FOREWORD

In half a century, welding has evolved from shop repair through engineering method to scientific technology. Today, simple and highly-developed forms of welding exist side by side, so that a bewildering picture must be presented to the non-specialist.

The historical approach may help to bring perspective to the picture. A better understanding is to be desired to create such a condition in education and research that welding may flourish in these fields. Students and teachers are required, familiar with its disciplines. Almost everything made of metal, from ships to satellites, must have welded parts, and the techniques must be controlled by engineers and scientists.

John Convey

John Convey

Director,
Mines Branch

Mines Branch Information Circular IC 124

A BRIEF HISTORY OF WELDING TECHNOLOGY

by

K. Winterton*

ABSTRACT

The history of welding, including the auxiliary methods of soldering and brazing, has been traced from its beginning in the Bronze and Iron Ages to modern times. A simple, chronological treatment has been used:

Joining methods in early cultures (Period 5000 B.C.-1200 A.D.).
The dawn of science and technology (Period 1700 A.D.-1875 A.D.).
The appearance of the major welding processes (Period 1877-1903).
Welding primarily as a repair method (Period 1903-1918).
Welding for construction and fabrication (Period 1919-1951).
Welding as a scientific technology (Today).

In the first section of the report, dealing with early history, other joining methods such as rivetting are briefly discussed for comparison with welding. In later sections, these other methods are omitted.

The last four periods permit a more uniform treatment of the subject matter under the sub-titles (a) resistance welding, (b) arc welding and cutting, (c) gas welding and cutting, and (d) other methods.

In the early part of the twentieth century, welding became known as a useful repair method, and the subsequent history involves an account of a gradual release from this hampering designation. An attempt is made in the last section to show how welding has become a fully-fledged technology, but the review of present-day welding that this entails has been made indicative rather than complete, because adequate accounts are available elsewhere.

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* Head, Welding Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

Direction des mines
Circulaire d'information IC 124

BREF HISTORIQUE DE LA TECHNOLOGIE DE LA SOUDURE

par

K. Winterton*

RÉSUMÉ

L'histoire de la soudure, y inclus celle des procédés apparentés de brasage au cuivre ou à l'argent et de brasage à l'étain, a été retracée depuis ses origines aux âges de bronze et de fer jusqu'à nos jours. On a eu recours à une division chronologique simple:

Procédés d'assemblage utilisés par les civilisations anciennes (période comprise entre 5,000 ans av. J.-C. et l'an 1200 ap. J.-C.
Aurore de la science et de la technologie (période comprise entre l'an 1700 et l'an 1875).
Apparition des principaux procédés de soudure (1877-1903).
Soudure utilisée avant tout pour fins de réparation (1903-1918).
Soudure utilisée à des fins de construction et de façonnage (1919-1951).
Soudure envisagée en tant que technologie scientifique (période actuelle).

La première partie du présent rapport, qui traite de l'histoire ancienne, contient une brève étude d'autres procédés d'assemblage tels que le rivetage, pour fins de comparaison avec la soudure. Les sections subséquentes du rapport ne mentionnent pas ces autres procédés.

Les quatre dernières périodes permettent de traiter plus uniformément la question à l'étude dans le cadre des sous-titres suivants: (a) soudure par résistance, (b) soudure et coupage à l'arc, (c) soudure et coupage au gaz, et (d) autres procédés.

Au début du vingtième siècle, la soudure a pris de l'importance comme technique utile de réparation, et le reste du rapport mentionne de quelle façon la soudure s'est graduellement débarassée de cette désignation restrictive. Dans la dernière partie, l'auteur tente de demontrer comment la soudure est devenue une véritable technologie, mais l'examen de la situation actuelle de la soudure est presenté de façon plutôt sommaire, étant donné qu'il existe ailleurs des exposés satisfaisants.

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*Chef, Section de la soudure, Division de la métallurgie physique, Direction des mines, ministère des Mines et des Relevés techniques, Ottawa, Canada.

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INTRODUCTION

Much ingenuity has been exercised recently in defining welding terms. The task has been made more difficult by the variety and complexity of processes now available. In this report, the word "welding" changes in meaning when it is used to describe the joining methods of different periods. At first, any kind of join was acceptable, and later, more and more demands were made of the physical, chemical and mechanical properties of the joint as a whole.

The simple chronological system that has been followed preserves a narrative style for those who may wish to read the complete report. The period from 5000 B.C. to the present day has been divided into six periods of varying length, for convenience of treatment, each successive period representing an obvious step forward in technical progress. Following the introduction of the major welding processes in the period 1877-1903, it is possible to follow the modification of any particuler process by reference to the classification, (a) resistance welding, (b) arc welding and cutting, (c) gas welding and cutting and (d) other methods, that has been used for all the later periods.

JOINING METHODS IN EARLY CULTURES

PERIOD 5000 B.C.-1200 A.D.

Mechanical methods of joining were probably used before metals were discovered. For example, buttons may have been used to join the clothes worn in Palaeolithic times. Stone hammers and flint axe-heads were joined to cleft sticks or wooden handles by lashing.

Adhesives may have been used occasionally to supplement mechanical methods. Modern primitives provide examples. An Eskimo dagger has been described[1] that was made with a blade of jasper joined to a wooden handle with bitumen. A stone axe from North Australia had been made with a stone axe-head in a bent withy, lashed to provide a handle; gum had been used to help secure the stone in position.[1] No doubt expedients of this kind were used in Palaeolithic and Neolithic times, with materials locally available. A kind of enamel called niello, consisting of metal sulphides melted together, was used by the Egyptians and by the Mycenaeans as early as 1600 B.C.,[1] for inlay work on metal objects. Niello was very widely used in many lands from this time until the Middle Ages for the same purpose.

It is likely that, after metals began to be discovered, a long time was required for experiment before new techniques were evolved appropriate for the new materials; joining techniques would offer no exception. The unusual appearance of metals suggested magical and decorative uses, to which they were at first confined by scarcity. Later the production of valuable ornaments, implements and ceremonial objects, together with the increasing complexity of decoration, led to new joining methods more appropriate for metals, namely cold-pressure welding, rivetting, and brazing. Probably these three methods were all practised by about 3000 B.C., though it is impossible to be sure of the order in which they appeared or the extent to which each was used.

Native copper and gold are supposed to have been noticed and collected from about 5000 B.C. onwards. The discovery of malleability and the production of simple shapes such as discs, plates, bowls, rings and amulets followed slowly. Occasionally when hammering gold parts together, for example to form a ring or amulet, a true cold-pressure weld may have resulted. It has been suggested that the Egyptians made copper pipe around 5500 B.C., by hammering the overlapping sheet edges together.(2) Modern writers speculate freely about the joining of metals by hammering, though some of them may not be acquainted with the difficulty of joining metals in this way.(1)

Gold would certainly be easier to join than copper, because its surfaces are not coated with an oxide skin as are those of copper.(1) It has been said that by about 3000 B.C. the Egyptians coated objects with silver or gold by hammering foil onto the surfaces.(3) When the object was made of copper, some bonding would occur, and to the extent that this was deliberate, the practice provides an early example of cold-pressure welding. It is not easy to find good examples from these very early times of deliberate joining by hammering or pressure that would merit the name of welding by modern definition. At a much later date, perhaps about 1000 B.C., there is an example of a gold object produced in sheet metal by an Irish goldsmith in the early Iron Age, where the sheet edges were overlapped and joined by "burnishing" to produce an excellent lap weld.(1) However, this was not representative of a general technique, because the Irish goldsmiths at about this time normally joined the sheet edges by folding or by sewing them together with wire.(1)

Rivetting, like cold-pressure welding, may also have been used to join wrought metals before there was any knowledge of melting. Unlike cold-pressure welding, rivetting cannot have originated accidentally. Its invention required original abstract thought. Its use leaves no doubt about the intention of joining. An early example is provided by a rivetted copper vessel from Ur, Mesopotamia, which is believed to have been made before 2500 B.C.[1] There are many examples from the Bronze Age of rivetted swords, daggers and halberds. Rivetting was used for an increasing variety of objects as time went on, and, like welding, rivetting is still widely used today. However, because of its simplicity and inherent limitations, rivetting has shown a far less complex development than welding.

Brazing* may have been developed not long after the discovery of melting. Melting, the smelting of simple copper ores, and casting are all believed to have been discovered during the period 4000-3000 B.C.[1] It has been suggested[1] that, somewhere in the Near East, a gold worker, melting gold nuggets from various sources, noticed that the metal from one particular source melted earlier, because of a greater impurity content, and fused together the other solid pieces. Without knowing the reason for this behaviour, this worker may have set the special gold on one side to be used for brazing purposes.

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*Brazing is a modern term, derived from brass, used to describe joining with an alloy (or metal), of high strength and fairly high melting point, that melts at a lower temperature than the metal to be joined.

Later, deliberate alloying was used to achieve the same results. A copper panel from Im-Dugud in Mesopotamia (Figure 1) has separate parts joined to the main panel by brazing, and is believed to have been made before 3000 B.C.[1] In 2500 B.C., brazing was known in Ur, Mesopotamia,[1] and from the same period there is an example of its use in Egypt from the tomb of Queen Metephires, Dynasty IV, the canopy for which was arranged on copper poles fixed into sockets by brazing.[1] Brazing was also used for works of art decorated by granulation and filigree. These arts entailed handling innumerable tiny wires and granules and fixing these into place individually by brazing. Typical is a gold dagger sheath and cosmetic case from Ur, Mesopotamia, believed to have been made before 2500 B.C.[1] Many similar examples are extant.

Flow welding, called in the foundry "burning-on", was also probably known in ancient times. This consists in casting molten metal in contiguity with a previously made casting to make an addition to it, or between component castings to join them, or into cracks or holes in a casting to effect a repair. Sometimes a subsidiary mould may be necessary to hold and shape the additional metal. For a Greek statue made in 500 B. C. the technique was used to fasten to the head separately-cast pieces representing locks of hair.[1] However, it seems likely that flow welding was known and used much earlier. The picture is obscure, and it is difficult to dissociate the technique as a branch of welding from techniques that belong, rather, to the foundry.

In illustration of the difficulties of precise classification, mention may be made of a battleaxe from Ras Shamra, in Syria, consisting of an iron blade with a copper socket made about 1300 B.C.[1] The socket had been cast onto the blade, but the joint relied on the mechanical locking provided by contraction rather than on true welding.[1]

Forge welding, or the joining of iron parts by hammering while hot, must date from about 1400 B.C., when iron began to be more extensively used. There is considerable scope for speculation, because meteoric iron was known from about 4000 B.C. onwards,[1] and iron ores may have been occasionally smelted from about 3000 B.C. onwards.[1] On the other hand, there is evidence that iron was valuable because of its scarcity before about 1400 B.C.,[1] and was treated as a metal difficult to form and unsuitable for practical use. It seems reasonable to take as a turning point the extensive iron smelting and forging by the Chalybes people, subjects of the

Hittite kings, in the period 1400 to 1200 B.C.[1] An early example of forge-welded ironwork is the uncomfortable-looking iron head-rest of Tutankhamen, made about 1350 B.C.[1] It is thought that this may have been a gift from a Syrian ruler, because ironworking in Syria was more advanced than in Egypt at this time.[1] The technique of forge welding has been used for a great variety of purposes. Figure 2 shows some forge-welded Iron Age fire-dogs found in Cambridgeshire.

There is the somewhat brash claim that the welding of iron, "Kollesis", was invented by a Greek, Glaukos of Chios, in the period 700-600 B.C.,[1] but, though this "discovery" may have heralded a more extensive usage, there is little doubt that forge welding must have been used many times and many centuries earlier.

It is possible, though unlikely, that soldering was used before 1400 B.C. Soft soldering* connotes the joining of metals with a metal alloy of low melting point. Tin is the most effective and almost essential ingredient of solder, and was not available in quantity before about

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*Without further qualification, the term "soldering" should be taken to mean soft soldering as here defined. The nomenclature is obscured by the use of terms such as "silver solder" and "hard solder" for alloys used in brazing.

1400 B.C.,[1] when tin ores were smelted to make tin directly. (Before this time, bronzes were made indirectly by heating copper in contact with tin ores and reducing agents.[1]) No very clear and precise distinction exists between soldering and brazing. Although these two processes may be distinguished, many writers on excavation and ancient history have failed to do so. The ancients, for their part, may have attempted to use many kinds of metal combinations for joining. The special qualities of tin for this purpose would quite likely soon become known after it became available in quantity, perhaps when attempts were made to make bronze directly from its component metals.

The Romans were acquainted with several aspects of welding, but did not introduce any new methods.

The Roman smiths practised the "steeling of blades", that is, the forge welding of steel edges onto the iron body of the blade.

Lead pipes were used in Roman plumbing, and often required joining. One example of jointed pipes is in the museum in Bath, England, and shows[4] two distinct passes, so that the structure in cross-section resembles that of a multi-run weld. The lead was poured molten into the joint,[5] so that the technique should be classed as flow welding.

Brazing was familiar to the Romans. One example is provided by the mention of an iron ring brazed with copper.[6]

Special furnaces were introduced in Roman times for the agglomeration of small ingots from the smelting furnace in order to make large blooms for forging.[6] This process involves welding in the wide sense, though not in the sense of joining finished parts.

