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APPLICATIONS OF CONTROLLED THERMONUCLEAR
REACTOR (CTR) FUSION POWER IN
THE STEEL INDUSTRY

by

R.K. Jordan and Meyer Steinberg

Radiation Division

March 1975

MASTER

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

INFORMAL REPORT

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with electrolytic hydrogen and the use of thermal energy for reforming coal with steam or CO_2 for production of reducing gas. The electrosmelting of scrap metal using CTR power could become an important operation in the future. A complex of steel, fertilizer, fuel and chemical production is presented. Steel capacity and power requirement data are presented and projected to the year 2020.

A SURVEY OF APPLICATIONS
OF FUSION POWER TECHNOLOGY TO THE
CHEMICAL AND MATERIAL PROCESSING INDUSTRY

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Summary

A review of the process and economics of basic steel production is presented for the purpose of indicating where CTR fusion energy may be applicable. The present conventional air blown blast furnace produces a relatively low Btu value top gas with limited usefulness. The industry consumes relatively large amounts of natural gas for reheating ingots, plates, etc. A concept is presented wherein oxygen is used in the blast furnace which would double the capacity of the furnace and produce a rich carbon monoxide gas stream useful as synthesis gas for methanol and ammonia production. A CTR supplying high energy radiation in a blanket would disproportionate carbon dioxide to carbon monoxide and oxygen which could be used at high temperatures in the blast furnace in place of an oxygen supply stream. Coke would be used in this scheme. In a second scheme the oxygen is separated from the disproportioned CO_2 stream and CO is used in a direct reduction furnace which is followed by an electric furnace to refine the reduced product. Other schemes include iron ore reduction

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I. THE NATURE OF THE BASIC STEEL INDUSTRY

The primary purpose of a controlled thermonuclear reactor (CTR) facility as now envisioned is the generation of electricity. An installation of some 20,000 megawatts would probably provide the base load for a given area. The controlled thermonuclear reactor presumably would operate continuously at a constant level of out-put and all energy economically convertible to electricity would be so consumed. But analysis shows that a large portion of the energy generated by a CTR could be in forms that may be more economically utilized for other purposes. Presumably large quantities of energy in the form of gamma, ultraviolet and neutron radiations will emanate from the unit along with thermal energy available from high temperature surfaces or from gaseous streams. Thus it has been suggested the steel industry, a very large consumer of energy, might utilize some kinds of the various forms of CTR energy available presumably on a continuous basis.

Some 150 million tons of steel a year are currently produced in the United States, about two thirds of which are produced through the reduction of iron ore in blast furnaces. In essence, the blast furnace is a vertical shaft apparatus

wherein a mixture of ore and coke charged to the top descends through a hot reducing atmosphere comprised essentially of 30 percent carbon monoxide in nitrogen. A relatively small portion of the coke is consumed during its trip down through the shaft so that at the bottom of the furnace it is partially combusted with preheated air to provide the heat and carbon monoxide required in the production of the hot metal. As both the liquid and solid iron is in contact with carbon, and as carbon is relatively soluble in iron, the product unavoidably contains about 4.5 percent carbon. Iron so produced is very brittle because of its carbon content and removal is effected in a subsequent steelmaking operation by selective oxidation of the carbon to carbon monoxide by the addition of air or oxygen. A number of steelmaking methods have been practiced including the Bessemer, open hearth and basic oxygen (BOF) processes. As the hot metal from the blast furnace is in the form of a hot liquid and more heat is added or generated in the operation, steel scrap is advantageously added to the operation. Until recently, the open hearth method was most extensively practiced in this country and it could consume large quantities of scrap, perhaps 40 percent of the total charge. Lately, most steel is being made in the basic oxygen furnace which can handle only limited amounts, about 20 percent, of scrap.

The economics of basic steel production are highly complex. An understanding of the important factors requires a detailed knowledge of the operation of a blast furnace. Further it is necessary to comprehend the integration in steel operations to appreciate alternative steelmaking processes. In practice about 1.5 tons of iron ore (containing 65 percent iron) and some 0.5 tons coke, both in the form of pellets or chunks, are required per ton of hot metal produced in the blast furnace.

The two are mixed as they are charged at the top of the furnace and are progressively heated by the hot countercurrent gases as the charge descends the furnace: When the mixture of ore and coke reaches the reducing zone, two important reactions take place, (1), ore is reduced by carbon monoxide through lower oxides to metallic iron, carbon dioxide being simultaneously produced, and, (2), is in turn reduced with coke back to carbon monoxide;

Thus a fraction of the coke is consumed in converting carbon dioxide back to the essential reducing agent of the process, carbon monoxide. As the metal is further heated, to near its melting point, it absorbs carbon rapidly, about 10 percent of the carbon in the coke is dissolved into the molten iron product. The dissolved carbon lowers the melting point from 1535°C to about 1200°C . And the remaining coke is burned with a deficiency of oxygen in the hot air blast so that little or no carbon is wasted through tapping with the slag. The combustion process can be expressed approximately by the equation;

which tends to emphasize the relatively low, 30 percent, concentration of the carbon monoxide in the reducing atmosphere which contains mostly nitrogen. While the molten metal is collected by periodic tapping, top gas is evolved continuously from the top of the furnace.

About 3.4 tons of top gas is evolved for each ton of hot metal produced. Although greatly diluted by nitrogen and carbon

dioxide, the 3.4 ton of top gas contains about 0.7 tons of carbon monoxide which gives it a heating value of some 80 Btu per cubic foot. This low heating value compares to 330 Btu per cubic foot for pure carbon monoxide and 1,000 Btu per cubic foot for natural gas. As a ton of carbon monoxide contains 8.7 million Btu, the approximately three-fourths ton associated with the ton of hot metal contains 6 million Btu. A part, about 40 percent, of the top gas is used in creating the hot blast of air as follows. Adjacent to each blast furnace is a series of stoves in the form of three or more up-right cylinders which are filled with an open brickwork. The brickwork is heated by burning top gas sequentially in the stoves and then by sequentially passing compressed air over the hot bricks, the air is heated to upwards of 850°C to form the hot-blast used in the combustion zone of the blast furnace. The material and energy balance is represented in Figure 1.

Production of a high temperature hot-blast is very important to the thruput of the blast furnace because the higher the temperature of the hot blast, the higher the resulting flame temperature in the combustion zone of the blast furnace which in turn results in increased rates of hot metal production. It can also lower the coke rate. Because the top gas from the blast furnace has little value, as much as can usefully be used is consumed by burning in the stoves to achieve a hot blast temperature as high as can be handled by the system that conducts the hot compressed air into the combustion zone, as noted about 40 percent of the top gas. This amounts to about 2.4 million Btu per ton of hot metal produced. However, handling hot air via the stoves through the bosh-tuyeres into the combustion zone, is the major cause of blast furnace problems in terms of maintenance and down time.

The remainder of the top gas, some 3.6 million Btu per ton of hot metal, is converted by burning in boilers to create steam. Some of the steam is used to drive the air compression system needed for the hot blast and the remainder is converted to electricity in small old generating plants which require as much as 15,000 Btu per kwh which compares to about 9,000 Btu per kwh for a modern large electric steam based generating plant. Thus assuming the remaining top gas is combusted to electricity, about 260 kwh per ton of hot metal could be produced in these facilities. Since electricity can be purchased for less than one cent per kwh, this sets a limiting value for the 0.42 tons carbon monoxide (3.6 million Btu) remaining in the top gas at a maximum of \$5.77 a ton of contained carbon monoxide. But in these small generating plants, the value of the fuel is perhaps 50 percent of the total value of the electricity, so that a more realistic assignment of value to the carbon monoxide is roughly \$3 a ton. In terms of 1974 dollars, the energy cost per ton of hot blast furnace metal can be approximated as follows;

Coke, 0.5 ton @ \$30/ton	\$15.00
Top gas credit	<u>1.30</u>
Net cost	\$13.70

Blast furnace hot metal contains 4.5 percent dissolved carbon which is removed in a subsequent steelmaking operation by selective oxidation to carbon monoxide by injecting up to about 180 pounds of oxygen per ton of hot metal into the liquid metal, to which has been added about 20 percent scrap, if a BOP shop (basic oxygen process) is used. As oxygen is about \$15 a ton, this adds at least \$1.50 in cost and of course, only 0.95 tons steel remains with the carbon removed. But the fact that scrap is usually cheaper than hot metal results in a net lower cost.

