DEVELOPMENT OF THE COPPER MOTOR ROTOR - MANUFACTURING CONSIDERATIONS AND MOTOR TEST RESULTS

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1. INTRODUCTION

Because the electrical conductivity of copper is nearly 60% higher than that of aluminum, one would expect the I2R losses in the rotor to be substantially lower if copper were substituted for aluminum as the conductive material of the squirrel cage structure. Motor modeling by several manufacturers has shown that motors with copper-containing rotors would have overall loss reductions of 15 to 20%. Aluminum has been the material of choice for all but very large motors because the intricate squirrel cage is readily manufactured by pressure die casting through the rotor lamination stack. The large motors (>250 Hp, 200 kW) and a few smaller special purpose motors with copper in the rotors are assembled by a slow and costly fabrication technique that is not economical for production of the millions of integral and fractional horsepower motors sold annually. Die casting of the copper will be required for rapid and cost-effective manufacture, but the process has not been practical because of short die life resulting from the high melting temperature of copper.

Several phases of this development are summarized in this paper. The first phase concerned the manufacturability of the copper rotor and addressed the problem of die life in pressure die casting copper by surveying a number of candidate high temperature die materials and the optimum conditions for their use to maximize die life. The significant results of the die material study are outlined here; more complete accounts have been published elsewhere [1, 2]. Although the motor test results indicated that the copper rotor die castings were of high quality,

subsequent examination of sectioned end rings showed some large pores. Porosity is a common problem in high pressure die casting. This prompted a study to minimize the occurrence of large pores by modeling of shot profiles and experimental confirmation of the model predictions. In the second phase, copper rotors were die cast for several major motor manufacturers for evaluation by dynamometer testing in their own facilities. This paper presents these data on performance of motors incorporating the die-cast copper rotors and compares performance to that of the same motor with an aluminum rotor. Available data from the literature on motors built with copper rotors are also summarized.

Finally, in a phase still ongoing at this writing, frequency response modeling of the rotor bars is being used to guide the design of the slot pattern in the rotor to optimally utilize copper to minimize losses and improve starting performance. Some initial results comparing rotor designs are presented to show the utility of the approach and the importance of slot design.

2. SIGNIFICANCE OF COPPER IN THE ROTOR

Use of copper in the rotors in a broad range of sizes of induction motors could represent a significant advance in motor technology. This is because the readily available and least expensive improvements to increase motor energy efficiency have been adopted in recent years. Motor losses have been forced down steadily over time, but with diminishing returns as additional increments come at much increased cost.

The nameplate efficiency of a typical in-service 15 Hp (11 kW) 1800 rpm motor today is about 89.5%, still below the 1997 Energy Policy Act standard of 91%. As shown by the test results presented here, adoption of the copper rotor should bring efficiencies to the 94 to 96% range exceeding the requirements of today's premium efficiency motor, nominally 93%. There are few material and engineering options to reach higher efficiency short of suffering greatly increased costs by employing amorphous iron alloy laminations or superconducting windings. Apart from energy efficiency for its own sake, the related benefits of reduced operating temperature and the increased motor life and reduced maintenance costs that follow, are in themselves very important to motor and drive system economics. In addition, analyses by motor manufacturers have shown that the copper rotor can be employed to reduce overall manufacturing costs at a given efficiency or to reduce motor weight, depending on which attribute the designer chooses to emphasize.

The potential energy savings achievable through the use of copper rotors is substantial. The U.S. Department of Energy reports that motors above 1/6 Hp use about 60% of all electricity generated in the United States and that medium power motors (1 to 125 Hp), the most likely candidates for conversion to copper rotors, use about 60% of the electricity supplied to all motors [3]. In the U.S. alone, a one percentage point increase in motor electrical energy efficiency would save 20 billion kW-hrs or $1.4 billion (at 7 cents per kW-hr) and 3.5 million barrels of oil annually.

3. DIE MATERIAL STUDY

Although motor manufacturers have long recognized the value of using electrical grade copper in the rotor, the poor manufacturing economics of die casting copper has been an impenetrable barrier. The high melting point of copper (1982°F, 1083°C) results in very rapid deterioration of tool steel dies. The principle failure mechanism is referred to as "heat checking" by die casters, but decarburization and softening of the steel at the high surface temperature are also contributors [4]. Heat checking is a thermal fatigue phenomenon resulting from the rapid cyclic expansion of the die surface layer on contact with molten metal and the constraint of the surface by the much cooler inner portions of the die. Cooling of the outer layer on each cycle to a temperature below that of the bulk of the die puts the surface under a large tensile stress that can exceed the yield point of the die material. This surface-to-interior differential expansion and contraction is greatly exacerbated in die casting high-melting metals such as pure copper. Clearly much improved die life must be achieved for the copper rotor to be practical. This meant that an important objective of this work was to identify suitable high temperature die materials. Consideration of the thermal fatigue failure mechanism suggests that the surface-to-interior ΔT and resulting large strains can be minimized by raising the temperature of the bulk of the die insert. Herman et al [5] in 1975 and Doehler [6] in 1951 made this same suggestion. A second objective of the development effort was to devise and demonstrate a practical system for heating and insulating the die inserts to maintain the high temperature critical to improving die life.

3.1 Computer modeling of die temperature profiles

A 3-D thermal modeling exercise of die thermal profiles was carried out prior to the die casting program. Considerable insight into the heat checking failure mechanism and how to prevent or minimize it was obtained. It was shown that in the cases of molybdenum- or tungsten-base die inserts, preheating and operation of the die at 550ºC or slightly higher would reduce cyclic strains on the surface to below the plastic range. Because of the lower thermal conductivity of nickel base alloys, the minimum operating temperature was estimated to be 625ºC.

3.2 Test dies, copper melting and die heating

A test die consisting of six separate inserts was designed. Thousands of shots to evaluate a number of candidate die materials by casting rotors would be impractical because of the huge quantities of expensive lamination stampings that would be consumed. The test die simulated a single gate of a rotor die for a 15 Hp (11 kW) motor. The die set was fitted to a 660-Tonne real-time shot controlled Buhler die casting machine at Formcast Development, Denver, Colorado. To control oxygen and hydrogen pickup from the atmosphere, chopped copper wire rod (copper alloy C10100) was induction melted on a just-in-time basis in phase with the shot cycle of the die casting machine. No cover was provided to the molten copper surface. Eight pounds of copper was melted every two minutes using twin induction furnaces alternatively switched to the 60-kW power supply. The copper melt temperature at the time of pouring into the shot sleeve was 1220ºC (2228ºF).