In India, huge composite blooms were made by forge welding. The famous Delhi pillar (310 A.D.), twenty-four feet long and sixteen inches in diameter (Figure 3), has been shown to have been made from many separate blooms, each weighing about eighty pounds.[7] The less-well-known pillar of Dhar (321 A.D.) was larger, being forty-two feet in length.[7] At about the same time, other large iron objects were made in a similar way, including a large iron girder at Puri, iron gates at Somnali, and a pillar twenty-four feet long at Miniri.[7]

In England, in the Anglo-Saxon period (410-1066 A.D.) small tools were rivetted and frequently decorated with inlay.[6] Piling of blooms was practised, and in fact the blooms were so small that several might be required to forge a single axe-head.[6]

Sufficient literature remains to show that, in Europe in the Dark Ages, the earlier techniques were not forgotten, but were, rather, extended and refined. The monk Theophilus, describing arts and practices in church-building, gives details of soldering techniques used for ecclesiastical plate.(7) He also describes smelting, refining, hammering, casting, wire-drawing and gilding, as practised in the period 1000-1200 A.D.(7)

The Normans made extensive use of the draw-plate,(6) then available for making wire for the manufacture of chain mail, grilles for shrines, and mesh for the reinforcement of wooden gates.(6) Joints in wire mesh or mail were made by clipping, rivetting or welding. The smith was a master not only of the forging of iron but also of forge welding. It is known that William the Norman took with him many smiths(8) in the war resulting in the English conquest. Even in England, the smith was an officer of the highest rank.(7) The Norman victory was made possible because of more and better arms.(7)

THE DAWN OF SCIENCE AND TECHNOLOGY

PERIOD 1700 A.D. - 1875 A.D.

In 1724,* a man named Desaguilius gave an account to the Royal Society of "Some experiments concerning lead" which is remarkable as an early study of cold-pressure welding and also for its quantitative approach. His own record (see Rollason(9)) states:

> "Having, on Thursday 29th April last, made mention of some experiments----by Mr. Trievall at Newcastle and Edinburgh, I made the following experiment to the same purpose before the Royal Society.
>
> I took the leaden balls----the first weighing 1 pound, and the other 2 pounds, and from each cut off a segment of about 3/4 inch in diameter, I pressed them together with my hand with a little twist--------. The balls stuck together----though loaded with scale and weights------amounted to 16 pounds. A little more weight separated them----- viewing the touching surfaces it appeared that they did not exceed a circle of 1/12 inch diameter --------. The experiment was repeated several times and the cohesion of the balls was different every time."

(With a circular contact area of 1/12 inch diameter, and a load of 16 pounds, the strength of the weld is 2,930 pounds per square inch.)

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*From this point onwards, the letters A.D. are omitted from the year designations.

In 1800, Humphrey Davy provided a foundation for modern welding with two discoveries that were later to lead to two methods of producing intense local heating. The first of these was the discovery of acetylene[10] and the second was the production of an arc between carbon points when experimenting with Volta's battery.[7] In 1802, V. V. Petrov also made a study of the arc.[10] It was because of its possibilities for illumination, rather than its possibilities for melting, that Davy was interested in the arc, and by 1809 he had shown that it was possible to maintain a high voltage arc for reasonable periods.[2] However, both arc-lighting and electric welding had to await the development of the generator before they could become practical methods. In 1842, Woolrich devised a magneto-electric machine, but it was expensive.[3] An improved dynamo invented by Wilde in 1866[3] was followed by the Gramme ring dynamo in 1871, which proved to be satisfactory for arc-lighting.[1] Arc-lighting found practical use for many years, but was overtaken by the carbon-filament lamp, invented first by Swan in 1878[1] and later by Edison.[1] In 1849, W. E. Staite obtained a patent for welding using the electric arc.[10] J. P. Joule, in 1857, also called attention to the possibility of using electricity for joining, in a lecture entitled

"On the fusion of metals by voltaic electricity", as recorded in the Memoirs of the Literary and Philosophical Society of Manchester, 2nd Series.[2] Joule reported the successful joining of steel to brass, and of iron to platinum, and the joining of a bundle of iron wires.[2] It has been pointed out that Joule was anticipated in some of his ideas by Lord Kelvin, then Professor William Thomson.[11] However, the ideas and experiments of Kelvin, Staite and Joule made little impact at the time, and the credit for the introduction of joining methods foreseen by them is usually given to other men who appeared later on the scene. It is perhaps of interest to note that as early as 1849 the LaGrange-Hoho Company used electrical-resistance heating for initial heating before forging, in the manufacture of water-pails.[7]

With the discovery by Davy of acetylene in 1800,[10] and the discovery of oxygen independently by Priestley in England and Scheele in Sweden in 1774,[2] the foundation was laid for gas welding and gas cutting. Some give a later date for Davy's discovery of acetylene, but this is of little consequence, because use was not made of the new gas for welding and cutting until early in the twentieth century. As early as 1847, Robert Hare of Philadelphia successfully used the oxy-hydrogen flame to melt 2 lb of platinum.(12) It was not then known that the oxy-acetylene flame is much hotter.

Another interesting discovery, that was not to be turned to practical use for some time, was the violent reaction that occurred between aluminum powder and metal oxides (notably iron oxide) when heat was applied; this was remarked by the Tissier Brothers in 1858.(7)

Faster rivetting was made possible in 1837 with the introduction of a rivetting machine by Sir William Fairbairn.(7) It was greeted with alarm by the boiler-makers, and strike action was suggested.(7) Metal fasteners were becoming much lower in cost by about 1850 and in the years that followed, with the introduction of semi-automatic manufacture.(2) Prior to this time, bolts, for instance, were usually made individually by the blacksmith.(2)

Various methods were suggested in this period for making welded tube, and most of these found application for a time. In 1808, Benjamin Cook was granted British patent No. 3122 for making welded tube.(7) Osborn, in

1812, introduced machinery for welding the barrels of fire-arms, etc., using a method in which the sheet edges were lapped and welded.[7] The first butt-welding process appeared in 1821, when James Russell of Wednesbury succeeded in making butt-welded tube, using a mandrel and a tilt hammer. Cornelius Whitehouse was responsible for further development of the butt-welding process in 1825.[7]

In the period 1840-1844, better methods of lap welding were worked out, using a mandrel and grooved circular rolls.[7] By the end of the period being discussed, both lap-welded and butt-welded tube were being made in large quantities. In connection with forge welding, it is also of interest to note that the company of Birkenshaw-Bedlington Ironworks, which produced rolled iron rails as early as 1820, proposed to join lengths of rail by welding;[7] unfortunately, it is not recorded whether or not this was attempted.

Flow welding was tried in 1870, to provide steel tires for railroad car wheels. The heated tire ring was placed in a mould, and the hub and plate cast into it.[7] In a talk by F. J. Bramwell[13] in 1875 to the Royal Society of Arts, the method of making the tire was described. One end of the strip was forked, by hammering, to fit over the other end. The joint was compressed by screw action while heated in a fire. Bramwell records that it was usual practice to place a mark near the welded joint to show its position, as a warning to avoid drill holes or other weaknesses in the vicinity.

In the last example, the welded joint was regarded as a kind of defect, indicating an attitude that would end the period on a sour note for welding. To offset this, it may be noted that an obscure mechanic in Philadelphia, on January 5, 1873, proposed to join whole ships by welding.(7) He claimed to have invented machines to accomplish this, and pointed out that great savings in time and money would be possible, combined with an increase in strength and durability of the ships.(7) This early vision was quite striking, since the means at hand were far short of those required for its fulfilment.

THE APPEARANCE OF THE MAJOR WELDING PROCESSES
PERIOD 1877 - 1903

Before 1877, the only welding processes known were forge welding, flow welding and cold-pressure welding, together with soldering and brazing, all of which had been known for at least 3,000 years. In the comparatively short period of 26 years between 1877 and 1903, the following major processes made their appearance (not necessarily in the order given):

<u>Resistance Welding</u>

1. Resistance butt welding
2. Spot welding
3. Seam welding
4. Projection welding
5. Flash-butt welding

<u>Arc Welding and Cutting</u>

6. Carbon-arc welding
7. Plug welding
8. Arc cutting and piercing
9. Metal-arc welding (bare wire)
10. Metal-arc welding (coated electrodes)

<u>Gas Welding and Cutting</u>

11. Oxy-acetylene welding
12. Oxy-acetylene and oxy-gas cutting

<u>Other Methods</u>

13. Thermit welding

Rather than to adhere to the precise order in which the individual modifications appeared, it is more convenient to consider separately each group of processes.

(a) Resistance Welding

Professor Elihu Thomson is usually given the credit for originating resistance welding. An accidental discovery with far-reaching consequences was made while Thomson was giving a lecture in 1877 to the Franklin Institute in Philadelphia.[2,11,14] While demonstrating the reversibility of the transformer (sparking coil), he connected several Leyden jars across the secondary terminals, and held together the terminals of the primary winding.[14] The terminals stuck together and could not be pulled apart.

Thomson was aware of a current problem of dynamo construction, in that only short lengths of wire were available from the wire manufacturers.[14] The frequent joints made by soldering or brazing were often too thick, so that smooth winding was difficult.[14] He commenced experiments[11] and in the period 1883-1885 constructed a resistance-welding machine[2] (butt welder), for experimental purposes.[15]

For a long time Thomson displayed very limited vision about the possibilities of resistance welding, as is illustrated by the fact that in lectures given by him in 1886 and 1887 he was still talking about the butt welding of wires for windings as being an important application.[11] This single possibility had occupied his thoughts for a period of ten years. His first patent in 1885[16] and the welding machine demonstrated at the American Institute Fair in 1887[2] were both for resistance butt welding. This was in fact less important than the other resistance-welding processes that followed, and had found few applications by the end of the nineteenth century.[1]

In view of this early limited vision, it is all the more remarkable that Thomson succeeded in making himself the czar of resistance welding in the period that followed. His remarkable empire was built over a period of forty years, from 1884 to 1924. The basic patent in 1885[16] was followed by others in the following year.[2,11] Thomson was a prolific inventor, and was granted ninety-seven patents related to resistance welding,[16] apart from patents on generators, motors, lamps, meters, welders, transformers, insulation, and many other matters.[16] He also attracted to himself a group of collaborators, Coffin, Dewey, Lemp, Rasmussen and others, who themselves were granted over fifty patents in the field of resistance welding.[11] His group also acquired the rights to the patents of other inventors.[11]

Thomson's company, the Universal Electric Co. of New York, basically owned the rights to the process of resistance welding. The system that they used was to lease the welding machines to users for a given rental, and to impose an additional levy of 25-33% of the savings effected by the new method of joining.(11) In 1888, Mr. M. A. Jevons of Birmingham was appointed the British agent for the Thomson interests.(14) Jevons himself invented and patented a process for the seam welding of tube, equipment for making welded chain, etc.(14) He was also the central figure of the company formed later, Pontelec Welding Patents Ltd., as an agency for Thomson.(14) An early resistance-welding machine by the Thomson Electric Welding Co. is shown in Figure 4.

The increasingly profitable arrangements persisted for many years and even as late as 1916 resistance welding was still virtually in the hands of one company.(11) In that year, five other companies were licensed to make resistance-welding machines.(11) The period of monopoly was accompanied by many claims, counter-claims and lawsuits.(11) Perhaps of most importance were the patent issued to Coffin (of the Thomson group) for flash-butt welding in 1889,(2,11) four patents to Coffin for spot welding in 1890,(2) patents to Thomson for seam welding in 1890,(11) a patent to

Robinson for projection welding in 1897,[2] a patent to Kleinschmidt for the use of copper electrodes in spot welding in 1898,[11,15] and a patent to Harmatta for spot welding in 1903.[2,11] Bouchayer patented the use of duplex copper electrodes for spot welding in 1903.[15] A long legal battle between Harmatta and the Thomson group for the proprietorship of spot welding was not ended until 1924, and was concluded in Thomson's favour.[11]

Coffin's process of flash-butt welding required a higher voltage than resistance butt welding, and pressure was applied in two stages, permitting local arcing to facilitate heating at the interface.[11] This was destined to become the most important of the butt welding processes, resistance butt welding being relegated to the wire-joining application for which it was initiated.[11]

Seam welding was first carried out using circular copper electrodes and continuous current.[11] This proved to be satisfactory only for thin-gauge material.[11] Its application was limited because of excessive roller wear. Around 1891, a great improvement was effected with the introduction of intermittent current to produce a series of overlapping spot welds instead of a continuous seam.[11]

Several applications for resistance welding appeared in the latter part of the 19th century. As early as 1879, Alexander Siemens saw that Thomson's idea might be applied to the joining of cables.(11) In 1881, he succeeded in joining the armouring wires of cable,(11) using 60-100 amp at 20 volts. The wire diameter was in the range 0.073 to 0.13 in. The ends were scarfed rather than butted. Under tension, about half the test lengths broke outside the joint.

Many examples of the application of resistance welding were cited by Duff in a lecture in 1893 to the West of Scotland Iron and Steel Institute;(11) these included pipes, chain links, copper-to-brass and lead-to-brass joints, iron axes with welded-steel tip, wheel tires, bicycle hubs and gun barrels. In the same year, J. C. Perry introduced electrically-welded fence fabrics for the Bates Machinery Company.(7) Towards the end of the 19th century, the resistance butt-welding process was used for joining rods and wires for wiredrawing.(1) McBerty is credited with the first commercial application of spot welding in 1901.(2)

(b) Arc Welding and Cutting

It is generally accepted that the first man to use the heat of the arc for joining was Auguste de Meritens. With a carbon electrode as the negative pole, he made joins in lead plates for storage batteries, in the year 1881.[2,15] However, it was a pupil of his, N. de Benardos, who is usually given credit for the invention. This is justified by the fact that it was Benardos who brought the possibility to public attention. He also showed remarkable insight into the potentialities of welding.

