deformations even when de-icing is not on, high complexity of transmission of compressed air from non rotating elements to rotating rotor and impossibility of combination of pneumatic de-icing with leading edge erosion protection.

The attempts to apply such a systems are known, in particular the results of such works were reported by respected mr. James T. Hindel and mr. Norbert A. Weisend at ERF in Berlin in 1991. However we know nothing about any production of the systems of this type.

3. ELECTRO-PULSE ANTI-ICING SYSTEMS

The works on application of electro-pulse systems were the next step forward in development of the direction mentioned as it has been reported in the same paper. We have evaluated the possibility of their use too. However, no positive results and recommendations of production application has been achieved so far because the blade surface besides the icing is affected by various factors including sand and rain erosion and therefore the development comprehensive protection system with the use of electro-pulse method is a very complicated task.

4. HOT-AIR ANTI-ICING SYSTEMS

It is also difficult to make a hot-air blade anti-icing. This could be explained by the fact that it is hard to transfer a sufficient amount of hot air from the airframe to the rotating rotor and by practical impossibility to accommodate air-pipes and air-ducts within a small blade cross-section with due account to structural fatigue strength and appropriate chordwise centre of gravity position.

5. LIQUID ANTI-ICING SYSTEMS

The first blade anti-icing system (AIS) developed by our company in the 50-60th was a liquid one. The methods of liquid delivery known from airplane technology were unusable in this case. In order to achieve a relatively even distribution of liquid along the blade leading edge surface the scheme of its supply through the holes in the anti-abrasion tip was used.

To have a uniform wash of the surface it was very important to select the optimum diameter and position of the holes relative to a leading edge. This parameters were chosen by experiment.

The liquid anti-icing system layout is shown on figure 1.

Side by side with the standard elements of any hydraulic system as a tank, pump, pipes etc. the system includes an original device - the distributor located on a rotor hub. This device enables to transport the anti-icing liquid from non rotating elements to rotating rotor and to distribute it between the blades.

The very first experiments have shown that in order to have even distribution of liquid along the blade it is required to divide the blade spanwise into sections and to deliver liquid to every section separately. The rotating rotor being a large centrifugal pump provides transportation of liquid to any section of the blade.

Alcohol or alcohol-glycerine mixture were used as anti-icing liquid. Such a system was first made for Mi-1 helicopter. At that time it was expedient because the helicopter without anti-icing has been already in production and it was advisable to use self-contained system requiring minimum changes to the helicopter.

Because of the very short period of the Mi-4 helicopter development the experience and design available were practically in full transfered to this aircraft.

However a broad experience of successful operation of multi-thousand fleet of Mi-1 and Mi-4 has shown a serious shortcomings of liquid anti-icing systems.

The main disadvantage is that this system is a preventive one and should be switched on when entering an icing area. It doesn´t guarantee ice drop when ice formation has already happened. The system action time is limited and defined by amount of liquid available on board. Usually is doesn´t exceed 30-40 minutes. Liquid system doesn´t provide icing protection at very low temperatures. Though this conditions are rare enough, in Russia and other countries with similar climate they are quite possible.

The important disadvantage among the others is the fact that the availability of large amounts of alcohol on board creates a certain conditions for undisciplined personnel especially in cold season.

6. ELECTRO-THERMAL ANTI-ICING SYSTEMS.

At present time the devices including the electro-thermal de-icing systems are the best means to meet the requirement of blade surface complex protection from the icing, abrasive erosion and effect of other factors of environment. These devices are effective and reliable; their action time is practically unlimited and the parameters may vary in wide range depending on operational conditions.

Of course electrical anti-icing system is not free of shortcomings and the first one is the requirement to have on board a relatively high-capacity source of electric power. However, the application of such methods as cyclical AIS switch on, heating elements sectioning as well as an increasing number of helicopter instruments and mechanisms consuming electric power enable to use such an electric circuits which reduce the mentioned disadvantage.

6.1. The electro-thermal elements located under a blade surface heat it and that is the way how the electro-thermal anti-icing system works like. A general layout of electro-thermal anti-icing system is shown on figure 2. If all the blades surface is to be heated at once this will require a very large expenditures of electric power. To reduce it, the heating elements are divided into sections and they are cyclically switched on in turn (fig. 3).

Unlike a liquid anti-icing system the cyclic electro-thermal one doesn´t prevent the ice formation, but drops off the ice that has already formed. The ice on the blade to same extend reduces the heat removal from the surface connected with its blowing by air flow that promotes the thaw of the layer adjacent to the heated surface with subsequent ice drop off under the influence of air flow and centrifugal force.

To prevent formation of so-called "barrier ice" the heated part of the blade should be about 13-15% of chord. Sectioning of heating elements may be both chordwise (as on the Mi-8 blades) and spanwise (as on the Mi-24 and other helicopters).

Spanwise sectioning requires wires laying and their connections with heating mats along the blade, which brings in additional difficulties to design and production and increases the chances of malfunction. However, this type of parceling is preferable as it enables to heat all the perimeter of airfoil nose part through the length of the switched-on section and thus to increase the efficiency of system operation. At present the number of sections on each blade is 6 compared with 2-3 in the past.

6.2. The main environmental parameters defining icing conditions are ambient temperature and humidity. With ambient temperature increase the maximum possible water contents falls. This dependency is defined by both Russian standards and FAR-29 requirements.(fig.4).

6.3. Thermal analysis of electro-thermal anti-icing system.

The requirements of efficiency of cyclic AIS in general may be defined as the ability to remove the ice from protected surface during one complete cycle of work and prevent the formation barrier ice in icing conditions. This requirements fulfillment depends on correctness of selection of thermal parameters-specific power, its distribution over the protected surface, complete cyclic duration and time of section heating.

The thermal analysis of cyclic AIS at its preliminary stages is performed at "dry" air conditions. It is based on the existing dependency between the temperature of wet and dry surface and is quite sufficient to define specific power of the heater, required to maintain a temperature needed.

The methodology of thermal field analysis that has been developed allows (fig. 5) :

1. To define the main parameters of cyclic AIS :

   - the value and distribution of specific power over the heated surface;
   - the duration of cycle and time of heating;
   - the number of sections as well as to obtain a pattern of non-stationary temperature field in the structure.

2. To perform a check-out calculation in icing conditions.

3. To define the temperature difference in "dry" air, providing the efficiency of flight test.

This methodology may be used in all stages of blade designing, testing and refinement. The of method calculation is based on drawing up and solving of thermal balance equations. The description of this method would take a considerable time and is not a subject of this paper (fig. 6). You are welcome to study it in details at our company facilities. I will confine myself to description of calculation results of the temperature changes on the particular blade surface during the cyclic of heater operation.

For the purpose of calculation method perfection and heat emission definition a series of wind-tunnel testing for blade samples of different designs incorporating AIS heaters has been performed at TsAGI wind tunnel (Fig. 7).

The experimental evaluation of structural material thermophisical properties and installation of thermocouples distributed over the surface and in depth of the design has been performed beforehand. In experiment when blowing at the blade sample, the specific power of the heater and duration of heating and cooling cyclic has been varied. Temperature differences both on the surface and in depth and on the heater as well as heat-transfer coefficients and airflow local velocities on the airfoil were defined during the experiments.

The results of calculations and experiments are shown on fig. 8 and it can be seen that they are in satisfactory concordance.

6.4. Heating device design.

Heating devices are located in the nose part of the blade on its surface and are exposed to direct influence of environment factors. At the same time they must provide reliable cyclic heating of this surface.

Therefore a number of specific requirements are demanded from heating devices (Fig. 9):

1. Electroconductivity and quite definite and stable heater resistance.

2. Thermal resistance of materials and connections (surface temperature of the heater may be up to 100° - 120° C .)

3. High electro isolating and thermoconductive properties of isolating layers.

4. The ability to form a monolithic structures by bonding the heating element to isolating layers which separate this element from blade structure without any defects, air bubbles etc. The same is required for connection of complete device to the blade.

5. High fatigue strength, including high temperature conditions of the heating device as it is directly connected with the surface of the blade which has considerable alternative elongations.

6. High abrasive resistance of the blade leading edge surface.

7. Smoothness of the outer surface.

8. Environmental resistance (solar radiation, humidity high and low temperatures etc.)

9. Stability of all the properties through a long time of operation.

10. Reliability of wire to heater connections under all the conditions mentioned. Possibility to accommodate these connectors within a minimum size and along the whole length of the blade.

6.4.1. Rotor blade anti-icing system layout is presented on fig. 10.

As usual the heating strap consist of electro-thermal heating element, isolating layers, separating it from the main structure, layers of outer coating to protect the device from environment and anti-abrasion tip protecting from sand and water erosion. All the elements of heating strap should be well bonded together and the strap itself is to be bonded to the blade structural element (to the spar). These connections should have no air bubbles as they do not conduct the heat well and are the cause of considerable heating element and neighbouring structure overheating. As it was mentioned above, the heater is divided into sections switched on in turn and sectioning may be either chordwise or spanwise.

6.4.2. The first blade electroheating elements were thin stainless steel strips serial connected by brides. Such a design provided a chordwise sectioning that eliminated the need to lay along the blade a large amounts of wires and also made possible to change as required the specific power along the chord by changing strips cross-sections (Fig. 11).

However this design has a number of serious disadvantages. The main one is that the metal heaters have relatively low fatigue strength, quite often lower than of the main structure and this strength depends on the quality of technological operations such as edge processing and so on.

Such heaters are still being used on Mi-6, Mi-10, Mi-8, Mi-17 helicopters.

In order to eliminate this defect Kamov Design Bureau proposed to crimp and bake this metal strips into rubber isolation. However, the experience of operation including that on the Mi-8 helicopters has shown no reduction of the heating elements destruction.

6.4.3. As a further development of this design the application of steel grids as heating elements was used. They have sufficient permissible elongation that practically take off the problem of fatigue strength (Fig 12).

Such heaters were used in Mi-26 main and tail rotor blades.

6.4.4. However as for the blades made of composite materials it is advisable to apply the heaters made of the material with better combination of characteristics and in particular with similar thermal expansion properties as of the main structure. Therefore, the original design of heaters made of electro-conductive fabric with a given resistance has been developed and used. The required resistance can be adjusted in wide range. In order to provide electric power supply and its even distribution over the heater, the buses made of metal grid are bonded to the fabric´s edges by electro-conductive adhesive. Then supply wires are bonded to the buses.(Fig. 13). It should be noted that such a design called for careful matching of adhesive, materials for heater and other parts in terms of properties conformation.