To obtain the high die insert temperatures shown to be necessary in the die thermal study, the arrangement of electrical resistance heaters and die insert insulation shown schematically in Fig. 1 was designed and built. This design was modified and improved upon over the course of the die material evaluation program.

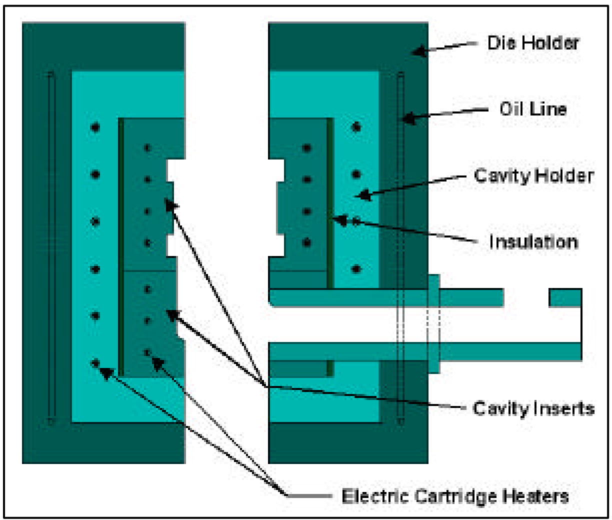


Fig. 1 - Schematic illustration of the placement of electric resistance heaters and insulation in the die material tests.

3.3 Die material tests

Die inserts of the conventional die material used in production of aluminum rotors, H-13 tool steel, were machined and tested to gain experience and to establish a base line for die performance. As expected, the H-13 inserts showed distinct heat checking after only 20 shots of molten copper. More serious cracking was generated on subsequent shots. Several high temperature materials were then tested. Two runs to simultaneously evaluate the molybdenum alloy TZM and the tungsten alloy Anviloy were carried out. The first heated die configuration was capable of preheating and maintaining the dies at 450°C (842°F), about 100°C (212°F) below the minimum temperature determined in the thermal analysis. Failure of some heaters meant that the operating temperature was actually somewhat lower during the initial 500 shot run. Despite these problems, no heat checking of either alloy was evident. Some minor cracking of the Anviloy inserts at sharp radii was noted and radial cracks at the ejector pins holes were seen on both materials due to thermal expansion mismatch with the H-13 pins. In a second run bringing the total number of shots to 940, all heaters were operating. Additional radial cracking at ejector pinholes was noted, but otherwise these refractory alloy die inserts appeared to be capable of extended runs in this severe copper die casting exercise. The TZM alloy is however subject to severe oxidation at copper casting temperatures and would not be suitable unless appropriately coated to provide protection.

A number of nickel base alloys were then evaluated because of their generally excellent combination of high temperature strength and oxidation resistance. Three alloys were run simultaneously with two inserts of each alloy in the test die. These nickel-base alloys were of very different types including solid solution strengthened INCONEL alloy 617, gamma prime strengthened INCONEL alloy 718 and the mechanically alloyed dispersion strengthened INCONEL alloy 754. In the first run, with the heating system achieving an operating temperature of only 350°C (662°F), the 617 alloy showed the best results with only minor crazing after 250 shots. A second extended run was done to evaluate other solid solution strengthened alloys, INCONEL alloys 601 and 625 together with the INCONEL alloy 617. At the point in time of the first series of shots into this group of die inserts, the heater array had been improved to achieve preheat and operating temperatures of 540°C (1004°F) and with further tweaking for a second run to 625°C to 640°C (1175°F-1187°F). In this last 330 shots at the higher operating temperature, there appeared to be no deterioration of the inserts of the die set.

3.4 Conclusions from die material tests

Extended production runs will be required to prove the point, but these tests show promise that the INCONEL alloys 617 and 625 operated in the 600-650°C (1112-1202°F) temperature range are very promising die materials for die casting of copper motor rotors. Although not tested in this study, Haynes alloy 230 is also a strong candidate die material. This alloy has slightly higher yield strength and ductility than alloy 617 and is weld repairable. Alloy 230 has been used in the first copper rotor production die set now in operation.

An important conclusion from this work is that it is absolutely essential to operate at elevated temperature to extend die life. The higher die temperature reduces the surface-to-interior ?T on each shot which in turn greatly minimizes the cyclic expansion and contraction and thus the thermal fatigue mechanism causing heat checking and more severe cracking. Temperatures above 650°C (1202°F) are not required and in fact would reduce productivity by increasing cooling time. The copper die castings were found to have a sound structure and only small well distributed shrinkage voids. Chemical analyses showed iron, nickel and oxygen pickup to be minimal. Electrical conductivity of these castings averaged no lower than 98% IACS. A practical die heating and insulation design has been developed.

4. ROTOR DIE CASTING AND PERFORMANCE TESTS

4.1 Die casting and melting practice

Copper rotors were cast for four motor companies for evaluation in their own facilities. These rotors were die cast on the same machine at Formcast Development used in

the die material study. H-13 die inserts were used because only a few rotors were required for testing. These die inserts were mounted in a three-platen master mold assembly of the type conventionally used in rotor die casting.
Chopped copper wire rod was again inductively melted on a shot-by-shot basis to avoid a large holding furnace and the attendant problems of control of oxygen and hydrogen in the molten copper over an extended time. The largest rotors cast required nearly 39 lbs (18 kg) of molten copper per shot. With the limits imposed by the 60-kW power supply available, melting time was about 13 minutes. This was longer than desirable in terms of possible oxygen pickup and in terms of the two-minute machine cycle time typical in production of aluminum rotors of this size. Smaller rotors were cast in shorter cycles. The copper was heated to 1230°C (2246°F) providing about 150°C of superheat.

To maintain superheat, a heated shot sleeve surrounded with a thermal wrap was used. The shot sleeve had a replaceable insert at the pour point. Heat was provided by both preheating with a gas torch and by an array of resistance heaters surrounding the sleeve. The shot sleeves were specifically sized for each rotor size to minimize air entrapment and porosity in the casting.