A typical present blast furnace of 28 foot hearth diameter has a capacity of about 1 million tons of hot metal a year. The recent trend to giant blast furnaces, that is with hearths of about 38 feet diameter as compared to the heretofore 28 foot diameter have not greatly altered the economics of the conversion of ore to hot metal mainly because the capital cost increases and attendant high interest rates have more than offset the hoped-for lower operating costs. A new 38 foot hearth diameter blast furnace facility costs about \$140 million and is capable of producing about 2.5 million tons hot metal a year. At 10 percent interest this works out to \$14 million and depreciation over 20 years another \$7 million resulting in capital charges of \$21 million a year or about \$8 for each ton of hot metal produced.

Scrap does not play a major role in the economics of steel via the blast furnace. As stated earlier, the trend in the conversion of blast furnace hot metal into steel is away from the open hearth process to the basic oxygen process. In the latter some 40 tons of scrap is heated in a large pear-shaped vessel and then about 180 tons of molten blast furnace hot metal is poured in and the mass blown with a controlled amount of pure oxygen which selectively reacts with the contained carbon to form carbon monoxide. That is evolved with considerable violence from the vessel. The oxygen is injected over a period of 20 minutes. An entire cycle requires only 40 minutes.

Surprisingly, integrated steel operations generate rather huge quantities of scrap which are usually reprocessed by charging it into the BOP or open hearth processes. While the open hearth processes can consume high portions of scrap compared to the BOP process, it also consumes much energy and time. In

the past one of the great scrap generating processes was that of pouring ingots. The molten steel from the steelmaking operation, whether open hearth or Basic Oxygen Process, is poured into ingot molds and allowed to cool. The shape of these ingots are roughly like a popsicle without a stick. In most ingots the upper 20 percent have sponge-like characteristics caused by gas bubbles and this portion must be cut off and recycled in the steelmaking operation. Scrap is also generated in rolling, forging and other operations performed in the shaping and treating of steel. Usually the shaping and forming begins with a reheated ingot.

Clearly the molding of ingots and cooling is a great loss of heat. Worse, that lost must be added back into the ingot in soaking pits before it can be made sufficiently plastic for conducting the forming operation. Thus in the past several years there has been a trend away from ingot molding towards continuous casting. In continuous casting the hot molten metal from the steelmaking operation is poured continuously into the top of an open mold resulting in a continuous plate of steel. In this way the ingot top scrap is obviated and much heat is conserved. The heat saved is usually reflected in natural gas savings. In the not too distant future, a large portion of production by integrated steel complexes will be through continuous casting.

The availability of scrap is somewhat constant, but the price varies greatly as steel production and demand is quite cyclic. Prices over a single year can range from \$10 to \$130 a ton, and of course, the prices are also dependent on location. Clearly as the distance from a steelmaking facility increases, the price of scrap decreases. Also certain kinds of scrap are easier to handle and process than other kinds which is a

big factor in wide price differentials.

Likewise, the further the distance from the steel mill, the more costly is new steel because of freight costs. Years ago it was not too much more expensive to ship by rail than by water. Today, and even more tomorrow, a great differential exists. While it can cost well over \$30 to ship a ton of steel from Pittsburgh to New Orleans by rail, the cost by barge may amount to \$5 a ton, including terminal fees. Another analogy is found in the shipping of limestone which usually sells at the mine for about \$1.50 a ton. By rail to Detroit from Rogers City, Michigan costs over \$3 a ton, but it can be landed at Painesville, Ohio by a self unloader vessel via water for less than \$2 a ton. Soda ash by unit train from Green River, Wyoming to Toledo, Ohio costs about \$12 a ton, while bauxite can be boated from Australia to Tacoma, Washington for about \$3.50 a ton. Likewise iron ore can be shipped from Duluth, Minnesota to Conneaut, Ohio for about \$1 a ton, but it costs about \$4 a ton to take it from there to Pittsburgh, Pennsylvania by rail.

Because of the high cost of shipping steel products to certain market areas and also because of the high cost of returning the scrap, a new kind of integrated steel complex has been developed called "minimills". Minimills are electric furnace based facilities which consume scrap as melting stock for steel and are sufficiently integrated usually by small continuous casters, to produce heavier steel products, for example reinforcing bars for concrete, for the local market. Today electric furnace steel production amounts to 30 million tons/ year. Typical electric furnaces for minimills are about 20 feet in diameter and are able to handle batches of up to 200 tons, mostly from scrap, in a tap-to-tap time of about 5 hours. Some 700 kwh of electricity are consumed per ton of

steel which at a nominal 7 mils would amount to about \$5 a ton. But this is deceptive, almost 20 pounds of electrodes with a cost of \$2 are used per ton and frequent relining is required since roof and lining life is roughly 50 and 120 heats respectively. Moreover, capital investment per ton is in excess of that required for a blast furnace BOP shop installation. A further basis of comparison is the amount of labor and supervision required per ton of steel. An electric furnace operation requires some 2 man-hours per ton compared to less than 0.4 man-hour per ton for a blast furnace-BOP system. Clearly today the blast furnace BOP complex is far more economic than electric furnace steel production. Heretofore the electric furnace has been localized with a limited capacity. A typical single furnace described above limited to about 300,000 tons a year or less because of downtime for relining and reroofing. Today a complex requiring over a million tons of steel would probably opt for one or two small blast furnaces rather than electric furnaces if the complex can be assured of a sufficient quantity of coke for running the furnaces.

The notion of cheap electricity potentially available from a controlled thermonuclear reactor (CTR) is an intriguing prospect for a potential steelmaker. But even at 3 mils/kwh or about \$2 a ton electricity cost or perhaps a savings of \$3 a ton of steel if compared to 7 mil electricity, the cost of scrap and the nature of the adjacent market are still very important.

As noted earlier, the availability and price of scrap fluctuates wildly in any given year. And it is a distinct advantage to the large integrated blast furnace based steel producer to keep scrap prices high if possible because it represents a minor part of his steel cost while it is a

substantial part of the minimill's cost.

One factor which could stabilize scrap prices at a very desirable low (for the electric steelmakers level) is the development of direct reduction steel plants. For some reason it is not widely understood that the product of direct reduction is not steel in a form ready to be shaped or otherwise processed. In direct reduction the ore is treated with a mixture containing either or both of hydrogen and carbon monoxide at a temperature below the melting point of iron so that the product obtained is a sponge iron containing most of the impurities contained in the ore. As such it cannot be processed by simply rolling or otherwise shaping techniques into finished products. Instead the direct reduction iron is a feedstock for electric furnaces, open hearth furnaces, basic oxygen furnaces and even the blast furnace.

When direct reduction processes were first investigated and developed in the United States, natural gas was cheap and the industry was contemplating its availability at roughly 20 cents a thousand cubic feet (which is 20 cents/MM Btu). But no such gas is now available except in small quantities in relatively remote locations. Now the promoters of direct reduction processes are installing facilities in locations where ore and cheap natural gas are found together, for example Venezuela and Iran. There is another consideration of great importance, the proximity of these to deepwater or navigable water transportation. This imposes severe siting limitations on any steelmaking complex that would utilize the direct reduction product, essentially that the steelmaking facility must be located also on water if it is to enjoy the optimum economics afforded by the product. But this siting limitation is already in existence because of the logistics of

ore handling alone. All new major steel facilities are located on water. The older facilities such as those located at Youngstown, Ohio and Johnstown, Pennsylvania suffer now, and in time even Pittsburgh, Pennsylvania which is the birthplace of America's giant steel industry may find its share decreasing.

