THESIS

Induction Welding.

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Professor A. L. Merrill
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

This thesis, entitled "Induction Welding", is respectfully submitted by the authors in partial fulfillment of the requirements for the degree of "Bachelor of Science" from The Massachusetts Institute of Technology.

The nature of this thesis made it necessary for us to do much of our work outside our immediate department, and the interest and desire to held which we found in all cases was of great value to us. We wish especially to acknowledge our indebtedness to

Prof. R. G. Hudson, Thesis Advisor.

Prof. M. DeK. Thompson

Dr. R. S. Williams

Dr. Comfort Adams, Harvard University.

Prof. R. H. Smith

Mr. M. F. Gardner

Mr. W. L. Barrow

Mr. G. P. Swift

Mr. F. M. Gager

Mr. Schaeler, Wireless Specialty Company.

Introductory Note.

Since the Induction Method of Welding had never been tested before we attempted it, we were forced to base our work in this thesis upon first principles of electricity and welding. A large amount of our time had to be spent in studying these principles, and in attempting to design apparatus which would show whether the method was possible, and at the same time be sufficiently general in application. As a result, there were many phases of the work which we did not attempt to develop fully and others which we did not even reach. If, for any reason, a desire should be felt to carry this work further at some future time, a complete schedule of tests which might be carried out will be found at the end of the thesis.

In writing up this report the procedure will be treated in the nature of a diary of events, since a simple statement of the actual result and tests gives no idea of the nature of the difficulties encountered, which were responsible for the time required.

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PURPOSE AND RESULTS.

The purpose of this thesis was to determine whether or not it is possible to weld by induction at high frequencies and voltage, and whether this method, if it is possible, is of any commercial value.

No actual welds were obtained, but we did manage to heat two half inch bars of Bessemer steel to a temperature so near the melting point that they stuck at the edges. (The melting point is 1400° C., and the temperature reached was 1200°C.)

Our results showed that as a general method of welding the induction system is commercially useless. Certain special cases could, we believe,, be well handled by this method. This will be discussed in detail in part 5 of this thesis.

The objections to the induction method of welding are:

Initial cost of apparatus is great.
Power required is, in the general case, fare out of proportion to the work done.
The time required is greater than that required by existing methods.

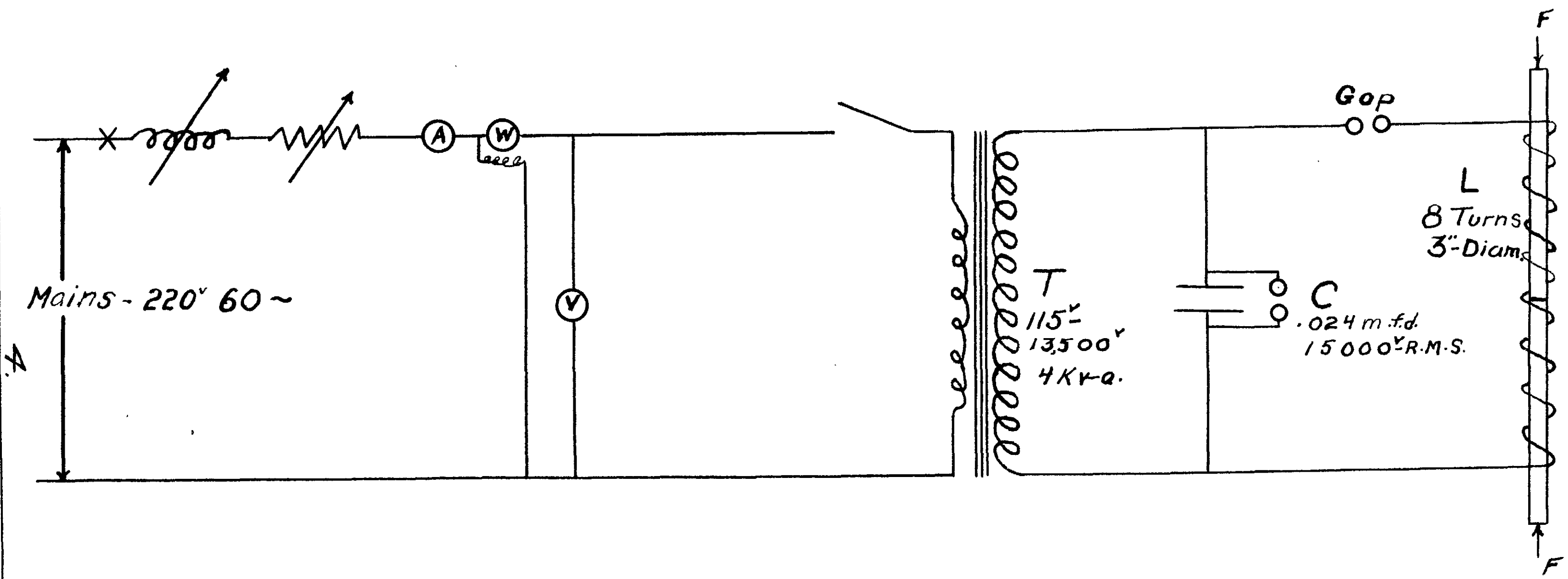
(These results apply only to the general case, in which the object to be welded is exposed in the loses of heat from that object, due to conduction, convection and radiation are great. Possible applications which would be successful are taken up in Part 5 of this thesis.)