In 1885, Nicholas de Benardos (Gentleman) and Stanislaus Olszewski (Engineer of St. Petersburg) secured British Patent No. 12984.[14] The following extracts[14] give some idea of the scope of the invention:-

"An improved method of and apparatus for

1. The union of metals.
2. Their disunion or separation.
3. The formation of apertures in metals.
4. Union of metals in layers." (Presumably Benardos had in mind the fabrication of thick armour).

"The process, which we call electrohephaest, consists of the formation of voltaic arcs, when necessary------"

"This process of working metals may be combined with a gas apparatus, whereby gas, or a mixture of gases, could be introduced by pipes into the voltaic arc, to increase its tension-----"

"Electrode----either a solid or hollow pencil or rod. The hollow carbon is filled with various metals or their alloys, which play the part of solder."

A sketch of the original apparatus is shown in Figure 5.

It seems quite clear that Benardos and Olszewski should have the credit for introducing the generalized concept of carbon-arc welding. Their description of the use of the carbon arc for piercing, for making apertures, and for generalized cutting operations also leaves no room for doubt. It has been suggested that the original patent wording covers spot welding,[11] but this is difficult to substantiate. It is true that the inventors mention the joining of metals at discrete spots, but they probably had in mind a series of plug welds, using the arc to melt through two or more layers of the plates to be joined. This was still an advanced idea, and it is interesting to remember that Elihu Thomson was still absorbed with the butt welding of wires and rods at this time.[11] It has even been suggested that Benardos and Olszewski invented metal-arc welding,[14] but this seems to be incorrect. The idea of welding with a hollow carbon electrode containing metal does not constitute metal-arc welding; in fact, the suggestion sounds impractical, and does not appear to have been mentioned thereafter.

The Benardos and Olszewski patent was a far-sighted and original document which must have been very stimulating at the time. They had envisaged the following possibilities:

(1) Carbon-arc welding in continuous or intermittent seams
(2) Plug welds, for use in "spot" welding
(3) Cutting and piercing with the carbon arc
(4) The welding of headless rivets
(5) The use of rolls and automatic hammers for "purposes of further cohesion", later to be known as peening
(6) The use of welding for building up metals at chosen locations
(7) Manipulation of the arc atmosphere
(8) Constructional possibilities, inherent in welding, far in advance of the repair techniques that were the preoccupation of the early users of arc welding

In 1885, Zerner introduced a carbon-arc welding process using two carbon electrodes (Figure 6), in which the arc was directed downwards with a magnetic field.[15]

This process, and the "Voltex" process, which used a carbon electrode impregnated with metal oxide, saw limited trials in Germany, but ultimately proved to be impractical.[15]

In 1887, Benardos undertook further work with the carbon arc and demonstrated the feasibility of the method for the repair and joining of ferrous materials.[2] He tried to do the same for spot welding,[15] but was less successful. In the following year, he obtained patents for welding equipment, and for elaborations of the carbon-arc welding process.[11,15]

The credit for introducing metal-arc welding, using bare electrodes, belongs to the Russian, N.G. Slavianoff, and according to Russian sources he put forward this idea in 1888.[10] The earliest English reference to his work appeared in 1892 with a brief abstract[17] of a paper by Slavianoff[18] on the possibilities of the method for welding, and for the repair of broken machinery.[17] The metal rod was to be joined to one pole of a dynamo, and the work to the other.[17]

In the United States, Coffin, working independently of Slavianoff, also conceived the idea of using metal electrodes, and took out patents for metal-arc welding in 1892.[11]

Welding with bare metal electrodes is difficult, and it was in 1889, the year following Slavianoff's invention, that Arthur Percy Strohmeyer introduced coated metal electrodes.(14) Strohmeyer was associated with the Quasi-Arc Company of London, now in Bilston. He had found that metal electrodes performed better with a wash coating of clay or lime.(2) There is a story that it had been observed that rusty electrodes performed better than those not so affected, but whether this was known to Strohmeyer is not recorded.

The arc-welding processes began to find applications in the last years of the 19th century. Carbon-arc welding was first used commercially by Lloyd and Lloyd, now Stewarts and Lloyds, of Birmingham, in 1887.(14) It has been reported that carbon-arc welding was on a sound commercial basis from about 1894.(14) It was also used before 1900 to make metal barrels by the Steel Barrel Company Ltd. of Uxbridge.(14) An employee of that company, Mr. T. I. Heaton who apparently had not heard of Slavianoff's work, had suggested in 1893 the possibility of using mild steel electrodes for welding, but though the idea was tried it was not pushed to a successful conclusion.(14)

Arc cutting was impressively demonstrated in 1902 in the removal of an enormous boiler foundation in Milwaukee.

The contractor did the work quickly and efficiently, using carbon-arc cutting.[19]

The advantages of coated electrodes over bare electrodes were not immediately apparent, and both methods for a time made independent progress. By 1890, Slavianoff in Russia was demonstrating the use of bare electrodes for the welding of wrought iron, cast iron and steel.[4] Metal-arc welding began to be used in England and in the United States for repair work on the railways and for other purposes, towards the end of the 19th century.

(c) Gas Welding and Cutting

The final foundations were laid for oxy-acetylene welding and cutting.

Taking advantage of the development in 1880 of the Brins process for the production of oxygen,[1] Thomas Fletcher, of Warrington, introduced in 1887 a blowpipe, burning hydrogen or coal gas with oxygen.[1] He showed that the blowpipe could be used to melt metals or to cut steel. Almost immediately, this was used successfully in practice, the first application being for safe-breaking. At the time, bankers and others were seriously alarmed.

In 1884, Z. Wroblewski and K. S. Olszewski, Cracow University, Poland, succeeded in liquefying air,[2] and this was later to become the basis of a cheaper method introduced by Carl von Linde in 1893 for commercial oxygen production.[2] Finally, oxy-acetylene welding became possible with the development by Fouche and Picard in 1903 of a torch suitable for use with low-pressure acetylene (15 pounds per square inch).[2] Earlier, in 1901, Fouche had made an experimental torch for use with high-pressure acetylene.[11]

(d) Other Methods

In 1895, C. Vautin studied the reaction between metal oxides and aluminum powder,[2] and showed that, even with substantial quantities, the reaction occurred quickly and was usually over in less than 30 seconds. Moreover, high temperatures were obtained, in excess of 5000°F. Vautin may not have been aware of the work of the Tissier brothers in 1858. In any case, no commercial use was made of the studies until 1898, when Dr. Hans Goldschmidt showed that the Vautin process could be used for welding.[7] He patented this application under the name thermit welding, and in 1902 he demonstrated its use for the joining of iron bars and the repair of rails, ship rudders, mine equipment, etc.[2] In 1903, thermit welding was first successfully used in marine work for the repair of large castings and for joining large cast components.[19]

The retention of the older processes contrasts strangely with the advances made in the latter part of the 19th century. In 1878, it is recorded that smith's work was required on the New York elevated railroad.[20] For this purpose the smith had a small forge and anvil high over the city. The work he had to do would include forge welding in the way known from early times.

In 1887, the first steel pipe was made, using both lap-welding and butt-welding methods developed earlier for wrought iron.[7]

WELDING PRIMARILY AS A REPAIR METHOD
PERIOD 1903 - 1918

This was a period in which many trends may be discerned. The advantages of oxy-acetylene welding and the good control that it offered tended at first to stifle the proper development of arc welding.[4] Resistance welding flourished and produced new methods and applications, and was never regarded primarily as a repair technique. Looking back with the present-day point of view, it seems most characteristic of the period that gas welding and, particularly, arc welding were regarded primarily as tools of repair. Consequently the full potential of welding for construction and fabrication was not realized.

(a) Resistance Welding

Percussive welding was invented in 1905.[15] A few years later, in 1912, a United States patent was granted to Harmatta for spot welding,[11,15] following his application in 1903. However, this was finally to be revoked in favour of Thomson in 1924.[11] In 1913, Kleinschmidt, then with the Lorain Steel Company, accidentally rediscovered flash welding.[10,11] The method had not been used much until that time, but the increased production during the war years gave an impetus to its application.[11] The important modification, projection welding, was put forward by Hamilton and Oberg in the United States in 1918, and apparently resulted from an accidental discovery.[11] It was noticed that local welding occurred at centre-punch markings on an otherwise flat surface.[11]

Applications for resistance welding and, particularly, spot welding expanded rapidly during the period under discussion. Spot welding, according to Hornor, was used in England from about 1905 onwards, at first in the manufacture of domestic hollow ware.[11] In 1909, a catalogue of the Thomson Electric Welding Company describes butt welders, seam welders and spot welders. It is interesting to note that flash welders were not mentioned at this time.[11] Spot welding was used in 1911 to make a steel gondola car for the railways in the United States.[11] Its application for car production started around 1912.[11] The spot-welding machines used were small by modern standards, with an average capacity of about 15 KW, and about 60 KW maximum. Even so, it is recorded that in the Dodge Brothers automobile plant, with 67 spot-welding machines, the main fuse was often blown.[11] By 1917, spot welding had become a necessity for automobile production, for the construction of bodies and other parts.[11]

(b) <u>Arc Welding and Cutting</u>

Improvements in transformers, notably with the introduction of silicon steel by Hadfield (Figure 7), began to make alternating-current welding a more practical possibility.

An important advance for metal-arc welding came in 1907, when Kjellberg obtained a patent for certain electrode coatings.[2,4,14] The earlier wash coatings by the Quasi-Arc Company had done little more than help to maintain the arc, but Kjellberg perceived that the covering could be made to serve other functions. Two extracts from the application[14] follow:

> "Gaseous flux process------covered with a sleeve of non-conducting material---so that the sleeve projects----but forms a guide for the

molten metal. The sleeve protects the metal from oxidation and reduces heat losses."

"-----sleeve can be made the vehicle for constituents that will give the desired characteristics to the added metal."

In a second patent in 1912, Kjellberg gave more details of satisfactory mixtures for coatings, and reference was made for the first time to the use of powdered ferro-alloys in the coating, as a convenient method of addition in place of alloying the steel core wire.(2)

In England, a little later than in Sweden, coated electrodes made an early appearance. The Quasi-Arc Company introduced metal electrodes wrapped with blue asbestos yarn (ferrous silicate), with an aluminum wire incorporated of a diameter corresponding to 2% of the electrode cross-section.(14) The melting point of the flux was controlled by further additions of sodium silicate and aluminum silicate.(14) The original idea had been to lay the coated rod in the seam, and to melt it in position with the carbon arc.(14) However, spurred by the difficulty of overhead welding, the more direct idea of using the rod itself as electrode was soon tried.(14) The company explained that the arc should be formed with the electrode vertical, but that the electrode should then be dropped back to form an angle with the work.[14] The arc would soon be extinguished as the coating passed to an "igneous state", but the resultant slag would act as a secondary conductor, maintaining electrical contact.[14] The coated electrodes were supplied in various sizes from 14 gauge (B.S.W.) to 3/8 in. diameter.[14] The largest size required a welding current of 300 amp. Cutting could also be accomplished using an 8-gauge electrode at 200 amp.[14] The company suggested that the new welding method would be suitable for constructional work including ship construction, pressure tanks, air-receivers in boiler work, the reinforcement of iron plates, crankshaft journals, key beds, hydraulic rams, and repairs generally.[14] One customer of the time said that the process was satisfactory with female and other unskilled labour.[14]

A changing attitude, rather than a technical advance, was marked by the collaborative tests commenced in 1917 by Lloyd's,* the British Admiralty, and United States authorities to determine the strength of welded joints.[21] It was recognized, at least implicitly, that welding had become a competitor for rivetting.

In 1917, Jones in the United States produced the first electrodes with extruded coatings.[4] The importance

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*The abbreviated form for Lloyd's Register of Shipping, London.

of the invention derived from the coating uniformity that resulted. The dipped coatings available prior to this were uneven and resulted in erratic behaviour. Eventually, extruded coatings became almost universal.

In the application of arc welding in the period under discussion, there is an emphasis on repair work. In the early years of the century, arc welding began to be used in England and in the United States for repair in railway work.(14) Lloyd's recorded that in March 1906 repairs were made by arc welding to the combustion-chamber seams of a boiler, and that subsequent examination years later showed that the repairs were satisfactory.(21) In the period 1906-1911, Lloyds' records show that 160 boilers were repaired by welding.(21) There were, in addition, twenty arc-welding repairs to the hull structures of ships in the same period.(21)

In 1907, Kjellberg was recommending metal-arc welding for the repair of massive boilers, stern frames and other parts of ships, and for building-up operations on worn parts, propeller shafts, crankshafts, and axles.(14) Significantly, he felt constrained to add that arc welds and resistance welds could be as reliable as acetylene welds and blacksmith welds.(14)

Welding was employed to exceptional advantage in rendering damaged enemy ships seaworthy. In 1917, after the entry of the United States into the war, there was a total of 103 interned enemy ships in United States hands.[19] These were extensively sabotaged. In New York alone, there were 31 steamships, which included four small steamers and two sailing ships only slightly damaged; the remainder were in the size range from 3,900 to 56,000 tons and were seriously damaged and useless for transport.[19] The sabotage had been done using battering rams and sledge hammers, and also by drilling, and the most serious damage incurred was to cast-iron parts such as cylinders, liners, pump-casings, etc.[19] The re-servicing methods at first proposed would have been costly and too protracted for war service; they involved, for example, complete replacement of 70 steam cylinders.[19] Capt. Jessop, the United States Engineer-Officer of the New York Naval Shipyard, suggested the extensive use of welding for repair.[19] The suggestion was boldly adopted and resulted in great savings in time and money.[19] Eighty-two of the gravest injuries were repaired by welding, and thirty-six others were repaired by mechanical methods.[19] The money saved was estimated at twenty million dollars, and the repaired ships transported half a million troops to France.[19] Figure 8 shows the welding repairs made to one of the sabotaged vessels.