At present it would appear that direct reduction is limited to places other than the United States because of the lack of cheap natural gas. Yet throughout the world, another approach to direct reduction is being investigated, that which would utilize the high temperature gases provided by high temperature nuclear reactors, HTGR, such as those constructed by the General Atomics, jointly owned by Gulf and Shell. The Japan Agency of Industrial Science and Technology approach uses the indirect high temperature heat, up to 1000°C, to pyrolyze asphalt to light gases and pitch. Both are converted to hydrogen and carbon monoxide again at high temperature to provide the reducing media for the direct reduction process. A consortium of European companies also see the HTGR as a means of making a reducing gas for direct reduction and like the Japanese expect the low cost electricity to run electric furnaces for melting the direct reduction product. In the U. S. a committee of the American Iron and Steel Institute, AISI, is studying a number of direct reduction schemes.⁽¹⁾ While practically all the emphasis is now directed to hydrogen for direct reduction, it should be borne in mind that carbon monoxide too can be used alone in the process. Further, depending on the temperature available from the system, it could be feasible to produce molten steel by a direct reduction process. At least one company in the United States, two in Europe and one in Japan has investigated a direct reduction process wherein a molten mixture of iron ore and lime (lime lowers the

melting temperature of magnetite and hematite) is contacted with a hot reducing gas, either carbon monoxide or hydrogen. Normally at lower temperatures, hydrogen is a more effective reducing agent for iron oxides than carbon monoxide, but for long range planning there must be some assumption of progress in the handling of molten ores and metals at somewhat higher temperatures than they can be handled today.

It has long been known that hydrogen can reduce ferrous ores at relatively low temperatures $>800^{\circ}\text{C}$ at rates sufficient for economic production. While carbon monoxide does not become as effective until almost 1000°C , it must be considered in any direct reduction analysis for the future. The present availability of pure hydrogen and pure carbon monoxide is somewhat limited. About 400,000 tons a year of hydrogen are produced as a by-product in the electrolysis of brine to chlorine and caustic soda. Much of this hydrogen is wasted because it has a relatively low heating value, about 300 btu per cubic foot. From the producing locations the hydrogen can often be purchased at or below its fuel value so it is somewhat surprising that no direct reduction facilities have been erected at such gross hydrogen makers, as for example, Dow at Freeport, Texas. At present most pure carbon monoxide is obtained by the cryogenic separation of reformed natural gas, a mixture of hydrogen and carbon monoxide. Under these conditions it is not cheap, a reasonable present cost being about \$60 a ton, so that it can not be considered as such an economic reducing agent for iron.

The production of synthesis gas, a mixture of hydrogen and carbon monoxide in about a 2:1 mole ration, has been accomplished for almost a half century on an industrial scale using natural gas as the feedstock with steam. An expensive reforming furnace is required so that the economics are most favorable on

a large scale. Further, a catalyst such as platinum is needed to catalyze the interaction of the hydrocarbon feedstock with steam as generally expressed by the equation;

In practice a mixture containing hydrogen, carbon monoxide, carbon dioxide and unreacted steam is obtained, though by several means the latter two can be minimized or obviated. Typically the mole ratio of hydrogen to carbon is a little over 2:1 and in a direct reduction process the gas from a reforming furnace is passed through a preheater to bring its temperature up to about 800°C and then is fed to the reactor where it is contacted with preheated ore. The various direct reduction processes are described in Chemical Engineering (1974).⁽²⁾ As the ore is reduced without melting, the impurities are occluded in the metallic product which is usually briquetted while hot and if necessary in other ways passivated. By passivation is meant a treatment to prevent oxidation of the product. It is important to note that briquetting or pelletizing is a necessary step in the process because this step facilitates handling and is important especially if the product is to be used as a feedstock for a blast furnace.

At their first appearance all the direct reduction processes consumed about 15 million Btu per ton of reduced product which consists of an average of 85 percent metal. By process development the requirement has been lowered and will continue to be lowered, ultimately to about 12 million Btu. While natural gas was until very recently available at 20 cents per million Btu the energy cost was reasonable, i.e. \$3 a ton, but with natural gas projected at perhaps a dollar a million Btu, even in Texas, the resulting energy cost

of \$10 a ton is not. Actually the total energy cost is a little higher because some 50 to 100 kwh electricity is also required per ton of product. Direct reduction in the United States using natural gas as a fuel appears out of the question for the foreseeable future.

Natural gas is wasted for the most part in many oil producing countries which are not industrially developed. It is unavoidable as a co-product with much of the crude oil that is produced. Thus in many countries of the Middle East and Venezuela especially, uses for this gas are being sought. At little capital investment this waste natural gas can be consumed in the production of ammonia, a nitrogenous fertilizer, or in methanol, a chemical intermediate and also liquid fuel. Liquefaction to LNG is another possibility, but facility costs, especially in terms of handling, storing, shipping and receiving are orders of magnitude greater than for ammonia or methanol. As it turns out, in some of these countries iron ore and natural gas lie in reasonable proximity. These countries so blessed can pipeline the gas to a convenient ore processing point and in essence the energy cost in converting the ore to impure metal pellets is almost insignificant. However, the capital required for a direct reduction facility is about that required for a blast furnace of equal capacity. In terms of 1974 dollars a blast furnace facility of 2.5 million tons annual capacity would cost about \$150 million, the optimistic cost of the same size direct reduction facility. Unfortunately, once in place the price of natural gas to the direct reduction facility can be expected to rise because of government ownership of the gas, i.e., in these foreign countries.

The capital cost and depreciation of direct reduction product will amount to at least \$8 a ton in terms of present

dollars. While this is about the same as for a blast furnace of equal capacity, the energy cost for direct reduction will probably come to about \$5 a ton compared to about \$15 a ton for the blast furnace. But in a modern BOP shop the conversion of blast furnace hot metal to molten steel is negligible compared to the cost for refining direct reduction pellets to steel in an electric furnace. The important fact in a comparative evaluation is that the availability of direct reduction product on a massive scale will stabilize the price of scrap to electric furnace steel producers. By the same token, the price of scrap and its availability may in time be a controlling factor for the price of direct reduction product. In 1973 some 48 million tons of scrap was purchased (of which 8 million tons was exported) in the United States and perhaps another 20 millions tons was consumed internally by steel producers. There is said to be an availability or reservoir of 750 million tons of scrap lying about the United States.

The present day and future influences on scrap are dramatic and include:

1. Necessity to recycle metal heretofore recycled on a very limited basis, for example junked automobiles and solid wastes.
2. New technology for processing scrap and waste.
3. Increasing availability of scrap.
4. Probable decrease in the export of scrap.

As noted earlier, transportation figures largely in ore, scrap and steel processing. In the future it will figure even more significantly in the United States, especially by rail and truck. But with respect to scrap, which would include that from solid waste, it will be recycled first because it must be consumed at whatever transportation cost. The demand

beyond that will be supplied by direct reduction. In other words, there is a very definite limitation on the United States market for direct reduction product for the foreseeable future. Moreover, the availability of relatively cheap direct reduction product from countries having adjacent ore and natural gas, with little use for the latter, will limit the opportunity for direct reduction in this country.

A sustained growth in the steel industry can be anticipated and while 200 million tons consumption is projected for 1980, it is probable that by the year 2020 the market will be almost 400 million tons. While it is only an estimate, perhaps 125 to 200 million tons of this will come from scrap which means that considerable electric furnace capacity will have to be added to the present 25 million tons electric furnace capability. As the present blast furnace 100 million capacity can be very cheaply almost doubled to about 200 million tons by the simple expedient of adding oxygen plants, there does not appear to be a big place for direct reduction product. Present, 1985 and 2020 projections for the steel industry are presented in Table 1.

