rautomead

RAUTOMEAD TECHNOLOGY FOR CONTINUOUS CASTING OF OXYGEN-FREE COPPER AND DILUTE COPPER CONDUCTOR ALLOYS

Paper by Sir Michael Nairn, Chairman of Rautomead Limited, Dundee, U.K.
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BACKGROUND

Since the company's foundation in 1978, Rautomead Ltd of UK has specialised in continuous casting technology for non-ferrous metals. Over that period close to 400 systems have been built and installed at customer sites in 47 countries around the world. Graphite furnace technology is a distinguishing feature of a majority of Rautomead designs.

Rautomead plants are being used world-wide in production of

- oxygen-free copper
- copper conductor alloys
- copper-based engineering alloys
- gold and silver alloys
- zinc and zinc alloys
- lead and lead alloys

Forms of semi-finished products include wire rod, straight length bars, flats and hollow sections. According to material and section size, the casting process may be vertically upwards, vertically downwards or horizontal. Casting machines are used either as integrated melting, holding and casting units or are arranged to be fed with pre-alloyed liquid metal. In general, integrated lines are preferred when processing conductor materials to avoid oxygen pick-up in metal transfer and loss of volatile minor elements. Further processing by drawing, rolling, swaging, forging, heat-treatment or continuous extrusion is required according to material and end-use before finishing as familiar products in every day use.

It is a characteristic of Rautomead technology that this has often been adopted in place of more traditional metal-making techniques to reduce the overall number of individual process stages and thus total cost of production.

OXYGEN-FREE COPPER ROD

It was in 1993 some 15 years after the company's foundation that Rautomead introduced an upwards vertical casting process to produce 8mm dia. oxygen-free copper rod (C10200) directly from Grade A copper cathode feedstock (Cu-CATH-1) using a single electrically-heated graphite crucible furnace. The graphite crucible is large enough to permit whole cathode sheets to be fed into the melt chamber and to accommodate two separate chambers linked by a submerged bottom transfer port. Rod withdrawal is vertically upwards through water-cooled graphite dies immersed in the liquid copper. The whole rod withdrawal carriage is arranged to move up and down and to maintain a constant immersion depth of the casting dies. Four to eight strands are cast. Wire rods are guided to the front of the machine and formed into coils of up to 5 tonnes weight. Heating is by low voltage graphite resistance elements. High purity graphite pellet/flake is used to cover both chambers of the furnace to protect the surface of the molten copper from oxidation. The cast rod is warm to the touch and below oxidation temperature when emerging from the casting dies.

This was a novel process when first introduced in the senses that it produced an oxygen-free copper wire rod cast directly at 8mm

- for drawing to wire on a conventional rod breakdown machine
- of a quality that could be drawn down to fine and superfine wire sizes
- with appreciably less wire breaks
- at a competitive operating cost
- on a relatively small scale

Fig. 1 Rautomead RS 3000 Copper Rod Casting Machine

Many refinements to the process have been introduced over the twenty years since its introduction, but core technology has remained unchanged. Given a good quality Grade A cathode feedstock, the process produces an outstandingly consistent high quality oxygen-free copper wire rod. While the specification of oxygen-free copper to C10200 calls for an oxygen content of <10ppm, the natural reducing characteristics of the Rautomead system result in an actual oxygen content of <3ppm, so that the product is in fact almost invariably the superior electronic grade C10100.

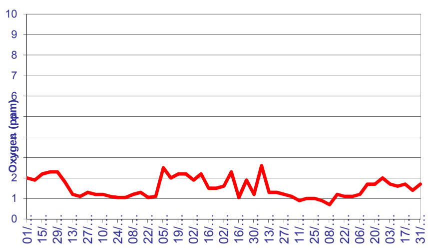

Fig. 2 Oxygen content measured over 12 months operation

Oxygen-free copper (Cu-OF) wire rod in its as-cast state is softer and more malleable than electrolytic tough pitch copper C11000 (Cu-ETP) which is hot-rolled to size. In drawing, Cu-OF is work-hardened at the initial breakdown stages. For all subsequent drawing Cu-OF wire behaves similarly to Cu-ETP with no further adjustments to the wire drawing process necessary.

Graphite Crucible

At the heart of the machine is a crucible machined from a discrete extruded or vibration-moulded graphite block. Sacrificial linings and inert gas are used to protect exposed surfaces from oxidation. The naturally reducing effect of the graphite material assists in ensuring the full de-oxidation of copper and avoids contact with and contamination of the melt by refractory particles.