World War I (1914-1918) gave a great impetus to welding, the number employed in welding operations rising from about 8,000 just before the war to 33,000 at its end.[19] Unfortunately, welding was becoming known mainly as a repair technique.[4] It is interesting, therefore, to turn to the idea of using welding for construction.

The possibilities of welding for ship construction were being realized in this period. In 1918, it was reported that a partly-welded ship, the "Dorothy M. Geary", had been in service on Lake Erie for a number of years.[4] The hull of this ship was welded, and a certain amount of welding had been used on the decks.[4] The first all-welded ship was a 125-ft barge launched in 1918 and built at Richborough for the British War Office.[21] In 1920, Kjillberg was responsible for the first all-welded ship built to Lloyd's approval, the "S.S. Esab". Shortly after the entry of the United States into the war, the Council of National Defence set up an Engineering Committee to investigate the possibility of using welding in the shipyards.[19] Later, this committee work was taken over by the Emergency Fleet Corporation, and its scope was broadened to include acetylene and thermit welding along with arc welding.[19] After the Armistice, the American Association of the Welding Industry was created and this body assisted in maintaining a Bureau of Welding.[19]

In 1918, Lloyd's in England issued "Tentative regulations for the application of electric arc welding to ship construction".[14] It is interesting to see that they demanded, for welded specimens, comprehensive mechanical testing for elasticity, elastic limit, ultimate tensile strength, and elongation; fatigue, cold bending and impact tests; and, in addition, chemical analysis and macroscopical examination.[14] The impact test somewhat resembled a modern drop-weight test, in that heavy weights were dropped onto welded plates, the deflection and condition of the plates being examined after each blow.[14]

In 1918, comparative tests were being made in the United States to examine the strength of various joints in which rivetting, spot welding, fillet welding and butt welding were used separately and in various combinations.[14] They showed that a simple butt weld was usually best.[14]

(c) Gas Welding and Cutting

The handling of acetylene was made very much safer with an invention of T. G. Allen in England in 1916. The acetylene, dissolved in a liquid solvent, was mixed with a solid absorbent, Kapok.[19]

The fact that little space is here devoted to oxy-acetylene welding should not disguise the important advances made in this period. It was regarded as the most satisfactory and reliable method of joining, offering good control. Many applications were found, both for repair and for construction.

(d) Other Methods

Pressure thermit welding of rails was introduced in 1906.[11] Thermit welding found application for the joining of rails, repair of large castings, etc., in the period under discussion.

WELDING FOR CONSTRUCTION AND FABRICATION
PERIOD 1919 - 1951

In this period, welding continued to grow in complexity, both in method and in application. Some tendencies that were beginning to appear towards the end of the previous period, i.e. the assessment of welds by testing, the control of welding by more careful techniques, and the use of specifications and inspection, were also much extended. However, the most characteristic trend of the period was the recognition of the inherent possibilities of welding, and particularly of arc welding, for construction and fabrication.

An index of the growth of welding is that Lloyd's approved six welding processes in 1922, and thirteen in 1931.[21] Today there are over forty satisfactory methods.

The complexity of metal-arc welding is symbolized by Lloyd's' list (1959) of 1200 approved electrodes.[21]

(a) Resistance Welding

In 1920, copper-tungsten alloy electrodes were first used for spot welding,[2] and soon became popular because of the extended life that they offered. Also in this year, better current-interrupting devices became available, which facilitated the application of seam welding to metal of thickness in excess of 20-gauge.[16]

Resistance-welding processes were rather poorly controlled at this time; for example, J. H. Davies, writing in 1922, said that no preparation of the metal surfaces was necessary for spot welding, except that they should be cleaned if they were very dirty.[19]

Harmatta's patent for spot welding, for which he made application in 1903, was finally invalidated by the U.S. Supreme Court in 1924, in favour of Elihu Thomson's patents.[2,11] In the period 1930-1932, thyraton tubes were first used in place of mechanical contactors for supply-line interruption to time the current pulse in spot welding,[2,12] and in 1934, a further improvement was made with the development of the ignitron control.[11] Further developments appeared around 1939 with the development of stored-energy machines, and after 1950 with the introduction of three-phase spot welders, facilitating the application of the method for the light alloys.[11] There were also considerable advances made in the timing of the welding current, using electronic devices. Similar devices were used for controlled heat input before and after welding, and there was an increasing trend towards making the machines fully automatic.

Applications for resistance welding increased quickly, partly as a result of the variety of welding equipment that became available. Even in 1920, there were many spot-welding and butt-welding machines of different design and both processes were well established;[11,15] for example, butt welders specifically for chain making became available.[15] In 1920, a wide variety of resistance-welding machines was available in England from British Insulated and Helsby Cables Ltd., and the following list of applications illustrates the multiplicity of purposes for which resistance welding was recommended and used:[14] pipes, refrigerator coils, milk-can rings, perambulator rims, printer's chases, fittings to casement frames, carriage and coachwork parts, trellis work, coupling links, brake rigging, travelling-bag frames, tipped tools, drills, taps, valves, etc.; enamelled hollow ware, tanks, pulleys, straight sheet iron tubes and elbows, fittings to chassis, etc.; machinery guards; sheet and expanded metal to flat and profile iron for shelves, lockers, etc.; and agricultural machinery parts, fuses, fan propellers, tin ware, lattice for reinforced concrete, etc.

E. Viall,[15] writing in 1921, said that although spot welding was used mostly for joining thin sheets of iron, mild steel or brass, it could be used for practical work with plate up to 3/4 in. thick, and had been used experimentally to join together three layers of steel each one inch in thickness. According to this author, resistance welding at this time (1921) appeared to be more highly developed as a constructional tool than the other major welding processes.[15] Resistance welding had been so successful, in fact, that its protagonists overreached themselves. At about this time, in 1920-1921, the General Electric Company in the United States completed an experimental spot-welding machine with 100,000 amp capacity, and capable of applying 75,000 lb load.[14] However, the maximum values used in practice appeared to have been 72,000 amp with 30,000 lb load for spot welding one-inch-thick steel plate.[14] Another huge machine made in the United States at this time was a duplex spot welder (Figure 9), which was designed to make two spot welds simultaneously in 3/4-in.-thick steel plate.[14] This machine had a maximum capacity of 50,000 amp and was capable of applying a load of 30,000 lb on each of the electrodes.[14]

These gigantic machines were intended for the prefabrication of ship hulls,[14] but were not used for this purpose. They were never fully developed, because they had the same disadvantage as rivetting in requiring lapped joints.[11] The simple butt joint made possible by arc welding invited economy with a considerable saving in weight, and this dominated the course of ship-construction practice. The huge spot-welding machines suffered the fate of the dinosaur, and no mention of them may be found a few years after their first appearance. Even larger spot welders have been used in later times but applications are limited.

Viall[15] recorded in 1921 that mixed joints--for example fillet welding and spot welding used in combination, or spot welding and rivetting used in combination--were becoming less common, and that the practice of using mixed joints was not to be recommended. According to Hall, it was not until about 1926 that seam welding became a really satisfactory operation.[16]

In 1924, the Lackawanna Steel Company introduced machines for the butt welding of tramway rails.[11] This produced satisfactory results, but, in England at least, the machine was thought to be too expensive.[11]

In the period from 1927 to 1937, 3,800 miles of rail on the German railroads were joined by flash-butt welding, and this became the preferred method.(11)

The development of three-phase spot welders, from about 1939 onwards,(16) eventually led to applications for the joining of light alloys.(11) An example, from late in the period under discussion, of a modern resistance-welding machine developed for specific purposes, is shown in Figure 10.

As early as 1933, the Northrop Aircraft Company realized the possibilities of resistance welding for aircraft construction, and commenced testing.(22) Aircraft with spot-welded parts were in production during the second world war, including the P-61 Black Widow with spot-welded booms.(22)

(b) Arc Welding and Cutting

In 1920, Wortmann introduced an alternating-current welding transformer.(10) This type of source was not suitable for bare electrodes, but coated electrodes were developed for use either with direct-current or alternating-current sources. The two types of power source were each found to have a distinct set of advantages, and both types are in use today. At about this time, it was becoming desirable to standardize on either direct or alternating current for general power supply. The competing interests involved put forward many claims and counter-claims, not all of them genuine, resulting in much confusion.(14)

M. Roberts and van Nuys carried out some tests in 1919 on the effect of various shielding gases on the arc,(10) and, in 1920, Hobart and Devers made a similar study, culminating in a proposal to use argon and helium for shielding purposes.(2)

Necessary for the implementation of the new ideas for using welding for construction and fabrication was a realization of the importance of applying metallurgical knowledge to welding control. Until this time, the quality of welding was largely in the hands of the operator. For example, in 1922 Davies naively reported that most operators did not think that a flux coating was necessary on metal electrodes,(19) as though this antipathy had some technical significance. The same author was advocating at this time the training of operators on the lines then customary in Germany:-(19)

> "German operators are scientifically trained--taught chemistry and metallurgy---employ microscopical and macroscopical examinations."

The need for better metallurgical knowledge is illustrated by the composition of wires available in 1922 for the metal-arc welding of thin-walled tanks:-(19)

C	Mn	Si	P	S
0.05-0.19%	0.02-0.16%	0.03-0.08%	0.010-0.032%	trace-0.08%

(A higher manganese level of 0.56% was present in one composition.)

This shows that the sulphur content could be rather high, and that the manganese and silicon levels were in general too low. Davies(19) made the comment that welding wire must be free of phosphorus, sulphur, manganese, and other impurities.

Another illustration of misinformation is also provided by Davies,(19) who stated that protracted hammering, or low temperatures, leads to "crystallization" in the metal. This old theory of Tschernoff(23) (c1862 A.D.) dies hard, and is still current in lay opinion.

However, in the period 1919-1922, Lloyd's, the British Admiralty and others in England, and also the Research Sub-Committee of the Emergency Fleet Corporation headed by Spraragen, the Bureau of Standards and others in the United States, were sponsoring investigations, devising mechanical, physical and chemical tests suitable for welded joints, and issuing specifications.[14,15,19] There was much to be done. One of the tests developed at the time was a bend test in which a slice was cut across the welded joint, and afterwards bent in a vice, using an iodine etch to detect flaws and cracks.[19] Metal-arc welds had rather poor properties associated with nitride and oxide inclusions in the weld metal.[19] It was noticed that porosity often occurred in welds on mild steel, then defined as a steel with less than 0.5% carbon content.[19] The microscope was used to some extent, and many of the welding defects, for example nitride inclusions, could be reasonably identified.[15] However, the structure of "satisfactory" welds as illustrated by photomicrographs of this time[15] would not inspire much confidence today.

In 1921, the temperature of the arc was estimated to be in the range 3500-4000°C,[15] and, though an under-estimate, it illustrates the application of a more versatile scientific approach.

There was in 1920 a difference of opinion on whether or not it was good practice to use a flux covering on metal-arc electrodes.[14] However, a trend to use more coated electrodes and fewer bare electrodes could be noted at that time both in England and in the United States.[14]

It was stated in 1922 that copper and aluminum alloys were difficult to join and that welded joints in these materials should be paid careful attention if they were to be used for purposes of construction.(19) On the other hand, the welding of cast iron was a relatively simple process.(19) Today the position is reversed: copper and aluminum alloys are often fully weldable, whereas the welding of cast iron, in which little progress has been made, may be a source of some anxiety.

In 1930, Hobart and Devers patented the use of a refractory electrode in conjunction with argon or helium atmospheres.(2) This was the basis of inert-gas tungsten-arc welding, which was to make possible the easy joining of magnesium alloys, aluminum alloys, stainless steels, copper alloys and many other materials that would have been difficult to join by other means.

After some experience had been obtained in the welding of boilers and vessels by metal-arc welding, codes appeared in 1931 to control its use in all-welded power boilers and unfired pressure vessels.(2)

Submerged-arc welding, another new arc-welding process, was first used commercially at the Consolidated Steel Company in Los Angeles in 1934.(2) In this method, the arc is buried under powdered flux. It permitted high current densities, and was easily adaptable to automatic use, so that much higher speeds could be used in welding thick steel sections. The method was patented in the United States in 1935.[4]

The first commercial use for inert-gas tungsten-arc welding, foreshadowed by the invention of Hobart and Devers, was for the joining of magnesium alloy assemblies by Northrop Aircraft Inc. in 1948.[2]

Atomic-hydrogen welding, which had been developed earlier, tended after this to be overshadowed by the more successful inert-gas tungsten-arc welding, although still finding occasional applications.