However at present time the design is used practically without faults on the blades of the Mi-24 production helicopters, Mi-28 prototypes and others.

6.4.5. In connection with the blades life time increase the problem of leading edge sand and rain erosion protection became very important. Rubber coating provide good protection from effect of sand but are almost immediately destructed by a heavy rain.

We have performed a joint investigations together with the Moscow Aviation Institute on the resistance properties of various means of blade leading edge protection. These studies along with the broad experience of blade operation in different climate conditions prove that today the use of metal strips made of stainless steel, titanium alloy or nickel is the best method of protection. Metal strips do also conduct heat from the elements to the blade surface very well (Fig. 14).

If the thickness of the strip is less than some critical value its deformation is very intensive under the impacts of the particles compared with normal low-rate wearing out. Only when the strip thickness is higher that some certain critical value the mechanism of interaction changes.

Unfortunately this critical value is large enough and if the whole strip would have been done from that thick material it would cause big problems with bonding to anti-icing device, large deformation and sometimes even strip destructions at the spanwise junctions.

That is why we have developed the technology of manufacturing of the strips with variable cross-section geometry. Their thickness exceeds critical value at a quite narrow part at the very nose of the blade and falls gradually as we move away from this point.

6.5. Tests ensuring the reliability of electro-thermal blade AIS.

Along with standard electric device testing such as measuring of conductors and isolation resistance, testing for high voltage current isolation disruption both in normal and high humidity and high temperature conditions a number of specific test is performed.

For example, during blade samples dynamics testing the anti-icing system installed is switched on in cycles to get blade surface temperature of up to 90°C . Thus an anti-icing mat and adjacent blade sections are exposed to alternative loads and high temperature at the same time (Fig. 15).

The check-out of operational effectiveness of the of the device under full current and thermal loading at production facilities is to be performed with the external factors simulation (with high-speed airflow blowing). This could be only possible if wind-tunnel would be available at production shop.

We found a more simple method of using a medium with higher heat - transfer coefficient. Full current loading tests are performed in the bath with same water circulation. This allows to maintain all current and thermal loadings (Fig. 16).

6.6. Power supply and blade AIS control.

To transfer electric power from the generator to rotating rotor a current collector placed on the rotor hub is used. As there is a need to provide a cyclic switch on of separate heater section there is a number of contactors mounted in combination with collector (Fig. 17).

Therefore the current collector has both power rings for electric power transfer and contact control rings. For the first de-icing system the switch on and the adjustment of operational cycle duration were made manually by the crew. Later, the automatic devices for indication of system automatic switch on in icing environment have been developed. The cycle duration is also adjusted automatically depending on ambient temperature (Fig. 18).

6.7. Testing of electro-thermal AIS effectiveness.

At the first stage of electro-thermal AIS efficiency testing the differences between the temperature of protected surface and ambient dry air are measured in flight. These measurements are done at various blade sections along its radius and at different cycle durations. The example of such a measurements is given on Fig. 8. When the results are positive which means that positive temperatures on protected surface are guaranteed through the whole ambient temperature range for which ice protection is to be provided then the next step of effectiveness testing is carried out.

6.8. Flight tests of anti-icing system in natural icing conditions.

During this test the helicopter deliberately goes into clouds from higher to lower temperatures. The rate of ice crust formation and the ambient temperature are recorded and the anti-icing system is checked-out for compliance with the requirements of paragraph 6.4 above.

Helicopter behaviour, controlability, vibrations, changes of required power, etc are also monitored. After helicopter landing the presence of ice on protected surface, if any, is registered (Fig.19).

All the testings which have been performed proved the efficiency of the systems developed by the firm in the conditions specified.

As usual, such tests are rather long and expensive, they require a large number of flights in adverse weather and severe climate conditions.

Therefore we are developing the method of AIS efficiency testing in artificial icing conditions.

6.9. Blade testing in artificial icing

At the first stage we have built the ground bench for life-size main rotor testing. It has a fog-generating plant based on jet engine (Fig. 20).

For the same purpose the Mi-6 helicopter was equiped with a special water tanks of 8000m volume and water delivery and spray system. It was needed to meet strict requirements of generated water drops diameter. The system has special sprayers which helped to solve the problem. Fig. 21 shows one of the episodes of tests with the use of tanker helicopter.

Conclusion

As a result of multi-year work the M. L. Mil Helicopter Company has developed the methods of calculation, design and testing, reliable elements, technology of manufacturing and control for thermo-electrical anti-icing systems of main and tail rotor blades, which were used on all production and experimental helicopters of Mil (Mi-2, Mi-6, Mi-10, Mi-8, Mi-17, Mi-24, Mi-26,Mi-28, Mi-38) as well as on new projects.

These systems provided effective and reliable icing protection of main and tail rotor blades under any given conditions.

