Article by Alexander Graham Bell, October 11, 1910

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1910, Oct. 11, Beinn Bhreagh Recorder EDITORIALS AND ARTICLES A FEW NOTES OF PROGRESS IN THE CONSTRUCTION OF AN AERODROME, WITH AN HISTORICAL INTRODUCTION By Alexander Graham Bell

(The following article has been found preserved in Dr. Bell's presscopy book for 1906–1907, pp. 4–34. M.B.McC.)

Historical Introduction

The history of Aerial Locomotion is full of tragedies; and this is especially true where flying-machines are concerned. Men have gone up in balloons and most of them have come down safely. Men have launched themselves into the air on wings, or flying-machines, and most have met with disaster to life or limb.

There have been centuries of effort to produce a machine that should fly like a bird, and carry a man whithersoever ha? willed through the air; and previously to 1783, the year sacred to the memory of the brothers Montgolfier, all experiments at aerial locomotion had this end exclusively in view.

Then came a period when the conquest of the air was sought through the agency of balloons. For more than one hundred years the efforts of experimenters were chiefly directed to the problem of rendering the balloon dirigible; and the earlier experiments with gliding machines, and artificial wings — and the attempts of men to drive heavy bodies through 151 the air by means of propellers actuated by steam power— were largely forgotten.

The balloon was changed from its original spherical form to a shape better adapted for propulsion and through the efforts of Santos Dumont we have arrived at the dirigible balloon of today: But in spite of the dirigibility of the modern balloon, it has so far been found impracticable to impart to this frail structure a velocity sufficient to enable it to make headway against anything but the mildest sort of wind. The character of the balloon problem has, therefore, changed. Velocity of propulsion rather than dirigibility, is now the chief object of research.

It has long been recognized by a growing school of thinkers, that an aerial vehicle, in order to cope with the wind, should be specifically heavier than the air through which it moves.

This position is supported by the fact that all of Nature's flying models, from the smallest insect to the largest bird, are specifically heavier than the air in which they fly most of them many hundreds of times heavier— and that none of them adopt the balloon principle in flight.

It is also significant in this connection that some of Santos Dumont's most celebrated exploits were accomplished with quite a small balloon, so ballasted as to sink in the air instead of rise. He was then enabled, under the influence of his motive power, to steer his balloon upwards without the expenditure of ballast, and to descend without the loss of gas.

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This probably typifies the direction of change in the future. A reduction in the volume of gas, co-incidently with an increase in motive power, will lead to greater velocity of propulsion — now the main desideratum. Then, dependence upon velocity for support rather than gas, may gradually lead to the elimination of the gas-bag altogether:— In which case the balloon will give birth to a flying-machine of the heavier-than-air type.

However this may be it certainly is the case that the tendency of aerial research is today reverting more and more to the old lines of investigation that were pursued for hundreds of years before the invention of the balloon diverted attention from the subject.

The old devices have been re-invented. The old experiments have been tried once more. Again the birds are recognized as the true models of flight; and again men have put on wings — but this time with more promise of success.

Lilienthal boldly launched himself into the air in an apparatus of his own construction having wings like a bird, and a tail for a rudder. Without any motor he ran down hill against the wind; and then, upon jumping into the air, he found himself supported by his apparatus, and glided down hill at an elevation of a few feet from the ground landing safely at the bottom at a considerable distance from his point of departure.

This exhibition of gliding flight fairly startled the world, and henceforth the experiments of Lilienthal were conducted 153 in the public eye. He made hundreds of successful flights with his gliding machine varying its construction from time to time and communicating to the world the results of his experiments, with practical directions how to manage the machine under circumstances of difficulty; so that, when at last he met with the usual fate of his predecessors in this line the experiments were not abandoned, but were continued in America by Chanute of Chicago, Herring, and other Americans, including the Wright Brothers of Dayton, Ohio.