4.2 Die casting process variables

The real-time shot control capability of the die casting machine provided opportunity to study a number of die casting variables that might affect the quality of the cast copper and the performance of the rotors in motor tests. On the machine used, ram speed can be set at a number of positions and final compacting pressure and duration are adjustable. The machine allows independent control of die closure and shot sleeve velocities and pressures providing accurate and replicable machine settings for each shot. A wide range of these variables was used to assess the sensitivity of the copper die casting process to machine operating parameters [1], [2].

There was concern that the bar might weld to iron laminations or that the properties of the iron would be compromised by heat treatment. Welding of laminations to the copper would increase the magnetic loss component of the total motor losses. On ejection from the machine, half the rotors were water quenched on the theory that rapid cooling would shrink the copper from the iron and would minimize high temperature annealing of the iron. The other half was allowed to air cool.

4.3 Motor performance test results

A total of about 140 rotors were cast for four motor manufacturers to evaluate in their own laboratories. Three companies used dynamometer efficiency tests as per IEEE Specification 112, test method B, as required in the U.S. by the National Electrical Manufacturers Association (NEMA) and the Energy Policy Act of 1992 (EPAct). The fourth company used the IEC 34-2 test method.

The IEC method assumes a fixed percentage as stray load losses. The IEEE test method is a true watts in vs. watts out efficiency test that segregates the energy losses into five categories:
Iron Core Losses - Magnetic losses in laminations, inductance and eddy current losses.
Stator Resistance - current losses in the windings.
Rotor Resistance - current losses in the rotor bars and end rings.
Windage and Friction - Mechanical drag in bearings and cooling fan.
Stray Load Losses - magnetic transfer loss in the air gap between stator and rotor.

The first four are measured directly and the remainder is in the "stray load" category. For reasons explained below, stray load losses are reduced by the copper rotor and it is therefore important to determine this loss rather than assume a value for it.

To ensure an accurate comparison with the corresponding aluminum rotor, a single wound stator was used to test all rotors in each test program.

Participating motor manufacturers were assured confidentiality. Each agreed to disclose test data, but at their request are not identified.

4.3.1 15 Hp (11.2 kW) motor test results

4.3.1.1 Rotors tested

The first copper rotors cast were for a 15 Hp (11.2 kW) motor and were 5.7 inches (144.8 mm) in diameter with a 6-inch (152 mm) stack height containing 14 lbs (6.4 kg) of copper in the conductor bars and end rings. It is important to note that the laminations used here were designed for aluminum; i.e. the slot design had not been optimized for copper.

The Buhler horizontal die casting machine used in this work was equipped with real time shot control allowing programming of the shot ram speed - time profile and the final pressure. To see if the shot profile process variables materially affected the casting quality and motor performance, a number of rotors were cast covering three different injection pressures and speed transitions at two ram positions.

Table I IEEE Loss Segregation Test Results for a 15 Hp (11.2 kW) Motor				
	Al (W)	Cu(W)	?W	%
Stator Resistance	507	507	0	0
Iron Core Loss	286	286	0	0
Rotor Resistance	261	157	-104	-40
Windage & Friction	115	72	-43	-37
Stray Load Losses	137	105	-32	-23
Totals	1306	1127	-179	-14

Seven rotors covering these process variables were tested and compared to a large database of similar aluminum rotor motors averaged as a "typical" motor. Since the same "standard" stator was tested seven times, the spread of test results ranged from 502 watts loss to 522 watts loss. This represents an approximate plus or minus 2% testing error which has to be assumed across all test data. As a result, the data for stator resistance and core iron magnetic loss have been averaged and considered a constant in both copper and aluminum rotors since they are not affected by rotor material.

4.3.1.2 Test results

The test results shown in Table I were remarkably consistent across all process variables. The key measure of efficiency yielded virtually no difference with 90.7% as average and variation of only plus or minus 0.1 percentage points. Rotor watts loss averaged 157 watts with a maximum variation from 153 to 167 watts loss. With only seven tests, no pattern could be discerned relative to any of the process variables; pressure, stroke or quench. The consensus conclusion is that the process is very robust and process variations within the range tested have no predictable effect on final performance results. Although the post-casting cooling method seemed to have no effect on the results, water quenching reduced handling time to one minute versus a 20-minute air cooling time. This would allow much faster handling in a manufacturing plant.

From the remarkable consistency of the test results, it is concluded that the casting process is most viable. Results variations are all within test measurement accuracy and no pattern emerged in the variables. When compared to historical variation in aluminum rotor motors, these copper rotors were so consistent as to deem the data variation insignificant. Table I shows the IEEE test results as averages for seven rotors tested. Rotor resistance losses are the key item in rotor material substitution and yielded a 40% reduction in measured losses. This represents 80% of the theoretical maximum value possible in the conductivity difference between rotor materials. This is a very good start for a first attempt at real motors and may be improved further with detail lamination slot design discussed below. Windage and friction losses are mechanical losses retarding rotation. Although these seem to have no relevance to rotor material, they do in this case. The copper rotors cast had smooth end rings except for projections for balancing weights. They did not include cooling fins on the end rings that both dissipate rotor heat and circulate internal motor air to even out hot spots in the stator windings. With a lower resistance rotor, less heat is generated to be dissipated. These rotors, lacking fins, were adjoined on the shaft with an internal circulating fan for stator cooling. These fans are more efficient as they can be sized for their circulating job with less need to dissipate rotor heat. As a result, when compared to aluminum rotors with fins, total windage loses were down 37% from 115 watts to 72 watts. Friction in the bearings is assumed to be the same. The cooler running copper rotors allow reduced windage losses via a more efficient internal fan and reduce the amount of copper required by eliminating the rotor end ring fins.

Stray load losses are the cumulative effect of magnetic transfer efficiency between the stationary stator and the rotating rotor as experienced in the air gap between the two. Although this can be affected by consistent air gap and rotor balance, there is also an electrical component to the magnetic transfer efficiency. Consistency in rotor conduction bars is critical to proper induction magnetic transfer. Porosity or nonmetallic inclusions in these cast rotor bars can effectively change the "wire gauge" of the bars from one bar to another. Variation in rotor bar cross sectional area, and therefore resistance, causes variation in the magnetic field in the air gap. This increases stray load losses via inconsistent magnetic flux density between stator and rotor reducing overall efficiency. The seven copper rotors exhibited such rotor bar consistency so as to reduce stray load losses by 23%, from 137 watts to 105 watts. A more accurate and consistent casting process might possibly produce similar stay load improvements in aluminum rotors. It is clear that the copper rotors cast using the heated nickel alloy casting process developed in this project contributed to the overall motor efficiency via a consistency not normally achieved in typical motor production.