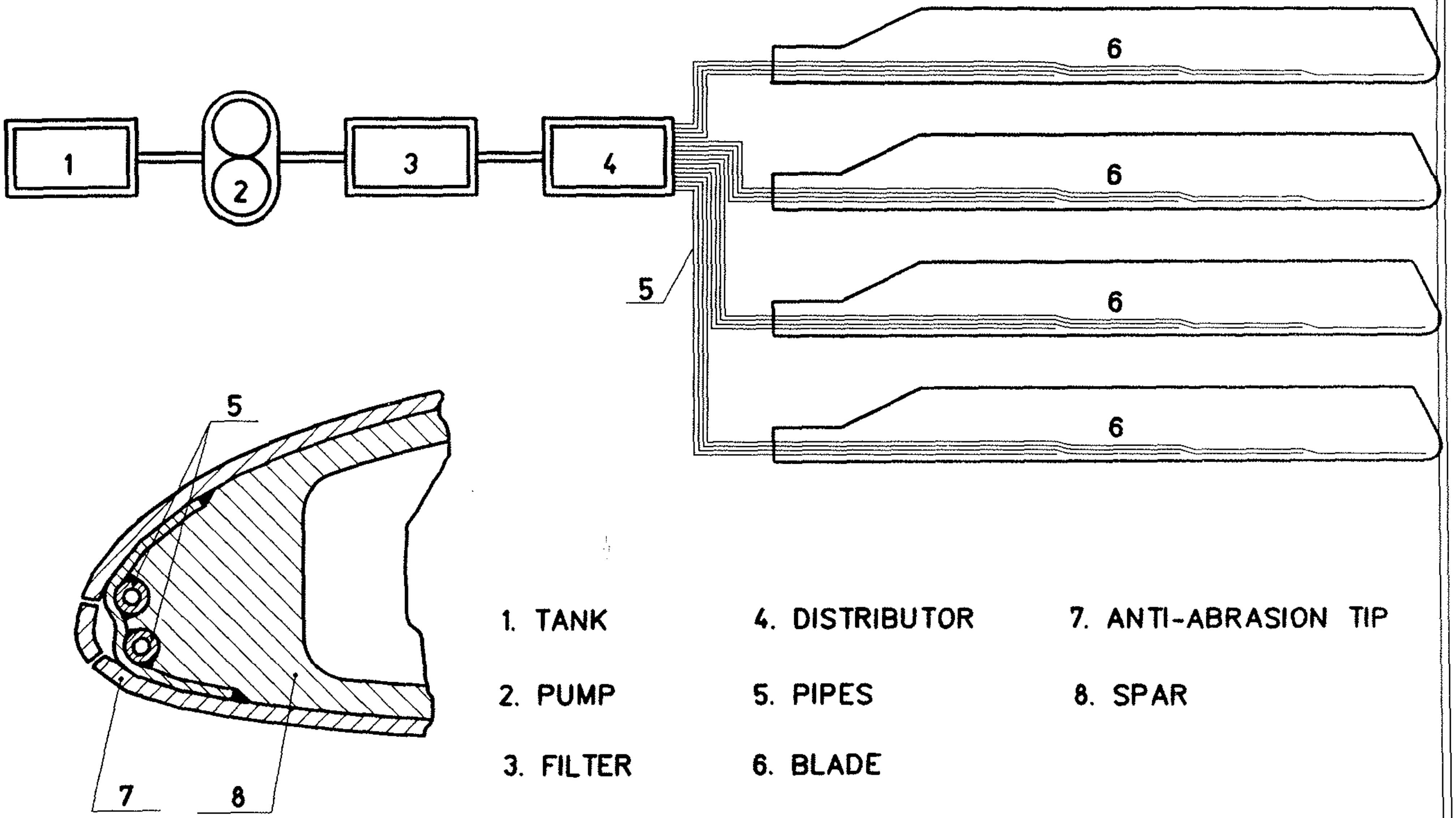


Fig. 1. THE LIQUID ANTI-ICING SYSTEM

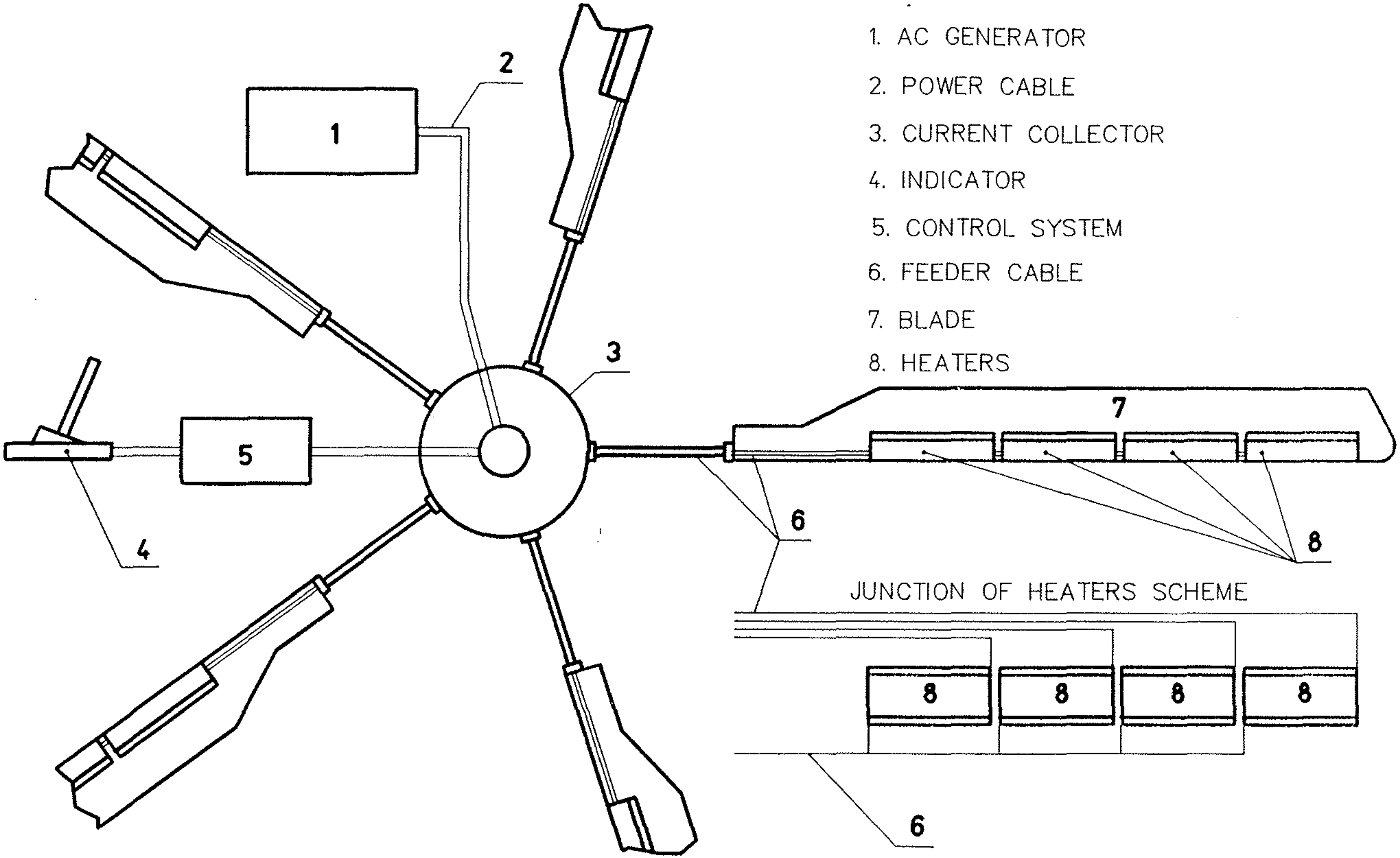


Fig. 2. ELECTRO-THERMAL ANTI-ICING SYSTEM

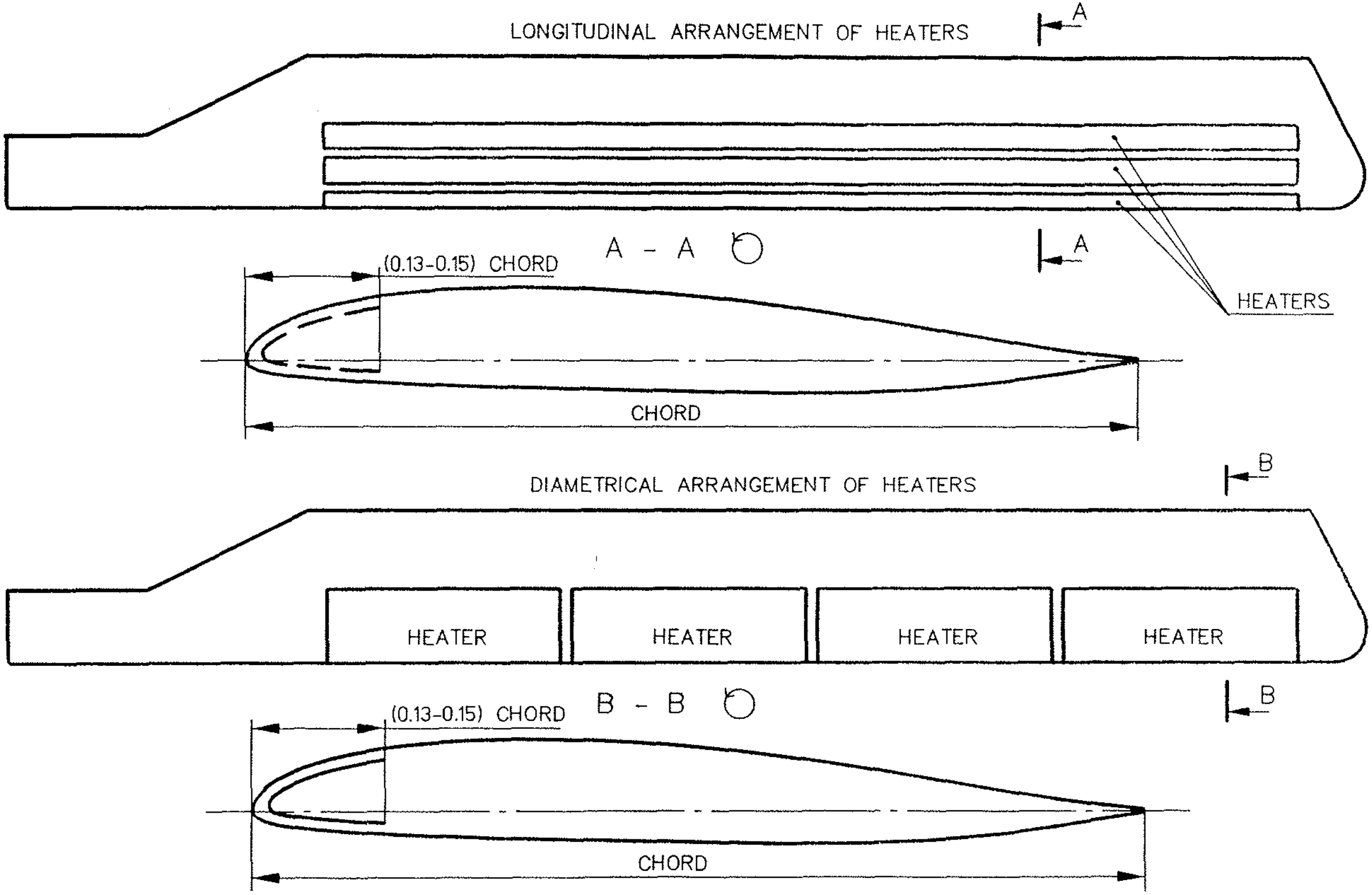


Fig. 3. ROTOR BLADE HEATERS ARRANGEMENT

AMBIENT AIR TEMPERATURE, C	0	-10	-20	-30
LIQUID WATER CONTENT, grams/cubic meters	2,5	2,2	1,7	1,0
ALTITUDE, meters	500- 5000	600-6000	2000-6500	3000-6500
DURATION OF ICING, minutes	3 . . . 4			

AMBIENT AIR TEMPERATURE, C	0	-10	-20
LIQUID WATER CONTENT, grams/cubic meters	0,8	0,6	0,3
ALTITUDE, meters	0...5000	0...6000	0...6500
MEAN DROP DIAMETER, microns	20		

Fig. 4 ICING CONDITION

THERMAL ANALYSIS PROBLEMS

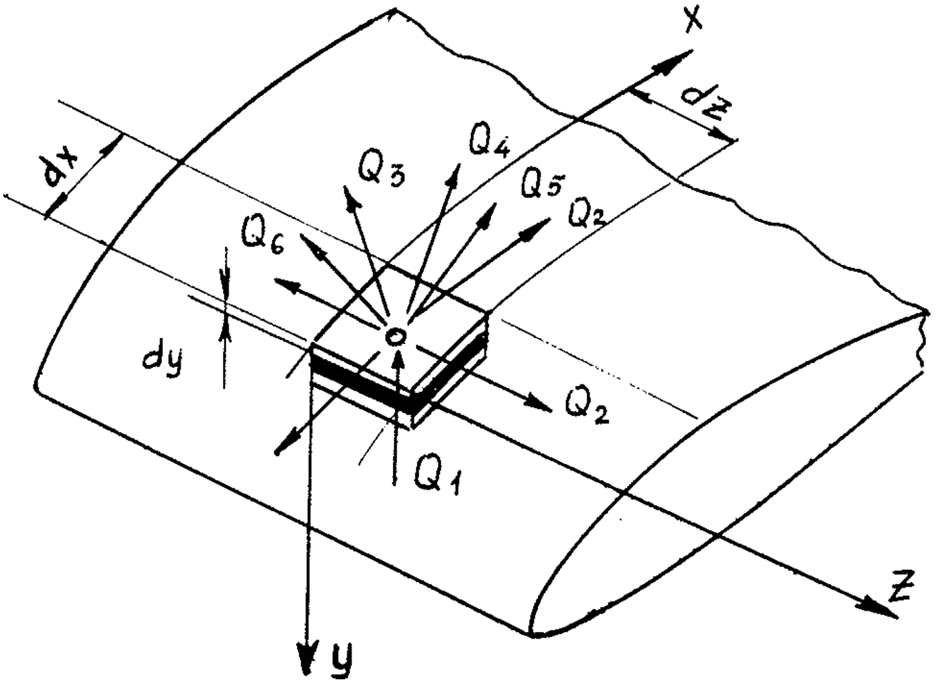
1. DEFINITION OF CYCLIC ANTI-ICING SYSTEM MAIN PARAMETERS:
   - THE VALUE AND DISTRIBUTION OF SPECIFIC POWER OVER THE HEATED SURFACE
   - THE DURATION OF COMPLETE CYCLE AND TIME OF HEATING
   - THE NUMBER OF SECTIONS