Hargrave of Australia attacked the flying-machine problem from the standpoint of a Kite, communicating his results to the Royal Society of New South Wales. It is to him we owe the modern form of Kite known as the “Hargrave Box Kite,” which surpasses in stability all previous forms of Kite. He also constructed successful flying-machine models on a small scale using a store of compressed air as his motive power. He did not attempt to construct a large sized apparatus, or to go up into the air himself,— so he still lives, to carry on researches that are of interest and value to the world.

No one has contributed more to the modern revival of interest in flying-machines of the heavier-than-air type than our own Prof. Langley, Secretary of the Smithsonian Institution, who has just passed away from our midst.

The constant failures, and disasters of the past had brought into disrepute the whole subject of aerial flight by man, and the would-be inventor, or experimenter had to face not only the natural difficulties of his subject but the ridicule 154 of a sceptical world. To Prof. Langley is due the chief credit of placing this subject upon a scientific basis, and of practically originating what he termed, the art of “Aerodromics”. In his epoch-making work on “experiments in Aerodynamics” published in 1691, among the Smithsonian Contributions to Knowledge, he prepared the world for the recent advances in this art by announcing “that the mechanical sustension of heavy bodies in the air combined with very great speeds is not only possible, but within reach of mechanical means we actually possess.”

He also attempted to reduce his principles to practice by the construction of a large model of an Aerodrome driven through the air by a steam-engine under the action of its own propellers.

I was myself, a witness of the memorable experiments made by Prof. Langley on the sixth of May, 1896, with an Aerodrome having a spread of wing of about 14 feet, and propelled by an engine. No one who witnessed the extraordinary spectacle of a steam-engine flying with wings in the air, like a great soaring bird, could doubt for one moment the practicability of mechanical flight. I was fortunate in securing a photograph of this machine in full flight in the air, so that an automatic record of the achievement exists. The experiment realized the utmost hopes and wishes of Prof. Langley at that time. “I have brought to a close,” he says, “the portion of the work which seemed to be specially mine — the demonstration of the practicability of mechanical flight; and for the next stags, 155 which is the commercial and practical development of the idea, it is probable that the world may look to others. The world indeed will be supine if it does not realize that a new possibility has come to it, and that the great universal highway overhead is now soon to be opened."

But the world was not satisfied with this position, it looked to Prof. Langley himself to carry on the experiments to the point of actually transporting a human being through the air on an Aerodrome like his model, and so with the aid of an appropriation from the War Department of the United States, Prof. Langley actually constructed a full-sized Aerodrome and found a man brave enough to risk his life in the apparatus (Mr. Manley of Washington, D. C.) Great public interest was aroused; but Prof. Langley did not feel justified in giving information to the Public, and therefore to foreign nations, concerning experiments undertaken in the interests of the War Department. His own dislike to premature publicity, cooperated with his conscientious scruples, to lead him to deny the newspapers the opportunity of witnessing the experiments. But the newspapers insisted upon being represented. The correspondents flocked to the scene, and camped there for weeks at considerable expense to their papers. They watched the house-boat containing the Aerodrome by day and by night; and, upon the least indication of activity within, newspaper reporters were on hand in boats. After long delay in hopes of securing privacy, experiments were made but the newspaper representatives, embittered by the attempts to exclude them, were already to presage defeat.

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Two experiments were made; but on both occasions the apparatus caught in the launching-ways, and was precipitated into the water without having a chance to show what it could do in the air.

The newspapers, however, immediately announced to the world the failure of Prof. Langley's machine, and ridiculed his efforts. Now, the fact of the matter is that the machine was never tried, and that there was no more reason for declaring it a failure, than for deciding that a ship would not float that has never been launched.

After having witnessed the successful flight of the large sized model of 1896, I have no doubt that Prof. Langley's full-sized Aerodrome would have flown had it been safely launched into the air. When the machine was for the second time precipitated into the water it was not much damaged by the accident. Prof. Langley, of course, was more anxious about the fate of his intrepid assistant than of his machine, and followed Mr. Manley into the house-boat to ascertain his condition. During this temporary absence from the scene of the catastrophy, the crew of the tug-boat grappled the frail frame work of the submerged Aerodrome; and, in the absence of anyone competent to direct their efforts they broke the machine to pieces, thus ending the possibility of further experiments without the expenditure of further capital. But the ridicule effectually prevented Prof. Langley from securing further financial aid, and broke his heart.

