3 copies

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April 11, 1986

Mr. Ron Visness
Manager Material Development
DNR-Minerals
500 Lafayette Road
St. Paul, Minnesota 55146

Dear Mr. Visness:

I am submitting this report entitled "The Current and Future Status of the ADI Industry as a Potential Market for KR Iron". I have described some of the history of ADI's development, current applications, process controls necessary to product it, and some future possibilities. Producers, heat treaters, and ancillary technical people were interviewed about their role in ADI and what their projections for the future were.

I also surveyed them about the desirability of KR Iron as a possible low manganese charge material and plotted demand curves from that data. Demand curves based on selling price are included.

The last part of the report is a brief account of the 2nd ADI Conference in Ann Arbor, Michigan, which I attended in March, 1986. The complete proceeding will be published shortly and will be available for your reviewal.

Thank you for the opportunity to work on such an exciting project. If I can be of any service again please call me.

Sincerely yours,

John E. Brynildson, P.E.

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THE CURRENT AND FUTURE STATUS OF THE ADI INDUSTRY AS A POTENTIAL MARKET FOR KR IRON

Prepared By

John E. Brynildson, P.E.
Consultant

For
Minnesota
Department Of
Natural Resources
Minerals Division

April 11, 1986

PART I - Section A
ADI INDUSTRY, PAST, PRESENT, FUTURE

The earliest practical development of Austempered Ductile Iron (ADI) was done in the 1950s. The International Harvester Company began a search for an alternative material to cast steel track shoes. This was done under a contract with the U.S. Army. By 1955, International Harvester had formulated an austempering process to produce ADI track shoes weighing almost 60 pounds. This early development lost its support and it wasn't until 1976 when General Motors announced large scale use of ADI in its ring and pinion gears used in the differentials of their rear wheel driven passenger vehicles. This drew widespread interest to ADI which lead to other applications such as large gears, rail car wheels, and crankshafts.

Greater impetus was given to the growth of ADI by involvement of companies like Kymmene-Stroember of Finland, Metallgesellschaft Ag of West Germany, Amax Corporation of the United States, and others. Companies with potential applications began serious evaluation of ADI; companies such as Caterpillar Tractor Co., Deere & Company, Ford Motor Company, J.I. Case, Chrysler Corporation, and others. Once the necessary criteria was established for producing the base iron in the foundry, the next hurdle was finding heat treaters with the expertise and capabilities of performing the austempering treatment. Many, if not all, heat treaters have austempered steel for many years. Problems arose when the same methods and attitudes were applied to ductile iron. The process is quite similar but the products of transformation are totally different. When steel is austempered, the austenite transforms to ferrite and carbides. When ductile iron is austempered, the high silicon and high carbon cause the austenite to transform to acicular ferrite and carbon rich austenite which is stable at room temperature. This transformation is the first stage of two possible stages. If left at the austempering temperature for two short a time complete Stage I transformation may not occur. Therefore some martensite could form which would reduce the impact and fracture toughness properties of the ADI. If left too long, the Stage I transformation products of acicular ferrite and carbon rich austenite will begin to transform to ferrite and carbides which have an embrittling effect. This condition in turn leads to poor fatigue life and low fracture toughness. It was due to this special behavior of ADI that many otherwise very competent heat treaters could not perform successfully.

Presently nine heat treating facilities austemper ADI. One is in Norristown, PA, one is in Livonia, MI, one is in Elk Grove Village, IL, one in Philadelphia, PA, one in Meadville, PA, one in St. Louis, MO, one is in Wichita, KS, and two are in Minneapolis, MN. The heat treat facility in Norristown, PA uses hot oil as the austempering bath while the rest use salt. There are at least twenty foundries in the United States which are producing ADI base iron on a production or experimental basis with more interest developing every day. Ongoing research programs such as Professor Rundman's at Michigan Technological University in Houghton, Professor Carl Loper's at the University of Wisconsin- Madison, the ASME-Gear Research Institute's three-year study and many "grass roots" R&D programs are revealing more positive aspects of ADI continually.

Once the foundries who want to produce ADI accept the more restrictive chemistry and processing conditions there will be a very rapid growth of ADI base iron capabilities. The major bottleneck in the near future could be not having the heat treat capacity to perform the austempering. There is sufficient capacity at this time (40000 tons per year heat treating capacity by some experts estimates, with 16000 tons to be produced in the foundries during 1986.) It is predicted that 1987 will see 32000 tons of ADI produced which is still within the capacity available. However, after 1987 there could be a shortfall in capacity unless more austempering furnaces are installed. There is presently research going on which may alleviate part of the potential problem of limited heat treat facilities. An alloyed ductile iron Ni-Mo-Cu (Nickel-Molybdenum-Copper) could be subjected to controlled cooling during shakeout to approximate the condition experienced during austempering. Energy could be saved because this procedure would occur during the cooling down from solidification. This is still very experimental and would be a solution only for those ADI castings which did not require machining beforehand.

There is another consideration in sourcing ADI castings; the capabilities of the machining facilities near the heat treater are important. Due to the work-hardening characteristics of the carbon rich austenite phase in ADI's microstructure, castings are difficult to machine after the austempering treatment. Some producers and users of ADI have reported minimal machining problems with single point tooling (such as a lathe) but multiple cutter tooling such as end or facing mills and boring and reaming tools cause this work hardening which prohibits machining ease. It naturally causes dimensional problems also. So for future growth to continue in the application and use of ADI, close coordination between the user, the foundry, the machining facility and the heat treater must be further nurtured. With cooperation this problem may be overcome in the future.

A tentative specification for the production of ADI has been submitted to the appropriate committees of the American Society for Testing and Materials (ASTM) for reviewal. When a specification is in place growth will accelerate. It will then be easier for the user, foundry, machine shop, and heat treater to establish procedures and guidelines.

There was a concern raised at the first International Symposium of ADI held in April, 1984 that the process requirements for the foundry and heat treater would be too stringent. The consensus from the second International Symposium on ADI held in March, 1986 was that ADI base iron is being produced and there are heat treaters who can austemper it. There is no doubt as more applications are uncovered and specifications are established the projected growth could appear conservative.

PART I - Section B
IN-PLANT PRODUCTION REQUIREMENTS

In order to produce acceptable ADI there needs to be strict adherence to process controls. Two processors must follow proper procedures: the foundry and the heat treater. It is necessary to explain the heat treatment of ADI and the base iron requirements in order to understand the process and material controls needed in the foundry operation.

Austempering consists of heating a ductile iron casting to an appropriate austentizing temperature (1550°F - 1650°F) followed by a rapid quench into a medium (oil or molten salt) which is maintained at a temperature in the bainitic transformation range (475°F - 725°F). It is then held in the austempering bath for a time long enough for transformation to occur. The transformation which takes place during the austempering of ductile iron is unlike that which occurs during austempering of steel. In steel, the austenite which has formed at 1650°F undergoes a transformation in the austempering bath. The austenite phase transforms to ferrite and fine carbides to form bainite. The products of transformation in ADI are different.

The austenite phase of ADI heat treatment transforms to acicular ferrite and carbon rich austenite which is stable at room temperature. This is known as Stage I transformation. If left in for too short a time some of the austenite would transform to martensite instead. If left at the austempering temperature too long, a transformation known as Stage II will occur. The carbon rich austenite will transform to ferrite and carbides in the grain boundaries. Both conditions are detrimental to the properties of ADI: impact strength, fracture toughness and fatigue life are lowered considerably. In order to achieve maximum properties, there needs to be a homogeneous carbon level in solution and Stage I transformation must be complete while Stage II is prevented. These are conditions which good foundry process control and procedures can avoid.

