Abstract

Smelting reduction technology is the only recent serious contender to replace the conventional energy-intensive blast furnace that has been the dominant ironmaking technology for centuries. In this chapter we evaluate the effect of government intervention on the development of smelting reduction technology.

The theory underlying smelting reduction technology has been known since the 1930s. Only from 1975 did a technology network emerge. By then, other innovative ironmaking technologies had proved disappointing and there was a threat that obsolete coke ovens might have to be replaced at great expense. From 1975 onwards, R&D efforts were undertaken. Only one of these early efforts achieved commercial application, the Corex process. Some efforts evolved into micro-networks that studied ‘second generation’ processes. The technology network, consisting of nine micro-networks, was heterogeneous. Various types of actors had various technical preferences due to earlier (R&D) experiences. Three micro-networks stopped their R&D activities; these were all initiated by integrated steel manufacturers. They lost interest because the existing capital stock was being continuously improved and they did not need additional ironmaking capacity. Smelting reduction technology was ‘locked out’. However, the future of smelting reduction technology is still undecided. Mining firms and steel mini-mills are still interested. The changes in the technology network reflect the dynamics in the development of smelting reduction technology.

If we look at the role of government, we find that environmental regulations were not decisive in initiating R&D efforts. The major arguments for R&D were the lower capital costs and the possibility of processing cheaper coals. Reducing environmental emissions and energy-efficiency improvements were only additional reasons for integrated steel firms to be interested. Another conclusion is that financial R&D support enlarged the technology network by supporting processes that were likely to be energy-efficient. However, R&D support did not accelerate the technology development (so far). The case study illustrates that in steelmaking existing capital stock tends to constrain technological development in steelmaking; this considerably limited the effect of government intervention and R&D support.
6.1. Introduction

Improving the energy efficiency of manufacturing industries is considered to be one of the ways to attain a more sustainable use of energy in modern society. Breakthroughs in industrial energy efficiency are appealing to both government and industry; both greenhouse gas emissions and energy costs for making these energy-intensive products are reduced. In the scientific literature on energy efficiency in industry we find detailed overviews of innovative energy-efficient technologies (see e.g. [Martin et al., 2000; De Beer, 1998]). Although these analyses serve the purpose of estimating the long-term potential of energy-efficiency improvement in the industry, they are not sufficient to answer the important question of how the development of such industrial innovative energy-efficient technologies can be enhanced by government. Their strength lies in a detailed bottom-up assessment of relevant characteristics such as energy-efficiency improvement and investment costs. If one wants to enhance the development of such technologies, one needs insight into the actual processes by which such technologies develop. Understanding technological development in terms of networks allows us to assess the importance of government intervention in orienting technological development.

In this chapter we evaluate the effect of government intervention on the development of an energy-efficient technology. For this purpose we make a detailed investigation of the networks in which the energy-efficient technology is developed.

As a case study we selected smelting reduction technology, an innovative technology for the production of iron. The iron and steel industry is a major consumer of energy and is therefore always mentioned as a sector where energy efficiency needs to be encouraged. Both scientific researchers in energy-efficiency analysis and policy makers consider smelting reduction technology to be one of the most important innovative energy-efficient technologies (see e.g. [IWG, 2000; Arthur D. Little, 1998; Martin et al., 2000; De Beer, 1998; IPCC, 2001; AISI, 1998; IISI, 1998]).

This chapter is structured as follows. In Section 6.2, we briefly introduce the two conventional routes for the production of steel. We locate the production of iron as the first and major energy-intensive step in the production of steel and introduce smelting reduction technology as an innovative alternative. In Section 6.3, the technology case study is analysed using a set of questions relating to the networks in which the technology was developed and the materialisation of the technology. This section closes with a short resumé of the current status of the technology network. Section 6.4 analyses in more detail the role of government intervention. The chapter closes with some conclusions about the effect of government intervention in stimulating the development of smelting reduction technology (Section 6.5).
6.2. Conventional iron and steel production and smelting reduction technology

The conventional production routes

The production of iron is the first step in the production process of steel. It is also the most energy-intensive step [Fruehan, 1999; De Beer, 1998; IISI, 1998]. The iron ore is reduced at a high temperature. The iron is subsequently converted into crude steel, cast into semi-finished products (blooms, billets and slabs), and rolled and shaped into final products. There are two major conventional routes for producing final steel products (see Figure 1). Both steel production routes play a role in the development of smelting reduction technology and it is therefore interesting to look briefly at the differences.

![Figure 1: The two major routes for producing iron and steel: Integrated steel mills and mini-mills.](image)

The first route is the integrated mill (upper half of Figure 1). Iron ore is reduced in a blast furnace. Coke, agglomerated ore and limestone are charged into the top of the blast furnace. The coke is gasified at the bottom, providing both the reductant (carbon monoxide) and the heat needed for the chemical reactions in the blast furnace. Coke has better physical characteristics for operating the blast furnace and is therefore preferred to coal. One of the major – and for this chapter relevant – improvements in the operation of blast furnaces is that coal is injected directly into the blast furnace, so that less coke is needed for producing hot metal. Both the coke and the agglomerated ore are produced in separate facilities (see Figure 1). The blast
furnace delivers hot metal, which is most often transported to a basic oxygen furnace to produce crude steel. In an integrated mill, high quality steel products can be produced. The annual output of such a mill typically ranges from 2 to 3 million ton steel per year. The specific energy consumption for the most efficient integrated mill is 19 GJ primary energy per ton of crude steel\(^1\). 85% of this energy is needed for operating the blast furnace (including agglomeration and coke production) [De Beer, 1998]. Cost of coal and other energy sources make up 25 to 30% of the cost of producing one ton of hot metal\(^2\).

The second route is known as a mini-mill (see lower half of Figure 1). In most mini-mills, recycled steel, scrap, is melted in electric arc furnaces and further processed into final products. The mini-mill route has no iron production step and is therefore also considerably less energy-intensive than the traditional integrated mill. The best practice SEC value for a mini-mill is 5 GJ / ton crude steel. Mini-mills generally deliver lower quality steel products. Not all kinds of final products can be made. Its annual output typically ranges from 0.5 to 1.0 million tons steel per year, so mini-mills are considerably smaller than integrated steel mills.

Smelting reduction technology is an alternative technology to the conventional blast furnace. The blast furnace has been the dominant technology for iron production for centuries. Its operation has been improved and optimised continually; this has resulted in very efficient large-scale operating facilities\(^3\). In addition to smelting reduction technology, direct reduction technology is a second alternative technology to the conventional blast furnace route. Direct reduction technology was explored as a possible replacement for the dominant blast furnace before R&D interest in smelting reduction technology emerged\(^4\).

\(^1\) The specific energy consumption in integrated mills varies between 19 to 40 GJ per ton crude steel [WEC, 1995].

\(^2\) Literature estimates of the cost price of a ton of hot metal range between 120 to 180 US$. Amortisation makes up 30 to 35% of the costs. Costs for iron ore represent 25 to 30% of the cost price of a ton of hot metal. Energy costs represent 25 to 30 % [Astier, 1991; De Beer, 1998]. The energy costs for producing a ton of steel are about 10% lower that the energy costs for producing a ton of hot metal [Faure, 1993]. The cost price of a ton of steel ranges between 200 to 300 US$. The hot metal costs make up a considerable part of the total cost price, 60 to 70%. Mini-mills typically produce crude steel for around 200 US$ per ton [Faure, 1993; Abildgaard et al., 1997; Schors, 1996].

\(^3\) The design of the blast furnace has remained essentially the same since the Stuckoven was introduced in 1300. Charcoal was used as fuel and reductant. Its physical properties limited the capacity of the blast furnace. The physical properties of coke permit larger capacity operation. From 1718 onwards, charcoal was replaced by coke. For a more elaborate description of the improvements in blast furnace technology, see [De Beer, 1998; Chatterjee, 1994].

\(^4\) Whereas the first direct reduction facility was already operational in 1952, it is only recently that direct reduction technology has began to be used on a wider scale. Direct reduced iron (DRI or sponge iron) is increasingly processed in mini-mills, primarily in developing countries where cheap natural gas is available [IISI, 1998; Chatterjee, 1994; Astier, 1991]. Direct reduction facilities are usually not built at the site of mini-mills. They are built at locations were natural gas is cheap. In 1990 about 3.5% of the world-wide iron production was based on direct reduction technology. In 1999, this share has increased to 6.7%. If DRI is used in mini-mills the energy needed for manufacturing steel increases to roughly the same level as in an integrated mill, i.e. 18.5 GJ / ton crude steel (assuming 100% DRI) [De Beer, 1998].
Smelting reduction technology

Smelting reduction technology is a coal-based ironmaking process and thus different from the conventional coke-based conventional blast furnace. The production of coke is avoided. Most smelting reduction processes also avoid the agglomeration of iron ore (see Figure 1). Smelting reduction technology, as the name clearly suggests, involves both solid-state reduction and smelting. Smelting is melting involving chemical reduction reactions. Smelting reduction technology exploits the principle that coal can be gasified in a bath of molten iron. Figure 2 gives a schematic lay-out of smelting reduction technology.

Figure 2: Schematic lay-out of smelting reduction technology.

