The EPRI Center for Materials Production

An Economic Analysis of TFIH Annealing of Carbon Steel Sheet

A Summary Analysis of the Economics and Environmental Impact of Transverse Flux Induction Heating (TFIH)

Prepared by

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The EPRI Center for Materials Production

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R E P O R T   S U M M A R Y

SUBJECTS	Transverse flux induction heating of metals/annealing of steel/heat treating of steel
TOPICS	Transverse flux induction heating Steel industry Annealing of sheet Heat treating of metals Induction heating
APPLICABLE SIC CODES	3316, 3398
AUDIENCE	Steel mill operators, utility marketing, customer service engineers, researchers

An Economic Analysis of TFIH Annealing of Carbon Steel

This report presents a summary of the results of an economic and environmental impact analysis by Hatch Associates of TFIH annealing of carbon steel sheet.

BACKGROUND

The cold-rolled sheet and strip market for the important commercial metals, such as carbon steel, stainless steel, aluminum, and copper, exceeds 50 million tons per year. During production of these materials they are reduced to final gage by cold rolling, followed by annealing in order to restore ductility and permit fabrication into finished products such as automobiles, appliances, and steel buildings.

The majority of annealing furnaces in operation today are gas-fired. A developing technology, transverse flux induction heating (TFIH) offers an alternative to gas-fired furnaces for continuous annealing of sheet and strip products. The annealing of aluminum with TFIH is commercial and is presently being used in Japan and Europe. A recent EPRI-sponsored project in injunction with Allegheny Ludlum and Ajax Magnethermic showed TFIH to be an attractive technology for annealing stainless steel. The largest sheet market however, is carbon steel. About 30 million tons of cold-rolled and coated carbon steel is annealed annually. Development of TFIH annealing for this market would mean a large new load for EPRI Utilities as well as potential benefits for steel mills.

OBJECTIVES

The purpose of this project was to examine the economic feasibility of TFIH for annealing carbon steel.

APPROACH

Recognizing the possible advantages that TFIH annealing of carbon steel may offer over conventional gas-fired annealing, The EPRI Center for Materials Production funded a project with Hatch Associates to evaluate the economics of TFIH annealing under the following conditions.

1) New continuous TFIH annealing line versus new box-annealing.facility.
2) Replacement of existing box annealing facility with new TFIH installation.
3) TFIH replacement for gas-fired section of in-line anneal on a hot-dip

galvanizing line.

4) Use of TFIH annealing for titanium treated interstitial-free carbon steel (IF) to eliminate overaging step required when processing a regular low-carbon steel.
5) Evaluation of the impact of TFIH on the environment.

RESULTS/ PERSPECTIVE- The results of the study showed that at present anew continuous TFIH annealing installation was not economically attractive compared to hydrogen box-annealing because of higher capital cost. Similarly, retrofitting an existing box-annealing facility is not economically feasible because of the high capital cost of the TFIH system and mechanical equipment. The overaging zone required for annealing regular low-carbon steel by a continuous TFIH annealing process can be eliminated with the use of IF steel. However, this would only reduce capital costs associated with the TFIH process by 10% while increasing steel cost $25/ton.

A possible niche application that appears promising is replacing or supplementing the in-line gas-fired furnace of a continuous hot-dip galvanizing line with TFIH. Other potential niche areas of application for TFIH annealing, but not included in this study are producing high-strength steels for automotive applications and producing certain electrical steels. Neither of these steel products would require an overaging treatment which increases capital costs. TFIH may also be useful in boosting the capacity of gas annealing lines by supplying extra heating in a limited space.

While TFIH annealing itself results in no emissions, total environmental impact of TFIH plus required electricity generation offers no benefits over natural gas based processes with regard to air emissions based on the current mix of power generating fuels.

It is concluded from this study that TFIH annealing can best compete against gas-fired annealing in the production of stainless steel, aluminum, copper, and brass as these metals do not generally undergo a phase change and thus do not require an overaging step in the annealing process as is the case for regular low-carbon steel.

PROJECT RP 3243
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AN ECONOMIC ANALYSIS OF TFIH ANNEALING OF CARBON STEEL SHEET

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ABSTRACT

Recognizing the potential advantages that transverse flux induction annealing (TFIH) may offer over conventional gas-fired annealing of carbon steel, The EPRI Center for Materials Production funded a project with Hatch Associates to evaluate the economics of annealing. The results of the study showed that TFIH continuous annealing was not economically attractive compared to hydrogen box annealing for either anew installation or the retrofit of an old facility because of higher capital cost TFIH annealing with required generation of electricity offers no benefits over natural gas based processes with regard to air emissions based on the current mix of generating fuels.

Possible niche applications that did appear promising for TFIH include replacing or supplementing the in-line gas-fired furnace of a continuous hot-dip galvanizing line. Other areas of potential application for TFIH annealing include producing high-strength steels for automotive applications and certain electrical steels. Research and development programs would be required to develop these applications.

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Section 1

SUMMARY

The study examines the economic feasibility of transverse flux induction heating (TFIH) for annealing low carbon steel. Capital and operating rests were generated for four cases using TFIH and comparing it with existing or new gas-fired annealing facilities. Also, the effect of energy prices on the economics was considered and the impact of TFIH and energy conversion on the environment was assessed.

The resulits of the study show that constructing a new TFIH installation is not economically attractive when compared to hydrogen batch annealing because of higher capital investment. A replacement of an existing conventional batch annealing facility yields some operating cost savings but the payback time is still high. The overaging zone required for annealing regular low-carbon steel by a continuous TFIH annealing process can be eliminated with the use of IF steel. However, this would only reduce capital costs associated with the TFIH process by 10% and have minimal impact on the payback time. Further, IF steel would cost an additional $25/ton.

A possible niche application that appears promising is replacing or supplementing the in-line gas-fired furnace of a continuous hot-dip galvanizing line with TFIH. Other niche areas of potential application for TFIH annealing, but not included in the study, are producing high-strength steels for automotive applications and producing certain electrical steels. Neither of these steels would require an overaging treatment which increases capital costs. TFIH may also be useful in boosting the capacity of gas annealing lines by supplying extra heating in a limited space.

While TFIH annealing itself results in no emissions, total environmental impact of TFIH plus required electricity generation offers no benefits over natural gas based processes with regard to air emissions, based on the current mix of power generating fuels.

It is concluded from this study that TFIH annealing can best compete against gas-fired annealing in the production of stainless steel, aluminum, copper, and brass as these metals do not undergo a phase change and thus do not require an overaging annealing step which is the case with regular low-carbon steel.

Section 2

INTRODUCTION

The cold-rolled sheet and strip market for the important commercial metals, such as carbon steel, stainless steel, aluminum, and copper, exceeds 50 million tons per year. These materials are reduced to final gage by cold rolling, followed by annealing in order to restore ductility and thereby permit fabrication into finished products such as automobiles, appliances, and steel buildings. Although, continuous annealing of sheet products is the preferred method for annealing sheet and strip, substantial quantities of these materials, particularly carbon steel sheet and strip, are still being box annealed. The majority of the box-annealing furnaces are gas-fired, with a smaller number being heated by electric resistance. A developing technology,transverse flux induction heating offers an alternative to gas-fired furnaces for continuous annealing of sheet and strip products.

Induction Heating

The most common induction heating method is solenoidal flux induction heating. Figure 2-1 shows a solenoid induction coil surrounding the metal strip. When an alternating current is passed through the coil, a magnetic field causes an alternating current to flow round the periphery of the strip (eddy currents) thus generating heat. As the strip gets thinner and resistance increases, the amount of current in the strip decreases and less heat is generated Efficiency decreases rapidly when heating thin steel strip in the paramagnetic range (at temperatures above the Curie temperature). To overcome this loss in efficiency, a different approach to induction heating of strip, called transverse flux induction heating (TFIH) is required. In this case the inductor, Figure 2-1, is in the shape of a pancake which causes the magnetic flux to pass perpendicular to the strip surface. This causes induced currents to circulate in the plane of the Strip thus avoiding the skin effects which decrease the efficiency of solenoidal induction heating. An important feature of the TFIH inductor is that its width must closely match the strip width. If the inductors too wide, the strip edges will overheat, whereas a narrow inductor will not provide sufficient edge heating.

The first development of TFIH was pioneered in 1970 by the Electricity Council Research Centre (now known as EA Technology) in England(1). In 1982, license from The Electricity Council was granted to Davy-McKee Ltd to manufacture and sell transverse flux induction heating equipment, which Davy refers to as TFX. In the late 1980s, Davy McKee constructed two