An important feature of Rautomead furnace design is that the graphite crucible itself becomes part of the stored energy of the system, thus contributing significantly to thermal stability and enabling smaller furnaces with smaller reservoirs of molten copper to be used than in conventional channel induction furnace designs.

Fig. 3 Graphite Crucible

Graphite is elemental carbon. Mechanical properties of graphite are similar to those of ceramic materials while thermal conductivity and electrical resistivity correspond to those of metals (see Table 1 below).

It is this unique combination of refractory and metallic properties which makes graphite so well suited for use in electro-thermal processes at higher temperatures.

Key Parameters of Graphite in Crucibles

bulk density of graphite crucibles	1.83	g/cm^3
open porosity	9	%
Young's modulus	10.8	kN/mm^2
flexural strength	21.5	N/mm^2
Resistivity	7.7	Ωμm
thermal conductivity	165	$Wm^{-1} K^{-1}$
coefficient of thermal expansion	2.7	$10^{-6} K^{-1}$

Table 1

The change in electrical resistivity of carbon during the graphitization process is very marked. The material is transformed from being an insulator to a conductor. Thermal conductivity of graphite is at its maximum at about room temperature. Strength and Young's modulus increase with temperature and peak at ca. 2500 deg C., where values are 50-100% higher than at room temperature. Above 1400 deg C, the specific strength (strength/density) of graphite is greater than that of metals and most other refractory materials. Graphite used at higher temperatures is often exposed to sudden temperature changes or large temperature gradients, both introducing mechanical stresses.

Graphite Heating Elements

The good electrical conductivity of graphite enables this material also to be used as heating elements in a low voltage resistance furnace heating system. Secondary power is fed to water-cooled graphite busbars and to a chain of accurately rated heating elements which surround the crucible. Heat is fed to the metal at low voltage (typically 40V) through the walls of the crucible by radiation and convection. The furnace interior is protected from oxidation by a pressurised inert gas atmosphere The arrangement is not only thermally efficient but also very safe in operation.

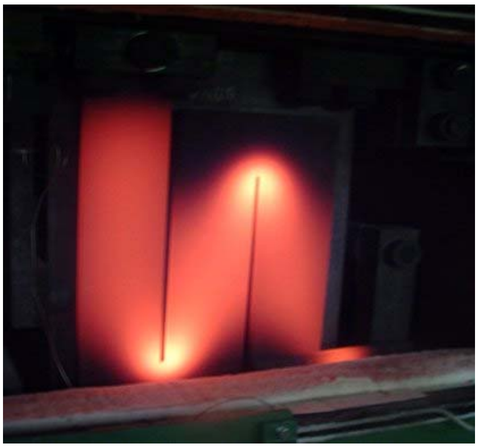

Fig. 4. Graphite Heating Elements

Oxygen Reduction

It is common to all casting systems of this type, whether using a graphite furnace or a refractory-lined induction furnace that it is necessary that oxygen must be reduced to extremely low levels (less than 10ppm) to conform to the relevant Standard and to achieve an adequate casting die life. Normal grade A cathode (Cu-CATH-1) may be expected to include 60-80 ppm oxygen.

In the Rautomead system oxygen is reduced in five steps:

- graphite pellet metal cover over melting chamber
- graphite sacrificial lining of upper part of melting chamber
- graphite walls of crucible
- graphite sacrificial lining of casting chamber
- graphite flake cover over casting chamber

