CORROSION

Recent developments in the production and testing of grinding media

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ABSTRACT

The effect of composition and process variables on the properties of Marmet and modified Ni-Hard slugs will be discussed. The effect of shape on the over-all performance of grinding media and its relationship to the end product has been investigated and these results will be reviewed. The cost effectiveness of slugs versus balls has been well documented under various operating conditions and this will be presented in detail.

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Gordon G. Jacox graduated from the University of Alberta in 1955 with a Bachelor of Science degree in geology and from the University of Western Ontario in 1957 with a Master of Business Administration. In 1960, he received a diploma in metallurgy from the Erie County Technical Institute in Buffalo, N.Y. From 1957 to 1967, he worked for a specialty steel company in the production of stainless steel flat-rolled products. In 1967, he joined the Noranda Group and spent time on the Aluminum Smelter project in Missouri. He joined the Zinc Die Casting Division in 1969 and the foundry group in 1973. He is currently vice-president and general manager of the Norcast Division of Noranda Metal Industries Limited, based in Toronto.

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J.C. Farge graduated from McGill University in 1960 with a Bachelor's degree in metallurgical engineering. He then joined the Noranda Group as a research engineer at Canadian Copper Refiners and was later transferred to the Noranda Research Centre. In 1963, he returned to McGill University and obtained, in 1965, a Master's degree in metallurgical engineering. For the past fourteen years, he had been at the Noranda Research Centre, involved in the development and processing of ferrous and non-ferrous alloys. He is currently head of the Physical Metallurgy Department.

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Introduction

The selection of grinding media is based on the cost-to-wear ratio combined with the consideration that it must stand repeated impacts without breaking. The specific consumption of grinding balls and slugs depends primarily on their microstructure, which, in turn, is controlled by chemical composition and by the processing conditions to which they are subjected during manufacture.

The first part of the paper deals with the optimization of alloy content to produce cast iron slugs with microstructures consisting essentially of martensite and carbide and with hardnesses of 650 B.H.N. and higher. The second part deals with the use of cast iron slugs to replace forged steel balls in milling operations. Tests indicate that the shape of the media has little if any effect on results and that the hardness and microstructure of grinding media will determine its relative performance. Where price is equal under similar milling conditions, the cost effectiveness of cast iron slugs is superior to that of forged steel balls.

In order to understand the role of alloying elements in cast irons, it is judicious to consider the microstructural changes which occur during solidification and subsequent cooling, particularly from above the eutectoid temperature. Solidification starts with the formation and growth of dendrites of austenite. As temperature decreases, an eutectic nucleates and grows between the primary austenite dendrites. Immediately after solidification, the structure consists of proeutectic austenite and of the eutectic of primary carbides and austenite. On cooling to room temperature, austenite can be retained or transformed to pearlite, bainite, martensite or mixtures thereof. It is necessary to prevent decomposition of austenite into pearlite by adjusting the alloy content. For best abrasion resistance, the microstructure at room temperature should consist essentially of martensite and carbide. These types of irons are known as "martensitic irons". Depending on the carbon content of the austenite and cooling rate, "as-cast" martensitic irons will contain different proportions of martensite and retained austenite. The more carbon in solution in the austenite, the lower is the temperature at which the martensitic transformation takes place. By the time room temperature is reached, the transformation is seldom complete, and the end product is generally a mixture of martensite and retained austenite.

The composition of martensitic irons varies considerably and therefore the effect of each alloying element deserves individual consideration.

Silicon lowers the solubility of carbon in austenite and increases the tendency to form pearlite. Care must be taken not

TABLE 1. Properties of 1½-in. cast iron grinding slugs containing 1% Mn, 1% Cu and 0.5% Mo and cooled with water sprays from the unmoulding temperature

Nominal Composition (%)		As-Cast		Heat Treated for 4 Hours at 260°C	
C	Si	Average Hardness (B.H.N.)	Microstructure**	Average Hardness (B.H.N.)	Microstructure**
2.0	0.9	495	RA + M + C	570	M* + C
2.5	0.9	705	M + C + RA	690	M* + C
3.0	0.9	710	C + M + RA	700	C + M*
3.5	0.9	655	C + M + RA + (G)	635	C + M* + (G)
4.0	0.9	670	C + M + RA + G	655	C + M* + G
3.0	0.3	655	C + M + RA	705	C + M*
3.0	0.6	690	C + M + RA	705	C + M*
3.0	1.2	670	C + M + RA + (G)	690	C + M* + (G)
3.0	1.5	535	M + G + C + RA	445	M* + G + C