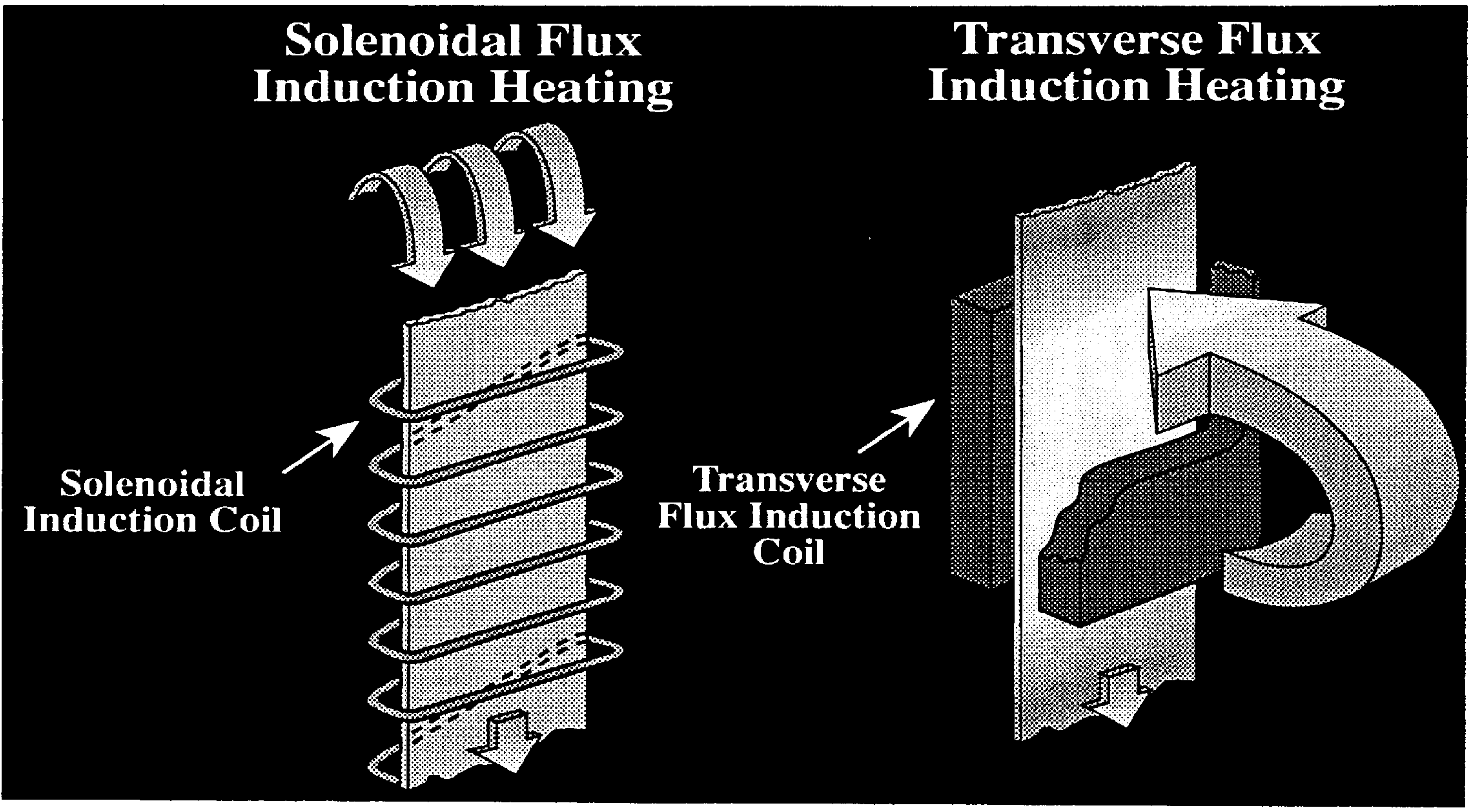

Figure 2-1
Solenoidal and TFIH induction heating.

transverse flux induction annealing lines for processing aluminum sheet. One line was built for Nippon Light Metals in Japan and the other for Hoogovens in Sidel, Belgium. However, further acceptance of TFIH has been deterred primarily due to the lack of a workable adjustable width inductor which would adapt to strip width changes. In the case of the two aforementioned Davy aluminum lines the unit has to be shutdown to change the inductor width.

In 1989, the Electric Power Research Institute's Center for Materials Fabrication funded a project to evaluate TFIH for annealing stainless steel (2). The program was conducted jointly by Allegheny Ludlum Corporation and Ajax Magnethermic Corporation at a pilot facility located at Allegheny Ludlum's plant in Vandergrift, PA. This research work confined the practicality of an adjustable Width inductor(2). Since that time, Davy McKee in England, Inductoheat in the US, Sumitomo in Japan, and Junker in Germany also began marketing adjustable width inductors.

The Allegheny Ludlum - Ajax project also showed that the TFIH process for stainless can produce comparable metallurgical structures, mechanical properties, and surface appearance as that obtained by the conventional gas-fired furnace(3). Also, there are many advantages in the areas of equipment and control of TFIH annealing compared to conventional processes which will be discussed later.

The Allegheny - Ajax work showed TFIH to be an attractive technology for annealing stainless steel. However, the largest sheet market is carbon steel. About 30 million tons of cold-rolled and coated carbon steel is annealed annually in the United States. Development of TFIH annealing for this market could offer opportunities.

Scope of Work

The aim of this study was to perform an economic assessment of TFIH annealing of carbon steel. Capital, operating, and maintenance costs for new and retrofitted TFIH installations are compared with existing or new gas-fired annealing installations. The study includes the following components:

1. Heating cycles for annealing commercial quality carbon steel and galvanized steel products.

2. Capital and operating costs for:

a) A new TFIH installation in a minimill with a reversing cold mill producing 150,000-200,000 tons per year of commercial quality cold rolled steel products, Strip gages of 0.024 inches to 0.06 inches and widths to 52 inches were considered.

b) A high flow hydrogen batch annealing facility for the same application.

3. Capital and operating costs for a retrofit as follows:

a) An existing batch annealing facility replaced by TFIH. The facility is assumed to be medium-sized having a tandem cold mill and producing 500,000 tons per year. Strip gages of 0.024 inches to 0.06 inches and widths to 66 inches were considered.

b) The annealing furnace for an existing indirect-~ galvanizing line is replaced by TFIH Strip gages of 0.022 inches to 0.06 inches and widths to 52 inches were considered.

4. Use of interstitial free(IF) Steel to eliminate overaging step in annealing.

5. An evaluation of the environmental considerations of utilizing TFIH,

Section 3

BACKGROUND

Batch Annealing of Sheet

Annealing is an integral part of the process in the production of cold-rolled strip. Prior to shipment from the steel mill, some form of heat treatment is required for cold-rolled steels in order to restore some of the ductility that is lost during cold rolling. Cold-rolled steel products are also annealed to improve magnetic response for carbon steels used in electrical applications such as motor laminations. Annealing consists of heat treatment during which the grain structure of the cold-rolled strip is recrystallized at an elevated temperature in order to increase grain size, which results in a decrease in yield strength and suitable formability characteristics for the desired product. Annealing generally takes one of two forms: batch annealing or continuous annealing. Continuous annealing lines for tinplate and other high yield strength products have been in existence for 35 years. During the last 20 years, the technology has changed and upgraded and new continuous annealing lines are capable of treating the full range of sheet grades and properties. However, about 12 million tons of carbon steel sheet and strip are still batch annealed annually in gas-freed furnaces.

Batch annealing is used primarily for uncoated low-carbon sheet steels. Steel coils are stacked in a box or bell furnace and are heated to temperature between 1100" to 1350°F to soften the steel. The actual temperature of the annealing cycle depends on the type of product being produced. The duration of the cycle will depend on the charge weight, product width, product type, type of annealing equipment, charge configuration, etc. Total process cycles can last from several days up to a week depending on the atmosphere used inside the furnace. An 870 hydrogen in nitrogen atmosphere (HNX), typically gives cycle times of 3 to 7 days and a temperature gradient in the coil of 28°C (50°F). A typical cycle includes a two hour purge of the furnace with HNX followed by heating for 16 hours, then soaking for 25 hours and finally cooling for 35 hours.

Annealing with a hydrogen atmosphere reduces the cycle time. Hydrogen conducts heat seven times faster than nitrogen. In practice, thermal conductivity in the coil radial direction is 2.5 times higher with hydrogen annealing than with nitrogen. These factors account for a 40 to 50% increase in heating and cooling rates when hydrogen is used instead of nitrogen for batch annealing. A 100% hydrogen atmosphere in the furnace gives cycle times in the order of 40 to 50 hours.

Continuous Annealing of Sheet

In continuous annealing, the sheet or strip is rapidly heated to a temperature normally at or above the lower critical temperature. Sometimes it is heated above the upper critical temperature for normalizing. The choice of annealing temperature and time depends upon the grade and quality of the steel produced. The time at temperature is only a few minutes or less and the cooling rate is very fast compared to batch annealing.

Continuous annealing lines have been in operation since the mid-fifties to anneal Strip for tinplate production. This product lends itself to short anneal times (minutes) because of the relatively hard tempers required for can production. However, for many other applications, steels must be annealed to a softer condition. Since the early seventies a number of continuous annealing lines have incorporated rapid quench systems following the anneal in order to keep the carbon in solution and have added a furnace section following quenching designed to overage the product by precipitation of carbon from the ferrite microstructure. As a result one can produce a ductile steel with properties that do not change (age) during storage.

After hot rolling, steels to be continuously annealed are usually coiled at higher temperatures compared to coils to be batch anneal. Coiling at high temperatures precipitates aluminum nitrides and coarsens the carbides, which leads to acceptable formability for Commercial Quality (CQ) and Drawing Quality (DQ) cold-rolled steels if chemical composition and heat treatment are also well controlled For Deep Drawing Quality (DDQ) grades, however, the mechanical properties of continuously annealed sheet are less consistent than with box-annealed product unless titanium or columbium bearing IF steels are used.

Continuous annealing lines are generally used to produce steels for automotive applications which are subsequently coated by electroplating or hot-dipping. Continuous annealing lines appear to be economical only for operations on the order of 500,000 tons per year due to their high capital cost ($175 to $240 million).

Annealing With Transverse Flux Induction Heating

The principle of induction heating including TFIH was discussed earlier in the introduction. For TFIH annealing of aluminum a thermal efficiency of 75% has been reported. This is higher than for gas-fired batch and continuous annealing which have efficiencies of 25 to 45% and 20 to 50%, respectively. During earlier research on induction annealing of strip conducted by Davy McKee using a line speed of 0.13 meters/second (26 fpm), the efficiency of transverse flux induction annealing was found to be 59 to 63% for low carbon steel (4). During this trial, a strip 200 mm (7.87 inches) wide with a thickness of 0.25 mm (0.01 inch) was heated to a peak temperature range of 800” to 927-C (1475° to 1700°F). Although the efficiencies estimated by Davy McKee were good, efficiencies around 80% are believed to be possible for a TFIH facility designed specifically for steel sheet and strip.

The advantages claimed for TFIH annealing over conventional annealing from the work conducted by Allegheny Ludlum and Ajax (5) on annealing stainless steel include:

1. **Compactness of equipment – TFIH** gives the highest industrially available power concentration for continuous heating of strip. Thus, the TFIH equipment occupies much less space than an equivalent conventional annealing process.

2. No thermal inertia - Heat is generated within the strip itself rather than by surface heat transfer. Therefore, thermal response is dependent only on power input which can be rapidly changed and easily controlled. Cold starts require only a few seconds and furnace heatup and cooldown time is eliminated. In addition, no overheating of the strip occurs during line stoppages.

3. Ease of automation – TFIH is easily adapted to automation and computer control.

4. **Ease of maintenance - TFIH** is a clean process and has less auxiliary equipment associated with it which leads to less maintenance.

5. Consistent product quality - TFIH temperatures can be measured, adjusted, and maintained throughout the length of a coil. Elimination of in-furnace support rolls because of short furnace length removes a major source of surface defects.

6. Reduction or elimination of subsequent acid pickling - Short TFIH cycle results in only a thin oxide layer on the strip.

7. **Increase yield and productivity** - The above factors all contribute to increased yield and productivity.

8. Lower operating costs - All of the above factors lead to lower annealing costs than conventional processes. Cost reductions as high as 22% were estimated for stainless steel.

Section 4

REPRESENTATIVE ANNEALING CYCLES

Commercial and Drawing Quality Grades

For CQ and DQ grades, heating cycles were estimated for HNX and hydrogen annealing using Mizikar's regressions (6). The heating time for DQ grades is assumed to be two to four hours (three on average) higher than for CQ. As a result the difference between the hottest and coldest spots in the coil is lower for DQ. This is in accordance with the work done by Brun et al. (7) and Mizikar et al. (8).

