

June 3, 1952

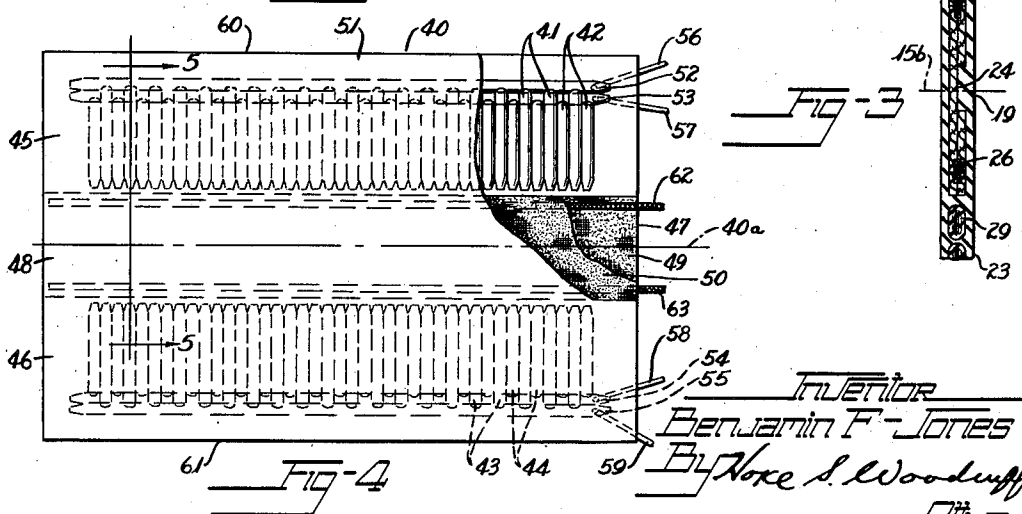
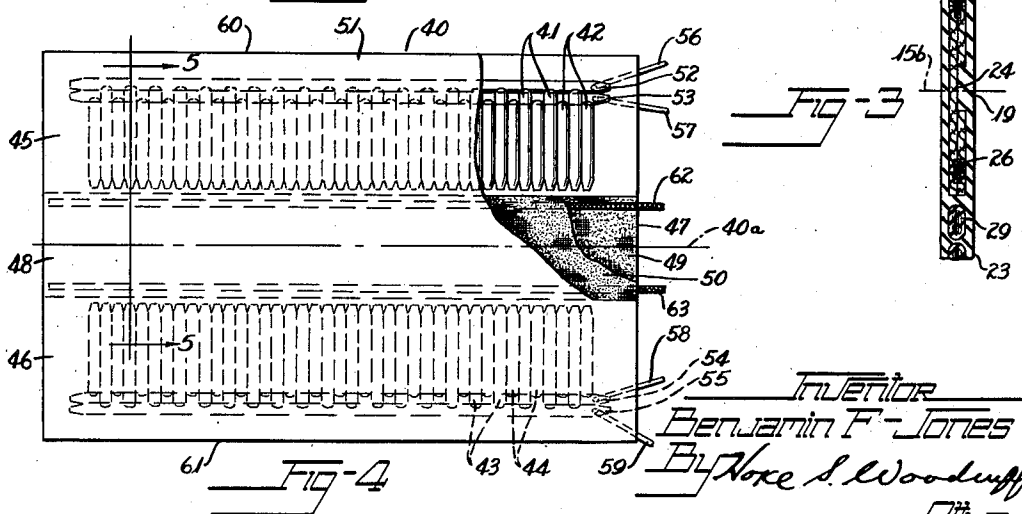
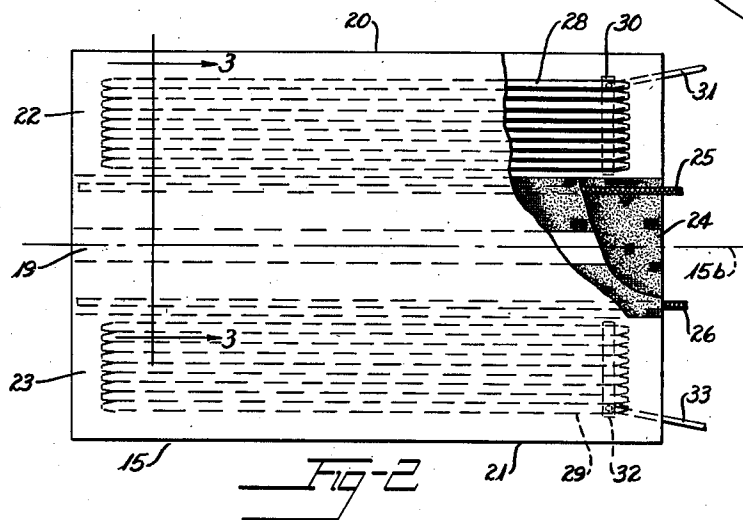
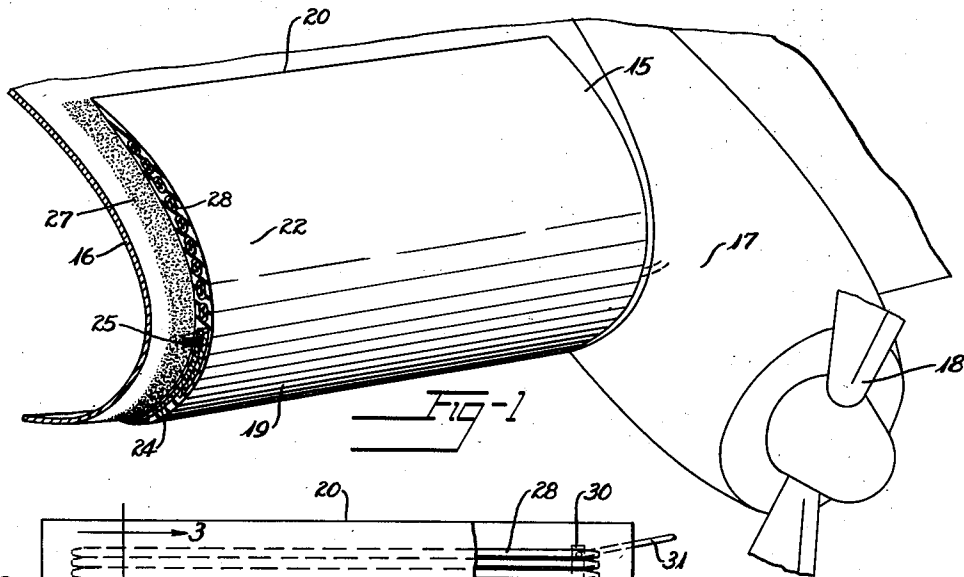
B. F. JONES

