Control of Slag and Insoluble Build-up in Melting Furnaces

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by

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Introduction: During the past 30 years, the melting methods and associated molten metal-handling systems used by the U.S. foundry industry have changed significantly. Further, the quality of metallic scrap and other iron-unit feed stocks has steadily deteriorated. The result: slag generation and slag-related melting problems have become widespread issues in recent years. A search of the foundry technical literature about-slag control and buildup from the past 30 years finds only a handful of articles.

A new flux, Redux EF40L, has been developed that controls and minimizes buildup in pouring ladles, melting furnaces, pressure pour furnaces and magnesium converter vessels without adverse effects on refractory linings.

Slag Formation: The formation of slags in the melting of ferrous metals in the foundry is an inevitable process. The composition of slag varies with the process used and the type of iron or steel being melted. The cleanliness of the metallic charge, often consisting of sand-encrusted gates and risers from the casting process or rust-and dirt-encrusted scrap, significantly affects the type of slag formed during the melting operation. Additional oxides or nonmetallic compounds also can be formed when liquid metal is treated with materials to remove impurities (deoxidation) or to change the chemistry of the system (inoculation and nodulizing). Because these oxides and nonmetallics are not soluble in iron, they float in the liquid metal as an emulsion. This emulsion of slag particles remains stable if the molten iron is continously agitated, such as in the case of the magnetic stirring inherent in induction melting. Until the particle size of the nonmetallic increases to the point where buoyancy effects countervails the stirring action, the particle will remain suspended.

When flotation effects become great enough, nonmetallics rise to the surface of the molten metal and agglomerate as a slag. The use of fluxes accelerates this process.

In some instances, oxides may have a lower melting point than the prevailing metal temperature, and a liquid slag is formed. In other cases, where the oxides have a higher melting point than the metal temperature, a dry, solid slag is formed.

When a previously formed slag makes contact with the refractory lining of a furnace wall or other areas of the holding vessels that are colder than the melting point of the slag, the slag is cooled below its freezing point and adheres to the refractory lining. This adhering material is called buildup.

High-melting point slags are especially prone to promoting buildup. If not prevented from forming or not removed as it forms, slag will reduce the efficiency of the metal handling system.

Three important physical characteristics of slags are melting point, viscosity and wetting ability. Generally, a slag should remain liquid at temperatures likely to be encountered during melting, metal treatment, or metal handling. The viscosity of the slag needs to be such that removal from the metal surface is easy and at the same time, a fluid slag of low melting point promotes good slagging reactions and prevents buildup in channel furnace throats and loops as well as coreless furnace side walls. In electric furnaces and pressure pour furnaces, slags must have a high interfacial surface tension to prevent refractory attack and to facilitate their removal from the surface of the molten metal.

Slag Composition: The composition of furnace and ladle slags is often very complex. The slags that form in electric furnace melting result from complex reactions between silica (adhering sand on casting returns or dirt), iron oxide from steel scrap, other oxidation byproducts from melting, and reactions with refractory linings. The resulting slag will thus consist of a complex liquid phase of oxides of iron, manganese, magnesium and silicon, silicates and sulfides plus a host of other compounds, which may include alumina, calcium oxides and sulfides, rare earth oxides and sulfides, and spinels and fosterites. Table 1 illustrates the chemical analysis and ceramic phases present in a sample of inductor buildup taken from a 30-ton vertical channel furnace used to melt ductile iron.

Table 1: Composition and phase present in build-up from a 30 ton vertical Channel Furnace*

Compound	Percent Present
MgO	45.2
SiO_2	31.0
Al_2O_3	17.4
Fe_2O_3	3.5
CaO	1.6
MnO	0.29