If 200 million tons of scrap are to be melted and refined in electric furnaces, it is clear that at about 700 kwh per ton, a large amount of electricity, 140 billion kwh will be needed requiring an electric power capacity of approximately 20,000 MW(e). Certainly CTRs can help provide this energy, but the minimills will be widely distributed throughout the country and only a few areas might support a sufficiently large direct reduction-electric furnace complex to be economically viable. But even then new technology, in the form of continuous electric furnaces capable of 2-5,000 tons a day, must be developed. These could be akin to electroslag remelting units, but on a much larger scale.

The real futuristic place for CTRs lies in replacing the blast furnace of the present, though this will be no mean feat

because of an imminent change the blast furnace is about to undergo. The change in the blast furnace will take place in two steps. First the hot blast of air will be replaced by the injection of pure oxygen along with some recycled top gas, the carbon dioxide in the top gas acting as a tempering agent in the process. While this will consume about 10 percent more coke, the net result will be the essentially doubled capacity and the availability of a top gas mix of 80:20 carbon monoxide:carbon dioxide with a heating value of almost 300 Btu per cubic foot, capable of replacing the natural gas used by the steel mill complex in all but a very few uses. Assuming all present blast furnaces were to be so operated, some 200 million tons of carbon monoxide would be available which at 8.7 million Btu per ton would amount to 1,800 trillion Btu or the equivalent of 1.8 trillion cubic feet of natural gas. While this top gas could not be sold for residential purposes, that which the steel industry could not consume internally could and probably will form the basis of a giant carbochemical industry. The immediate import of this technology is that of releasing the present steel industry natural gas consumption to other uses.

A second step in the upgrading of present blast furnaces is that of replacing most or all of the coke required in the blast furnace operation by coal through injection as a slurry in liquid carbon dioxide through the tuyeres. Assuming that only coal will be used, the economics may be estimated as follows:

0.5 tons coal per ton hot metal at \$15/ton	\$7.50
0.5 tons liquid carbon dioxide at \$5/ton	2.50
0.5 tons oxygen at \$5/ton	<u>2.50</u>
Total energy cost/ton hot metal	\$12.50

However, with each ton of hot metal there is also produced a ton of carbon monoxide which for all practical purposes is a valid

replacement for natural gas at \$1 per million Btu, or \$8.70 a ton of carbon monoxide. Thus the net energy cost is only \$3.80 a ton. If this technology comes to pass, and it appears highly likely that it will, there may not be a place for the utilization of energy from a CTR in much more than providing the electricity for oxygen production, melting scrap, or, in localized situations, melting direct reduction pellets imported from a country blessed with ore and cheap natural gas. But as noted earlier, the expected growth in the recycling of scrap is considerable and the amount of electricity required is considerable.

In the following sections some futuristic processes are examined which are based on the utilization of energy potentially available from a CTR. Instead of some kind of direct reduction using heat from a CTR, more radical schemes are seriously proposed because they provide new vistas in terms of integration of the basic steel complex with a vast chemical complex. The basic technology for accomplishing this rests on the assumption that at least one form of energy available from a CTR can be adapted to the economic disproportionation of carbon dioxide to carbon monoxide, i.e.,

II. CTR IRON FURNACE COMPLEX TO PRODUCE METHANOL AND AMMONIA

There are a number of ways in which iron and steel production might be tied into a controlled thermonuclear reactor, CTR. Several will be discussed at length herein because they relate to new developing technology and could show potential. But as these new concepts depend in part on undeveloped processes, it should be understood that the potential degree of participation by the CTR lies in finding ways to utilize the various kinds of energy

it can produce.

As the CTR is clearly now thought of as a future provider of vast quantities of electricity, this study will begin with a concept developed by Jordan beginning in 1966 which is entirely feasible today.⁽³⁾ But it is relevant to the CTR in that relatively large quantities of electricity are required, i.e., in terms of today's thinking, since conversion of the entire industry to the concept would necessitate the consumption of 2,000 megawatts.

As noted in the preceeding discussion, the present version is no more than a crude scale-up of technology of at least a hundred years ago. At the moment it would appear that this trend is continuing in spite of the fact that the major steelmakers know it is not in their better interests. No doubt the only reason for the development of giant blast furnaces of the present ilk of some 7,000 tons a day hot metal capacity is that the Japanese have done it. A sort of reverse psychology, as heretofore it has long been believed that the Japanese copied the technology of the United States. But throughout the past twenty years there have been a number of patents relating to the conversion of the present blast furnace away from using air, replacing it with oxygen, at least in part. Patents by Coutant⁽⁴⁾ and Sellers and Paull⁽⁵⁾ are simply noted as examples of the thinking on the subject. It is reported that a trial was conducted several years ago in Russia, but improved performance was not achieved, probably because there was no attempt to operate at higher temperatures. Also noted above, Jordan began with an extensive study of the subject culminating with the report. But unlike paper patent processes, a persistent effort was then directed towards a computational study of operability and also towards the utilization of the by-products anticipated from an oxygen blown blast furnace. The concept became known in the United States Steel Corporation as

the Jordan Blast Furnace Concept, but it encompassed far more than the simple production of hot metal, it contained also the basis for a grandiose chemical venture.

Reviewing the present blast furnace, (Figure 1), iron ore and coke are fed to the top of the furnace and as they descend, the iron ore is reduced by carbon monoxide, the essential reducing agent, to metallic iron, first as a solid and then as it dissolves some carbon into molten hot metal. Most of the coke descends almost to the hearth, actually to the combustion zone where a deficiency of preheated compressed hot air is forced into the furnace through the tuyeres. The oxygen in the air and the coke combust to provide both the carbon monoxide and the heat required for the process. Because of the nitrogen contained in the air, the concentration of carbon monoxide is limited to about 30 percent;

As the gaseous mixture of carbon monoxide and nitrogen rise in the shaft of the furnace, the carbon monoxide reduces the iron ore to metallic iron and is itself oxidized in turn to carbon dioxide. In the high temperature zones, the carbon dioxide reacts endothermically with coke to yield more carbon monoxide.

As the gas mixture rises it is cooled by the descending cooler burden (ore and coke); the gas expelled at the top of the furnace is comprised of about 25 percent carbon monoxide, 20 percent carbon dioxide and 55 percent nitrogen. Some 3.4 tons of top gas is produced for each ton of hot metal, but the gas heating value is only some 80 Btu per cubic foot. Actually about 0.7 tons of carbon monoxide is contained in the less than four tons of top gas obtained as a by-product of each ton of hot metal which provides about 6.6 million Btu.

There are not many uses for a gas with a heating value of only 80 Btu per cubic foot. Natural gas has a value of 1,000 Btu per cubic foot and even pure carbon monoxide has a value of about 300 Btu per cubic foot. As mentioned earlier, about 40 percent of the top gas is sequentially burned in the adjacent stoves, heating the contained brickwork which subsequently heats compressed air passed over it to form the so-called hot air blast, which gives the blast furnace its name. The remaining 60 percent of the top gas is burned in boilers to give steam for driving the blowers and to run small adjacent electric plants which, because of their small size and other limitations, are grossly inefficient. But because the top gas is low in heating value, and also because natural gas has heretofore been very cheap, these were the only uses for the top gas.

The use of oxygen alone as a replacement for air in the blast furnace is not realistic because such localized high temperature flames at perhaps 4800^oF or higher and would burn holes in the burden. The flame temperature in the combustion zone of the present blast furnace is about 3500^oF. Enrichment of the hot air blast with tonnage oxygen has been practiced extensively for over ten years, even small percentage additions improving the rate by about 4% per 1% increase oxygen in the air. But this is true over a rather narrow range, up to roughly 26 percent oxygen, whence the rate of increase begins to drop off rapidly. As the conventional blast furnace consumes a great amount of air, the amount of oxygen required for say 30 percent concentration amounts to over 450 pounds. Yet this hardly affects the top gas composition and heating value, clearly if considerable quantities of oxygen are to be added to an iron-making process, it should be used in some way that the top gas is upgraded significantly.