** M - Martensite
C - Carbide
RA - Retained austenite
M* - Complex phase consisting of tempered martensite, retained austenite, bainite and fresh martensite.
G - Graphite
( ) - Traces

TABLE 2. Properties of 1½-in. cast iron grinding slugs containing 3% C and 0.9% Si and cooled with water sprays from the unmoulding temperature

Nominal Composition (%)			As-Cast		Heat Treated for 4 Hours at 260°C	
Mn	Mo	Cu	Average Hardness (B.H.N.)	Microstructure**	Average Hardness (B.H.N.)	Microstructure**
0.5	0.5	1.0	655	C + M + RA + (P)	670	C + M* + (P)
1.0	0.5	1.0	710	C + M + RA	700	C + M*
1.5	0.5	1.0	685	C + M + RA	690	C + M*
1.0	0.5	0.5	655	C + M + RA + (P)	670	C + M* + (P)
1.0	0.5	1.5	685	C + M + RA	710	C + M*
1.0	0.25	1.0	615	C + M + RA + P	635	C + M* + P
1.0	1.0	1.0	655	C + M + RA	710	C + M*

** P - Pearlite
Rest of legend identical to that of Table 1.

to add too much silicon, otherwise graphite will be precipitated. Nickel is added to render the austenite stable to a temperature below which pearlite cannot be formed. Nickel, however, has a strong graphitizing effect, and its presence must be counterbalanced with carbide stabilizing elements such as chromium. Manganese promotes the stability of austenite and, therefore, assists in suppressing its transformation into pearlite; but, as in the case of chromium, it forms carbides and its ability to retard the decomposition of austenite is thus reduced. Molybdenum and copper are principally added to increase the hardenability of austenite.

The principal criteria in selecting alloying elements for martensitic irons should be:

(1) low silicon, to reduce the tendency for graphite precipitation and pearlite formation;
(2) the presence of proper elements to stabilize austenite and prevent the formation of pearlite;
(3) the presence of carbide-stabilizing elements to avoid graphite precipitation.

Alloy Optimization

In the present study, the effect of alloy content on the microstructure and hardness of two groups of martensitic irons was investigated.

Experiments were first carried out to determine the effect of variations in carbon, silicon, manganese, copper and molybdenum on the microstructure and hardness of the first group of irons. These experiments were aimed at establishing the preferred range of each addition element for subsequent grinding media production. The following alloys were prepared and cast into 1½-in. slugs:

(1) Iron containing 0.9%, Si, 1% Mn, 1% Cu, 0.5% Mo and either 2.0, 2.5 3.0, 3.5 or 4.0% C.
(2) Iron containing 3% C, 1% Mn, 1% Cu, 0.5% Mo and either 0.3, 0.6, 0.9, 1.2 or 1.5% Si.
(3) Iron containing 3% C, 0.9% Si, 1% Cu, 0.5% Mo and either 0.5, 1.0 or 1.5% Mn.
(4) Iron containing 3% C. 0.9% Si, 1% Mn, 0.5% Mo and either 0.5, 1.0 or 1.5% Cu.
(5) Iron containing 3% C, 0.9% Si, 1% Mn, 1% Cu and either 0.25, 0.5 or 1.0% Mo.

Alloy charges consisted typically of the following components: pig iron, steel scrap, ferro-manganese, ferro-silicon, ferro-molybdenum and copper scrap. The various materials were melted in a 50-lb coreless induction furnace equipped with an alumina crucible. The molten metal was de-slagged and poured into a pre-heated, moveable clay graphite tundish located above a casting stand. The casting stand comprised cast iron moulds each containing a number of 1½-in. slug cavities and a cooling tank equipped with water sprays. The slugs were unmoulded at about 900°C and immediately subjected to water-spray cooling. The cooling rates were measured with thermocouples inserted into the slug cavities while the metal was still molten. Recording of the temperature was started from the time of unmoulding and continued until the slug temperature reached 150°C. It was found that the cooling rate varied from 5 to 10°C/sec. The as-cast slugs were then subjected to a heat treatment of four hours at 260°C.