Submerged-arc welding was invented in the U.S.S.R. by the Paton Electric Welding Institute of the Ukrainian Academy of Sciences in Kiev in 1940,[10] six years after it had been used successfully in practice in the United States!

Another new process was inert-gas metal-arc welding using a consumable electrode, introduced by the Air Reduction Company in 1948.[2]

In the period 1919-1951, welding, and particularly arc welding, became the most important metal-joining method for construction and fabrication. It was in ship construction that this tendency may first be noticed. In 1919, the Cast Steel Corporation of New York made plans for casting the component parts of ships and joining these by welding.(7) However, this did not prove acceptable. Vessels of rolled steel plate could be made cheaper and lighter. The first all-welded sea-going ship was a coaster, "Fullager", of 500 tons and 150 ft in length, built in 1920 by Cammell Laird under Lloyd's' Survey.(4,21) After this time, progress was rapid. Sweden, which had always made good use of arc welding for ship repair,(14) was quick to take advantage of the savings offered by welded ship construction. Other maritime nations followed suit.

It is significant that the books on engineering of around 1920 made no mention of welding.(24) No doubt this would have been defended on the grounds that welding was not sufficiently controlled to submit to the discipline of engineering. Whatever the reason, there was a failure by engineers to comprehend the potentialities of welding for construction. In 1920, the first all-welded building was erected. This was a small mill building, 60 ft by 40 ft, erected by Leonard MacBean in Brooklyn for the Electric Welding Company of America.(15) It is amusing to recall that local approvals were not granted until each of the trusses had been loaded with gravel bags to give 48 tons dead weight.[15]

At about this time, 1919-1922, arc-welding equipment was available in great variety, including many portable sets.[14] Often the equipment was mounted on light trucks[14] to facilitate contract work.

Metal-arc welding was beginning to grow, and found new applications at the expense of other methods. Metal-arc welding was used much more often around 1920 than carbon-arc welding.[14,15] One of the important reasons for this was the advantage of metal-arc welding over carbon-arc welding for vertical and overhead work.[19] In addition, it was recognized in general that, for thick steel exceeding about 3/8 in. in thickness, arc welding was faster and cheaper than oxy-acetylene welding.[19] On the other hand, the carbon arc was thought to be better for cutting.[19] Metal electrodes could be used for cutting but required occasional cooling by dipping them into water.[19]

In 1921, arc welding was used extensively in shipping work, on the railways, and generally in industry, though there was still an accent on repair work for these applications.[15] One example of welded fabrication from about this time was the production of arc-welded tipped tools.[15]

In the period approximately from 1925-1935, welded design began to appear;[2] design was affected by the new ways of construction made possible by welding, for ships, tanks, buildings, pipelines and bridges.[2] In the same period, large all-welded engineering structures began to make an appearance, at first in Germany and then in the United States.[24] In 1930, the first all-welded merchant ship in the United States was built in Charleston, S. Carolina.[4]

Germany made good use of welding in preparation for the second world war. After the Versailles Treaty of 1920, a limit on capital ships of 10,000 tons dead-weight was imposed on Germany.[4] About 1930, Germany turned to welding as a means of building war vessels of vastly superior striking power compared with conventionally constructed ships.[4] By dint of hard and brilliant work the problems of welding thick armour were overcome, and the weight saved was used to provide heavier guns, additional armour and greater speed.[4] The German pocket battleships were a success. As a result of similar work, German tanks in 1940 were welded, whereas British and other tanks were of rivetted construction.[4]

Welding was also used very effectively on Allied ship-building programs. In the period 1939-1945, 5,777 welded ships were built in the United States, with a total weight of forty million tons.[21] This number included 2,748 Liberty ships and 705 tankers.[21] A small number of these failed at sea. Many were sunk. The remainder effectively helped to win the war. The occasional catastrophic failure of some of these ships, at that time mysterious, received disproportionate publicity that left welding for many years in lingering discredit, despite the magnificent performance of the great majority.

(c) Gas Welding and Cutting

By 1922, bottled dissolved acetylene was used quite extensively.[19] In addition, new purifiers for acetylene were introduced, providing some improvement; previously, some trouble had been encountered on occasion from the use of impure gas.[19] Torches were introduced in which the danger of "flash-back" was virtually eliminated.[19]

Automatic versions of oxy-acetylene welding and cutting were used in 1922.[19] In one of the cutting machines, the Oxygraph, manufactured by the Davis Bournville Company of the United States, the cutting head followed a drawing with a motor-driven tracer.[19]

By 1922, oxygen cutting was being used to cut steel of 20 in. thickness.[19]

It was recognized by most people at about this time that oxy-acetylene welding was more effective in the thinner gauges, i.e. thicknesses less than about 3/8 in., but that for thicker material arc welding was faster and cheaper.[19]

Despite this understanding, Davies gave an example in 1922 of the welding of $1\frac{1}{2}$-in.-thick boiler plate using oxy-acetylene welding.[19]

Automatic equipment for oxy-acetylene welding was used in 1922 for making long seams in transformer sheet, seam welds in drums and other containers, etc.[19] Reference has also been made to the use of oxy-acetylene welding for the repair of joints in a pipeline, the pipe for which was in the range 4-6 ft diameter.[19]

Oxy-acetylene welding was used for joining aluminum and copper alloys in 1922, but the resultant welds were not always of very good quality.[19] New applications were appearing for the manufacture of aeroplane and automobile parts.[19] Cast-iron welding was described in 1922 as a simple process.[19] Today, the joining of cast iron still presents some problems, but oxy-acetylene welding has remained one of the preferred methods.

(d) <u>Other Methods</u>

In 1922, thermit welding was used for joining railway and tramway rails, and in the construction and repair of large gears.[19] Davies mentions also the repair of a large rock-crushing machine, for which a thermit crucible of 2,000 lb capacity was required.[19]

Cold-pressure welding, although it had appeared from time to time for many centuries, found its first important application in 1935 in the roll-bonding of clad metals.[9] After about 1945, more interest was shown in cold-pressure welding, with a gradual increase in development and applications.[9]

In 1951, electro-slag welding was invented in Soviet Russia,[24] and has beenconsiderably developed in Russia and other Communist countries since that time. It appears to have some merit for the joining of very thick material, and equipment for this process is now available in the United States (see Figure 11) and in Europe.

WELDING AS A SCIENTIFIC TECHNOLOGY TODAY

We have entered a period in which welding is well recognized as a technique of engineering for construction and fabrication. Welding is essential for a good deal of present-day metal technology; without it, high-pressure boilers and jet aircraft would be impractical, and automobiles and a host of other manufactured goods would be prohibitively expensive.

Today, there are over forty distinct welding processes available to join innumerable metals and alloys.

This variety in specialized alloys has appeared because of increasing demands for lightness and greater strength, for better resistance to impact, corrosion, fatigue and brittle failure, and for better service at high temperatures. The same demands are made of welded joints in these materials. It frequently happens, now, that in the development of new alloys, good weldability is one of the prime requirements. For example, the high-strength steels used for nuclear submarines require high strength, good weldability and good notch toughness, and were designed with these three requirements in mind.

In all modern countries, welding research occupies a prominent place. In the United States, the Welding Research Council annually sponsors a great deal of research at various centres. The British Welding Research Association in England has unrivalled facilities. In Canada, apart from Government research, some welding research is being done within industrial organizations and elsewhere.

It is not surprising that there is a current trend for still more research in welding and allied subjects, and an increasing demand for specialists and technicians trained in welding. Welding provides a discipline to extend the abilities of metallurgists, mechanical engineers, physicists and mathematicians. Despite the diversity of its applications, the fact that the technology of welding is founded on and nourished by the basic sciences lends the whole subject a coherency which can attract the academically inclined.

There is a growing literature; a dozen or more journals in the English-speaking countries, including two Canadian journals, are concerned with welding. Various national organizations are represented in the International Institute of Welding and in the work of its fifteen Commissions; over one thousand people took part in the last annual meeting in Liege in 1960.

The review of present-day welding techniques that follows is so brief that some readers may wish to supplement the information by referring to two excellent reviews,[2,25] or to the latest edition of the Welding Handbook.[26]

(a) Resistance Welding

Resistance welding has continued to make important progress in all kinds of metal-manufacturing industries. One of the reasons for this success is the fact that resistance welding lends itself so well to mass-production methods and to automation. The new electronic industry has made especially good use of resistance welding. However, it is in the construction of aircraft and automobiles that resistance welding makes its greatest contribution to our present civilization.

The United States Air Force aeroplane F-89 Scorpion has many spot-welded assemblies, including the engine access doors.[22] Many tests were made before these doors were put into production. Each door has between 1800 and 2800 individual spot welds. Other major structural parts completely spot welded are the keel or backbone, skins, wing tanks, main landing-gear door, etc., and almost all other assemblies are partially spot welded.[22]

Figure 12 shows the X-15 rocket-powered manned aeroplane designed to fly at speeds in excess of 3,600 miles per hour and at altitudes up to about 100 miles. Inconel "X", a nickel alloy, had to be used for the outer skin because of the high temperatures expected from frictional heating; most materials would be ruled out because of the fall in strength under these conditions. Spot and seam welding have been used extensively and it has been claimed that the X-15 has 65% welded construction.

Very large spot welders have been used at the Rouen (France) plant of Enterprises Metropolitaines and Coloniales for the fabrication of 200 composite beams for use in power stations at Volaines and Hornaing.[27] This entailed the joining of the 32 mm flange ($1\frac{1}{4}$ in.) of one beam to the 14 mm web (5/8 in.) of another.[27]

By means of percussion welding, very rapid production rates can be achieved for electric lamps, electron tubes, telephone relays, etc. For percussion welding, a capacitive circuit charged to a high potential (several thousand volts) is discharged across the gap between parts as they approach each other under a propelling force.

Magnetic-force welding permits accurate synchronization of the electrode force and the welding current in resistance welding. This is done by using the welding current to produce a magnetic force acting on the electrodes. It is most useful where welding time is very short. Applications include welding of high-conductivity metals for electrical contacts, commutator assemblies, plastic-coated steel sheet, etc.

(b) Arc Welding and Cutting

Metal-arc welding and submerged-arc welding, either manual or automatic, account for most of the welding that is being done today. Some of this can be very exacting work. A good example is shown in Figure 13, which shows the nuclear-powered submarine, Triton. Weldability was taken into account in designing the high-strength steels from which nuclear submarines are built. High standards are required in the workmanship and inspection to achieve the quality laid down by specification.

Arc welding is being used increasingly for the construction of steel buildings and offers considerable savings in steel and money. In addition, a radically new method of structural design called plastic design has grown up over the past 25 years, made possible only by welding, with further economies difficult to match by traditional building methods. Instead of designing the unit components of a structure on the basis of yield strength as in conventional design, plastic design utilizes the fact that rigid joints are made possible by welding in a system where the basis of design is the crushing strength of the structure as a whole. Much lighter components are used throughout, and, in the last few years, dozens of buildings have been erected in the United Kingdom and in the United States following the new design method. Figure 14 shows the first building designed and constructed in accordance with this method. This is the fatigue laboratory of the British Welding Research Association, with a floor area of 5,000 sq.ft., opened in 1952. Plastic design represents an important milestone in building construction, that would not have been possible with joining methods other than welding.

Figures 15 and 16 provide impressive examples of modern welded construction using conventional materials.

Ordinary constructional steels may provide practical problems in welding but the technical problems are usually not serious. An important exception is the problem of brittle failure. Although primarily a materials problem, welding unfortunately provides notch effects that can initiate cracking, and residual stresses that can maintain it. A great deal of work has been done on various aspects of the problem, and many valuable contributions have been made by welding investigators. Theoretical work remains to be done, but the practical difficulties have now been brought under control. In many countries, including Canada, special grades of steel are available with diminishing susceptibility to notch-brittleness, from which a choice can be made, depending on the severity of the conditions.

Welding of steel often requires special properties of the weld metal to combat corrosion, high-temperature degradation, unusual stresses, etc. For example, metal-arc electrodes have been designed, with extremely low controlled moisture content, to deposit alloy-steel weld metal with tensile strength up to 160,000 psi, or up to 250,000 psi in the heat-treated condition. High-strength low-hydrogen electrodes are used in the construction of nuclear submarines and for the joining of aircraft steels.

Various arc-welding processes have been devised for manual, semi-automatic and automatic use using consumable metal electrodes, with flux added in various ways. Flux can be provided through a hopper, or in the form of a continuous coating, or in the form of sintered beads, etc. Sometimes flux protection is used in conjunction with a gaseous shield of carbon dioxide.

The inert-gas tungsten-arc process is still very valuable for joining aluminum, magnesium, stainless steel and alloy steel in thin sheet, and also for joining unusual materials. It offers flexibility and good protection. However, for thicker gauges of aluminum, stainless steel, etc., the inert-gas metal-arc process with consumable electrodes is now used extensively. This latter process is also being used increasingly for low-alloy steels and constructional steels, with carbon dioxide or argon as the shielding gas. Many different forms of equipment and types of power source can now be used for inert-gas metal-arc welding with consumable electrodes, and the new dip-transfer method using a short arc will probably be utilized more extensively because positional welding is thereby facilitated. A new method of cutting, sometimes known as plasma-arc cutting, has been introduced with inert-gas metal-arc equipment for aluminum and stainless steel, using an argon-hydrogen, shielding-gas mixture. These methods are much more satisfactory than the methods they replace.

