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SUMMARY

The paper begins with a survey of the present and future supply position for coking coals in relation to overall resources of fossil fuels and other energy sources. This shows that optimum technology for ironmaking will change considerably during the next half-century.

In relation to the near future, consideration is given to techniques of improving coke technology with the objects of maintaining quality standards whilst extending the range of usable coals. Classical prime coking coals can be replaced or supplemented by inferior grades with the application of sophisticated techniques of blending, and coke quality and performance can be improved by charge preheating. More basic solutions involve the manufacture of artificial or formed cokes.

In the immediate future, the injection of gaseous and liquid hydrocarbons into the blast-furnace tuyeres can be economically advantageous, and wider possibilities are opened up by the injection of reducing gases in the bosh or shaft.

Prospects for direct-reduction systems based on fossil fuels, eventually supplemented by the use of nuclear heat, are examined. Finally, consideration is given to the problem of iron-oxide reduction in the absence of all fossil fuels.

World resources of coking coals are more than enough to smelt all the classical iron-ore reserves.

At first sight this statement would appear to remove any vital necessity to change ironmaking technology to a radical degree but, of course, commercial and local considerations must have an important effect on development. For this reason it seems desirable to consider the broad pattern of availability of energy sources during the next half-century.

ENERGY SOURCES

Primary sources relevant to the manufacture of iron include coking grades of hard coal, other hard coals, fuel oil, natural gas, and nuclear energy, this last including direct use of the heat of nuclear reaction. All the fossil fuels have been used for the reduction of iron ore but the situation has hitherto been completely dominated by the blast furnace using coke as prime fuel.

Fossil Fuel Reserves

Many estimates have been given of reserves and their geographical distribution, and large discrepancies are to be found.[1-4] Despite this, the overall picture is reasonably clear and useful conclusions can be drawn.

Hard coal reserves may be taken as about 5×10^{12} tons, of which half is in the U.S.S.R. and China and one-third in the U.S.A. Various projected rates of consumption tend to give a lifetime in excess of 1000 years. It is, of course, more difficult to obtain reliable figures for coking coal, if only on account of the problem of accurately defining coking grades; differences in this respect could introduce a factor of 2. It is probably sufficient to follow Bellano[4] and to consider a world reserve figure of 10^{12} tons. Three-quarters of this tonnage lies in U.S.A., U.S.S.R. and China and large areas of the world will have to depend on imports.

Estimates of oil reserves have varied widely and been subject to repeated reappraisal. In recent years, however, a better appreciation of the characteristics of the earth's crust has led to estimates which are more likely to remain stat[illegible] recent years, despite improved techni[illegible] lifetime of known reserves has [illegible] are complicated by inadequate de[illegible] in potential extraction rates but a working [illegible] coal equivalent may be taken as a basis f[illegible] of this being located in developing countries, [illegible] Authorities differ but most are agreed [illegible] relative prices and consequent consump[illegible] century.

The position [illegible] similar with substantially lower reserves and [illegible] use as a convenience fuel. Serious world wide [illegible] by 2000 A.D., certain areas having major problems [illegible].

The impact of [illegible] various fossil fuels on ironmaking technology will be [illegible]. As a particular resource approaches exhaustion, its price will [illegible] and this may lead to the abandonment of its use or its replacement by [illegible] 'synthetic' substitute. In the case of coking coal there are [illegible] the ground to meet all possible requirements of the iron [illegible] an indefinite period: estimates of iron-ore reserves vary [illegible] the highest suggested being just over 0.5×10^{12} tons. [illegible] of coke in any particular location will be determined by [illegible] of the following factors:-

(1) social-economic [illegible] of mining the coal.

(2) economies of [illegible] by liquid or gaseous hydrocarbons - this may be [illegible] with time. Currently replacement is favour[illegible] locations, a state of affairs not likely to con[illegible] the present century.

(3) new technologies [illegible] energy sources other than fossil fuels may become [illegible] favourable at any time after the next few years.