***Ref: DC Williams, Modern Castings, August 1990**

Melting Methods

Coreless Induction Furnaces: The coreless induction furnace is a refractory-lined vessel with electrical current carrying coils that surround the refractory crucible. A metallic charge consisting of scrap, pig iron and ferroalloys typically are melted in this vessel. When electrical current from the coils is passed through the charge, a magnetic field is formed. The field creates thermal energy, which melts the charge. The magnetic currents in the molten metal cause an intense stirring action, thus ensuring a homogenous liquid. During the melting process, – slag – nonmetallics and insolubles – are generated from oxidation products, dirt, sand, and other impurities from the scrap, erosion and wear of the refractory lining, oxidized ferroalloys, and other sources. Sometimes, the term "dross" is also used to describe these insoluble by-products of the melting process. These nonmetallics remain in the liquid metal as an emulsified slag until they increase in size and buoyancy. Once the nonmetallics coalesce into a floating mass on the liquid metal they can be removed. The slags normally are deposited along the upper portion of the lining or crucible walls – above the heating coils – in a coreless induction furnace. Figure 1 shows typical slag buildup in a coreless induction melting furnace.

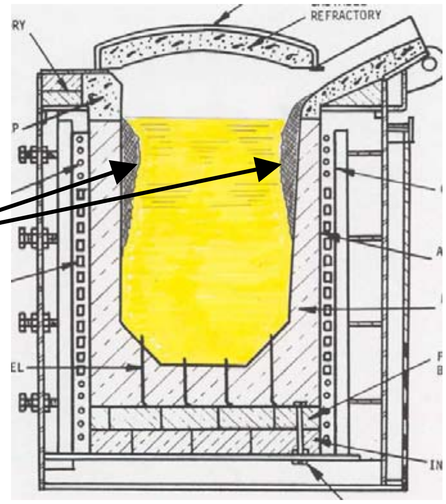

Figure 1: Typical Slag Build Up in a Coreless Induction Furnace

The areas of slag deposits are at a much lower temperature than the center of the furnace walls. Slag also is deposited in areas midway down the crucible lining, where insufficient metal turbulence from magnetic stirring occurs.

Channel Furnaces: Another type of induction melting furnace is the channel furnace. The channel and the coreless induction furnaces mainly differ in the placement of the induction coil and the metal bath. In a coreless furnace, the coil completely surrounds the crucible. In a channel furnace, a separate loop inductor is attached to the main crucible, which contains the major portion of the metal bath. A vertical channel furnace may be considered a large bull ladle or crucible with an inductor attached to the bottom. Figure 2 shows how slag accumulates over time in the bottom inductor loop or throat area.

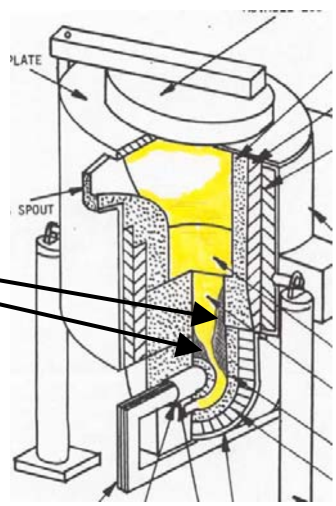

Figure 2: Slag Build-up in Inductor throat of Vertical Channel Furnace

When this happens, insufficient metal flow through the inductor loop hampers heat transfer and interferes with the melting operation. It is very difficult to remove accumulations of slag from the inductor loop or throat area. Often, a furnace operator will attempt to insert a steel rod or green wooden pole into the throat area even though accessibility is often severely limited. It almost appears that the designers of these furnaces didn't give much consideration to slag generation and its removal. When significant accumulations of buildup cannot be removed, the furnace is taken out of operation and a newly refractory lined inductor is installed. Typically, inductor life may be as long as 18 months, however, if slag buildup occurs, the useful life may be reduced to only a few months - and - in some cases, a few weeks.

Pressure Pour Furnaces: Pressure pour furnaces are sealed holding furnaces normally blanketed with a nitrogen atmosphere and have an induction coil attached to the bottom. Pressure pour furnaces are designed to hold liquid metal at a constant temperature for short or extended periods of time such as over a weekend or longer. They are widely used in the processing of magnesium treated ductile irons. When the furnace is pressurized, a stream of molten metal exits the vessel for mold filling. These furnaces are not designed to melt metal. Circulation of liquid metal through the inductor throat or loop provides the heating of liquid metal to keep a constant temperature in the furnace. As in a vertical channel furnace, slag often builds up in the inductor loop and throat areas (Figures 3). Slag buildup also occurs along the side walls, effectively reducing the capacity of the vessel.   Additional buildup in the fill siphon and pour siphon areas restricts metal flow rates into and out of the vessel.