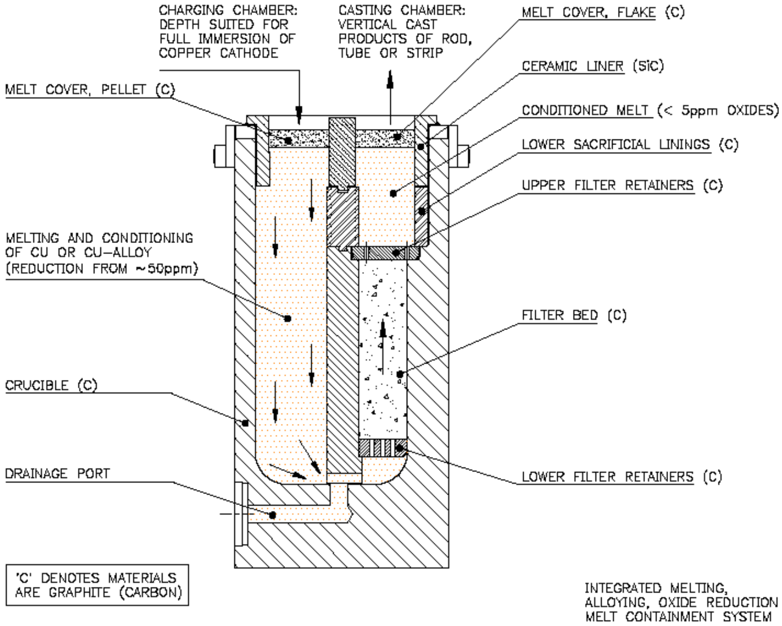

Fig. 5 Graphite Crucible Cutaway

Early tests (Fig 6 below) showed that a retention time of two hours was sufficient to reduce the oxygen content to less than 5ppm. Crucible holding capacity is typically 2,500-3,500kg and output 500-700 kgs/hour, giving a retention time of 3.5 to 7 hours.

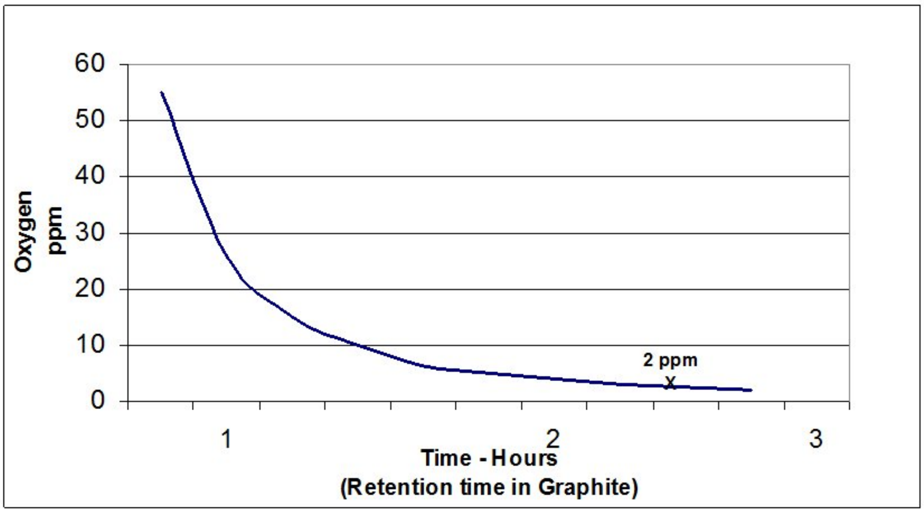

Fig. 6 Oxygen Reduction in Graphite Lined System

Casting Die Life

In production of 8mm dia. Cu-OF rod, graphite casting die inserts can be expected to produce around 12 tonnes of rod before the abrasive effect of the casting and solidification process causes the inside bore of the die to roughen. It is convenient to change the dies on all strands simultaneously coinciding with the completion of full coils. This takes approximately 60 minutes.

Channel Induction Heating for Larger Machines
Output of 700kg per hour the maximum comfortably achievable from a graphite crucible furnace. This is governed by the maximum size of extruded or vibration-moulded graphite block available. For larger outputs up to 1400kg per hour, Rautomead uses proprietary channel induction furnaces to melt and hold the copper at temperature and casting up to twelve strands.

The Place in the Market for Small-scale Copper Rod Manufacture
It is often asked what is the place for small-scale production of Cu-OF copper rod in a market environment where by far the majority of copper rod for the wire and cable industry is produced on large CCR plants producing electrolytic tough pitch copper (Cu-ETP) with its attendant advantages of scale.

In Cu-ETP production, oxygen is intentionally alloyed with the copper and is controlled to around 200-400ppm. The oxygen acts as a scavenger for dissolved hydrogen and sulphur and also reacts with most other impurities to form insoluble oxides at the grain boundaries. This prevents them from dissolving in the copper matrix adversely affecting conductivity and annealability. However, these hard particles are prone to cause wire breaks when drawn as a wire to fine and superfine sizes.

By contrast the Rautomead process typically has 3ppm or less oxygen. It is thus inherently more demanding in terms of the purity of the cathode feedstock, but the negligible presence of oxide particles greatly reduces the incidence of wire breaks in drawing to fine and superfine wire of 50 microns and less. Modern multiwire machines are designed with up to 56 strands and where one break interrupts the process.

The benefit of reduced wire breaks becomes of significant importance in reducing overall cost of manufacture.