The hardness and the microstructure of the as-cast and heat-treated slugs are given in Tables 1 and 2. Hardness values of 650 B.H.N. and higher were obtained in several cases. Nominal compositions were used throughout the paper for ease of comparison. In no case did the actual composition vary by more than 10% from the nominal composition. The following observations can be made from the tables:

1. The risk of graphite flake formation in irons containing 0.9% Si increases as the carbon content increases beyond 3%.
2. The risk of graphite flake formation in irons containing 3% C, 1% Mn, 1% Cu and 0.5% Mo increases as the silicon content increases beyond 0.9%. It has generally been recognized that a silicon content of less than 0.6% adversely affects the fluidity of molten iron, and the present results show that silicon contents higher than 0.9% increase the tendency for graphite precipitation. Thus, the silicon content should preferably fall within the limits of 0.6 to 0.9%.
3. Traces of pearlite are present in irons containing 3% C, 0.9% Si, 1% Cu, 0.5% Mo and 0.5% Mn. This indicates that more than 0.5% Mn must be present in order to avoid pearlite formation. On the other hand, manganese contents greater than 1.5% cause severe burn-back of furnace refractories normally used for cast iron.
4. Traces of pearlite are present in irons containing 3% C, 0.9% Si, 1% Mn, 0.5% Mo and O.5% Cu. However, with 1% Cu, no pearlite is formed in the microstructure. A further increase from 1.0 to 1.5% Cu results in an increase in hardness after heat treatment.
5. Increasing the molybdenum content from 0.25 to 0.5% significantly increases the hardness of irons containing 3% C, 0.9% Si, 1% Mn and 1% Cu. Increasing the molybdenum content from 0.5 to 1% lowers the hardness of the as-cast slugs because of the presence of a larger amount of retained austenite; it does, however, increase the hardness of the heat-treated slugs.

On the basis of the above observations, it was clear that the preferred alloy composition to avoid the formation of graphite

TABLE 3. Properties of cast iron grinding slugs containing 3% C, 0.6% Si and 0.7% Mn and cooled with water sprays from the unmoulding temperature

Slug Size (in.)	Nominal Composition (%)		As-Cast		Heat Treated for 4 or 8 Hours+ at 260°C	
	Ni	Cr	Average Hardness (B.H.N).	Microstructure**	Average Hardness (B.H.N.)	Microstructure**
	1.0	2.0	625	C+P+(RA)+(M)	615	C+P+M*
	1.5	0.8	575	C+RA+M+P	655	C+M*+P
14	2.0	0.8	635	C+RA+M+(P)	655	C+M*+(P)
	2.0	1.2	575	C+RA+M	635	C+M*
	3.0	1.2	575	C+RA+M	575	C+RA+M
	1.5	1.2	575	C+P+RA+M	630	C+P+M*
	2.5	0.8	560	C+RA+M	655	C+M*
3	2.5	1.2	550	C+RA+M	635	C+M*
	3.0	0.8	570	C+RA+M	655	C+M*
	3.5	1.2	455	C+RA+M	495	C+RA+M

\+ 4-hour treatment for 14-in. slugs and 8-hour treatment for 3-in. slugs.
** Legend identical to that of Tables 1 and 2.

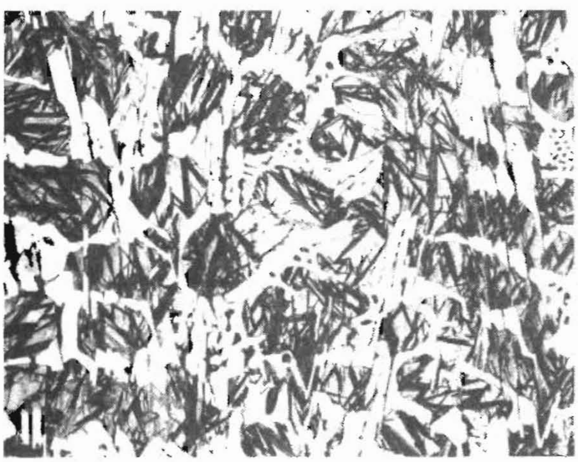

FIGURE 1. Microstructure of a Marmet grinding slug (270 x).