2,599,059

MEANS FOR PREVENTING ICE ACCUMULATION ON AIRFOILS

Filed July 31, 1945

2 SHEETS—SHEET 1



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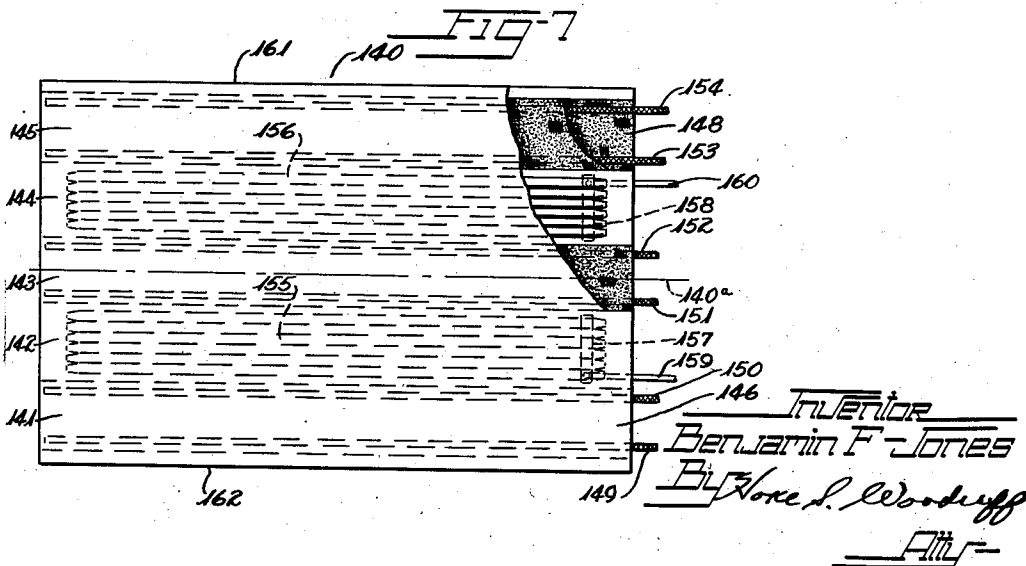
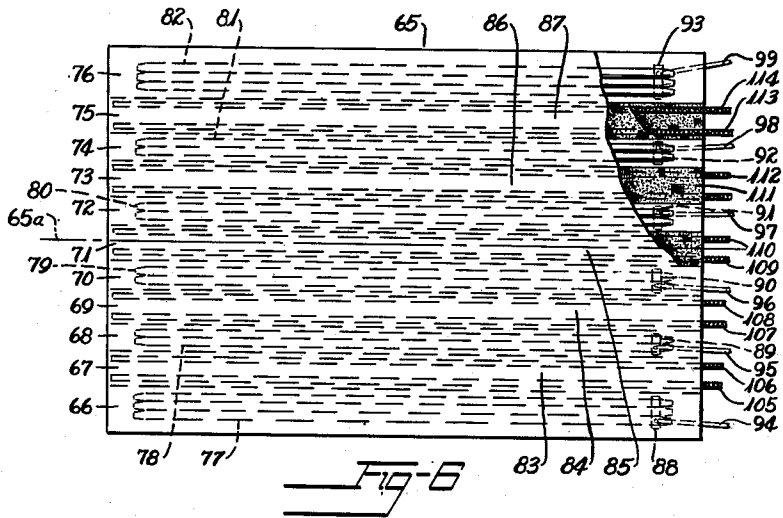
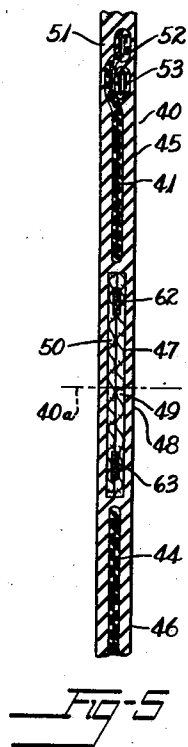
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MEANS FOR PREVENTING ICE ACCUMULATION ON AIRFOILS

Filed July 31, 1945

2 SHEETS—SHEET 2



UNITED STATES PATENT OFFICE

2,599,059

MEANS FOR PREVENTING ICE ACCUMULATION ON AIRFOILS

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Application July 31, 1945, Serial No. 608,066

9 Claims. (Cl. 244-134)

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The invention relates to protective coverings for preventing the accumulation of ice on the leading edges of airfoils and other exposed surfaces, and especially to such coverings having inflating and heating actions for ice-removal and prevention purposes.

Prior constructions of coverings generally having inflatable tubes in a central zone and stretchable portions extending rearwardly therefrom, have not been wholly satisfactory under some icing conditions in preventing objectionable ice-deposits on the leading edges of wings and other airfoils. Also, the prior inflatable coverings have been generally attached only along their margins to the wings or other airfoils thereby permitting objectionable lifting of intermediate portions of the coverings at regions of relatively low pressure rearwardly of the leading edges, and such coverings have presented the difficult problem of venting beneath the coverings to prevent objectionable bulging.

Prior constructions of coverings having heating action only for ice-removal purposes have likewise not been wholly satisfactory under some icing conditions in preventing objectionable ice-deposits thereon. Also, such heated coverings generally have one or more other disadvantages such, for example, as aerodynamic and thermal inefficiency, complicated and heavy construction, excessive electrical power requirement necessitating objectionably large and heavy generators, objectionable heat losses to the airplane structure, and objectionable "run-back" or "flow-back" of water from melted ice at the leading edge of an airfoil flowing rearwardly and refreezing on the covering aft of the heating zone.

Variation in the character of ice-deposits or formation such as glaze, rime or rime frost on the airfoils adds to the difficulty of effectively preventing the accumulation of ice at the leading edges, as each form of ice presents distinct problems of removal. Also, the bond of adhesion of the ice to the covering has been found to increase as the air temperature is decreased, i. e., relatively high adhesion is encountered at low temperatures, which further increases the difficulty of effective ice-removal for the several species of ice-deposits.

Objects of the invention are to provide for effectively overcoming such disadvantages and difficulties of the prior constructions and for promptly and thoroughly removing ice-deposits from the leading edges of airfoils and other exposed surfaces; to provide for combined inflating and heating actions effective in apparatus

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or protective coverings for ice-removal and prevention purposes; to provide for breaking the bond of types of ice which heretofore have been difficult to remove; to provide for a configuration of surface deformations together with a heated zone or zones in a covering for breaking and removing the ice-deposit thereon under a wide variety of icing conditions; to provide for stability of heating action at one or more zones; and to provide simplicity and thinness of construction, convenience of manufacture and installation and for effectiveness of operation.