A very useful constructional method is inert-gas tungsten-arc spot welding. The great advantage is that the joins can be made when access is available only from one side. The method is used to join panelling onto a supporting structure.

The carbon arc is used to some extent still for cutting, but its applications for welding are now rather limited.

(c) <u>Gas Welding and Cutting</u>

Automatic methods are now used extensively for cutting. Complex shapes can be cut using an electronic tracer, and if the material is thin it can be stacked to cut many layers. Great thicknesses of steel can be cut using the oxygen lance. The steel companies are the largest users of oxygen for cutting, piercing, gouging, lancing and surface cleaning.

Manual oxy-acetylene welding is the favourite of the small operator because of its adaptability. It is still the preferred method for gray cast iron.

Oxy-acetylene heating is used for one method of pressure butt welding of pipes.

(d) Other Methods

The technique of shell moulding has been used in conjunction with thermit welding for the joining of rails and reinforcing bar for concrete construction.

The old process of forge welding has been used recently for joining of aluminum and magnesium alloys, with exceptionally close control of pressures and temperatures.

A similar process from a different source developed from cold-pressure welding is thermal compression welding, for which controlled elevated temperatures are used to assist the joining. Heavy deformation is still necessary. An important use is to join wire conductors to transistor semi-conductors.

Cold-pressure welding is used to join aluminum electrical connectors, to join aluminum foil to similar material of medium thickness, and for lap joints in copper, etc. The materials must be in a fairly soft condition. The main advantage of the method lies in the simplicity of the equipment.

Induction welding is really a pressure-welding process that uses high-frequency current to provide heat for welding. It is used in pipe-making for the longitudinal seams, and for butt welding of pipe and bar stock. Induction brazing is also well established.

Ultrasonic welding uses ultrasonic vibrations to effect joining at two mating surfaces. It is used effectively to join wire or foil to a thick base.

Electron-beam welding uses a focussed beam of electrons to provide a heating source. The parts to be welded are placed in a vacuum chamber, and the direction of the beam is externally controlled. There has been a tendency for increasing size in the vacuum chamber to accommodate larger articles to be welded. Advantages are low distortion and extremely good protection during the welding operation.

Electro-slag welding offers some advantages for very thick material. In fact, the advantages of the method become more apparent as thickness is increased. Lack of refinement in the weld metal has been one of the limitations, though efforts are being made to overcome this.

Friction welding, to which much attention has been given in Soviet Russia, uses high rotational speed and sudden upset pressure to provide sufficient surface friction heating for welding. The method is good only for simple shapes such as bars, thick-walled tubes, etc.

On the other hand, energy requirements are low compared with flash or resistance butt welding.

Explosive welding, tried at various centres on the American continent, uses an explosive force to bring together the surfaces to be welded. Though only experimental at present, it may in the future offer advantages for some applications.

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Figure 1 - Copper panel of Im-Dugud, Mesopotamia, height 3½ ft. Before 3000 B.C. The stag antlers are brazed. (Reference 1, Vol. 1, p.640)

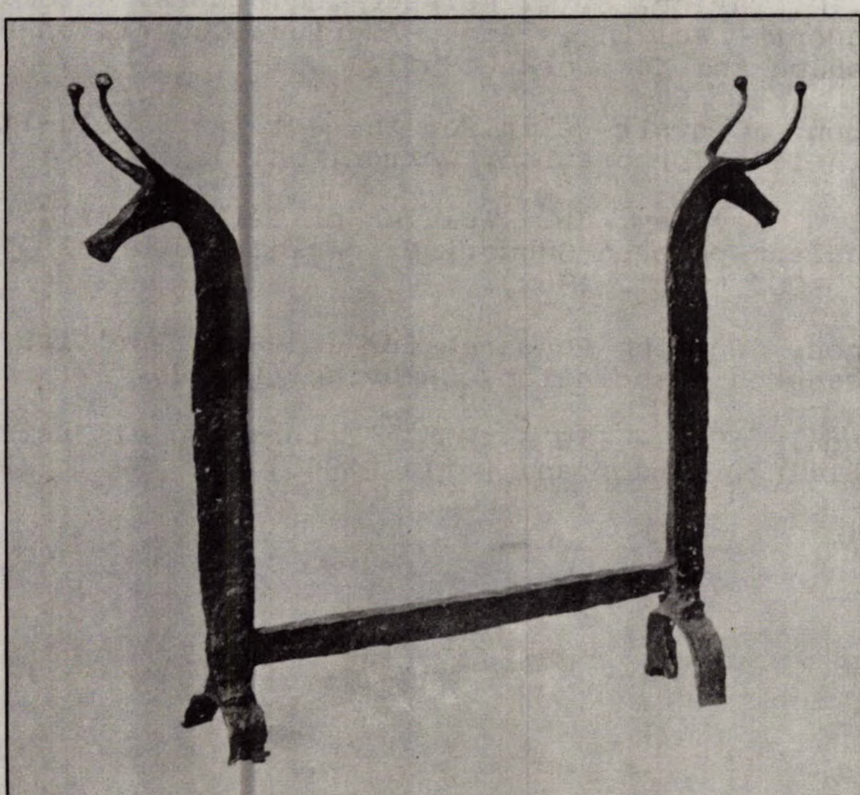


Figure 2 - Iron-age fire-dogs from Cambridgeshire. Forge-welded construction. (Reference 1, Vol. 1, plate 5B)

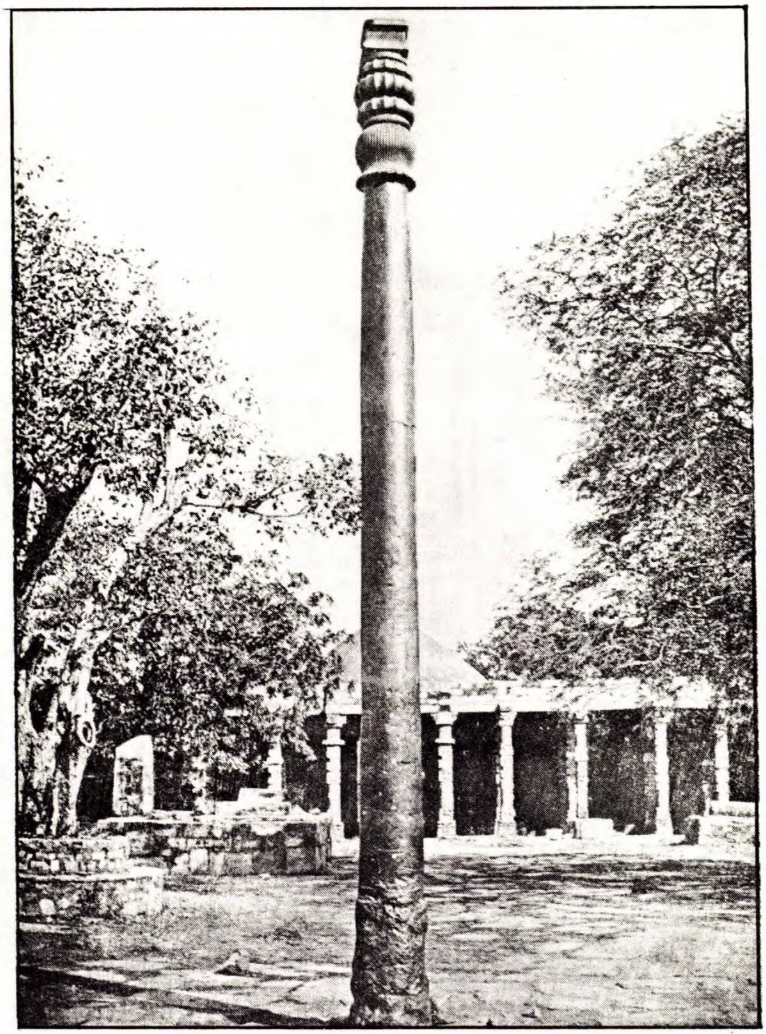


Figure 3 - The iron pillar of Delhi, 310 A.D. Made from many separate blooms welded together. (Reference 28, plate 12, facing p.40)

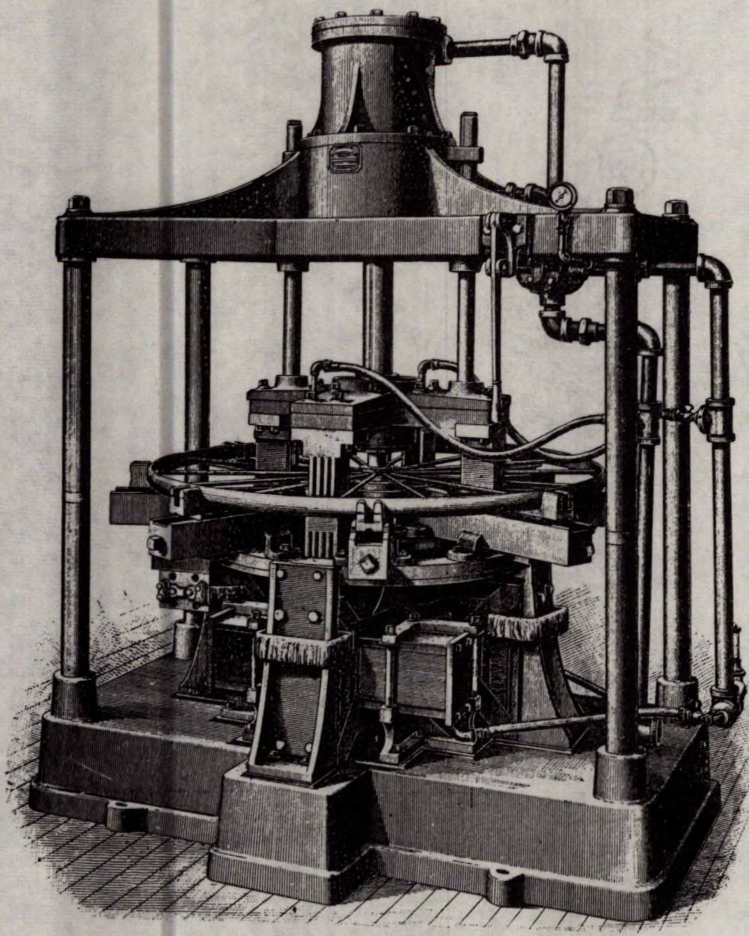
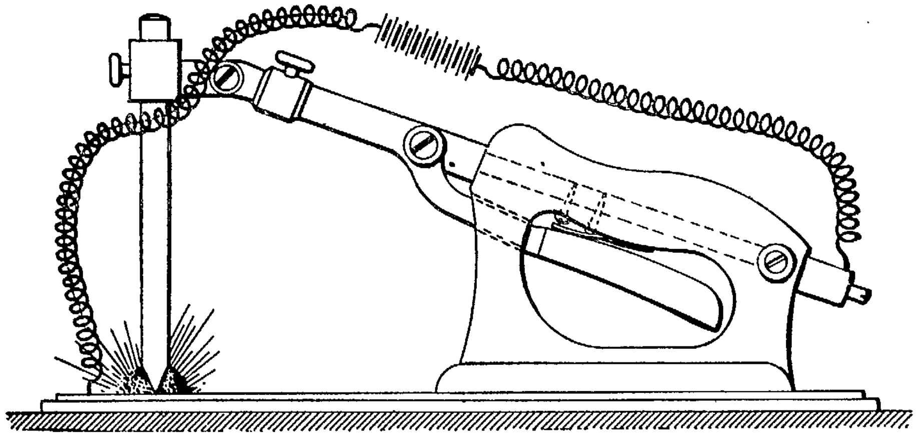


Figure 4 - Resistance-welding machine designed by Lemp of Thomson Electric Welding Co. to make spoked wheels for wheelbarrows and farm vehicles, 1896 A.D. (Reference 29, p.105)



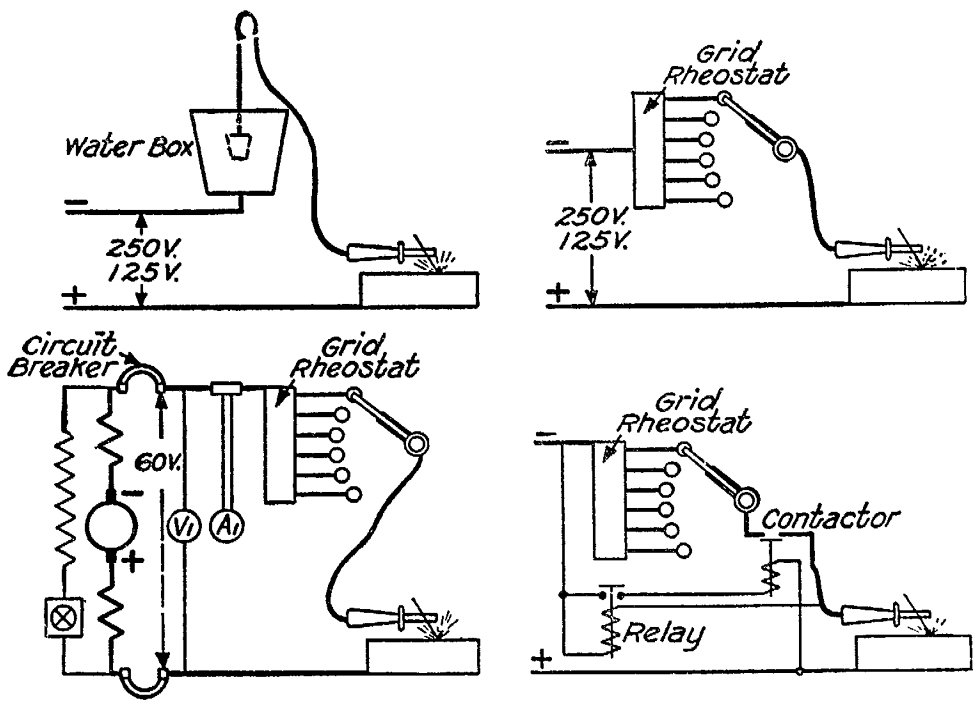


Figure 5 - Original Benardos carbon-electrode apparatus, 1885 A.D. (above), and early arc-welding circuits (below). Note the use of a pail of water for variable resistance. (Reference 15, p.3)