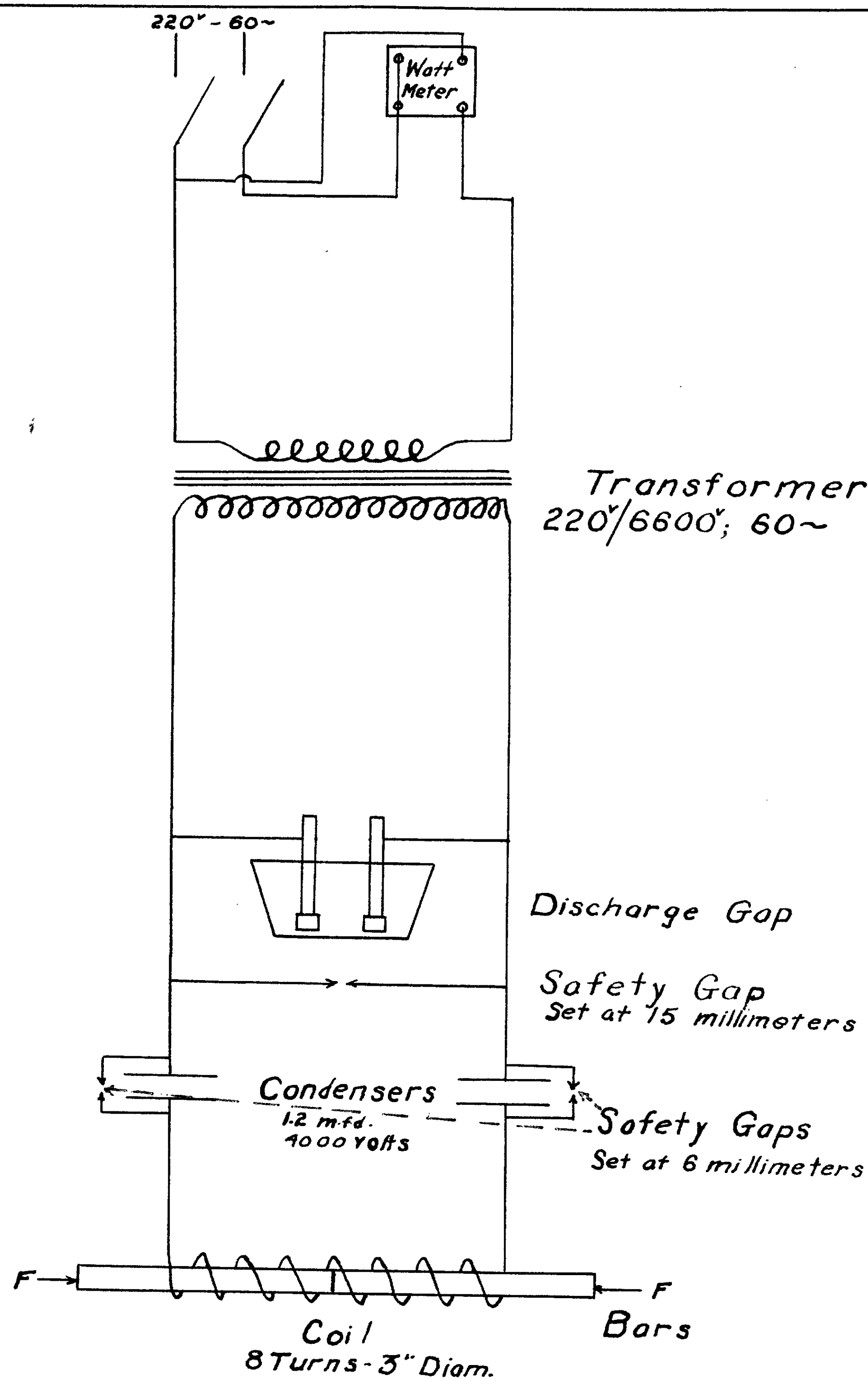
THEORY OF INDUCTION WELDING.