Other objects of the invention are to provide for preventing the entrapment of air beneath the covering and the lifting of the covering away from the airfoil or other structure at regions of low pressure; to provide for overcoming "flow-back" to the rearward regions of such covering; and to provide for maintaining the aerodynamic characteristics of the airfoil.

More specific objects of the invention are to provide for distending and stretching a portion of the covering and for heating an adjacent portion of such covering; to provide for such distention and stretching at one or more spanwise-extending zones of the covering and for electrical heating at one or more other spanwise-extending zones of the covering; to provide for a surface-configuration of one or more portions of the covering including relatively small, curved-in-section ridges in closely adjacent parallel relationship to one another and arranged in series in the direction across such ridges; to provide such surface-configuration substantially throughout the whole extent of a distensible portion; to provide for cyclical distension and heating actions respectively at spaced-apart regions substantially throughout the whole extent of the covering; and to provide for heating temperatures at one or more zones of the covering effective for ice-removal and prevention purposes and/or in accordance with the thickness of the ice-deposit immediately at such zones.

These and other objects and advantages of the invention will be apparent from the following description.

In the accompanying drawings, which form a part of this specification, and in which like numerals are employed to designate like parts throughout the same:

Fig. 1 is a perspective view from above of a protective covering mounted upon the leading edge of a wing of an aircraft and constructed in accordance with and embodying the invention, parts being broken away;

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Fig. 2 is a plan view from above of the protective covering shown in Fig. 1 before its attachment to a wing, parts being broken away;

Fig. 3 is a sectional view taken along line 3—3 of Fig. 2, parts being broken away;

Fig. 4 is a view like Fig. 2 showing a modified construction of the protective covering shown in Figs. 1 and 2, parts being broken away;

Fig. 5 is a sectional view taken along line 5—5 of Fig. 4, parts being broken away;

Fig. 6 is a view like Fig. 2 showing another modified construction of the protective covering, parts being broken away; and

Fig. 7 is a view like Fig. 2 showing a further modification of the protective covering, parts being broken away.

To the ends of effectively removing ice deposited at the leading edge of an airfoil or other surface exposed to flow of air under icing conditions, the invention provides apparatus comprising a covering of elastic material for the leading edge having distending and stretching and heating actions intermediate opposite margins of the covering; and such apparatus includes means for locally distending and stretching the covering to a surface-configuration effective to loosen and break ice deposited thereon and means for heating the covering to temperatures effective for ice-removal purposes. The combined heating and distending and stretching actions of the covering cooperate in effecting ice-removal from such leading edge by providing sufficient heat to prevent the formation of ice and evaporate the water droplets, or by melting the ice at the bonded interface between the ice and the covering effectively breaking the adhesive bond of the ice, or by preventing the freezing of super-cooled water droplets at such heating zone, and also by stressing the ice deposit together with so distending the surface of said covering such that the bond of the ice at the distensible zone is broken effectively and the ice-formation loosened and/or broken for removal by the scavenging action of the flow of air across the covering. The distending action may coact additionally with the heating action in lifting the loosened ice-formation, especially at a rearward heating portion, and moving outwardly such ice into the airstream for removal purposes.

In an illustrative embodiment of the invention shown especially in Figs. 1, 2 and 3, the construction includes a covering 15 of elastic material such, for example, as resilient rubber or other rubber-like material 15a positionable about the leading edge of a wing 16 for an aircraft, which may be of the heavier-than-air type having one or more engines (not shown) mounted in one or more nacelles 17 for rotatively driving one or more propellers 18. The covering 15 may be positioned upon other surfaces of the aircraft such, for example, as the leading edges of the empennage members, propeller blades, struts, cowlings, masts, and other elements which it is desired to protect against the accumulation of ice.

The covering 15 includes a sheet-like body 15a of suitable resilient rubber material, fabric reinforced or unreinforced, having a central heating zone 19 extending spanwise of the covering substantially to chordwise margins and intermediate opposite spanwise margins 20, 21 and having spaced-apart distensible zones 22, 23 extending spanwise to such chordwise margins in substantially adjoining relation with the central heating zone, which distensible portions also ex-

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tend rearwardly from the central heating zone substantially to the respective spanwise margins 20, 21. The rubber material at the inner face of the covering desirably has heat and electrical insulating characteristics for minimizing heat losses by conduction to the material of the wing and for electrically isolating the covering from the wing.

At the central zone of the covering 15 is a flexible heating element 24 substantially coextensive therewith for producing the desired temperatures effective for ice-removal purposes. The heating element 24 is preferably imbedded in the rubber body 15a intermediate the inner and outer faces of the covering 15 as shown especially in Fig. 3, and facilitates obtaining effective and substantial stability of heating action throughout the central zone 19.

The heating element 24 is constructed preferably of stretch-resisting woven fabric sheet material of cotton, glass-fiber, nylon, rayon or other suitable filamentary material having the characteristics of little or no electrical conductivity, relatively high strength, and resistance to deterioration from heat. Electrically conductive resilient composition including suitable rubber-like material having particles of acetylene black, channel black, graphite or other suitable conductive substance therein, is coated or spread as in paste or semi-liquid form desirably on both sides of the woven fabric. Each coating is relatively thin and in electrical contact with the other by virtue of the penetration of such conductive composition through the interstices of the woven fabric and to some extent into the threads of the latter fabric. One or more thin coats or layers of the conductive composition may be spread in superimposed relation on the respective sides of the woven fabric sheet to provide the desired uniformity of thickness and uniformity of conductivity, whereby a finer adjustment of such conductivity may be obtained as compared to that obtained by painting or calendering the woven fabric with the conductive composition. Such construction of the heating element provides the desired stability of conductivity and also provides a highly flexible element for facilitating smooth conformance of the covering to the curvature of the wing or other airfoil and a heating element capable of being integrally bonded and united with the rubber body 15a of the covering.

The heating arrangement shown especially in Figs. 2 and 3 may have a double layer or thickness of fabric reinforced electrically conductive composition at spaced-apart rearward marginal regions of the zone 19 relative to the longitudinal center-line 15b of the covering 15 and a single layer or thickness of such conductive composition at an intermediate region immediately at such center-line, whereby relatively higher temperatures are provided at the central zone 19 along its intermediate region as compared to the temperatures at its marginal regions more remote from such centerline. In this manner, a heating action at the central zone 19 is provided in accordance with the varying thickness of the ice-formation, which may be in the form of a glaze ice-cap or rime ice formation, for example, both of which may be thicker at the stagnation zone or immediate leading edge region of the airfoil than at regions rearwardly thereof, or the heating action may be such as to maintain said intermediate region of the zone 19 free of ice and loosen the bond of ice deposited at said marginal regions

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for removal by the scavenging action of the airflow aft of the stagnation zone. It is to be understood that such differences in temperatures chordwise of the covering may be obtained, if desired, by varying the thickness or the specific conductivity of the conductive composition reinforced with only a single layer of woven fabric sheet material throughout the extent of the zone 19.