The majority of users of the Cu-OF rod process have purchased their machines not so much because they required a product which would be oxygen-free as because they wished to have a process which offered
- consistently high quality copper rod
- less wire breaks
- less operators in wire drawing operations
- output which matched their requirements
- investment which matched their means
- freedom to operate independently for the major mills
- ability to recycle in-house scrap arisings
- reduction in overall operating costs

Equally it is often asked why a wire and cable producer needs Cu-OF, when Cu-ETP is the standard product in the industry. Some customers have purchased their Rautomead machine with a specific requirement for Cu-OF. Those have tended to be copper strip producers and specialist cable companies requiring properties in the copper rod of:
- minimal surface oxides
- greater ductility
- lower noise
- avoidance of hydrogen embrittlement

Examples include:

- The continuous extrusion process patented originally by the UK Atomic Energy Authority. This has proved to be an elegant and simple method to produce fine-grained copper conductor strips used commonly as commutator sections in electric motors and as busbars in transformer and heavy electrical switchgear manufacture. The continuous extrusion process requires a very clean surfaced feed stock rod **to avoid contamination by surface oxides** or protective wax entering the extrusion machine. Oxygen-free copper rod produced by the Rautomead process has been found to perform very well in this application and is the feedstock of choice for many copper strip producers. Only three steps are required from refinery cathode to finished product:
    - continuous casting machine (clean 12.5mm to 20mm Cu-OF rod)
    - continous extrusion machine (to fine grain fully soft copper strip)
    - drawbench (to final size and temper)

- automotive wiring harnesses, aerospace, robotic arms, ribbon cables where the copper conductor of the cable is subjected to **repeated flexing**

- headphones in the civil and military spheres and audio cables where **low noise** is critical.

Each of these are niche markets where quality and special properties are key features and where annual output requirements of 5,000 to 10,000 tonnes are often appropriate.

Process Improvements
Over the years, significant steps have been taken to improve the process and to reduce operating costs. Some of the more significant of these include:

- **Automatic cathode feed**
  3 tonne bundles of cathodes are delivered by fork lift truck to the rear of the machine. Other than periodic changes of casting dies, no further routine operator intervention is required until full coils of wire rod are removed from the coilers

- **Cathode weighing**
  Each individual cathode sheet is weighed as it is automatically lifted by suction pads. The electrolytic refining process by its nature results in variable cathose weights. This facility provides an accurate time-related record of the weight of copper fed to the machine for production management purposes. It is also a key tool in dilute copper alloy production where precise additions of alloying elements are made.

- **SCADA data recording with remote monitoring**
  Over 30 key parameters of production are now measured & recorded, inter linked with
    - warning alert systems
    - alarm action systems
    - maintenance systems
    - process information systems
    - touch screen controls
    - production control systems

- **SCADA data recording with remote monitoring (cont'd)**

  Data may also be monitored remotely and (by agreement) shared with Rautomead as part of a technical support package.

- **Touch screen controls**
  Pre-programmed and actual production data is provided visually to the opererator on the platform and with read/write permissions as set by management

- **Rod sizes 8mm to 32mm**
  Most machines are supplied with twin withdrawal drives enabling wire rods of at least two separate sizes top be produced simultaneously and casting speeds best suited to each of them.

Other process improvements to increase furnace service intervals are at an advanced stage of testing.

DILUTE COPPER CONDUCTOR ALLOYS

By a process of lateral thinking, technical innovation to meet a specific need in the market place often leads to parallel advances in other applications of a process. In the Rautomead case, it has been found that the compact single furnace graphite crucible design has led to other opportunities for production of difficult-to-produce dilute copper conductor alloys and new opportunities to replace conventional billet extrusion.

Most of these are in conductor applications of copper with the alloying elements added to provide special properties including:

- greater strength
- greater abrasion resistance
- reduced creep
- higher softening temperature
- lower materials cost

than would be offered by copper alone

Examples include:

alloy type ***principal applications***	**CuAg**	**CuSn**	**CuMg**	**CuCd**	**CuZr**	**CuCrZr**	**CuFe**
railway catenary wire		X	X			X	
medical applications					X		
automotive signal wire	X	X	X	X	X		X
commutator sections	X						
switchgear					X		
cable terminals & connectors			X				X
welding nozzles					X	X	

Table 2

Dilute Copper Alloys for Catenary Systems

When copper-cadmium was banned in Europe for toxicity reasons as a conductor alloy for railway catenary systems, the industry was left with a choice of other materials (table 3 below)