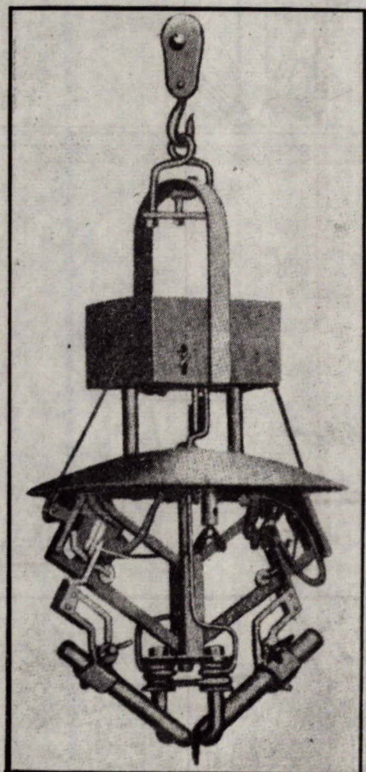
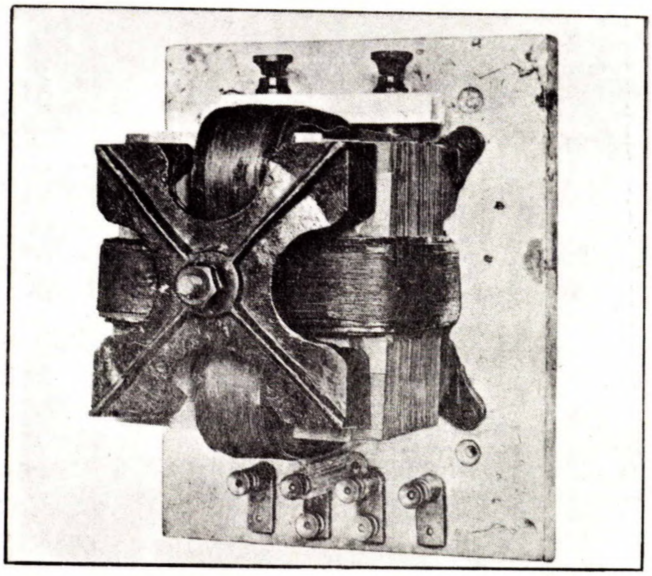
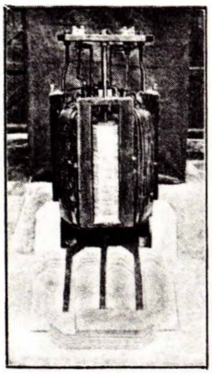


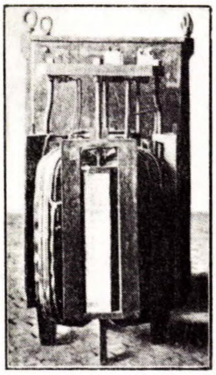
Figure 6 - The unsuccessful Zerner electric "blow-pipe". (Reference 15, p.2)



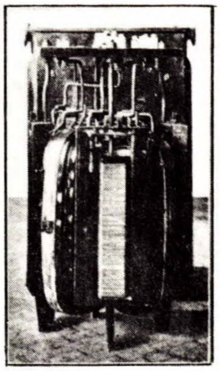
THE ORIGINAL SMALL TRANSFORMER, CONSTRUCTED IN 1903, OF HADFIELD'S SILICON STEEL.



40 K.W. TRANSFORMER, CONSTRUCTED IN 1905.



60 K.W. TRANSFORMER, CONSTRUCTED IN 1906.



40 K.W. TRANSFORMER, OF BEST TRANSFORMER IRON.

Figure 7 - Early transformers using silicon steel, 1903-1906 A.D. (Reference 28, plate 26, facing p.128)

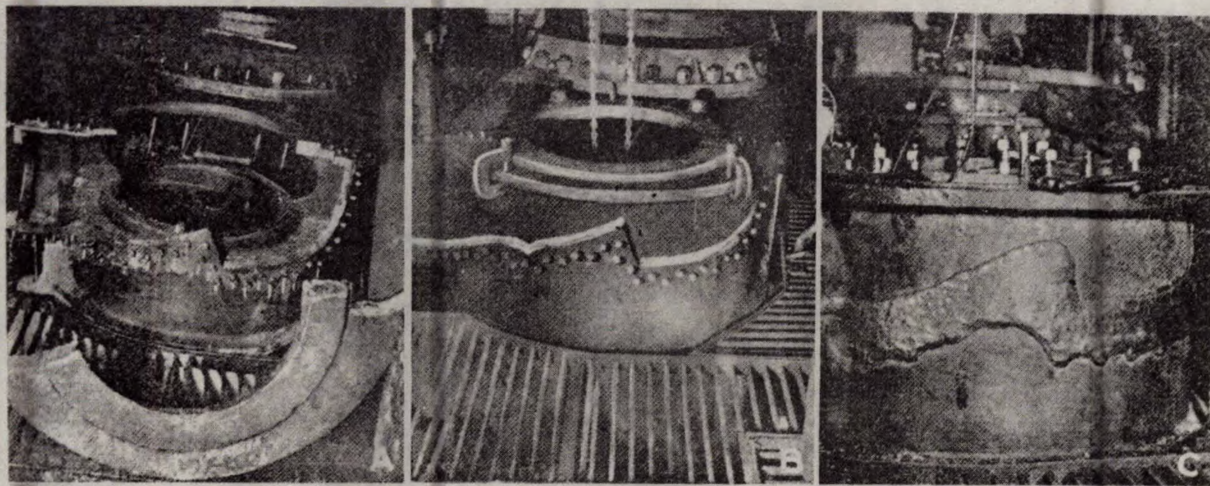


Figure 8 - Repair by welding of first intermediate cylinder in one of sabotaged German vessels, 1919. The U.S.S. "Pocahontas", formerly Prinzess Irene. (Reference 15, p.133)

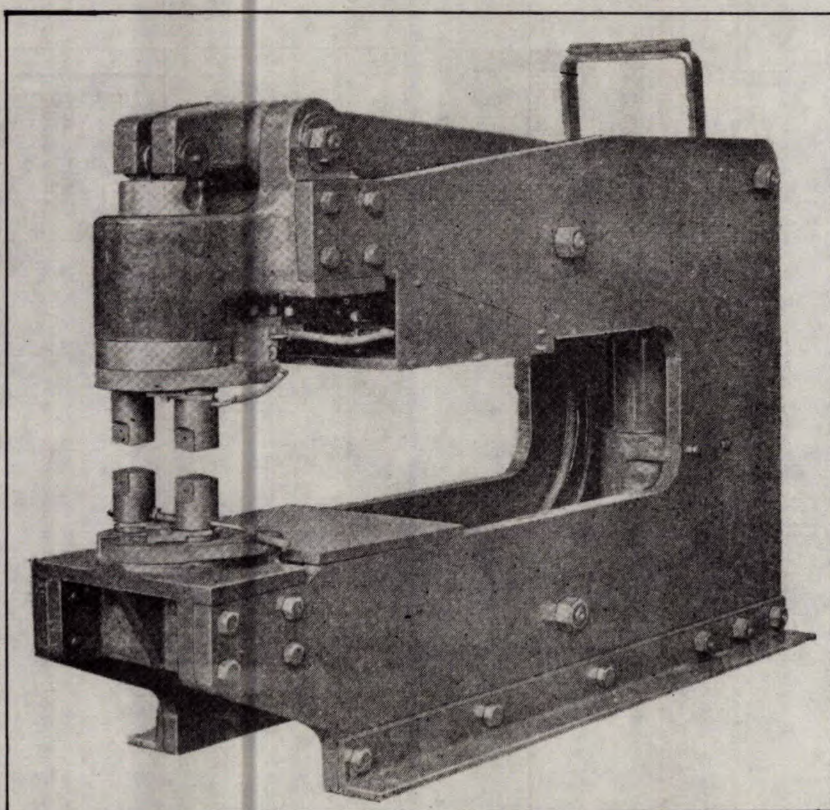


Figure 9 - Giant duplex spot welder, with 6 ft throat depth, to join 3/4 in. steel plate. Intended, but not used, for ship construction. (Reference 15, p.316)

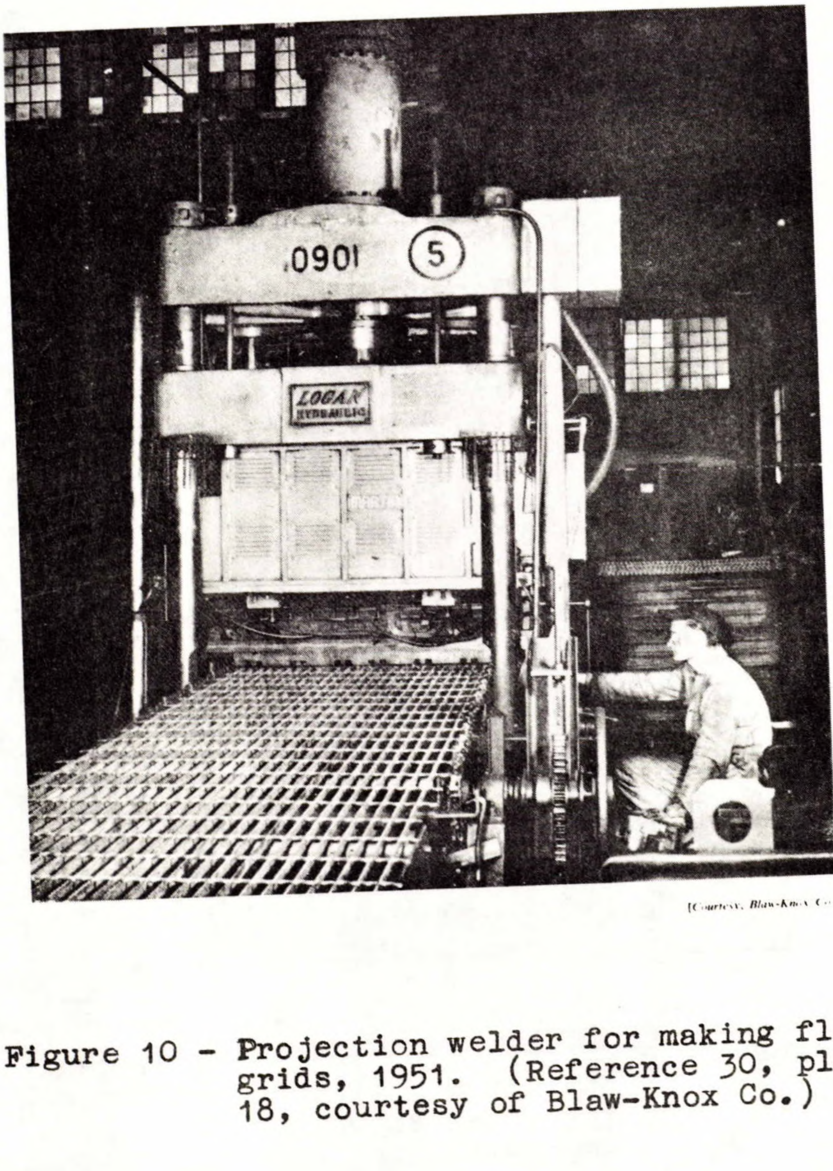


Figure 10 - Projection welder for making floor grids, 1951. (Reference 30, plate 18, courtesy of Blaw-Knox Co.)