2. PERFORMANCE OF CHECK-OUT CALCULATIONS IN ICING CONDITIONS

3. DEFINITION OF TEMPERATURE DIFFERENCES TO PROVIDE THE EFFICIENCY TO OF FLIGHT TESTINGS

4. OBTAINING OF THE PATTERN OF NON-STATIONARY TEMPERATURE FIELD IN THE STRUCTURE

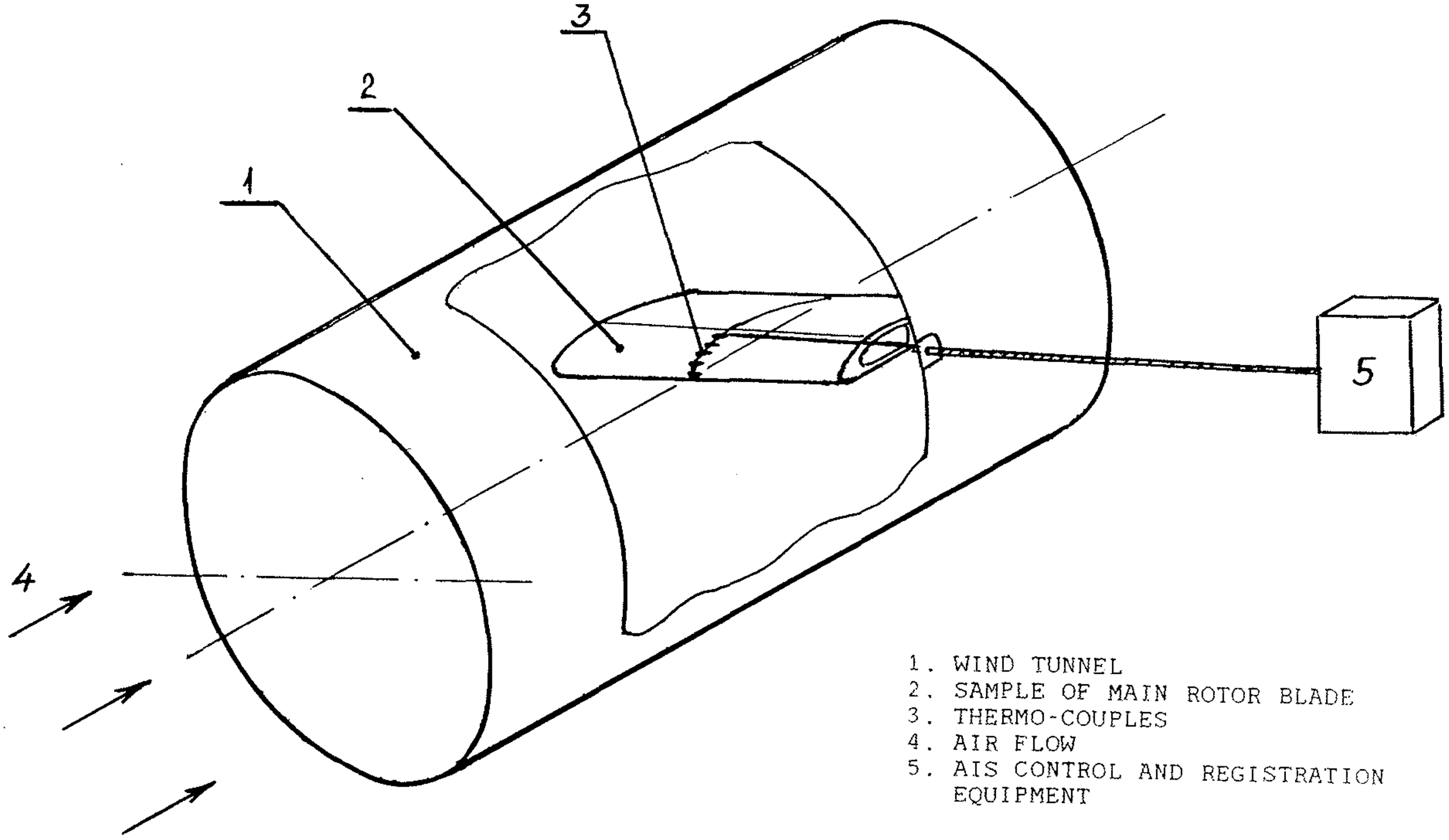
Fig. 5



HEAT FLOW OF:

Q_1 - ANTI-ICING SYSTEM
Q_2 - HEATCONDUCTIVITY
Q_3 - HEAT CONVECTION
Q_4 - EVAPORATION
Q_5 - HEATING OF WATER
Q_6 - RAYING

Fig. **6** SCHEM OF ANTI-ICING SYSTEM HEAT FLOW



1. WIND TUNNEL
2. SAMPLE OF MAIN ROTOR BLADE
3. THERMO-COUPLES
4. AIR FLOW
5. AIS CONTROL AND REGISTRATION EQUIPMENT

Fig. 7 WIND-TUNNEL TESTING OF AIS MAIN ROTOR SISTEM

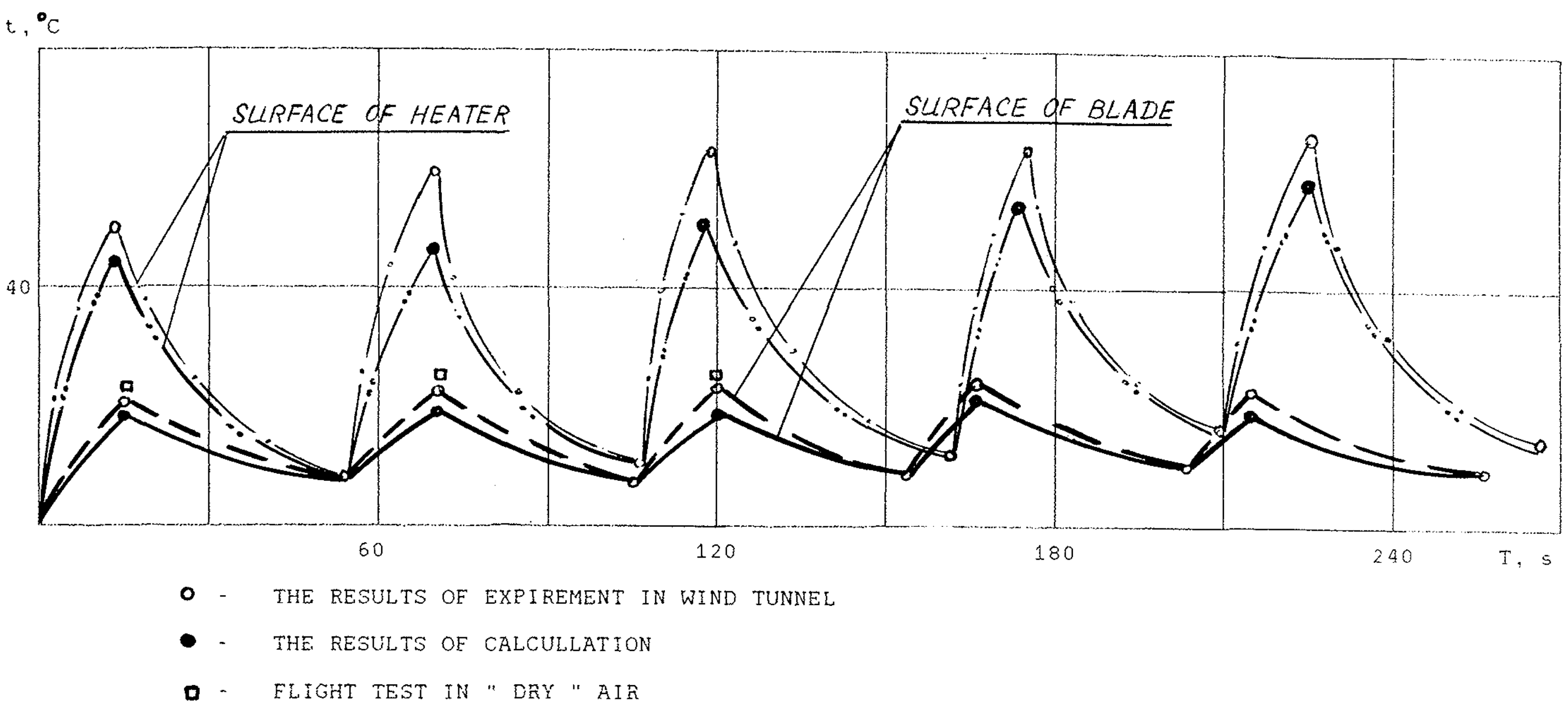


Fig. 8 COMPARISION OF TEST AND CALCULATION RESULTS

(t - TEMPERATURE DIFFERENCE, T - TIME)

REQUIREMENTS TO THE MATERIAL, DESIGN AND CONNECTIONS OF THE AIS

- ELECTROCONDUCTIVITY
- DEFINITE AND STABLE HEATER RESISTANCE
- THERMAL RESISTANCE OF MATERIALS AND CONNECTIONS
- HIGH ELECTRO-ISOLATING AND THERMO-CONDUCTIVE PROPERTIES
- THE ABILITY TO FORM A MONOLITHIC STRUCTURE BY BONDING OF HEATER ELEMENT TO ISOLATION AND OF THE WHOLE DEVICE TO A BLADE
- HIGH FATIGUE STRENGHT OF HEATING ELEMENT INCLUDING HIGH TEMPERATURE CONDITIONS
- HIGH ABRASIVE RESISTANCE OF THE BLADE LEADING EDGE
- SMOTHNESS OF THE OUTER SURFACE
- ENVIRONMENT RESISTANCE (SOLAR RADIATION, HUMIDITY, TEMPERATURE DIFFERENCE)
- STABILITY OF PROPERTIES THROUGH THE OPERATIONAL LIFE TIME
- RELIABILITY OF CONDUCTORS CONNECTION UNDER ANY OPERATIONAL CONDITIONS
- POSSIBILITY TO ACCOMODATE THE ELEMENTS WITHIN A MINIMUM SIZE ALONG THE BLADE