Smelting reduction technology consists of two vessels or two zones, a pre-reduction unit and a smelting reduction vessel (see Figure 2). Smelting reduction technology, however, does not necessarily require two separate vessels. The coal is fed into the smelting reduction vessel where it is gasified. This delivers heat and hot gas containing carbon monoxide. The heat is used for melting the iron in the smelting reduction vessel. The hot gas is transported to the pre-reduction unit and used for pre-reducing the iron oxides (in a solid state), which are fed directly into the pre-reduction unit. The pre-reduced iron is subsequently transported to the smelting reduction vessel, where final reduction takes place.

The hot gas produced in the smelting reduction vessel has a high chemical energy content due to the presence of carbon monoxide. This can be exploited in two ways. First of all, the carbon monoxide can be used for the reduction of iron oxides in the pre-reduction unit. The hot gas generated in the smelting reduction vessel is transported directly to the pre-reduction unit. Secondly, the carbon monoxide can be oxidised in the smelting reduction vessel, which then delivers more heat. This can be used for smelting the iron. This is called post-combustion. After post-combustion, the hot gas is transported to the pre-reduction unit and the remaining carbon monoxide is used for pre-reducing the iron oxides.

The richness of carbon monoxide in the hot gas determines the degree of pre-reduction in the pre-reduction unit. As post-combustion decreases the reduction potential of the hot gas, compromises have to be made between the degree of post-combustion and the degree of pre-reduction. If the degree of post-combustion is low,
higher pre-reduction degrees are achieved in the pre-reduction unit. The product delivered to the smelting reduction vessel is quite similar to the reduced iron that is produced in direct reduction technology, namely direct reduced iron (DRI). More coal is needed in the smelting reduction vessel to melt the iron. Processes operating at such a high level of pre-reduction are referred to as first generation processes. The Corex process is the best known first generation process.

If the degree of post-combustion is high, lower degrees of pre-reduction are achieved. Less coal is needed, because extra heat is generated and used to melt the pre-reduced iron (provided heat exchange is optimised). Processes operating under such a regime are referred to as second generation processes [Tomellini, 1994; Poos, 1993].

As will become clear throughout this chapter, smelting reduction technology is not a homogeneous technology. There is a variety of smelting reduction processes. In this chapter we discuss the development of ten smelting reduction processes.

### 6.3. Analysing the development

In this analysis, we focus on ten smelting reduction processes which were developed in nine micro-networks. We start by giving a short historical description of the technology in order to illustrate the background against which the technology network emerged. We subsequently focus on the technology network. The technology network is the collection of all the actors who are active in developing a specific technology. A technology network usually consists of a number of smaller micro-networks in which a few actors co-operate. Before we continue with a more detailed analysis of the micro-networks, we look at the materialisation of the technology. We close with a short resumé of the current status of smelting reduction technology.

#### The early days

The technology network of smelting reduction technology grew seriously from 1980 onwards, although, the principle of gasifying coal in a molten bath is much older. It was conceived in the late 1930s\(^5\) [Chatterjee, 1994]. In the late 1950 and 1960s, steel manufacturers were interested in developing a technology that could convert iron ore into crude steel in just one step. The principle of gasifying coal in a molten bath was also popular at that time [Smith, 2000; Feinman, 1999; Poos, 1993]. However, attempts to develop direct steel making technology were stopped, on the one hand by

---

\(^5\) Martin Wiberg in Sweden (1938) injected a mixture of iron ore and coal into an open hearth furnace (steelmaking furnace). The Engell brothers in Denmark (1938-1939) studied a process in which iron ore and coal powder were sprinkled into a moving high carbon bath. The generated carbon monoxide was burned (post-combusted) above the bath [Chatterjee, 1994; Smith, 2000].
the fact that not all technical problems could be solved and on the other hand by the trend in ironmaking towards giant high capacity blast furnaces. The steel industry expanded rapidly. There was a huge demand for higher quality steel products and with the introduction of the basic oxygen furnace for converting hot metal into crude steel (1952), there was a tremendous demand for cheap hot metal. The cheapest way to meet this requirement was to operate large scale blast furnaces [Smith, 2000; Feinman, 1999; Poos, 1993; Smith and Corbett, 1987]. This dominant trend created the opportunity for the development of ironmaking processes, which were economic on a smaller scale. A first contender was gas-based direct reduction technology which gradually emerged from the mid-1960s onwards [Papst, 1987; Smith, 1992; Poos, 1993]. In those days, direct reduction technology was projected as the best possible alternative to the dominant iron production route. However, direct reduction technology did not break through as a serious alternative. Several inherent drawbacks namely the high reactivity of the solid-state direct reduced iron and the high price of natural gas, forced actors to look for alternative coal-based iron production routes [Papst, 1987; Chatterjee, 1994; IISI, 1998].

Technology network
What is the composition of the technology network?

From 1975 onwards, a new contender appeared on the scene: smelting reduction technology [Smith, 1992; Chatterjee, 1994; Feinman, 1999; Smith, 2000]. R&D activities were undertaken to develop a coal-based ironmaking process producing liquid iron (or hot metal). The idea was to smelt pre-reduced iron. Between 1975 and 1985 a considerable number of efforts were initiated namely between 15 to 20. The efforts differed primarily in the type of smelting reduction vessel employed for (s)melting a direct reduced iron-like product [Smith, 1992; Smith and Corbett, 1987; Papst, 1987]. Most of the efforts were limited to pilot scale activities and the generation of engineering concepts for industrial scale facilities. There was one exception [Smith, 1992; Feinman, 1999; Scott, 1994]. The German engineer Deutsche Voest6 and the Austrian machine supplier Voest commercialised the Corex process. A South-African steel maker ordered the first facility in 1985. After two false starts, the facility was handed over definitively to the South African steel firm in 19897. The Corex micro-network is one of the smelting reduction processes included in our analysis (see Figure 3).

6 When the R&D activities started, Deutsche Voest was known as Korf Engineering.
7 The Corex process still requires agglomerated ore. Corex is a first generation process. It has a high degree of pre-reduction. The solid state DRI-like pre-reduced iron is melted in the smelting reduction vessel. Since most of the reduction is done in the solid state, Corex is a slower process than the other smelting reduction processes [Fruehan, 1999]. Due to the Asian crisis, which had a negative impact on hot metal prices in South Africa, the South-African steelmaker Iscor decided to shut down the Corex facility temporarily in 1998 [VAI, 2000].
Three of these early efforts evolved into R&D activities in which actors tried to achieve higher post-combustion levels. The processes with higher post-combustion levels are referred to as second generation smelting reduction processes. As a result the following three micro-networks can be distinguished (see also Figure 3). Some Japanese integrated steel firms continued earlier private R&D activities in the DIOS micro-network [Fruehan and Cramb, 1990; Chatterjee, 1994]. The UK British Steel and the Dutch Hoogovens continued their earlier experiences with smelting reduction in the CCF micro-network in 1989 [Robson, 2000; Meijer, 2000]. The Australian mining company CRA approached the German steelmaker Klöckner Werke, who had already gained experience in smelting reduction processes. The HIsmelt micro-network resulted [Smith and Corbett, 1987; Innes, 2001; Brotzmann, 1992].

In Figure 3, we distinguish five additional micro-networks which developed a smelting reduction process that also involved a high degree of post-combustion [Sarma and Fruehan, 1998; Anonymous, 1996a]. Figure 3 gives a general overview of the technology network from 1980 onwards.

**Figure 3:** Technology network of smelting reduction technology. Nine micro-networks developed ten smelting reduction processes. The capacity of equipment is used to denote up-scaling of the technology. For reasons of clarity we did not include all actors in Figure 3, nor did we indicate when certain actors stopped their active R&D.
Figure 3 shows that the Austrian machine supplier Voest has continued the development of the process after the first Corex facility was realised. Voest and a Korean steelmaker joined forces to develop a variety of the Corex process which could use fine iron ores rather than agglomerated ore. We regard the Corex process and the so-called Finex process as having been developed within one micro-network.\textsuperscript{8}

Figure 3 illustrates that the nine micro-networks are widely distributed across the world. Two of the micro-networks are based in Australia, one in the former USSR, one in Japan, one in the US, one in Brazil and three in Europe.

Six of the nine micro-networks are still active, one of them being the Austrian machine supplier Voest. In two of these six micro-networks, after a period in which R&D activities were stopped, interest by external actors induced renewed (R&D) activity. This happened in the Romelt and HIs melt micro-networks [SAIL, 2000; Kemp, 2000; HIs melt, 2000; Anonymous, 2000a]. In the Tecnored micro-network there is a plan to build a pilot facility in 2001 [Anonymous, 2000b; Ritt, 2000]. In the DIOS micro-network and the AusIron micro-networks, actors intend to develop the process further.\textsuperscript{9}

Three micro-networks stopped their activities. Integrated steel manufacturers initiated these three micro-networks. None of the micro-networks merged. Only the CCF micro-network branched in 1992, from then onwards the Dutch and the Italians continued the development of the same process separately.\textsuperscript{10}

\textsuperscript{8} The argument for regarding the Finex process and the Corex process as one-micro-network is that the developments are very closely related. Whereas POSCO had started R&D activities towards smelting reduction technology in 1989, they could not have undertaken the development of Finex without Voest. POSCO started R&D activities relating to smelting reduction technology as one of the long-term R&D projects that began when POSCO decided to expand its R&D capacity in order to improve the firm’s competitive operation [Shin, 2000]. The Austrian machine supplier Voest had already filed some patents in the area of pre-reducing iron ore fines instead of agglomerated ore [Eberle et al., 1996; Delport, 1991]. The Korean steelmaker POSCO bought the second Corex facility. Its capacity was twice the capacity of the first Corex facility in South-Africa. Voest installed three more Corex C-2000 facilities, two in India and one in South-Africa.