The substitution of copper as rotor material directly achieved 58% of the total savings and was materially involved in saving the other 24% in windage losses and 18% in casting accuracy stray load losses. The combination resulted in 179 watts of savings or a total of 14% reduction in total losses. These results support the efficacy of both the material and the process. The rotors did not even require balancing weights that are usually used to compensate for rotor bar inconsistencies.

4.3.1.3 Performance measures

In addition to the loss measurements, the test method itemizes performance issues such as temperature rise above ambient, full load speed and power factor. They reveal a motor with different

Table II
Characteristics of the15 Hp (11.2 kW) Motor

	Al	Cu	Difference	% Change
Efficiency	89.5	90.7	-1.2	+1.4
Temp. Rise, °C	64.0	59.5	-4.5	-7.0
Full Load RPM	1760	1775	+15	+0.85
Slip, %	2.22	1.37	-0.85	-38
Power Factor, %	81.5	79.0	-2.5	-3

characteristics than a typical aluminum rotor motor. Overall efficiency resulted in a solid addition of 1.2 percentage points added directly to the motor nameplate efficiency. As noted above, this is significant in that 20 years of motor efficiency improvements have already utilized all of the easy things that reduce losses.

Temperature rise above ambient is significant in the life expectancy of the motor. The general rule of thumb in the motor industry is that for every 10 degrees Centigrade hotter a motor runs, life expectancy can be cut in half. With nearly 5°C reduction in the copper motor temperature rise, we can expect a possible 50% increase in motor life when the motor is operated near design capacity. Only real field tests and time would be able to prove this hypothesis, but similar results have appeared in premium efficiency motors.

Power factor is down slightly (3%) but is very near measurement accuracy levels. Power factor is only an issue if the electric utility measures a low power factor for the entire factory facility. It adds a low power factor penalty to the electric bill to pay for correction capacitors added to the utility yard to compensate for the phase shift. Most customers do not have this penalty but if they do, it is the entire facility that is corrected, not each individual motor.

Slip is the difference between the synchronous RPM of the field rotation at 60 Hz (or 50 Hz elsewhere in the world) and the full load RPM of the rotor and shaft assembly. This difference is what creates the torque to rotate the load. The copper rotors achieve this torque point with less slip or a higher measured RPM. This creates what is called in the industry a "stiff" motor or one that does not slow down much under load. This implies a very responsive motor on variable frequency drives if high performance servo-like speed changes are desired. It does, however, also imply potential problems on variable torque loads like fans and pumps. These applications are subject to the Cube Law of energy input since it varies with the cube of the speed change. With a 1% increase in full load speed, the energy used on these applications will go up by the cube, or 3%, because of the higher speed. They are moving more air or water but it appears that energy usage has gone up despite a more efficient motor. This can cause problems in application as experienced in past improvements from standard motors to premium efficiency which produced similar increases in full load RPM amp draw. This is solvable in proper application engineering by simple adjustment in pulley ratios to bring the fan back down to its design speed.

With the rotor laminations designed for aluminum used in these test rotors, torque is down, but this problem is solvable. The production motors that the copper rotors were compared to are historically very high torque motors well above NEMA required minimum levels. The copper rotors exhibited a significant drop in each of the torque measurements but only from an historical high level to near NEMA minimum levels. A certain amount of this is expected from a higher conductivity rotor. Normal motor design utilizes a variety of aluminum alloys with different resistances to achieve different torque characteristics. High resistance aluminum allows higher slip and therefore higher torques. As shown in Table III, these copper rotors with higher conductivity and lower slip did not produce the same torques..

Table III
Measured Torque Values in lb-ft for the
15 Hp (11.2 kW) Motor

	Al	Cu	Difference	%
Starting Torque	58.2	37.0	-21.2	-36
Breakdown Torque	152.0	125.9	-26.1	-17
Locked Rotor Torque	69.0	65.0	-4.0	-6

Locked rotor torque is the static measurement and the copper rotors performed very close to normal motor expectations. Dynamic performance of starting torque to get the load up and running is the most alarming at over 1/3 reduction. This could imply problems on high inertia loads. Breakdown torque (load required to stop a running motor) is also down 17% but still within NEMA minimums and down only from already very high levels in the data base. With further design adjustments we surmise that these torque factors could be corrected with changes in the cross sectional shape of the rotor bars not necessarily requiring an increase in total copper cross sectional area and cost.

4.1.3.4 Efficiency, material and process economics

These test data do not give all that is necessary to do a complete economic analysis, but a number of important implications can be drawn. A total drop of 179 watts implies a nearly 1600 kilowatt-hour reduction in energy use per year on continuous duty or over $100 per year savings at typical industrial electric rates in this 15 Hp (11.2 kW) motor. This adds measurably in the life-cycle costing over a typical 10-year life span and even more if the life is extended due to the lower temperature rise. Moreover, there is another significant factor in that this "optimized"' copper rotor design was only a 6-inch (152.4mm) stack of lamination material as opposed to a standard EPAct aluminum rotor stack length of 6.5 inches (165.1mm) in Open Drip Proof motors and 7.5 inches (190.5 mm) in Totally Enclosed Fan Cooled motors. This implies savings of 0.5 to 1.5 inches (12.7 to 38.1 mm) of both rotor and stator core iron as well as the stator windings and rotor conductive material.

4.3.2 Other motors tested

In a larger 25 Hp (18.5 kW) motor tested, the end rings were 6.5 inches (165 mm) in diameter with a stack height of 9.5 inches (241 mm). The squirrel cage contained 25 lbs (11.4kg) of copper and required melting 39 lbs (17.7kg) of copper per shot. The motor manufacturer provided sufficient laminations for 14 rotors. Motor tests of this second set of larger rotors showed even more dramatic results. This in part is due to the use of a rotor lamination slot design specifically designed for copper.