Voskoboinikov, V.G., et al., ⁽⁶⁾ reported on the use of oxygen and reformed natural gas (with top gas) in a blast furnace, but the aim was the reduction of the coke rate, not increased temperature and increased thruput. However, the top gas was greatly upgraded. As noted earlier, Jordan had proposed a concept by which either recycled top gas or carbon dioxide alone was added through independent or the same tuyeres as tonnage oxygen, the oxygen concentration adjusted with carbon dioxide to provide tempering to increase the flame temperature over that conventionally employed, ideally as high as possible, 4,000°F being the target. The reasons in addition to increasing the thruput include a reduction of the coke rate on a relative basis. Estimates have been made of the thruput using oxygen at the two temperatures of 3500°F and 4000°F and are presented in the following:

Flame Temperature	3500°F	4000°F
O ₂ required, lb/THM	1040	870
Carbon required, lb/THM	1117	948
Coke rate, lb/THM	1380	1120
Amt. coke above normal, lb/THM	330	150
Production, % of normal	160	200

The data indicate that about a ton of carbon monoxide would be accompanied with each ton of hot metal produced and further, that the top gas composition would be roughly 80 percent carbon monoxide--20 percent carbon dioxide having a heating value of almost 300 per cubic foot. As carbon monoxide burns with a high emmisivity, there is no question that this gas would be an adequate replacement of natural gas in all but a very few steel industry applications. The question arose concerning the economics of the process especially when natural gas was selling at a low price, prior to 1972.

The question of the economic top gas compared to natural

gas rests in the evaluation of oxygen costs. One can assume the purchase of oxygen, but it can be contended that an oxygen plant for the Jordan Blast Furnace Concept should be treated as a replacement for the stoves of a conventional blast furnace. While at first blush it seems unreasonable, both the capital and operating costs for an oxygen separation plant are lower than that required for stoves. The capital for the stoves of a new 7000 tons a day blast furnace in 1972 was estimated at about \$30 million, while a 6000 tons a day oxygen plant was estimated at less than this value. A 6000 tons a day oxygen plant would provide oxygen for over 10,000 tons a day hot metal plant, probably 14,000 tons a day of hot metal at 4000°F flame temperature. On this basis it can be seen that the capital for an oxygen plant is almost half that for stoves of the same hot metal capacity. As noted earlier, 40 percent of the top gas of a conventional blast furnace is burned in the stoves to provide the heat for the hot air blast. Since about 0.70 tons carbon monoxide are contained in the top gas from a ton of hot metal, by multiplication using the heating value of 8.7 million Btu per ton of carbon monoxide, it can be seen that the stoves at 40 percent consume about 2.6 million Btu's per ton of hot metal. Converted to electrical energy at 9,000 Btu per kwh, this amounts to 288 kwh, but does not include the energy required to run the blowers of a conventional blast furnace. However, about a half ton of oxygen is required per ton of hot metal by the Jordan Blast Furnace Concept which at 300 kwh per ton of oxygen amounts to about 150 kwh per ton of hot metal, almost half that required for the conventional blast furnace.

At this point it is reasonable to discuss the relative merits of using the CTR to provide a means of heating air to produce

the hot blast of a conventional blast furnace versus simply using the electricity from a CTR to drive an oxygen plant. Clearly it is desirable to provide heat to the compressed air at as high a temperature as possible. Just to maintain the present coke rate in a conventional blast furnace requires that the air be preheated to almost 2000^oF; moreover, there would be no increase in the rate of hot metal production. To achieve significant coke economies and increased rates of hot metal production would require that the air be preheated to above 2500^oF, preferably 3000^oF, which does not appear feasible. But even if it were, the quality of the top gas would not be significantly improved, one might expect a heating value of 100 Btu per cubic foot, which again is useless for most heating applications beyond making steam. While the production of oxygen does not require nearly so much energy per ton of hot metal as would be required in preheating the hot air blast, tonnage oxygen enables the essential doubling of the rate of hot metal production and in addition provides a top gas composed essentially of carbon monoxide. Because air preheat via CTR does not appear to offer any significant improvements in hot metal or gas production, further study is not recommended.

It is necessary to find uses for the top gas which would give it a greater value than as a replacement for natural gas. Presumably, if it could be shown that such uses could provide a market for the top gas, there would be justification for further development of the concept.

Early in this paper it was noted that there exists in the world a trend to giant blast furnaces. A typical 28 foot hearth diameter blast furnace can now produce about 3000 tons a day of hot metal. The giant blast furnaces of 38 to 40 foot hearth dia-

meters are capable of some 7,000 tons a day of hot metal. Thus on a yearly basis this comes to about one and 2.5 million tons respectively, but if the Jordan Blast Furnace concept is adapted to these furnaces the thruputs become 2 and 5 million tons respectively. Clearly the latter situation would represent a case of too much production for one facility, causing real production problems if for some reason it had to be shut down. There are other reasons which argue against building these large furnaces, pollution and noise being just two.

Operation of a typical conventional blast furnace by the Jordan Blast Furnace Concept would increase the hot metal rate from about 3000 tons a day to about 6000 tons a day and in addition provide about 6000 tons a day of carbon monoxide in the form of an 80 percent mixture in carbon dioxide. On a yearly basis some 2 million tons of carbon monoxide are produced. As a potential replacement for natural gas, if the present capacity of 100 million tons a year of hot metal were converted to the Concept to produce 200 million tons of hot metal, some 200 million tons of carbon monoxide top gas which at 8.7 million Btu per ton would give 1.7×10^{15} Btu which at 1,000 Btu per cubic foot for natural gas would be equivalent to 1.7 trillion cubic feet of natural gas. As the steel industry itself consumes now about half this, there is no question that the industry could become self sufficient and in addition provide a like amount for industrial uses. Carbon monoxide is toxic so that its residential use is not contemplated; natural gas will asphyxiate, but is relatively nontoxic. But now that the price of natural gas has increased greatly over the 35 to 45 cents per million Btu of only a few years ago, there is also no question but what the concept is now economically viable, regardless of the criteria used in the evaluation.

The economics of the production of methanol from carbon monoxide potentially available from the Concept has been evaluated. The process entails the steam conversion of two of three moles of carbon monoxide to hydrogen and carbon dioxide, in a relatively cheap shift reactor and subsequent catalytic conversion of CO and H₂ to methanol.

Thus it is evident that besides the carbon dioxide contained in the top gas, a ton of it is produced for every ton of carbon monoxide. The 2 million tons of carbon monoxide in the top gas of a Concept furnace would be accompanied by about 0.8 million tons of carbon dioxide and another two million tons would be produced by shifting, a total of 2.8 million tons which compares to only 0.67 million tons methanol from the overall scheme. After considerable study the economics of the process were found to be competitive with those for producing methanol from natural gas only if the excess carbon dioxide were removed using a solvent process and further, that the heat of reaction from the methanol synthesis recovered and applied to the overall heat consumption.

In making methanol from natural gas, the natural gas is reformed with steam in a very expensive reformer furnace at about 1400°F,

to yield a gas mixture comprised mainly of hydrogen and carbon monoxide in roughly the appropriate proportions for the production of methanol. Some small amount of excess hydrogen is present, as is some carbon dioxide and unreacted steam and the mixture is passed, as is, into the methanol synthesis unit. While the reaction of hydrogen with carbon monoxide over copper containing catalysts to form methanol is very exothermic, the available methanol

processes handle the excessive heat formation differently. The most popular process is the ICI process which ideally uses some carbon dioxide in the synthesis reaction, to consume excess hydrogen, and uses a water quench to control the temperature and heat. Unfortunately, this does not enable the recovery of the heat and further, somewhat adds to the subsequent purification of the product methanol. On the other hand, the Lurgi methanol process operates best with an exact balance of hydrogen and carbon monoxide, using a shell and tube apparatus wherein low grade steam is used for control and cooling the heat of reaction, but in the process it becomes upgraded to high temperature steam, useful for driving compressors, etc. Thus after a careful comparative analysis, it has been found that although the equipment is quite different, the production of methanol via carbon monoxide shifting is competitive in capital and operating costs to the natural gas based process. The real economic difference lies in the value one associates with the starting materials. At one time most methanol plants had cheap natural gas available, perhaps 20 cents a million Btu would be a representative number. But now it is difficult to see natural gas at these same plants at anything less than 80 cents a million Btu for the future. Carbon monoxide top gas appears promising at \$1 a million Btu or \$8.70 a ton, and at this level significantly lowers the cost of hot metal production. However, the upgraded analysis in terms of capital and operating costs for comparing natural gas and blast furnace based methanol processes was conducted using values of 1972, though it did not take into account the differences in shipping costs. As blast furnaces are located adjacent to the markets, the cost of shipping methanol is nil, whereas natural gas based methanol is available only on the Gulf Coast necessitating

a differential of at least \$5 a ton in favor of the blast furnace produced product. Cost estimates have been made and the results are shown in condensed form in Table 2 for the processes schematically given in Figure 2.