It is a well known fact that when current flows in a coil a magnetic field is developed. If, further, the current in the coil is varying, the field intensity will also vary; and if a conducting medium is placed within the coil, a current will be induced in this core. This induced current will, of course, vary with the flux density which produces it, and is known as eddy current. Since the core must have some resistance, the result of the flow of this current in the core is to heat the core at the cost of electric energy from the source which supplies the coil. Steinmetz showed by experimentation that the power used up in supplying these eddy loses is expressed by the equation $P = K_e f^2 B^2$. If, in addition, the core is of iron additional heat is developed in it due to the action of the current in the coil in magnetizing, demagnetizing and then magnetizing it in the opposite direction. This second loss is known as hysteresis, and the power lost due to it was also determined by Steinmetz. $P = K_h f B^{1.6}$.

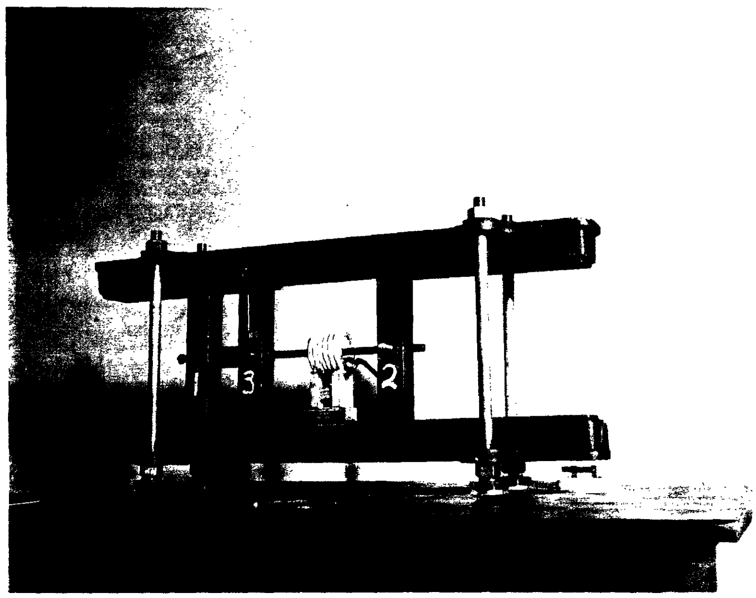
It is evident from the two equations given above that as the frequency of the current in the surrounding coils is increased the amount of power lost by the coil, and hence the rate of heat development in the core, is certain to increase very rapidly. At the same time, an increase in the impressed voltage will cause an increase in the flux density which will also increase the rate at which heat is developed in the core. Obviously, if the values of the frequency and impressed voltage are made sufficiently great, the core will melt. Applying these facts to the purpose of welding, it merely becomes necessary to produce the desired high voltage and frequency; impress this across the ends of a coil; place the object to be welded within the coil with the break at the center of the coil, where the flux density is a maximum; wait for this section to reach the melting point; and then complete the weld by applying pressure at the ends of the object.

Induction Welding Circuit.





Ajax Furnace
Furnace Inductor Replaced by welding Coil



BAR AND COIL HOLDER

and

PRESSURE DEVICE.

DESCRIPTION OF APPARATUS.

On page (4) is a diagram of the circuit which we used in our first attempt at welding, while on the following pages are a photograph or the combined bar and coil holder and pressure device, and a diagram of the wiring of the Ajax-Northrup induction furnace which we used at a later time.

It will be seen that our own circuit is the Tesla Oscillatory circuit. It consists of a bank of condensers and our heating coil, both in parallel with the secondary of the transformer supplying the high voltage; while between these two in the line is a spark gap adjusted to break-down just before the peak of the high voltage wave is reached. This combination of gap, coil, and condensers acts to produce the high frequency; for when the 60 cycle wave passes its crest the spark breaks and the charge on the condenser damps out by creating and destroying magnetic fields in the coil. The frequency is determined by the constants of the resonant circuit, and is equal to

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The coil is made of copper tube, through which water flows to prevent overheating. It is electrically insulated between turns to prevent sparking over due to the high voltage, and is also carefully heat insulated from the bar.