For hydrogen batch annealing of both CQ and DQ, the heating is more rapid and more uniform than with HNX, with a heating time reduction over 40%. The throughput is increased in the same proportion. Figure 4-1 illustrates typical annealing cycles for hydrogen and HNX batch annealing.

Galvanized Commercial and Drawing Quality

For a continuous galvanizing line the annealing cycle is usually similar to that during continuous annealing except that the time when external heating is needed is much shorter, and the strip is cooled to only 900°F (480°C) prior to coating. A typical cycle during annealing of CQ and DQ in a galvanizing line operating at a speed of 2 m/s (400 fpm) is shown in Figure 4-2.

For CQ the processing requirements complete recrystallization during annealing. For this, a soak time of 10 seconds is required at subcritical temperatures of 1200" to 1250° (650° to 675°C), depending on gage and extent of prior cold reduction. Variations in soak time, temperature, and cooling rate are not critical for this type of grade.

For DQ, the processing requirements to achieve optimum mechanical properties are somewhat more restrictive. A typical cycle includes:

1. Fast preheating in the nonoxidizing section to 900°F (480°C) for 7 seconds to remove the residual oil from the product surface which has collected during cold rolling.
2. Residence in the heating zone up to 1330"* 90°F (720° ± 30°C) for 20 seconds.

3. Soaking for a minimum of 25 seconds above 1275°F **(690°C)** for complete recrystallization of steel.

4. Convective cooling for 16 seconds in the fast cooling zone at a rate of 40° to 60°F/s (6 to 14°C/s).

5. Cooling for 32 seconds in the control cool section by radiation to air at a rate of 35*F to **40°F/s** (0.6 to 2.8°C/s). To retard cooling and achieve a shelf at 1000° to 11OO”F (538° to **593°C),** some heating is required.

6. Convective cooling for 7 seconds in the second fast cooling zone to bring the strip to the desired entry temperature in the zinc pot.

7. Residence in the snout for 15 seconds at 850” to **900°F** (454° to **482°C).**

TFIH Annealing Cycle

The annealing cycle proposed for TFIH is based on the best information currently available. The study by Battelle outlined the following cycle:

1. Heating from room temperature to peak temperatures of 1475” to **1700°F (800°C** or 930°C) at rates of **545°F/s** (286°C/s) and 635°F (332°C/s), respectively.
2. Cooling to 1245” to 1355°F (675° or 735*C) under a controlled atmosphere”
3. Quenching in an air/water chamber.

The two annealing cycles illustrated in Figure 4-3 represent heating of the steel to slightly above the critical temperature. No overaging is assumed after quenching. Rapid cooling may produce undesirable small carbides so an intermediate cooling of around **212°F/s (100°C/s)** can be used.

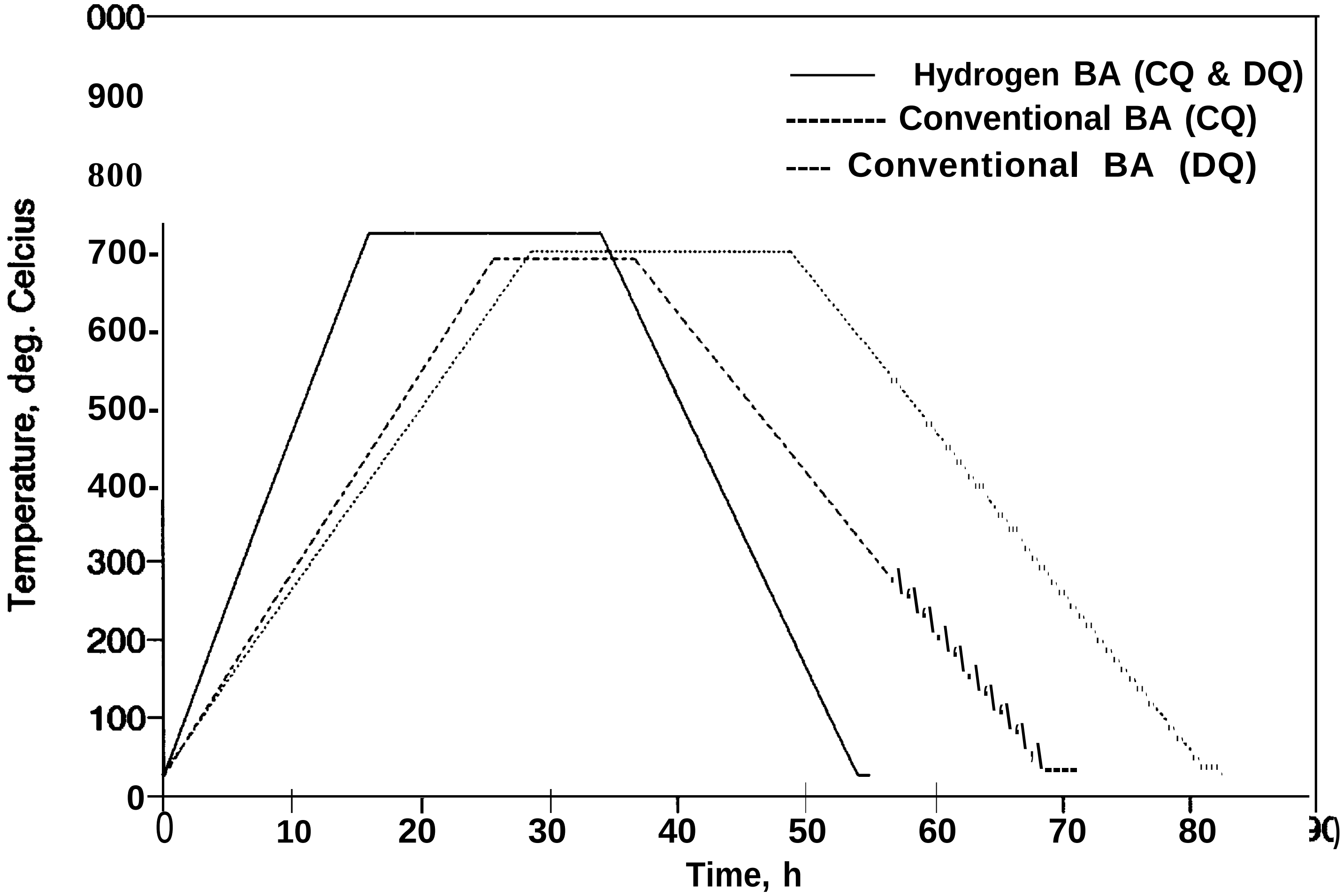

Figure 4-1
Representative annealing cycles for carbon CQ and DQ during BA.

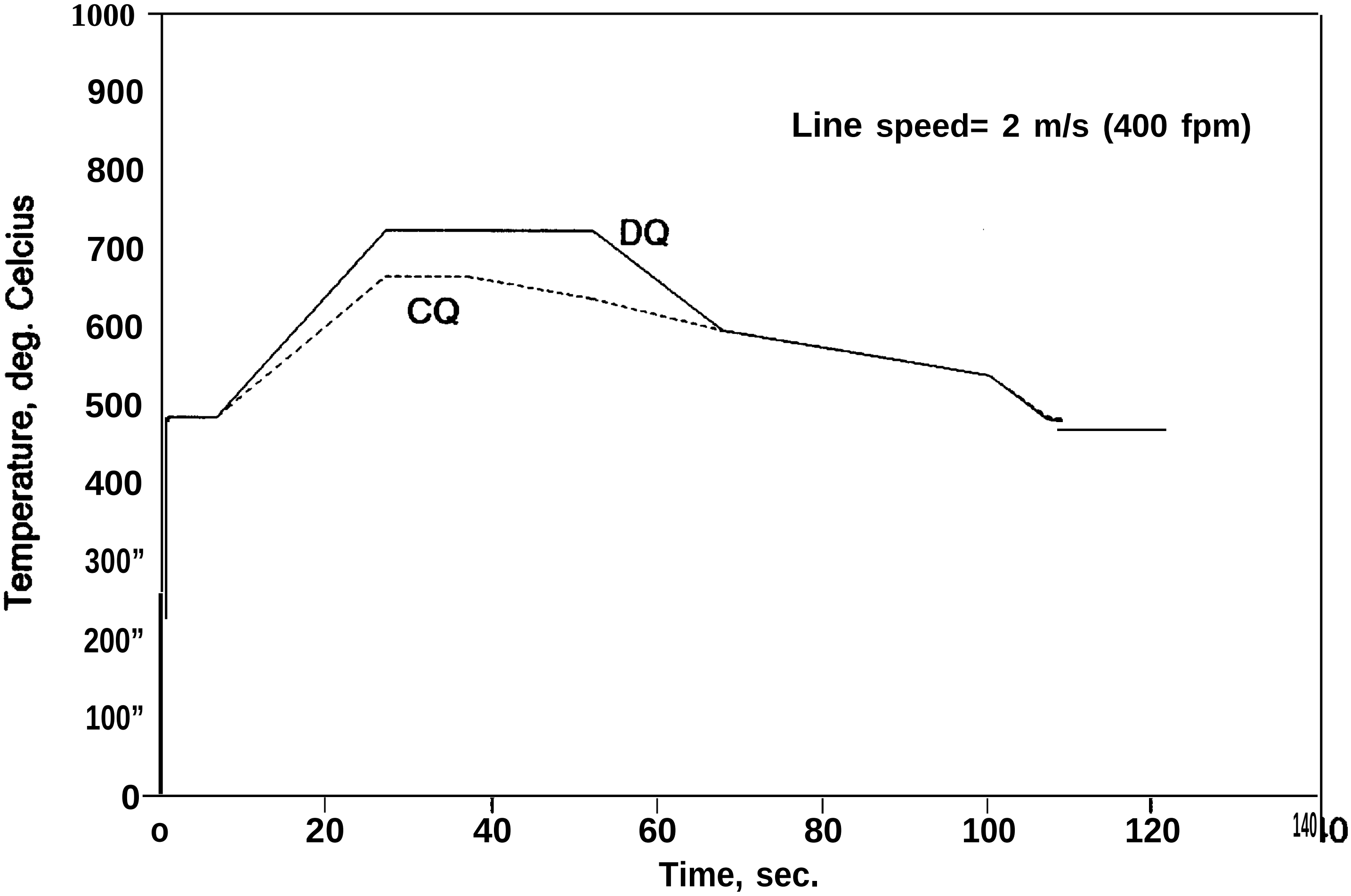

Figure 4-2
Representative annealing cycles for galvanized CQ and DQ.