It is well known that methanol and ammonia processes are very similar when using natural gas as a starting material, the essential differences in making ammonia entailing the total shifting of the carbon monoxide to hydrogen and carbon dioxide, the necessity to have nitrogen present in place of carbon monoxide, the removal of all carbon monoxide and dioxide and finally a different catalyst system under conditions of somewhat higher pressures. Thus in using natural gas in a reformer to produce hydrogen, some air is added as a replacement of some steam to accelerate the reforming process and to provide the necessary nitrogen. Using the same 3 moles carbon monoxide as required in the production of methanol, all three moles are shifted with steam in a cheap shift converter to hydrogen and carbon dioxide.

After removal of all the carbon dioxide, (again it is critical to the economics to remove the carbon dioxide using a solvent process, ideally the methanol based Rectisol process of Lurgi) nitrogen from the air separation plant, is added,

and the heated mixture passed over an iron containing catalyst. Again the parameters noted for the reactor in the methanol process apply to the ammonia process. From the stoichiometry of the process it can also be easily seen that the 2 million tons of carbon monoxide potentially available from a furnace of the Jordan Blast Furnace Concept would provide the raw material for about 800,000 tons of ammonia. But it is also of interest

to note that almost 4 million tons of carbon dioxide would accompany the 0.8 million tons of ammonia.

The present market for methanol is about 3.5 million tons, (about a billion gallons, 300 gallons/ton), most being used in the production of formaldehyde, acetic acid and methyl esters. Assuming the market will nearly double by 1985 to about 7 million tons and grow by 2020 to perhaps 10 million tons, it can be seen that the potential availability from a Concept furnace society from 200 million tons of carbon monoxide is 66 million tons of methanol, many times the market. As methanol is an excellent fuel for automobiles, it is proposed that this route offers a viable means of solving the so-called fuel crisis. On a per pound basis, methanol has about half the Btu value of gasoline, (though in performance it works out to the advantage of methanol) so that this would be equivalent to 35 million tons of gasoline, potentially enabling the United States to be self sufficient.

Ammonia now has a market of about 16 million tons and will increase to some 25-30 million tons for 1985 and by 2020 may grow to about 40-50 million tons which compares to the potential availability of 60 million tons for 1985 from carbon monoxide via the Concept and 80 million tons for 2020. For the most part, ammonia is used as a fertilizer or is converted to compounds such as urea and ammonium nitrate which are also fertilizers.

As noted, the greatest by-product from the methanol and ammonia processes in terms of quantity is carbon dioxide, potentially hundreds of millions of tons could be available. But the present market for carbon dioxide in all forms, (liquid, gas and solid) is only 1.6 million tons. As noted the largest potential for the use of carbon dioxide lies in its use as a tempering agent in the oxygen-blown blast furnace, whether the Jordan Blast Furnace

Concept or some similar scheme.

Clearly the availability of such quantities of carbon dioxide as might be produced from even one Concept furnace based methanol or ammonia plant is such as to require serious investigation into possible uses. The authors have concluded that one use of potential interest would be its conversion to carbon monoxide. The technology for this, via reaction with coke or carbon, is well known. But this again would necessitate some kind of facility akin to the Concept itself, so it was decided to look at new processes that would provide a dual purpose. A review of applications of CTR by Steinberg, et al.,⁽⁷⁾ indicates the feasibility for the conversion of carbon dioxide by high energy gamma radiation to a mixture of oxygen and carbon monoxide which can be stabilized at even 600°C by the addition of small concentrations of nitrogen oxides.

Since CTR energy is seen as a potential source of very cheap energy, especially in the form of high-energy radiation, two schemes were tied into the Jordan Blast Furnace concept. First it was assumed that a very high conversion would be within the realm of 2020 technology, and that a CTR converter could yield a gas composition of oxygen 32%, carbon monoxide 57%, and carbon dioxide 10% volume percent at a temperature of 600°C (1112°F). It is believed that such a mixture could be directly fed into the tuyeres of a present blast furnace to provide a flame temperature near 4000°F (2200°C). If not it is certain that a small amount of supplemental tonnage oxygen would need be added. In essence then, the oxygen contained in the mixture will react or combust with the coke to produce heat and carbon monoxide while the carbon dioxide will also react with coke to form carbon monoxide, but endothermically. One can simply

visualize that the carbon monoxide contained in the mixture supplied by the CTR as simply passing through the furnace without change. For evaluation purposes it is assumed here that 0.6 tons of oxygen are required per ton of hot metal and it turns out that the CTR carbon dioxide disproportionation product provides in itself a ton of carbon monoxide with the required 0.6 tons of oxygen. As the oxygen in turn provides another ton of carbon monoxide to the top gas in its combustion with coke, the effect is to produce two tons of carbon monoxide for each ton of hot metal produced. Thus a Concept furnace of 26 feet hearth diameter would have its top gas carbon monoxide doubled from 2 million tons to 4 million tons though the hot metal rate would remain at 2 million tons a year. On a projected industry wide basis then of 200 million tons of hot metal, some 3.4 trillion cubic feet of natural gas equivalent could be potentially available. Similarly, it could provide the availability of some 130 million tons of methanol or 160 million tons of ammonia. The effective doubling would be based on only carbon dioxide, some 315 million tons potentially being converted in a CTR.

Steinberg et al.⁽⁷⁾ indicate the possibility of perhaps 35 percent conversion, though still at about 600°C (1112°F). Unfortunately, it is clear that the resulting mixture of carbon dioxide 65, carbon monoxide 22.3 and oxygen 12.7 volume percent is far too low in oxygen content for operation of even an ordinary blast furnace. To separate out a mixture comprised essentially of carbon monoxide and oxygen it is necessary to cool and compress out the carbon dioxide. Fortunately, as the CTR gas mixture is at a temperature of 600°C (1112°F), considerable energy can be recovered using steam as the media for cooling and converting the contained energy to electricity in conventional electric generating equipment. Because of the availability of

this electricity, the balance was worked out for electrosmelting some additional 2 million tons steel from scrap. This in keeping with the projection of at least half future steel production by reprocessing scrap and thus providing a balanced complex. The overall complex is shown in Figure 3.

The reprocessing of steel scrap in an electric furnace on a large scale necessitates the development of (a) continuous electric furnaces capable of (b) operation over a protracted period of time without relining, or even shutdown. In incorporating an electric furnace complex into a Concept furnace based system, it was assumed that the internally generated scrap level would be far below that now experienced in the steel industry. Probably 80-85 percent of the scrap will be bought from a variety of sources, including solid waste recycle and reconstruction because by 2020 much of the easier to recover 750 million tons of junk now potentially available will have already been processed. The recycling of scrap through an electric furnace now consumes some 600 kwh of electricity and this will not change significantly in the future, even with the advent of radically new continuous electric furnaces.