Process controls needed to make ADI base iron are not unlike those needed to make a regular high quality ductile iron. High quality charge material, good melting practice, proper alloying and treatment technique, good inoculation practice and correct pouring practice are all needed to make acceptable ADI. In order to achieve homogeneous carbon solution, a low manganese level is required. Manganese affects carbon solubility because of segregation at grain boundaries. This in turn can lead to inhomogeneous carbon solution which will adversely affect fatigue properties. The foremost experts in ADI technology advocate a maximum manganese level of .30% while encouraging achievement of an even lower level.

Another foundry practice which requires close control and monitoring is nodule count. This, as the name implies is the number of graphite nodules per unit volume. Because microstructural analyses is done by polishing the surface of the iron and viewing it under a metallurgical microscope, we commonly talk about nodule count as number per unit area. A number which experiments are proving to be valid is 150 per mm^2 and higher. A higher nodule count can also help overcome some of the adverse affects of manganese above .30%. High nodule counts are achieved by inoculation practices either post-treatment or in mold. Caution must be used with inoculating for high nodule counts as the shrinkage tendency of the iron is generally increased as inoculation is increased.

Assurance of complete Stage I transformation while delaying the start of Stage II transformation is aided by alloying with molybdenum and nickel. Addition of (.25% - .30%) Mo and (1.00% - 1.50%) nickel have been found to be very effective in opening the "process time window" of the austempering treatment. Care is needed to add the molybdenum, usually in the form of ferromolybdenum, at a high enough temperature to assure complete solubility. Segregation of manganese could promote some untransformed austenite which could convert to martensite in service, causing premature failures.

Magnesium and Cerium are the elements which cause the graphite nodules to form in ductile iron. Care must be taken to add enough during the nodularizing treatment to form and maintain nodularity while solidifying but not so much it promotes excessive dross (magnesium oxides) which can cause surface porosity which promotes poor wear performance of ADI.

The foundry practice will need to be established which will ensure castings will have either an all ferritic or all pearlite microstructure as-cast. This will result in uniform dimensional changes after austempering. This is vital as the castings will most likely be machined before austempering.

A brief review of requirements for successful production of ADI: first in the foundry. Aim for a low manganese level which can be achieved with low manganese charge materials. Add enough alloy to allow austempering to be done without Stage II transformation products. Control nodule count so $150/mm^2$ or higher is maintained. Regulate magnesium level to achieve nodularity but restrict dross formation. Next in the heat treat operation, be sure the austentizing temperature is maintained to ±10°F and the soak time is sufficient for a fully austenetic structure to form. Make sure the transfer from the austenizing bath to the austempering bath is rapid enough to prevent transformation from austenite to pearlite. After choosing the appropriate austempering temperature, make sure the parts are maintained within ±10°F of this temperature. After the part is in the austempering bath observe the time faithfully to ensure consistent, repeatable results.

Metallographic techniques are being developed so the heat treater's quality control presonnel can interpret ADI microstructure properly. Standard reference micrographs need to be made so austempering cycles can be monitored for effectiveness. In-house impact testing of unnotched charpy bars will also be instituted as the ADI industry becomes more fully developed.
(For futher details refer to Appendix A.)

PART I - Section C
PRESENT AND POTENTIAL APPLICATIONS OF ADI

There had been a great emphasis on converting many carburized and hardened steel gears to ADI. This is still going on but at a slower pace than earlier predicted. Conversions of steel gears to ADI will continue on into the future. One type of application which is growing is torque and torsion-related components such as crankshafts. This is a result of exhaustive tests by companies such as Ford Motors and Chrysler Corporation demonstrating the outstanding fatigue properties of ADI compared to forged steel components. In many of these tests ADI proved superior to forged steel in endurance limits and fatigue life. A leading automotive materials engineer stated that he predicts all engines in automotive vehicles built worldwide will have ADI crankshafts in 5-10 years.

Much work has been done in agricultural and mining applications. Thre is a growing minimum tillage technology in agriculture which is utilizing more digging equipment which must possess good wear resistance and toughness. ADI has proven to be the answer to this demand. This is definitely a growing segment of the ADI market. The mining industry has applications which are expanding. Rock crusher rolls and segments, ball mill liner segments, protective covers subjected to severe impact are just some of the growing markets there.

Research results will become available soon which demonstrate the enhanced stress corrosion resistance of ADI. This has great possibilities in the production and transportation of energy.

Dr. Muhlberger of Metallgesellschaft stated at the 2nd ADI Conference that all applications are open and that ADI can be machined and drilled after austempering, contrary to popular opinion. This would surely accelerate the discovery of new applications even more.

PART I - Section D
ADVANTAGES AND POSSIBLE DISADVANTAGES OF ADI VS. COMPETING MATERIALS

Austempered Ductile Iron (ADI) has a number of advantages over other engineering materials. One of the key advantages is a 30-35% cost reduction due to less complex production requirement. Tooling costs for castings are generally much less than that for forgings. An ADI casting can result in as much as 25-30% reduction in weight and in most cases maintain properties equivalent to a steel forging. ADI has excellent resistance to lubricated and unlubricated wear, superior contact fatigue resistance, and better damping properties than steel for noise reduction. This makes it a very excellent alternative to steel in gearing applications.

The endurance limit and fatigue life of ADI has been found to be in most cases equal to or superior to steel forgings which are quench and tempered. This makes it ideal for crankshafts and other applications requiring high torsional strength. When subjected to impact type of wear, ADI has outperformed Hadfield manganese steel and high chromium white iron. This opens up many uses in the mining and construction industry.

Compared to standard ductile (nodular) iron ADI exhibits high tensile and yield strength while maintaining good ductility (elongation). The impact strength and fracture toughness are usually much higher than standard ductile iron and match those of steel in many applications.

One of the disadvantages of ADI is the apparent need to machine the casting before austempering. This need arises from the fact that the ADI microstructures will work harden during some machining operations. If the foundry process control is adequate the casting will have a consistent ferritic or pearlite microstructure. This will result in a predictable uniform dimensional change after austempering. If the microstructure is mixed, i.e. partially pearlitic and partially ferritic the resulting dimensional changes will be erratic thereby causing out of spec parts. With more machining research, this problem, I'm sure, will be overcome.

The unnotched impact strength of ADI is very high but the notched strength is somewhat lower than carburized case hardened steel. It is quite critical that no surface inclusions or porosity be allowed to occur. With better foundry pouring practice, this is being remedied also.

Over all the advantages of ADI over other engineering materials far outweigh the disadvantages.

PART I - Section E
POTENTIAL ADI MARKET GROWTH

One of the key objectives of this study was to determine the market potential and market growth of Austempered Ductile Iron (ADI) up to and including 1995. Based on research and testing both in laboratories and by field service applications there appears to be great optimism about the properties of ADI. It will not replace very much gray cast iron nor will it be a wholesale replacement for standard ductile (nodular) iron. The greatest growth appears to be in the replacement of components made from steel forgings, steel castings, and steel fabrications: weldments, machined bar stock, etc. There are more companies and organizations developing ADI applications than are talking about it. A great aura of secrecy has made obtainment of exact figures very difficult. I have listed a number of various potential growth patterns in TABLE I. It varies from 137,000 tons to 8,192,000 tons in 1995. However, based on information reported at the 2nd ADI Conference in Ann Arbor and comments made by people interviewed a growth rate of 65% per year through 1995 is the most likely. This would equate to 1,758,000 tons of ADI produced in 1995. Based on a 50% yield, this would require 3,516000 tons of melt.