\textsuperscript{9} In the DIOS micro-network, the Japanese integrated steel manufacturer NKK is trying to commercialise DIOS technology independently. NKK wants to exploit its expertise and tacit knowledge in designing and operating the DIOS process. NKK wants to transfer the technology to other firms. A first DIOS facility of 4,500 thm/day is expected for mini-mills in a few years [Kitagawa, 2000]. A facility of 40 thm/day recently became available in the AusIron micro-network. The SASE joint venture regularly states that they plan to build a 7,000 thm/day facility. Note that Ausmelt Ltd., the engineering firm in the SASE joint venture, has experience in commercialising the technology for non-ferrous metals [Arthur and Floyd, 1999; Arthur and Hamilton, 1996; Sherrington, 2001].

\textsuperscript{10} Note that we regard the CCF micro-network as being no longer active. The Italians however are still working on the development of the cyclone. They changed the name of the CCF process to CleanSMelt [Anonymous, 1997b; Malgarini et al., 1996]. The Italians were not willing to co-operate in our research for reasons of confidentiality.
To what extent and how often do micro-networks exchange knowledge?

In the development of smelting reduction technology, the various micro-networks performed R&D activities on their own, although each of the micro-networks closely monitored the developments within the entire technology network. In several cases, results of other micro-networks influenced decisions and R&D activities [Meijer, 2000; Fruehan, 2000; Burrow, 2000; Lassat de Pressigny, 2000]. The most far-reaching example in this regard is the Dutch Hoogovens decision in 1992 to restrict R&D to the pre-reduction unit only. After reviewing worldwide ongoing smelting reduction efforts, Hoogovens concluded that the cyclone was unique. It was decided to use all financial resources for building a pilot scale cyclone. If the cyclone proved satisfactory, Hoogovens would start looking for a partner to ‘complement’ the process [Meijer, 2000; Moors, 2000b].

The major arguments for exchanging knowledge are to learn from the solutions suggested by others and to avoid repeating their mistakes and re-inventing the wheel [Burrow, 2000; Robson, 2000; Meijer, 2000; Lassat de Pressigny, 2000; Floyd, 2000]. Usually articles, conference visits and patents are a first source. If R&D activities seemed of to be real interest for a firm’s R&D activities, personal contacts were established and site visits were organised. There was for instance regular contact between the North-American Steel association AISI and its Japanese counterpart JISF for the development of DSM and DIOS [Kavanagh and Obenchain, 2000; Kitagawa, 2000]. People from the Dutch Hoogovens and AISI visited the Russian Moscow Institute of Steel and Alloys (MISA), which developed the Romelt process. Hoogovens also visited JISF once [Furukawa, 1994]. JISF held several technology exchange meetings, and also met representatives from the Jupiter process [Kitagawa, 2000; Badra, 1995]. The Australian mining firm developing the HIsmelt process also had personal contacts with other micro-networks [Burrow, 2000].

Are there dominant micro-networks in the technology network?

In the development of smelting reduction technology, none of the nine micro-networks had a decisive influence on the entire technology network. None of the micro-networks set the rate and direction of the technology development. Although the Corex process is the first smelting reduction process that became commercially available, its general applicability was limited. To avoid this, the later second generation processes tried to achieve higher levels of post-combustion [Lassat de Pressigny, 2000; Sarma and Fruehan, 1998; Chatterjee, 1994; Astier, 1991].

The lack of dominance is due partly to the variety in the types of pre-reduction units and smelting reduction vessels, the different ways chosen to optimise either post-combustion or pre-reduction, and the variety of vessels used in various smelting reduction processes. Smelting reduction technology is not a homogeneous technology.
**Materialisation**

What is the rate of development and what steps in up-scaling can be distinguished?

In this section we focus on the materialisation of the technology in order to see how many years were needed to develop smelting reduction technology. Figure 3 indicated the number of years that micro-networks actors were active. Figure 4 gives a more detailed account of the capacity of the equipment used in R&D.

If we glance at Figure 4, it becomes clear that most of the processes are operational on a relatively modest scale. In some micro-networks there are plans for taking the next step, although such plans do not give any guarantee. The plan to build a HiSmelt facility on the site of a US mini-mill steel manufacturer has recently been postponed till at least 2003.

Figure 4 indicates that steps in up-scaling the technology differ among the various micro-networks. We can only give a rough indication of the difference in scale that is a factor 5 to 10 between the subsequent steps.

Figure 4 also demonstrates that it is difficult to generalise about the time frame needed for developing smelting reduction processes, primarily because nine of the ten processes are not yet operational on a near-commercial or demonstration scale.

At the moment only the Corex process is commercially available. Roughly ten years were needed to make the first Corex facility run satisfactorily on a scale of 1,000 thm/day. More than fifteen years were needed to make it operational at 2,000 thm/day. Figure 4 indicates that two processes might become operational on a demonstration scale in the near future. In both these cases, at least 20 years were needed to reach the status of materialisation.

A final interesting observation was made in the CCF micro-network: historic decisions on the materialisation of the CCF process likely affected its later development. Hoogovens and the Italian integrated steelmaker Ilva have separately continued R&D since 1992 (see Figure 4). The major reason was that the firms could not agree on where to build a new pilot research facility. Meijer (2000) speculates that if the firms would have continued co-operation and if they would have built a complete smelting reduction process – including both the pre-reduction unit and the smelting reduction vessel –, the course of events might have taken a more positive direction. Such a complete facility might have delivered results that would have enhanced the decision to build a demonstration facility between 1995 and 1999. As shown Figure 4 and as will be discussed in a later section, the demonstration facility was not built.

If we look at the up-scaling of the processes (Figure 4) and at the time frames of active R&D (Figure 3), we conclude that it takes at least 10 to 20 years to perform the necessary steps. In this estimate, we did not take into account the delay caused by the shelving of some of the processes.

---

11 The C-3000 with a capacity of 3,500 – 4,000 thm/day is currently up for sale [VAI, 2000].
Figure 4: The steps taken in up-scaling the ten smelting reduction processes.\(^{12}\)

\(^{12}\) The scale of equipment or facilities is usually expressed in tons of hot metal per day (thm/day). There is however no uniform standard regarding what is a near-commercial scale or demonstration facility, a pilot facility or a lab scale facility. Whereas Hoogovens considered a 1,400-2,000 thm/day facility as a demonstration facility, the Corex facility in South Africa is seen as the first commercial facility, i.e. 1,000 thm/day. On the other hand, the recent AusIron facility of 40 thm/day is referred to as a demonstration facility. We make a distinction between lab / bench scale facilities, which are <100 thm/day; pilot scale facilities, which are >100 and <750 thm/day; and demonstration or near-commercial scale facilities, which are > 750 thm/day.
What are the perceived performance characteristics of the technology?

Smelting reduction technology overcomes some major disadvantages of the conventional blast furnace route for iron production. This causes that the cost price of a ton of hot metal is likely to be reduced [Smith, 2000; Kitagawa, 2000]. This is the most important characteristic of smelting reduction technology. Lower capital investment (avoiding coke ovens and agglomeration plants and replacing the capital intensive blast furnaces) and the use of coal instead of expensive metallurgical coals are two major factors in this cost price reduction. Smelting reduction technology is cost competitive even on a relatively small scale in that it increases operational flexibility. Smelting reduction processes also show a larger flexibility in the type of raw materials that can be processed. Finally, smelting reduction technology has clear-cut environmental advantages over the conventional blast furnace route [Pollock, 1995; Millbank, 1995; Fruehan, 1999; De Beer, 1998; IISI, 1998].

Whereas some performance data can be found in the literature, these merely affirm what was formulated in more general terms in the former paragraph. Only the Corex data are backed up by industrial operation. The other performance data found represent targets for pilot or demonstration facilities under construction but are not an elaborate account on what was actually measured in R&D. The ranges reflected in e.g. cost price data found are largely due to differences between smelting reduction processes.

The performance data reported for smelting reduction technology are promising – in fact they form the core arguments used by actors to legitimise their investments in developing smelting reduction technology. However, it is difficult for the technology to compete with the conventional increasingly optimised and very efficient blast furnace route. Most often the performance data quoted in the literature do not reflect the competitive position very accurately. By now, most of the smelting reduction processes seem to have lost ground to the incrementally improved conventional route for producing iron. For a more elaborate discussion of these changing circumstances we refer to the next section in which we discuss some arguments put forward for stopping the development of smelting reduction technology in various micro-networks.

---

13 In literature we found that estimates of a cost price reduction varied from +10 to -25 US$ per ton hot metal (after off gas-creditation) [Anonymous, 1996b; Meijer et al., 1994; Furukawa, 1994]. In literature the cost price of a ton hot metal in a smelting reduction ranges from to 80 to 160 US$ [Weston and Thompson, 1996; MacCauley and Price, 1999; Dry et al., 1999; Meijer et al., 1996; Abildgaard et al., 1997].
Micro-networks

How are the various micro-networks made up?

Table 1 gives an overview of the composition of the nine micro-networks. Table 1 clearly illustrates that a wide variety of actors played a role in the nine micro-networks. A variety of types of actors also initiated the R&D activities. In four of the nine micro-networks, integrated steel manufacturers took the lead. In the North American DSM micro-network an association of steel companies played an important role in initiating R&D activities (AISI). Machine suppliers or engineering companies initiated three micro-networks, mining firms initiated two micro-networks and research institutes initiated one micro-network. Note that the micro-network that was initiated by a research institute operated in the former USSR planned economy [Pokhvisnev, 2000].