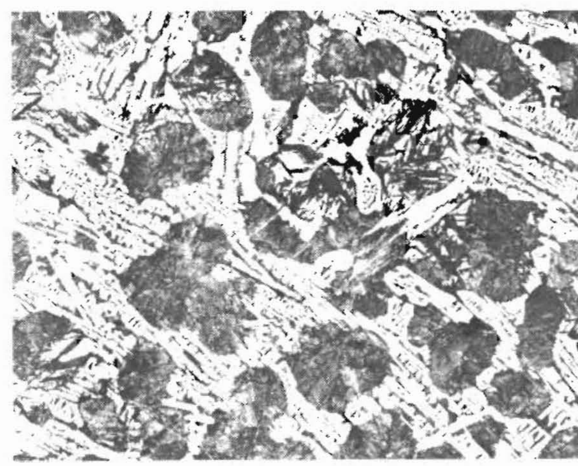

FIGURE 2. Microstructure of a grinding slug containing 1% Ni (270 x).

flakes and to obtain a high hardness and a microstructure consisting essentially of carbide and martensite, as shown in Figure 1, was: 2.5-3% C, 0.6-0.9% Si, 1% Mn, 1% Cu and 0.5% Mo. This composition was subsequently adopted by Norcast Ltd. for the production of Marmet® grinding slugs.

A second series of experiments was carried out under the same conditions as for the first group of irons. Here, 1½- and 3-in. slugs were cast from charges containing 3% C, 0.6% Si, 0.7% Mn, 0.8 to 2% Cr and 1 to 3.5% Ni. The main objective was to determine whether high hardness values and microstructures consisting essentially of martensite and carbide could be obtained with lower nickel levels than normally used in regular Ni-Hard. Table 3 gives the properties of the slugs in the as-cast condition and after a heat treatment of either four or eight hours at 260°C. Hardness values of 635 and 655 B.H.N. were attained in heat-treated 1½- and 3-in. slugs containing 2% Ni and 1.2% Cr and 2.5% Ni and 0.8% Cr respectively. In each case, the microstructure consisted of carbides and a number of phases containing tempered martensite, retained austenite, bainite and fresh martensite.

When the nickel content was too high, excessive amount of austenite were retained because of the stabilizing effect of nickel. However, when the nickel content was too low, pearlite was present. Figures 2 and 3 are photomicrographs of irons containing 1 and 3.5% Ni respectively.

FIGURE 3. Microstructure of a grinding slug containing 3.5% Ni (270 x).

Industrial-scale trials were made with process conditions similar to those used in the laboratory and it was found that superior grinding slugs could indeed be produced with a lower nickel content than generally specified for regular Ni-Hard.

FIGURE 4. Forged steel balls (Supplier A) at different stages of wear.

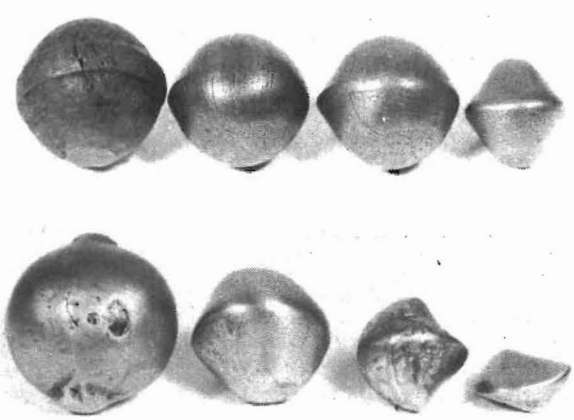

FIGURE 5. Forged steel balls (Supplier B) at different stages of wear.