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There can be little doubt that the unjust treatment to which he was exposed contributed materially to the production of the illness that caused his death.

He lived long enough, however, to know of the complete fruition of his hopes by others; and only two days before his death he had the gratification of receiving a communication from the newly formed Aero Club of America recognizing and appreciating his efforts to promote mechanical flight.

Both in the case of Lilienthal and Langley their efforts have not been in vain. Others have continued their researches, and today the world is in possession of the first practical flying-machine — the creation of the brothers Orville and Wilbur Wright of Dayton, Ohio. Indeed we have news from France that a second has just appeared constructed by the same Santos Dumont to whom the world already owes the first practical dirigible balloon.

The Wright Brothers began by repeating the gliding experiments of Lilienthal with improved apparatus of the Hargrave type. After having made many successful glides through the air without a motor, they followed in the foot steps of Langley and propelled their machine by means of twin-screws operated by engine-power. They were successful in launching their apparatus into the air; and it flew, carrying one of them with it. Their machine has flown not once simply, but many times, and in the presence of witnesses so that there can be no doubt that the first successful flying-machine has at last appeared. Each of the brothers in turn made numerous 158 flights over their testing field near Dayton, Ohio, sometimes at an elevation of about 80 feet, at other times skimming over the field at a height of ten feet from the ground. They have been able to circle over the field of operation and even to describe in the air the figure eight, thus demonstrating their perfect control over their apparatus both in the vertical and horizontal directions. They have succeeded in remaining continuously in the air for more than half an hour, — 38 minutes, in fact — and only came down on account of the exhaustion of their fuel supply. They state that the velocity attained was one kilometer per minute, or about 37 miles an hour. The machine has not only sustained its own weight in the air during these trials, but has also carried a man, and a gasolene engine weighing 240 lbs. exerting a force of from 12 to 15 Horse Power, and in addition an extra load of 50 lbs. of pig-iron. The apparatus complete with motor weighed no less than 925 lbs. while the supporting surfaces consisted of two superposed aeroplanes each measuring six by forty feet; so that the machine as a whole had a flying weight of nearly two lbs. per square foot (1.9 lbs.).

Thanks to the efforts of the Wright Brothers the practicability of aerial flight by man is no longer problematical. We can no longer consider as impossible that which has already been accomplished. America may well feel proud of the fact that the problem has been solved by citizens of the United States.

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1910, Oct. 12, Beinn Bhreagh Recorder A Few Notes of Progress in the Construction of an Aerodrome

For many years past the subject of aerial flight has had a great fascination for me; and in 1896, the sight of Langley's steam aerodrome circling in the sky, convinced me that the age of the flying-machine was at hand.

I therefore quietly worked away at the subject in my Nova Scotia Laboratory in the hope that I too might be able to contribute something of value to the world's knowledge on this important subject.

Warned by the experiences of others, I have sought for a safe method of approach — a method that should risk human life as little as possible during the earlier stages of experiment.

Experiments with aerodromes must necessarily be fraught with danger, until man, by practical experience of the conditions to be met with in the air, and of the means of overcoming them, shall have attained skill in the control of aerial apparatus.

A man cannot even ride a bicycle without practice; and the birds themselves have to learn to fly.

Man, not having any inherited instincts to help him in this matter, must first control his flight consciously, guided by knowledge gained through experiment.

Skill can only be obtained by actual experience in the air; and this experience will involve accidents and disasters of various sorts before skill can be obtained.

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If these disasters should, as so often in the past, prove fatal to the experimenter skill cannot be gained. The knowledge obtained by the would-be aviator will then be lost to the world; and others must begin all over again instead of pursuing the subject where he left off, with the benefit of his knowledge and his experience.

It is therefore of the utmost consequence to progress in the art of aviation, that the first attempts to gain experience in the air, should be made under such conditions of safety as to reduce to a minimum the liability to fatal results.