It is interesting to compare this variety with the composition of the micro-networks developing strip casting technology. In the development of strip casting technology, another important innovative energy-efficient technology, steel manufacturers generally took the lead and controlled the R&D activities. Steel manufacturers initiated ten of the eleven micro-networks (see Chapter 5). The larger variety of actors involved in developing smelting reduction technology clearly has to do with the position of the technology in the steelmaking process. Production of hot metal is also interesting for mining firms or for engineering companies who have an existing technology that can also be used for smelting iron. Only in one micro-network a well-known machine supplier to the iron and steel industry initiated the R&D activities, i.e. the Austrian machine supplier Voest.

Table 1 makes a distinction between the role of integrated steel manufacturers (column 3) and the role of the so-called mini-mill operators (column 2). In three of the five micro-networks in which integrated steel manufacturers did not take the lead, mini-mill operators became involved when the technology was claimed to be ready for operation on an industrial scale (see also Figure 3).

The second column of Table 1 gives a detailed overview of which actors played a role in developing smelting reduction processes. With the exception of Romelt’s micro-network, in all the micro-networks various actors co-operated in developing smelting reduction technology.

---

14 The Russian steel firm Novolipetski Metallurgical Kombinat (NLMK) was appointed by the USSR government as host for the pilot facility (450 th/day) and a commercial facility (2,500 thm/day). After the fall of the former USSR regime, the Russian economy collapsed and there was no need for additional ironmaking capacity. The commercial facility was never built [Valavin and Pohvisnev, 2000; Thompson, 2000].
Table 1: Overview of all the actors in the technology network. ♦ = Actor that initiated R&D activities; • = Other actors.

<table>
<thead>
<tr>
<th>Process</th>
<th>Actors</th>
<th>Country</th>
<th>Supplier / engineer</th>
<th>Minimill steelmaker</th>
<th>Integrated steelmaker</th>
<th>Research institute</th>
<th>Government</th>
<th>Mining company</th>
<th>Steel association</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corex</td>
<td>Deutsche Voest</td>
<td>Germany</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MISA USSR government NLMK ICF Kaiser (licence 1995) Nippon Steel Corp. (licence 1995) NMDC (licence 2000 / via RSIL)</td>
<td>Russia Russia Russia US Japan India</td>
<td>♦</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>Usinor Lurgi Thyssen (1993 – 1994)</td>
<td>France Germany Germany</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AusIron</td>
<td>Ausmelt Ltd. Aulron Energy Ministry for Mines and Energy Krakatau Steel (1997-now) Australian universities</td>
<td>Australia Australia Australia Indonesia Australia</td>
<td>♦</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td>♦</td>
<td>♦</td>
</tr>
<tr>
<td>Tecnored</td>
<td>Tecnologos North Star (1998-now)</td>
<td>Brazil US</td>
<td>♦</td>
<td>♦</td>
<td></td>
<td></td>
<td></td>
<td>♦</td>
<td>♦</td>
</tr>
</tbody>
</table>

Initiators (counted per micro-network) 3 - 4 1 1 2 1
Total number of actors involved (counted per micro-network) 6 3 8 5 2 3 2

¹ The US government had a role in preparing the legal framework through which a co-operative R&D programme could be established between public and private actors. The so-called Steel Initiative through which government aimed at promoting long-term R&D in the steel industry paved the way for the development of the DSM process in a co-operative R&D programme [Kavanagh and Obenchain, 2000; Sharkey, 1998; Badra, 1995].
In seven of the eight micro-networks co-operation was established right from the start. In the four micro-networks which were initiated by integrated steel manufacturers ‘competing’ steel firms co-operated. In two of these micro-networks, the North-American DSM micro-network and the Japanese DIOS micro-network, a larger number of integrated steel manufacturers co-operated (with substantial R&D support from the government) in developing smelting reduction technology. We asked the experts what the actors’ arguments were for co-operating in the micro-networks. They gave two major arguments: sharing the R&D expenditure and creating access to specific knowledge or earlier R&D experience [Burrow, 2000; Kitagawa, 2000; Fruehan, 2000; Meijer, 2000; Robson, 2000; Kavanagh and Obenchain, 2000; Lassat de Pressigny, 2000; Birat, 2000; Floyd, 2000; Freydorfer, 2001].

**What motivates actors to start and / or stop R&D activities?**

To supplement the knowledge gained from articles, conference papers and journal articles, we asked the experts why actors became actively involved in developing smelting reduction technology. By discussing these arguments with the experts it was possible to get a better idea of what really got them moving. Table 2 gives an overview of each of the actor’s arguments for initiating or becoming involved in the development of smelting reduction technology.

Table 2 shows that actors’ arguments differ per ‘type’ or ‘category’ of actor. Mining firms are interested primarily in exploiting existing deposits. Smelting reduction technology allows them to give added value to their raw materials or waste products. Table 2 illustrates that mini-mill steel makers showed interest in smelting reduction processes at a moment when the processes could be applied on a scale suitable for electric arc furnaces. Whereas the South-African Iscor was interested in applying the first Corex facility because of their limited access to metallurgical coals in South-Africa, the major argument why mini-mill operators were interested in smelting reduction technology was that it guaranteed a fixed priced supply of high quality hot metal. Feeding a mini-mill with hot metal increases the productivity and also opens up possibilities for the production of higher quality products. Table 2 shows that it was primarily the wish to reduce the cost of producing a ton of hot metal which caused the integrated steel manufacturers to be interested. Avoiding capital expenditure on new coke ovens (and also blast furnaces) and the possibility of using relatively cheap coals (instead of scarce and expensive metallurgical coals) were the two major factors in this cost price reduction. The threat of environmental regulations and the necessity to invest in order to comply with these requirements delivered an additional cost advantage.
<table>
<thead>
<tr>
<th>Type of actor</th>
<th>Actor</th>
<th>Micro-network</th>
<th>Replace pulverizer coke ovens (and BF)</th>
<th>Coal instead of metallurgical coal</th>
<th>Flexibility (operation + raw material)</th>
<th>Environmental emissions</th>
<th>Low-cost hot metal</th>
<th>High-quality hot metal supply EAF</th>
<th>New process in portfolio</th>
<th>Research application existing process</th>
<th>Obligation / deal with government</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated steelmaker</td>
<td>Klockner(^1)</td>
<td>HSmelt 1981</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Japanese firms(^2)</td>
<td>DIOS 1988</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NKK(^3)</td>
<td>DIOS 1997</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nippon Steel</td>
<td>licence Romelt 95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>British Steel(^4)</td>
<td>CCF 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoogovens(^5)</td>
<td>CCF 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ilva/CSM(^6)</td>
<td>CCF 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North-American Firms(^7)</td>
<td>DSM 1988</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stelco(^8)</td>
<td>DSM 1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Usinor(^9)</td>
<td>Jupiter 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>POSCO + RIST(^10)</td>
<td>Corex/Finex 1992</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mini-mill steelmaker</td>
<td>Iscor(^11)</td>
<td>Corex 1984</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nucor(^12)</td>
<td>HSmelt 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North Star(^13)</td>
<td>Tecnored 1998</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine supplier or engineer</td>
<td>D Voest + Voest(^14)</td>
<td>Corex 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICF Kaiser(^15)</td>
<td>licence Romelt 95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Midrex(^16)</td>
<td>HSmelt 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lurgi</td>
<td>Jupiter 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ausmelt Ltd(^17)</td>
<td>AusIron 1986</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tecnologos(^18)</td>
<td>Tecnored 1990</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research institute</td>
<td>MISA(^19)</td>
<td>Romelt 1980</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mining firm</td>
<td>NMDC(^20)</td>
<td>licence Romelt 00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRA(^21)</td>
<td>HSmelt 1981</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Auliron Energy(^22)</td>
<td>AusIron 1995</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is interesting to take a closer look at British Steel’s and Hoogovens’ arguments for becoming involved in smelting reduction technology. First of all, their arguments are fairly typical for the other integrated steel manufacturers. The promising reduction in the costs of producing a ton of hot metal made these firms go into action in 1986. The need to reduce costs guided R&D decisions. Secondly, it is almost paradoxical that the circumstances that allowed the start-up of the CCF development in 1989 later caused the CCF process to be shelved (in 1999).

In 1986, British Steel and Hoogovens started to develop the CBF process, a predecessor of the CCF process (see also Figure 3). Both firms were interested in developing this coal-based CBF process so that they could move away from reliance on coke ovens and avoid huge capital investments and the use of expensive metallurgical coals. Reducing the cost of a ton of hot metal was the major driving force. In 1989, R&D activities concentrated on CCF. The major argument for this change was that the cost advantage of the CBF process over the conventional route turned out to be modest. On the hand this was caused by the technology itself; agglomeration was still needed. But the improvements in the existing iron production route had also improved the coke situation in both firms. So in 1989 there was time left to switch R&D to a more explorative new process that promised even larger reductions in the cost price of hot metal by avoiding agglomeration of the ore. However, ongoing improvements in the existing coke ovens and blast furnaces in both firms eventually led to the shelving of the CCF process [Robson, 2000; Meijer, 2000; Boom, 1998; Dekker and Knol, 1996; Moors, 2000a].

The circumstances that permitted the switch from the CBF process to the CCF process in 1989 – in a way Hoogovens’ and British Steel’s ‘escaped to the future’ – turned out to be the major reason why integrated steel manufacturers lost interest in smelting reduction technology.