The product quantities shown in Figure 3 were arbitrarily selected based on the conversion of a new conventional 28 foot hearth diameter to the Jordan Blast Furnace Concept, i.e., from about a million tons a year to about 2 million tons a year. As noted, because it is believed that almost half of the steel production of 2020 will be through electric furnaces, 2 million tons from that source was included arbitrarily to indicate the balance. This normally would provide 2 million tons of carbon monoxide, but through the use of disproportionated carbon dioxide potentially available from a CTR, there is another 2 million tons of carbon monoxide that comes along with the required 1.2 million

tons of oxygen. While the total of 4 million tons of carbon monoxide could make either 1.3 million tons of methanol or 1.6 million tons of ammonia, it was decided to use 2 million tons of carbon monoxide in the production of each, again to indicate the versatility possible. However, much more is possible in terms of chemicals, metals and fertilizers via carbon monoxide available from even a present blast furnace, but this work has yet to be published.

Thus the product mix of a basic CTR-steel complex includes;

- 2 million tons steel from scrap
- 2 million tons of steel from a Concept iron furnace
- 0.6 million tons of methanol
- 0.8 million tons of ammonia

As the whole idea of the integrated complex is the utilization of the energy potentially available from the CTR, a summary of the potential energy consumption is shown in Table 3.

The energy required for disproportionating carbon dioxide to carbon monoxide and oxygen must be very low in cost to make real sense. One need only consider the operation of the concept furnace at a level of 2 million tons a year using 1.3 million tons of oxygen obtained by air separation which uses about 300 kwh per ton of oxygen. This would amount to 450 million kwh or 75 MW(e). Probably the added value of the 2 million tons made available along with the oxygen is best valued at \$10 a ton (roughly a dollar per million Btu). But there are other considerations which include (a) the fact that carbon dioxide would be reused, (b) methanol production would be independent of natural gas availability, (c) the potential industry conversion would make available 40 billion gallons a year of methanol, sufficient to operate the major portion of the automobiles in the U.S., (d) ammonia and methanol could be made in vast quantities near the markets, effecting transportation savings, and (e) having ammonia and carbon monoxide available together in large

quantities could form the basis of a giant chemical industry.

As noted, it was decided to show the versatility of the complex in this analysis by including the production of ammonia and methanol. While the methanol production can easily be doubled at the expense of ammonia, the same cannot be said of ammonia at the expense of methanol. This is because the production of ammonia requires the availability of nitrogen which comes about in the production of oxygen for the BOP shop using air separation. However, air separation plants are relatively cheap, especially with respect to nitrogen capacity, so that providing nitrogen capacity to enable conversion of all the carbon monoxide to ammonia would necessitate a very small investment. It should also be noted that with carbon dioxide separation processes in place, addition of a unit to separate carbon dioxide from stack gas, lime kiln gas or cement kiln gas would provide essentially pure nitrogen capable of being used in an ammonia plant. In this regard, it is also of interest to note that if another source of nitrogen were available, there would be no need of an oxygen plant since the gas mixture from the CTR (oxygen-carbon monoxide) could probably be used in a modified BOP shop, i.e., the so-called "Q-BOP".

This proposed scheme for a methanol venture tied in with a Jordan Blast Furnace Concept and a CTR, (Table 4) reflects the potential for methanol at the level of production for a typical 28 foot blast furnace, a Concept furnace of the same size, and the potential for the industry.

Many see the CTR as holding the potential for cheap hydrogen, but whether cheap hydrogen does come about through coal, CTR or even shift reaction of carbon monoxide from a Concept furnace, hydrogen is not transportable. Most likely it will be converted to either or both methanol and ammonia. If indeed some way is

found to make cheap hydrogen from coal or via the CTR or any other way excepting through iron-making, it is obvious that in its utilization with carbon monoxide from a Concept Furnace the potentials above are essentially tripled, in other words the concept furnace could provide 200 million tons of carbon monoxide which when combined with 28.6 million tons hydrogen would yield a little over 200 million tons (60 billion gallons) of methanol. The CTR-Concept combination has the potential for 120 billion gallons of methanol if cheap hydrogen is available at the site.

III. CTR THERMAL ENERGY AND THE CARBON DIOXIDE DISPROPORTIONATION FOR THE DIRECT REDUCTION OF IRON ORE

The difficulties associated with direct reduction of iron ore have been discussed earlier, but several important factors need be reiterated. First of all, the interest in direct reduction arose as the result of cheap natural gas here and abroad, but in the United States natural gas is no longer cheap and certainly not plentiful. Secondly, direct reduction yields a form of crude iron which must subsequently be refined in some other manner, either in a blast furnace or in an electric furnace where smelting in the molten state can be conducted. Thirdly, direct reduction requires more energy than other methods of ore reduction. Perhaps in spite of these difficulties, a considerable effort has been made world-wide to somehow utilize heat potentially available from nuclear fission reactors to reform natural gas, oil and asphalt to essentially hydrogen and carbon monoxide at a temperature near 1400°F (760°C) which it is proposed will reduce iron ore. Blickwede⁽¹⁾ has summarized the preliminary report of the AISI (American Iron and Steel Institute), Committee on General Research, noting that to really be applicable, heat must be available and useable at well above 1400°F (760°C) as

the kinetics of direct reduction demand that the temperature of the reducing gas be at perhaps 900-1000°C (1650-1838°F). Direct reduction using electrolytic hydrogen was also considered in the study. As the paper was given in May, 1974, it is supposed that the Task Force on Nuclear Energy began its study at a time when natural gas was cheap and finished it at the time of increasing price and decreasing availability.

What is surprising is that the study did not appear to include an evaluation of gases produced from the reforming of coal itself with steam. Further, the operation of a direct reduction facility using a gas comprised essentially of carbon monoxide from the high temperature reaction of coal, carbonaceous material or hydrocarbonaceous compound with carbon dioxide was not considered. The chemical reaction is simplified in the general equation

and like the reforming process is best conducted at temperatures in excess of 1400°F (760°C). While it is admitted that at lower temperatures hydrogen is a more effective reductant for iron ore than carbon monoxide, at the temperatures necessary for practical reduction kinetics, carbon monoxide is almost equally effective. Clearly the kinds of coal which can be utilized in such a process can be of the very cheapest grades, certainly much less than the \$20 a ton noted for coking coal. Probably the process could be conducted using chars of coal refining processes.

The simplest direct reduction scheme utilizing carbon monoxide could be based on top gas from Jordan Blast Furnace Concept Furnace which would necessarily be washed free of carbon dioxide in a solvent removal system and then indirectly reheated to about 1000°C whence it would then be passed into the direct reduction reactor. If the nuclear reactor could provide this heat all the

better. But probably the heating value of the off-gas from the direct reduction reactor would be sufficient for supplying the necessary indirect preheat. The implication here is that in the United States, added direct reduction capacity might best be achieved adjacent to conventional and Concept converted blast furnaces. As perhaps 15 million Btu's are required by a direct reduction facility per ton of direct reduction product, somewhat less than two tons of carbon monoxide would be needed since the heating value of carbon monoxide is 8.7 million Btu/ton. It is of further interest to note that the top gas from carbon monoxide direct reduction would have a higher flame temperature than the analogous top gas from essentially hydrogen direct reduction, improving the capability of high temperature preheat of the reducing media (by indirect heating).

Logically extending the concept of direct reduction using carbon monoxide or a gas comprised mainly of carbon monoxide to a nuclear reactor such as a high temperature CTR, using carbon dioxide and a carbonaceous material such as char or coal enables one to think independently of a source of carbon monoxide. In essence, a part of the hot top gas from the direction reduction reactor can then be recycled back through the CTR into the carbonaceous material in a bed or fluid bed system or a combination thereof to provide the high temperature reducing media. But again it should be emphasized that somewhat higher temperatures will have to be available from a nuclear reactor to make the scheme practical. But in that respect it is little different from the case using reformed (by CTR) natural gas or asphalt.

The potential application of the heat available from the coolant blanket of a CTR to reforming with steam or with carbon dioxide is evident. Again the question of the temperature of the

heat available is the problem, to achieve a viable process for a direct reduction gas at about 1000°C it is supposed that surface temperatures somewhat in excess that are required since both the steam reforming and carbon dioxide reforming reactions are endothermic, but the steam reforming being more endothermic than carbon dioxide reforming. The scheme will look like that of Figure 4.