The Wright brothers' successful flying-machine travels at the rate of about 37 miles an hour; and judging from its great flying-weight (nearly 2 lbs. per sq. ft. of supporting surface), it is unlikely that it could be maintained in the air if it had a very much less velocity:— But should an accident happen to a body propelled through the air with the velocity of a railroad train, how about the safety of the occupants? Accidents will happen, sooner or later, and the chances are largely in favor of the first accident being the last experiment.

While, therfore, we may look forward with confidence to the ultimate possession of flying-machine exceeding in speed the fastest railroad trains, it might be the part of wisdom to begin our first experiments at gaining experience in the air, with machines traveling at such moderate velocities, and at such moderate elevation, as to reduce the chances of a fatal catastrophe to a minimum. This means that they should 161 be light flying-machines, That is:— The ratio of weight to supporting surface should be small. While theory indicates that the greater the weight in proportion to supporting surface consistent with flight the more independent of the wind will the machine be, yet it might be advisable to begin, if possible, with such moderate flying weights as to permit of the machine being flown as a lite. There would be little difficulty then in raising it into the air; and, should an accident occur, the machine would descend gently to the ground; or the aviator could cast anchor and his machine would continue flying as a kite.

One of the chief causes that have led to disasters in the past has been a lack of stability in the air. Automatic stability under varying conditions is of the very first consequence to safety:— For what would it profit a man were he to gain the whole world and lose his own equilibrium in the air.

It occurred to me that the question of equilibrium could most safely be studied by constructing an aerial vehicle that could be flown as a kite, then it would follow as a matter of course that, if propelled through calm air with the velocity of the wind that supported it as a kite, the machine would also be supported in the air as a free flying-machine.

On two previous occasions I have presented communications to the Academy relating to experiments with kites. The first was on “Kites with Radial Wings” presented April, 1899; and reviewed with illustrations, in the Monthly Weather Review for April, 1899 (Vol. XXVI pp 154–155, Plate XI).

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The second was upon “The Tetrahedral Principle in Kite Structure” presented April 23d, 1903; and published, with 91 illustrations and an Appendix, in the National Geographic Magazine for June, 1903 (Vol. XIV, pp 220–251).

The experiments referred to, which were undertaken at first for my own pleasure and amusement, have gradually assumed a serious character from their bearing upon the flying machine problem.

The word “Kite” unfortunately is suggestive to most minds of a toy — just as the telephone at first was thought to be a toy — so that the word does not at all adequately express the nature of the enormous flying-structures employed in some of my exploits. These structures were really aerial vehicles rather than kites, for they were capable of lifting men and heavy weights into the air. They were flown after the manner of kites, but their flying cords were stout Manilla ropes. They could not be held by hand in a heavy breeze; but had to be anchored to the ground by several turns of the ropes around stout cleats like those employed on steamships and men-of-war.

One of the great difficulties in making a large structure light enough to be flown as a kite, has been pointed out by Prof. Simon Newcomb in an article in McClure's Magazine published in September, 1901, entitled “Is the Airship Coming?”; and this difficulty had so much weight with him at that time, as to lead him to the general conclusion that “The Construction of an Aerial Vehicle which could carry even a single man 163 from place to place at pleasure, requires the discovery of some new metal, or some new force.”

This conclusion, the Wright brothers and Santos Dumont, have demonstrated to be incorrect; but Prof. Newcomb's objections undoubtedly have great force; and reveal the cause of the failures of attempts to construct large-sized flying-machines upon the basis of smaller models that actually flew.

Prof. Newcomb shows that where two aerial vehicles are made exactly alike only differing in the scale of their dimensions, the ratio of weight to supporting surface is greater in the larger one than in the smaller, — the weight increasing as the cube of the dimensions, whereas the supporting surfaces only increase as the squares.

From this conclusion it is obvious that if we make our structure large enough, it will be too heavy to fly even by itself — far less be the means of supporting an additional load like a man, and engine for motive power. This conclusion is undoubtedly correct in the case of structures that are “exactly alike excepting in their dimensions”, but it is not true as a general proposition.