The bar holder consists of two guides fastened rigidly to the uprights (1)and (2). A third upright,(3), is free to move along the guides. The uprights (2) and (3) are drilled to accommodate the bar to be welded, which is held in place by set screws. Uprights (1) and (2) are countersunk to hold a two hundred pound compression spring, which may be compressed by means of a third set screw acting through the rigid member, (1). The method used was to place the bars to be welded in their holes in members (2) and (3) with their ends in contact and fasten them by means of their set screws; adjust the coil so that the bar was in position along its axis with the break under the center of the coil; and tighten up the spring by means of its set screw until the two bars forced against each other with considerable pressure. Then, when the metal at the neighborhood of the break melted, the spring, acting on the free member, (3), would force it forward and the section of the bar which it held would be pressed against the other section of the bar, completing the weld. An indicator was fastened to the frame so that the observer might know when this action had taken place by watching the position of this indicator with respect to lines painted on the moving member.

The ratings of the original apparatus used were

1 Marconi Transformer: 115-13500 volts, 4 KVA.

6 Faradon Condensers: 15000 volts, .004 mfds. (Paralleled to give a total capacity of .024 mfds. at the same safe voltage.

1 coil of 1/4" copper tubing: 8 turns, 3 inches cross section.

The primary circuit contained a rheostat and an induction regulator used to vary the voltage impressed upon the transformer. The meters were also placed in this circuit since there were none available capable of holding the magnitudes involved on the high side of the transformer.

Condensers were protected by means of a safety gap, as shown.

Due to the high voltage used, it was considered advisable that all apparatus starting with the transformers should be encased. This was accomplished by making use of the small room situated in Room 10:088 which had previously been used for heat runs and had numerous windows through which the progress of the experiement could be watched. As an added precaution, a safety switch was placed on the door, making it impossible for anyone to forget to turn off the power before examining the apparatus.

The connections of the Ajax-Northrup Furnace are essentially the same as those which we used, with the exception that the spark gap is placed in an atmosphere of hydrogen to make its break-down voltage more exact, and the location of the spark gap is changed so that it is in parallel with the high side of the transformer and with a series circuit consisting of the condensers and coil. The condensers are built up in two series banks of three in parallel to give an effective capacity of .6 mfds., and a safe voltage of 8,000 volts.

The ratings of the furnace are:

1 Transformer: 220-6600 volts, 30 KVA.

6 Condensers: 4000 volts, .4 mfds.

Furnace Inductor was replaced by our coil.

PROCEDURE.

Early last term the authors became interested in heating by induction. It seemed remarkable that so little work had been done in this field; examination of all references available in the Institute Library showed that the principle development to date was the Ajax-Northrup High-Frequency Inductive Furnace, which was designed by Dr. E. F. Northrup some ten years ago. We believed that this principle could be applied to welding equally well, and set out to find out what work if any had been attempted along this line.

We first consulted Dr. R. S. Williams of the Department of Metallurgy. He said that to his knowledge no one had ever attempted to weld by induction. Furthermore, he considered that such a weld might produce more even grain growth and hence be stronger obtained by the present methods, due to the nature of heating under a solenoid; the heat developed being a maximum under the center of the coil and grating off to a minimum under the ends of the coil. For further reference he advised us to see Dr. Comfort Adams of Harvard University, who is in close touch with experimental work carried on by General Electric Company.

Dr. Adams agreed with Dr. Williams in the opinion that no experiments had been carried out in this line, but was not sure that such a method would have any advantage over those existing.

He said, however, that he would be interested to learn the results of an experiment of this nature.

We then obtained permission from Prof. Laws to devote our thesis to this subject, and were assigned to Prof. Hudson, who advised us to try a rough test using the power supply of Prof. Thompson's Ajax Furnace before buying any equipment.

This trial test was extremely rough. We constructed a small coil of copper tubing consisting of (8) turns of a diameter of 3 inches, with no insulation, and connected it in series with the Ajax Furnace coil. A broken bar was then placed within the coil with its break approximately at the mid point of the coil, and held in place by (2) ring-stands. The power was then turned on. Within a minute the bar had risen to a temperature of about 900 degrees centigrade . Here it held steady, showing that the rate at which heat was being radiated from the bar was the same as the power supplied. Owing to the low power factor caused by the turns of the furnace in series with the coil which we were using, no more power could safely be supplied.