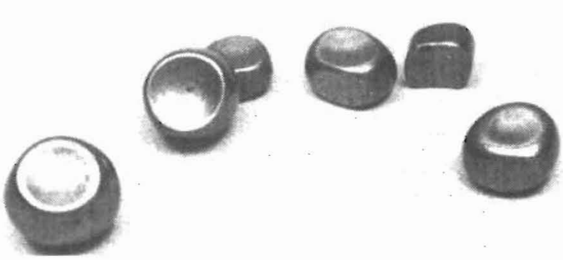

FIGURE 6. High-chromium cast iron balls at different stages of wear.

Grinding Media Performance

The shape of grinding media and their influence on the results obtained in milling ores have been the subject of controversy for years, but field experience and independent research have indicated that shape has little effect on operating results. In modern-day ore milling, shapes range from irregular pebbles or rock and completely asymmetrical ore pieces used in pebble grinding or autogenous milling to cast or forged metal products of varying shape and alloy content. During past periods of grinding media shortage, mines have had to use chain links,

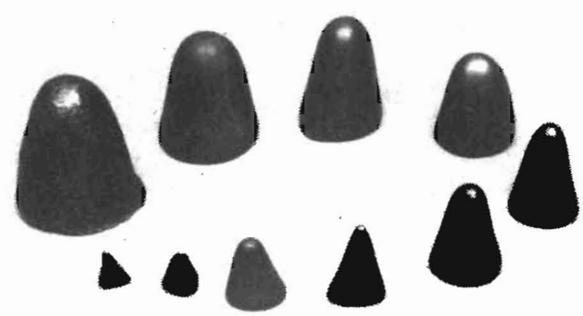

FIGURE 7. Martensitic iron slugs at different stages of wear.

FIGURE 8. Various grinding media shapes used in comparative grinding tests.

scrap metal and cut grinding rods as well as sprues and gates from cast ball foundries in order to keep their operation going, and no serious effects on results were reported.

In the actual grinding process, balls tend to wear in an irregular fashion and eventually bear little relationship to the original spherical shape (Figs. 4-6). Cast slugs, on the other hand, keep their shape throughout their life and can be identified as slugs in the discharge trunnion of the mill (Fig. 7).

Grinding media performance is dependent, not on the shape of the product, but on the hardness and the microstructure of the alloy used. Other factors that will affect performance include the size of the media, the type of mill lining material, the effectiveness of the mill cyclone classifying system, the variation in the ore, the mill operating practice and mill design. Generally, the cost effectiveness of one product against the other will be measured by the net cost of grinding media per ton of ore milled.

Comparative grinding tests were conducted at an independent research organization to determine the effect of grinding media shape on the fineness of the product. All the tests were done in a 3-ft-diameter by 6-ft-long Denver mill and three separate ores were used. Five grinding tests were carried out on each ore. The variable in each case was the grinding media—the three separate shapes of slugs, a mixture of balls and slugs, and balls alone (Fig. 8).

The performance of each grinding medium was summarized by the comparison of the product screen analyses from each test, as illustrated in Figure 9. In terms of product fineness, the following order of merit was obtained:

	Rating	Grinding Media
Increasing fineness ↑	1	1½" tapered slugs
	2	1½" oval slugs
	3	Mixture of 1½" balls and 1½" tapered slugs
	4	2" hemispherical slugs
	5	1½" balls

Over the 35-year period that Norcast manufactured both balls and slugs, there has never been a case where the shape of the media had by itself any influence on the outcome of the product. The regular addition of grinding media on a consistent basis so that kilowatt power draw is maintained at a constant rate will produce the best results in daily operation regardless of media shape. Slugs have been freely substituted for balls in mills using balls with no adverse effects on results; in some cases, an increase in performance has resulted with a mixture of slugs and balls.

Manufactured grinding media today are available in a variety of forms and alloys: forged high-carbon steel, forged alloy steel, alloy cast steel and alloy cast iron.

The principal means of producing grinding media is by forging steel bars or by casting slugs or balls. The processes can be compared in general as shown in Table 4.

Cast iron slugs depend principally on alloy content to obtain hardness and proper microstructure. The extra alloy cost is possible because of the manufacturing savings obtained by fewer processing steps and higher yields.