SOLID FUEL FOR THE BLAST FURNACE

Despite the extensive resources of first-class coking coals distributed around the world, many countries have a real economic interest in manufacturing good blast-furnace fuel from relatively inferior raw material. The situation arises where coals abound of grades other than those ideal for coking. A great deal of research and development has gone into the problem and has made it possible to maintain economic operation in the face of a continually degenerating supply position.

Blending

Experience in the United Kingdom has been concerned largely with the manufacture of classical coke in normal-type coke ovens. Prime coking coals of 15-25% volatile matter (dry basis) have become increasingly scarce and also more expensive to win and it has been necessary to resort more and more to the higher volatile ranges with varying degrees of coking power. In terms of the British National Coal Board classification, this corresponds to a move from 301 type to types 500 and 600 (say from 434/534 to 634/734 on the I.C.C. classification[7]). Under these circumstances it is possible to effect improvements in physical properties of coke by incorporating various low-volatile additives in the charge.

Detailed accounts of work in this field have been given by the British Coke Research Association and the National Coal Board.[8,9]

This work, together with a great deal of subsequent development at coke-oven plants, showed that substantial improvements can be made in the strength of coke made from the more readily available medium caking coals. Breeze, a cheap and readily available additive, will increase the M40 or stability index and raise the mean size of the product, but it has an adverse effect on the abrasion (M10) index and in consequence may need to be supplemented by other materials. Low-volatile coals of the semi-anthracite type are found generally to be beneficial additives, the only disadvantage being usually that of cost due to regional shortage or to high transport charges in the U.K. Somewhat similar improvements can be brought about by the use of char manufactured by partially devolatilising high-volatile coals.

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Reports also have further [illegible] of furnace trials using different products, but in most cases the amount of fuel available was limited and the test was of short duration or the furnace small.

F.M.C. coke was used in the U.S. Steel Corporation experimental blast furnace[14] and B.F.P. briquettes in the Liège furnace[15].

Russian trials involving the usage of formed coke on a 750 m³ furnace for a week were successful but some slight loss in efficiency was reported. [illegible] claimed complete success in trials on a 1350 m³ furnace over two months with a final period of a week at over 80% substitution[16]. The trials using B.F.P. briquettes were of particular interest. A furnace of 50 m³ capacity was operated exclusively on carbonised briquettes for a week but in addition a trial of 3 days duration was carried out using briquettes which had not been subjected to the final carbonising stage[17]. The results suggested that this last operation could be omitted, a fact which if substantiated could have a markedly favourable influence on the economics of the process.

More recently the British Steel Corporation has run full-scale trials on B.F.P. and F.M.C. fuels preceded by a laboratory study of these together with the Japanese D.K.S. product.

In addition to chemical analysis and physical testing, the preliminary studies involved observation of behaviour in a tuyere raceway carried out in a special combustion rig. This apparatus[18] allows fuel to be burnt in front of a tuyere using high-velocity hot blast. A raceway is formed and this region can be explored by a series of analysis probes to show the progress of the combustion reactions.

[illegible] in addition to [illegible].

The two [illegible] trials carried out by [illegible] were made at a [illegible] of [illegible] diameter, [illegible]. [illegible] conducted using [illegible] tons of [illegible].

The first trial was of large [illegible] briquettes. This process is based on a mixture of [illegible] and a relatively good [illegible]. [illegible] British [illegible] briquettes. [illegible] of potentially suitable [illegible] leading to [illegible] of the [illegible] had the properties [illegible] in Table II.

The first bulk sample of [illegible] was transported to the works and passed through a handling system to ascertain how much degradation would occur before use. The results were encouraging and manufacture of 1000 tons continued.