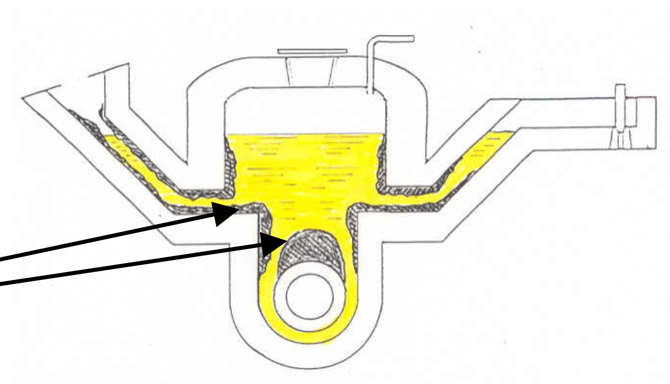

Figure 3: Traditional throated pressure pour vessel showing slag build-up in (black cross hatched)

impossible, to remove the buildup. Attempts to modify the inductor with a throatless inductor (Figure 4) When this happens, the inductor will have to be replaced because it is extremely difficult, if not have been only partially successful in eliminating buildup.

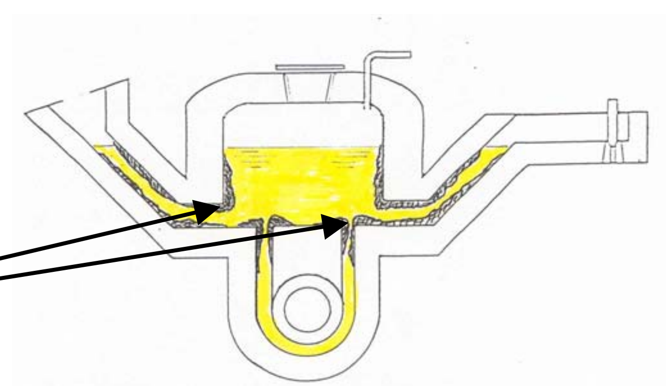

Figure 4: Throatless pressure pour vessel showing slag build-up in (black cross hatched)

Depressurizing the pressure pour vessel and removing the top hatch for cleaning allows additional air to enter the vessel. This increases metal oxidation and worsens buildup problems. To remove the buildup for restoring electrical efficiency, it must scraped from the side walls and inductor throats. If the buildup is hard, it is very difficult to remove. If the buildup is soft, then it is possible that routine maintenance (scraping the sidewalls and rodding the inductor throat area with a metal tool or green wood pole) can minimize accumulations. When the buildup becomes severe, power factor readings and the efficiency of the pressure pour drop~~s~~ dramatically.

Slag~~s~~ and dross from the electric melting methods detailed above, if not totally removed at the melting furnace, will be transferred to the metal pouring ladles. Because the walls of the pouring ladle are much cooler than the furnace refractory lining, slag buildup is inevitable. The task of continually keeping the pouring ladles clean requires a significant amount of labor. Failure to do so may result in costly casting scrap from slag inclusions.

Slag and dross formation are usually very troublesome problems in the production of ductile irons. Buildup occurs initially in treatment ladles and then may continue in downstream holding vessels. Buildup is also a major problem in ductile iron treatment vessels utizing the pure magmesium process and in the using flow-through process.

Slag buildup in ductile iron treatment ladles is a very common problem at ductile iron foundries. Buildup reduces ladle volume and likewise results in lower productivity. The inability for dispersed slag particles and other emulsified slag droplets to float out in the slag may lead to carry over into downstream metal holding vessels, leading to inductor in-efficiencies.