In recent tests conducted at different mill locations, the results shown in Tables 5 and 6 were obtained using martensitic iron slugs and forged steel balls. One of the users has since converted to 100% slugs, with an annual saving of $500,000 in net milling cost reduction.

In a nickel ore milling operation, tests were conducted over a period of a year to determine the cost effectiveness of martensitic iron slugs versus forged steel balls. The results were as shown in Table 7. This operation has since converted 50% of its grinding media requirements to martensitic iron slugs.

In another test, conducted on iron ore to determine relative grinding costs, the results shown in Table 8 were obtained using three different types of media. The cost effectiveness of the martensitic iron slugs was decisive both in terms of base price and consumption per ton milled.

TABLE 4. Comparison of grinding media

Type:	Forged Steel Balls	Permanent-Mould Cast Iron Slugs	Sand-Cast Cast Iron Balls
Process:	Melting Slab or ingot casting Reheating Billet rolling Bar rolling Cutting to length Forging Heat treatment Shipping	Melting Slug casting Tumbling Stress relieving Shipping	Melting Ball casting Shaking out Tumbling Heat treatment Shipping
Yield:	70-80%	80-90%	50-60%
Alloy Addition:	Low	Medium	Medium to High
Price/Ton:	$360-$450	$340-$390	$400-$1,200

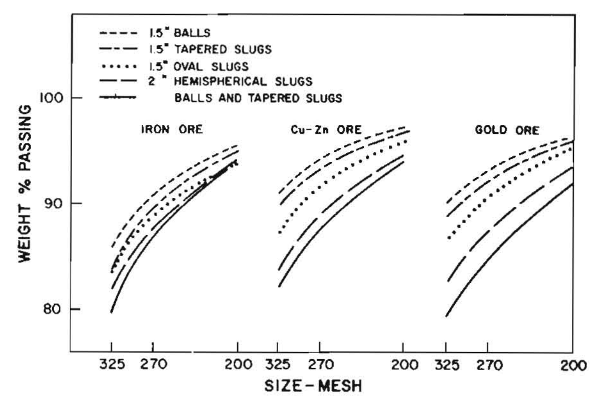

FIGURE 9. Plot of test product size distribution.

TABLE 5. Test 1

Material: lead/zinc ore
Mills: Two 10½-ft-diameter by 13-ft-long, trunnion overflow mills closed circuit with cyclones
Drive: 900 hp—16 rpm—66% critical
Recirculating Load: 300%
Mill Discharge: 70% minus 400 mesh—69% solids
Mill Liners: rubber
Grinding Media Charge: 50 tons
Test Duration: 23 weeks

	Grinding Media	
	1½-in. Martensitic Iron Slugs	1½-in. Forged Steel Balls
Operating hours	3,178	3,192
Avge. tons milled/hr	68	68
Grinding media consumed/ton milled	2.46 lb	2.60 lb
Avge. KWH/ton milled	9.70	9.76

TABLE 6. Test 2

Material: specular hematite/magnetite
Mills: Two 144-ft-diameter by 32-ft-long, trunnion overflow mills in closed circuit with cyclones
Drive: 3500 hp—15.7 rpm—76.5% critical
Mill Discharge: 75% minus 325 mesh—65% solids
Mill Liners: Ni-Hard double wave
Grinding Media Charge: 225 tons
Test Duration: 30 weeks

	Grinding Media	
	14-in. Martensitic Iron Slugs	14-in. Forged Steel Balls
Operating hours	3,844	3,782
Avge. tons milled/hr	110.3	107.4
Grinding media consumed/ton milled	4.84 lb	5.67 lb
Avge. KWH/ton milled	25.67	28.05

TABLE 7. Test 3

	Mill No. 5	Mill No. 6	Mill No. 7
Grinding media	1½-in. Martensitic Iron Slugs	1½-in. Forged Steel Balls-A	1½-in. Forged Steel Balls-B
Media consumed/ ton milled	0.686 lb	0.731 lb	0.670 lb
Media cost/ ton milled	$0.1133	$0.1273	$0.1167
Relative cost	100%	112%	103%

TABLE 8. Test 4

Grinding Media	Average Media Cost Per Ton Milled	Difference
Martensitic Iron Slugs	$0.90	-
High-Chromium Cast Iron Balls	$1.06	+ 18%
Forged Steel Balls	$1.12	+ 24%

Conclusion

Cast iron grinding media in the form of slugs have been available to the mining industry for the past 40 years. In the last five years, newly developed martensitic cast irons have been available which greatly improve the abrasion resistance of slugs and enable them to compete favourably with high-carbon forged steel grinding balls. The net cost per ton of ore milled is generally lower when these slugs are substituted for balls and, with steadily increasing mine processing costs, the use of slugs can help to keep operational expenditures under control.