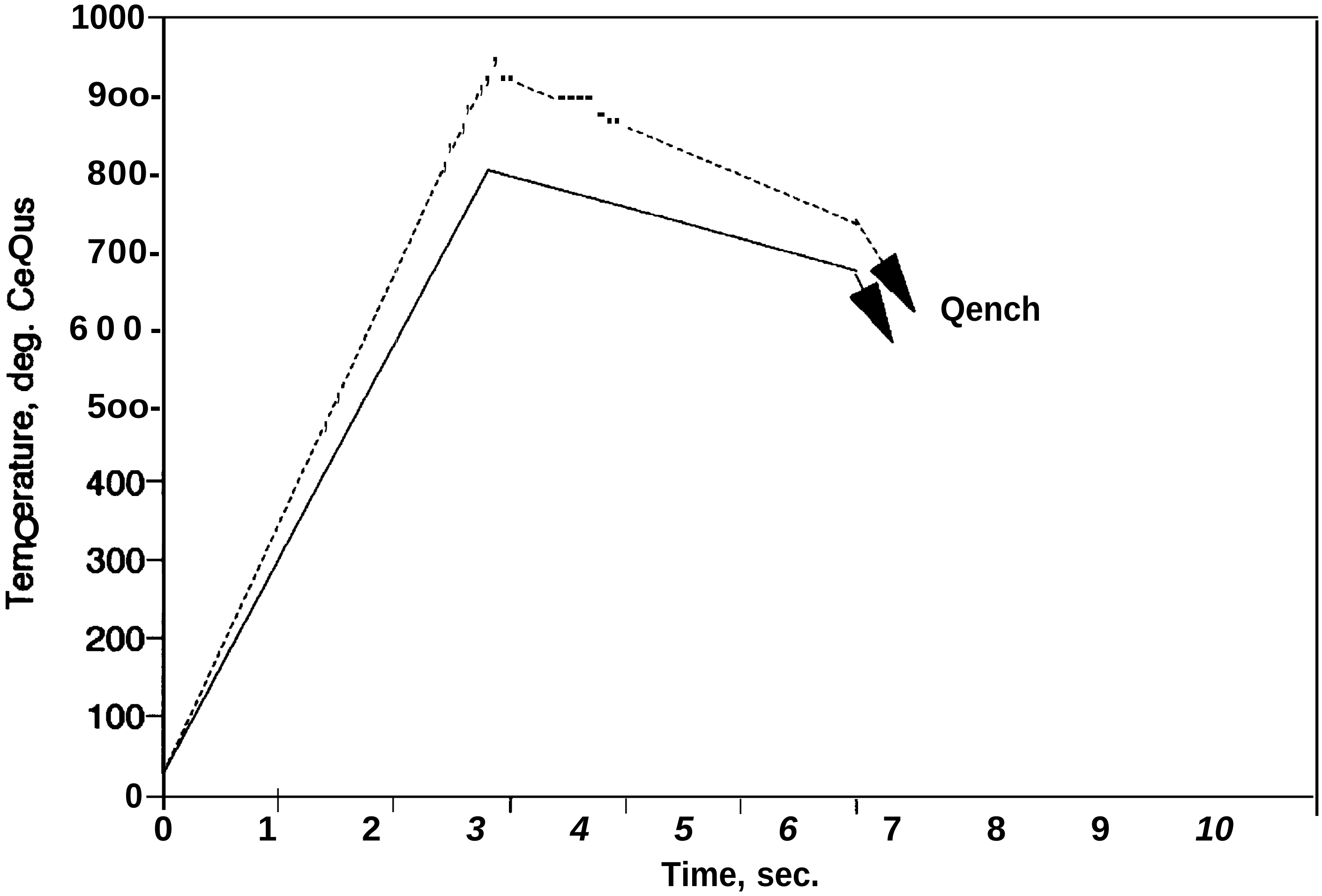

Figure 4-3
Representative TFIH annealing cycles for carbon CQ and DQ.

SECTION 5

CAPITAL AND OPERATING COST MODELS

Sources of Data

The cost models used to evaluate the various options for this study have been based on information from the following sources:

1. Vendor information
2. Hatch in-house data
3. Data from the literature

For each of the scenarios described, a cost model has been developed to compare the base configuration to TFIH. Typically the cost models include the following information:

1. Capital cost
2. Labor cost
3. Maintenance cost
4. Utility cost
   - electricity
   - steam
   - water
5. Material cost
   - natural gas
   - nitrogen
   - hydrogen
   - chemicals
   - miscellaneous
6. Services (material handling, waste water, etc., if applicable)
7. Product yield

Regional Energy Prices

It is realized that a major driving force for implementation of TFIH is operating cost, specifically, electricity. Energy costs make up a major portion of the operating costs and these rests will vary by geographic location. As a result, for each of the scenarios under evaluation, a “cost model” based on geographic regions has been set up. Four locations were chosen and include:

- Northeastern United States
- Midwestern United States
- Southwestern United States
- Eastern Canada

Energy costs for these regions ranged from 3.65 to 4.8¢/kWh for electricity and 2.5 to 3.1 $MCF for natural gas. In performing this analysis, the capital costs were assumed not to change with region.

Cases Evaluated - Assumptions Used

During the present study, the following cases are evaluated:

- A new TFIH installation is compared to a new hydrogen batch annealing facility in terms of capital and operating costs.
- An existing medium-sized HNX batch annealing facility is replaced by a TFIH line. Payback period is calculated for this retrofit as a function of TFIH line capital cost and possible savings on operating costs.
- The indirect gas-fired annealing furnace of a galvanizing line is replaced by a TFIH furnace and possible paybacks calculated.
- The above scenarios were evaluated for four North American regions.

Prior to conducting the study, a number of assumptions regarding quality and process/equipment were made. The more critical of these are:

- The product mix consisted mainly of CQ (80%) and DQ grades with 0.02 to 0.06% carbon and 0.2 to 0.3% Mn. These grades have straightforward metallurgy and represent a major portion of the market. The main requirements on the product are:
    - Clean surface finish
    - Flat Strip
    - Unifom properties
    - Medium level ductility (40 to 45% total elongation)

- Decreasing before TFIH annealing is assumed necessary as no data is available to prove that surface contamination after cold rolling and during contact with the rolls before entering the furnace is eliminated during annealing.

- With a protective atmosphere during TFIH annealing and high processing speeds, scale is assumed to be minimized so that a surface finish equivalent to that of hydrogen BA is obtained.

- A skin pass is carried out after annealing.

- Cooling rates after TFIH annealing are of the same order of magnitude as those during conventional continuous annealing.

- No stretcher/levelling is necessary because the required flatness is assumed to be achieved by the skin pass following annealing.

- No acid pickling of carbon steel is practiced after annealing in both TFIH and hydrogen BA because of the reduced scale formation in the former and reducing atmosphere in the latter. Carbon steel is only pickled following annealing if water is used to cool the strip.

- When installing a new annealing facility, all necessary utilities related to electricity, natural gas, steam, water, sewage, and waste water treatment are available.

- No additional costs related to steelmaking and rolling are necessary for CQ and DQ for the TFIH installation.

• Although TFIH annealing cycles are much faster than batch annealing cycles, no economic benefits were attributed to factors such as the potential for reducing inventory or faster product turnaround times.

SECTION 6

ANALYSIS OF RESULTS

New TFIH Installation vs. Hydrogen Batch Anneal

Capital Costs

A description of product range and annealing capacity for hydrogen BA and TFIH new installations is shown in Table 6-1 and a comparison of the capital cost of these installations is presented in Table 6-2. The costs include:

- Furnace
- Mechanical equipment
- Electrical utilities for the furnace
- Piping utilities
- Instrumentation and process control systems
- Building
- Installation labor
- Engineering and indirect costs

Table 6-1
Product and Operating Parameters **for New Annealing Installations**

Characteristic		*New TFIH*
Production, tpy	200,000	180,000
Product mix	CQ & DQ	CQ & DQ
Gage, in	0.024-0.08	0.024-0.08
Width, in	52	52
Ton/hour (average)	24	25
Ton/h/base	1.7	..
Line speed (max.), fpm	..	820

Induction heating capital cost and specific electrical consumption information was provided by INDUCTOHEAT. The costs are based on the following equipment configuration:

- Heating from ambient to the Curie temperature with solenoid coils operating at a frequency of 30 kHz.
- Heating from the Curie to the final temperature with TFIH coils operating at a frequency of 10 kHz.
- The power split between the solenoid and TFIH heating was 65% and 35%, respectively.

The reason given for the hybrid (solenoid and TFIH) system was that it reduced the overall capital cost. In addition, bigger air gaps are possible with solenoid coils thus reducing the amount of mechanical adjustment required (since TFIH requires close coupling to be effective) and therefore, reducing capital cost.

Figure 6-1 shows the obtainable speeds with an inductor having 2 MW power and Figure 6-2 gives the number of inductors required as a function of line speed. For a maximum speed of 2.5 m/s (500 fpm), five inductors are required (see also Figure 6-2). During the Allegheny Ludlum/Ajax study, four 2000 kW units were necessary to anneal stainless steel to 2100-2190°F (1150” - 1200°C) It was mentioned during that study that the maximum cost for a TFIH furnace would be $5,000,000. This figure is used as a capital cost for the TFIH system in the present study. Thus, it is expected that calculations based on theoretical efficiencies will provide a lower bound for evaluation of TFIH and the numbers provided by INDUCTOHEAT, an upper bound.

The capital cost for a new TFIH facility(Table 6-2) is more than twice as high as that for an equivalent hydrogen batch annealing facility. This is due to the mechanical equipment required for a continuous annealing line in addition to the TFIH furnace.