Table 3 gives an overview of the actors who ceased being active role in developing smelting reduction technology. If we compare Table 2 and Table 3 we conclude that it was primarily integrated steel producers who ended their involvement. The major argument was that they no longer had the need to replace obsolete conventional coke ovens (and possibly blast furnaces) early 21st century. And secondly, the integrated steel manufacturers, all of whom operated in industrialised countries, did not need additional ironmaking capacity [Sexton, 2000].

It became unnecessary to replace existing coke ovens and blast furnaces due to a number of reasons. The introduction of pulverised coal injection in the blast furnace reduced the need for coke in hot metal production in integrated steel works. Most of the integrated steel manufacturers invested in R&D concerned with pulverised coal injection at the same time as they were active in developing smelting reduction technology. This reduced the pressure on the existing coke ovens. Furthermore, the steel firms succeeded in upgrading and improving the existing coke ovens so that their lifetime could be extended. The possibility of importing coke from e.g. China further relieved the pressure on coke production. Furthermore, new and cleaner coke ovens were developed and offered for sale (and implemented). Finally, the existing
blast furnaces were also continually improved. This resulted in a higher productivity, longer lifetimes and a lower demand for coke for the production of hot metal. Not all these reasons were equally important for each of the integrated steel manufacturers in Table 3. However, all in all, the improvements in the existing capital stock and conventional technology were so large that the cost advantage of the innovative smelting reduction technology became smaller and smaller as time went on.

Table 3: Overview of actors’ arguments for stopping their R&D activities.

<table>
<thead>
<tr>
<th>Type of actor</th>
<th>Actor</th>
<th>Micro-network</th>
<th>Bankruptcy / Restructuring / Merger</th>
<th>No need to replace coke ovens</th>
<th>No need for additional or new capacity</th>
<th>Other capital investments</th>
<th>Capital investment / performance</th>
<th>Research completed</th>
<th>No (external) financial resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated steel-maker</td>
<td>Klöckner1</td>
<td>HIsmelt 1987</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Japanese firms2</td>
<td>DIOS 1996</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>British Steel3</td>
<td>CCF 1992</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoogovens4</td>
<td>CCF 1999</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>North-American firms5</td>
<td>DSM 1994</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stelco6</td>
<td>DSM 1995</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Usinor7</td>
<td>Jupiter 1994</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine supplier or engineer</td>
<td>ICF Kaiser8</td>
<td>licence Romelt 99</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Midrex9</td>
<td>HIsmelt 1994</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research institute</td>
<td>MISA10</td>
<td>Romelt 1980</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Lassat de Pressigny (2000), who led the development of the Jupiter process stated: “The current situation in coke oven and blast furnace operation shows that huge investments in smelting reduction process would have been premature. Smelting reduction was possibly studied at the wrong time”. Smith (2000), who has been well informed about the technology network since the technology network emerged (see
e.g. [Smith and Corbett, 1987]), phrased it like this: “To put it really simplistically\textsuperscript{15}: at the moment smelting reduction technology R&D efforts were started the technology was expected to be needed in 10 years. This has not changed”.

One of the integrated steel manufacturers did not stop its R&D activities. The Japanese firm NKK is still active in trying to commercialise DIOS technology. Kitagawa (2000) stated: “Only recently we engineered a revised process using DIOS \ldots, which attracted the interest of several steel makers. We are having intensive and serious discussions with them. Smelting reduction technology must be one of the right answers for the future”.

In general, however, integrated steel manufacturers stopped their activities because they could not foresee any opportunity for smelting reduction technology in the near future. The expenditure needed for developing the processes was simply too high to continue without any applications in sight [Meijer, 2000; Smith, 2000; Lassat de Pressigny, 2000; Kavanagh and Obenchain, 2000; Fruehan, 2000; Sexton, 2000].

How much money is spent and by whom?

Table 4 (see next page) summarises the expenditure on developing smelting reduction technology.

Table 4 does not indicate expenditure data for all micro-networks. The data available point to roughly 550 million US$. We estimate that the total expenditure lies somewhere between 600 and 700 million US$.

The expenditure for bringing strip casting technology towards commercialisation (per micro-network) is of a similar order of magnitude\textsuperscript{16} (see Chapter 5).

What important decisions are made with regard to the direction of technological development?

As was indicated before, the variety of smelting reduction processes is rather large. There is simply no single technological origin of smelting reduction technology. The technical roots are quite diffuse (see e.g. [Sarma and Fruehan, 1998; Anonymous, 1996a; Ritt, 1996]). Various micro-networks made rather deviant decisions regarding their R&D activities.

\textsuperscript{15} In the context of replacing existing blast furnaces in companies like his own (British Steel, UK). Additional ironmaking capacity is not required.

\textsuperscript{16} Note that over the last 15 years, the IEA/OECD countries spent on average 220 million US$ per year on industrial energy-efficiency R&D [IEA, 1997]. Annual expenditure on developing smelting reduction technology has been about 30 to 45 million US$ per year.
Table 4: Expenditure on R&D and government R&D support.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Corex</td>
<td>1,000</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>German Ministry of Research + Technology</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Austrian Research Promotion Foundation</td>
</tr>
<tr>
<td>Finex</td>
<td>150</td>
<td>40</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Romelt</td>
<td>450</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>USSR government</td>
</tr>
<tr>
<td>HIsmelt</td>
<td>300</td>
<td>200</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>tax deduction</td>
</tr>
<tr>
<td>CCF</td>
<td>400</td>
<td>18</td>
<td>7</td>
<td>40</td>
<td>European Coal and Steel Community</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ECSC</td>
</tr>
<tr>
<td>DIOS</td>
<td>500</td>
<td>150</td>
<td>100</td>
<td>67</td>
<td>MITI / DIOS R&amp;D programme</td>
</tr>
<tr>
<td>NKK</td>
<td></td>
<td>26</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>DSM</td>
<td>160</td>
<td>60</td>
<td>46</td>
<td>77</td>
<td>US Department of Energy / DSM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>6</td>
<td>70</td>
<td>US Department of Energy / waste oxides</td>
</tr>
<tr>
<td>Jupiter</td>
<td>8</td>
<td>&gt; 10</td>
<td>0.25</td>
<td>&lt;5</td>
<td>European Coal and Steel Community</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ECSC</td>
</tr>
<tr>
<td>AusIron</td>
<td>40</td>
<td>40</td>
<td>6.5</td>
<td>20</td>
<td>Australian Federal Government</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>South-Australian Government</td>
</tr>
<tr>
<td>Tecnored</td>
<td>50</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
<td>Brazilian government</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>550</td>
<td>165</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Estimated range</td>
<td></td>
<td>600 - 700</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 n.a. = no data available. Freydorfer (2001) and Shin (2000) do not comment [Anonymous, 1997d; Smith and Corbett, 1987]. 2 Valavin and Pokhvisnev (2000) do not comment. 3 Burrow (2000) does not comment. Estimate comes from [Badra, 1995] and [Cusack et al., 1995]. 4 Total expenditure includes the R&D activities of British Steel, Hoogovens and CSM performed in three ECSC supported projects [Meijer, 2000; Robson, 2000; Cordis, 2000]. 5 [Furukawa, 1994; Kitagawa, 2000]. 6 The DSM R&D programme evolved into a programme that used the pilot facility for testing the reduction of waste oxides. AISI is obliged to repay DOE’s contribution from the net proceeds of commercialisation (R&D support + 50%). If AISI refuses to commercialise the DSM process, the patent rights are forfeited to DOE [Kavanagh and Obenchain, 2000]. 7 Usinor acquired ECSC support for one project (1992-1995). This project’s budget was less than 5% of Usinor’s total expenditure [Lassat de Pressigny, 2000; Cordis, 2000; Birat, 2000]. 8 [Floyd, 2000; Sherrington, 2001]. 9 [Poos, 1983].

Looking at the energy-efficiency of the various processes, we can distinguish three categories\(^\text{17}\). The first category consists of the Corex process. Its high-degree of pre-reduction, makes it a relatively energy-intensive process. The second category consists of second generation processes, which consist of one vessel; these are the processes known as Romelt, Ausmelt and Tecnored. They tend to have a high specific energy consumption [Sarma and Fruehan, 1998; Chatterjee, 1994; Anonymous, 1996a]. The third category includes second generation processes, which consists of a pre-reduction unit and a smelting reduction vessel; such as HIsmelt, DIOS, CCF and DSM\(^\text{18}\). These four ‘converter-based’ processes aim to optimise the

\(^{17}\) The Jupiter process does not fit into any of these categories (see e.g. [Poos, 1993]).

\(^{18}\) Note that the HIsmelt process can also operate as a one-vessel process. The productivity/economics improve significantly by coupling it to a pre-reduction unit. Note that the CCF process consists of one vessel. However, in the vessel a pre-reduction zone (the cyclone) and a smelting reduction zone can be distinguished. The difference between CCF and the other one-vessel processes is that in CCF the degree of post-combustion can be controlled.
exchange of heat, which is generated by post-combustion, back into the smelting reduction vessel [Scott, 1994].