Annual cement industry technical conference

The 22nd Annual Cement Industry Technical Conference, sponsored by the Institute of Electrical and Electronic Engineers (IEEE), will be held in Toronto, Ontario, **May 19 to 22, 1980**, at the Royal York Hotel.

Conference Chairman Gene Wrinkle, of St. Marys Cement Co., stated that this year's technical program will be one of the most stimulating ever presented at a North American cement industry conference. The over-all program is comprised of presentations in the general areas of Automation, Drives and Related Products, General Practices, Maintenance and Safety, and Power Generation and Distribution.

Information concerning the conference can be obtained by writing George Alcock, Registration Chairman, 1980 I.E.E.E. Cement Industry Conference, c/o Canadian General Electric, 1900 Eglinton Ave. East, Scarborough, Ontario, M1L 2M1.

Battelle conference on corrosion failures

How engineers can identify and prevent corrosion failures will be discussed at a conference on **March 24 and 25** at the Houston Oaks Hotel, Houston, Texas.

The conference, being sponsored by Battelle's Houston Operations, is aimed at acquainting engineers with the mechanisms of corrosion, how they are manifested and how they can be prevented. Various forms of corrosion in a variety of structural alloys will be examined.

At the conference, speakers from Battelle and industry will discuss technologies with emphasis on case histories of corrosion failures and preventions.

Topics include: forms of corrosion; general, localized and intergranular corrosion; parting, impingement and cavitation; environmental cracking—stress corrosion cracking, hydrogen embrittlement and corrosion fatigue; high-temperature corrosion-erosion; corrosion control—cathodic protection inhibitors and coatings.

Additional information about the conference can be obtained from Ruth Anne Gibson, Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201.

Conference on solidification technology in the foundry and casthouse

The Metals Society is sponsoring a conference on 'Solidification Technology in the Foundry and Casthouse' at the University of Warwick, England, **September 15-17, 1980.**

The conference will build on the highly successful events, 'Solidification of Metals' (Brighton, England, June 1967) and the international conference on 'Solidification and Casting' (Sheffield, England, July 1977) by updating and extending the subject in relation to shaped castings in the foundry and the wrought-alloy casthouse. Accordingly, the conference will deal with aspects of liquid-metal treatment and of casting technology relevant to the production of cast metal of desired composition, cleanliness, shape, soundness, surface quality and structure, concentrating on more recent developments.

Offers of papers are expected to fall in the following categories:

1. *Liquid metal: alloying, treatment and quality assessment*—methods of degassing, cleaning, modifying and inoculating liquid metal; assessment of the results obtained, fading and poisoning phenomena; general aspects of pore nucleation and formation.
2. *Solidification processes, and origin and control of structure in cast alloys*—
(i) *shaped castings:* structural controls in sand, metal and inverstment mould casting; macro- and microstructures; porosity; segregation, as affected by moulding materials; feeding and gating; unidirectional solidification;
(ii) *billet, slab, rod and strip:* structural control in billet, slab, rod and strip; surface quality; subsurface zones associated with heat extraction; effects of electromagnetic stirring; core structure; influence of structure in subsequent properties; effects of mould design and cooling systems; hot-top moulds; duplex moulds; automatic casting; alloys development for cast strip compositional limitations with moving and stationary moulds.
3. *Properties of the cast structures and of castings*—structure; mechanical and physical properties; defects in cast metals—origins, detection, diagnosis, prognosis.
4. *New casting processes and associated alloy development.*

Further information can be obtained from R.B. Wood, The Metals Society, 1 Carlton House Terrace, London SW1Y 5DB, England.