The blast-furnace trial was conducted by a team of [illegible] from various divisions of [illegible]. An elaborate sample testing [illegible] already existed in the [illegible] and this [illegible] detailed [illegible] of raw materials. Integrated [illegible] samples were collected and all weights into and out of the system [illegible] by special [illegible]. Vertical

[illegible]

[illegible]

[illegible]

[illegible]

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[illegible]

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Injection at Tuyere Level

Tuyere injection of natural gas, oil, or other hydrocarbons has been practised for many years ... Major developments have been the use of natural gas in the U.S.A. and the U.S.S.R. and the injection of oil in Europe and Japan. It has been estimated[20] that injection practices are used in the production of over [illegible]% of the world's iron. The quantities of injectant vary widely and also the replacement ratio, the latter being apparently mainly determined by the blast temperature available or, in other words, the ability to maintain raceway temperature in spite of the chilling effect of the injectant. In addition, difficulties may be experienced in securing complete conversion of the hydrocarbons to reducing gas. Two recent developments show much promise in overcoming this problem. In one system steam is injected into the oil upstream of the lance. This has proved successful at the Port Talbot and other plants of the British Steel Corporation. An alternative approach which is used successfully in Germany[21] is the use of a water-in-oil emulsion with 5-10% water. Both systems would appear to promote the formation of fine oil droplets by the explosive evaporation of contained water drops.

Injection in the Bosh/Stack

An interesting alternative to the injection of hydrocarbons with the blast is the technique of supplementing the reducing gases of the blast-furnace stack by injecting essentially carbon monoxide/hydrogen at a level above which solution loss is not likely to occur. If the gas is preheated to the appropriate temperature, say 900 - 1000°C, and can be adequately distributed and mixed with the normal stack gases, considerable improvement in gaseous reduction can be achieved with consequent savings in coke. Calculations suggest potential economic benefits, the advantages being largely additional to those of tuyere level injection. Very low requirements of solid fuel are implied, perhaps of the order of [illegible] kg/tonne, or less.

Technical problems centre on the provision of reducing gas with minimum oxidising constituents and on the correct temperature and on its effective introduction to and distribution in the furnace stack. In partial oxidation systems soot formation can be serious. If this is overcome by steam addition the gas becomes too oxidising unless the excess water is condensed out - this requires loss of the sensible heat. Operation of the reformer at high temperature (1400°C) is helpful but leads to engineering problems of cooling to the desirable injection temperature. Catalytic reforming is an alternative but this demands extreme physical properties in the heat-exchanger material and also restricts the choice of feedstock to natural gas or light petroleum fractions.

Distribution and mixing of the injected material is evidently important and it seems clear that the method of injection can have little influence on it. Theoretical studies are of a certain limited value but practical trials are necessary: a start has been made in this direction. Inevitably some of the early work was done on small experimental furnaces in which the mixing problem is unlikely to be significant.

In the U.S. Bureau of Mines furnace[22] stack injection was based on a mixture of natural gas reformed by oxygen with dry top gas used as a coolant. Injection was at 980 - 1050°C and the R/O ratio $(CO + H_2)/(CO_2 + H_2O)$ was only 5½ to 6 and replacement ratios were in the range 0.5/0.7 kg coke/m^3 natural gas.

Nippon Kokan Kaisha[23] worked with a furnace of 0.6 m hearth diameter, 3.2 m^3 volume, and injected the products of partial oxidation of oil at 1200 - 1300°C. The R/O ratio was about 8½ and there was 4% of soot. Replacement ratios of about 0.9 (coke/oil) were obtained; indirect reduction in the stack, initially 45%, went up to 55%.

ATRD using the experimental furnace at Liège[24] studied the use of partial oxidation natural gas-oxygen with an R/O about 5. The fact that the gas was injected at 1400°C encouraged reaction of the oxidising constituents with the coke. The resultant replacement ratio is given as 0.45 kg coke per 1 m^3 natural gas. This work also showed that stack

[illegible]

In [illegible] of a [illegible] of [illegible] oxygen and steam [illegible] injected [illegible] capable of [illegible] of hot metal, and a [illegible] was confirmed.