The double thickness construction described above is advantageous in promoting the secure attachment of flexible conductor elements 25, 26 to such heating element 24 between the two thicknesses of woven fabric and adjacent the spanwise margins of the central zone 19, in addition to protecting such flexible elements, especially during the molding and assembling of the covering.

The rubber covering 15 being flexible to conform to the profile of the wing 16 and being adhesively attached throughout its entire extent to such wing as by a suitable rubber cement 27 of the air-curing type, although, if desired, it may be marginally attached by known constructions, contracts and expands correspondingly with the contraction and expansion of the material of the supporting surface thereby avoiding the setting-up of objectionable stresses in such surface or wing; consequently the flexible elements or electrical conductors 25, 26 are, preferably, of stranded material and of flexible, relatively loosely-braided wire construction in substantially flat strip form for providing the desired flexibility, expansion and contraction characteristics. The braided conductor elements may be secured adhesively between the respective sheets of woven fabric material of the heating element 24 but such adhesive attachment may permit some lateral distortion and shifting of adjacent portions of each braided conductor during the molding and curing operations in the manufacture of the covering 15.

Such shifting occurs in opposite chordwise directions with respect to the longitudinal centerline 15b of the covering since the rubber material itself tends to flow away from such longitudinal centerline toward the spanwise margins. The lateral distortion and shifting of the conductors generally results in a heating zone having irregular, non-rectilinear or sinuous boundaries spanwise and having variable and different conductivity in spanwise adjacent portions of the heating zone.

Accordingly, for overcoming the objectionable shifting, the relatively loosely-braided conductor elements 25, 26 are desirably fixedly secured to the heating element 24 by stitching or sewing the conductor elements continuously along their extent, the sewing extending through and engaging both of the fabric reinforcements of the heating element 24 and the material of the conductor elements 25, 26. In the preferred construction, each conductor element is sewed along its inner margin with respect to the longitudinal centerline 15b of the covering and then additionally secured between the layers of the heating element 24 by a suitable conductive rubbery adhesive, which further bonds the wires of the braided conductor to the heating element 24. This arrangement resists effectively lateral shifting and distortion of the respective conductor elements 25 and 26 toward the spanwise margins 20, 21 and holds the conductor elements permanently in the desired spaced-apart relationship facilitating maintaining the desired stability and uniformity of temperatures in the heating zone 19.

It is to be understood that other temperature

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distributions of the heating zone than that described hereinabove may be provided and that other heating means such as electrical resistance wires may be used. For example, the conductivity characteristics of the respective conductor elements 25, 26, and the conductivity characteristics of the conductive composition (variable thickness and/or changes in the composition per se) of the heating element, or both may be varied, if desired, to provide uniformity of temperatures along the spanwise extent of the covering or to provide different or graduated temperatures along the same. Also, the conductivity characteristics of such conductors and/or composition may be varied to provide different or graduated temperatures in adjacent regions chordwise of the covering.

The specific construction described hereinabove for Figs. 2 and 3 makes possible spanwise uniform and higher temperatures at the intermediate region of the zone 19 than the spanwise uniform temperatures at the rearward marginal regions of the zone 19. The power dissipation of the heating element 24 at the central zone 19 may be, for example, approximately 3 to 6 watts per square inch for providing temperatures effective for ice-removal purposes despite the super-cooling action of the airflow across the covering and some heat loss by conduction to the wing. The conductor elements 25 and 26 are of opposite polarity and are connected to a suitable source of power and electrical control means, which source of power may be an electrical motor-generator disposed, for example, within the aircraft structure at any desired location.

The heating action at the zone 19 may be continuous (anti-icing and/or ice-prevention) or intermittent (de-icing and/or ice-removal) and some water droplets or water from melted ice or both may flow rearwardly over the distensible zones or portions 22, 23 of the covering 15 and refreeze thereon, generally in the form of glaze ice at relatively high temperatures. As a consequence of such "flow-back," the ice-formation at the distensible portions 22, 23 may be of relatively thin or thick sheet-like form, the ultimate thickness being dependent to some extent upon whether or not there is an initial deposit of ice prior to such "flow-back." To the end of effectively stressing and breaking the bond of the ice including "flow-back ice" deposited at the rearward regions of the covering and also for moving the loosened ice away from the wing to a position where the rapid laminar flow of air can dislodge the broken pieces, the invention provides in each distensible portion 22, 23 a plurality of inflatable tubes 28, 29 also imbedded in the rubber body 15a of the covering 15 between the inner and outer faces thereof, as shown especially in Figs. 2 and 3.

The inflatable tubes 28, 29 of the respective distensible portions 22, 23 each extend spanwise substantially throughout the extent of such portions. Such tubes extend desirably in closely adjacent parallel relation to one another having adjacent margins of adjacent tubes substantially adjoining one another, the spacing between adjacent tubes being preferably less than the width of one of such tubes. The walls of the tubes 28, 29 being of suitable resilient rubber material may have imbedded therein reinforcing material of suitable woven fabric, which fabric may be extensible or substantially inextensible, or may be cut on the bias to give a slight extensibility, if desired. The woven fabric reinforcement may

be of cotton, rayon, nylon or other suitable material.

While the construction shown in Figs. 1 to 3 has the inflatable tubes disposed to extend wholly in the spanwise direction, it is to be understood that such tubes may, if desired, extend wholly in the chordwise direction as shown especially in Fig. 4, or may be disposed in part chordwise and in part spanwise in any suitable arrangement thereof for obtaining the desired surface-configuration of the covering while maintaining the aerodynamic characteristics of the airfoil.

To the ends of obtaining the desired surface-configuration at the distensible portions 22, 23 such that the desired stretching and stress for breaking the bond of the ice to the covering is provided; and also for distending the covering so as to loosen the ice and lift the latter sufficiently into the airstream for its removal by the scavenging action of such airstream while avoiding objectionable turbulent flow across the wing or airfoil, the tubes 28, 29 are desirably relatively small in diameter as compared to the inflatable tubes of prior constructions. The small tubes are effective to break the bond of the ice to the surface in cases where such prior constructions have lacked full effectiveness.