The pressurized magnesium converter process is very susceptible to buildup of MgO and MgS reaction byproducts. In addition, rare earth oxides and sulfides may also form. In large converter vessels, 8 to 12 inches of buildup on inter-cylindrical surfaces may accumulate over in just a few days, neccesitating converter replacement and re-lining. Premature chamber plate failure due to slag buildup may also result, again neccesitating costly replacement.

The flow-through process utilizes a refractory-lined reaction chamber. The reaction chamber is filled with a nodulizing alloy such as magnesium ferrosilicon. Slag and dross buildup often occurs in the reaction flow-through chamber. It tends to clog the opening of the chamber as well as the exit hole.

Slag Additives and Fluxes: Additives to the melting process that e~~i~~nsure that slags have a melting point below the coldest temperature in the system are called fluxes. The fluxes prevent slags and other insolubles from freezing on the cooler refractory surfaces. The use of a flux usually ensures floatation of the emulsified oxides and reduces the melting point of the slag to below the lowest temperature encountered in the melting furnace and associated liquid metal handling system.

Fluxes are widely used throughout the basic steel industry, and their extensive use is considered a science. In the foundry industry, however, there has historically been a reluctance to use fluxes. Improper use of fluxes can rapidly erode refractory furnace linings, especially if potent fluxes are used. More often, though, operator error causes problems with fluxes. The saying of "if a little works well, then a lot should work better" doesn't necessarily apply. Doubling or tripling the amount of recommended flux additions can result in reduced lining life, especially with highly reactive fluxes. Meanwhile, refractory suppliers have convinced foundrymen that use of any flux will greatly shorten refractory life, often without having any knowledge of the chemistry or potency of the flux.

Some fluxes can reduce refractory life, but if a flux is carefully engineered for specific applications and used properly, reduced refractory life isn't an issue. Redux EF40L fluxes meet these criteria. In fact, some users of Redux EF40L have reported increased refractory life that is the result of reduced slag buildup. Improved refractory life associated with using Redux EF40L fluxes results from reductions in chipping and other sources of mechanical damage to the lining that are the result of slag buildup.

Fluxes lower the melting temperature of slags. If the slag formed is viscous and has an affinity to adhere to the funace side walls, a fluidizing flux can significantly reduce this tendency. The type of flux required will depend on the specific operation. Great care must be exercised when using a flux because overzealous use may result in undesirable reactions with the furnace refractory lining.

Fluxes are compounds that are added to molten irons and steels principally to decrease the fusion or melting temperature of the slag. Fluxes undergo complex reactions with slags at elevated temperatures. Fluxes will generally dissociate into alkaline metal oxides that disrupt the silica space lattice structure of most slags. By disrupting the bonds of the three-dimensional space lattice, fluxes typically reduce slag viscosity. Fluxes also affect the surface tension of slags. Further, fluxes allow for the coalescence of low melting point slag droplets that otherwise may become emulsified in the liquid metal bath of high frequency induction furnaces.

Iron and steel fluxes containing alkali elements also aid in sulfur reduction and removal. Flux additions provide a nonmetallic liquid to absorb extraneous impurities; they help produce a liquid slag of absorbed nonmetallics, providing the slag is sufficiently low in viscosity at existing furnace operating temperatures. Fluxes also modify slags so they will separate readily from iron and facilitate the removal of nonmetallics. A flux addition primarily aids in the removal of silica and metal oxides, such as MgO and rare earth oxides, all of which have a relatively high melting point. The high melting point of these nonmetallic materials fosters the formation of a viscous or a pasty constituent in electric melting furnaces.

The viscous nonmetallics can negatively affect coreless, channel and pressure pour furnaces. For instance, they can cause slag formations on the furnace and/or inductor walls. The adhesions interferes with melting, thereby decreasing furnace efficiency. Many of the materials in the slag are acidic. The acidity interferes with the absorption of sulfur. As a result, most cupola fluxes are basic, such as dolomitic limestone and other lime and limestone-containing materials are used to neutralize this acidity.