We felt that by insulating the bar from the coil and from the air of the room its temperature could readily be brought up to the melting point, an opinion with which Mr. Swift, who was aiding us in handling the furnace, agreed. The Ajax furnace had a voltage of 6600 volts much of which dropped in this trial run was across the coil of the furnace, where it did us no good. We intended to at least double this voltage; which, with other conditions equal, would give us (4) times the power, roughly. A report of this trial run was made to Prof. Hudson, who considered the evidence of possibility strong enough to warrent continuing the thesis.

We now set about the design of the necessary apparatus. The trial test had shown the necessity of holding the bars to be welded firmly together, and it was evident that pressure would be needed to force these bars to weld when the melting point should be reached. The holder shown in the photograph was the result of our efforts. The weight of the frame gave the whole welding unit stability, it being made of cast iron. The slides were made by milling out slots in a pair of old motor beds. The uprights were cut from bar stock and holes drilled and countersunk as described in part 3 of this thesis. The uprights (1) and (2) were made slightly longer between shoulders than was the moving member, (3). Thus, when the stay bolts at the four corners of the frame were tightened, the uprights (1) and (2) were held rigidly in place while (3) was free to slide along the slot. A 200 pound valve spring was loaned to us by Prof. Eames to supply the necessary pressure.

Mr. Gardner of the Research Laboratory gave us permission to use the small room which that department had sometime before built into Room 10:088, and further aided by loaning us two old Marconi transformers and a spark gap. Unfortunately the transformers were not rated, and it became necessary to consult the files in the Institute Library for a list of all the transformers that this company had made and their ratings. When this information was finally found, we made the usual transformer test to determine the ratio of transformation of the high to low coils. This was found to be 77:1 for a single high side coil or 154:1 for the two high side coils of one transformer in series. With this added information we were able to determine with which of the Marconi transformers we were dealing. The rating per transformer , with high side coils paralleled, was 115:13,500 volts and 4 KVA. Both transformers had to be opened and cleaned and minor repairs made. They were then filled with new oil and were ready for use.

We now needed sufficient high voltage condensers to store the power and produce oscillation in the coil. We obtained six Faradon 15,000 volts, .004 mfd. condensers from the Communications Laboratory and apparently had all the equipment needed. The house was wired in the manner shown in the diagram; all meters and regulating devices outside, all apparatus within. Safety gaps were placed across the condensers and adjusted to break down at 14,000 volts, thus insuring that the condensers would not be punctured. The coil which we had used in the trial test had been carefully insulated with silica to prevent sparking between turns and overheating of the coil by radiation from the bar. Apparently everything was ready for the test.

When the circuit was closed, however, an inordinately large current was at once drawn, which opened the circuit breakers. After a complete examination of all sources of trouble, we found that one of the transformers had a partial short circuit in its primary turns so that when more than a very short voltage was applied it acted as a dead short circuit. Therefore, this transformer had to be discarded, which reduced the power which we could safely supply by half; since the transformers had been connected in parallel. We now tried closing the circuit again. This time the meters showed small amount of power being drawn. Examination of the bar showed that a small amount of heat was being developed, the temperature being about 100°. But attempts to raise the temperature of the bar above this point failed.

Here it would be well to stop and consider the mathematical side of induction heating. The amount of power drawn from the line is determined by the hysteresis and eddy losses of the core being heated. But the core in turn, unless completely insulated from everything else, loses power. The equations of heat loses from heated bodies show that the rate at which heat is disseminated is practically proportional to the difference in temperature between that body and the surrounding medium. Hence, to bring a core to any temperature it is necessary to supply power at the rate that power would be given off by the core at that temperature. But the power supply depends upon the Steinmetz equations given in the discussion of the theory, and upon the use of condensers of sufficient capacity to store up the portion of the power not developed into heat during the rest of each half cycle. It will then be returned to the coil during the next half of the high frequency cycle. If the condensers are of low capacity, the power, instead of being stored, goes back onto the line and as a result, there is very little effective heating.