As to the size of the tubes effective to produce the improved ice-removing action, satisfactory results may be obtained where the diameter of the tube passage is on the order of one-quarter ($\frac{1}{4}$) of an inch, and good results may also be obtained with tubes up to about one (1) inch in diameter. Tube sizes greater than about one inch may be less effective in removing strongly bonded ice for some icing conditions.

Each of the spanwise tubes 28, 29 in the upper and lower rearward distensible portions 22, 23 is preferably less than about one (1) inch in diameter and each tube may be of uniform bore throughout its length. Inflatable tubes within the designated dimensional range make possible distending and stretching the surface of the covering into a plurality of ridges having relatively small radius of curvature and cause relatively sharp changes of contour having a wash-board-like arrangement at such surface during inflation, whereby sufficiently severe, highly localized disrupting and stressing forces are applied to the adhered ice for breaking the bond of such ice to the covering and loosening and breaking the ice-deposit free from the covering. The smallness of the tubes is further advantageous in that they may be arranged close together so that an appreciable number of tubes are operative on a small zone of ice and diverse directions of the disrupting forces are obtained on a small area of ice spanning several adjacent tubes.

The improvement in the ice-removing action of the small tubes is noticeable especially where strongly adhered ice is deposited in a thin layer upon the surface of the covering; since with such small tubes, upon inflation and as soon as a crack in the ice develops, the rubber material stretches in the crack and a high stress-concentration at the edge of the ice-piece results. The stress imposed by the inflation of such small tubes is greater than the strength of the adhesive bond and such loosening action combined with the relatively sharp curvature of each ridge causes the rubber to peel away from the ice deposit, which action continues until the stress decreases to an extent such that the remaining stress in the rubber equals that of the strength of the adhesive bond. Such relatively high stressing

action of the small tubes combined with the relatively sharp curvature of the surface deformations effectively loosens and breaks the ice deposited. Also, the tubes being relatively small project, upon inflation, only a relatively short distance into the flow of air and create little or no aerodynamic disturbance.

While the respective series of inflatable tubes 28, 29 may, if desired, be arranged to have alternate tubes inflated simultaneously, all of the tubes for each distensible portion 22, 23, for the construction shown in Fig. 1, are desirably inflated simultaneously. If desired, each chordwise series of spanwise tubes for the respective distensible portions may be inflated in alternation with one another.

For inflating purposes, the series of inflatable tubes 28 beginning at the upper margin of the zone 19 and extending chordwise in the distensible portion 22 are in communication desirably at their inboard ends with an inflating manifold or conduit 30 of suitable reinforced rubber material extending in the chordwise direction across the tubes, and such manifold 30 is connected to a supply conduit 31 in communication with a source of air under pressure suitably located within the aircraft structure. The other chordwise series of inflatable tubes 29 beginning at the lower margin of the zone 19 are also desirably in communication at their inboard ends with an inflating manifold 32 of suitable material extending in the chordwise direction across such tubes, which manifold is connected to a supply conduit 33 in communication with the aforesaid source of air under pressure.

The fabric and rubber parts of the covering 15 are preferably united under vulcanization under heat and pressure. The respective spanwise margins 20 and 21 are preferably tapered in section for promoting smooth flow of air across the covering, as shown especially in Fig. 1.

The covering 15, which may be marginally attached, is attached desirably to the leading edge of the airfoil by being adhered to such wing 16 continuously throughout the extent of the covering by a suitable adhesive 27 such, for example, as rubber cement. Such a mounting arrangement has the advantages of permitting only substantially outward expansion of the inflatable tubes facilitating distending and stretching the distensible portions at the outer surfaces thereof each into a plurality of closely-adjacent parallel ridges relatively sharply curved-in-section, and of eliminating objectionable lifting of the covering from the airfoil at regions of low pressure rearwardly of the leading edge. The adhesive attachment also eliminates the necessity for additional marginal attaching structures such as metal reinforcing beads and fairing strips of prior constructions and the necessity for venting air from the space beneath the covering, thereby simplifying the construction of the covering and facilitating providing a covering of light-weight and thinness. Such construction and mounting facilitates providing a relatively smooth outer surface of the covering whereby objectionable protuberances, which promote the local formation of ice, are avoided.

In the operation of the protective covering 15, the heating action at the central zone 19, which may be continuous or intermittent, makes possible temperatures substantially uniform in the spanwise direction and varying chordwise in accordance with the thickness of the ice-deposit for effectively preventing the accumulation of

ice by preventing the formation of ice and evaporating the water droplets (greater temperatures, continuous heating) or by breaking the adhesive bond at the interface between the ice and the covering (lesser temperatures, intermittent heating) and dynamically unbalancing the ice at such zone for facilitating removal of the ice by the flow of air. The heating action at lesser temperatures by virtue of the insulating effect of ice relative to convection cooling of the covering by the airflow is effective for removing the various kinds of ice such as glaze ice, rime ice and rime frost, especially at the stagnation zone or immediate leading edge region of the airfoil.

"Flow-back" ice, which results from the melting of the ice at the central zone 19 and refreezing at the rearward distensible portions 22, 23, together with such ice-deposit as may be initially formed at such rearward portions, is removed upon inflation of the respective series of inflatable tubes 28, 29, which inflation also dynamically unbalances any loosened ice remaining at the central zone 19 facilitating the removal of the latter ice by the airflow. The simultaneous inflation of the tubes for each series thereof distends the surface of the covering into spanwise ridges of small radius of curvature at each rearward portion thereby imparting highly localized rupturing and stretching stresses at each of the tubes to the ice-deposit thereon effectively loosening such ice and lifting the same into the rapid laminar flow of air for removal by the scavenging action of such flow of air.

In some cases, the rearward ice at zones 22, 23 by virtue of its thickness and total strength, may be broken loose in the form of relatively large chunks. Due to the localized and high stressing action of the inflated tubes, only a relatively narrow bonded zone as compared to the tube width may remain at each of the tubes, the intermediate regions of ice between such latter zones being unadhered. The large chunks of ice, when lifted into the laminar flow of air, are blown away by the force of such flow of air. Such inflation of the tubes also lifts and dynamically unbalances any remaining loosened ice-deposit spanning the heating zone 19 for removal by the airflow. In this manner, the protective covering 15 effectively prevents the accumulation of ice upon the wing 16.

The modified construction 40 of the protective covering shown especially in Figs. 4 and 5 differs from the covering 15 in that inflatable tubes 41, 42 and 43, 44 at rearward distensible zones or portions 45, 46 are arranged such that they extend substantially parallel with one another in the chordwise direction, and in that a heating element 47 extending spanwise in a central heating zone 48 comprises two layers 49, 50 of suitable fabric reinforced conductive composition, each coextensive in length and width with one another and substantially coextensive with the heating zone 48, the heating element being disposed between the inner and outer faces of a suitable resilient rubber body 51 of the covering 49.