Fluorspar, a calcium fluoride mineral (CaF_2,) is a powerful supplemental fluxing agent that is commonly used in small proportions with limestone and lime to improve slag fluidity. Fluorspar, though effective, has serious disadvantages. Fluorspar is a very aggressive flux and works extremely well in integrated steel mill as well as cupola operations. But the overzealous addition of fluorspar or fluorspar-containing fluxes to electric-melting furnaces results in severe lining erosion. In addition, as fluorspar decomposes in the furnace, it releases highly reactive gaseous fluorides. In electric melting operations with emission control systems that use fiberglass bags as a filtration device, the gaseous fluorides attack the glass fibers.

Other supplemental fluxes may include sodium carbonate, calcium carbide, borates, olivines, sodium chloride (rock salt), calcium aluminates, and ilminite. Again, overzealous use of any of these supplemental fluxing compounds can cause refractory attack.

Within the past year, a new, proprietary flux based on sodium oxide (Redux EF40L) has been developed for use in electric melting furnaces, pressure pour furnaces, ladles, and certain ductile iron treatments. Redux EF40L provides excellent fluxing action comparable with that of fluorspar, however, it is not aggressive toward furnace linings and is environmentally friendly - no fluoride emissions result. This new flux is available in 20-gram and 50-gram sizes for ease of use. The addition of 1 pound to 2 pounds per ton of molten metal is sufficient to cleanse the metal, remove slag and prevent buildup of slag and other insolubles on furnace walls and on channel furnace and pressure pour inductors. Figure 5 illustrates the shape and size of the new flux.

Figure 5: Illustration of Redux EF40L sodium oxide-based electric furnace and pressure pour flux.

Production Results: To date, many foundries in the United States and Japan are using Redux EF40L sodium oxide-based fluxes to solve buildup problems in coreless induction furnaces, channel furnaces, pressure pour furnaces, Fisher converters, and ductile iron treatment ladles.

The production experience of three foundries, each of which hasd different needs, is discussed in detail in this section.

Foundry A is a medium-sized, foundry that manufactures gray iron and ductile iron valves. Daily production capacity is 150 tons. The foundry was experiencing extensive slag buildup on the upper sidewalls of its three 3 -15 -ton coreless induction furnaces. Each coreless furnace was lined with a silica lining. The buildup reduced furnace capacity and a contributing cause of slag-related casting blowholes. In addition, considerable refractory maintenance was required on weekends to remove the buildup with chipping hammers.

Initially, 12 pounds (approximately 1 pound per ton) of Redux EF40L flux was added to each 23,000-pound charge. The EF40L was placed in the furnace before back charging. After about a week, buildup along the side walls was virtually eliminated while extensive weekend maintenance on pouring ladles was reduced to almost nothing. The pouring ladles stayed far cleaner. In addition, the majority of slag-related casting defects were significantly reduced. No evidence of refractory wear or attack was present. However, melting personnel objected to the reduced viscosity of the slag. They had greater difficulty removing the lower viscosity slag - because of its fluidity - from the furnace. The addition rate was reduced to 0.5 pound of Redux EF40L flux per charge; this allowed a far easier removal of furnace slag. Refractory lining life has been extended mainly because of reduced mechanical damage from slag buildup. The foundry has been using the flux additions for more than a year and is extremely satisfied with the results.

Foundry B is a high-production ductile iron foundry that makes automotive castings. Melting is accomplished in two 10-ton coreless induction furnaces. The induction furnaces each have a silica linings. A 65-ton silica-lined vertical channel furnace is used as a holder. Treated ductile iron from the holder is post-inoculated with a 1.5 percent magnesium containing 50 percent ferrosilicon and then transferred into a 9-ton, 300- kilowatt pressure pour furnace. The upper case of the pressure pour furnace is lined with a high alumina castable refractory. The inductor is lined with an alumina-magnesia spinel forming dry vibratory mixture.

Buildup in the pressure pour long has posed a problem. The buildup is extremely tenacious and high in magnesium oxide (MgO). Table 2 lists the composition of the buildup removed the inductor area.