Fig. 9

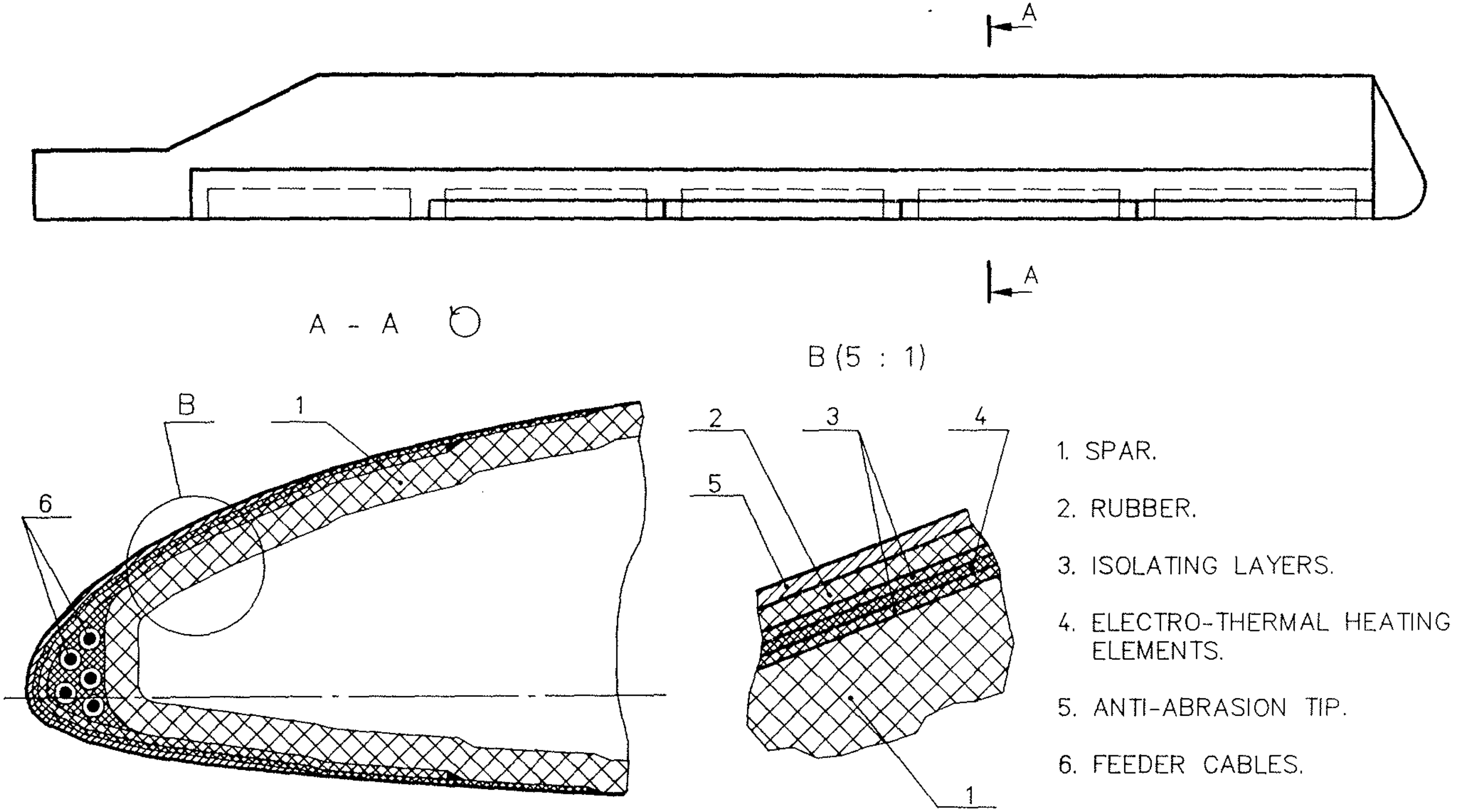


Fig. 10. HEATING STRAP

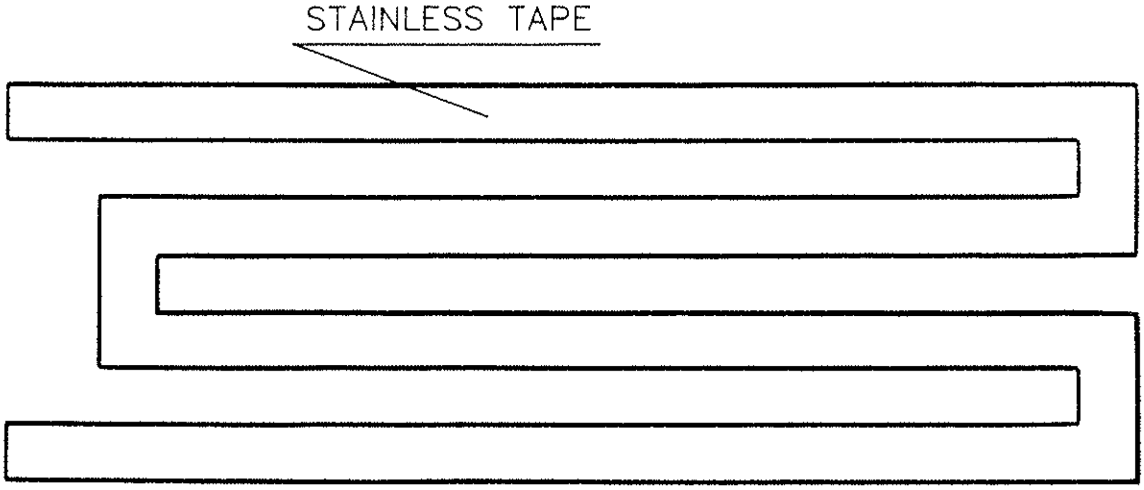


Fig. 11. TAPE HEATER

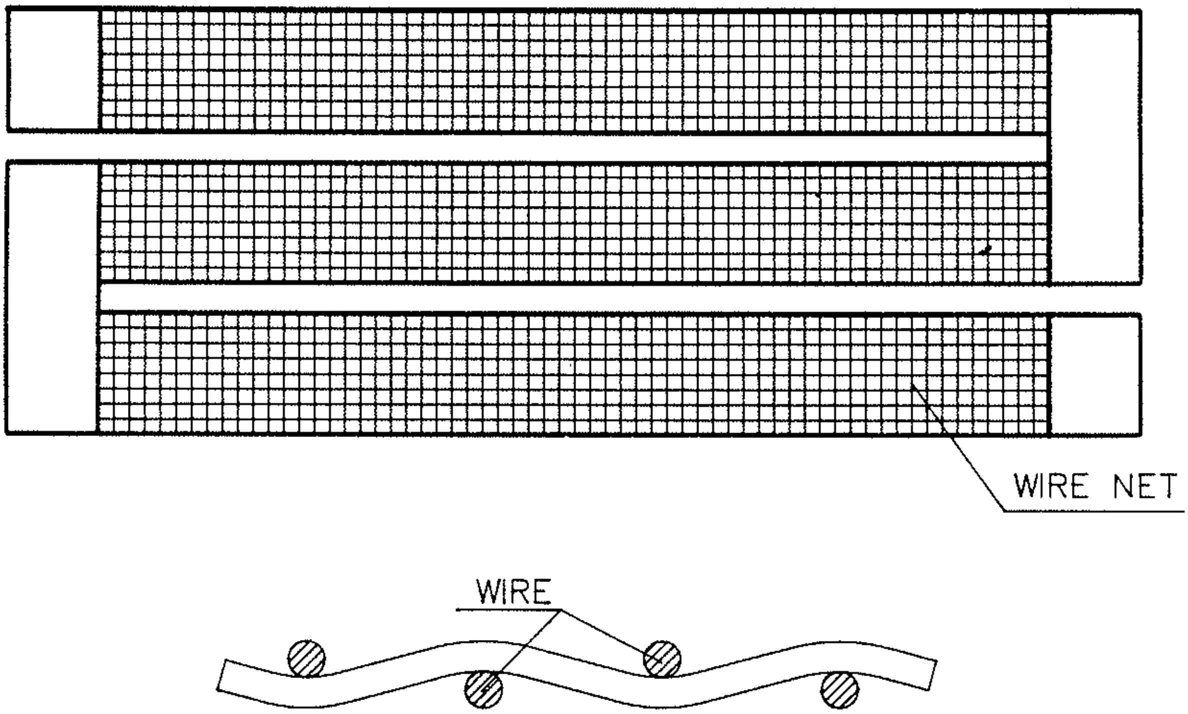