Other work on a production unit has been sponsored by the European Coal and Steel Community in association with I.R.S.I.D. and S.A. Cockerill[46]. The furnace has a hearth diameter of 4.5 m and the gas for injection was taken from an existing reforming plant and preheated before injection. The gas was manufactured by steam reforming of natural gas. Trials were made with an excess of steam, which was subsequently removed, to give a favourable R/O value of 15 - 40. Horizontal probe traverses suggested that penetration across the stack was good and a replacement ratio of 1.35 kg coke/Nm^3 reformed gas (0.8 kg/m^3 natural gas) was obtained, this being independent of simultaneous injection of 75 kg/t hm of oil through the tuyeres.

Top Gas Recirculation

The blast furnace is an extremely efficient device, having very small thermal losses, but it does convert a large proportion of the total energy input into a fuel gas of low calorific value. A useful proportion of this heat can be got back into the system via blast preheating; much of the attraction of fuel injection stems from the fact that it increases the amount of heat in blast which the furnace will accept. There are other possibilities of recycling top gas chemical energy. In particular the oxidising constituents can be utilised in the reforming of hydrocarbons, the reducing components then providing part of the injection stream. Analogous operations can form part of the reducing gas generation in the Midrex and Purofer sponge iron processes so it should eventually be possible

[illegible]

[illegible] possibly by [illegible] injection of top gas, possibly [illegible] of CO_2 [illegible] analysed [illegible] work has been done at [illegible][30] on the injection of modified top gas [illegible] together with [illegible] oxygen [illegible] and no [illegible].

The combination of high-carbon processing and reducing gas injection opens up interesting possibilities for increasing production as well as for saving coke and, at current prices, securing economies.

DIRECT REDUCTION

In recent years many processes designed to supplant the blast furnace have been the subject of special articles, reviews, and international conferences[illegible]. Few of the hundreds of processes proposed have survived to reach the stage of industrial operation and of these the majority show little promise of extended application.

The consensus of opinion at present is that direct-reduction processes are applicable in situations where demand is insufficient to support economic blast-furnace operation, where natural gas is cheap or where coke is particularly expensive. Otherwise the blast furnace may be expected to dominate the field.

Of direct-reduction plants installed in recent years, some (for example, Midrex, HyL) depend on relatively cheap natural gas to produce a sponge iron product, and their fortunes are likely to be bound up with its future availability under conditions of world-wide demand for 'convenience fuels'.

Systems using solid fuel, particularly non-coking coal, include the SL/RN process and the electric low-shaft furnace, the latter having the particular advantage of producing a molten product, the impurities being removed in a slag. With the development of ample electrical energy supplies and an increasing difficulty in obtaining fossil fuels, this process could become important in the long run.

NUCLEAR ENERGY APPLICATIONS

With the development of fission energy plants much thought has been given to the possibilities of application to iron and steel technology. The potential availability of cheaper electrical energy from this source opens up a number of interesting prospects but in general few technical problems are involved. Of much more interest, however, is the question of the use of nuclear heat without the loss of efficiency consequent on its conversion to electricity.

High-temperature reactors exist in the U.K. (Dragon), in the U.S.A. (Peach Bottom), and in the Federal Republic of Germany (Jülich); it seems likely that this type of device can operate with coolant helium outlet temperatures up to 1000°C. Before passing to a power-generation system, the coolant can be used to provide heat to sustain endothermic reforming or reduction reactions.

Extensive studies have been carried out under sponsorship of the Commission of the European Communities(32,33). In this co-operative work, various groups examined reduction processes based on coal or on reformed reducing gas and analysed the overall energetics of various systems(34-36). Similar studies have been carried out by the British Steel Corporation in association with the Dragon project team(37) and by the Japanese Iron and Steel Institute(38).