The inflatable tubes 41, 42 and 43, 44 are desirably each less than about one (1) inch in diameter and may be $\frac{1}{2}$ inch in diameter; and extend chordwise in substantially adjoining relation to one another throughout their extent, the space between adjacent margins of adjacent tubes being less than the width of one of such adjacent tubes. The chordwise tubes are arranged in series spanwise and all of the tubes of each series at each portion 45, 46 may, if desired, be inflated

simultaneously; but preferably, alternate tubes are inflated in alternation in a cyclical manner with the other tubes of each aforesaid series and to this latter end, inflating manifolds 52, 53 and 54, 55 are provided. Such manifolds are interconnected through conduits 56, 57 and 58, 59 with a suitable source of air under pressure for accomplishing such alternate inflation.

For example, at the distensible portion 45 the alternate inflatable tubes 41 are each in communication with the manifold 52 and the other tubes 42 are each in communication with the manifold 53. Similarly, the alternate tubes 43 at the distensible portion 46 are each in communication with the manifold 55 and the other tubes 44 are each in communication with the manifold 54. In this manner, alternating inflation of alternate tubes in each series may be accomplished for distending the surface of the covering into chordwise-extending ridges in closely-adjacent parallel relation with one another throughout their extent, the ridges being relatively small and generally rounded-in-section whereby the desired relatively high and localized stresses are imparted to the ice deposited thereon to loosen the ice for removal by the airstream. Such alternate inflation further provides a rocking action dynamically unbalancing the ice further facilitating its removal.

Since the stress created upon inflation of the tube increases in proportion to the rate of curvature of the tube wall, better removal of ice at such rearward portions, as compared to that of relatively larger tubes, is obtained with the small tubes having diameters within the designated range. Desirably, all of the tubes 41 to 44 are of uniform diameter relative to one another and throughout their extent, thereby promoting uniformity of ice-removal action. Such tubes also provide the desired lifting action for placing the ice into the path of the rapid laminar flow. The chordwise arrangement of the tubes is advantageous in minimizing turbulence of flow of air across the rearward portions 45, 46; since such tubes extend generally parallel with the direction of the laminar flow of air. Spanwise margins 60, 61 may be tapered in cross-section for facilitating smooth flow of air across the covering.

The heating element 47 at the central heating zone 48 comprises a pair of sheets 49, 50 of suitable electrically-conductive resilient composition having a suitable fabric reinforcement therein, the sheets being positioned in superimposed relation to one another and substantially coextensive with one another throughout the extent of such central zone 48. Suitable flexible braided conductor elements 62, 63 in substantially flat strip form are sandwiched between the sheets of conductive material and extend spanwise along the heating zone adjacent the opposite spanwise margins of such zone. The conductor elements 62, 63 are desirably fixedly secured in place as by a suitable adhesive and by sewing engaging the reinforcing material of the conductive sheets 49 and 50 and the material of the conductor elements 62, 63, such sewing preferably being along the inner margins of each conductor element 62, 63 with respect to the longitudinal center-line 40a of the covering, thereby effectively resisting lateral shifting and distortion of the conductor elements during the molding and curing operation. The heating element 47 is embedded in the resilient rubber body 51 between the inner and outer faces of the covering, as shown especially in Fig. 5. The respective fabric and rubber parts of the

covering 40 are united preferably by molding and vulcanizing under heat and pressure.

The covering 40, which also may be marginally attached, is desirably adhesively attached throughout its entire extent to the airfoil or wing 16, which attachment eliminates the problem of venting and facilitates outward bulging only of the inflatable tubes. Such bulging further promotes the desired sharpness of curvature of the ridges for effective removal of the ice.

In the operation of the covering 40, the heating action at a central zone may be continuous (anti-icing action) or intermittent (de-icing action), the temperatures at such zone 48 being effective for preventing the formation of ice and evaporating the water droplets, and/or for ice-removal purposes. The heating at the central zone 48 may be such that the temperatures may be varied or uniform in the spanwise and/or the chordwise directions, and for the construction shown, the temperatures are desirably uniform both spanwise and chordwise substantially throughout the entire extent of the heating zone 48. "Flow-back water" re-freezing at the distensible zones 45, 46 and any initial ice-deposit at such zones are removed by the cyclical inflation of the inflatable tubes which, by virtue of their action described hereinabove, effectively lift, loosen and break the ice for removal by the rapid laminar flow of air. Such inflation of the tubes also lifts and dynamically unbalances any remaining loosened ice-deposit spanning the heating zone 48 for removal by the airflow.

Another modified construction 65 of the protective covering, as shown especially in Fig. 6, has a plurality of alternately chordwise-arranged heating and distensible zones 66 to 76, inclusive, extending spanwise of the covering. Like the coverings 15 and 40, the covering 65 has a body of suitable resilient rubber material and includes inflatable tubes 77 to 82, inclusive, extending spanwise in the respective distensible zones or portions 66, 68, 70, 72, 74, 76 in closely-adjacent parallel relation to one another. The covering also includes heating elements 83 to 87 desirably of suitable resilient conductive composition having suitable fabric reinforcement therein extending spanwise at the heating zones or portions 67, 69, 71, 73 and 75, the respective heating elements each being desirably coextensive with the extent of each said heating portions. The respective distensible and heating zones are relatively narrow in width as compared to the distensible and heating zones of the coverings 15 and 40, thereby providing a plurality of narrow zones each effective for ice-removal purposes and each cooperating with one another to this end.

The inflatable tubes 77 to 82 are desirably relatively small in diameter, each being less than about one (1) inch in diameter. In the preferred construction, the opposite rearward distensible portions 66, 76 each include three inflatable tubes 77, 82 of uniform diameter, arranged in chordwise series and having adjacent margins of adjacent tubes substantially adjoining one another. The intermediate distensible portions 68, 70, 72, 74 each may have a pair of inflatable tubes 78, 79, 80, 81 of uniform diameter, similarly arranged, whereby all of the aforesaid tubes 77 to 82 inclusive make possible the desired surface configuration of ridges relatively small in curvature, arranged in chordwise series at spaced-apart positions across the covering.