Fig. 12. NET HEATER

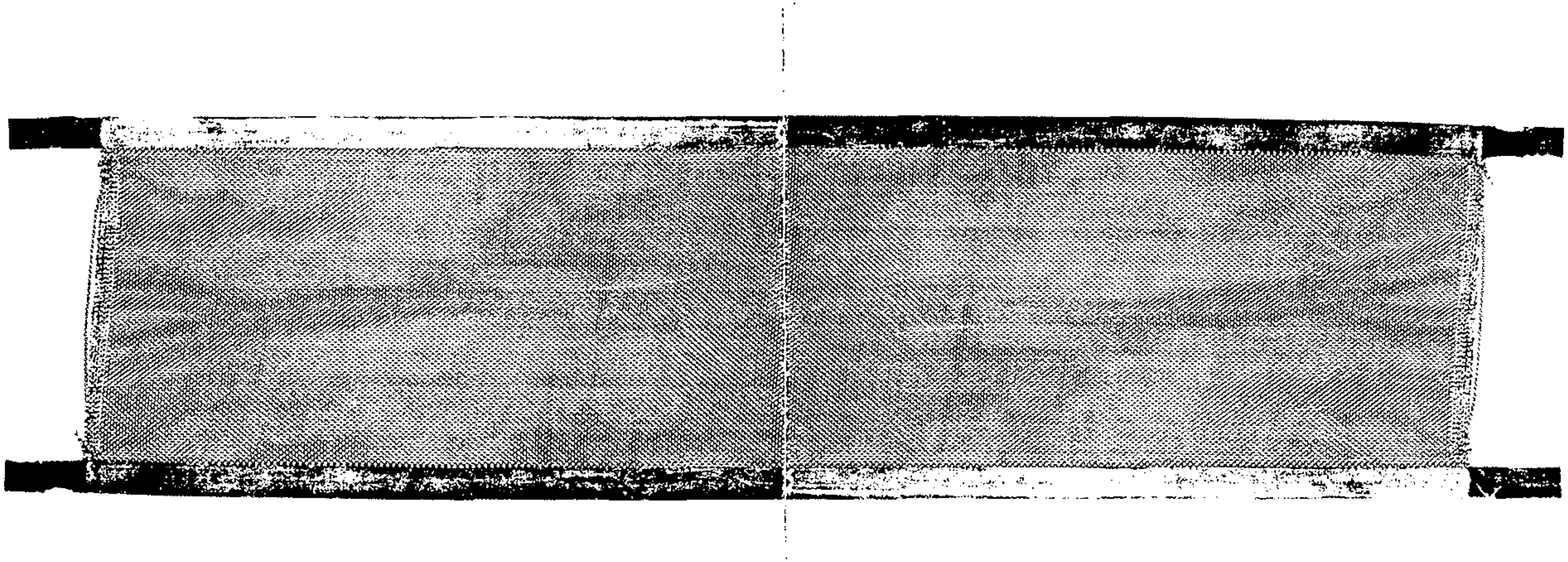


Fig. 13 ELECTRO-CONDUCTIVE FABRIC HEATER

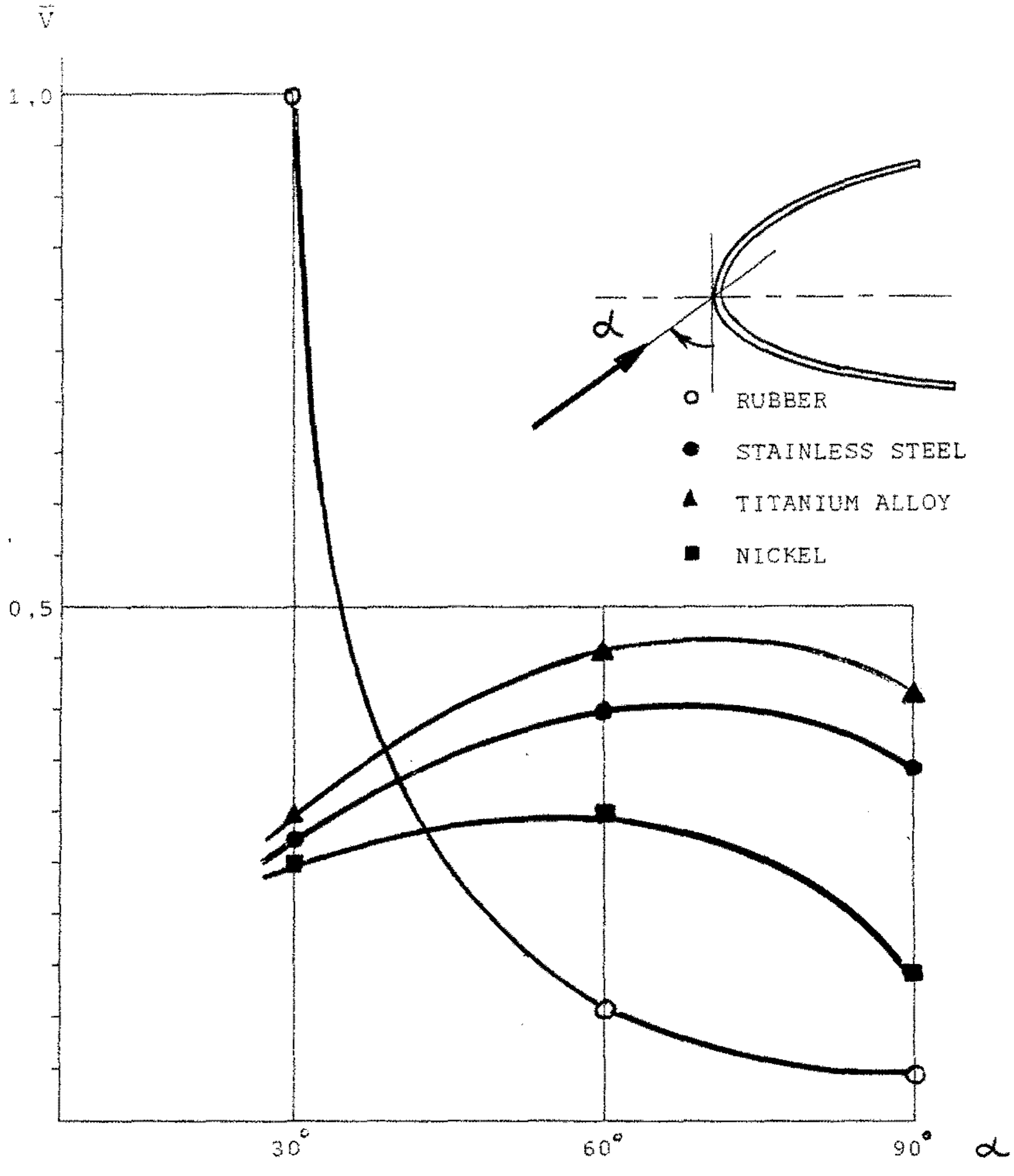
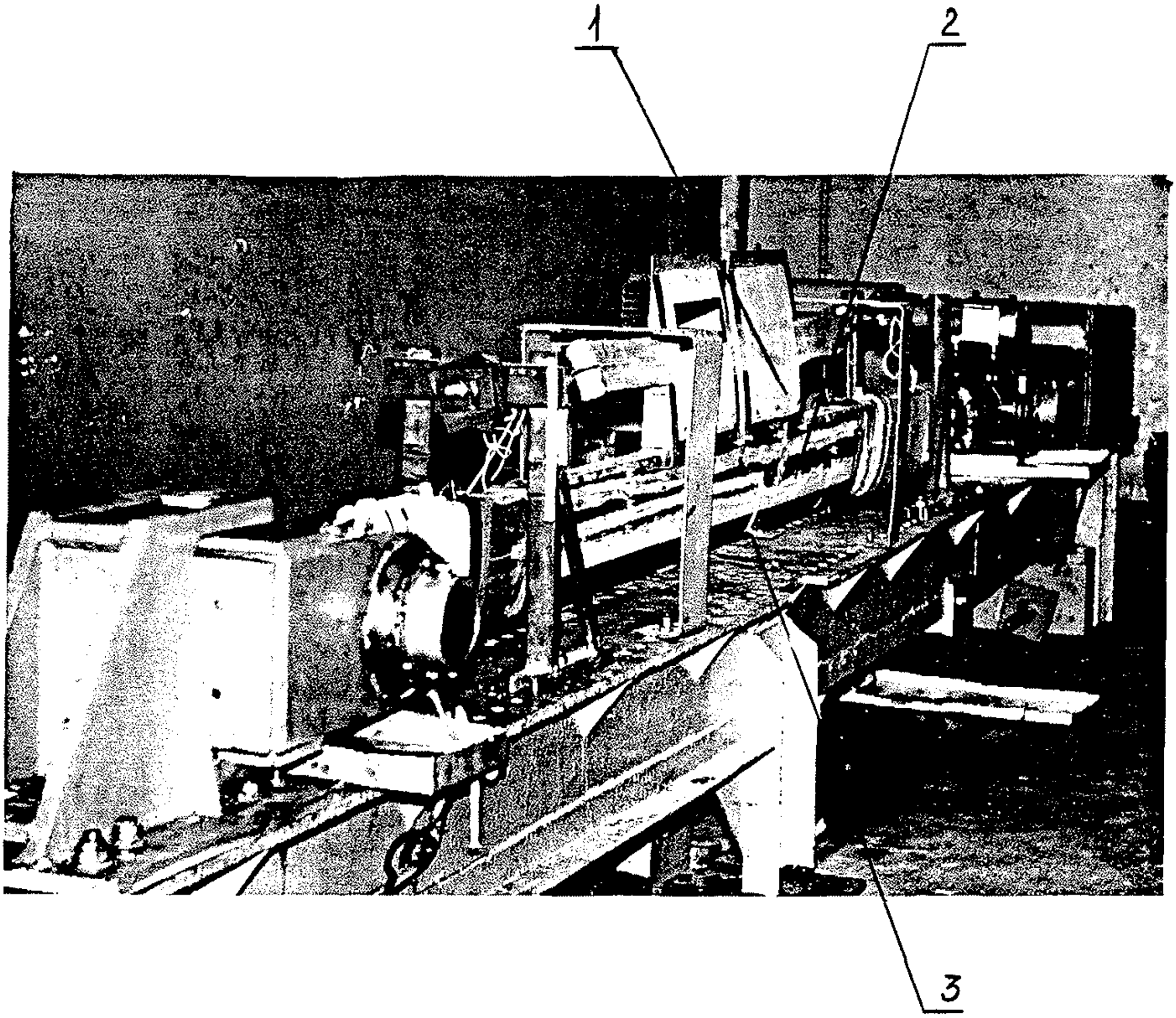