Note the base figure of 32,000 tons in 1987. One of the leading experts in ADI stated at the conference that ADI production in 1986 would be 16,000 tons while doubling in 1987. This was the general consensus of attendees. Therefore, this was adapted as the base figure to use for projected growth.

TABLE I

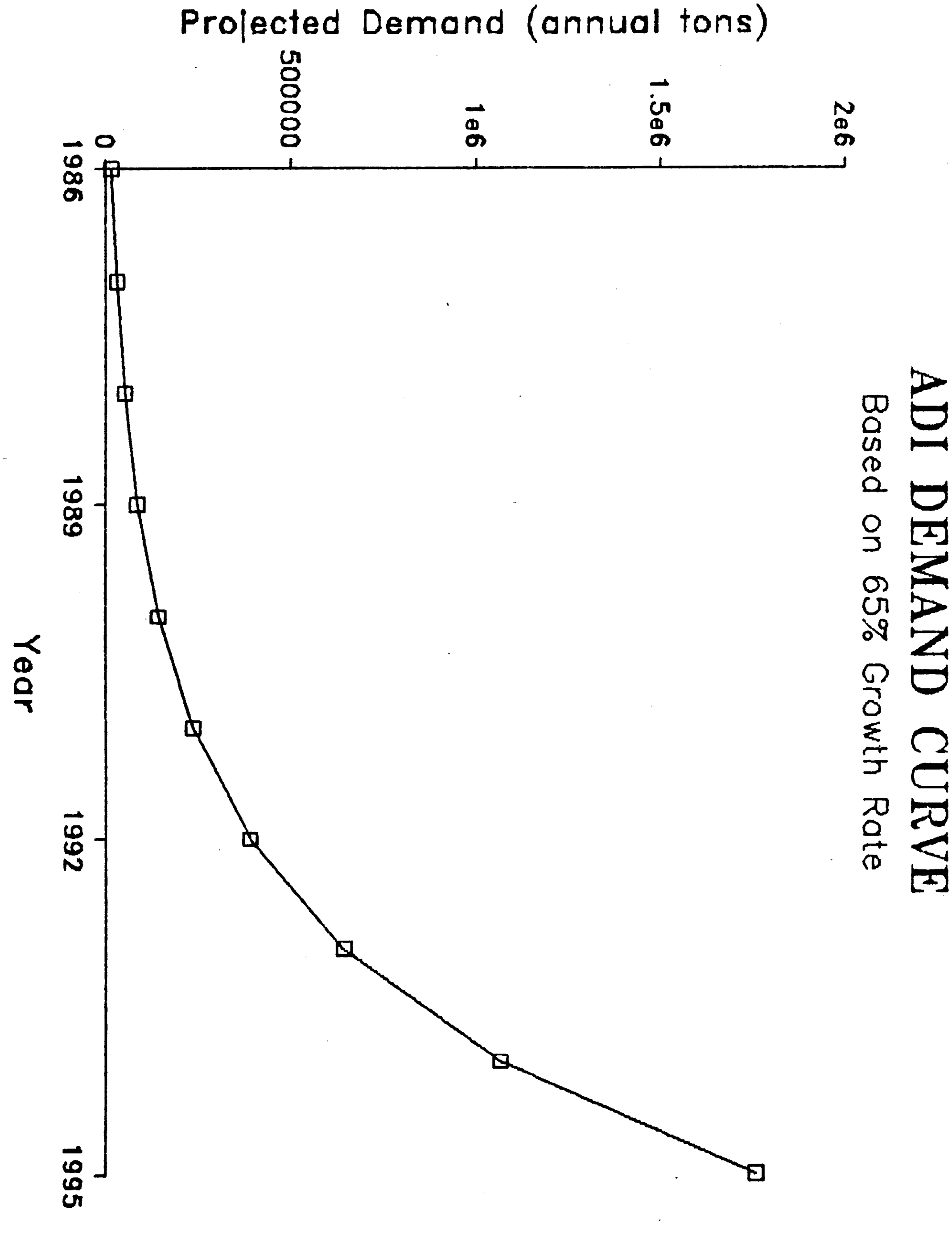
POSSIBLE ADI GROWTH RATES

	20%	30%	40%	50%	60%
1987	32000	32000	32000	32000	32000
1988	38400	41600	44800	48000	51200
1989	46080	54080	62720	72000	81920
1990	55296	70304	87808	108000	131072
1991	66355	91395	122931	162000	209715
1992	79626	118813	172103	243000	335544
1993	95551	154458	240945	364500	536870
1994	114661	200795	337323	546750	858993
1995	137594	261033	472252	820125	1374389

	65%	70%	80%	90%	100%
1987	32000	32000	32000	32000	32000
1988	52800	54400	57600	60800	64000
1989	87120	92480	103680	115520	128000
1990	143748	157216	186624	219488	256000
1991	237184	267267	335923	417027	512000
1992	391355	454354	604661	792351	1024000
1993	645733	722402	1088391	1505468	2048000
1994	1065461	1313083	1959104	2860389	4096000
1995	1758010	2232242	3526387	5434740	8192000

"Stratecasts as of April 1986"
Forecasts — 100000 Tons 1990
200000 Tons 1992

*All figures are net tons.


ADI DEMAND CURVE
Based on 65% Growth Rate
Projected Demand (annual tons)
0
500000
1e6
1.5e6
2e6
1986
1989
1992
1995
Year

PART I - Section F
THE SUITABILITY OF KR IRON FOR PRODUCING ADI

Charge materials used for producing ADI have the same requirement as those used to produce other cast irons. They must have a composition of such a nature that they can be melted economically while maintaining proper iron chemistry.

In most, if not all, ductile iron foundries the most predominant charge material is the returns from the casting process: downsprue, gates, runner bars, risers, and any scrap casting which may occur. The amount of returns available for remelt depends on the casting yield. The casting yield is calculated by dividing the weight of castings produced by the total weight of iron poured into the mold. A figure used quite commonly throughout industry, and verified in the survey, is 50% yield. This obviously means 50-55% of the charge could consist of returns. This leaves 45-50% to be made up of other materials. For gray iron and some ductile, this can consist entirely of steel scrap. Steel scrap is low in carbon and silicon but unless it is a premium grade of deep drawing steel (.25 - .30%) the manganese level is about .60 - .90%. For gray iron and pearlite ductile, this is no problem, but a ferrite grade of ductile cannot tolerate it. As ADI has been found even more sensitive to manganese over .30%, the high steel charge would not do. The bath would need to be diluted with a low manganese source of iron units. Some possible sources of these iron units are low manganese steel, sorelmental, direct reduced iron pellets or briquettes, and KR iron.