Table 2: Composition of Build-up from 9-ton pressure pour furnace

Compound	**Percent Present**
MgO	85.6
Fe_2O_3	9.4
Al_2O_3	1.4
CaO	1.5
SiO_2	0.2
TRE oxides	0.30

Because of the high levels of magnesium oxide in the slag, inductor life typically averaged only 2-½ months.

In an attempt to increase inductor life, Foundry B investigated the use of sodium chloride (rock salt); however, the rock salt additions failed to reduce buildup. In addition, the generation of chlorine gas from sodium chloride (NaCl) dissociation created an extremely unpleasant working environment.

The foundry then tried Redux EF40 proprietary sodium oxide flux briquettes in an attempt to increase inductor life. Foundry B added 18 pounds of EF40 briquettes to its pressure pour furnace at the end of each day. The life of the inductor after treatment with EF40 flux has tripled — inductors now last more than seven months. Foundry B has been using the flux for more than a year; no erosion or refractory attack has been observed during this period.

Foundry C is a producer of specialty high-chrome wear-resistant mining parts. It melts a total of 250 tons to 300 tons per day in its three 5-ton, magnesite-lined arc furnaces. The high-chrome irons from the arc furnaces are transferred to 7.5-ton pressure pour furnaces via 70 percent alumina mullite, 30 percent silica-lined transfer ladles. The pressure pour furnace has a high alumina spinel forming castable lining for the upper case and a high-alumina spinel-forming dry-vibratory lining for the inductor. Slag buildup and premature inductor clogging has been a continuing problem for Foundry C. In some cases, inductor failure within a month of installation was not uncommon. The composition of the buildup taken from two locations in the pressure pour furnace is shown in Table 3.

Table 3: Composition of Build-up from 7 ton pressure pour furnace

Compound	**Slag from PP**	**Build-up from PP**
Al_2O_3	60.9%	76.5%
Fe_2O_3	9.5%	4.6%
MgO	7.2%	4.8%
Cr_2O_3	11.1%	5.9%
SiO_2	5.2%	5.1%
MnO	4.8%	2.6%

After consulting with refractory supplier, Foundry C purchased 2,000 pounds of Redux EF40L proprietary flux briquettes. After using the initial sample, Foundry C found that the slag buildup was considerably softer and could be more easily removed with periodic "rodding". Without the flux addition, the buildup was "rock" hard and almost impossible to scrape loose from the walls and inductor throat. The foundry said that before they switched to the sodium oxide flux briquettes, "rodding" the inductor produced marginal and inconsistent results. After the switch, inductor power readings sometimes dropped to as little as 360 amps. Normally, inductor power readings of 480 amps were considered good for this furnace.

Foundry C has been using the Redux EF40L briquettes for more than four months. It adds 1 pound EF40L per ton of alloy melted. The briquettes are added to the transfer ladle, the ladle is then slagged off and then is transferred into the 7.5-ton pressure pour furnace. Flux additions are made to every ladle: as many as 60 taps of 5 tons each per day are treated with flux additions. Foundry C has found that although buildup remains in the inductor loop, it is soft and easily removed. Power factor readings now consistently run between 460 amps to 480 amps. Foundry C's inductor replacement target now is six to eight months. The foundry also plans to modestly increase flux additions to the transfer ladle in hopes of reducing the amount of soft slag that still forms in the pressure pour furnace.

Foundry D is a large high production foundry that produces both gray and ductile automotive and truck castings. Melting is accomplished in two 100-inch plus cupolas with a melt capacity of 3,000 tons per day. The metal handling system is composed of 3-150 ton rotary drum channel furnaces, 15-ton transfer ladles and tilt pour furnaces on the molding lines. Mainly because of the high melting volume, slag buildup in the holding and treatment vessels has been a continous battle waged by the melting personnel. Buildup problems occur in the inductors of all three rotary drum furnaces, transfer ladles, to a lesser extent in the transfer ladles. Another major area of buildup is in the 12-ton Fisher converters and downstream tilt pour furnaces.