The preference of various actors for the different processes can be explained by their earlier (R&D) experiences with (parts) of the smelting reduction processes. Both Deutsche Voest and Voest sold natural-gas-based direct reduction technology. They were thus familiar with the ‘shaft furnace’ they adopted as a pre-reduction unit. They were also familiar with highly pre-reduced iron. All three one-vessel processes, Romelt, AusIorn and Tecnore, derived from an ‘existing’ smelting technology. The actors had been involved in developing these preceding smelting processes [Floyd, 2000; Poos, 1993; Pokhivisnev, 2000]. The four ‘converter-based’ second generation smelting reduction processes all evolved from integrated steel manufacturers’ experiences with converter operations (e.g. the addition of coal in steel converters to increase scrap processing) [Smith and Corbett, 1987; Brotzmann, 1992; Robson, 2000]. These converter-based second generation smelting reduction processes are the most interesting from an energy-efficiency point of view. To decrease coal input by optimising heat exchange was an explicit R&D criterion in developing these processes. However, in two of these micro-networks R&D activities were stopped. The application of the H1smelt process by the US mini-mill operator Nucor would not be an energy-efficient application if hot metal is replacing scrap. It remains to be seen whether and where NKK succeeds in commercialising the DIOS process.

**Resumé**

Smelting reduction technology is not yet a proven technology. Only one of the nine micro-networks succeeded in bringing a specific smelting reduction process to the market, although this specific process lacks general applicability and has a high specific energy consumption. In five of the eight additional micro-networks R&D activities are still going on. However, the composition of the technology network has changed over time. Most of the integrated steel manufacturers who played an active role in various micro-networks lost interest in smelting reduction technology. Existing blast furnaces and coke ovens were continually improved and the lifetimes of the existing stock was extended. The threat that obsolete coke ovens and blast furnaces would have to be replaced did not (yet) come true. They did not need an expansion of their iron production capacity. Smelting reduction technology was ‘locked out’ by a

---

19 In 1998, IISI expected that the specific energy consumption of smelting reduction technology would be of the same order of magnitude as an optimised blast furnace. Dispensing with coke ovens and sinter plants makes smelting reduction technology overall more energy-efficient [IISI, 1998].

20 If a smelting reduction unit is implemented in a mini-mill, hot metal can be supplied to an electric arc furnace, so that the furnace’s power consumption for melting the raw material will decrease. Its productivity will increase. It overall specific energy consumption will increase if it replaces scrap as raw materials. If hot metal replaces direct reduced iron (DRI), specific energy consumption is likely to decrease slightly.
continuous, incremental improvement of the conventional production route and the existing capital stock. However, the future of smelting reduction technology is still undecided; actors like mining firms continue to be interested and there is a growing interest of mini-mill steel operators. Application of smelting reduction technology in mini-mills may be a short-term niche for proving the feasibility of some of the smelting reduction processes. A successful introduction of smelting reduction technology in mini-mills may enhance the market position of the mini-mill route.

6.4. The effect of government intervention

In this section we focus on the effect of government intervention on the development of smelting reduction technology. We analyse the effect of environmental regulation and government R&D support. We discuss the role of stimulating co-operation in various multi-actor micro-networks. Finally, we focus on the support that government intended to give in connection with the building of two demonstration facilities.

Environmental regulations

In countries like the US, Canada, Japan, Australia and in Western Europe industry is confronted with regulations regarding environmental emissions in the production of iron. Coke ovens and sinter plants are most affected [Hogan and Koelbe, 1994; EIPPCB, 1999; Prabhu and Cilione, 1992]. The environmental advantage of smelting reduction technology over the conventional route is generally articulated by all actors involved in developing smelting reduction technology (see e.g. [Sexton, 2000; HIsmelt, 2000; VAI, 2000; AISI, 1998; Weston and Thompson, 1996]).

We asked the experts whether the environmental emissions had been a decisive argument for initiating or performing R&D activities. The need to comply with environmental regulations was usually indicated as one of the factors leading to the cost advantage of the smelting reduction technology over the conventional blast furnace route. If smelting reduction technology were be applied, other environmental investment would not be needed. However, this incentive would never have been large enough to initiate huge and technologically complex R&D efforts such as the development of smelting reduction technology21. As was indicated before, avoiding capital expenditure and using cheaper coals were the two main factors in favour of

21 The importance of such environmental regulations in driving R&D differs among the technologies under development. Hoogovens was the first to apply Emission Optimised Sintering (EOS) technology on a commercial scale primarily because it had to reduce environmental emissions of sulphur dioxide and nitrogen oxides. Lurgi (Germany) originally developed EOS. EOS allows the reuse of the flue gas that is released during the sintering process (agglomeration of iron ore). The investment in the EOS facility was easily recouped through savings on energy costs [Meijer, 2000; Moors, 2000a].
smelting reduction technology. The environmental advantage of smelting reduction processes was clearly taken into account, although it was a modest part of the overall (cost) considerations [Smith, 2000; Kavanagh and Obenchain, 2000; Kitagawa, 2000; Robson, 2000; Meijer, 2000].

Waste disposal regulations in the US are such that land-filling is increasingly taxed [Weston and Thompson, 1996; Anonymous, 1996c; Kavanagh and Obenchain, 2000; Thompson, 2000]. This tax on waste disposal makes it attractive for integrated steel manufacturers to recycle waste material from steel sites. It is interesting to note the following two observations from the empirical material.

First of all, the US engineering firm ICF Kaiser International tried to enter this ‘niche’ of recycling waste oxides. They wanted to offer a smelting reduction process as a commercial product in their engineering activities. Although ICF Kaiser did not succeed in applying the Romelt process on a commercial scale22, this example shows that actors actively use niches created by government intervention for extending and strengthening their business.

Secondly, these waste disposal regulations were influential in the continuation of the co-operative R&D programme for developing the DSM process. At the end of the R&D programme in 1994, the steel association managed to mobilise R&D support from the government for continuing R&D activities. In view of the fact that the steel firms were not really enthusiastic about up-scaling the DSM process, continuation of R&D was an non-committal next step [Thompson, 2000; Ritt, 1998b; Nelko, 1994; Fruehan, 2000]. Continuing R&D was a fruitful strategy in postponing large capital investments.

With regard to the effect of regulations we come to the following conclusions:
- Environmental regulations were not critical in initiating the development of smelting reduction technology, nor did they affect the R&D decisions taken. However, they provided researchers and engineers within a firm with an additional argument for continuing R&D.
- Environmental regulations were not selective. They did not favour the development of smelting reduction technology over the conventional technology (nor did they prevent steel firms from investing in new coke ovens)23.

**Government R&D support**

We now look more closely at what effect government R&D support had on stimulating the development of smelting reduction technology. Government

---

22 ICF Kaiser acquired a licence for the Russian Romelt process in 1995. ICF tried to sell the Romelt process by claiming it could process waste disposal and waste oxides in integrated steel plants [Weston and Thompson, 1996]. There are a number of reasons why ICF Kaiser’s attempt failed. The process turned out to be a ‘rough diamond’. The process required further development. ICF Kaiser did not have the financial resources. They did not succeed in finding a partner. Furthermore, the steel industry itself was reluctant to invest in high-risk projects [Thompson, 2000].

23 See [Lassat de Pressigny, 2000; Birat, 2000; Kavanagh and Obenchain, 2000; Ritt, 2000]).
supported R&D activities financially in eight of the nine micro-networks (see second column in Table 5). Two micro-networks received R&D support through the Research Technology and Demonstration programme of the European Coal and Steel Community (ECSC). The budget for the RTD programme comes from a levy on the steel price, so it is not government R&D support in a strict sense. Table 4 gives a more detailed account of government’s contribution to the total expenditure in the separate various micro-networks. Table 4 shows that government support has been substantial in developing the DIOS process, the CCF process and the DSM process.

For evaluating the effect of government R&D support on the development of smelting reduction technology, we make a distinction between additionality, acceleration and effectiveness. Additionality indicates whether R&D support led to activities that would not have been undertaken without government R&D support. Acceleration indicates whether R&D support led to an accelerated materialisation of the technology within the entire technology network. Effectiveness indicates whether the innovative smelting reduction process may lead to improvements in energy-efficiency once the technology is applied commercially.

<table>
<thead>
<tr>
<th>Micro-network</th>
<th>Was there external R&amp;D support?</th>
<th>Did R&amp;D support lead to additional R&amp;D activities?¹</th>
<th>Did support lead to an acceleration of the technology’s development?</th>
<th>Will the process improve energy-efficiency?</th>
<th>Scale of the process</th>
<th>Micro-network still active?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corex / Finex</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>No</td>
<td>Pilot</td>
<td>Innovation</td>
</tr>
<tr>
<td>Romelt</td>
<td>Yes</td>
<td>Yes²</td>
<td>No</td>
<td>No</td>
<td>Pilot</td>
<td>Yes</td>
</tr>
<tr>
<td>HIsmelt</td>
<td>No</td>
<td>-</td>
<td>-</td>
<td>Likely</td>
<td>Pilot</td>
<td>Yes</td>
</tr>
<tr>
<td>DIOS</td>
<td>Yes</td>
<td>Very likely</td>
<td>Maybe</td>
<td>Likely</td>
<td>Pilot</td>
<td>Yes</td>
</tr>
<tr>
<td>CCF</td>
<td>Yes</td>
<td>Yes²</td>
<td>No</td>
<td>Likely</td>
<td>Pilot</td>
<td>No</td>
</tr>
<tr>
<td>DSM</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Likely</td>
<td>Pilot</td>
<td>No</td>
</tr>
<tr>
<td>Jupiter</td>
<td>Yes</td>
<td>No²</td>
<td>-</td>
<td>Likely</td>
<td>Lab</td>
<td>No</td>
</tr>
<tr>
<td>AusIron</td>
<td>Yes</td>
<td>Yes²</td>
<td>No</td>
<td>No</td>
<td>Lab</td>
<td>Yes</td>
</tr>
<tr>
<td>Tecnored</td>
<td>Yes</td>
<td>n.a.</td>
<td>n.a.</td>
<td>No</td>
<td>Lab</td>
<td>No</td>
</tr>
</tbody>
</table>

¹ Assessment based on [Freydorfer, 2001; Burrow, 2000; Floyd, 2000; Lassat de Pressigny, 2000; Meijer, 2000; Robson, 2000; Fruehan, 2000; Ritt, 2000; Thompson, 2000; Kitagawa, 2000; Kavanagh and Obenchain, 2000]. ² The Romelt process was developed in the former USSR. When the USSR collapsed, government R&D support came to an end [Valavin and Pokhvisnev, 2000; Thompson, 2000]. ³ R&D support through the European Coal and Steel Community (ECSC). ⁴ The South Australian government has a direct stake in the SASE joint venture which is responsible for developing the AusIron process. The ministry for Mines and Energy of South Australia is no longer a partner in SASE, though the joint venture owns the rights to explore the government’s iron ore deposits [Floyd, 2000; Meekatharra, 1998].