Table 6-2
Capital Cost Comparison – TFIH vs. Hydrogen BA

Area	Cost in Thousands of Dollars	
	New H_2BA	New TFIH
EQUIPMENT	6,460	17,005
BUILDING	735	*3,010*
SUB TOTAL	7,195	20,015
INSTALLATION (20%)	1,439	4,003
ENGINEERING, FREIGHT & ESCALATION (20%)	1,439	4,003
TOTAL CAPITAL COST	10,073	28,021
INVESTMENT COST		
Amortization over 10 years	1,007	2,802
8% interest/year (av. of 5%)	504	1,401
2% maintenance	201	560
$/ton	8.56	26.46
NOTES:		

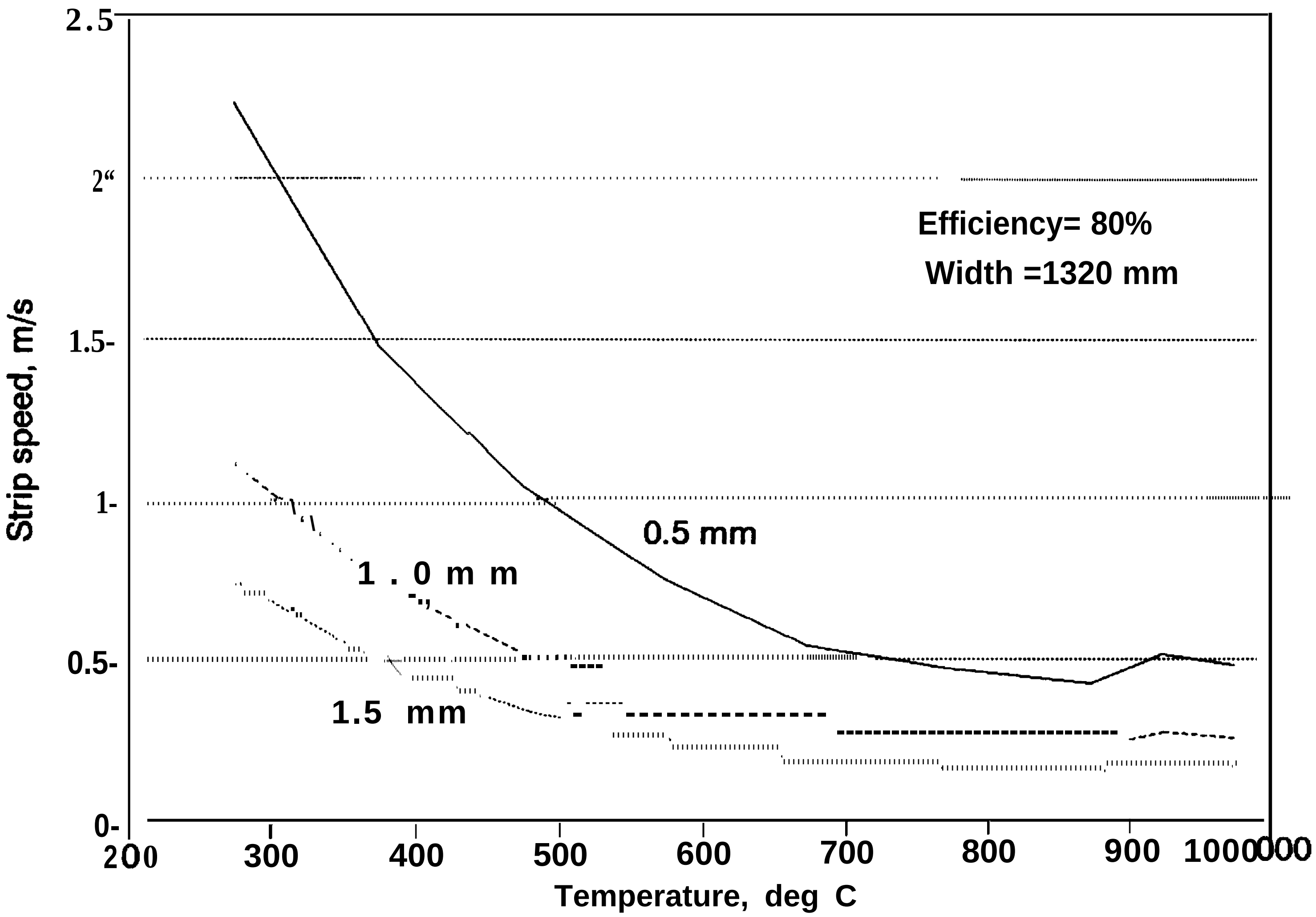

Figure 6-1

Line speeds obtainable with 2MW TFIH inductor for various CQ steel strip thicknesses.

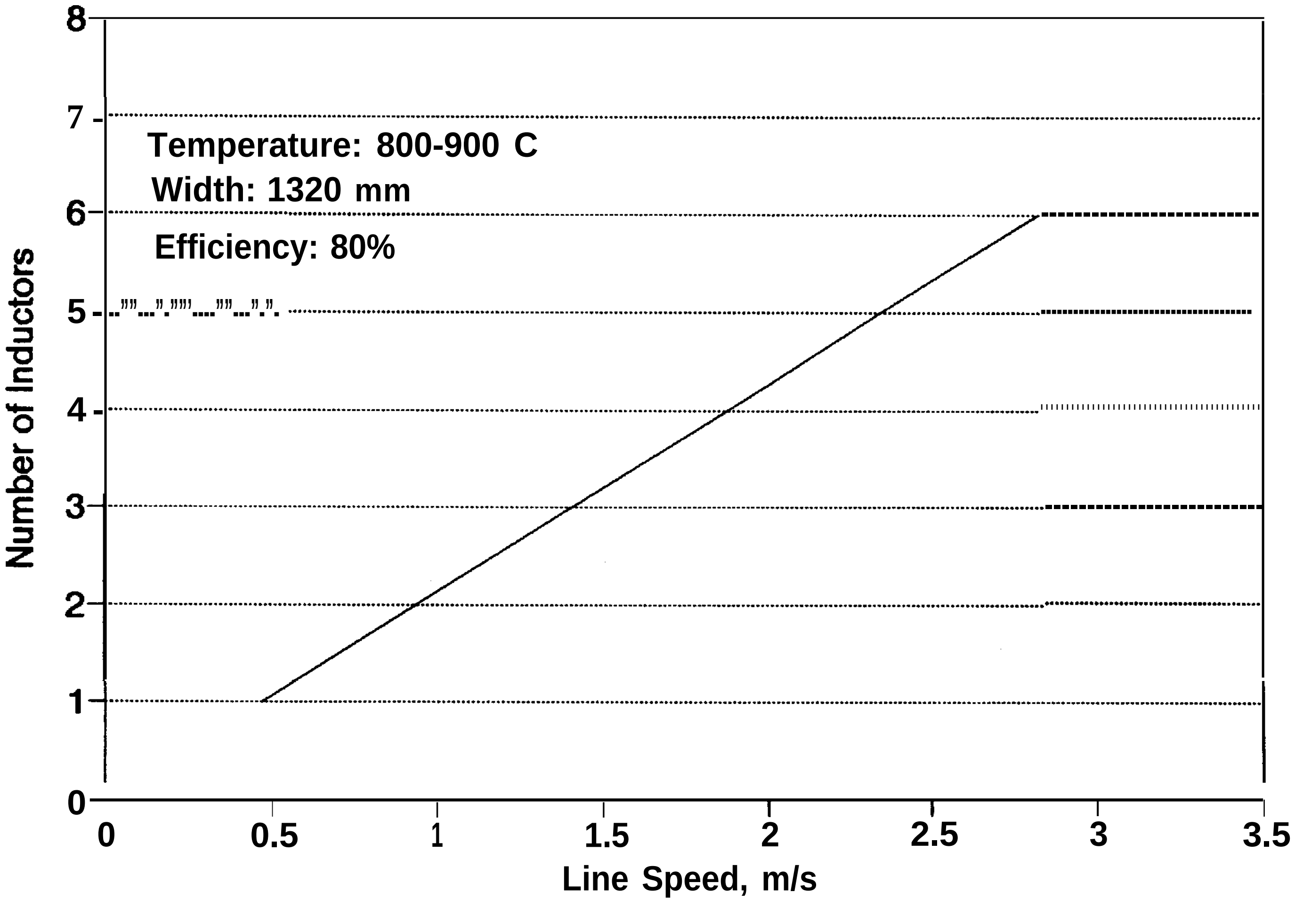

Figure 6-2
Number of required 2MW/3kH inductors as a function of TFIH line speed.

Operating Costs

An estimate of the electrical consumption for TFIH annealing was made by Hatch based on the net energy required to heat steel. The relationship used was:

$$Psteel = w\ h\ v\ e\ C_p$$

where:

P	=	Power input to strip in W/K
w	=	width of the strip, in m
h	=	gage, in m
v	=	strip speed in m/s
e		steel density, in kg/m^3
$C_p(T)$	=	heat capacity of the steel at the peak temperature, in J/kg°K

The system power requirement and then the power consumption (kWh/ton) were calculated using a system efficiency of 8090. Although values of 44 to 48% efficiency were reported during the Allegheny Ludlum/Ajax study for stainless steel, the optimistic 80% value was used as an upper limit for the study. This can be supported by the work of Davy McKee which projected an efficiency of this order for low carbon steel (9). Figure 6-3 shows the heat content of the steel as well as electrical consumption for a range of peak temperatures. For an annealing temperature around 1475*F **(800°C),** the consumption is approximately 220 kWh/ton. This compares to an electrical consumption of 300kWh/ton provided by INDUCTOHEAT. Also, the kWh/ton was factored at 270kWh/ton based on heating cycles for stainless steel described in Figure 7 of the Battelle report(10). In all cases, the minimum consumption required is more than 200kWh/ton. This value was then used, but should be considered as being a lower limit; consumption higher than 200 kWh/ton would be necessary if the efficiency of the inductors is, for instance, lower than 80%.

Table 6-3 compares the direct operating costs for a new TFIH installation against hydrogen batch annealing in a minimill producing cold rolled CQ and DQ. Operating costs for a TFIH installation are 21% lower than for hydrogen batch annealing. A fraction of this difference is due to lower maintenance, material costs, and rejection rate. A significant portion of this difference is due to the costs related to the coil storage and handling equipment for hydrogen batch anneal and other costs related to the degreaser. These additional costs are $10.85 /ton and $4.43 /ton for hydrogen BA and TFIH, respectively.