Again there was remarkable consistency in the results for the four rotors tested and compared to the same motor with an aluminum rotor. The rotor losses were 40% lower in the copper rotors and the overall losses were reduced by 23 %. Lower losses led to reduced rotor and stator temperatures. On completion of tests, the temperature of the stator winding of the motor with the copper rotor was 32°C (90° F) cooler that the aluminum design; the copper rotor was 29°C (84°F) cooler than the aluminum rotor. Lower running temperatures mean that smaller internal cooling fans can be used and this had a significant effect in reducing the parasitic component of the friction and windage losses on this motor designed for the copper rotor. Motor temperature translates directly to motor life and maintenance costs. As a general rule, for motors operating near design capacity, insulation life is doubled for every 10 C degree decrease in motor operating temperature. Motors with cast copper rotors, properly maintained, will last longer and will be more reliable.

A set of rotors cast for another motor company were for a 4 Hp (3 kW) motor. The end ring was 3.54 inches (90 mm) in diameter, stack height 6.1 inches (155 mm) and contained 7 lbs (3.2 kg) of copper. Overall motor losses were reduced by 21% with the copper rotor compared to the conventional aluminum.

Copper rotors for a 5 Hp (3.7 kW) motor were cast for a fourth manufacturer. A cross-section of this rotor is shown in Fig. 2. Rotor I^2R losses were reduced by 38% compared to the aluminum counterpart motor, but surprisingly, the iron core loss component was much higher for the motor with the copper rotor. This was apparently due to insufficient consideration of the rotor and stator lamination designs from the aluminum rotor used. It appears that the iron was almost totally saturated in the aluminum design. The higher current in the copper could not further magnetize the iron and appeared as a large apparent loss.

As shown in Table IV, the I2R losses for all motors fitted with copper rotors from this test program showed reductions of 29 to 40% with one smaller motor showing a higher value.

4.3.3 Structure and chemistry of die-cast rotor copper

Metallurgical examination of cast copper rotors confirmed that there was no interaction between the copper conductor bars and iron laminations. The conductor bars showed small defects at the copper-iron interface and lamellar defects in the copper resembling intergranular cracks and cold folds due to micro-shrinkage and entrapped inclusions, although these copper defects were not numerous. Chemical analysis revealed that small amounts of iron (10 to 11 ppm) and oxygen (0.084 to 0.163 wt. %) were picked up during casting. The combined effects of the presence of microstructural defects and chemical contamination reduced the electrical conductivity of the cast copper conductor bars only slightly to 96.8 and 98.7% IACS in the two measurements performed on the first set of rotors cast.

Fig. 2 - Cross-section of rotor for three-phase motor showing copper filling the conductor bar slots.

Table IV
Rotor I2R Losses - Copper vs. Aluminum

Hp	kW	Poles	Al	Cu	Difference	%
4	3	4	221	92	129	-58
5	3.7	4	——	—	—*	-38
15	11	4	262	157	104	-40
25	19	4	410	292	118	-40

*Actual loss values not reported

Table V
Overall Motor Efficiency and Loss Reductions by
Substituting Copper for Aluminum in the Rotor

Efficiency Hp	kW	Poles	Al	Cu	Difference	Loss Reduction, %	Reference
4	3	4	83.2	86.4	3.2	19.0	This study
7.5	5.5	4	74.0	70.0	5.0	19.2	7
10	7.5	4	85.0	86.5	1.5	10.0	8
15	11.2	4	89.5	90.7	1.2	11.4	This study
25	18.8	4	90.9	92.5	1.6	17.6	This study
40	30	4	88.8	90.1	1.3	11.6	9
120	90	4	91.4	92.8	1.4	16.3	9
270	200	4	92.0	93.0	1.0	12.5	4

Porosity in the far end ring of the first set of copper rotors appeared to be 2 to 3 percent but did not extend into the conductor bars. The uniformity of the conduction paths in these copper rotors shows up as a reduction in stray load losses and had not been expected. Little balancing to compensate for uneven weight distribution was required. The larger rotors of the second group cast were more of a problem in this regard showing as much as 25% voids in the first shots and 8 to 10% in rotors tested for electrical performance. As discussed below, this porosity had little apparent effect on the performance of these copper rotors. Die-cast aluminum rotors very often have considerable porosity requiring use of extra aluminum to compensate for porosity and always require balancing.

4.3.4 Comparison with literature data

Table V summarizes the overall motor efficiencies and loss reductions observed in motors fitted with copper rotors including the data of this study and that of several others from the literature where comparisons with aluminum are reported. A broad range of motor power from 4 Hp (3kw) to 270Hp (200kw) is covered. A clear pattern of increased efficiencies with higher values for the larger motors and loss reductions averaging 14.7% is evident.

4.3.5 Conclusions from motor tests

The motor performance tests reported here have verified years of calculations on the part of motor manufacturers about the prospective benefits of incorporating copper in the squirrel cage structure. The results show conclusively that overall motor energy losses are reduced by an average 14% and the nameplate efficiency is increased by at least a full percentage point. Improved design of lamination slots and other motor components to optimize the copper rotor design promises to result in further improvements and to mitigate reduced torque characteristics. The test results show that the copper die casting process is robust and capable of consistent quality not seen in the current aluminum rotor manufacturing process. Conventional aluminum rotor manufacturing inconsistencies frequently require the addition of extra materials (stack length) to compensate for the low end of the performance range that is required under NEMA guaranteed minimums of torque and efficiency. The copper performance and consistency allows design to exact requirements without the addition of "safety factor" materials. Preliminary cost estimates indicate a continued cost premium for copper versus aluminum, but offsetting factors of reduced total material requirements and selected applications may well justify the substitution of copper in a broad range of induction motors. Demonstration of substantially improved energy efficiency together with the development of much improved die materials and manufacturing economics has encouraged motor manufacturers worldwide to further develop and to adopt the die-cast copper rotor.

5. POROSITY CONTROL IN DIE CASTINGS

High pressure die casting is the most economical process to form the squirrel cage of the induction motor rotor, but the high rate of introduction of liquid metal to the die cavity generally results in some distributed porosity in the casting. As reported above, rotors tested by several motor manufacturers were remarkably easy to balance and showed significantly reduced stray load losses. Both factors seemed to indicate the absence of large pores in the structure. The low stray load losses are only possible when the currents in each rotor conductor bar are essentially equal. The existence of large pores would reduce the bar cross section and current in that bar. Rotor castings for a large motor produced after those described above were found to be difficult to balance. Sectioning of the end rings revealed large pores. This porosity was as much as 25% in some castings and 8 to 10% in others. Subsequent examination of rotors for the 15 Hp (11.2 kW) motor described in section 4.3.1 also revealed more porosity than expected (Fig. 3). These findings prompted an investigation of the origins of the porosity and means to eliminate formation of large pores. The work is fully described elsewhere [10] and is summarized here.