Fig. 14 THE RESULTS OF INVESTIGATION OF RESISTANCE PROPERTIES OF BLADE TIP PROTECTION

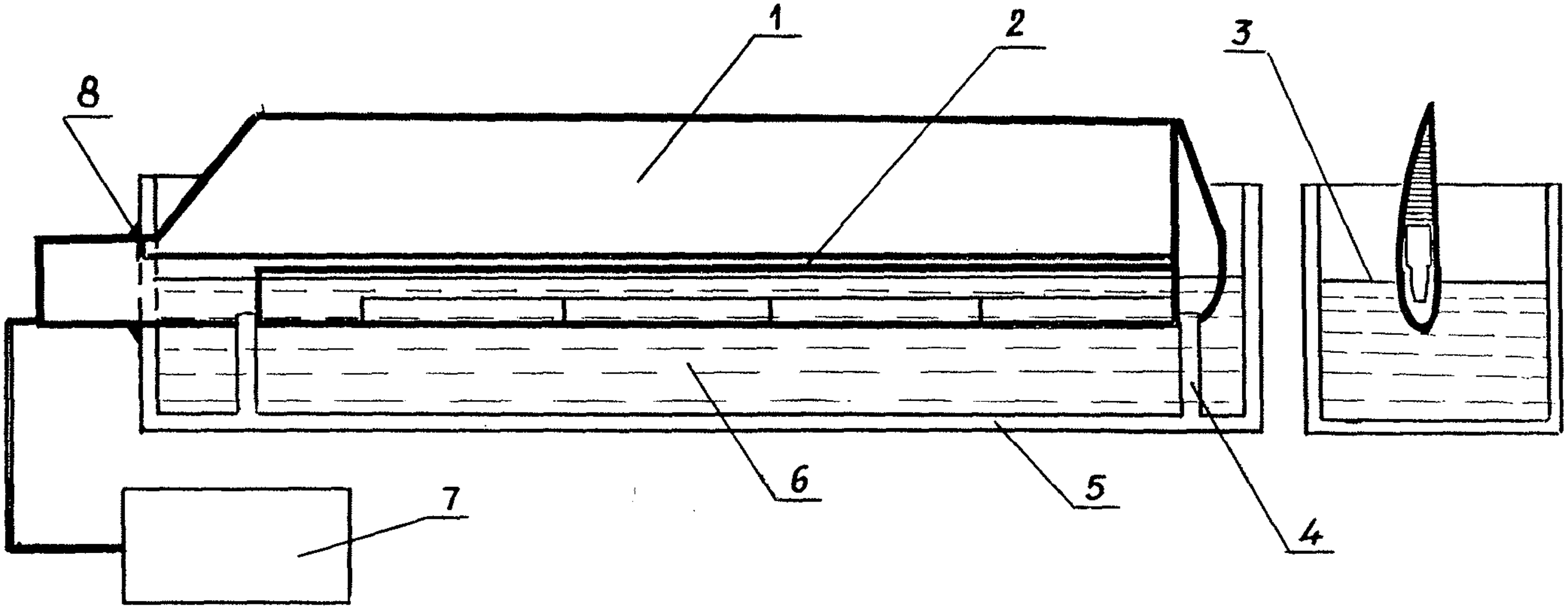
$\bar{V}$ - MASS CHARACTER OF WEAR

α - ANGLE OF ATTACK



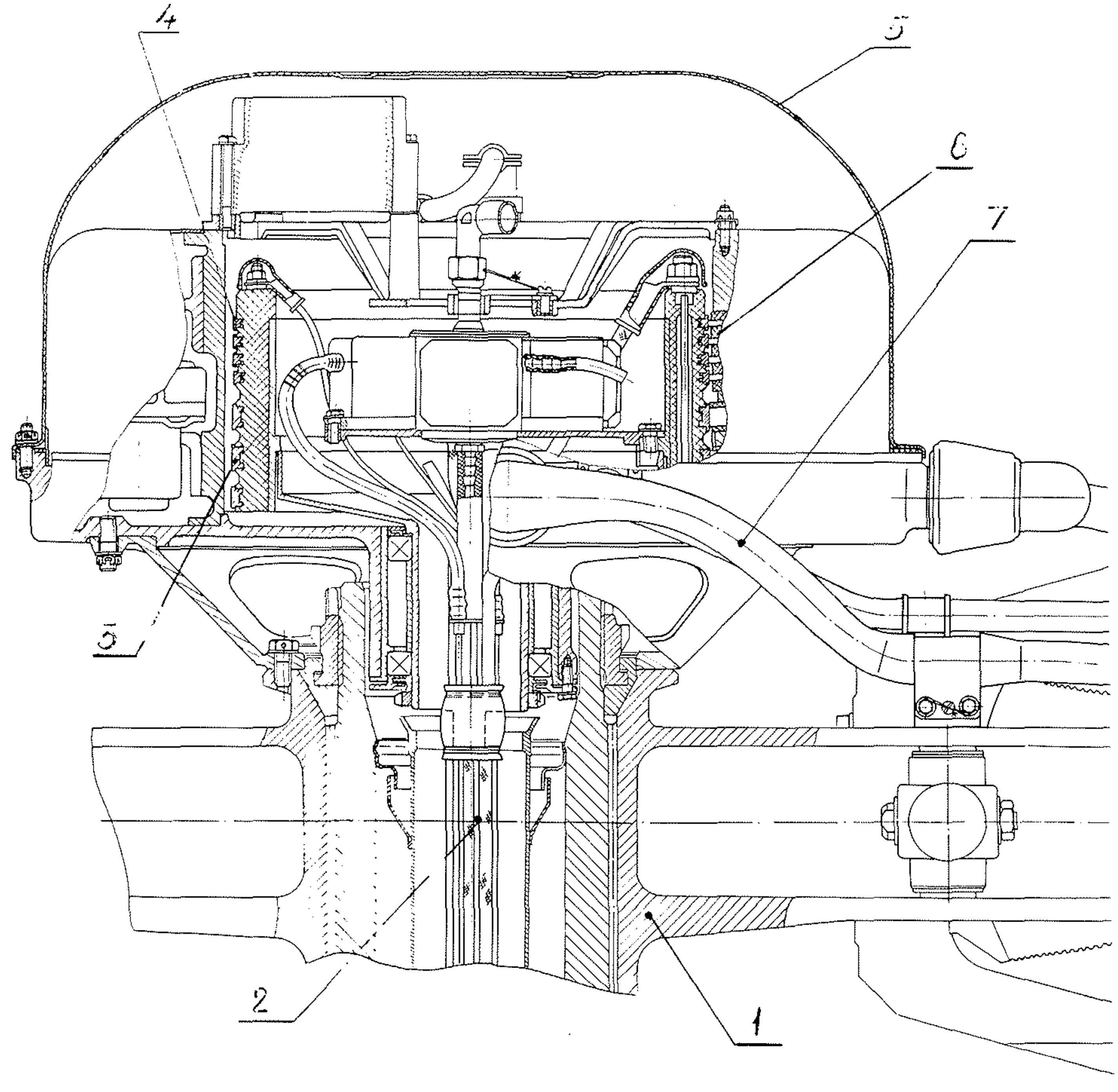
1. BLADE SAMPLE
2. THERMO-COUPLES
3. AIS STRAP

Fig. 15 DINAMIC TEST OF BLADE SAMPLE



1. BLADE
2. EDGE OF HEATING STRAP
3. WATER LEVEL
4. BLADE SUPPORT
5. BATH
6. COLD WATER
7. AIS CONTROL AND REGISTRATION EQUIPMENT
8. HERMETICAL SUPPORT