Most attention has been directed to sponge-iron plants based on a reducing gas, the reactor heat being used to supply the heat of the reduction reactions and sensible heat for the incoming gas and, in some cases, the thermal requirements of a reforming process. In the present state of technology, temperature levels in the various schemes are somewhat critical and much reliance has to be placed on future improvements in performance of materials, particularly heat-exchanger elements. Processes studied in some depth are basically analogous to the existing sponge plants such as H-Iron or FIOR in that they use hydrogen or CO/H_2 mixtures which are derived from fossil fuels. This generally demands a source of heat effectively at 900°C or more. It is true that high-pressure hydrogen systems operate at much lower temperatures but the reforming units designed to convert natural gas to hydrogen have thermal demands in the higher-temperature range. Moreover, the primary helium coolant circuit must operate at elevated pressure - say, 40 kg/cm^2 - and must be protected against cross-contamination with the reacting gases by secondary heat exchange. This means that materials must be employed capable of withstanding pressure differentials of many atmospheres at a temperature of 1000°C and in presence of CO, H_2, and He. These are formidable requirements but they will no doubt be met. The association of ore reduction reactors with atomic piles also presents problems arising from the need to bring handling facilities for ores and products into close proximity to highly sophisticated systems involving complex safety devices.

Another problem is involved in the necessary scale of operation. A reactor of 2000 M W (Thermal) is probably the smallest that can be contemplated on economic grounds and this would provide heat for iron production appropriate to an ingot capacity of 5,000,000 t.p.a. together with appreciably more electrical energy than the works could use[37]. Suggestions have been that a large reactor system be used to produce hydrogen which would then be transmitted through pipe-lines to the point of use. This would mean that the reactor could not supply the sensible heat required by the iron reduction process.

Insofar as schemes currently under discussion are based on fossil fuels they could have a beneficial effect on the requirements of the iron and steel industry. In comparison with gaseous reduction processes which rely on natural gas both as chemical feedstock and source of reaction heat, a combined nuclear/fossil scheme would save 50% of the hydrocarbon demand. This in itself is unlikely to influence the date of effective exhaustion of reserves but it could maintain a favourable economic balance for a longer period. Moreover, the conversion of solid fuels to gases, including hydrogen, is likely to benefit from cheap nuclear energy also.

On the whole it seems that the direct effects of nuclear energy on iron and steel manufacture are likely to be long-term ones and, of course, the possibilities mentioned so far imply the continued availability of fossil fuels. For the 21st century in fact they probably require coal which, at least, could be used more directly via formed coke.

It is perhaps appropriate at this stage therefore to consider the prospects for ironmaking when solid fuels are no longer available. Such a state of affairs is likely to arise before the complete exhaustion of reserves on one of the following grounds: (a) the impossibility of persuading anyone to mine the coal, (b) a general prohibition of 'dirty' operations associated with coal mining and processing or (c) concern with the rising level of CO_2 in the atmosphere resulting from combustion of fossil fuels.

This essentially leaves hydrogen as reducing agent and water as the only source of hydrogen. A number of authors have studied the characteristics of an energy economy involving hydrogen as an important secondary energy carrier(39-40). Electrolytic hydrogen suffers the disadvantage of efficiency factors in the generation of electricity from nuclear heat and also in the process of electrolysis but there are possibilities of obtaining hydrogen by a sequence of chemical reactions sustained by process heat(41) and these, or other techniques of converting water into hydrogen may in the very long term provide the basis for the manufacture of iron and steel.

APPLICATION PROSPECTS

The future pattern of fuel/energy usage in ironmaking will be determined primarily by the cost and availability of the various alternatives.

At the present time the position appears to be dominated by problems of securing adequate supplies of coking coal at reasonable cost. Cost price structures are perhaps somewhat distorted at present in that demands have risen rapidly in relation to the practicable possibilities of stepping up extraction rates by new investment. A further factor, which also has long-term implications, is the increasing attention which is having to be paid to safety in mining. This apart, running costs are likely to rise and there may be increasing difficulties, reflected in prices, in securing sufficient labour to work in this field.