Additionality
The assessment of the additionality of R&D support is a first and crucial step. We asked experts about the importance of external support in initiating and continuing
R&D support. We tried to verify their statements by asking other experts. We were able to understand and evaluate experts’ responses in the light of their arguments for investing in R&D and of their drive for up-scaling the technology. The second column in Table 5 shows our assessment.

It is plausible that in five of the eight micro-networks R&D support was additional; in these micro-networks government R&D support has been important in initiating or continuing R&D activities. As is indicated in Table 5, in two of these micro-networks external support was ‘special’. The Russian Romelt process was developed in the former USSR. In the case of the AusIron process, the South-Australian government wanted to exploit its iron ore deposits and generate added-value economic activity in the region.

In both the North American and Dutch micro-networks, R&D support was important in starting and continuing the R&D activities. The US government played an active role in establishing the legal framework which allowed co-operative R&D programmes. The R&D programme for developing the DSM process was one of these. The Steel Initiative of the US Department of Energy stimulated co-operative R&D between public and private actors to support the deteriorated R&D in the steel industry [Kavanagh and Obenchain, 2000; Sharkey, 1998]. The financial support was a motivating factor for the actors – AISI, the steel firms and some research institutes – to get together and initiate R&D [Kavanagh and Obenchain, 2000]. The ECSC support had an additional role in the development of the CCF process. Cost sharing by the ECSC made it easier to continue R&D at the moment when British Steel and Hoogovens ceased the development of the CBF process and continued with the CCF process in 1989 [Meijer, 2000; Robson, 2000].

With regard to the Japanese micro-network, it is likely that government R&D support led to additional R&D activities. Government R&D support allowed the micro-network of Japanese integrated steel manufacturers to continue former private R&D activities and to build a pilot scale facility on a reasonable scale. After the co-operative DIOS R&D programme was finished NKK continued. The comments of NKK’s Kitagawa illustrate that it is not easy to assess additionality. Kitagawa (2000) states that NKK ‘probably’ would not have continued R&D either. “The reason why I write ‘probably’ is that when we carried out our own development we were in the middle of an economic bubble. So we might have spent additional budget to demonstrate the process” [Kitagawa, 2000].

**Acceleration**

We can assess whether R&D support accelerated a technology’s development by comparing the materialisation of a specific process within the framework of the entire technology network. Only the Corex process achieved innovation (see column six in Table 5). Corex, however, is a first generation process.

If we leave out the Corex process, it is rather difficult to assess whether government R&D support did actually accelerate the materialisation of the technology, because the majority of the efforts has not reached the scale of a demonstration facility and,

---

24 It took two years to develop the proposal for the R&D programme.
more importantly, a number of efforts were stopped. The HIsmselt process and the
DIOS process are the most likely to become a near commercial facility in the next
few years (although no firm decisions have been taken yet). The HIsmselt process was
developed without any government R&D support. Because the R&D efforts in
developing the DSM process and the CCF process have both been shelved, it is only
in the case of the Japanese R&D activities that government R&D support may
possibly result in ‘accelerated’ development of the second generation processes.

Effectiveness
Finally we take a look at the effectiveness of R&D support. An evaluation in terms
of energy-efficiency is still speculative; most of the processes did not prove
operation on a near commercial scale. We conclude that government had an
additional effect on three of the five micro-networks that were developing smelting
reduction processes that were likely to be energy-efficient (if it may come to
commercial application).

With regard to the effect of government R&D support we conclude that:
- Government R&D support enlarged the technology network, but did not
  accelerate technology development. Government R&D support did not play an
  additional role in developing the two processes that had reached the most
  advanced stage of materialisation so far.
- However, government did play an additional role in expanding the number of
  micro-networks that invested in developing smelting reduction processes and that
  were likely to be energy-efficient.

Stimulating co-operation
The DSM and DIOS micro-networks received substantial R&D support from the US
and Japanese government, namely 75 and 67% respectively. In both these micro-
networks a large number of actors in a competitive relationship, co-operated. The
CCF micro-network received substantial support from the European Coal and Steel
Community’s RTD programme, roughly 40%. The ECSC’s RTD programme
stimulates co-operative projects and also obliges the participants of various
supported projects to meet and exchange R&D results. Because stimulating co-
operation is widely acknowledged as an interesting way for stimulating technological
development, these ‘network’ aspects of R&D support in this case study are
commented upon briefly.

As was already indicated, the so-called Steel Initiative in the US made it possible for
the Department of Energy to stimulate co-operative R&D between public and private
actors. The philosophy was that co-operation among steel manufacturers and
research institutes would enhance the effect of the public money spent. In the case of
the DSM R&D programme, the possibility of co-operation seemed to provide an
opportunity to explore the possibilities of the technology (at a relatively low cost
stake for each of the separate firms). The actors were not really seriously interested in investing in the commercialisation of the technology [Freuhan, 2000; Thompson, 2000; Ritt, 1998b].

The Japanese co-operative R&D programme relating to DIOS allowed the Japanese integrated steel manufacturers to continue their earlier private R&D activities [Kitagawa, 2000; Meijer, 2000; Fruehan, 2000; Anonymous, 1997a]. Earlier ideas gained from their private R&D activities and the needs of individual firms were included in the R&D programme. NKK proposed the basic layout of the DIOS process. NKK also hosted the pilot facility. NKK was eager to acquire know-how concerning plant engineering and the operation of the process [Kitagawa, 2000]. Currently NKK is the only one of the eight Japanese integrated steel manufacturers who is seriously pursuing further commercialisation of DIOS. In the words of the engineer who is leading the activities at NKK: “The other Japanese steel firms know how important such tacit knowledge is in constructing and operating the facility. ... DIOS will die as the people who have the knowledge hidden in their heads retire from NKK. We thus have to commercialise the technology as early as we can. ... Probably the other steel firms simply observe what NKK does and they may ask NKK to transfer the technology in the end” [Kitagawa, 2000].

The example of the co-operative DIOS R&D programme illustrates that the firm which was one of the proponents of the DIOS R&D programme is also the one who continued activities after the co-operative R&D activities had finished. Such firms appear to play a decisive role in the continued effect of the co-operative R&D programme in terms of accelerating its development.

The European integrated steel manufacturers British Steel, Hoogovens and Ilva knew each other through regular meetings of the ECSC’s RTD programme. They had also co-operated in earlier projects that were supported by the ECSC. Experts see this set up with meetings and exchange of views as a positive aspect of the RTD programme. It promotes contacts with other firms because you know the people you may address. Steel firms apply for ECSC support typically in pre-competitive stages of a process development when it is attractive to share expertise and equipment and to learn [Meijer, 2000; Robson, 2000].

The requirement of contacts and exchange between the firms participating in the RTD programme make these firms decide to do without ECSC support when projects reach a more strategic stage of development. However, the RTD programme allows firms to meet other actors who have similar R&D interests and R&D experiences. There is a ‘pool’ of actors who can meet and initiate explorative projects.

It is also interesting to see the role of government in the HIs melt micro-network. The Australian mining company who took the lead in developing the HIs melt process had an agreement with the Australian government. CRA’s right to develop the ore deposits was accompanied by the obligation to consider technologies that could lead to processing operations like the production of iron or steel. This obligation was subject to technical and economic viability tests [Burrow, 2000; Dry et al., 1999; Prideaux, 1996; Innes, 1995]. Whereas Innes (2001) indicates that CRA would have
undertaken the activities towards exploring smelting reduction without this government obligation, it did govern CRA’s thinking concerning appropriate technologies. In the case of Hoogovens’ CCF process there was a similar sense of commitment, this time to the Dutch government (due to the voluntary agreement on industrial energy-efficiency improvement) [Meijer, 2000].

Apparently firms feel committed to agreements they make with government. Naturally firms will put their own interests first when establishing such agreements, but if they feel a certain commitment to and a positive relationship with government, they are likely to consider the agreements seriously. Such agreements and commitments are not easily thrown overboard.

Although the evidence from this case study is not very strong, we feel justified in making the following suggestions about how government can stimulate networks and co-operation and maintain relationships with firms:

- The effect of co-operative R&D programmes in terms of accelerating a technology’s development depend strongly on actors’ intentions to participate in such co-operative R&D programmes.
- If government stimulates network formation and knowledge exchange it is important that firms or other actors in the target group can really learn from each other’s experiences.
- If one-to-one agreements are made with firms, specific topics can be anchored in a firm’s (R&D) agenda. Without harming their business stakes, firms appear to take their relationships with government seriously.