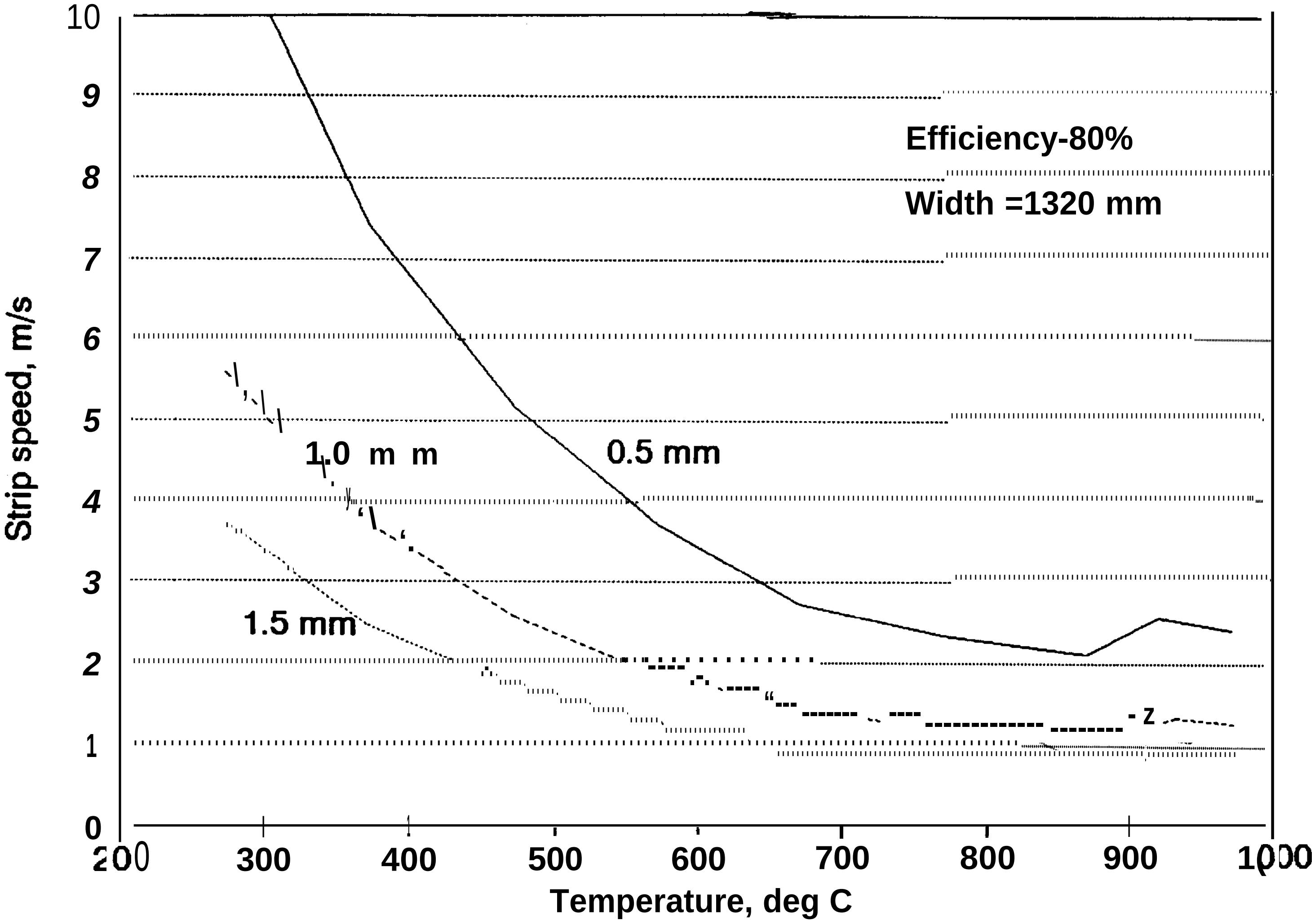

Figure 6-3
Dependence of heat content of steel and electricity consumption on temperature.

Table 6-3
Operating Cost Comparison – TFIH versus Hydrogen BA

		New H_2 BA	New TFIH
1) BASIS			
LABOR	(MANHOURS/t)	0.064	0.060
NATURAL GAS	(MCF/t)	0.626	
ELECTRICITY	(kWh/t)	7.7”	200
FURNACE ATMOSPHERE			
NITROGEN	(MCF/t)	0.175	0.100
HYDROGEN	(MCF/t)	0.078	
REJECTS	(%)	1	0.7
LABOR COST	$/HOUR	30	
NATURAL GAS	$/MCF	3.5	
POWER COST	¢/kWh	5	
NITROGEN cost	$/MCF	2.5	
HYDROGEN COST	$/MCF	11	
STEEL COST	$/t	400	
2) COSTS($/t)			
LABOR		2.52	2.40
Maintenance		2.30	1.30
NATURAL GAS		2.19	
ELECTRICITY		0.39	10.00
FURNACE ATMOSPHERE		1.30	0.25
OTHER UTILITIES		0.86	0.20
SUPPLIES		2.59	1.12
SERVICES		2.23	1.60
REJECTS		4.00	2.80
OTHERS		12.55	4.43
DIRECT OPERATING COSTS		30.91	24.30

NOTES: • For workbase fans, combustion air blowers and cooling bell.

It is concluded that although the operating costs for TFIH are significantly lower than for hydrogen anneal, the total costs including investment are 2590 higher for TFIH. If the electrical consumption is 300 kWh/ton, (INDUCTOHEAT), the operating cost for TFIH is almost equal to that of a hydrogen annealing facility.

Existing Batch Anneal Installation for Tandem Mill Replaced by TFIH

Table 6-4 gives the specification parameters for an existing conventional batch annealing and the retrofitted installation using a TFIH continuous line. For the same tonnage and product mix, the average productivity would increase from 60 tons/hour to 81 tons/hour.

Table 6-4
Product and Operating Parameters for Existing and Retrofitted HNX Facility

Characteristic	Existing HNX	Retrof. HNX
Production, tpy	500,000	
Product mix	CQ & DQ	
Gage, in	0.022-0.080	
Width. in	88	
Ton/h (average)	80	81
Ton/h/base	0.95	..
Line speed (max.), fpm	..	820

To retrofit the existing batch annealing facility, the capital cost of the equipment (furnace and mechanical) required is the same as for a new continuous line. However, the cost per ton is only $6.48 as shown in Table 6-5.

Table 6-5
Capital Cost for HNX Retrofit

Area	Cost in Thousands of Dollars
EQUIPMENT	13,650
INSTALLATION (20%)	2,721
ENGINEERING, FREIGHT & ESCALATION (20%)	2,721
TOTAL CAPITAL COST	19,047
INVESTMENT COST	
Amortization over 10 years	1,905
8% interest/year (av. of 5%)	953
2% maintenance	381
$/ton	6.48
NOTES: --	

Table 6-6 is a comparison between operating costs before and after the retrofit. Although the electrical consumption accounts for a large portion of costs during TFIH annealing, this cost is balanced by a reduction in labor, maintenance costs, natural gas consumption, supplies, and improvement of yield which is due to the absence of thermal inertia, efficient on-line control, and consistent product properties. Operating cost savings of 7% are possible with TFIH but since the capital investment is high, an unsatisfactory payback period for the retrofit (27 years) is obtained even at the 200 kWh/ton level for power. With the estimates from INDUCTOHEAT, the payback period was longer.

Table 6-6
Operating Cost Comparison - Existing vs. Retrofitted HNX Installation

		HNX	Retrofit	Diff.
1) BASIS				
LABOR	(MANHOURS/t)	O.084	0.037	0.047
NATURAL GAS	(MCF/t)	0.730		0.730
ELECTRICITY	(kWh/t)	5	200	-195
FURNACE ATMOSPHERE				
NITROGEN	(MCF/t)	0.248	0.100	0.148
HYDROGEN	(MCF/t)	0.005		0.005
REJECTS	(%)	1.5	0.7	0.8
LABOR COST	$/HOUR		30	
NATURAL GAS COST	$/MCF		3.5	
POWER COST	¢/kWh		5	
NITROGEN COST	$/MCF		2.5	
HYDROGEN COST	$/MCF		11	
STEEL COST	$/t		400	
2) COSTS (s/t)				
LABOR		2.52	1.12	1.41
MAINTENANCE		2.30	1.30	1.00
NATURAL GAS		2.56		2.56
ELECTRICITY		0.25	10.00	-9.75
FURNACE ATMOSPHERE		0.68	0.25	0.43
OTHER UTILITIES		0.86	0.20	0.86
SUPPLIES		2.59	1.12	1.47
SERVICES		2.23	1.80	0.43
REJECTS		6.00	2.80	3.20
DIRECT OPERATING COSTS		19.99	18.59	-1.41
PAYBACK (years)			27	
NOTES:				

Indirect-Fired Galvanizing Line Furnace Replaced by TFIH

The continuous galvanizing line is assumed to keep the **same** product mix, **production,** and average tons/hour although some improvement in the productivity (speed) is expected with the new automated furnace (Table 6-7). If this occurs, extra looping capacity at the entry and exit of the line might **be required** and some extra capital investment **would** be necessary. In Table 6-8, the **only** capital outlay considered is for the **TFIH** furnace and process control, **resulting** in an investment **cost** of only $5/ton. This **investment,** coupled with 14% saving in operating costs, **results** in a payback period of 7 years (Table 6-9). Reduction in operating costs occur **mainly** because of lower furnace maintenance, **reduction** in **furnace** atmosphere requirements and reduced gas consumption. Capital cost is reduced because no furnace rolls are **necessary** which, together with the operating factors mentioned earlier, improve yield.

Table 6-7
Product and Operating Parameters for Existing and Retrofitted CGL

Characteristic	Exist. & Retrof. CGL
Production, tpy	250,000
Produet mix	CQ & DQ
Gage, in	0.022-0.060
Width, in	52
Ton/hour (average)	38
Line speed max., fpm	500

When the capital cost and **electrical** consumption figures supplied by **INDUCTOHEAT** were used in this option, the resulting combined operating and capital cost were greater than for the existing installation.

Table 6-8
Capital Cost for CGL Retrofit

A r e a	Cost in Thousands of Dollars
EQUIPMENT	5,240
INSTALLATION (20%)	1,048
ENGINEERING, FREIGHT & ESCALATION (20%)	1,048
TOTAL CAPITAL COST	7,336
INVESTMENT COST	
Amortization over 10 years	734
8% interest/year (av. of 5%)	367
2% maintenance	147
$/ton	4.99
NOTES:	

Table 6-9
Operating Cost Comparison - Existing vs. Retrofitted CGL

		Galv. Line	Retrofit	Diff.
1) BASIS				
LABOR	(MANHOURS/t)	0.079	0.079	0.047
NATURAL GAS	(MCF/t)	0.750		0.730
ELECTRICITY	(kWh/t)	28	200	-172
FURNACE ATMOSPHERE				
NITROGEN	(MCF/t)	0.610	0.100	0.146
HYDROGEN	(MCF/t)	0.037		0.005
REJECTS	(%)	3	2	0.8
LABOR COST	$/HOUR		30	
NATURAL GAS COST	$/MCF		3.5	
POWER COST	$/kWh		5	
NITROGEN COST	$/MCF		2.5	
HYDROGEN COST	$/MCF		11	
STEEL COST	$/t		400	
2) COSTS (s/t)				
LABOR		2.38	2.38	0.00
MAINTENANCE		3.16	1.30	1.86
NATURAL GAS		2.63		2.63
ELECTRICITY		1.40	10.00	-8.6
FURNACE ATMOSPHERE		1.94	0.25	1.69
OTHER UTILITIES		0.86	0.86	0.00
SUPPLIES		1.45	1.12	0.33
FURNACE ROLLS		1.79		1.79
SERVICES		2.23	1.60	0.43
REJECTS		12.0	8.00	4.00
DIRECT OPERATING COSTS		29.83	25.71	4.13
PAYBACK (years)		7		
NOTES:				

Energy Comparisons

To obtain a consistent comparison of energy consumption, the gas consumption per ton was converted to an equivalent kwh/ton. Table 6-10 shows the total energy consumption during annealing for each case. From this table, it is concluded that the energy consumption is of the same order as that for hydrogen BA if a 200kWh/ton, 80% efficiency TFIH operation can be achieved During a retrofit, a maximum energy reduction of the order of 20% can be expected when replacing a gas-fired vertical furnace by TFIH.