The position is likely to continue that coal will be available in any quantity required for ironmaking over the next half-century at least but at prices which will encourage the use of alternative energy supplies. Extension of the range of coals which can be used in the classical blast furnace, whether by blending or more fundamental techniques such as the manufacture of formed coke, will lead to [illegible] the [illegible] developments may be expected.

The use of gaseous and liquid hydrocarbons in the blast furnace is economically attractive at the present time and techniques for intensifying their use will be pressed. In the case of injection at the tuyeres, relatively little capital investment is involved and the practice can readily be changed in the face of varying fuel availability. The more elaborate systems based on reforming hydrocarbons will undoubtedly require considerable investment and it would seem that the time required to pay off such schemes is of similar order to the time during which such fuels will remain cheap in the face of approaching exhaustion of reserves. If such techniques are successfully applied it may be doubted whether 'second generation' schemes will equally be economically advantageous and it is possible that solid-fuel-fired blast furnaces may be built at the end of the present century without benefit of hydrocarbon injection. Top-gas recirculation schemes which have made little progress to date may be then more attractive as they conserve fossil fuel.

Direct-reduction processes based on natural gas or oil seem likely to have a limited life and to be restricted to specific regions where such fuels are abnormally cheap. Solid fuel processes are in principle much more attractive and of course the most effective and reliable one is the blast furnace. The electric low-shaft furnace could well become more important as the cost of electricity declines relative to other energy sources.

In the longer term it may be expected that the iron industry will be brought to depend increasingly on nuclear energy. Present ideas for employing thermal energy from atomic reactors to support processes otherwise based on gaseous and liquid fuels are extremely difficult to evaluate. By the time they could be in a state to make a serious impact on [illegible] the natural fuels could well be approaching exhaustion necessitating their replacement by substitutes from coal. The economics of such a situation are complex but it is not likely that they will be attractive vis-à-vis the blast furnace.

In the really long term various factors such as the unattractive nature of the coal mining industry, atmospheric pollution by combustion and perhaps exhaustion of fossil fuel resources would be expected to lead to a technology based on reduction of iron oxide by hydrogen derived from water with the aid of nuclear power.

[illegible]

(1) [illegible]

(2) [illegible]

(3) [illegible]

(4) [illegible]

(5) [illegible]

(6) [illegible]

(7) [illegible]

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(9) [illegible]

(10) [illegible]

(11) [illegible]

(12) [illegible]

(13) [illegible]

(14) [illegible]

(15) [illegible]

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TABLE I

Type of briquette	[illegible]	B.D.P.	F.R.G.	[illegible]
Coal source	German	British	U.S.	Japan
Analysis H_2O as received	3.0	5.0	4.7	5.1
FC dry	[illegible]	[illegible]	80.9	[illegible]
Ash "	5.5	12.1	5.5	12.6
VM "	9.1	6.0	3.9	6.5
S "	0.9	1.0	0.7	0.5
Bulk density kg/m³	578	[illegible]	[illegible]	770
Mesh + 40	[illegible]	[illegible]		
Mesh + 30			[illegible]	
Mesh + 20				[illegible]
Mesh - 10	9.3	10.9	5.1	5.6
Carbon loss (see text) %	11	2.7	0.9	0.6

TABLE II

	Char Source	Coking Constituent
Name	Ollerton	Cortonwood Silkstone
Rank (N.C.B.)	802	401
(E.E.C.)	711	635
Moisture % (as received)	14.6	7.5
Ash % (dry)	9.3	5.1
Sulphur % (dry)	1.12	1.90
Volatile Matter (dry)	32.2	33.4
(daf)	35.5	35.2
Fixed Carbon (dry)	58.5	61.5
Calorific Value (as rec'd) cal/g.	6070	7680
Swelling Number	1.0	9.0
Proportions	75%	25%

17.6.74