Fig. 3 - Photographs of sectioned end rings from copper rotors typical of baseline die casting conditions.

Flow 3D software using computational fluid dynamics methods was used to simulate metal flow into the die cavity. The output for the model simulations was a series of flow videos. These were analyzed to identify shot speed - time profiles that would cause large pores in the end rings or conductor bars. Profiles to eliminate large pores in favor of uniformly dispersed fine pores were sought. The model of the rotor squirrel cage with the gates and runner bar is shown in Fig.4.

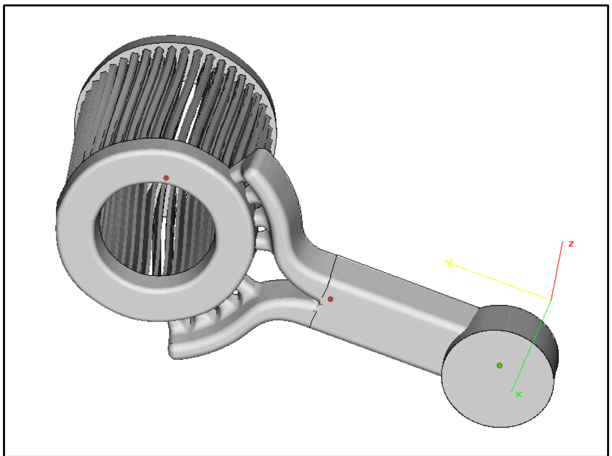


Fig. 4 - Model of squirrel cage with gates and runner. Symmetry of the part allows simulation of the fill to be done on half of the model thereby saving computer run time.

Simulation of the baseline casting conditions was performed to determine if the observed void pattern could be predicted. This baseline shot profile extends the initial slow plunger speed so that about 10% of the gate end ring is filled before transition to fast shot speed to complete the fill. The simulation is shown in Fig. 5. This is a single frame from the Flow 3D video. These representations show only the skin of the casting next to the cavity wall and the skin surrounding any pores present. Pores are seen by the skin formation around the air bubble. Otherwise the casting appears to be empty where metal is actually present.

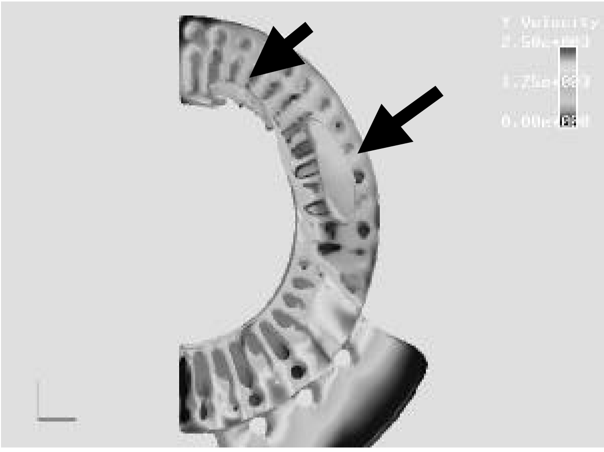


Fig. 5 - Simulation of the gate end ring fill for the baseline shot profile used for production of copper rotors early in the program.

Arrows in Fig. 5 show the predicted porosity in about the same locations as seen on the sawed cross sections of Fig. 3. The video of the ejector end ring also showed bubbles consistent with the physical examination, but the videos also seemed to indicate bubble formation in the conductor bars which may or may not be forced into the ejector end ring later in the fill. Large pores or bubbles were never seen in the conductor bars of rotors that had been machined to expose the point of largest bar thickness. As shown in Fig. 6, only a few pin head size pores are seen in the bars.

The significant result from the model simulation of fill trying several shot profiles was the discovery that slow pre-fill of the cavity beyond the gates of 40 to as much as 55% was predicted to be a strategy for avoiding large pore formation in the end rings.

A number of copper rotors were cast to test the Flow 3D simulation predictions. Rotors 5.7 in. (145 mm) in diameter by 5.25 in. (133 mm) high were cast using the 660-tonne real time shot controlled Buhler horizontal die casting machine at Formcast. This machine provides for precise programming of the shot profile. The die used for the trials was a commercial two-plate rotor die, edge gated, with a vertical core pull to assist with rotor stack insertion and ejection of the cast rotor. Copper in the form of chopped C10100 wire rod was induction melted under nitrogen cover on a shot-by-shot basis using a push-up crucible and the 60-kW power supply. The shot weight was 24 to 26.5 lbs (11 to 12 kg).

As concluded above, commercial production of copper rotors requires the heated nickel-base alloy dies. This type of tooling was not available for these experiments, so an H-13 steel die set was used. Die temperatures measured

Fig. 6 - Photograph of copper rotor turned on the OD to expose the conductor bars. Trapped air bubbles are not seen in the bars but are clearly visible in the end ring.

prior to each shot at six points on the die faces ranged from 240 to about 600°F (115 to 315°C). This is not nearly as hot as the 1200°F (650°C) die temperature prescribed and known to be essential to extending die life. With relatively cold tool steel dies, a rather high melt temperature of nearly 2600°F (1425°C) was found to be necessary to compensate for heat loss from the liquid copper to the cooler shot sleeve, die inserts and lamination stack. The high melt temperature was critical to avoid freezing in the gates with the slow pre-fill programs being tested. The shot sleeve was heated to 840°F (450°C) to help in this regard.

The shot profile was varied so that the speed transition occurred below the gates about half way up the runner and at pre-fills of 33 and 55%. Results are show in the sawed cross sections of Fig. 7. Porosity is seen to decrease markedly with increasing pre-fill compared to acceleration before the metal reaches the gate. Presumably the amount of pre-fill cannot be increased indefinitely. Additional experiments to determine the limit would be valuable.