Government support for demonstration

In two micro-networks, government intended to give support in connection with the building of two demonstration facilities. In both micro-networks government’s contribution was legitimised by the wish to improve the energy efficiency of iron production [Kavanagh and Obenchain, 2000; Meijer, 2000]. We describe briefly why neither of these plans was ever realised and comment on the importance of ‘energy efficiency’ as an argument for integrated steel firms to invest in these demonstration facilities.

In North America, there was talk of building a demonstration facility at one of Stelco’ steel sites in Canada. Stelco was interested in a demonstration facility that could process the firm’s waste oxides [Ritt, 1998b; Anonymous, 1996d]. The demonstration facility was to cost 160 million US$. The US Department of Energy, the Canadian government and Stelco were to contribute 33% each [Kavanagh and Obenchain, 2000]. The US Department of Energy had to withdraw the warranted R&D support when the US Congress became Republican in 1994. As a result the whole demonstration facility was cancelled. Stelco could not find another firm willing to co-invest, nor was it willing to increase its own investment. None of the North American steel firms really felt the need to invest so much risk capital in a
non-proven technology [Fruehan, 2000; Kavangah and Obenchain, 2000; Meijer, 2000; Thompson, 2000].

In the Netherlands since 1997 there has been talk of building a demonstration facility at the Hoogovens’ steel site in Ijmuiden. From 1995 onwards, Hoogovens’ intention was to realise such a demonstration facility. Hoogovens started looking for a partner to co-invest. First, Hoogovens tried to join in with the plan for a demonstration facility in North America after all they needed a partner who could deliver the smelting reduction vessel to complement their CCF pre-reduction unit. They failed. In 1997, the Dutch government announced an intensification of Dutch climate policy in the so-called the CO₂ Reduction Plan. The large amount of financial support made Hoogovens apply for a demonstration facility in Ijmuiden [Meijer, 2000]. Hoogovens was awarded 30 million US$, about 25% of the total expenditure required. Hoogovens had a similar budget available. There was thus still a financial gap of roughly 60 million US$. There were serious contacts with the actors developing the HIsmelt process. Once again, finance turned out to be the bottleneck. No firm wanted to increase its expenditure [Meijer, 2000; Burrow, 2000]. In March 1999, it was formally announced that the development of the CCF process had come to a halt for reasons already discussed.

In both micro-networks government support for the demonstration facilities was legitimised by claims on an improved energy-efficiency [Fruehan, 2000; Meijer, 2000; Moors, 2000a]. The steel firms were primarily interested in reducing the cost of a ton of hot metal (whether using iron ores or waste oxides). Improvements in energy-efficiency alone would never have been a big enough incentive for Stelco and Hoogovens to invest in such a high-risk (and capital intensive) demonstration facility [Kavanagh and Obenchain, 2000; Meijer, 2000; Moors, 2000b].

Regarding the question of whether government can successfully contribute to the realisation of demonstration facilities we come to the following conclusions:
- The amount of government support can trigger a firm’s interest in building a demonstration facility (even if the project is strategic).
- Government and steel firms’ arguments for investing in a demonstration facility differed; governments interests in energy-efficiency was only part of the overall cost considerations of the steel firms. In spite of such differences, government involvement can be additional in building a demonstration facility.
- The empirical material shows that at this stage of technological development when firms are hesitant steering is an appealing, though highly complex task. On the one hand government support can be additional and - possibly - greatly accelerate a development. On the other hand there is a substantial budget of public money at stake. Firms were rather reluctant to commit themselves,

25 The Dutch government set aside a major budget for concrete investment projects that would lead to the immediate reduction of CO₂ emissions. In spite of the fact the CCF process was not yet in at the stage of a commercial scale investment project that would lead to immediate CO₂ reductions government support was granted. In the contract with the Dutch government Hoogovens committed themselves to investment in a commercial facility if the demonstration facility was to operate satisfactorily and if the process was to be economically feasible [Meijer, 2000].
because large-scale investment decisions affect the daily business routine of steelmaking operations. Many factors are beyond government control and these may thwart the plans for demonstrating an innovative technology. In giving a firm and a specific technology a preferential treatment government should be well aware of the technical, economic and energetic consequences and opportunities.

6.5. Conclusion

Smelting reduction technology is widely acknowledged as an important innovative technology that can improve the energy efficiency of iron production. In this chapter we have evaluated the effect of government intervention on the development of smelting reduction technology. We investigated in detail the composition of and the changes in the networks developing this specific energy-efficient technology. We increased insight into actors’ arguments for being involved in the development of this innovative technology and thus found out how government intervention affected actors’ R&D decisions.

The network
Our network analysis has illustrated the various roles played by integrated steel manufacturers and mini-mill steel operators. Whereas several integrated steel manufacturers in industrialised countries were active in developing smelting reduction technology most of them lost interest. The innovative technology was ‘locked out’ by a continuous improvement of the existing ironmaking facilities. In addition the integrated steel manufacturers did not need to expand the existing ironmaking capacity. Mini-mill operators typically did not invest in the development of such core process high-risk technologies, but recently some mini-mill operators have shown interest in smelting reduction technology. Although application of smelting reduction technology in integrated mills has probably been postponed for at least ten years, application of smelting reduction in mini-mills may be a first niche application for proving the feasibility of smelting reduction technology. However if hot metal replaces processing of scrap, the production of steel in mini-mills will become more energy-intensive.

Government intervention
Various national governments and the European Coal and Steel Community played an active role in stimulating the development of smelting reduction technology. We estimate that 20 to 25% of the total expenditure needed for smelting reduction technology was supplied by various national governments or by the ECSC. The interesting questions are whether government support resulted in additional activities, whether it accelerated technological development and whether it might results in a lower consumption of energy for future production of iron.
We conclude that government R&D support enlarged the technology network. In five of the nine micro-networks, government R&D support definitely underpinned the performance of additional R&D activities. Three of these five micro-networks developed a smelting reduction process that is likely to be energy-efficient. We use the term ‘likely’ because the micro-networks are not yet ready to commercialise the technology. Two of these micro-networks have even shelved their efforts. Therefore, we must conclude that whereas government R&D support was additional, so far it has not accelerated technological development.

We have also seen that a commitment by government to support a demonstration facility can be a factor that persuades a firm to demonstrate a technology. Steering in this stage of a technology’s development may be an appealing, though highly complex task. In giving a firm and a specific technology a preferential treatment government should carefully assess whether support may accelerate technological development (in the international technology network).

In addition to financial support, environmental regulations were not decisive in initiating or continuing R&D efforts. Reducing environmental emissions – and also improvements in energy efficiency – were only additional reasons for integrated steel firms to be interested. However, they provided researchers and engineers within a firm with an additional argument for continuing R&D.

All in all, the case study illustrates that integrated steel firms tend to constrain technological development so that it prefers certain – more incremental – directions. The existing capital stock was continuously improved which caused a decrease in the cost advantage of the innovative energy-efficient technology. This mechanism considerably limited the effect of government intervention and R&D support.

Acknowledgements
Frauke Spaan is thanked for her valuable preliminary analysis of the historical R&D development of smelting reduction technology (see [Spaan, 2000]). The authors wish to thank all the experts for taking time to respond to the questions. We would also like to thank Mr. Burrow (Hlsmelt Corporation, Australia), Mr. Innes (formerly working at CRA, Australia), Mr. Valavin and Mr. Pokhvisnev (both MISA, Russia), Mr. Kitagawa (NKK, Japan), Mr. Smith and Mr. Robson (both Corus / formerly British Steel, UK), Mr. Meijer (Corus / formerly Hoogovens, The Netherlands), Mr. Obenchain (AISI, US), Mr. Kavanagh (AISI, US), Mr. Birat (IRSID / Usinor, France), Mr. Floyd (Deputy chairman, Ausmelt Ltd., Australia), Mr. Sherrington (Ausmelt Ltd., Australia), Mr. Freydorfer (VAI, Austria) and Mrs. Moors (Utrecht University, The Netherlands) for making useful comments on a draft version of this article. Financial support form the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP / RIVM, Bilthoven, The Netherlands) is gratefully acknowledged. Finally, the authors also thank Sheila McNab for her linguistic help.
References


Arthur D. Little (1998), Breakthrough industrial energy conservation technologies. Phase 2 – Promoting development and implementation, reference no. 34533, Rotterdam.


EIPPCB (1999), Best Available techniques reference document on the production of iron and steel, European Integrated Pollution Prevention Bureau (EIPPCB), European Commission, Brussels.


IWG (2000), Scenarios for a clean energy future, Inter-National Laboratory Working Group (IWG), ORNL/CON-476 / LBNL-44029, Oak Ridge National Laboratory / Lawrence Berkeley National Laboratory, Oak Ridge / Berkeley, US.


Poos, A. (1993), Present status of alternative ironmaking technologies, Centrum voor Research in de Metallurgie (CRM), S 14/93, Luik, Belgium.


SAIL (2000), Engineering services for Romelt project for M/s NMDC, Centre for Engineering & Technology, engineering and consultancy unit of the Steel Authority of India (SAIL), www.sailcet.com/romelt.htm, December 12th 2000.


Smith, R.B. (2000), personal communication, director Teesside Technology Centre, Corus (formerly British Steel), Cleveland, UK, November 22nd 2000.