Table 6-10
Energy Comparisons with Different Scenarios

	New installation		'Retrofit			
	New TFIH	New H_2BA	Existing HNX	Ret. HNX	Existing CGL	Ret. CGL
Electricity	200	7.7	5	200	28	200
Gas	o	183	214	0	220	0
TOTAL	200	191	219	200	248	200

Note: 1 MCF = 29.3 kwh

Effect of Energy Prices

A sensitivity analysis was carried out to see the effect of changing various components of the capital and operating costs. Some of the factors considered are:

- Productivity
- Rejects
- Gas consumption
- Electricity consumption

Increasing the productivity by 20% resulted in only $0.4/ton saving on operating costs for both hydrogen anneal and TFIH. However, reducing rejects by 50% can result in $2 /ton and $1.4/ton savings for hydrogen anneal and TFIH, respectively.

A decrease of 10% in gas consumption results in savings of around 0.25 $/ton for hydrogen anneal. Finally, a reduction of electricity consumption by 10% resulted in a saving of 1.35 $/ton for TFIH.

Table 6-11 shows the effect of energy prices on the operating costs for each scenario. Operating costs for TFIH can be up to 25% lower than for hydrogen batch annealing in the US Midwest and Eastern Canada. The savings on operating costs during retrofits are higher in these two regions and yield payback periods of 10 and 5 years for a retrofit of a conventional BA and CGL, respectively.

Table 6-11
Sensitivity of Operating Costs to Energy Prices

Case	Direct Operating Costs $/ton		TFIH Cost Advantage $/ton	Operating Cost Savings $/ton.	
	H_2BA	TFH		HNX Retroflt	CGL Retrofit
Northeast	28.94	23.88	5.06	1.49	4.16
Midwest	28.71	21.57	7.14	3.59	5.99
Southwest	28.49	22.94	5.55	1.93	4.49
East Canada	28.63	21.26	7.37	3.81	6.17

NO E

With INDUCTOHEAT's values for electrical energy, the operating cost savings were lower than those shown in Table 6-11. Using this, the payback period for the CGL retrofit was found to be 10 years instead of 4.8 years.

Payback Periods

The specific electrical consumption is the first component which dictates the economic feasibility of TFIH for annealing low carbon steel. Electrical consumption represents 30 to 45% of the total direct operating cost. Although a reduction of this consumption would not allow a new TFIH annealing line to compete against hydrogen BA, it would permit faster paybacks for a retrofit. Figures 6-4 and 6-5 show payback time as a function of the specific electrical consumption for different regions when retrofitting a conventional BA facility and a continuous galvanizing line, respectively. Reasonable payback periods in the steel industry are possible at or below 200 kWh/ton. This means that an improvement of the TFIH system efficiency is necessary. Although an increase of the TFIH system efficiency to 90% would not decrease the consumption sufficiently (see Figure 6-6) to justify global TFIH superiority over gas-find technologies, it would be beneficial for a retrofit. Where the annealing temperature increases (above the Curie temperature), the efficiency of TFIH goes down because of the increase in the critical depth of penetration. Maximum efficiency occurs when the thickness of the heated strip is around three times the critical depth. For a frequency of 36 kHz, this thickness was estimated to be 2.3 to 3.3 mm which is outside the gage range considered in this study. An alternative then would be to increase the frequency of the system beyond 36kHz, especially if a large portion of the product mix is below 1 mm thickness.

Another point that must be addressed here is the optimization of coil design. This can be achieved by physical and mathematical modeling of the induction heating process taking into account the metallurgical, thermal and electromagnetic interactions.

Finally, more research is needed to find out and confirm that yield loss due to scale formation(and other) can be further minimized. If this is achievable, together with the superiority of TFIH annealing in terms of quality, more attractive payback periods can be expected for continuous galvanizing line retrofits.

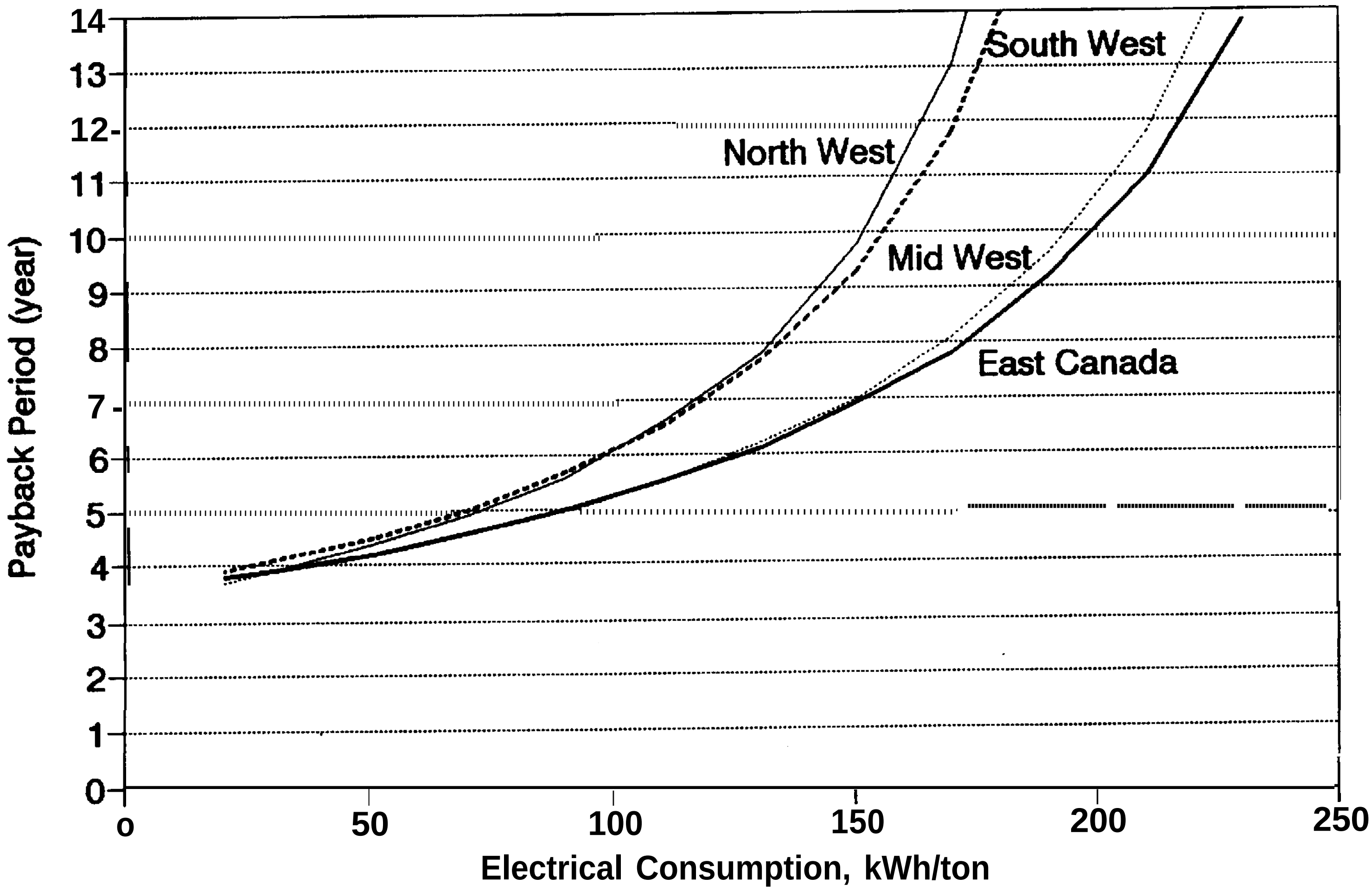

Figure 6-4
Payback period for a TFIH retrofitted HNX BA installation.

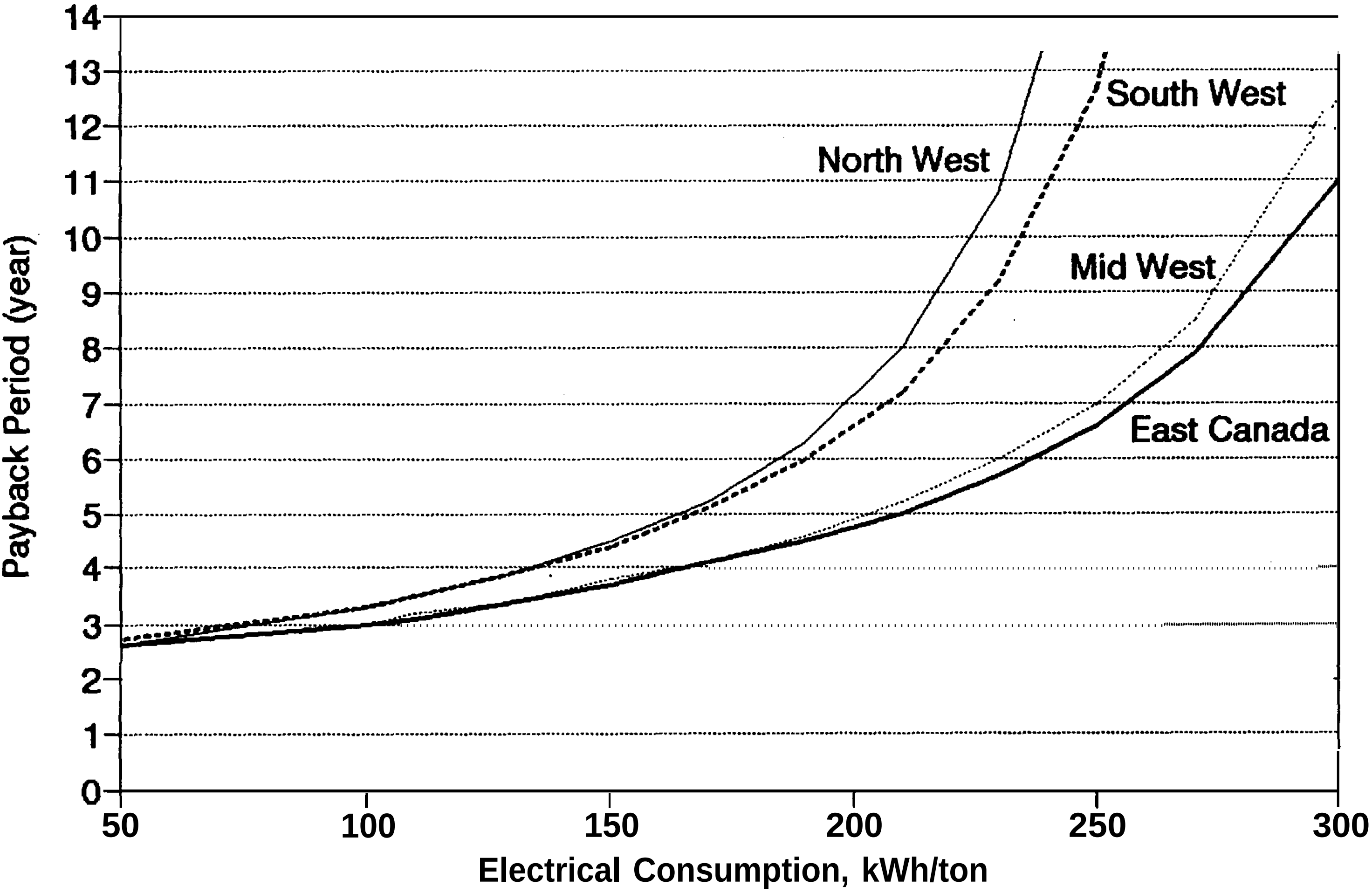

Figure 6-5
Payback period for a TFIH retrofitted galvanizing line.