The tubes for all of the distensible portions

may be of uniform size, or the tubes, by zones, may be of graduated and decreasing size in the rearward direction with respect to the longitudinal center-line 65a of the cover. For example, the adjacent innermost distensible portions 70, 72 may have tubes about one (1) inch in diameter, the other intermediate distensible portions 68, 74 may have tubes about three-quarter ($\frac{3}{4}$) inch in diameter, and the outer rearward distensible portions 66, 76 may have tubes about one-half ($\frac{1}{2}$) inch in diameter. Such tube arrangement is advantageous in facilitating removal of relatively heavy ice-caps at the immediate leading edge region of the wings together with effectively removing sheet-like ice formations rearwardly of the immediate leading edge region of the wings, while avoiding objectionable disturbance of the smooth flow of air across the covering, when such tubes are inflated. It will be appreciated that this arrangement using relatively small tubes is also effective in its ice-removal action; since the stress imparted to the ice is in proportion to the rate of curvature of the tube, under inflation, and such relatively high localized stretching and stresses at the respective spaced-apart distensible zones not only break the bond of the ice but also loosen the ice for removal by the airflow.

For inflating purposes, each group of tubes in the respective distensible portions is provided with an inflating manifold 88 to 93, inclusive, which manifolds are connected by suitable conduits 94 to 99, inclusive, to a suitable source of air under pressure. The arrangement is such that all of the tubes in each of the distensible portions are inflated simultaneously, and the respective groups of tubes in such distensible portions may be inflated simultaneously, or in alternation to one another with respect to the longitudinal center 65a of the covering, or in alternate sequence across the covering, or in any other desired manner.

The heating elements 83 to 87 inclusive, are imbedded in the rubber body of the covering 65 at the respective heating zones or portions 67, 69, 71, 73 and 75, each heating element being substantially coextensive in length and width with the extent of such heating portions for providing temperatures effective for ice-removal and/or ice-prevention purposes. Each heating element desirably includes a pair of superimposed layers of suitable electrically-conductive composition having a suitable fabric reinforcement therein, and each includes a pair of suitable flexible braided conductor elements 105 to 114, inclusive, extending spanwise adjacent the opposite margins of the distensible portions and sandwiched between the aforesaid layers. Each of the conductor elements 105 to 114 are fixedly secured as by a suitable adhesive and by sewing extending through the material of the fabric reinforcement and the material of the conductors per se, such sewing being disposed adjacent the inner margin of each conductor element with respect to the longitudinal center-line 65a of the covering for resisting lateral distortion and shifting of the conductor elements during the molding operation.

The opposite spanwise margins of the covering are desirably tapered in section to facilitate smooth flow of air across the covering. The rubber and fabric parts of the cover 65 are desirably united by molding and vulcanizing under heat and pressure. The covering 65 is also desirably adhesively attached to the wing substantially

continuously throughout the entire extent of the covering, advantageously eliminating the necessity for venting together with facilitating the desired light-weight, simplified construction.

In the operation of the covering 65, the heating elements may be operated continuously or intermittently and simultaneously or alternately, as desired, providing desirably uniform temperatures chordwise and spanwise throughout the extent of the heating zones, which temperatures may be different at different zones and are effective to prevent the formation or accumulation of ice, especially at the stagnation zone of the leading edge, and/or loosen the ice-deposits adhering to the covering at such heating zones. The inflation of the inflatable tubes loosens and breaks the ice at the respective distensible portions and also lifts loosened ice-formations spanning the respective heating zones into the path of the flow of air dynamically unbalancing the same for removal by such air. In this manner, the respective distensible and heating actions cooperate in effectively preventing the accumulation of ice on the covering 65.

A still further modified construction 140 of the resilient rubber protective covering, as shown especially in Fig. 7, includes a plurality of alternate heating and distensible zones 141 to 145 extending spanwise substantially throughout the entire extent of the covering, which zones or portions 141 to 145 may be relatively wide as compared to the zones of the construction 65 shown especially in Fig. 6. Each heating zone or portion 141, 143, 145 has a suitable heating element 146, 147, 148 of reinforced conductive composition desirably embedded in the rubber material of the covering for providing substantially uniform temperatures spanwise and chordwise throughout the entire extent of such heating portions, but the temperatures at the center element 147 may be higher than those at the rearward elements 146, 148. Also, each heating element is provided with a pair of spaced-apart flexible braided contactor elements 149—150, 151—152, 153—154, suitably fixedly secured as by sewing to such heating element, which sewing extends continuously along the inner margins of the conductor elements with respect to the longitudinal centerline 140a of the covering for preventing lateral shifting and distortion of such conductor elements.

Each distensible portion 142, 144 has a plurality of relatively small inflatable tubes 155, 156, each less than about one (1) inch in diameter, for providing the desired surface-configuration of ridges, upon inflation thereof. The inflatable tubes 155, 156 extend spanwise substantially throughout the entire extent of the distensible portions 142, 144 and are positioned such that adjacent margins of adjacent tubes are substantially contiguous with one another throughout their entire extent. For simultaneous inflating purposes, a suitable manifold 157, 158 is in communication with each chordwise series of inflatable tubes. The manifolds 157, 158 are connected to a source of air under pressure by suitable conduits 159, 160 in communication with such manifolds.

The covering 140 may have spanwise margins 161, 162 tapered in section and may be adhesively attached throughout its entire extent to the airfoil. When so mounted on the airfoil, the covering 140 is arranged such that the central heating zone 143 is at the stagnation zone or immediate leading edge region of such airfoil.

In the operation of the covering 140, the heating zones may be heated continuously or intermittently as described hereinabove, and have desirably substantially uniform temperatures throughout the heating zones for effective ice-removal purposes. Intermittent operation of the heating zones at relatively low temperatures eliminates the problem of "flow-back." Each series of tubes 145, 146 may be inflated intermittently or coincidentally and in a cyclical manner. Such inflation of the tubes provides the desired surface-configuration having a plurality of relatively small sharply-curved-in-section ridges in closely-adjacent parallel relation to one another throughout their extent. The ice-removing action of the tubes is substantially like that described for the inflatable tubes of the protective covering 20.

The invention thus makes possible new and useful protective coverings of elastic material having various arrangements of heating and distensible zones, which coverings are effective in preventing the accumulation of ice on the leading edges of airfoils by virtue of the cooperative action of their elements in a new relationship. The invention also makes possible the selection of a particular covering arrangement best fitted to cope with one or more kinds of icing conditions, which may be encountered in the operation of aircraft; and the selection of a particular covering arrangement best fitted to cope with the ice-formations which occur on streamline bodies or airfoils of different profiles and thicknesses. Such coverings also have further advantages in that they facilitate the provision of smooth surfaces about the leading edge, eliminate the difficult problem of venting, facilitate the attachment to the airfoil, and which are characterized by their thinness and light-weight construction and convenience of manufacture.

Variations may be made without departing from the scope of the invention as it is defined in the following claims.