Material		resistivity 10^{-08} Ohm.m	elong (min)* %	tensile strength (min)* N/mm^2	max speed (kmph)
electrolytic copper	Cu-ETP	1.777	3	355	160
copper-silver	Cu-Ag 0.1	1.777	3	360	250
copper-tin	Cu-Sn 0.4	2.155	3	430	300
copper-magnesium	Cu-Mg 0.5	2.778	5	490	400+

* nom. cross section 100mm^2

Source: European Standard EN 50149 of December 2001

Table 3

The choices to be made are matters for Railway Authorities around the world, but as design train speeds have increased so the tension required in the wire has risen to ensure a safe margin is maintained between maximum train speed and the wave propagation speed to avoid catastrophic accident. This has favoured copper-magnesium for use in such catenary systems as a rapidly work-hardening alloy. All the major CuMg producers in Europe as well as multiple producers in China have adopted Rautomead CuMg technology.

The distinguishing feature of this system from that of almost all its competitors is the adoption of a resistance heated graphite furnace for melting, alloying and casting. The characteristics of this design have shown themselves to be uniquely well-suited to production of CuMg and other dilute copper alloys. This is not induction melting, neither coreless or channel type. No eddy currents flow through the copper alloy charge. No clogging of inductors with magnesium oxide. Rather, the metal is heated by radiation and convection through the walls of the graphite crucible in an inert gas atmosphere, minimising turbulence and slag formation and facilitating close chemical composition control in alloy production.

Dilute Copper Alloys for the Automotive Industry

With the multitude of electric and electronic features now offered by leading automotive manufacturers even in lower priced models and the 3 years and longer vehicle warranty periods now commonplace, strong interest exists in in the industry for stronger, lighter and more ductile signal wiring harnesses.

Rautomead is thus working closely with leading suppliers to the automotive industry to enable them to offer alternatives to EC copper and aluminium. Current projects involve copper-zirconium, copper-iron and copper-magnesium where smaller cable sizes save weight, reduce materials cost and improve reliability.

Challenges in Dilute Alloy Production

- **Composition Control**
  Minor changes in alloy chemistry in dilute copper alloys often have marked effects on physical properties.

  In the case of CuMg for example, the challenge is to maintain a precise and delicate balance been low electrical resistivity of copper and high tensile strength introduced by the addition of magnesium. A typical CuMg alloy for railways trolley wire (EN 50149:2001) is specified as CuMg0.5 with a magnesium tolerance of +/- 0.03%. The product is finished either as a single strand shaped contact wire or as a stranded cable for the messenger wire and the droppers.

  Magnesium and zirconium are light and volatile elements prone to slag formation. Maintenance of such a tight chemical tolerance in continuous production is a serious challenge, but one where Rautomead totally enclosed furnace technology has shown itself to be a consistent and reliable choice.

- **Alloy Addition**
  A variety of techniques has been developed by Rautomead for alloy addition, according to the material to be produced. These include:

  - **Manual Addition of Elemental Magnesium Wrapped in Copper Foil**
    In simpler systems, this technique has shown itself to be effective, though it does depend on regular human intervention and the reliability of the operator.

  - **Automatic Grain Feed**
    This is used in production of copper-silver and copper-tin, where a PLC-programmed automatic grain feeder is positioned above the melting chamber of the crucible to deliver a measured weight of silver or tin grain through a graphite tube submerged in the melt. Cathodes are individually weighed and the PLC is used to calculate the precise grain addition to match copper feed rate.

Fig. 7 Automatic Grain Feeder

- **Single Cored Wire Feed**
  A recent introduction to continuous casting of dilute copper alloys has been a cored wire feed. This was developed initially to automate the addition of magnesium powder in production of CuMg alloys for catenary wires in high speed train systems. The cored wire comprises a copper sheath enclosing a core of magnesium powder. Typical OD of the cored wire is 13mm and the composition of the feed 50:50 copper and magnesium. Speed of the cored wire feed is electronically geared to copper feed rate. The cored wire is plunged through the protective graphite or charcoal cover to melt and disperse in the melt chamber of the graphite crucible. Practical long term testing in an operating environment has shown a marked reduction in magnesium losses and improved accuracy of composition control compared with manual feeding.

Fig. 8 Cored Wire Feed

- **Twin Cored Wire Feed**
  The cored wire feed principle now been extended to more challenging alloy work including copper-chrome-zirconium, with typical compositions of 0.6% chrome and 0.05% zirconium, where two alloying elements are added as separate cored wires.