Fig. 16 THE BATH FOR TESTS OF BLADE AIS



1 - HUB
2 - POWER CABLE
3 - POWER RINGS
4 - CONTROL RINGS
5 - COWLING
6 - BRUSH CONTACTS
7 - FEEDER CABLE

Fig. 17 THE MAIN ROTOR CURRENT COLLECTOR

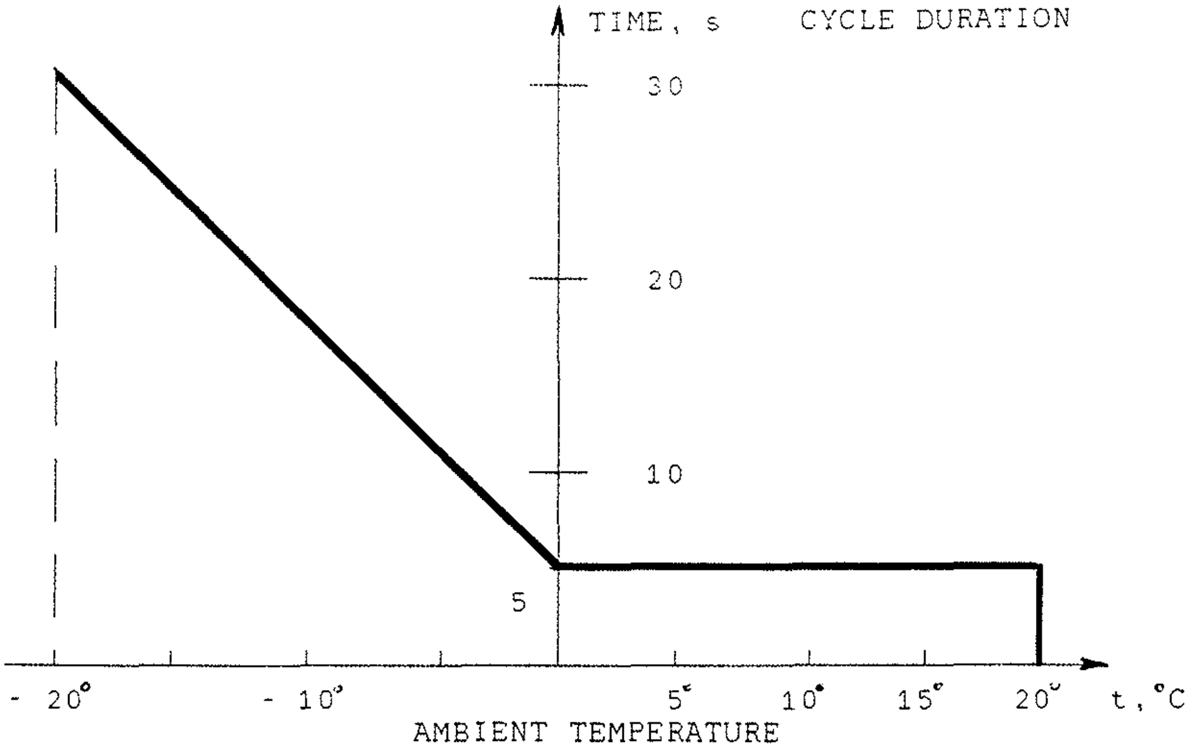
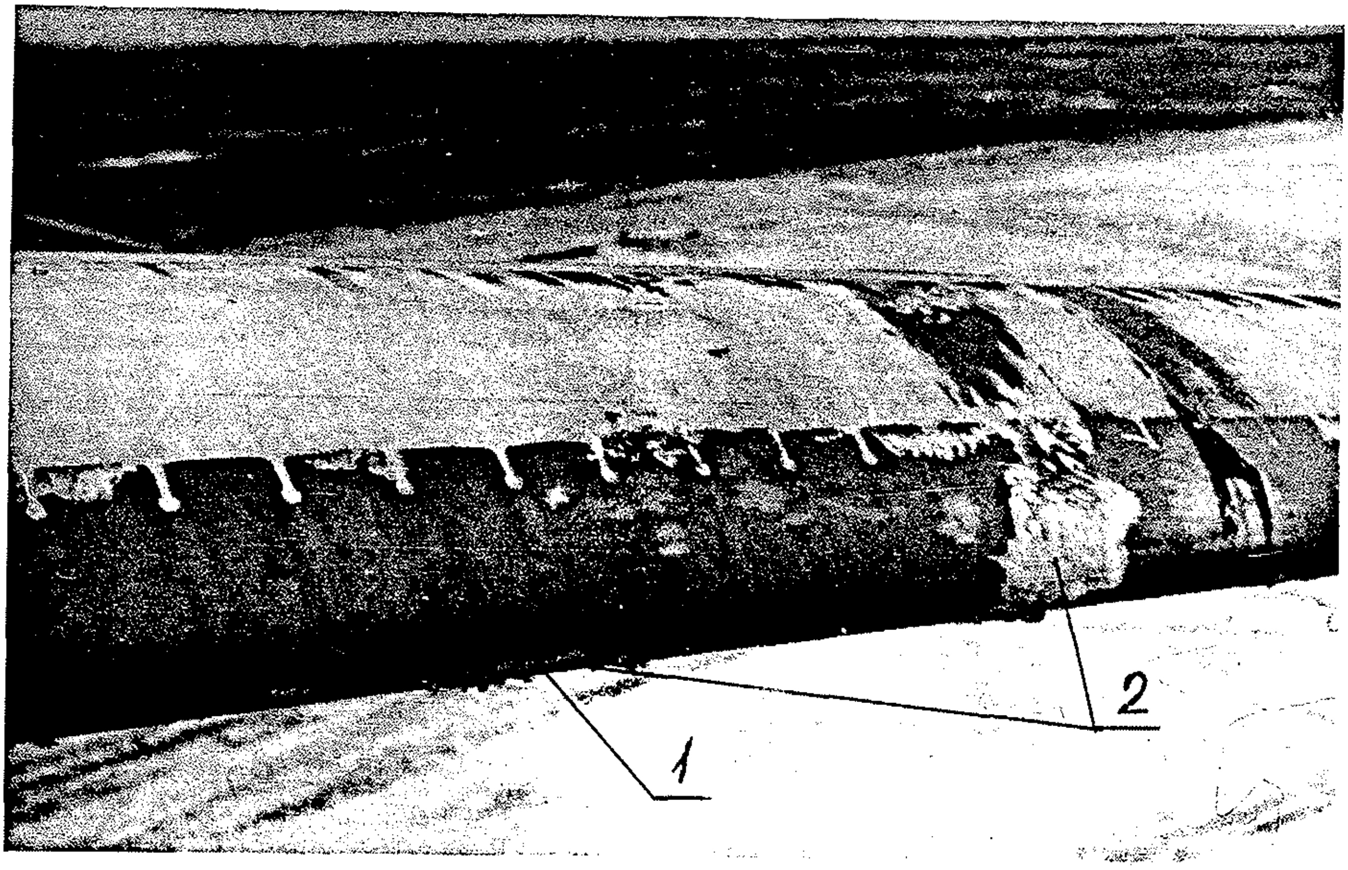
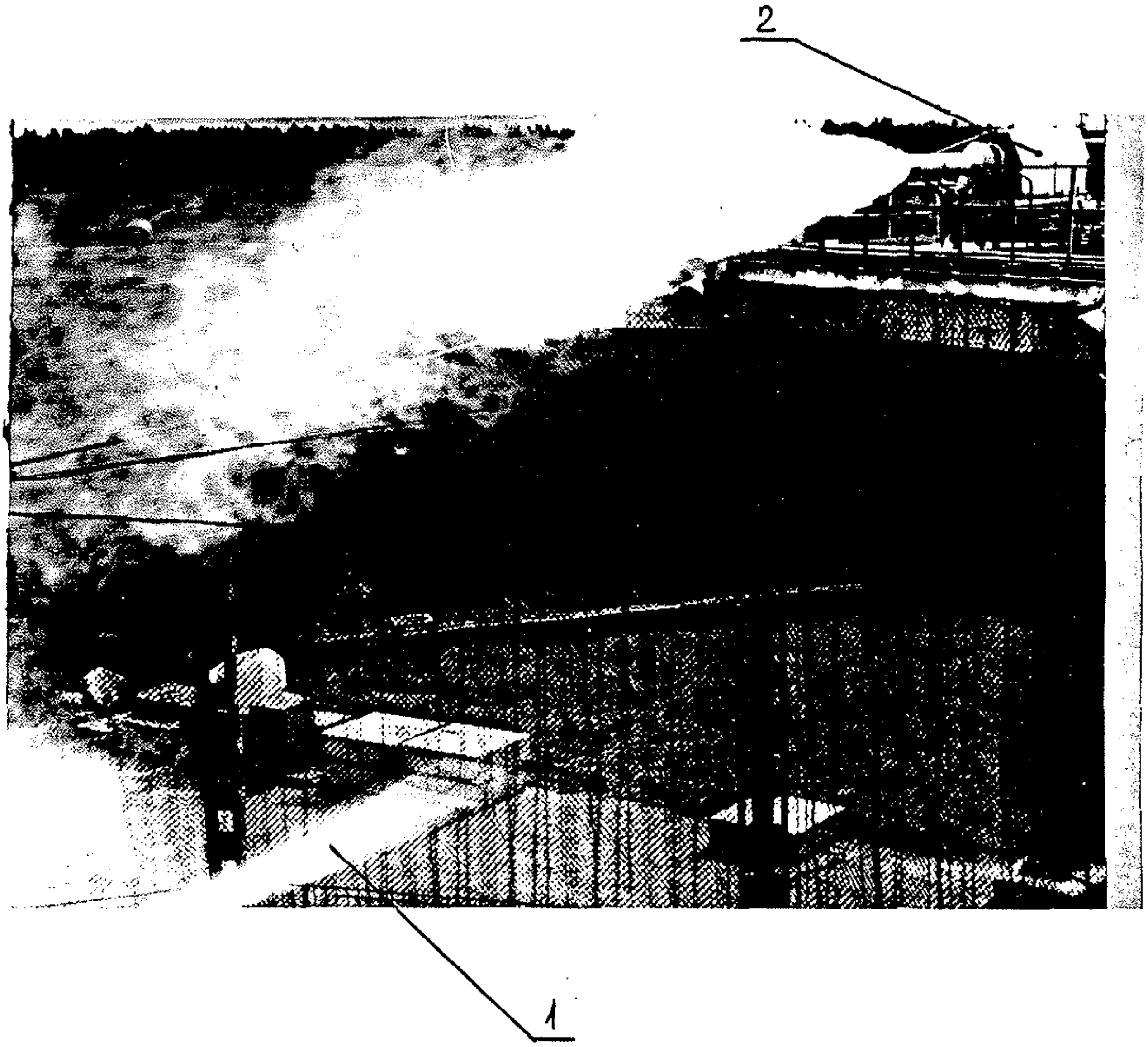


Fig. 18 DEPENDENCE OF CYCLE DURATION VS AMBIENT TEMPERATURE



1. MAIN ROTOR BLADE LEADING EDGE 2. ICE

Fig. 19 MAIN ROTOR BLADE AFTER FLIGHT TEST IN NATURAL ICING CONDITION



1. MAIN ROTOR   2. FOG-GENERATOR

Fig. 20 GROUND BENCH FOR LIFE-SIZE MAIN ROTOR TESTING IN ARTIFICIAL ICING

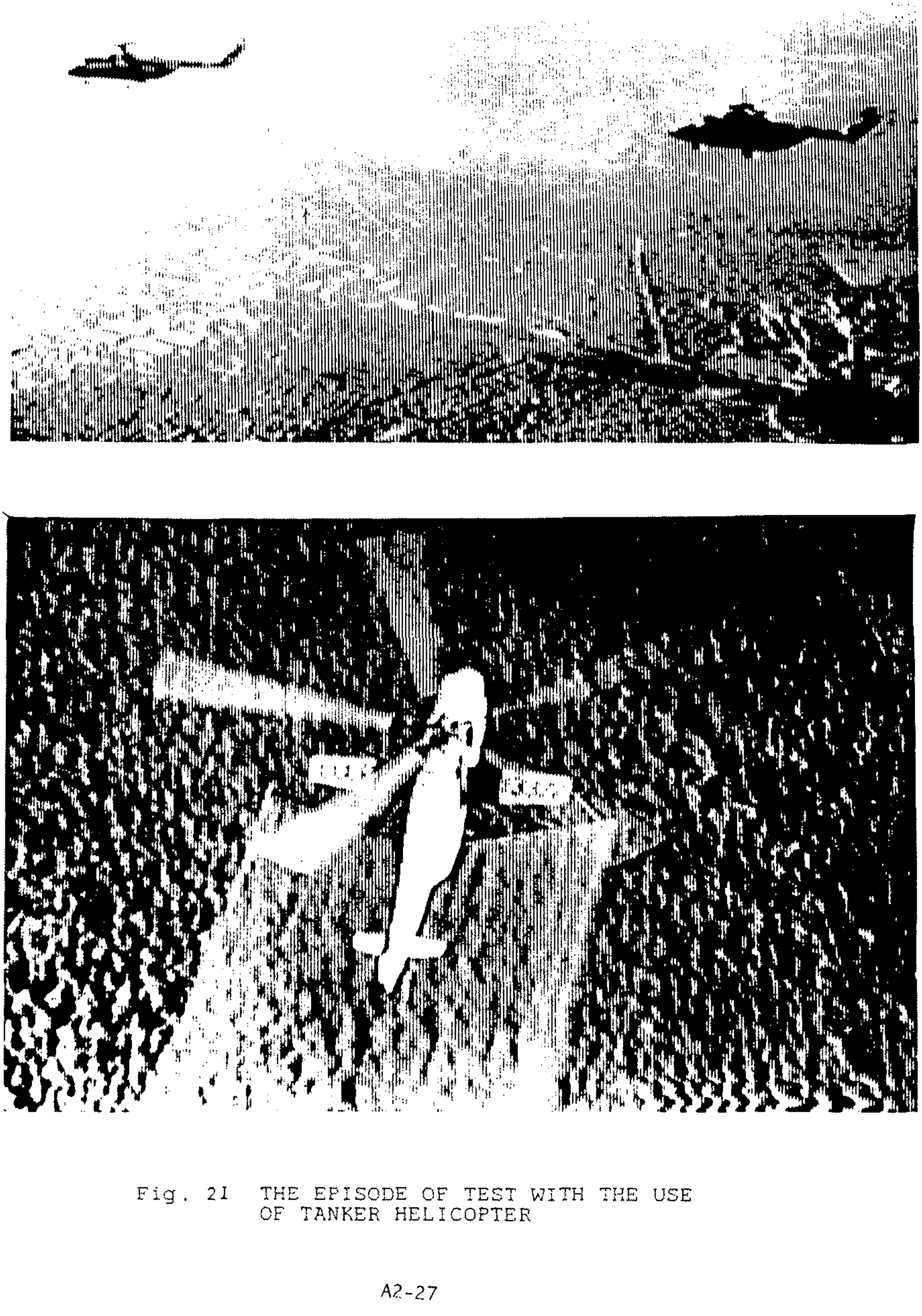


Fig. 21 THE EPISODE OF TEST WITH THE USE OF TANKER HELICOPTER