Low manganese steel is an item which is not readily available to all producers. Certain captive automotive foundries utilize it as it is internal scrap. However, it usually requires more energy to melt plus a need for carbon and silicon additions must be made. Direct reduced iron (DRI) is low in residuals but usually creates an unmanageable slag condition during the melt. Sorelmetal works extremely well as it low in manganese and silicon but it is on expensive charge material. KR iron is almost as attractive as Sorelmetal in regards to chemistry. The silicon is higher and the manganese is somewhat higher than soremetal. The silicon in Sorelmetal is .07%. While KR iron has a .80%. The manganese in soremetal is .01% while KR iron has a .15%. If Sorelmetal was used to dilute the manganese level in the bath a maximum amount of 25% of the charge weight would need to be Sorelmetal. If KR iron was used there would be a need for 35% of the charge weight to be KR iron. See calculations on the next page:

THE SUITABILITY OF KR IRON FOR PRODUCING ADI

Sorelmetal	**Mn**		
RETURNS	500 lbs. X .30% =	1.5 lbs.	
STEEL SCRAP	250 lbs. X .60% =	1.5 lbs.	
Sorelmetal	250 lbs. X .01% =	.025 lbs.	
	1000	3.025 lbs.	.302% Mn

KR IRON			
RETURNS	500 lbs. X .30% =	1.50	
STEEL SCRAP	150 lbs. X .60% =	.90	
KR IRON	350 lbs. X .15% =	.525	
	1000	2.925 lbs.	.2925% Mn

One can see that KR iron will not be as an effective diluent as Sorelmetal but it is still very suitable as a charge material for ADI. There also needs to be some research done as to the physical shape the KR iron pig would take. This would affect charging and melting operations. A 30 to 40 pound pig seems to be the optimum size. That will ease handling plus it is easier to trim the charge while weighing it up.

Overall KR iron seems to be a very attractive charge material for ADI and other ductile iron.

PART II

The potential demand for KR iron appears to be quite favorable.

Twenty-three persons from foundries, heat treating companies, and related technology suppliers were interviewed. All the foundries interviewed produced ductile iron and a few of them also produced gray iron. Everyone producing ductile iron had experimented with ADI and plan on producing it as user demand increases.

The foundry people interviewed were either present plant metallurgists or foundry managers who had been chief metallurgists. They were all very knowledgeable about the actual charge mixes being used in their melt departments.

Invariably the charge material common to all the foundries was foundry returns (~ 50% of the charge.) Only two used pig iron in their gray iron whole at least half used pig iron in their ductile. The material used in almost all cases was Sorelmetal. The balance of the charge material ranged from steel busheling and burnings to specially prepared shredded deep drawing grade steel which is low in manganese. The primary reason more pig iron wasn't used in ductile iron was the cost factor. The steel scrap being purchased ranges from $70 - $105 per ton. The average price for Sorelmetal FOB Q.I.T.'s plant in Canada is approximately $185. After transportation costs are added, a price of $210 - $220 per ton is likely.

The chemistry of the KR iron was described to the interviewees and most found it attractive as a source of low manganese. Three people expressed concern about the silicon (Si) level being over .50%. Their particular method of making ductile iron necessitates a low silicon content in the base iron. They felt they could work around it however. KR iron is not a trade-off with Sorelmetal when looking at just manganese but some concerns were expressed about trace elements of chromium, vanadium, and titanium in Sorelmetal which might adversely affect ADI properties. This remains to be proven as a valid fear but it is definitely a possibility.

(The material seems to be attractive at a price between $125 and $150 per ton. Even at $150, it appears as if a market exists for all the annual output of a facility on the Iron Range by 1995.)

Developing demand curves for gray iron and ductile iron was relatively straight forward. The demand curves for the ADI market was projected based on comments of the interviewees about how strongly they endorsed the low manganese prerequisite for production of ADI. As Sorelmetal is one of the only low manganese charge materials available, the pricing was based against those figures.

Some of the present foundries using "home" shredded automotive scrap may be in the market in the mid-90's as a movement is underway to convert more auto body sheet metal to high impact thermoplastics. This could cut the shredded auto scrap supply considerably. This will have to be followed closely.

PERSONS INTERVIEWED FOR ADI AND KR SURVEY

Alan Holtz - Metallurgist
Amcast
Meadville, PA
(814) 724-2600

Brent McComb - Manager of Metallurgy
Archer Creek Plant
Lynchburg Foundry
Lynchburg, VA
(804) 528-8711

Robert Bigge - Foundry Metallurgist
Briggs & Stratton
Milwaukee, WI
(414) 771-4210

Dale Kretschmer - Technical Director
Brillion Iron Works
Brillion, WI
(414) 756-2121

Jay Janowak - Mgr. Foundry Mktg Dvlpmnt
Climax Molybdenum Division
Amax
Arlington Heights, IL
(312) 392-7100

C.J. "Jim" Peterson - Technical Director
Columbus Foundry
Columbus, GA
(404) 323-5221 Ext. 225

Robert Mathews - Metallurgist
Dana Corporation
New Castle, IN
(317) 529-1560

Richard Kryzanek - Manager Metallurgy
John Deere Foundry
Deere & Company
East Moline, IL
(309) 752-6858

Bernardo Morgensteren - Casting Manager
Ford Castings Division
Ford Motor Company
Detroit, MI
(313) 594-1473

Bela Kovacs - Materials Engineer
Ford Motor Company
Detroit, MI
(313) 592-2535

Lee Edwards - Chief Metallurgist
Central Foundry Division
General Motors Company
Saginaw, MI
(517) 776-4865

Al Alagarsamy - Corporate Technical Director
Grede Foundry
Reedsburg, WI
(608) 524-6424

James Paternoster - Technical Director
Hayes Albion
Albion, MI
(517) 629-2141

William Minor - Marketing Manager
J & A Steel Treating
Elk Grove Village, IL
(312) 437-1980

Forest Barnhart - Chief Metallurgist
Kingsbury Castings Inc.
LaPorte, IN
(219) 393-3122

Roland Reutz - Metallurgist
Kohler Company
Kohler, WI
(414) 457-4441 Ext. 7566

Joseph Lincoln - Consultant
Lincoln Associates
Milford, MI
(313) 685-7464

Fred Preston - Plant Metallurgist
Lufkin Industries
Lufkin, TX
(713) 634-2211

Al Bielke - Foundry Manager
Murray Foundry
Wausau, WI
(715) 845-3155

P. Halasya "Paul" Mani - Technical Director
Wagner Castings Co.
Decatur, IL
(217) 428-7791

Peter Haakanson - Metallurgist
Wells Manufacturing
Skokie, IL
(312) 966-5050 Ext. 255

William Powell - Manager of Melt & Metallurgy
Waupaca Foundry
Waupaca, WI
(715) 258-8511

Dr. Carl Loper, Jr. - Prof. of Metallurgy Eng'g.
Metallurgical Engineering Department
College of Engineering
University of Wisconsin - Madison
(608) 262-2562

KR IRON MARKET SURVEY INTERVIEW FORM

1. What is your annual tonnage of production?
   Ductile____________________ Gray ____________________

2. What is your annual capacity?
   Ductile____________________ Gray ____________________

3. What is your average casting yield?
   Ductile________________ % Gray ________________ %

4. What are you main sources of iron units in your melt charge?
   Returns________________ % Pig Iron ________________ %
   Steel Scrap _____________ %

5. If you do use pig iron, what type(s) do you use? ____
   ____

6. If sorelmetal, what type? ____

7. Do you now produce ADI? ☐ Yes ☐ No
   If yes, how much? ______________________________

8. If not now, do you plan to produce it in the future? ☐ Yes ☐ No
   Prospective tonnage? ____________________________

9. If you now produce it or intend to, would you purposely keep manganese level low?
   ☐ Yes ☐ No
   What level?____________________________________

10. Would you use any special charge material to maintain low manganese?
    ☐ Yes ☐ No
    What material?________________________________

11. Would a low manganese pig iron similar to soremetal be an option if price was right?
    ☐ Yes ☐ No

12. (KR) Do you know about KR iron?