This explains why the apparatus we were using refused to draw more power. We had only .024 mfds. of capacity to work with. It was evident that we must secure more before we could hope to better our results; but condensers of this type were not available in the Institute. We finally located them at the Wireless Specialty Company in Roxbury; but the cost of a number sufficient to give us 1.00 mfds. capacity at our working voltage amounted to nearly a thousand dollars. Then too, considerable time would be required by the company to assemble a condenser of this size from the small units. Mr. Schaeler, of that company, to whom we talked was very kind and even suggested that he might be able to lend us the necessary condensers for a short period of time. As we were by now very limited as to time ourselves we felt that we could not afford to wait for this possibility. The

Ajax Furnace in the Electro-Chemistry Laboratories had the necessary capacity. We obtained permission to use this source of power in completing our thesis. This time the furnace was completely removed and our coil substituted in its stead. The same (8) turn coil was used, insulated this time, and with added insulation stuffed between the coil and bar at the ends to prevent convection and radiation from the highly heated part of the bar. The spark gaps were then adjusted until the oscillatory circuit was drawing 5 KW at .5 p.f. and 6600 volts. A pyrometer showed the temperature of the bar to be about 1200° C. We could not increase the power input further because the few turns of the coil made the conditions of oscillation very unsteady. At this point, the coil, which had not been water cooled in this run, burned out and the power had to be cut off. It was especially noticeable that the greatest amount of heat in the electric circuit was developed at connecting points, where the nature of these connections made the effective area of the current carrier small.

When the bar was removed, it was found to be stuck at the edges. This was, of course, weak; but it did show that the method would produce welds.

We made one more test. This time we used a coil of 16 turns, wound upon a fused quartz cylinder. There were two reasons for using this larger coil. In the first place, it permitted us to increase the power input to the oscillatory circuit, and it doubled the length of the heated area in an attempt to reduce the rate at which heat was radiated from the section of the bar near the break. With this new coil water cooled and all connections made by heavy clamps we had no further trouble with excessive heating of the electric circuit. Moreover we were able to increase the power input to the oscillatory circuit to 10 KW. with a power factor of .55, but the bar did not come up to the melting point. Another weak weld was secured and it became necessary to stop work.

5.

DISCUSSION OF RESULTS.

From our tests we can discuss the commercial possibilities of Induction Welding with certainty in some aspects. If condensers and a spark gap are to be used there will always be difficulties added to the mere use of the apparatus, due to the constant danger of puncture. A high frequency high voltage alternator as the power source would eliminate these difficulties. Some of the newer Ajax Furnaces use this method of supply and seem to be far more satisfactory than the Tesla type. With regard to the actual welding, the greatest difficulty is that of preventing conduction of heat away from the break. In our work, uprights and frame were hot at the end of each run, showing what had become of most of the heat energy developed in the bar. This could have been eliminated by making the uprights of some such material as asbestos board, but we wanted to find out just how serious this conduction would be, and it is certain that in the majority of welding jobs it would be as bad, if not worse, than in our case. As was shown in the trial test where two short bars were held together and insulated by means of asbestos, from the ring-stands which held them; where there is little conduction, the difficulties of securing a weld are tremendously reduced. The radiation can be made negligible, as can the loss by convection, by merely insulating the bar from free air. The coil with its insulation, together with end plugs does this. Conduction will be the chief loss of power, and it is certain that in any case of welding where this loss will be great it would be useless to use this method. It appears that the proper coil to use is one that does not extend for more than a few inches on each side of the break. The coil we first used, having only (8) turns, was better than the second, with twice that number and covering twice the area. For one thing, as the coil is increased in length the bar is heated to a high temperature over more of its length and seems to tend to bend before it has yet reached the melting point. Then too, the actual amount of heat used is increased by using a longer coil. The cross section of the coil should, of course, be little greater than is necessary in order to place the object to be welded within it.

Because of the nature of the heating, the time required to come up to welding temperatures is longer than it should be if the method were to be used commercially. We found that with the amount of conduction which was present in our tests it took about ten minutes for the bar itself to reach a fairly steady temperature.

It seems to us that the only place where Induction Welding would be of commercial value would be in the welding together of very small masses which could not well be Resistance Welded. These would merely have to be pressed together by means of some easily constructed clamp and placed inside the coil. The small mass in this case would make the speed of welding very great both because there would be less volume to heat up and because, with the ends of the coild sealed, the space within might be evacuated so that there would be no losses. Thus the welding, if carried out in a closed, heat insulated cylinder, would have the same favorable conditions as are present in the induction furnace. As is readily seen, this method would only be practical in the case of very small objects, and it is in this field that we believe that Induction Welding to have some possibilities of usefulness.

PROPOSED OUTLINE.

1. Determine power required to reach melting point of core, using present apparatus and several different types of core. Vary size and material.

2. Repeat part (1) using uprights made of aspestos wood to cut down conduction losses.

3. Try welding very small objects, at least enclosed, if possible, in a vacuum.

4. Make tensile tests of all welds produced and compare with similar material welded by standard methods.

5. Make examination of welds for nature of grain growth, and compare with ordinary methods.