I claim:

1. Apparatus for preventing the accumulation of ice on the leading edge of an airfoil, said apparatus comprising a unitary covering member having at least one spanwise-extending distensible surface portion for disposition at a rearward area of said leading edge and one spanwise-extending non-distensible portion adjacent the first said portion for disposition at the frontal area of said leading edge, the distensible portion comprising a plurality of spanwise-extending inflatable tubular passages each less than about one inch in diameter disposed in said member in closely adjacent parallel relation one to another inflatable to provide under inflation a plurality of sharply curved spanwise-extending ridges at the surface of said distensible portion for breaking the adhesive bond of overlying ice at said rearward area of the leading edge, means for inflating said tubular passages to distend said surface of the distensible portion into said spanwise-extending ridges without distending the adjacent non-distensible portion, and means in and constituting a part of said non-distensible portion of said member for heating the surface thereof at said frontal area to interrupt the continuity of ice deposited on said member.

2. Apparatus for preventing the accumulation of ice on the leading edge of an airfoil, said apparatus comprising a unitary covering member having at least one spanwise-extending distensible surface portion for disposition at a rear-

ward area of said leading edge and one spanwise-extending non-distensible surface portion adjacent the first said portion for disposition at the frontal area of said leading edge, the distensible portion comprising a plurality of chordwise-extending inflatable tubular passages each less than about one inch in diameter disposed in said member in closely adjacent parallel relation one to another inflatable to provide under inflation a plurality of sharply curved chordwise-extending ridges at the surface of said distensible portion for breaking the adhesive bond of overlying ice at said rearward area of the leading edge, means for inflating said tubular passages to distend said surface of the distensible portion into said chordwise-extending ridges without distending the adjacent non-distensible portion, and means in and constituting a part of said non-distensible portion of said member for heating the surface thereof at said frontal area to interrupt the continuity of ice deposited on said member.

3. Apparatus for preventing the accumulation of ice on the leading edge of an airfoil, said apparatus comprising a unitary covering member having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate the first said portions for disposition at the frontal area of said leading edge, a plurality of inflatable tubular passages in said member at each of said distensible portions for inflating the latter and distending the surface thereof in said rearward areas without distending the intermediate portion of said member, and electrical heating means in and constituting a part of said intermediate portion of said member for heating the surface thereof to interrupt in the region of said intermediate portion the continuity of ice deposited on said member.

4. Apparatus for preventing the accumulation of ice upon the leading edge of an airfoil, said apparatus comprising a unitary covering member of resilient rubber-like material having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate said portions for disposition at the frontal area of said leading edge, a plurality of spanwise-extending inflatable tubes each less than about one inch in diameter disposed in said member at each of said distensible portions in closely adjacent parallel relation one to another throughout their extent for distending the surface of the distensible portions in said rearward areas into a plurality of sharply curved ridges to loosen ice rearwardly of said frontal area without distending the surface of the intermediate portion, and electrical heating means incorporated in the rubber-like material of said intermediate portion of said member for heating the surface at said frontal area to interrupt the continuity of ice deposited on said member.

5. Apparatus for preventing the accumulation of ice upon the leading edge of an airfoil, said apparatus comprising a unitary covering member of resilient rubber-like material having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate said portions for disposition at the frontal area of said leading edge, a plurality of chordwise-extending inflatable tubes each less than about one inch in diameter disposed in said member at each of said distensible portions in

closely adjacent parallel relation one to another throughout their extent for distending the surface of the distensible portions in said rearward areas into a plurality of sharply curved ridges to loosen ice rearwardly of said frontal area without distending the surface of the intermediate portion, and electrical heating means incorporated in the rubber-like material of said intermediate portion for heating the surface at said frontal area to interrupt the continuity of ice deposited on said member.

6. Apparatus for preventing the accumulation of ice on the leading edge of an airfoil, said apparatus comprising a unitary covering member of resilient rubber-like material having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate the first said portions for disposition at the frontal area of said leading edge, a plurality of inflatable tubes in said member at each of said distensible portions for inflating the latter and distending the surface thereof in said rearward areas without distending the intermediate portion of said member, said tubes at each distensible portion extending in closely adjacent parallel relation one to another along their extent and being less than about one inch in diameter and inflatable to provide a plurality of sharply curved ridges at the surface of each of said distensible portions to loosen ice rearwardly of said frontal area, and a heating element incorporated in the rubber-like material of said intermediate portion of said member for heating the surface at said frontal area to interrupt the continuity of ice deposited on said member, said heating element comprising electrically conductive composition of resilient rubber-like material having particles of conductive substance therein.

7. Apparatus for preventing the accumulation of ice upon the leading edge of an airfoil, said apparatus comprising a unitary covering member of resilient rubber-like material having a series of spanwise-extending distensible surface portions spaced-apart chordwise for disposition at the rearward areas of said leading edge and a series of spanwise-extending non-distensible surface portions intermediate the distensible portions for disposition of a non-distensible portion at the frontal area of said leading edge, a plurality of spanwise-extending inflatable tubes each less than about one inch in diameter disposed in said member at each of said distensible portions in closely adjacent parallel relation one to another throughout their extent and inflatable to provide a plurality of sharply curved ridges at the surface of each distensible portion, means for inflating said tubes to distend the surface of said distensible portions in said rearward areas into said ridges to loosen ice rearwardly of said frontal area without distending the surface of the intermediate portions; and a heating element incorporated in the rubber-like material of each of said intermediate portions of said member for heating the surface thereof including that at said frontal area to interrupt in the region of each of said intermediate portions the continuity of ice deposited on said member, said heating element comprising electrically conductive composition of resilient rubber-like material having particles of conductive substance therein.

8. Apparatus for preventing the accumulation of ice upon the leading edge of an airfoil, said apparatus comprising a unitary covering mem-

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ber having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate said portions for disposition at the frontal area of said leading edge, means imbedded in the intermediate non-distensible portion of said member for heating the surface at said frontal area to interrupt the continuity of ice deposited about the leading edge, and a plurality of inflatable tubular passages in said member at each of said distensible portions for distending the surface in said rearward areas to loosen ice rearwardly of the interruption in the ice at said frontal area.

9. Apparatus for preventing the accumulation of ice upon the leading edge of an airfoil, said apparatus comprising a unitary covering member of elastic material having distensible surface portions spaced-apart for disposition at the rearward areas of said leading edge and a non-distensible surface portion intermediate said portions for disposition at the frontal area of said leading edge, electrical heating means im-

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bedded in the elastic material of the intermediate non-distensible portion of said member for heating the surface at said frontal area to interrupt the continuity of ice deposited about the leading edge, and a plurality of spanwise-extending inflatable tubular passages in said member at each of said distensible portions for distending the surface in said rearward areas to loosen ice rearwardly of the interruption in the ice at said frontal area.

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