☐ Yes ☐ No

13. KR chemistry

4.22% C	.019% P
.80-1.00% Si	.145% Mn
.017% S	

14. Would this be an attractive charge material at:

$200/ton _______________ $175/ton _______________

$150/ton _______________ $125/ton _______________

15. How much would you buy at:

☐ $200/ton ☐ $175/ton

☐ $150/ton ☐ $125/ton

16. Would you use KR in conjunction with other charge material?

☐ Yes ☐ No

PART II

U.S. DEMAND FOR KR IRON IN GRAY IRON

Selling Price ($ per ton)	Demand (tons)
$125	297500
$150	26150
$175	0
$200	0

US. DEMAND FOR KR IRON IN DUCTILE

Selling Price ($ per ton)	Demand (tons)
$125	211750
$150	86800
$175	22000
$200	0

U.S. DEMAND FOR KR IRON IN ADI - 1991

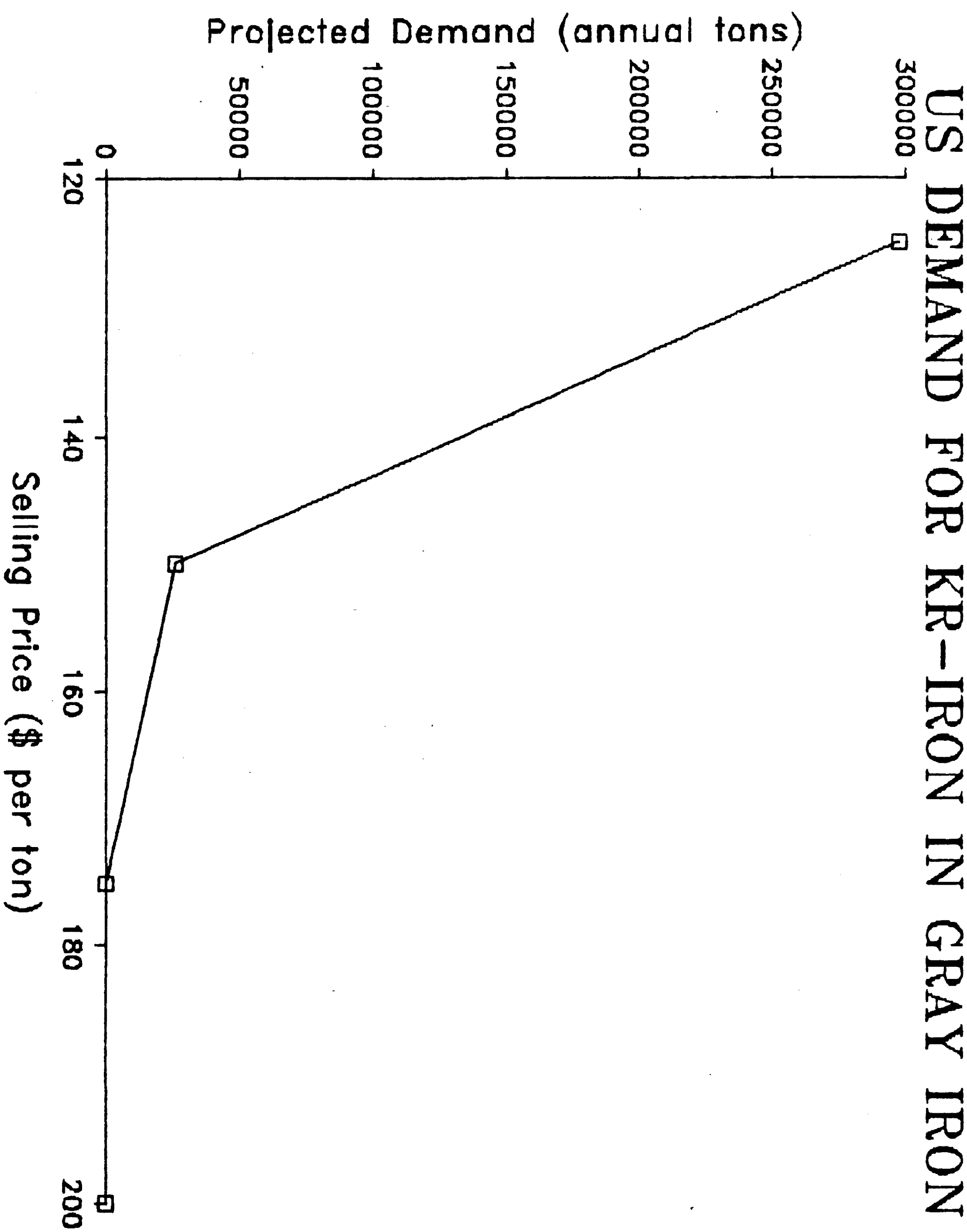
Selling Price ($ per ton)	Demand (tons)
$125	166000
$150	142000
$175	100000
$200	10000

U.S. DEMAND FOR KR IRON IN ADI - 1995

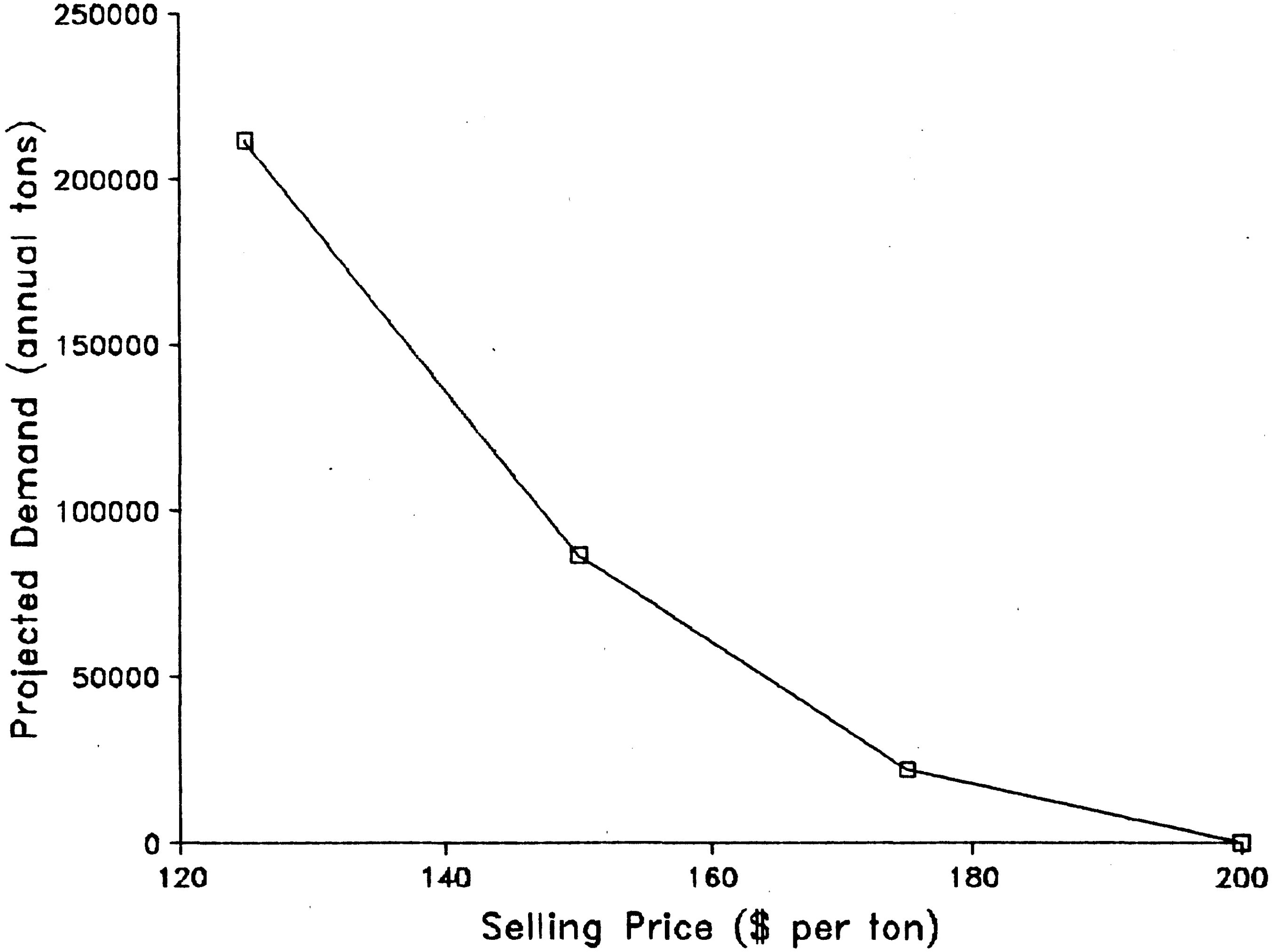
Selling Price ($ per ton)	Demand (tons)
$125	1230000
$150	1054000
$175	879000
$200	100000