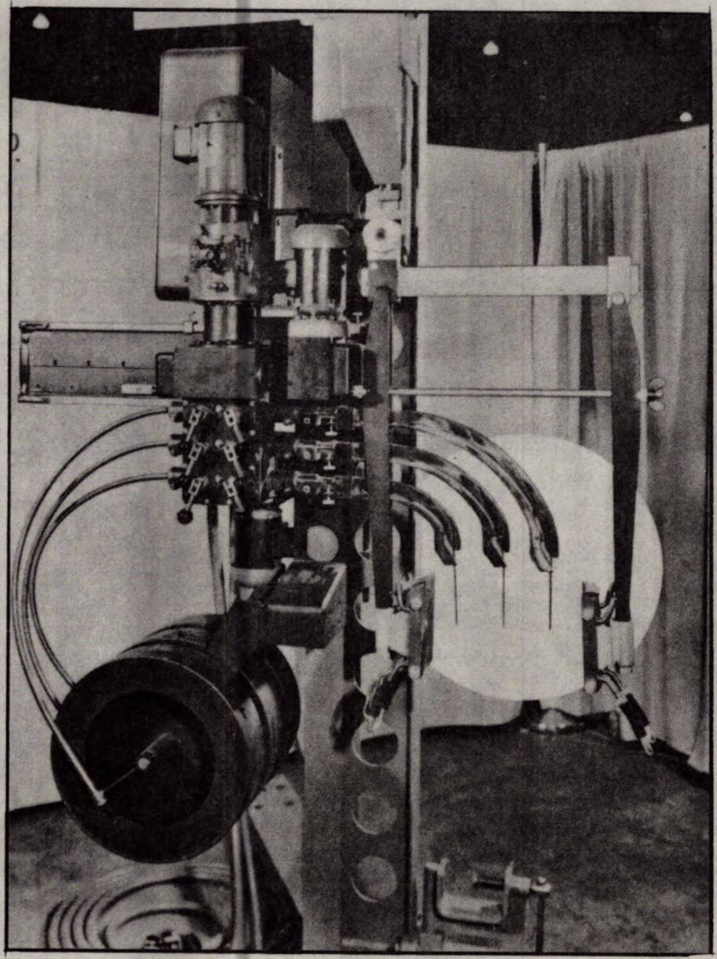


Figure 11 - Electro-slag welding equipment available in the United States. The model shown has three separate wire feeds. (Vertomatic equipment by Arcos Corp.)

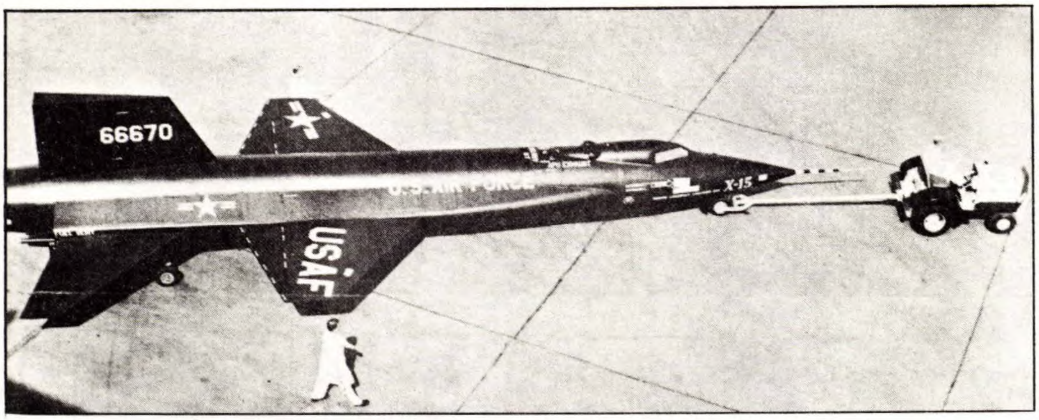


Figure 12 - The X-15 rocket-powered manned aeroplane, largely of welded construction. (Reference 31, Figure 3)

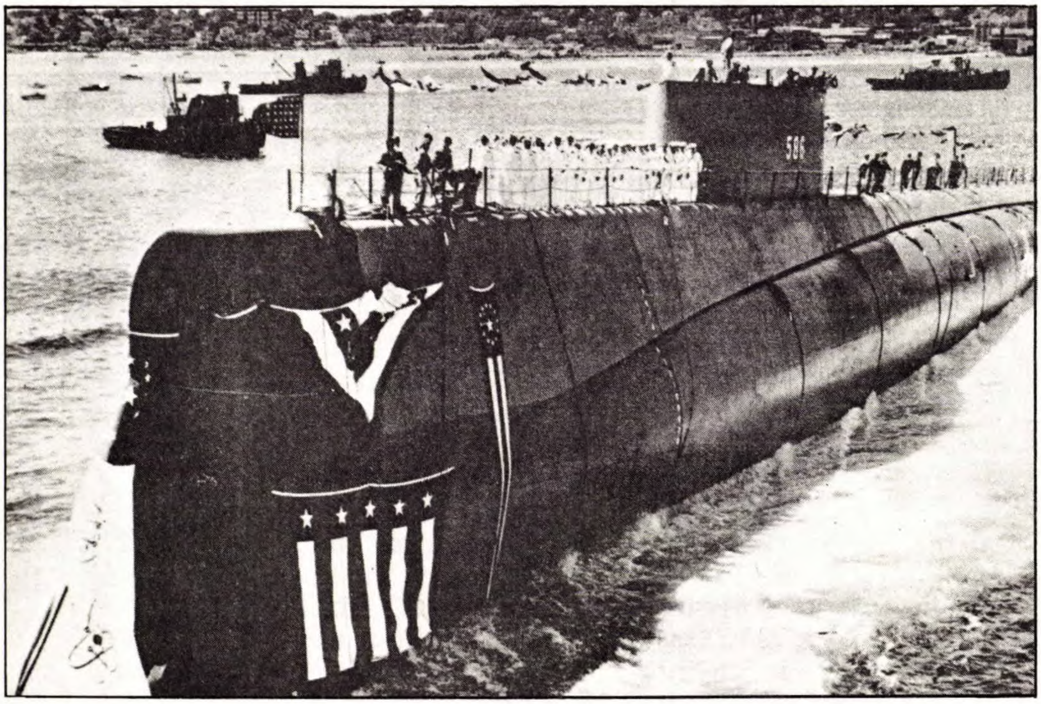


Figure 13 - The world's largest submarine, the nuclear-powered Triton, of welded high-strength steel construction. (Reference 32, p.893)

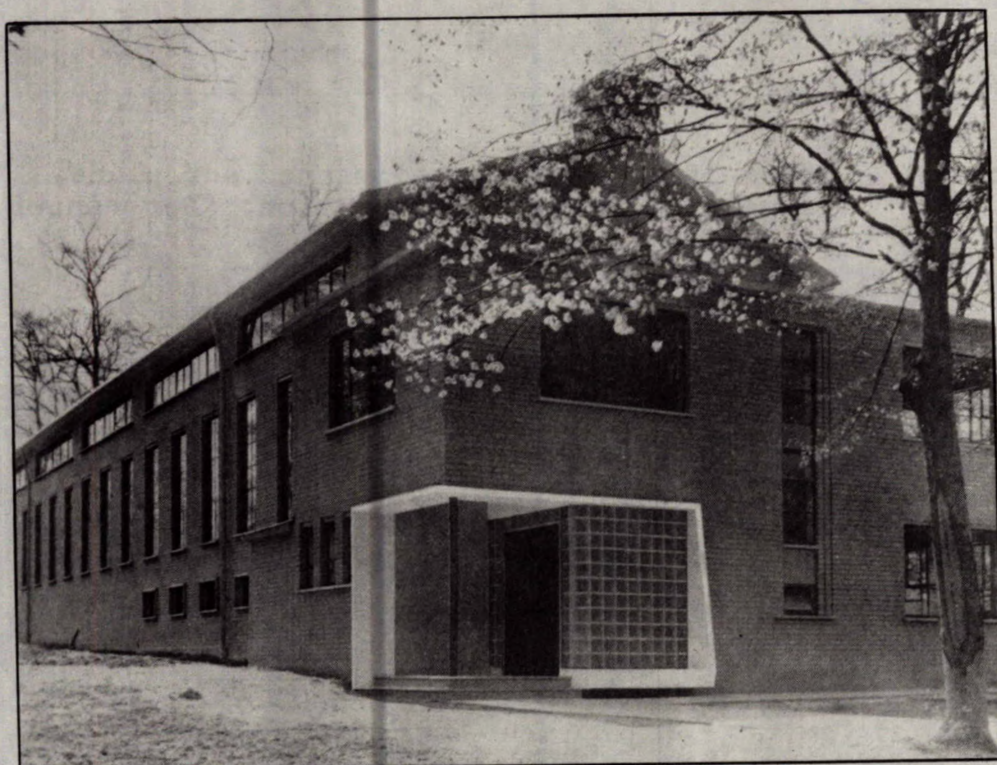


Figure 14 - The first steel-framed building built according to plastic design, i.e. the fatigue laboratory of the British Welding Research Association, opened in 1952. (Reference 33, section on new facilities)

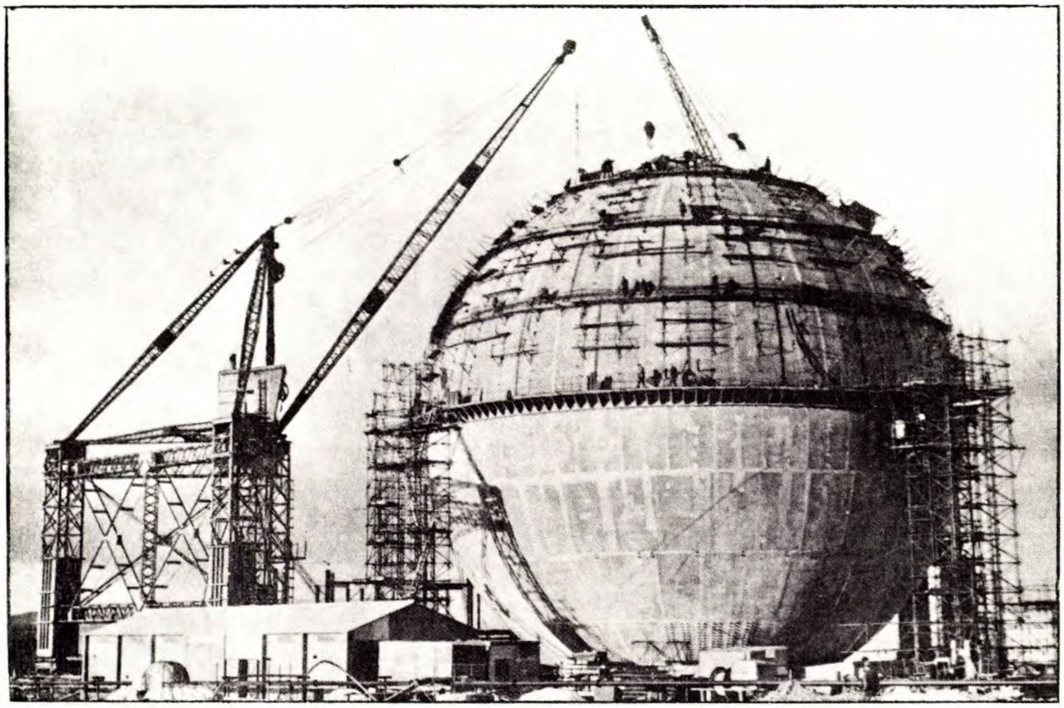


Figure 15 - Welded sphere for nuclear reactor at Dounray, under construction in 1957. (Reference 34, U. K. contribution, plates after p.253)

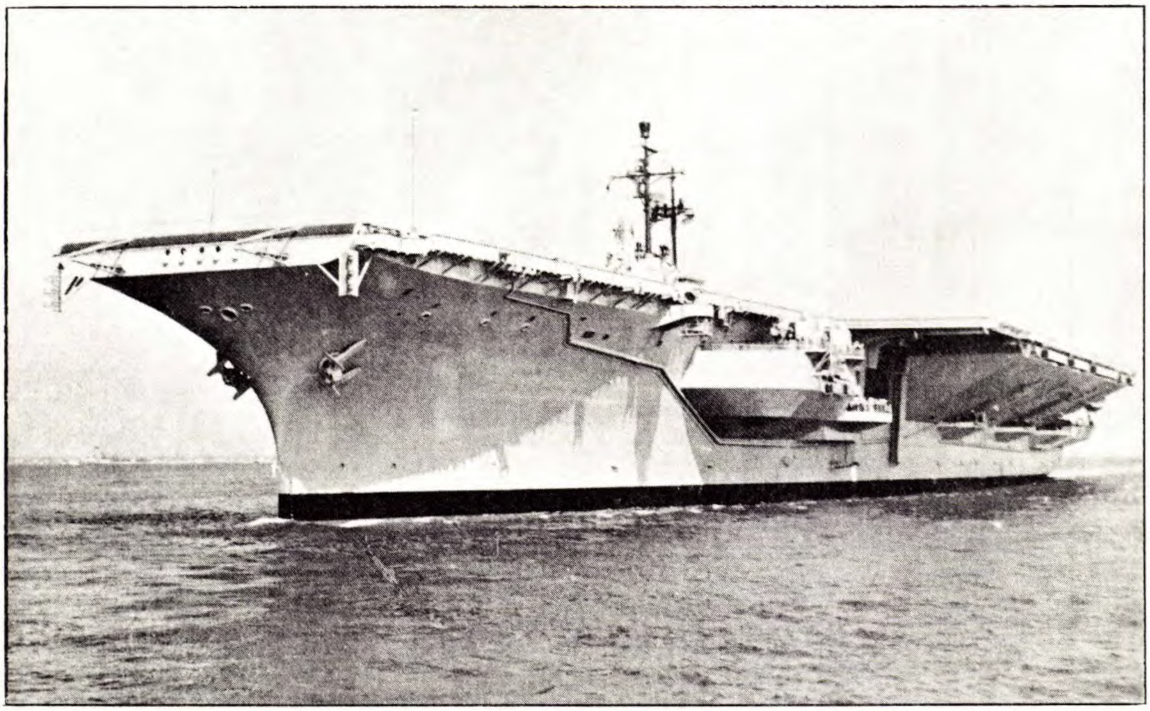


Figure 16 - United States aircraft carrier U.S.S. "Forrestal", of welded construction. (Reference 34, U.S. contribution, plates after p.253)