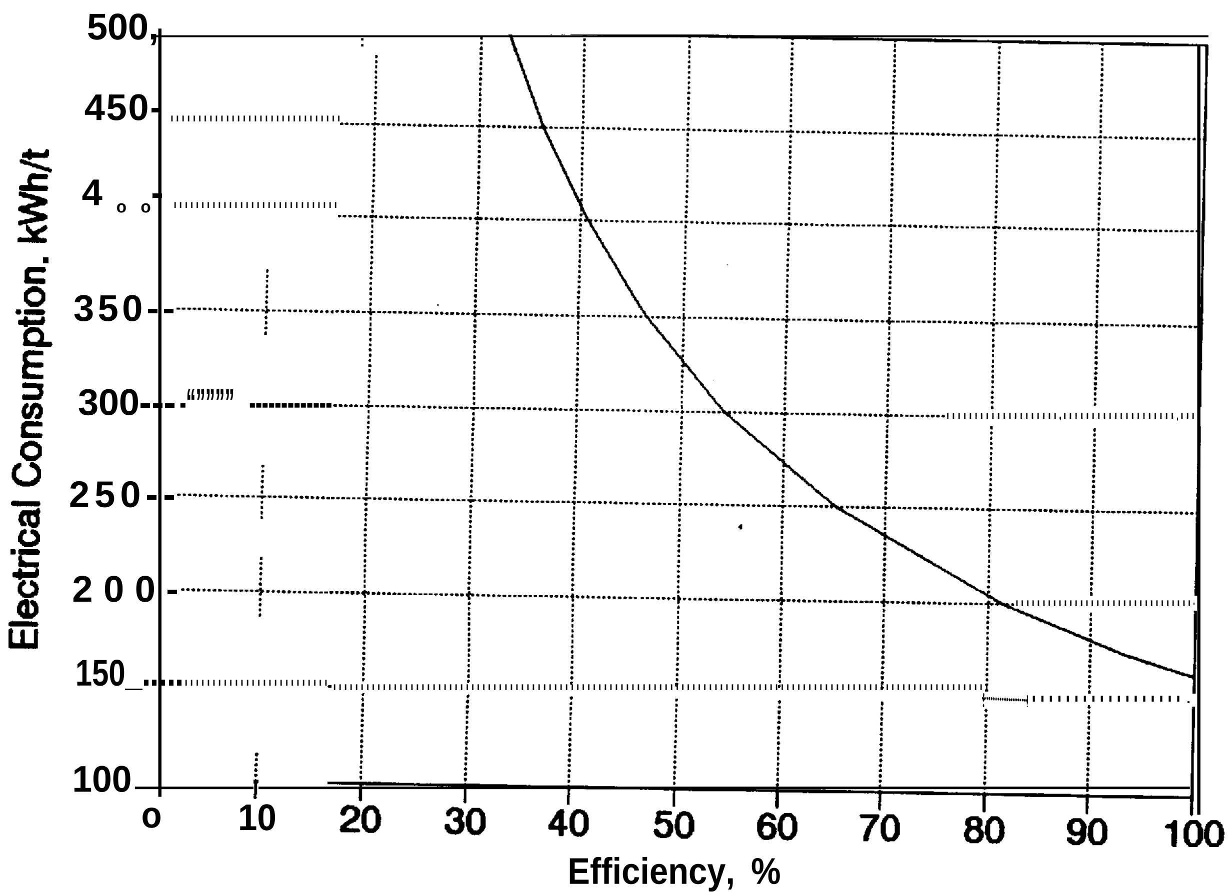

Figure 6-6
Dependence of electricity consumption on TFIH system efficiency at 12920F (700°C).

SECTION 7

ENVIRONMENTAL IMPACT

One of the criteria to be used for evaluation of TFIH is its impact on the environment. While TFIH annealing itself results in no emissions, total environment impact of TFIH includes required electricity generation. Thus,it was decided that for comparative purposes, emission rates for electricity produced by burning natural gas should be used since the energy source for both continuous and batch annealing processes is natural gas. The following emission rates, published by Ontario Hydro for electricity produced from natural gas were used:

NO_x	**0.8-1.80**	**g/kWh**
VOCs	4.2588 X 10-3	g/kWh
$S0_2$	9.288 X 10-4	g/kWh
CO_2	605	g/kwh

Based on these figures the following comparative tables have been constructed. The best case scenario for TFIH efficiency, (200 kWh/ton), has been used.

Table 7-1
Case 1 – Minimill, 150,000 to 200,000tpy

Process	Natural Gas mcf/ton	Electrlcity kwh/ton	Net Process Emissions g/ton			
			NO_x	VOCS	SO_2	CO_2
TFH	o	200	160-360	0.85178	0.18576	121,000
H_2BA	0.626	7.7	85-92	0.8144	0.1777	32,995

Table 7-2
Case 2 – Medium-Sized Mill, 500,000tpy

Process	Natural Gas mcf/ton	Electricity kwh/ton	Net Process Emissions g/ton			
			NO_x	VOCs	SO_2	CO_2
TFH	o	200	160-360	0.85176	0.18576	121,000
HNX	0.730	5	95-1oo	0.933	0.1989	38,476

Table 7-3
Case 3- Galvanizing Line, 250,000tpy

Process	Natural Gas. mcf/ton	Electricity kWh/ton	Net Process Emissions g/ton			
			NO_x	VOCs	SO_2	CO_2
TFH	0	200	160-360	0.85176	0.18576	121,000
CAL	0.750	28	116-144	1.056	0.204	39,530

Based on the power conversion, emission levels are generally higher for_ in all of the cases which have been evaluated For volatile organics and sulfur dioxide, the differences in emission levels for TFIH versus alternative technologies are small. Carbon dioxide emissions are much greater for TFIH in all cases. NO_x emissions are typically 50- 100% greater for TFIH.

Though TFIH, as a process is very clean and gives more efficient heating of the steel, the increased efficiency is offset by the inefficiency of producing electricity from natural gas and leads to the higher off-gas emissions described above. However, if electricity produced from a hydroelectric facility is considered, TFIH has obvious environmental advantages over natural gas-based technologies. Another positive note is that the emissions from a gas-fired generating station would probably be captured and treated thus resulting in low net emissions to the environment. This is unlikely to be the case gas-fired batch or continuous annealing facilities where most of these emissions would escape to the environment.

If during TFIH annealing oxide formation can be minimized or prevent@ yield can be increased by 1-2%. In addition pickling facilities can be eliminated. For these reasons it is important that test trials be conducted to determine the extent to which oxide formation can be prevented during TFIH annealing operations. This increase in yield cannot be quantified without further test work. However, a reduction of 33- 50% in the amount of oxide formed versus conventional technology has been assumed for payback calculations.

Section 8

CONCLUSIONS

The cost data obtained from INDUCTOHEAT were based on a combination of solenoid and TFIH heating and used to provide an upper bound for the cost of a TFIH annealing facility. The electricity consumption was also estimated from theory assuming 8090 system efficiency. The present study is based on an energy usage of 200 kWh/ton during annealing of low carbon CQ and DQ steel grades in a peak temperature range of 1292° to 1652*F (600° to 900°C). These figures establish a lower bound for the cost of TFIH. From this study, the following conclusions are drawn:

1) Operating costs for a new TFIH annealing line are 21% lower than for a new hydrogen box annealing facility. These savings are offset by the higher capital cost of a TFIH system, making the operating plus capital cost 25% higher than hydrogen box annealing.

2) Retrofitting an existing HNX box annealing facility is not economically feasible because of the high capital cost of the TFIH system and the line mechanical equipment.

3) Retrofitting a gas-fired annealing furnace of a galvanizing line with a TFIH system gives the best economic option. Payback periods of 4 to 5 years are possible.

4) Using IF steels eliminates the need for an overaging step but the $25/ton premium for IF steels is not offset by the savings in capital costs.

5) TFIH annealing offers no benefits over natural gas-based processes with regard to air emissions when it is assumed that the electricity is generated in a gas-fired generating station.

Section 9

FUTURE RESEARCH & DEVELOPMENT

High-strength Steels

An advantage of TFIH heating over gas-fired heating is its ability to rapidly heat metals to high temperatures. Rapid heating of low carbon steel by TFIH produces an annealed microstructure having an extremely fine grain size. A fine grain size increases the strength of the steel without an appreciable effect on ductility. Thus, for high-strength steels, TFIH continuous-annealed steels may require appreciably less expensive alloying elements to achieve a given strength level. Further, an overaging step is not required to produce the high-strength steels. Production of high-strengths could be a very attractive niche for TFIH and consideration should be given to a research program to prove this hypothesis. It should be recognized that the primary market for high-strength steel sheet is the automobile industry and for most applications this requires access to a coating line as the steel must be coated with a corrosion-retarding coating such as zinc.

MagnC Lamination & Electrical Steels

TFIH annealing could possibly be used to produce magnetic lamination and electrical steels which would not require an overaging step. A continuous-annealing line for the production of such steels would probably be relatively inexpensive. A research and development program would be required to develop this application.

In Line Annealing for Hot-Dip Galvanizing

Another possible application for TFIH is the in-line annealing section of hot-dip galvanizing lines. This could be for either greenfield or retrofitted lines. TFIH has the ability to turn the heat on or off instantaneously. This characteristic would improve product yield because it prevents a considerable amount of sheet from being downgraded as a result of line stops, a fairly common occurrence in continuous processing. The installation of TFIH would also offer a means for older hot-dip galvanizing lines to obtain the higher temperatures needed to anneal IF steels, which are being used more frequently by the automobile industry for applications requiring excellent formability.

Section 10

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