A small bird could not sustain a heavy load in the air; and while it is true that a similar bird of double the dimensions would be able to carry a less proportionate weight because it is itself heavier in proportion to its wing surface than the smaller bird eight times as heavy in fact, with only four times the wing surface — still it is conceivable that a flock of small birds could sustain a heavy load divided 164 equally among them, and it is obvious that in this case the ratio of weight to wing surface would be the same for the whole flock, as for the individual bird.

If then we build our large structure by combining together a number of small structures each light enough to fly; instead of simply copying the small structure upon a larger scale, we arrive at a compound or cellular structure in which the ratio of weight to supporting surface is the same, as that of the individual units of which it is composed, thus overcoming entirely the really valid objections of Prof. Newcomb to the construction of large flying-machines.

In my paper upon the Tetrahedral principle in Kite Structure, I have shown that a frame work having the form of a tetrahedron possesses in a remarkable degree the properties of strength and lightness. This is especially the case when we adopt as our unit structure, the form of the regular tetrahedron, in which the skeleton frame is composed of six rods of equal length, as this form seems to give the maximum strength with the minimum of material. When these tetrahedral frames or cells are connected together by their corners they compose a structure of remarkable rigidity, even when made of light and fragile material;— The whole structure possessing the same properties of strength and lightness inherent in the individual cells themselves. The unit tetrahedral cell yields the skeleton form of a solid, and it is bounded by four equal triangular faces. By covering two adjoining faces with silk or other material suitable for use in kites, we arrive at the 165 unit “Winged Cell” of the compound kite; the two triangular surfaces, in their flying position resembling a pair of wings raised with their points upwards, the surfaces forming a dihedral angle.

Four of these unit cells, connected together at their corners, form a four-celled structure, having itself the form of a tetrahedron containing in the middle an empty space of octahedral form, equal in volume to the four tetrahedral cells themselves. In my paper, I showed that four of these four-celled structures connected at their corners resulted in a sixteen-celled structures of tetrahedral form, containing, in addition to the octahedral spaces between the unit cells, a large central space equivalent in volume to four of the four-celled structures.

In a similar manner four of the sixteen-celled structures connected together at their corners from a sixty-four-celled structure: Four of the sixty-four-celled structures form a two hundred and fifty-six-celled structure, etc., etc.; and in each of these cases an empty space exists in the center, equivalent to half of the cubical contents of the whole structure, in addition to spaces between the individual cells, and minor groups of cells.

Kites so formed, exhibit remarkable stability in the air under varying conditions of wind, and I stated in my paper that the kites which had the largest central spaces seemed to be the most stable in the air. Of course these were the structures that were composed of the largest number of unit 166 cells; and I now have reason to believe that the automatic stability of these Kites depends more upon the number of unit cells than upon the presence of large empty spaces in the kites; for I have found, upon filling in these empty spaces with unit cells, that the flying qualities of a large kite have been greatly i i m proved.

The structure, so modified, seems to fly in as light a breeze as before, but with greatly increased lifting power; while the gain in structural strength is enormous. I had hitherto supposed that if cells were placed directly behind one another, without providing large spaces between them, comparable to the space between the two cells of a Hargrave box Kite, the front cells would shield the others from the action of the wind, and thus cause them to lose their efficiency but no very marked effect of this kind has been observed in practice. Whatever theoretical interferences there may be, the detrimental effect upon the flying qualities of a kite are not, practically, obvious; while the gain in structural strength and in lifting power outweigh any disadvantages that may exist. I presume, that there must be some limit to the number of cells that can be placed in close proximity to one another without detrimental effect; but so far my experiments have not revealed it.

To test the matter, I put together into one structure all the available cells I had in the Laboratory — 1300 in number. These were closely attached together without any other empty spaces in the structure than those existing between 167 the individual cells themselves when in contact at their corners. The resulting kite, known as “The Frost King”, consisted of successive layers, or strata of cells, closely superposed upon one another. The lowest layer, or floor of the structure, consisted of 12 rows of 13 cells each. The cells forming each row were placed side by side attached to one another by their upper corners;

and the 12 rows were placed one behind the other, the rear corners of one row being attached to the front corners of the row immediately behind. The next stratum above the floor had eleven rows of 14 cells; the next, 10 rows of 15 cells; etc., — each successive layer increasing in lateral dimensions and diminishing in the fore and aft direction; so that the top layer, or roof, consisted of a single row of 24 cells placed side by side.