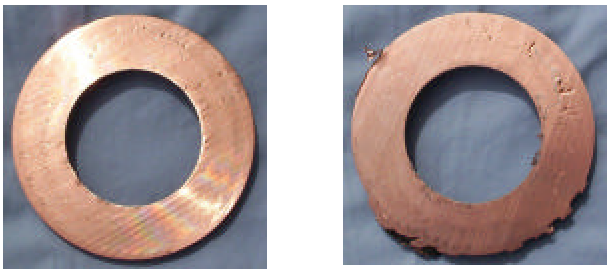
6. OPTIMIZING ROTOR DESIGN FOR COPPER

6.1 Introduction

Motor tests to characterize performance of copper rotors were done for the most part with rotor laminations and slot designs designed for aluminum

Speed transition in runner

33% pre-fill



55% pre-fill

Fig. 7 - Photographs of sectioned end rings with increasing pre-fill. Ejector end rings on left; gate end rings on right.

rotors then in production by the several participating motor companies. While this straight forward substitution of copper for aluminum showed very substantial reduction in losses and increases in motor efficiency, designing the motor as a whole and the shape of the rotor bars in particular for the high conductivity of the copper in the squirrel cage, would be expected to further enhance motor performance.

At first it seems that the substitution of copper for aluminum in induction motors would be straight forward. The higher conductivity of copper should make for higher motor efficiencies. It is not quite that simple, however. Consider the simple induction motor equivalent circuit shown in Fig. 8.

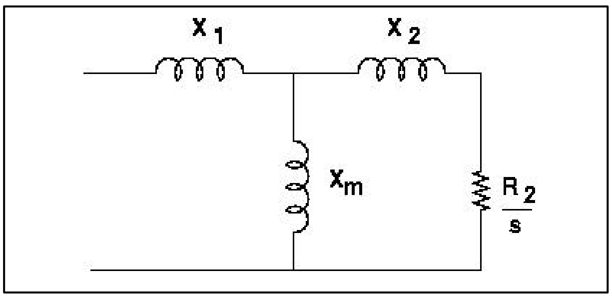


Fig. 8 - Simple induction motor model.

The value of the rotor equivalent circuit resistance R2 is inversely proportional to the conductivity of the cast rotor material. It is straight forward to estimate a torque-speed curve using this sort of model and an example is shown in Fig. 9. Shown are two hypothetical torque-speed curves. The difference between the two is the value of the rotor resistance R2. The curve that represents lower rotor resistance is to the right in the low "slip" region, indicating that it would run at lower slip (and so higher efficiency). On the other hand, it also exhibits lower starting torque.

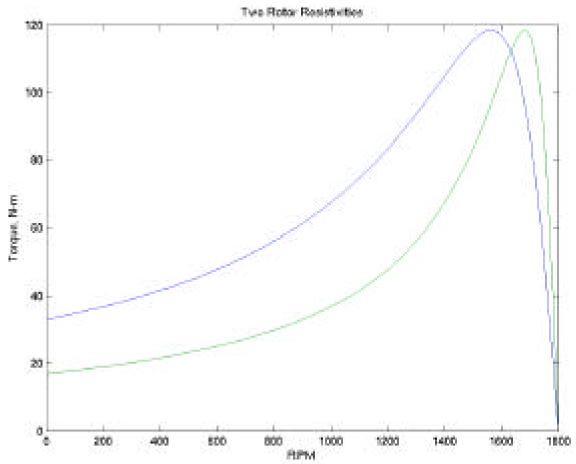


Fig. 9 - Torque speed curve as influenced by rotor resistance.

6.2 Using the skin effect

The high conductivity of copper allows the rotor designer to use the 'skin effect' to tailor the behavior of the rotor to improving motor performance. For example, when the motor is running, its slip is small and rotor frequencies are low (on the order of 1 Hz).

When the motor is starting the rotor is nearly stationary and electrical frequency seen by the rotor conductors is higher (about line frequency). Consequently the apparent rotor resistance can be higher. We might illustrate two ways in which motor designers have attempted to take advantage of this effect.

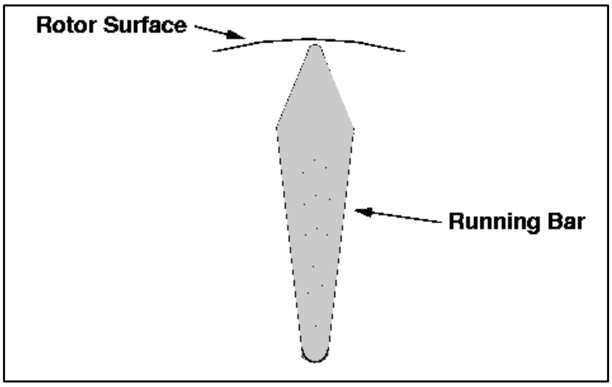


Fig. 10 - Aluminum bar.

Shown in Fig. 10 is the shape of a typical conductor bar as it would be cast into an integral horsepower motor. The bar has a taper to accommodate the shape of iron rotor teeth (they must be of enough width to carry flux and so are roughly rectangular). The bar is tapered toward the rotor surface, probably to make the magnetic aspect of the rotor surface more continuous.

One way of making eddy currents in the rotor work to increase bar resistance at high frequency (as in starting) would be to shape the bar as is shown in Fig. 11. This is the shape of a copper bar intended to
replace the aluminum bar of Fig. 10. All that has been done is to cut away some of the material above the widest part of the bar, making the top of it a narrow projection toward the rotor surface.

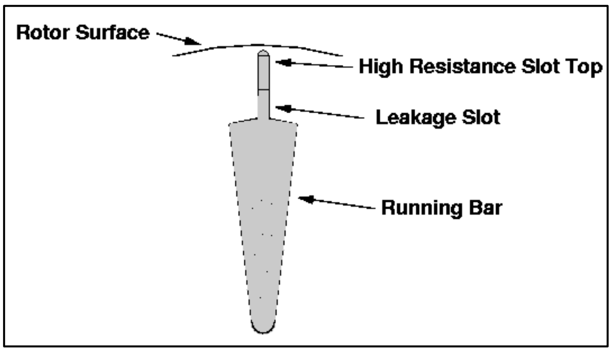


Fig. 11 - Copper rotor bar.

6.3 Frequency response

To understand how these different rotor bar structures might work, we have calculated the frequency response of their impedance per unit length. The apparent bar impedance is shown in Fig. 12 for both of the bars shown in Figs. 10 and 11.