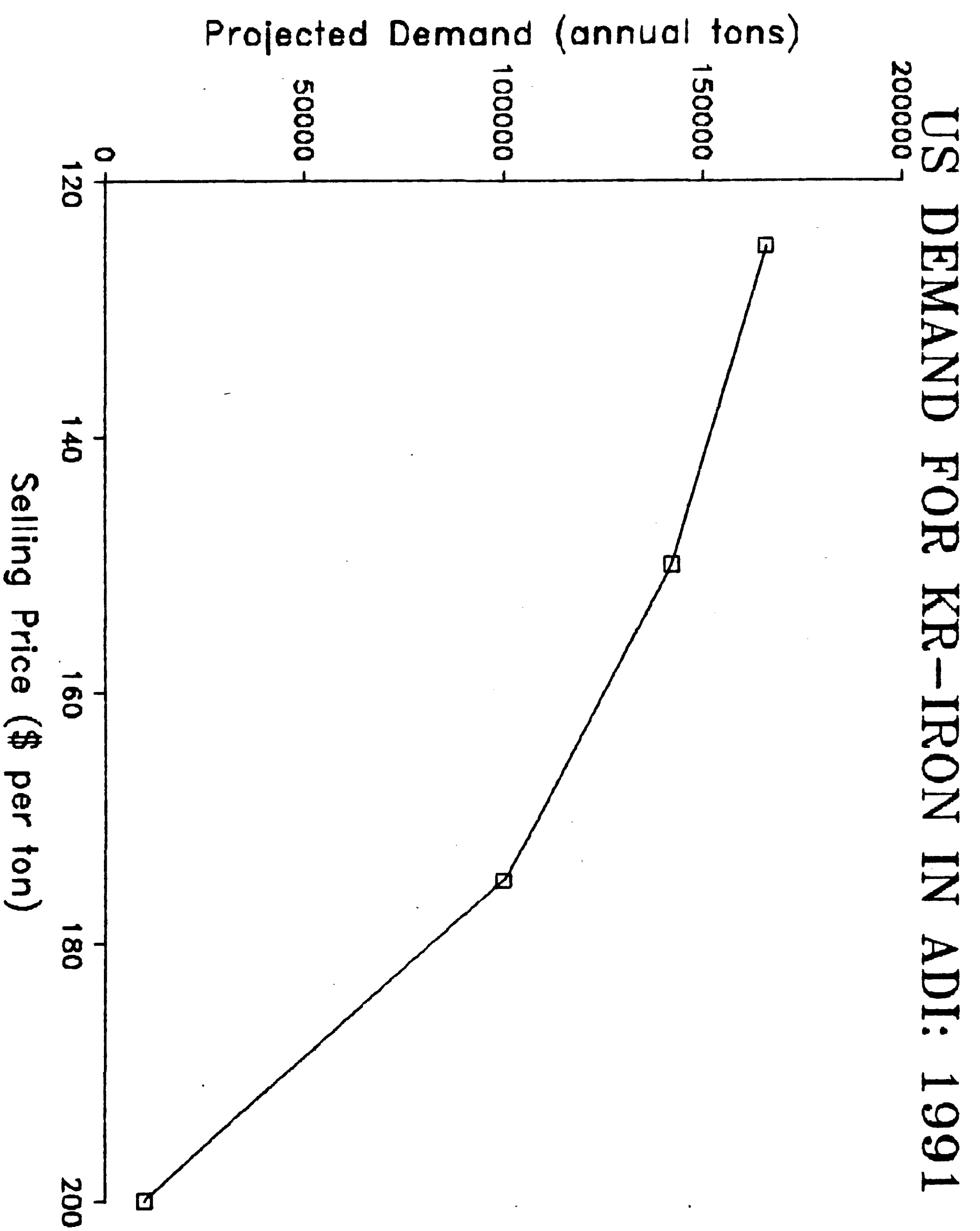
PART II
POTENTIAL KR IRON USAGE IN ADI AT VARIOUS PERCENTAGES

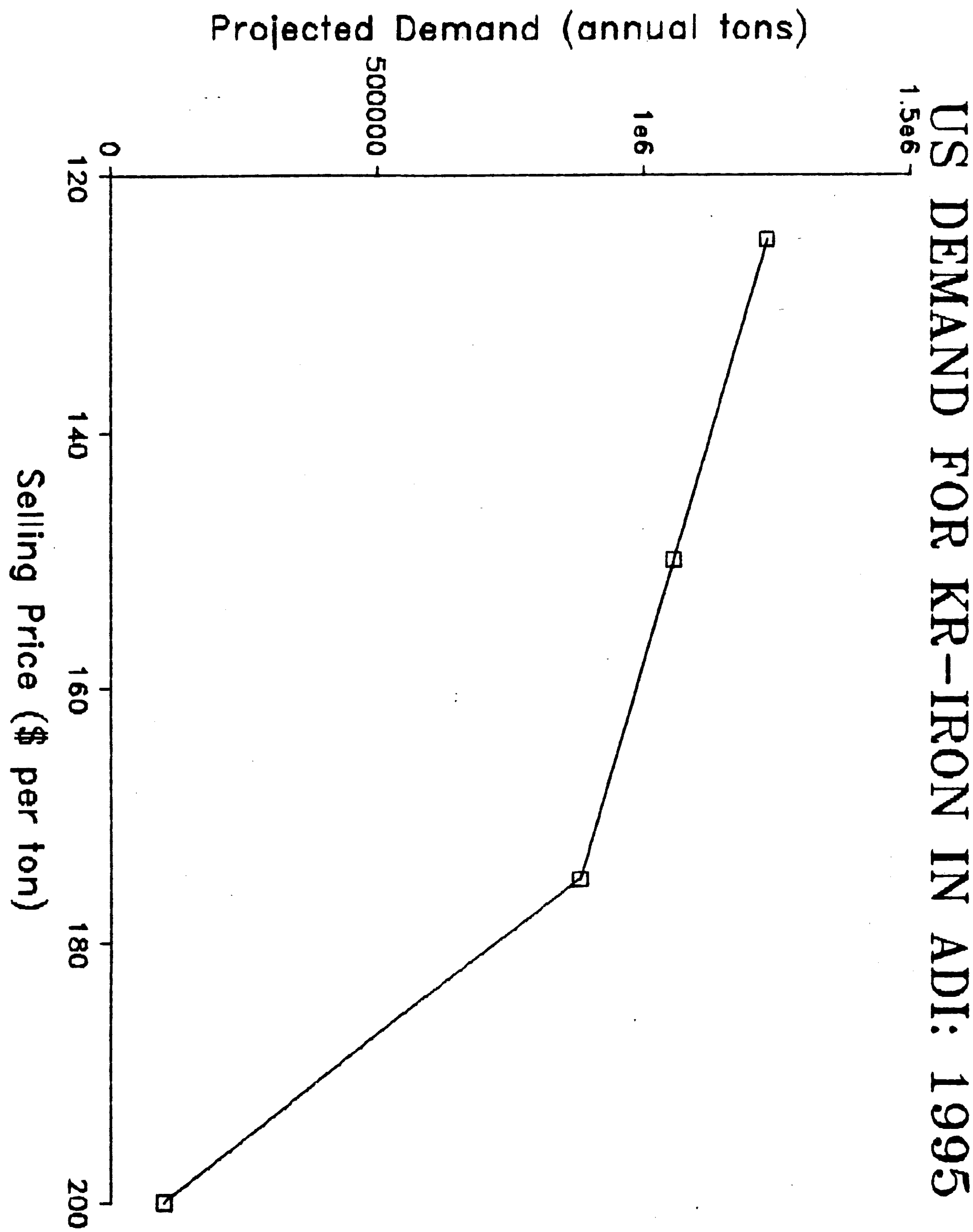
	Tons Castings	Tons Melt	KR IRON AS PERCENT OF CHARGE 35%	30%	25%
1986	16000	32000	11200	9600	8000
1987	32000	64000	22400	19200	16000
1988	52800	105600	36960	31680	26400
1989	87120	174240	60984	52272	43560
1990	143748	287496	100623	86248	71875
1991	237184	474368	166028	142310	118590
1992	391353	782706	273947	234810	195675
1993	645733	1291466	452013	387440	322865
1994	1065461	2130922	745822	639275	532730
1995	1758010	3516020	1230607	1054800	879000


US DEMAND FOR KR-IRON IN GRAY IRON
Projected Demand (annual tons)
0
50000
100000
150000
200000
250000
300000
120
140
160
180
200
Selling Price ($ per ton)

US DEMAND FOR KR–IRON IN DUCTILE IRON




US DEMAND FOR KR-IRON IN ADI: 1991
Projected Demand (annual tons)
0
50000
100000
150000
200000
120
140
160
180
200
Selling Price ($ per ton)


US DEMAND FOR KR-IRON IN ADI: 1995
Projected Demand (annual tons)
1.5e6
1e6
500000
0
120
140
160
180
200
Selling Price ($ per ton)

PART III

The 2nd INTERNATIONAL CONFERENCE on AUSTEMPERED DUCTILE IRON

The conference was held on March 17-19, 1986 at the University of Michigan in Ann Arbor, Michigan. The primary sponsors were: ASME - Gear Research Institute
ASME - Design Division
Amax, Inc.

The Co-Sponsors were:

American Foundrymen's Society
American Gear Manufacturers Association
American Society for Metals
British Cast Iron Research Association
Ductile Iron Society (USA)
German Foundrymen's Association
Iron Castings Society (USA)
Japan Ductile Cast Iron Association
Society of Automotive Engineers
University of Michigan

This 2-1/2 day conference was attended by 285-300 persons from worldwide, all with keen interest in ADI. The speakers at the conference were from the United States, West Germany, France, England, Finland, Sweden, Switzerland, and Japan. The general consensus seemed that the United States ADI technology was the furthest along the path of anyone. Good work has been done in England, West Germany, and Japan but overall progress has been the greatest in the U.S.

There were a few key points of criteria established at this conference which will affect successful production of ADI. First, the maximum austenitizing temperature which had been specified as high as 1700°F was recommended to be no higher than 1600°F. There could be a few exceptions to this but the range of 1550-1600°F appears to be the norm to use. Higher temperatures caused too much carbon to go into solution in the austenite which resulted in retained austenite in the matrix along with acicular ferrite and carbon rich stable austenite. This retained as untransformed austenite could transform to martensite and cause embrittlement of the ADI.

The second key point which seemed to have consensus was the maintenance of a maximum manganese level of .30%. Higher levels of Mn appear to cause uneven solubility of carbon leading to erratic fatigue and fracture toughness properties of the ADI. This lower manganese requirement is no doubt going to require a greater source of low manganese iron units as the production of ADI increases.