- **Closed Furnace Lid with Cored Wire Feed**
  In dilute copper alloy work prone to rapid oxidation, a closed furnace lid approach is now used with the surface of the molten metal protected in an inert gas atmosphere. In recent work at our research facility in Dundee, a steady furnace pressure of over 70mm water gauge has been maintained. In this case the copper is fed as a rod and the alloying elements as cored wire enabling very close tolerance to be maintained in feed rates of all elements comprising the alloy and avoiding exposure of the melt to atmosphere. This is not vacuum melting, but a combination of techniques which enable the continuous casting process to achieve comparable results. A patent application for this invention has been lodged.

- **High Temperature Alloys**
  Whereas a furnace temperature of around 1350 deg C is normal in production of Cu-OF, Rautomead has now developed a furnace designed to operate at 1550 deg C using ceramic crucibles and casting die materials for iron-containing copper alloys providing high strength and low materials cost.

IN SUMMARY

The Rautomead oxygen-free copper rod casting process has been around for over twenty years. It differs radically from the CCR process, both in terms of the specification of the copper produced and in the scale of operation. It is a complementary but not a competing process.

On the domino principle, Rautomead technology has now moved on to become a widely accepted process for production of dilute copper conductor alloys including copper-magnesium, copper-tin, copper-silver, copper-zirconium, copper-iron and copper-chrome-zirconium where accurate control of volatile minor elements is an essential feature of alloy production.

The company work closely with the rail, automotive and electronics industries around the world and with the companies which supply them in developing new products as conductor wire, signal wire, catenary wire, terminals and edge connectors and in evaluating new materials. To that end, the company is equipped with comprehensive R&D facilities including upwards vertical and horizontal casting test facilities, laboratory analytical facilities and most importantly a team of dedicated and experienced engineers and metallurigists. Close links are also maintained with the University of Dundee.

In the modern connected world in which we live, the thrust of much of this effort is for Rautomead to play an active role in providing technology which makes electrical conductors of all types and in many industries stronger, smaller, lighter, more durable and less expensive.

Fig. 9 Rautomead RS 3000/5-Cu-Mg Casting Machine

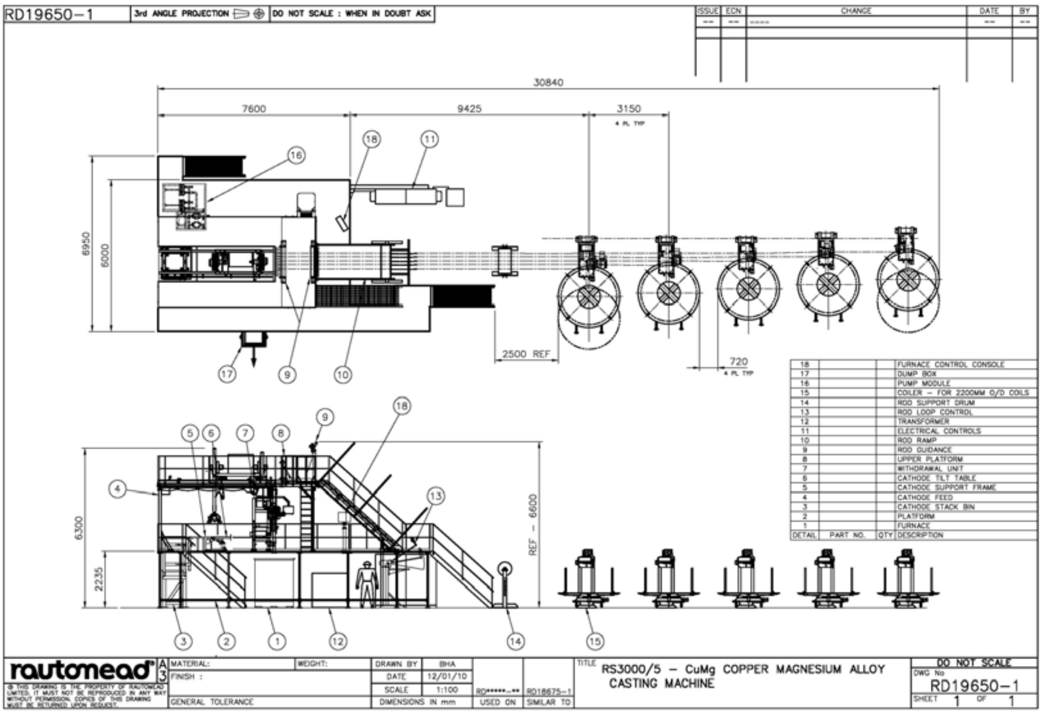

Fig. 10. Rautomead RS 3000/5-Cu-Mg Casting Machine Layout

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