Buildup in the converters is severe and converter life before lining maintenance is 2-days of operation, or roughly 2,600 tons of processing. Buildup of between 12 to 18 inches in the converter body was normal. Buildup was of sufficient magnitude to reduce the working volume of the converter by almost 4,000 lbs per treatment. Chamber plate buildup is also a problem with weekly maintenance replacement. Emulsified slag carryover from the converters also reduced the efficiency of the tilt-pour furnaces

To solve these problems, Foundry D adds 11 pounds of Redux EF40L briquettes directly to the body of the Fisher converters prior to magnesium treatment. Buildup in the converters has been drastically reduced. Converter life is now approaching five days before routine refractory maintenance is needed. Buildup is now only an inch or so; the SiC refractory chamber plate looks almost brand new. Further, buildup in the tilt-pour furnaces from MgO carryover has been greatly reduced.

Foundry E is a high production ductile iron foundry producing automotive castings. Foundry E melts with three - 8 metric ton medium frequency induction furnaces lined with a silica refractory. Daily production is 250 tons. Ductile iron is produced using with the sandwich technique; treatments are 6,000 pounds.   Significant buildup in the treatment ladle occurs along with some unwanted slag carryover that causes buildup in the 2 pressure pour furnaces. A ladle flux based on a blend of CaF and ferroalloy fines was initially used as a ladle flux but with only marginal results. Ladle life was one day of production, 3 shifts per day, before buildup in the ladle prevented further use. Futher, slag carryover and buildup in the pressure pour furnaces significantly reduced caused inductor life. In fact, buildup became so bad that a hot spot in one of the pressure pour furnace inductor’s caused a serious run-out.

To eliminate these problems, Redux EF40L was incorporated directly into the magnesium treatment process. The EF40L briquettes were added with the magnesium ferrosilicon at the rate of 0.66 pounds per ton of metal. Incoming ductile treatment temperature is 2,700^{o}F.

Starting with a new ladle lined with a 70% castible silica refractory, Foundry E quickly discovered that their sandwich ladles now could go 3 days or 9 shifts before refractory maintenance.

EF40L flux has a carryover effect on the 12.5 ton pressure pour Furnaces. The pressure pour furnaces have a 70 percent castible lining in the body and the inductor has a 80% alumina lining. Buildup in the pressure pour furnace has been reduced. Foundry E also adds 30 pounds (how much) per ton of flux to the pressure pour in the evening, once a day to insure that buildup on inductor walls and throats is minimized.

Other U.S. foundries with coreless induction furnaces have reported similar operating benefits after using of Redux EF40L proprietary fluxes. The foundries have stated that using Redux EF40L fluxes on a daily basis consistently results in cleaner pouring ladles and reduced maintenance. One ductile iron producer reported that adding 1 pound of EF40L flux to his treatment pocket during the course of a week resulted in negligible slag and dross buildup.

Conclusions: The incorporation of 0.5 pound to 1.5 pounds of Redux EF40L briquettes per ton of metal has improved the inductor life of pressure pour furnaces and coreless induction furnaces. In pressure pour furnaces, though slag buildup still occurs, it has the consistency of soft taffy and is easily removed.

At a ductile iron foundry that has been running EF40L flux for more than a year, inductor life has tripled and the need to scrape and rod its furnace has fallen. At another foundry, twice weekly maintenance time on their inductor has significantly decreased. Power readings are more consistent, and the furnace consistently operates better. In all cases where Redux EF40L flux is being run on a production basis, there haven't been any reports of refractory attacks.

A gray iron and ductile iron foundry utilizing coreless induction melting has seen refractory life increase, ladle maintenance reduced and the side walls of the furnace consistently stay of buildup with use of Redux EF40L flux. The foundry also observed that its ladles run far cleaner, eliminating the need for weekend chipping and scraping maintenance. Lastly, the foundry also experienced fewer slag-related blowhole defects.

Redux EF40L flux briquettes effectively combat slag buildup without the adverse effects of aggressive refractory attack or emissions of fluoride or chloride gases.