The third point was the expression of desirability of a high nodule count. A nodule count of $150/mm^2$ or higher was endorsed. This helps ensure better fatigue and wear properties as well as fracture toughness.

There were many examples of applications already converted to ADI from steel forgings, steel fabrications, steel castings, ductile iron castings, and even some gray iron castings. The main material being replaced will probably be steel forgings which are either Quench and tempered or carburize case hardened. No one fully addressed the question of machining before or after austempering which needs of further dialogue. This is an area of great concern due to potential uneven dimensional changes after the austempering.

Overall the outlook for the future of ADI was declared extremely healthy and there is a definite growing market.

APPENDIX A

(These guidelines were presented at the 2nd International Conference on Austempered Ductile Iron. specific chemistries and heat treating temperatures have already been changed by consensus although the enclosed could still be adopted by ASTM and other standards societies.)

GUIDELINES FOR AUSTEMPERED DUCTILE IRON

PREFACE

These guidelines are intended to serve as an aid to producers and heat treaters which will enable them to confidently make products that consistently meet the standards of reliability demanded by casting users. It is expected that these guidelines will be used by the various national and international organizations, responsible for standardization, to prepare realistic standard specifications for austempered ductile iron.

INTRODUCTION

Austempered ductile iron has been produced and used in a wide range of applications in the United States, Europe, and Japan since 1970. There are many variations in alloying as well as heat treating techniques. The response to the heat treatments for various compositions have been studied by many individuals in several countries. The results are published and show the wide variations possible by changing composition or heat treat cycle. It is necessary to have exacting process control of the ductile iron prior to austempering followed by a close control of the heat treat cycle.

In order to promote applications for austempered ductile iron (ADI), the Ductile Iron Society organized a committee of recognized experts to publish guidelines for the production of ADI. The mutually agreed-upon procedures can help a producer to make a product which will have consistent response to a controlled heat treatment process. This will result in a user having confidence that the castings he purchases will be uniform in quality piece to piece, day to day. The committee consisted of producers who recognized reasonable control requirements, researchers who have tested the properties of structure variations, technically oriented engineers who have observed the product of various companies all over the world, and users who have tested and applied ADI from a wide variety of sources and know the requirements necessary to be successful.