One would imagine that a closely packed mass of cells of this kind — 1300 in number — would have developed some difficulty in flying in a moderate breeze if the cells interfered with one another to any material extent:— But this kite not only flew well in a breeze estimated at not more than about 10 miles an hour because it did not raise white caps, but carried up a rope-ladder, several dangling ropes 10 or 12 meters long, and more than 200 meters of Manilla rope used as flying lines — and in addition to all this, supported a man in the air.

The whole kite, impedimenta and all, including the man, weighed about 131 kgs. (289 lbs.); and its greatest length from 168 side to side was 6 meters at the top and 3 meters at the bottom. The sloping sides measured 3 meters, and the length from fore to aft at the bottom was 3 meters.

It is obvious that this kite might be extended laterally at the top to twice its length without forming an immoderately large structure. It would then be 12 meters on the top (39 ft.) and 9 meters on the bottom from side to side without changing the fore and aft dimensions of 3 meters. It would then contain more than double the number of cells and so should be able to sustain in the air more than double the load; so that such a structure would be quite capable of sustaining both a man, and an engine of the weight of a man, and yet be able to fly as a kite in a breeze no stronger than that which supported the “Frost King.

An engine of the weight of a man could certainly impart to the structure a velocity of 10 miles an hour, the estimated velocity of the supporting wind, and thus convert the kite into a free flying-machine.

The low speed at which, for safety's sake, I have been aiming is therefore practicable.

In the “Frost King” and other kites composed exclusively of tetrahedral winged cells, there are no horizontal surfaces (or rather surfaces substantially horizontal as in ordinary kites), but the framework is admirably adapted for the support of such surfaces. Horizontal aeroplanes have much greater lifting-power than similar surfaces obliquely arranged, and I have made many experiments to combine horizontal surfaces with winged cells with greatly improved results so far as lifting-power 169 is concerned. But there is always an element of instability in a horizontal aeroplane, especially if it is of a large size, whereas kites composed exclusively of winged cells are deficient in lifting power: And the kites composed of the largest number of winged cells seem to be most stable in the air.

In the case of an aeroplane of any kind the center of air-pressure rarely coincides with the geometrical center of surface, but is usually nearer the front edge than the middle. It is liable to shift its position at the most unexpected times on account of some change in the inclination of the surface of the direction of the wind. The change is usually small in steady winds; but in unsteady winds great and sudden changes often occur. The extreme possible range of fluctuation is, of course, from the extreme front of the aeroplane to the rear, or vice versa — and the possible amount of change, therefore depends upon the dimensions of the aeroplane — especially in the fore and aft direction. With a large aeroplane the center of pressure may suddenly change to such an extent as to endanger the equilibrium of the whole machine. Whereas, with smaller aeroplanes, especially those having slight extension in the fore and aft direction, the change, though proportionately as great, is small in absolute amount; and where we have a multitude of small surfaces well separated from one another, as in the tetrahedral construction, it is probable that the resultant center of pressure for the whole kite can shift to no greater extent than the centers of pressures of the individual surfaces themselves. It is, therefore, extremely 170 unlikely that the quilibrium of a large kite could be endangered by the shifting of the centers of pressure in small surfaces within the kite. This may be the cause of the stability of large structures built of small tetrahedral cells. If so, one principle of stability would be: Small surfaces, well-separated, and many of them.

The converse proposition would then hold true if we desired to produce instability and a tendency to upset in a squall fiz: Large surface, continuous, and few of them.