While a direct reduction facility can be based on the carbon monoxide from a Concept furnace or a CTR-Concept furnace scheme, there are a number of other possibilities. As many see the CTR in some way providing cheap hydrogen, clearly such cheap hydrogen could be used for a direct reduction process. Another interesting possibility entails the use of carbon monoxide produced through the disproportionation of carbon dioxide via a CTR which has been discussed earlier, i.e.,

The availability of such a stream may be possible, however, in contemplating its use in a direct reduction process necessitates that either the contained oxygen be removed or reacted with a form of carbon (like coke or coal in a "blast" furnace) to form more carbon monoxide. The latter is not so bad in that at least high temperature carbon monoxide is available directly. But looking to avoid the necessity for having a carbonaceous or hydrocarbonaceous material at hand, relying only on carbon dioxide as a source of the carbon atom, it is presumed that oxygen can be removed from the carbon monoxide-oxygen mixture in the same way that oxygen is removed from the nitrogen of air, in that nitrogen and carbon monoxide have similar properties, i.e., molecular weight, boiling points, etc. Thus in separating a ton of oxygen from 5 tons of air, $2\text{N}_2\text{O} \rightarrow \text{O}_2 + 4\text{N}_2$, it can probably

be approximated that some half the 300 kwh for that will be required to remove a ton of oxygen from roughly three tons of the carbon dioxide disproportionation mixture, $2 \text{ CO}_2 \rightarrow \text{O}_2 + 2 \text{ CO}$. In other words approximating 75 kwh per ton of carbon monoxide as product, ignoring the value of the oxygen for this analysis.

Again, then, carbon dioxide would be passed through the CTR to provide a stream containing about two-thirds unreacted carbon dioxide, 23 percent carbon monoxide and 12 percent oxygen at about 600°C . The mixture would be passed through heat exchangers to cool it and at the same time generate steam to make electricity. The carbon dioxide would be compressed out and the remaining oxygen-carbon monoxide mixtures would be separated cryogenically in a facility much like a present air separation plant though differences would probably exist if for no other reason than the mixture represents a safety problem. In this case no consideration of the use for oxygen is made. The pure carbon monoxide is then heated to about 1000°C (1832°F) and fed into the direct reduction reactor, in this case the heat might be provided either by burning the top gas or using some form of high temperature heat potentially available from the CTR. The direct reduction product would then be fed to an electric furnace for refining, the electricity being provided by the CTR. The scheme is shown in Figure 5. For an operation of 2 million tons of steel per year and assuming that one ton of carbon monoxide is required per ton reduced iron, a thermal power level of 5700MW(t) is required. Thus a relatively large amount of energy is associated with the disproportionation of carbon dioxide to carbon monoxide and oxygen. Clearly also, it is difficult to contemplate a fuel, fertilizer or chemical complex in conjunction with such a scheme.

While it is not easy to visualize, there is always the

possibility that the CTR might provide a convenient form of heat at temperatures well above the melting point of pure iron of 1535°C (2795°F). Should this become practical, direct reduction of molten iron ore-lime mixtures by either or both carbon monoxide and hydrogen could provide refined molten steel directly. While this necessitates a "quantum jump" from conditions now thought practical, it would make more sense than direct reduction as now contemplated, to a crude form of iron.

Again, this study has emphasized the conversion of the present blast furnace because the facilities are there and can well be useful for another half century, but also because it is felt that in the future a much higher rate of steel will be produced by recycling scrap, probably through electric furnaces. Because of the high cost of operating electric furnaces, it is conceivable that cheap imported direct reduction product may simply be refined in the blast furnace or a converted form of the present blast furnace, thus lowering the coke rate. But in the long run it is believed that a present blast furnace can be made to operate using oxygen and a slurry of coal in liquid carbon dioxide through separate systems of tuyeres so that the coke rate can be drastically reduced, or conceivably, the use of coke obviated. Finally, it is the notion that a vast fuel, fertilizer and chemical complex can be associated with a modified blast furnace system, especially when associated in some way with the various kinds of energy potentially available from a CTR.

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TABLE 1

UNITED STATES RAW IRON AND STEEL PRODUCTION
FROM 1945 TO PRESENT AND PROJECTION TO 2020

(in Millions of Short Tons/Year)

<u>Year</u>	<u>Blast Furnace</u>	<u>Open Hearth</u>	<u>Basic Oxygen</u>	<u>Electric</u>	<u>Total Production</u>
1945		72.0		3.5	80.0
1955	50.0	105.5	0.3	8.0	117.0
1965	90.0	94.5	23.0	14.0	131.5
1975	108.0	33.0	85.0	30.0	150.0
1985	160.0		160.0	125.0	250.0
2020	220.0		220.0	200.0	400.0

TABLE 2

COMPARISON OF METHANOL COSTS BY CO ROUTE AND NATURAL GAS ROUTE
1470 TONS/DAY METHANOL PLANT

(1972 Dollars)

	<u>Concept Furnace CO Route</u>	<u>Natural Gas Route</u>
Capital Investment (Inc. utilities, offsites, license)	\$33,000,000	\$31,000,000
<u>Operating Costs</u> (\$/Ton MeOH)		
Total Raw Materials (CO @ \$4.50/t, Gas @ 48¢/MM Btu)	16.49	15.62
Utilities	1.56	0.75
Total Labor	2.50	2.50
Capital Charges (less depreciation)	<u>4.01</u>	<u>3.64</u>
Total Manufacturing Cost	24.56	22.51

TABLE 3

CTR ENERGY APPLIED TO A STEEL-METHANOL-AMMONIA COMPLEX

<u>Process</u>	<u>Raw Mat.</u>	<u>Products</u>	<u>Capacity tons/yr</u>	<u>Unit Energy Req.</u>	<u>MW(Power)</u>	<u>MW(t)</u>
Electric furnace	Fe scrap	Steel	2×10^6	600 kwh(t)/ton steel	172	430
CTR dispro- portionation	CO ₂	CO, O ₂	2×10^6 1.3×10^6	20,000 kwh(t)/ton CO		5700
Iron-Concept furnace	Fe ore, coke, O ₂	Iron	2×10^6			
BOP shop	Iron, O ₂	Steel	2×10^6			
Air sep'n, for BOP, for NH ₃	Air, O ₂ N ₂	Oxygen, Nitrogen	2×10^5 7×10^5	300 kwh(t)/t O ₂	8.6	21.5
Methanol	CO	Methanol	6.6×10^5 (200×10^6 gal.)			
Ammonia	CO	Ammonia	8×10^5			

TABLE 4

METHANOL VIA CO FROM BLAST FURNACE IRON-MAKING

	Hot Metal tons/yr	CO tons/yr	Methanol gallons/yr
Present 28' blast furnace	1×10^6	0.7×10^6	CO too dilute
Blast furnace by Stahl (Russ)	1×10^6	1×10^6	100×10^6
Jordan Blast Furnace Concept	2×10^6	2×10^6	200×10^6
CTR-Concept Furnace	2×10^6	4×10^6	400×10^6
Present industry production	100×10^6	75×10^6	CO too dilute
Potential Stahl, 1985	200×10^6	200×10^6	20×10^9
Potential Concept, 1985	200×10^6	200×10^6	20×10^9
Potential CTR-Concept 2020	200×10^6	400×10^6	40×10^9

CONVENTIONAL BLAST FURNACE OPERATION
FOR HOT METAL PRODUCTION
FIGURE 1

METHANOL VIA CO AND VIA NATURAL GAS
FIGURE 2

**CTR FUSION ENERGY
APPLIED TO THE STEEL-METHANOL-AMMONIA
PRODUCTION COMPLEX
FIGURE 3**

CTR FUSION REACTOR SUPPLYING THERMAL
AND ELECTRICAL ENERGY FOR STEEL MAKING
FIGURE 4

DIRECT REDUCTION OF IRON ORE USING
DISPROPORTIONED CO AND ELECTRIC POWER
FIGURE 5