The members of the committee with their company association are as follows:

A. Alagarsamy	Grede Foundries, Inc.
D. Bowman	Caterpillar Tractor Company
R. Forrest	QIT-FER-ET TITANE, Inc.
J. Janowak	Climax Molybdenum Company
L. Jenkins	Ductile Iron Society
J. Koucky	Wagner Castings Company
D. Kretschmer	Brillion Iron Works
J. Lincoln	Atmosphere Furnace Company
J. Lonnee	Caterpillar Tractor Company
T. Majewski	Caterpillar Tractor Company
P. Mani	Wagner Castings Company
L. McFarland	Caterpillar Tractor Company
R. Quinn	Caterpillar Tractor Company
J. Wilkinson	Amcast Industrial Corporation

The Ductile Iron Society appreciates the time, expertise, and experience these men have contributed to the advancement and improvement of austempered ductile iron.

SECTION I

PRODUCTION CONTROL OF IRON FOR AUSTEMPERING

Segregation Statement:

Segregation is a major concern in the achievement of consistent mechanical properties. Composition, nodule count, and section size, influence the level of segregation. Segregation particularly interferes in obtaining toughness and short austempering time. In general, high nodule count and controlled alloy levels; (Mn, Mo, Ni, Cu, P, Cr, Si) are preferred. As section size increases, molybdenum is increased and manganese, chromium, and phosphorus are generally reduced.

The key requirement is to have a narrow composition range to ensure consistent heat treat response.

The target composition range shall be agreed upon between the user and producer and shall be held within the operating range.

Chemical Analysis:

Element	Element Range	Operating Range
Carbon [1]	3.2 - 3.8	± .20
Silicon [1]	2.5 - 3.0	± .15
Manganese [2]	.35 Max.	± .05
Phosphorus [3]	.03 Max.	
Copper	1.00 Max.	± .10
Nickel	3.00 Max.	± .10
Molybdenum	.50 Max.	± .05
Chromium	.07 Max.	
Titanium	.04 Max.	
Magnesium [4]	.06 Max.	
Others [5]		

NOTES:

1. Carbon and Silicon should be controlled to minimize porosity.
2. For a higher manganese content, a minimum nodule count must be agreed upon between producer and user.
3. For any phosphorus in excess of .03 maximum, agreement should be reached between casting user and the producer because of toughness consideration.
4. Maintain lower magnesium level which will produce satisfactory nodularity.
5. Tin, antimony and arsenic - the amount allowable will be agreed upon between casting producer and user.

SECTION II

MICROSTRUCTURE OF IRON PRIOR TO AUSTEMPERING

ASTM A 536 and AFS "Foundrymen's Guide to Ductile Iron Microstructures" are two recommended references for base ductile iron.

A. **Nodularity**

Graphite configuration shall be 80% minimum spheroidal conforming to ASTM A247, Type I and Type II at 100 X magnification.

B. **Nodule Distribution:**

Uniform nodule distribution preferred. Method of illustration to be developed.

C. **Nodule Count:**

Sufficient to minimize segregation. Specific numbers may be agreed upon by casting producer and user.

D. **Carbides:**

Goal is to have no carbides. Specific amount to be decided by agreement between casting producer and user.

E. **Porosity:**

Goal is to have no porosity. Specific amount to be decided by agreement between casting producer or heat treater and user.

F. **Percent Pearlite:**

Pearlite-ferrite as-cast ratio to be established by agreement between casting producer or heat treater and user.

G. **Inclusions and Matrix Cleanliness:**

Goal is to have minimum inclusions in the matrix.

H. **Segregation:**

Goal is to have no segregation which contributes to "white etching structure" distribution after austempering.

SECTION III

AUSTEMPERING HEAT TREATMENT

A. **Pre-Austempering Heat Treatment:**

1. Ferritizing heat treatment may be done on castings provided the maximum temperature used for ferritizing does not exceed the austenitizing temperature for subsequent austempering.
2. Castings shall not be quenched and tempered prior to austempering.

B. **Austenitizing Temperature:**

Austenitizing temperature to be maintained within ± 10°F. The specific austenitizing temperature is a function of:

1. Composition.
2. Starting microstructure.
3. Final mechanical properties desired.

Range for austenitizing temperature is 1500°F - 1700°F. Actual austenitizing temperature to be agreed between casting producer or heat treater and user.

C. **Austenitizing Time:**

Range 30 minutes - 2 hours at temperature.
Austenitizing time to be maintained within ± 5 minutes.

D. **Furnace Atmosphere:**

Controlled atmosphere desired to prevent scale, decarburization, and surface carburuzation.

E. **Time to Transfer the Castings to Quench:**

Depends on composition and section size and must be determined for each use and closely controlled to insure uniformity lot to lot.

F. **Austempering Temperature:**

Range 450°F. - 750°F. This temperature to be controlled within the range of ±10°F.

G. **Time at Austempering:**

30 minutes - 2-1/2 hours at temperature.
No more than ±10% variation in austempering time permitted once the desired time is established.
Specific austempering time to be established for each composition and to be agreed upon between casting producer and user.

NOTE: Excessive austempering time will reduce mechanical properties.

H. **Post Cooling:**
Castings, other than gears, shall be cooled so as to avoid martensite formation.

I. **Post Austempering Heat Treatment:**
Once the castings have been austempered, no tempering will be permitted.

J. **Re-Austenitizing:**
Reheat treatment of austempered ductile iron castings may reduce properties, therefore, it may only be done as agreed upon between casting producer or heat treater and user.

SECTION IV

MICROSTRUCTURE AFTER HEAT TREATMENT

A. The final microstructure of austempered ductile iron must be agreed upon between casting producer or heat treater and user.

B. The microstructure shall be free of "white etching structure" when etched with 2% Nital and viewed at 50 X magnification. Illustrations to be developed.

C. Photomicrographs of acceptable and non-acceptable structures must be generated between casting producer or heat treater and user.

D. Since metallographic techniques for austempered ductile iron are more critical than normal ductile iron, caution should be taken in interpreting structures.

E. The preferred microstructure of austempered ductile iron is a matrix containing bainitic ferrite and carbon enriched austenite.

F. Decarburization Restricted as follows on the surface:
   1. No decarburization allowed on machine surfaces.
   2. M.A.D. (Maximum Affected Depth in mm on unmachined surfaces equals 0.5 + (.02 times the maximum section thickness in mm.)
   3. No surface carburization permitted.

SECTION V

MECHANICAL PROPERTIES (MINIMUM)[1]

Grade	Tensile Strength		Yield Strength (.2% Offset)		Elongation	Brinell Hardness[3]		Impact Energy[2]	
	Ksi	N/MM^2	Ksi	N/MM^2		B.I.D.	B.H.D.	Ft. lbs.	Joules
1	125	860	80	550	10	3.40-3.70	269-321	75	105
2	150	1035	100	690	7	3.20-3.50	302-363	65	90
3	175	1205	120	830	4	2.90-3.20	363-444	45	65
4	200	1380	140	965	2	2.80-3.10	388-477	30	40

The mechanical properties are for test bars machined from 1 inch Y-blocks in accordance with ASTM A-536.

1. In accordance with A.S.T.M. E-8.
2. Unnotched Charpy (A.S.T.M. E-23) at 22C± 7C.
   Four specimens tested, lowest value discarded, then average the remaining three. The average must meet the minimum requirement.
   Frequency of the impact test to be by agreement between casting producer or heat treater and user.
3. Hardness does not assure indicated properties.

REFERENCES:

A.F.S. Foundrymen's Guide to Ductile Iron Microstructures.
A.S.T.M. A247
A.S.T.M. A536-84
A.S.T.M. E-8
A.S.T.M. E-23