Another source of danger with large continuous surfaces is the fact that a sudden squall may strike the kite on one side, lifting it up at that side and tending to upset it. But the compound tetrahedral structure is so porous that a squall passes right through and lifts the other side as well as the side first struck; so that the kite has not time to be upset before the blow on one side is counterbalanced by a blow on the other. I have flown a Hargrave Box Kite simultaneously with a large kite of many tetrahedral cells in equally weather for the purpose of comparing them under similar circumstances. The tetrahedral structure often seemed to shiver when struck by a sudden squall, whereas the Box Kite seemed to be liable to a swaying or tipping motion that would be exceedingly dangerous in a structure of large size forming part of a flying-machine.

Another element of stability in the tetrahedral structure lies in the fact that the winged surfaces are elevated at a greater angle above the horizon than 45°.

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Supposing the wings of a cell to be opened out until they are nearly flat — or at least until they each make a comparatively small angle with the horizon — say 20° — then if, from any cause the cell should tip so as to elevate one wing (say to 25°) and depress the other (say to 15°) — then the lifting-power of the wind will be increased upon the elevated wing and diminished on the depressed wing, so that there would be no tendency to a recovery of position, but the very reverse, the pressure of the wind would tend to increase the tipping action, and favor the production of oscillation and a tendency to upset: For the lifting action of the wind upon a surface inclined at 10° would be less than at 20° and greater at 25° than 20°. The more the wings are opened out and the flatter they become — the more essentially unstable is the arrangement in the air.

Now, suppose the wings to be raised until they are nearly closed — or at all events until they make a small angle with the vertical (say 70° from the horizontal), then, if, from any cause the wing should tip so as to elevate one win (say to 75°) and depress the other (say to 65°), then the lifting-power of the wind will be increased upon the depressed wing, and diminished on the elevated wing; for the lifting force of the wind is greater at 65° than at 70° and less at 75°. Thus the moment a tipping action begins the pressure of the wind resists it, and an active force is involved tending to restore the structure to its normal position. The more the wings are raised, and the more they approach the perpendicular 172 position, the more stable essentially is the arrangement in the air.

The dividing line between these two opposite conditions seems to be drawn about the angle of 45° — and as the tetrahedral wing surfaces make a greater angle than this with the horizontal they constitute an essentially stable arrangement in the air: Whereas a horizontal surface represents the extreme of the undesirable unstable condition.

These considerations have led me to prefer a structure composed of winged tetrahedral cells alone without horizontal surfaces either large or small, although the lifting-power is less than when horizontal surfaces are employed — because the factor of safety is greater. Equilibrium is of the first consequence, and if the lifting-power is sufficient for our purpose, there is no necessity for introducing a factor of danger by the addition of horizontal surfaces. Of course the addition of the horizontal surfaces would enable us to secure the desired lifting-power with a smaller and therefore lighter structure — and this would be an advantage if we could be sure of perfect stability in the air. In employing the hollow construction with tetrahedral cells in which large empty spaces occurred, a great difficulty was encountered consisting in the enormous size of the structure required to support a man, combined with the increasing weakness of the structure as it increased in size. The discovery that the cells may be closely massed together without injurious effects has completely remedied this difficulty: For not only is the structural 173 strength improved by an increase of size, but the lifting-power increases with the cube of the dimensions; so that a very slight increase in the dimensions of a large kite increases very greatly its lifting-power. We now have the possibility of building structures of this kind that will support a man and an engine without the necessity of constructing a kite of immoderate size.

The experiments with the "Frost King" made in December 1905, satisfied me upon this point; and brought to a close my experiments with kites. My attention was then directed to other points necessary to be considered before an aerodrome of the kite variety could be made; and to the assembling of the materials for its manufacture. I have had to improve and simplify the methods of making the winged cells themselves. Through the agency of Mr. Hector McNeil, Superintendent of the Volta Laboratory, Washington, D. C., who is now taking up the manufacture of tetrahedral cells as a new business, I am now able to obtain cells constructed largely by machinery; and with stamped metal corners to hold the rods together. The process of tying the cells and parts of cells together had proved to be very laborious and expensive; and the process was not suited to unskilled persons.

By the new process most of the work is done by machinery, and no skill is required to connect the cells together.

I have also had to go into the question of motor construction, a subject with which I am not familiar; and while waiting for the completion of the material required for the