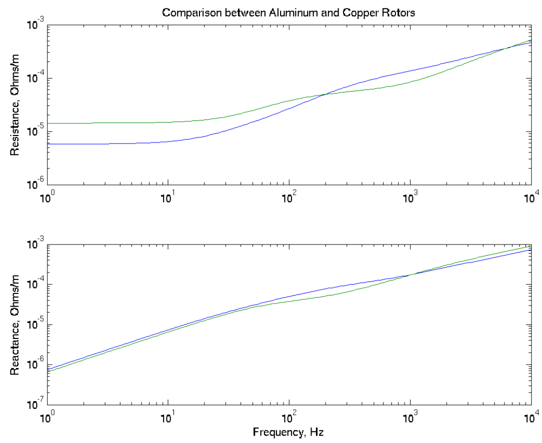


Fig. 12 - Rotor bar impedance.

As can be seen, the copper rotor has lower resistance at low frequency, corresponding to running conditions but higher resistance at higher frequencies. In this particular case, however, the resistance at starting conditions (60 Hz) is not actually higher for the copper bar. It does have higher resistance at frequencies well above 60 Hz, however, and thus will cause higher stray no-load and load losses.

6.4 Stray loss

All induction motor stator windings produce magnetic flux density which is not strictly sinusoidal. Deviations from purely sinusoidal waveforms are generally described as 'space harmonics', referring to components of the Fourier Series for the shape of the magnetic flux density. Three phase windings produce fifth and seventh space harmonics and these produce excitation to the rotor at approximately sixth harmonic frequency (360 Hz for 60 Hz motors). There are also important variations from pure sine waves at harmonic order about that of the number of stator slots per pole pair (for the four-pole, 36 slot motors we are considering, those excitations are at about 1,080 Hz). Higher resistance at those frequencies will produce higher stray load and no-load loss in a motor.

Shown in Fig. 13 is a comparison of predicted torque/speed curves for motors built with cast copper and aluminum rotor cages. Both motors have about the same starting torque. As can be seen, the aluminum rotor machine has higher breakdown torque because of the higher leakage impedance of the copper rotor machine (due to that narrow upper slot portion). The copper rotor machine appears to have lower running slip, but this is, as it turns out, offset by higher stray load losses due to the higher resistance at high order harmonic frequencies. These motors have almost identical performance.

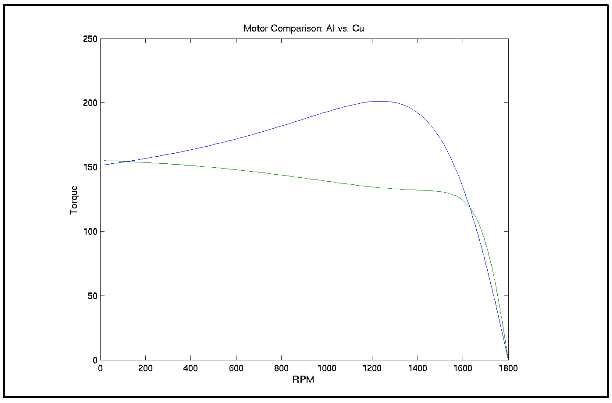


Fig. 13 - Copper vs. aluminum.

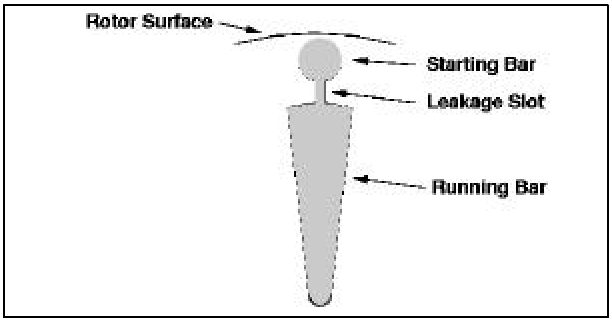


Fig. 14 - Copper rotor bar.

6.5 Alternative rotor bar designs

Another way of making a rotor bar shape is shown in Fig. 14.

The bar shown here has a relatively large rod of copper near the surface, a narrow slot which produces magnetic leakage below that and then the main 'running' part of the bar below. This bar will produce relatively high starting resistance, low running resistance, and resistance at high harmonic frequencies which is not unreasonably large. A comparison of two rotor impedances is shown in Fig. 15.

These two rotors have similar running resistance but one has higher starting resistance and lower resistance to high order harmonic currents.

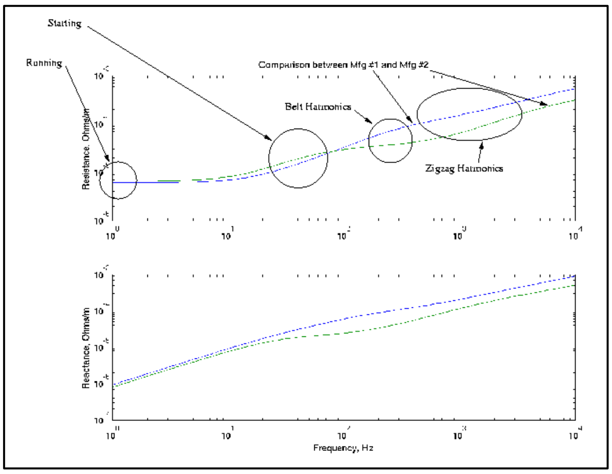


Fig. 15 - Comparison of two copper rotor bar impedances.

7. CONCLUSIONS

Seven years of development work on several fronts has led to the adoption pf copper in the squirrel cage of the induction motor as several companies are now producing or plan to produce a high efficiency line using this technology. This paper has reviewed these developments.

Testing of motors with copper rotors verified years of theoretical predictions about the benefits of using copper with its high electrical conductivity in the rotor. Rotor I2R losses were reduced by 29 to 40% and overall losses were reduced 11 to 19% resulting in increased motor efficiencies of no less than 1.5 percentage points. Ongoing work is showing the importance of design of the conductor bar shape to accommodate copper to achieve high starting torque and to reduce stray load losses.

Since high pressure die casting is the only practical manufacturing route for production of large numbers of integral horsepower motors with the intricate squirrel cage structure, the problem of inadequate die life in casting copper with its high melting temperature had to be solved. This was accomplished by development of the nickel-base alloy dies operated at elevated temperature to control the heat checking failure mechanism. Subsequent work using Flow 3D simulations of the shot profile showed the way to much improved copper rotor castings free of large pores in the end rings.

8. AKNOWLEDGEMENTS

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Gossau, Switzerland, provided the die casting tooling design and innovative approaches to the heated nickel alloy die insert technology that is being used in commercial production of copper rotors. W. G. Walkington of Walkington Engineering performed the Flow 3D simulations of metal flow into dies.

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